Figure 9.13: Lowering of the barrel LAr calorimeter down to the cavern in October 2004. The first barrel toroid coil can also be seen on a temporary support platform before it is installed in the cradles of the feet.

Side C: barrel calorimeter. The lower part of the tile calorimeter was lowered in March 2004. Individual tile calorimeter modules were then assembled together, one by one, until 32 of the 64 modules were completed. The LAr barrel calorimeter cryostat was then lowered into this half-cradle in October 2004, as shown in figure 9.13. The tile module assembly was then continued until the mechanical assembly of the full barrel calorimeter was completed.

Barrel: completion of barrel toroid and calorimeter installation. The last aluminium girder was put in place in September 2005, completing the mechanical assembly of the barrel toroid structure. Then the hydraulic jacks, which were supporting the complete structure during the assembly, were released. At this moment the load was transferred from the external temporary supporting structure (used during the magnet assembly) to the support feet at the bottom. The temporary support structure was then cut and removed to give space for the barrel calorimeter, which was moved inside the barrel toroid in October 2005.

9.6.3 Phase 3: end-cap calorimeters and muon barrel chambers

Side C: end-cap calorimeter. With the barrel calorimeter installed inside the bore of the magnet, the space on side C was now vacant for the assembly of the first end-cap calorimeter. This assembly was very similar to that of the barrel and was finished in January 2006. It was then moved inside the barrel toroid in February 2006, once the installation of the services (pipes, cables, etc.) was completed.
Figure 9.14: View of installed barrel muon spectrometer stations and end-cap calorimeter on side A.

Figure 9.15: View of barrel calorimeter and inner-detector end-flange after installation of the first inner-detector end-cap in early June 2007 (left). This was followed shortly thereafter by the installation of the second inner-detector end-cap and of the pixel detector with the central VI section of the vacuum pipe (right).

Side A: barrel muon chambers and end-cap calorimeter. On side A, the first of the 656 barrel muon chambers was installed in February 2006. When the assembly of the second end-cap calorimeter started in March 2006, it had to be carried out in parallel with the muon-chamber installation. The second end-cap calorimeter was mechanically completed in May 2006. It stayed outside the barrel toroid for a further two months for the installation of the services while the end-cap calorimeter on side C was moved to its nominal position and the magnetic field of the solenoid was switched on and measured in June 2006 (see section 2.2.4).
9.6.4 Phase 4: muon big wheels, inner detector and completion of muon barrel

Side C: big wheels. In April 2006, work started on the first end-cap muon middle station (often referred to as a big wheel) with the mounting of the tooling on the end-wall structure (HO). The first sector was installed in July 2006. Work progressed with an average rate of two sectors per week and this first wheel was mechanically completed in September 2006. After installing the services, the wheel was released from the end-wall structures and moved against the barrel magnet in November 2006.

In March 2007, the second of four big wheels was completed and the first wheel was then opened for the lowering of the inner detector end-cap C. Also all the remaining barrel muon chambers were installed before closing the end of the barrel on side C with the completed big wheels.

Side A: big wheels. After finishing the solenoid field mapping, the barrel section of the inner detector was lowered and installed inside the bore of the barrel cryostat in August 2006. While the work on the connections of the inner detector services continued, the end-cap calorimeter was moved partially inside to allow space for the completion of the muon barrel chambers. By the end of December 2006, 600 chambers or 90% of the total, had been installed (see figure 9.14).

In January 2007, the preparations for the muon big-wheel assembly started. The first sector was installed in March 2007, because the end-cap calorimeter needed to be moved to the open position to allow the lowering of the first inner detector end-cap.

Barrel. The installation of the barrel muon chambers continued in parallel with the assembly of the first muon big wheels. The installation of the services for the inner detector, calorimeters and muon chambers also continued. In May and June 2007, the two inner detector end-caps and the pixel detector together with the central VI section of the beam-pipe (see section 9.8) were lowered into the pit and installed, as shown in figure 9.15.
9.6.5 Phase 5: end-cap toroid magnets and muon small wheels

The two end-cap toroids were lowered onto the trucks in June-July 2007, as illustrated in figure 9.16. The muon end-cap small wheels were assembled to the shielding disks on the surface and installed in February 2008 (see also chapter 11).

9.6.6 Phase 6: beam-pipe and forward shielding

The last elements to be installed will be the beam-pipe and the forward shielding, and this will require that all the sub-systems are progressively moved into their closed positions along the beam axis.

9.7 Access and detector opening

9.7.1 Access scenarios

Three access scenarios have been defined, depending on the duration of the shutdown period and the degree of dismantling of the detector. These can be characterised as follows:

1. Very short accesses are typically of the order of a few hours. Such accesses can be provided immediately after the machine shut-down. They can happen on a daily basis, but are not scheduled. As a consequence, no detector components are moved and the access shaft to the surface is not opened (there is therefore no crane access through the shaft). All magnetic fields stay on.

2. Short accesses have a duration from a few weeks to five months. The shorter ones will be based on the needs of the ATLAS sub-systems. In agreement with the other sub-systems, the other LHC experiments and the LHC machine, such accesses can be provided for a short period. Short access is also considered as the standard configuration during the annual LHC shut-down for a period of approximately five months.

During such accesses, the cavern shaft is opened so that crane access to the surface is possible. The removable elements of the forward shielding (see section 3.2) are brought up to the surface, while the muon big wheels, the end-cap toroids, the small wheels and the end-cap calorimeters can be moved along the beam axis. The beam-pipe is left in place, but at atmospheric pressure, and flushed with very pure neon gas (see section 9.8). All magnetic fields are turned off. A maximum of ten persons are allowed inside at each end of the detector.

3. Long accesses are dedicated to the inner detector and small-wheel removal and installation. Such accesses are also for non-standard interventions, which require a break of the beam-pipe. Their duration is the same as that of the LHC annual shut-down (of the order of five months), but their frequency is expected to be much lower and will be related to requests of the experiment for a detector upgrade or for a major maintenance operation. In contrast to short accesses, the beam-pipe is dismantled and one of the end-cap toroids is moved sideways. A second truck is installed along the axis of the detector in order to move back the corresponding small wheel and lift it to the surface. The corresponding end-cap calorimeter
is moved back so that sufficient access is possible to the inner detector. All magnetic fields are turned off. The number of people allowed access is defined according to the evacuation plan of the cavern and the detailed operations which need to be performed.

Given the high levels of induced radioactivity expected in the regions of the detector closest to the beams, as discussed in section 3.5, strict access control and compliance with regulations as laid out in section 9.9 will be of paramount importance during access to any part of the main cavern.

### 9.7.2 Movement system

During access, a number of sub-systems move into their position on air-pads: the end-cap toroid magnets, the shielding disks (small wheels) and the end-cap calorimaters. The equipment for each detector movement system is basically the same: in the closed configuration, the detectors rest on hydraulic cylinders called blocking jacks. They are equipped with nuts so that the load can be transferred to solid feet, without the need for oil pressure. During movement, the load is transferred from the blocking jacks to the air-pads, which consist of two main components: a rubber air-skirt, which allows the lifting of the detector on a thin film of air, and a hydraulic jack, which allows for the height to be adjusted to a set limit during the movement. Thus, the detector can slide on its rails using the air-pad system with a low friction factor of 0.01. The number of air-pads underneath a sub-system will depend on its weight. They are grouped so that the load is supported by three iso-static points. The movement itself is provided by two hydraulic cylinders, parallel to the rails, and the detectors are moved step by step according to the stroke of the cylinders.

Because of the sensitivity of the detectors to vibrations, shocks, or tilt, the movement must be smooth and well controlled. Moreover, the clearance between detectors and the beam-pipe is only about 15 mm, a distance of similar size to that of the air-pad lift. Therefore a compensation of the pneumatic action has been implemented, so that the sub-system under air-lift is not raised by more than 5 mm. Four height sensors, located on each mobile sub-system, provide feedback to the controller, which drives the hydraulic valves of the air-pads.

The movement of the sub-systems is further complicated because of the services connected to them through the drag-chains, as described in section 9.4. Some of these chains are equipped with their own movement system, therefore it is necessary to monitor these movements with respect to those of the main movement system.

### 9.8 Beam-pipe

The beam vacuum system represents the main interface between the experiment and the LHC machine. It must therefore fulfil a dual set of requirements:

- the ATLAS requirements, particularly excellent transparency to particles, limited beam-gas backgrounds and conformity with environmental constraints, in terms of radiation, electromagnetic noise and thermal behaviour;
- the accelerator requirements, namely safe operation of the machine, adequate beam aperture and static and dynamic vacuum conditions compatible with the ultimate LHC performance.
The ATLAS beam vacuum system consists of seven beam-pipes of 38 m total length, spanning the distance between the two TAS collimators located at each end of the cavern. They are bolted together with flanges to form an ultra-high vacuum system, which can be fully baked out in situ. The central chamber, called vacuum inner detector (VI), is centred around the interaction point. It has an inner diameter of 58 mm and is constructed of beryllium metal with a thickness of 0.8 mm (see figure 4.34). The remaining six chambers are installed symmetrically on both sides of the interaction point and named after the detector, which supports them: VA (vacuum argon end-cap), VT (vacuum toroid end-cap) and VJ (vacuum forward shielding). They are constructed of thin-walled stainless steel tubes with diameters increasing progressively from 60 mm to 80 mm and finally to 120 mm. Chambers inside different detectors are mechanically decoupled by vacuum bellows, which also serve to absorb thermal expansion during bake-out.

The VI chamber was integrated into the pixel detector on the surface, and installed as part of the pixel package (see section 4.8.1). It is aligned on the beam axis using a system of laser and CCD cameras, which measure the chamber deformation. The VA chambers are centred inside the warm bore of the LAr end-cap cryostats by sliding supports, which allow the detector to move longitudinally along the beam-pipe. Special minimised ultra-high-vacuum flanges, with only 35% of the volume of a standard flange, have been developed to pass through the bore. The VT chambers are held by retractable jack supports on rails in the forward shielding. These can be adjusted from the back-face of the end-cap toroid or fully retracted to allow the end-cap toroids to move longitudinally along the beam-pipe. The VJ chambers are cantilevered from the forward shielding located on the cavern wall, inside a conical support designed to fit inside the opened end-cap toroid. The flanges between the VJ chambers and the TAS collimators are remotely actuated from the outside of the forward shielding, because of the high activation expected in this region at design luminosity.

This supporting system is conceived to allow ATLAS to rapidly move to a short access without the need to open the beam vacuum to air and hence re-activate the Non-Evaporable Getter (NEG) system (see below). However, the chambers are not able to support the stresses induced by offsets expected during opening whilst under vacuum. The chambers will therefore be vented to neon gas at atmospheric pressure, purified to the ppb level by a specially developed gas-purifying system mounted on side A of the HO structure. Neon is not pumped by the NEG system, so the beam vacuum system can be rapidly made operational at the end of a short intervention by simply re-pumping the neon gas.

The main pump used to eliminate desorbed gasses in the system is a non-evaporable getter (NEG) film sputtered onto the whole of the inner surface of the beam-pipe. After activation by heating the beam-pipe to ~ 200°C, this NEG film gives a very high distributed pumping speed for chemically active gasses. Chemically-inert gasses not pumped by the NEG system are removed by two minimised sputter-ion pumps [246] at ± 3.8 m and by larger pumps at ± 19 m from the interaction point.

The whole length of the vacuum system is permanently equipped with a mass-minimised system of heaters, thermocouples and insulation which allow the NEG system to be re-activated annually. This bake-out system consists of polyimide-foil heaters wrapped with silica aerogel, polyimide tape and aluminium foil. Flexible bellows, pumps and transitions are equipped with semi-permanent flexible heating jackets.
Significant optimisation of the forward beam-pipe chambers is planned for the LHC machine upgrade, as discussed in section 3.5. Stainless steel will be replaced by aluminium or other low-Z materials wherever possible to minimise both the background radiation in the muon chambers and access problems due to beam-pipe activation.

9.9 Safety in ATLAS

The safety responsibilities for ATLAS include the safety of the personnel as well as the protection of the environment, equipment and infrastructure during the installation and the various phases of operation of the detector (data-taking, access and maintenance).

The main risks are located in the underground experimental area, especially in the main cavern and the adjacent technical-service caverns. A risk assessment of these areas has been performed prior to the beginning of the installation. This was continuously revised and updated during installation and commissioning. The main risks are human operational errors, fire, cryogenic-fluid leaks, and radiation during beam operation. There are also dangers linked to the presence of magnetic fields, electrical hazards, laser beams, flammable gases and CO$_2$ gas. Other risks are related to the mechanical integrity of the detector components, in the case of major incidents or even of seismic events.

Potential risks, pertaining to the installation process of the various components, as well as to all operations of opening and closing of the detector during the shut-down periods, have received special attention. These risks are associated with the difficulties related to working at heights, to multiple parallel activities carried out by various working teams, which have to share the same working space, and to the manipulation tools for heavy objects. In order to minimise such risks, actions are taken at various levels:

- a safety organisation has been established in the experimental area and is enforced with an effective in situ presence;
- all activities are managed via the concept of work packages. Each activity is prepared, described and analysed before work can commence. All safety issues are discussed, and tasks optimised as appropriate to minimise risks;
- access to the underground areas is restricted to specialised and trained personnel;
- safety aspects are considered from the early design phase of the equipment and infrastructure, through all the installation and commissioning phases. For example, the barrel toroid coils have been equipped with surface-mounted heaters to warm the eight magnet cryostats and thus prevent condensation and ice formation in the event of a vacuum loss of the magnet system;
- safety systems have been designed and implemented to detect at a very early stage any possible sources of danger and to activate alarms and trigger the required safety actions;
- all alarm informations concerning underground safety and access are collected and managed in the ATLAS control room by the Shift Leader In Matters Of Safety (SLIMOS). This person acts in real time, a necessary condition to guarantee the highest level of safety for all personnel and equipment.
- specialised safety courses are required for all personnel working underground;
- dedicated courses for people doing specialised work such as electrical power, etc.

9.9.1 Organisation of safety

The ATLAS safety organisation is led by the GLIMOS (Group Leader In Matters Of Safety). The GLIMOS supervises the various activities, the specialised safety officers and the territorial safety officers, who are responsible for the safe operation of the underground areas and surface buildings. The specialised safety personnel includes officers for radiation protection, cryogenics, lasers, flammable gases, and electrical hazards. The territorial safety officers are responsible for the safety of the buildings and underground areas around the ATLAS site. Their duty, in particular for the underground area, is to ensure daily safety controls and visual inspections and to take appropriate actions where required. For the main cavern, given the size and the complexity of the work during installation or access, the territorial safety officer leads a team of technicians.

There is also an external safety coordinator, who leads a small independent team to verify the safety-condition levels inside the experimental area. This team has been active during the construction phase and will be kept operational during the access and maintenance periods. This group is reinforced by a team of engineers, who are in charge of supervising the installation, the commissioning and the maintenance of the various safety systems (see section 9.9.3).

From the beginning of the LHC operation, an additional safety organisation will be put in place around the SLIMOS in the ATLAS control room. The SLIMOS will be continuously on duty, as described in section 9.9.5.

The work packages for the underground activities are agreed upon and are integrated into the general planning to minimise overlap of work and resolve potential conflicts. These work packages cover all activities, from infrastructure or detector installation, to commissioning or maintenance work, and to the movements of heavy objects. A work package is declared active only when all crucial technical and safety issues have been reviewed and agreed upon.

9.9.2 Access control

9.9.2.1 General aspects

Access to the underground areas is restricted to persons who participate in an ongoing declared activity (work package), are authorised and have completed specific safety-training courses. These cover, in addition to the standard general safety training, specific training associated with the hazards which may be encountered in ATLAS: evacuation of the underground areas, cryogenic risks, hazards associated with static magnetic fields, radiation protection, electrical hazards, and handling and removal of equipment inside the caverns.

The control of the access authorisation and the verification of the training and personal biometrical parameters are performed by the LHC access control and safety systems. Personnel and material access control devices are implemented at the top of the lifts and at the entry points of the ATLAS main cavern. In addition to these checks, the access system of the main cavern (UX15) will deliver to each person a safety token during controlled accesses.
9.9.2.2 INB regulations

By a convention signed in 2000, CERN and the French nuclear authorities have agreed to apply the INB (Installation Nucléaire de Base) rules and regulations to the LHC machine and experiments. These rules and regulations govern and impose stringent limitations on the operation, maintenance and future dismantling and disposal of the ATLAS detector. They are written down in two documents, the Règles Provisoires de Sûreté and the Règles Générales d’Exploitation. In particular, they define yearly integrated dose-rate limits and assign specific labels to different regions of the detector depending on the induced activation.

For what concerns the long term and in particular the final disposal of the ATLAS detector, the regions of ATLAS closest to the beams have already been classified as radioactive, whereas regions further away from the beams will remain classified as conventional. This is based on calculations using as input a scenario corresponding to ten years of operation and two years of cool-down.

Detailed rules of operation are therefore required, in particular for managing the flow and traceability of equipment and materials to and from the experiment. The procedures for radiological controls of material from the main cavern are being documented and the ATLAS control procedures will be put in place soon. All equipment leaving the cavern will be measured for radioactivity and tracked.

9.9.3 Safety systems

Following the various risk assessments related to the underground work environment and especially the ones concerning fire and cryogenic leaks, a number of dedicated safety systems have been implemented under the direct supervision of the ATLAS GLIMOS and of the CERN Safety Commission. These safety systems have been designed and implemented so as to detect at a very early stage any event which might endanger the safety of personnel, environment or ATLAS equipment. The readout of most of these systems uses the standard DCS tools described in section 8.5 (ELMB, CANbus and basic communication software).

9.9.3.1 Hazard-detection systems

The main and service caverns are equipped with standard detectors, which detect the presence of smoke inside the infrastructure and service areas of the caverns. The electronics racks have been equipped with smoke-detection points and some of them with an associated CO2 gas extinguisher system.

Due to the large quantity of liquid argon (84 m3) in the three LAr cryostats, which might fill a large part of the main cavern in only a few minutes with an asphyxiating gas in case of a catastrophic failure, three large trenches have been built in the floor of the cavern. In case of a major leak, the cryogenic liquids and the cold and heavy gases would be contained in these trenches. Access is restricted to these areas and there is an oxygen-deficiency detection system installed. In normal conditions, air is permanently extracted from the lowest point of these trenches. If a leak is detected, the gas extraction can be increased to a massive rate of 32,000 m3/h.

The TGC’s in the small and big wheels are filled with a flammable gas mixture (see section 6.8 and table 9.5). Their distribution racks have therefore been equipped with flammable-gas
detection heads. The internal areas of the ATLAS detector are equipped with air-sampling tubes or sniffers, which may detect the presence of smoke, CO$_2$ or flammable gases, and hence a subsequent deficiency of oxygen. These tubes run on the inside of the various sub-systems and along the detector platforms. They serve as a protection of equipment and personnel working inside the ATLAS detector.

The barrel toroid warm structure, which supports the eight barrel toroid coils, is made of aluminium. In case of a major fire inside the ATLAS detector, the aluminium will begin to lose part of its structural properties at a rather low temperature of approximately 200°C. In order to minimise the risk of any mechanical-instability problem of the toroid warm structure, temperature sensors are fixed on these aluminium parts. These send the temperature information to the ATLAS SLIMOS desk in the control room.

The various safety systems, fixed detection systems and sniffers, generate alarms. Two different alarm-threshold values are defined for each type of detection. The first threshold generates a warning and triggers preventive actions on the ATLAS detectors via the Detector Safety System (DSS). The second threshold indicates that there is a serious danger to the personnel or the environment, which requires the immediate intervention of the fire brigade. In addition, this second threshold also triggers the evacuation from the ATLAS underground areas and immediate actions on the detector via DSS and on the infrastructure (for example, modification of the cavern-ventilation configuration as described above in the case of a cryogenic leak).

9.9.3.2 Foam extinguishing system

In addition to standard fire-fighting means, such as portable fire extinguishers and hose reels, a foam extinguishing system has been implemented in the vault of the cavern. This foam system may be used in the extreme case, to protect the detector and the CERN firemen in the event of a fire getting out of control. The system consists of 12 large blowers installed in the vault of the UX15 cavern which are fed by a mixture of water and detergent and can fill-up the cavern in less than 15 minutes, suffocating any fire. Since this foam has only a 1/1000 water content, personnel trapped in the foam would survive without problems until the foam settles (approximately one hour). Tests have also demonstrated that the foam does not penetrate into electronics racks.

9.9.3.3 Finding people inside ATLAS

The FPIAA system (Finding People Inside ATLAS Areas) detects the presence of persons in all areas of the ATLAS main cavern, including those inside the detector itself. This system does not require any special device to be worn by the personnel. It is based on the use of approximately 500 passive infra-red sensors, appropriately modified to be radiation-tolerant and to operate in a magnetic field. Each one of the 500 small volumes in the cavern and inside ATLAS is continuously monitored: if a person were to disappear without reappearing in the adjacent volume, an alarm would be generated.
9.9.4 Detector safety system

The Detector Safety System, DSS [247], is the central tool to bring (parts of) the ATLAS detector in a safe state in cases when an abnormal operational situation arises or a safety hazard is detected. Its main task is to protect the detector equipment. DSS works ATLAS-wide, i.e. across sub-detector boundaries and including all common infrastructure components of the ATLAS detector. It has its own sensors to detect potentially dangerous situations (e.g. over-temperatures) and receives input from the hazard detection systems described in section 9.9.3. This information is collected by DSS stations distributed over the different counting rooms and is analysed centrally by a redundant system based on programmable logic controllers. In a matrix-like fashion, all input signals can be combined by logic operations to trigger the appropriate action, usually a shut-down procedure of the relevant equipment. This process is fully automatic: operator intervention is only needed to analyse and correct the fault and to bring the detector back into operation. Care has been taken when implementing the DSS system not to rely on external services, such as computer networks or normal electricity supplies. The principle of positive safety has been used throughout, i.e. in case of missing sensor information or possible internal system problems of DSS, all relevant safety actions are executed. A dedicated operator interface in the ATLAS control room provides the SLIMOS with the detailed status of the DSS at all times.

9.9.5 Safety during operation

As described above, the safety organisation and access control will be coordinated during operation around the SLIMOS desk in the ATLAS control room. Responsibility for access control will normally be transferred to the SLIMOS from the central LHC control room (CCC). The SLIMOS will be in charge of controlling in real time the safety conditions inside the cavern via the various safety systems described above. The SLIMOS will also be responsible for providing information to the fire-brigade on the status of the main cavern and the detector, including: beam status, configuration of the detector, detailed instructions for accessing the region of intervention, number of people in the underground areas, radiation levels and environmental conditions, relevant information concerning the status of the ATLAS detector and the infrastructure (cooling, cryogenics, magnets), and status of all possible safety alarms.

9.10 Interface to the LHC machine

For safe and optimal operation of both the LHC machine and the ATLAS detector, the two parties will continuously exchange information about their overall status as well as about the status of relevant individual sub-systems. This data exchange will be used to synchronise actions during the different states of operation, to provide online feedback on tuning operations, to rapidly react to errors, and to understand quickly and efficiently their causes.

ATLAS and the LHC machine exchange most data over the network through the DCS information server (see section 8.5). In addition, dedicated hardware links are used for critical signals that have to be transmitted on time and in a reliable fashion, such as the beam permission signals and timing signals.
Table 9.6: Main operational parameters of the LHC machine for a few configurations: the nominal one (left), the initial one with a bunch spacing of 75 ns (centre), and the specialised one for the measurement of the total cross-section (right).

<table>
<thead>
<tr>
<th>Machine operation configuration</th>
<th>Nominal</th>
<th>75 ns</th>
<th>Roman pots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of bunches</td>
<td>2808</td>
<td>936</td>
<td>43</td>
</tr>
<tr>
<td>Number of protons per bunch (10^{11})</td>
<td>1.15</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25</td>
<td>75</td>
<td>2025</td>
</tr>
<tr>
<td>(\beta) function at the interaction point (m)</td>
<td>0.55</td>
<td>1–11</td>
<td>2625</td>
</tr>
<tr>
<td>Crossing angle ((\mu)rad)</td>
<td>285</td>
<td>250</td>
<td>0</td>
</tr>
<tr>
<td>Peak luminosity (cm(^{-2})s(^{-1}))</td>
<td>(10^{14})</td>
<td>(10^{13})</td>
<td>(10^{28})</td>
</tr>
</tbody>
</table>

The LHC communicates to ATLAS the total beam and individual bunch intensities, the average 2-dimensional beam size, the average bunch length, the luminosity at the four interaction points, the average beam loss, and the average horizontal and vertical beam positions. Table 9.6 lists basic beam properties for some of the interesting configurations envisaged for machine operation.

ATLAS reports to the LHC information that allows the machine to optimise and monitor the conditions of the beams, in particular the quality of collisions and machine-induced backgrounds. Experience from previous colliders shows that the machine-induced background in the detectors is very hard to predict. A number of different factors intervene in a complex manner:

- the local vacuum pressure as well as the vacuum at more distant places, such as the arcs, affects the halo entering the detector;
- inefficiencies of both the betatron and momentum-cleaning systems and the detailed settings of the collimators will also heavily influence the observed background levels;
- other factors, which have a direct impact on the beam halo, are of course the total beam current, the beam tune shift and the orbit positions.

It is therefore of prime importance to the experiment to define reliable background indicators and to communicate them to the LHC control room. These background indicators must be continuously available to the operating crew for monitoring, in particular before stable beam conditions have been reached during the setting-up phase of the machine. They must therefore be available in the experiment independently of the main data acquisition. The ATLAS beam conditions monitor (or BCM as described in section 3.4.1) meets these requirements and will be used in this context.

Among the parameters that ATLAS sends to the LHC are: the total luminosity, the luminosity per bunch, indicators for quality of collisions and amount of machine-induced backgrounds, counting rates for individual bunches, and the position and size of the luminous region.

The 40 MHz bunch clock of the LHC and a pulse per revolution is transmitted from the LHC radio-frequency system at point 4 to ATLAS over a total length of 14 km of optical fibre. Once
received in the ATLAS counting room, these signals are fine-adjusted in phase and distributed via
the L1 central trigger processor to all ATLAS sub-systems (see section 8.2.3).

ATLAS receives for each beam one signal from a beam position monitor, which is located
175 m upstream of ATLAS. These signals provide a precise timing reference in order to monitor
the phase of the LHC clock with respect to the bunches. In addition, they serve as inputs to the
L1 trigger, for which they provide a filled bunch trigger signal for each beam and a time reference
with respect to the abort gap of the LHC bunch train.

When in operation, the LHC machine undergoes a sequence of operational modes such as
filling, ramping, adjust, stable beams, and unstable beams. The current machine operational mode
is received by ATLAS via software, which is appropriate in most cases for synchronising ATLAS
operation with LHC operation. Before a state transition, a hand-shake protocol between the LHC
and ATLAS is used: the LHC operators request from ATLAS confirmation before going into e.g.
the state (adjust mode), where the low-β squeeze and other adjustments take place. A similar
protocol is used before a scheduled beam dump by the LHC operator.

A fail-safe and reliable beam interlock system is installed around the LHC ring, with sev-
eral systems giving permission for beams. The absence of a beam permission signal leads to an
immediate beam dump: the safe extraction of the beam from the LHC in less than 300 µs. The
ATLAS beam interlock system (BIS) consists of three parts, each of which gives beam permission:
the detector BIS, the spectrometer magnet BIS and the Roman-pot position BIS. The detector BIS
takes inputs from the BCM and possibly other detectors and gives beam permission only when
background conditions allow safe operation of the detector.

Additional flags related to the machine modes are transmitted from the LHC to ATLAS
through a fast, safe and reliable hardware link, as they are used in the context of the movement
control of the Roman pots and for the Roman-pot position BIS (see section 7.2). The ATLAS
BIS is complemented by additional interlocks, for instance to inhibit injection into the LHC and
to apply more sophisticated logic. The system is flexible enough so that it can evolve with the
experience obtained in the operation of the LHC and ATLAS.
Chapter 10

Expected performance of the ATLAS detector

10.1 Introduction

Since the publication of the ATLAS Detector and Physics Performance Technical Design Report [248] in 1999, all the detector components of the experiment have been constructed and integrated and most of them have been installed (see section 9.6). A detailed understanding of their features (geometry, amount of material and placement accuracy) has been achieved over this period, as described elsewhere in this article.

The purpose of this chapter is to present an overview of the main performance features of the ATLAS experiment, as expected today from the latest round of simulations and the current version of the reconstruction software and as validated wherever possible using test-beam measurements. It is therefore a snapshot of the present understanding of the performance of the detector. Somewhat in contrast to earlier documents, in particular the Detector and Physics Performance TDR [248], the performance results presented here will focus on the initial low-luminosity scenario for the beginning of data-taking at the LHC. Since the luminosity is expected to rise over the first year or so from $10^{31}$ cm$^{-2}$ s$^{-1}$ to $10^{33}$ cm$^{-2}$ s$^{-1}$, most of the results presented below will correspond to simulated events without pile-up nor neutron background (see section 3.1), except in certain explicit cases where their contributions at luminosities of $\approx 10^{33}$ cm$^{-2}$ s$^{-1}$ have been considered.

The first two sections are devoted to the expected tracking performance in ATLAS and its powerful but complex magnet system (see chapter 2). The overall expected performance of the inner detector is described in section 10.2, while that of the muon spectrometer, both stand-alone and combined with the inner detector, is presented in section 10.3. Sections 10.4 (electrons and photons), 10.5 (hadronic jets), 10.6 (missing transverse energy), 10.7 (hadronic $\tau$-decays), 10.8 (tagging of heavy flavours) and 10.9 (trigger) describe the expected performance of the overall ATLAS detector with respect to triggering, reconstruction, identification and measurement of the major final-state objects over the required range of energies for most of the physics channels of interest at the LHC.
10.1.1 Realistic data challenge

Over the past seven years, a large and modular suite of software tools for simulation and reconstruction has been developed and integrated into the ATLAS computing model and first full-scale exercises of the operation of this computing model have begun. A large number of high-statistics samples of Monte-Carlo events have been run through the complete ATLAS simulation, reconstruction and analysis chain to assess the readiness of the overall system to cope with the initial data. Results from this data challenge, in particular from its calibration and alignment component, will be presented wherever relevant in this chapter.

As part of the preparations for initial data-taking, the simulation software has been adapted to describe and simulate, in addition to the ideal ATLAS detector description most commonly used, an ATLAS experimental set-up with alignment and placement shifts which are similar in size to those anticipated in the real detector. These have been included from macro-assembly to individual module level, as for example in the inner detector. In addition, magnetic field and material distortions have been included wherever relevant, as well as calibration distortions of the electromagnetic and hadronic calorimeters for certain specific studies. The results presented here are based on many tens of millions of events, originating from a variety of physics processes and event generators, and with the detector response simulated using GEANT 4 (version G4.7.1.p01 and QGSP GN physics list) [220, 249].

The results published more than eight years ago in ref. [248] correspond to a detector description which is quite different from the current one. Several real changes happened to the layout of the ATLAS detector:

- the $\eta$-coverage of the TRT has been decreased from $|\eta| < 2.5$ to $|\eta| < 2.0$, resulting in a significant loss of performance in that region (momentum resolution, tracking performance and electron identification);

- the end-cap cryostats and the extended barrel tile calorimeters have been recessed by 40 mm in $z$ to make room for inner-detector services;

- certain end-cap muon chambers dedicated to momentum measurements in the transition region between the barrel and end-cap toroids have been deferred in terms of construction and installation in ATLAS, resulting in a significant loss in stand-alone performance (efficiency and momentum resolution).

In addition, the description of the installed detector has improved considerably:

- the amount of material in the inner detector and just in front of the electromagnetic calorimeter has increased substantially;

- the amount of material in the muon spectrometer has increased substantially in several areas.

For these reasons, the expected performance is somewhat worse than that published in ref. [248]. Only the most striking examples can be given in this article:

- the 25% degradation in the expected resolution for the invariant mass of four muons from Higgs-boson decay for $m_H = 130$ GeV reconstructed in stand-alone mode (see figure 10.40).
This degradation is due in equal proportions to the missing chambers in the transition region between the barrel and end-cap toroids and to the increase of the material in the description of the muon spectrometer;

- the 12% degradation in the expected resolution for the reconstructed invariant mass of four electrons from Higgs-boson decay for $m_H = 130$ GeV (see figure 10.60) and of two photons from Higgs-boson decay for $m_H = 120$ GeV (see figure 10.61);

- the expected degradations in performance are smaller for other channels such as $Z \rightarrow \tau\tau$.

The model of the set-up used for the results presented here differs nevertheless from the reality in the ATLAS cavern, as it is has been described in the inner-detector, calorimeter and muon-spectrometer chapters, in several important respects since it had to be frozen for large-scale simulation:

- the amount of material in the inner detector has increased in some services regions of the active volume by a few percent of a radiation length, $X_0$ (at maximum 7% $X_0$);

- the amount of material in the inner detector outside the active volume and therefore near to the barrel and end-cap cryostats of the LAr calorimeter has increased by substantial amounts in certain regions: by 3.5% $X_0$ for $|\eta| < 0.7$, by 35–40% $X_0$ for $|\eta|$ increasing from 0.8 to 1.1, by 50–80% $X_0$ for $1.1 < |\eta| < 1.8$ and by 15% $X_0$ for $1.8 < |\eta| < 2.2$;

- the amount of material in the muon spectrometer is larger in certain areas than what has been included in the detector description for the results presented here. The largest missing items are the support structures for the small and big wheels (a few tens of tonnes), the saddle support structures for the barrel calorimetry, the inner-detector PP2 patch-panels, and more generally specific mechanical supports and services throughout the muon spectrometer. The uncertainties on the knowledge of this extra material will remain large until the installation of the last few macro-components in the pit has been completed.

### 10.1.2 Combined test-beam

The understanding of the detector components has improved considerably over the many years of construction, especially with extensive measurements in test-beams of the stand-alone and combined performance of the various calorimeters in the H6 and H8 test-beam facilities at CERN. The main results of these measurements are summarised in section 5.7.

A dedicated effort to understand the combined performance of a complete slice of the ATLAS detector, from the pixel detectors to the outermost stations of the muon chambers, took place in 2004 with the large-scale combined test-beam (CTB) exercise. Figure 10.1 shows a sketch of the layout of the CTB set-up, and figures 10.2 and 10.3 show respectively pictures of some of the actual tracking and calorimeter components and of some of the muon chamber components, as they were operated in 2004.

This effort has led to an improved detector description, and also to first sets of detailed calibration and alignment procedures, essential to the initial understanding of the detector performance.
and to the extraction of the first physics results. The main results obtained from these measurements and from their comparison to the detailed simulation of the detector (used both for the CTB and for ATLAS itself) are presented in this article:

- the inner-detector alignment results are presented in section 10.2.2;
- the TRT electron identification results are presented in section 10.2.5;
- the muon-chamber alignment results are presented in section 10.3.2;
- the electromagnetic calorimeter energy measurement results are presented in section 5.7 together with all the other test-beam results related to stand-alone and combined calorimeter performance;

A general consequence of the various combined calorimeter test-beam efforts and of the CTB data analysis in particular is that the detector description of the barrel electromagnetic calorimeter and the calibration software of the various calorimeters have been considerably refined to reach agreement between test-beam data and simulation. These refinements are fully integrated into the ATLAS software framework for the experiment itself, a necessary condition to the desired tight coupling between test-beam simulation and data analysis and the actual simulation of physics collisions in ATLAS.
Figure 10.2: Picture of the combined test-beam set-up for the inner detector and the calorimeters. The beam particles come from the left of the picture, traverse the magnet and then hit the calorimeters on the right side of the picture. On the left, just behind the pole tips of the magnet in which the pixel and SCT modules were installed, are the barrel TRT modules. On the yellow rotating support table is the cryostat housing the LAr electromagnetic calorimeter modules and behind it (right side of the picture) are the tile calorimeter barrel (not visible) and extended barrel modules.

Figure 10.3: Picture of the combined test-beam set-up for the end-cap muon chamber system. The beam particles come from the right side of the picture, traverse the barrel muon chamber set-up, which is mostly hidden by the concrete blocks, and then go through three stations of end-cap MDT and TGC chambers.
10.2 Reconstruction and identification of charged particles in the inner detector

Charged particle tracks with transverse momentum \( p_T > 0.5 \text{ GeV} \) and \( |\eta| < 2.5 \) are reconstructed and measured in the inner detector and the solenoid field. The efficiency at low momentum is, however, limited because of the large amount of material in the inner detector (see section 4.10 and figure 4.45). The intrinsic measurement performance expected for each of the inner-detector sub-systems is described in section 4.1. This performance has been studied extensively over the years [60], both before and after irradiation of production modules, and also, more recently, during the combined test beam (CTB) runs in 2004 as described in section 10.1, and in a series of cosmic-ray tests in 2006 as described in section 4.9. The results have been used to update and validate the modelling of the detector response in the Monte-Carlo simulation. This section describes the expected performance of the inner detector in terms of alignment, tracking, vertexing and particle identification.

10.2.1 Track reconstruction

The inner-detector track reconstruction software [250] follows a modular and flexible software design, which includes features covering the requirements of both the inner-detector and muon-spectrometer reconstruction (see section 10.3 for a description of the strategies used for muon reconstruction). These features comprise a common event data model [251] and detector description [252], which allow for standardised interfaces to all reconstruction tools, such as e.g. track extrapolation, track fitting including material corrections, and vertex fitting. The extrapolation package combines propagation tools with an accurate and optimised description of the active and passive material of the full detector [253] to allow for material corrections in the reconstruction process. The suite of track-fitting tools includes global-\( \chi^2 \) and Kalman-filter techniques, and also more specialised fitters, such as dynamic noise adjustment [254], Gaussian-sum filters [255] and deterministic annealing filters [256]. Other common tracking tools are provided, e.g. to apply calibration corrections at later stages of the pattern recognition, to correct for module deformations or to resolve hit-association ambiguities.

Track reconstruction in the inner detector is logically sub-divided into three stages:

1. A pre-processing stage, in which the raw data from the pixel and SCT detectors are converted into clusters and the TRT raw timing information is turned into calibrated drift circles. The SCT clusters are transformed into space-points, using a combination of the cluster information from opposite sides of a SCT module.

2. A track-finding stage, in which different tracking strategies [250, 257], optimised to cover different applications, are implemented. The default tracking exploits the high granularity of the pixel and SCT detectors to find prompt tracks originating from the vicinity of the interaction region. First, track seeds are formed from a combination of space-points in the three pixel layers and the first SCT layer. These seeds are then extended throughout the SCT to form track candidates. Next, these candidates are fitted, outlier clusters are removed, ambiguities in the cluster-to-track association are resolved, and fake tracks are rejected. This
is achieved by applying quality cuts, e.g. on the number of associated clusters, with explicit limits set on the number of clusters shared between several tracks and the number of holes per track (a hole is defined as a silicon sensor crossed by a track without generating any associated cluster). The selected tracks are then extended into the TRT to associate drift-circle information in a road around the extrapolation and to resolve the left-right ambiguities. Finally, the extended tracks are refitted with the full information of all three detectors and the quality of the refitted tracks is compared to the silicon-only track candidates and hits on track extensions resulting in bad fits are labelled as outliers (they are kept as part of the track but are not included in the fit).

A complementary track-finding strategy, called back-tracking, searches for unused track segments in the TRT. Such segments are extended into the SCT and pixel detectors to improve the tracking efficiency for secondary tracks from conversions or decays of long-lived particles.

3. A post-processing stage, in which a dedicated vertex finder is used to reconstruct primary vertices. This is followed by algorithms dedicated to the reconstruction of photon conversions and of secondary vertices.

10.2.2 Alignment of the inner detector

The alignment of the inner detector is a crucial component in reaching the required tracking performance. The alignment procedure must determine accurately the actual positions in space of the silicon modules (pixel and SCT) as well as of the straws (or groups of straws) in the TRT modules. The task therefore corresponds to the determination of six degrees of freedom for each module, if it is treated as a rigid body. It will also be necessary to correct for imperfections within the modules, due to temperature gradients, module bows or other distortions. To ensure that the misalignment of silicon modules does not inflate the track parameter uncertainties by more than 20% above the intrinsic resolution at high-\(p_T\), the module positions need to be determined with a precision of approximately 10 \(\mu\)m or better in the bending plane [60]. For a precision measurement of the mass of the W-boson, an understanding of the module positions at the level of 1 \(\mu\)m or better is required. The expected as-built and survey precisions of the inner-detector components before data-taking are described in section 4.3, and their overall placement accuracy inside the inner bore of the barrel LAr cryostat is summarised in table 4.11.

Alignment constants for the inner detector will be derived from a dedicated stream of tracks selected at a rate of \(\sim 10\) Hz, and will be updated if required every 24 hours. To reach a precision of 10 \(\mu\)m on the silicon-module positions, approximately one million good tracks with various topologies will be selected within this 24 hour period and written out to the calibration and alignment stream at the time of the final high-level trigger decision.

Several different track-based alignment techniques have been applied to CTB data, to cosmic-ray data and to Monte-Carlo simulations of a misaligned inner detector. All the approaches are based on the minimisation of hit residuals from high-momentum tracks, which are preferred because of their lower multiple-scattering distortions. The minimisation of track residuals is a necessary but not sufficient requirement for the alignment of the inner detector. Certain global distortions
of the geometry may not be or may only weakly be constrained by such tracks (these are called "weak modes"). While preserving the helical trajectory of the track, these modes would, in general, lead to biases on the measured track parameters. Sagitta distortions, which arise from systematic biases in the measurement of \( q/\rho_T \), where \( q \) is the charge of the track, are one of the prominent examples.

To constrain and eliminate these weak modes, it is important to use tracks with different topologies:

- tracks from the interaction point, which will always constitute the bulk of the sample of tracks used for alignment. Using the primary vertex as an additional constraint will help to eliminate certain weak modes;
- cosmic-ray tracks, which have the advantage of providing a continuous helical trajectory across the whole inner detector, thereby mimicking a pair of opposite-sign equal-momentum and back-to-back tracks, when they pass close to the interaction point. In addition, a large fraction of the cosmic-ray tracks will cross the inner detector far from the beam axis, thereby providing additional constraints to eliminate certain weak modes;
- tracks from beam halo will help to constrain the initial alignment of the end-cap regions;
- tracks passing through the overlap regions of adjacent modules. These constrain the circumference of cylindrical geometries and thus improve the determination of the average radial position of the modules;
- track pairs from \( Z \) and \( J/\psi \) decays. Fitting these tracks to a common decay vertex and to a known invariant mass will provide sensitivity to systematic correlations between different detector elements;
- finally, additional constraints are provided by the information from survey measurements, which are, however, limited in practice to the relationships between nearby detector elements connected by rigid support structures.

With the unprecedented number of detector modules in the inner detector, the alignment task is immense in its scope and complexity. With the aim of simplifying it, the alignment procedure can be broken down into several steps. As a first step, the large detector structures (the barrel and the end-caps of each of the three sub-systems) are aligned with respect to each other. By treating these large-scale structures as rigid bodies with only a few degrees of freedom, the procedure converges on a global alignment with only limited statistics of reconstructed tracks. To achieve this goal, it is planned that sufficient cosmic-ray data be taken before LHC turn-on. In a second step, the individual barrel layers and end-cap disks can be aligned with respect to each other, leading to a system with several hundreds of degrees of freedom. In a third step, the complete alignment of all the detector modules implies resolving a system with almost 36,000 degrees of freedom (1744 pixel modules, 4088 SCT modules and 136 TRT modules) and therefore requires the large samples of tracks mentioned above. The last step in the whole process requires the study of possible residual biases, using resonances decaying to muons, \( E/p \) measurements combining inner detector and electromagnetic calorimetry, and combined muon measurements with the muon spectrometer (see section 10.3.2).
Figure 10.4: Distributions of pixel (left) and SCT (right) residuals for the most accurate measurement coordinate, as obtained for charged pions with an energy of 100 GeV in the combined test-beam data. The results are shown for tracks reconstructed in the pixel and SCT detectors before (dashed histogram) and after (full histogram) alignment. The curves represent Gaussian fits to the residuals after alignment. Because of the large misalignments of certain modules, most of the entries before alignment lie outside the boundaries of the plots.

10.2.2.1 Alignment in the combined test-beam

The alignment procedure has been applied to CTB data [258] using charged-hadron beams with energies between 5 and 180 GeV. The results obtained are shown in figure 10.4, in the case of one beam energy of 100 GeV, for the pixel and SCT residuals for the most accurate measurement coordinate. The striking improvement observed in the residual distributions after alignment arises from alignment constants changing by typically 100–200 µm for some of the pixel and SCT modules. The measured resolutions after alignment are in agreement with those expected from Monte-Carlo simulation of the CTB set-up with a perfect alignment.

Figure 10.5 compares the measured momentum resolution for pions after alignment with that expected from Monte-Carlo simulation as a function of the pion momentum which ranges from 5 to 100 GeV. The mean of the beam momentum as measured using the pixels and the SCT is correct to ~1% at the highest energy of 100 GeV, indicating that residual misalignments are small. The disagreement observed at the lower end of the momentum spectrum is most likely related to the quality of the data taken with low-energy beams (a mix of electrons and pions taken early in the run when the operation of the pixel and silicon detectors was less stable than for the higher-energy runs).
10.2.2.2 Misaligned inner detector in ATLAS simulation

Within the context of the realistic data challenge described in section 10.1, the inner-detector alignment algorithms are undergoing stringent tests, based on events simulated with a misaligned inner-detector geometry and reconstructed with the nominal geometry. The main focus of these tests is to study the various alignment approaches [259–261] within a realistic and full-scale scenario typical of what can be expected with initial data. One issue of particular interest is the implementation and validation of robust methods to determine and eliminate the weak modes, especially the sagitta distortions. The misalignments introduced for the realistic data challenge do not, however, cover all possible misalignment scenarios. In particular, systematic deformations of large scale structures like end-cap disks or barrel layers are not simulated. Twists or radial deformations of the barrel layers are known to correspond to weak modes of the alignment.

Nevertheless, a number of systematic displacements and rotations of large and smaller-scale structures were introduced, in addition to the smaller and random misalignments introduced at the module level. This resulted in initially low efficiency for reconstructing certain tracks and in track-parameter distortions of large magnitude (the expected mass peak for $Z \rightarrow \mu\mu$ decays was not initially visible). To converge on the first-pass alignment results presented here, reconstructed tracks were constrained to the beam-line and tracks from simulated cosmic-ray events were also used to provide additional constraints.

The impact of global sagitta distortions on the reconstructed invariant masses of neutral resonances decaying into oppositely charged particles is in principle only a small effect, since the momenta of the positively and negatively charged daughters are shifted in opposite directions. However, $\phi$-dependent sagitta distortions may give rise to larger effects, which can become very significant at relatively high momentum (depending on the size and systematic nature of the residual misalignments). Figure 10.6 shows the effect of these residual misalignments on reconstructed $Z \rightarrow \mu\mu$ decays after applying the corrections obtained from a first-pass alignment of the inner detector based on high-$p_T$ muons and cosmic rays. The monitoring of the evolution of the alignment constants during the various stages of this first-pass alignment has shown that residual distortions on the track parameters remain, even after using cosmic rays to remove some of the weak modes to which tracks originating from the interaction point are not very sensitive. The residual distortions are observed to be much smaller in the barrel than in the end-caps, for which the constraints provided by cosmic rays are much weaker. The fitted Gaussian widths of the reconstructed $Z \rightarrow \mu\mu$ peaks in figure 10.6 are 2.6 GeV for the ideal (or perfectly aligned) inner detector and 3.9 GeV for the inner detector after completing the first-pass alignment.

A measure of these residual distortions can be extracted, as one would do with real data, by searching for possible asymmetries between the $p_T$-spectra of negative and positive muons from $Z \rightarrow \mu\mu$ decays. This is illustrated in figure 10.7 which clearly demonstrates a significant residual asymmetry between the two spectra after the first-pass alignment. This large asymmetry is clearly related to the large residual contribution of 2.9 GeV to the resolution on the reconstructed dimuon mass after the first-pass alignment. If this residual width were for example ten times smaller, then a few days of data-taking at a luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$ would be required to actually detect a significant effect using $Z \rightarrow \mu\mu$ decays.
10.2.3 Tracking performance for single particles and particles in jets

The expected performance of the tracking system for reconstructing single particles and particles in jets is determined using a precise modelling of the individual detector response, geometry and passive material in the simulation. In this section, a consistent set of selection cuts for reconstructed tracks has been used throughout. Only prompt particles with $p_T > 1$ GeV and $|\eta| < 2.5$ are considered. Standard quality cuts require reconstructed tracks to have at least seven precision hits (pixels and SCT); in addition, the transverse and longitudinal impact parameters at the point of closest approach to the vertex must fulfil respectively $|d_0| < 2$ mm and $|z_0 - z_v| \times \sin \theta < 10$ mm, where $z_v$ is the position of the primary vertex along the beam and $\theta$ is the polar angle of the track. Stricter selection cuts, called $b$-tagging cuts, are defined by: at least two hits in the pixels and one in the vertexing layer, as well as $|d_0| < 1$ mm and $|z_0 - z_v| \times \sin \theta < 1.5$ mm. A reconstructed track is matched to a Monte-Carlo particle if at least 80% of its hits were created by that particle. The efficiency is defined as the fraction of particles which are matched to reconstructed tracks passing the quality cuts, and the fake rate is defined as the fraction of reconstructed tracks passing the cuts which are not matched to a particle.

The resolution of a track parameter $X$ can be expressed as a function of $p_T$ as:

$$\sigma_X = \sigma_X(\infty)(1 \mp p_X/p_T),$$

where $\sigma_X(\infty)$ is the asymptotic resolution expected at infinite momentum and $p_X$ is a constant representing the value of $p_T$, for which the intrinsic and multiple-scattering terms are equal for the parameter $X$ under consideration. This expression is approximate, working well at high $p_T$ (where the resolution is dominated by the intrinsic detector resolution) and at low $p_T$ (where the resolution is dominated by multiple scattering). Figures 10.8, 10.9 and 10.10 show the momentum resolution
Table 10.1: Expected track-parameter resolutions (RMS) at infinite transverse momentum, $\sigma_X (\infty)$, and transverse momentum, $p_X$, at which the multiple-scattering contribution equals that from the detector resolution. The momentum and angular resolutions are shown for muons, whereas the impact-parameter resolutions are shown for pions (see text). The values are shown for two $\eta$-regions, one in the barrel inner detector where the amount of material is close to its minimum and one in the end-cap where the amount of material is close to its maximum.

| Track parameter                          | $0.25 < |\eta| < 0.50$ | $1.50 < |\eta| < 1.75$ |
|------------------------------------------|--------------------------|--------------------------|
| Inverse transverse momentum $(1/p_T)$    | 0.34 TeV$^{-1}$          | 0.41 TeV$^{-1}$          |
| Azimuthal angle ($\phi$)                 | 70 $\mu$rad             | 92 $\mu$rad             |
| Polar angle $(\cot \theta)$             | $0.7 \times 10^{-3}$    | $1.2 \times 10^{-3}$    |
| Transverse impact parameter ($d_0$)      | 10 $\mu$m               | 12 $\mu$m               |
| Longitudinal impact parameter $(z_0 \times \sin \theta)$ | 91 $\mu$m               | 71 $\mu$m               |

for muons and the transverse and longitudinal impact parameter resolutions for pions, all without any beam constraint and assuming the effects of misalignment to be negligible. Table 10.1 shows the values of $\sigma_X (\infty)$ and $p_X$ for tracks in two $\eta$-regions, corresponding to the barrel and end-caps. The TRT measurements are included in the track fits for tracks with $|\eta| < 2.0$, beyond which there are no further TRT measurements. The impact parameter resolutions are quoted only for tracks with a hit in the vertexing-layer (this requirement has a very high efficiency, as illustrated below).

The determination of the lepton charge at high $p_T$ is particularly important for measuring charge asymmetries arising from the decays of possible heavy gauge bosons ($W'$ and $Z'$). Typically, such measurements require that the charge of the particle be determined to better than $3\sigma$. Whereas the muon charge can be reliably measured at the highest momenta in the muon system, only the inner detector can measure the charge of electrons. The fraction of electrons for which the sign of the charge is wrongly determined is shown in figure 10.11, together with the same fraction for muons, included as a reference (perfect alignment has been assumed). For the muons, the fraction is well described by the nominal (Gaussian) resolution, whereas electrons are more complicated since they are subject to bremsstrahlung. This should help for charge determination since the momentum is reduced, but sometimes the electrons overlap with subsequent conversion electrons from the bremsstrahlung photons, which may cause pattern-recognition problems because of extra hits and overlaps. For $p_T < 1$ TeV, the sign of the curvature of a track is sufficiently well determined that the benefit from bremsstrahlung is small and the overlap problem dominates the electron reconstruction, causing the electron charge determination to be of worse quality than for muons. However at 2 TeV, the poor intrinsic resolution is the dominant factor, and the effect of bremsstrahlung compensates for the pattern-recognition problems.

Figure 10.12 shows the efficiencies for reconstructing muons, pions and electrons with a transverse momentum of 5 GeV, whereas figure 10.13 shows the efficiencies for reconstructing pions with $p_T$ varying from 1 to 100 GeV. In addition to multiple-scattering, pions are affected by hadronic interactions in the inner-detector material, while electrons are subject to even larger reconstruction inefficiencies because of bremsstrahlung. As a result, the efficiency curves as a function of $|\eta|$ for pions and electrons reflect the shape of the amount of material in the inner detector (see figures 4.45 and 4.46). As expected, the efficiency becomes larger and more uniform as a function of $|\eta|$ at higher energies.
Figure 10.8: Relative transverse momentum resolution (left) as a function of $|\eta|$ for muons with $p_T = 1$ GeV (open circles), 5 GeV (full triangles) and 100 GeV (full squares). Transverse momentum, at which the multiple-scattering contribution equals the intrinsic resolution, as a function of $|\eta|$ (right).

Figure 10.9: Transverse impact parameter, $d_0$, resolution (left) as a function of $|\eta|$ for pions with $p_T = 1$ GeV (open circles), 5 GeV (full triangles) and 100 GeV (full squares). Transverse momentum, at which the multiple-scattering contribution equals the intrinsic resolution, as a function of $|\eta|$ (right).

Figure 10.10: Modified longitudinal impact parameter, $z_0 \times \sin \theta$, resolution (left) as a function of $|\eta|$ for pions with $p_T = 1$ GeV (open circles), 5 GeV (full triangles) and 100 GeV (full squares). Transverse momentum, at which the multiple-scattering contribution equals the intrinsic resolution, as a function of $|\eta|$ (right).
Figure 10.11: Charge misidentification probability for high energy muons and electrons as a function of $p_T$ for particles with $|\eta| \leq 2.5$ (left) and as a function of $|\eta|$ for $p_T = 2$ TeV (right).

Figure 10.12: Track reconstruction efficiencies as a function of $|\eta|$ for muons, pions and electrons with $p_T = 5$ GeV. The inefficiencies for pions and electrons reflect the shape of the amount of material in the inner detector as a function of $|\eta|$.

Figure 10.13: Track reconstruction efficiencies as a function of $|\eta|$ for pions with $p_T = 1, 5$ and 100 GeV.
Figure 10.14: Track reconstruction efficiencies and fake rates as a function of $|\eta|$, for charged pions in jets in $t\bar{t}$ events and for different quality cuts (as described in the text). "Reconstruction" refers to the basic reconstruction before additional quality cuts.

Figure 10.15: Track reconstruction efficiencies and fake rates as a function of the distance $\Delta R$ (defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$) of the track to the jet axis, using the standard quality cuts and integrated over $|\eta| < 2.5$.

Figure 10.14 shows the track reconstruction efficiency for prompt pions (produced before the vertexing layer) and the fake rate for tracks in jets in $t\bar{t}$ events as a function of $|\eta|$. For these events, the mean jet $p_T$ is 55 GeV, and the mean $p_T$ of the accepted tracks which they contain is 4 GeV. The loss of efficiency at $|\eta| = 0$ with the $b$-tagging criteria arises from inefficiencies in the pixel vertexing layer, which are assumed here to be 1%; this improves at higher $|\eta|$, owing to the presence of larger clusters when the track incidence angle decreases. Beyond $|\eta| \sim 1$, the tracking performance deteriorates, mostly because of increased material. As shown in figure 10.15, the fake rate increases near the core of the jet, where the track density is the highest and induces pattern-recognition problems. This effect increases as the jet $p_T$ increases. A few percent efficiency can be gained at the cost of doubling the fake rate in the jet core.

10.2.4 Vertexing performance

Vertexing tools constitute an important component of the higher-level tracking algorithms. The residuals of the primary vertex reconstruction are shown in figure 10.16, as obtained without using any beam constraint, for $t\bar{t}$ events and $H \rightarrow \gamma\gamma$ events with $m_H = 110$ GeV. The results shown here for $H \rightarrow \gamma\gamma$ events are based on tracks reconstructed from the underlying event and do not make use of the measurement of the photon direction in the electromagnetic calorimeter, which is discussed in section 10.4. The primary vertex in $t\bar{t}$ events has always a rather large multiplicity and includes a number of high-$p_T$ tracks, resulting in a narrower and more Gaussian distribution than for $H \rightarrow \gamma\gamma$ events. Table 10.2 shows the resolutions of the primary vertex reconstruction in these $t\bar{t}$ and $H \rightarrow \gamma\gamma$ events, without and with a beam constraint in the transverse plane, as well as the
Figure 10.16: Primary vertex residual along \( x \), in the transverse plane (left), and along \( z \), parallel to the beam (right), for events containing top-quark pairs and \( H \rightarrow \gamma \gamma \) decays with \( m_H = 110 \text{ GeV} \). The results are shown without pile-up and without any beam constraint.

Table 10.2: Primary vertex resolutions (RMS), without and with a beam constraint in the transverse plane, for \( t\bar{t} \) events and \( H \rightarrow \gamma \gamma \) events with \( m_H = 110 \text{ GeV} \) in the absence of pile-up. Also shown, in the presence of pile-up at a luminosity of \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \), are the efficiencies to reconstruct and then select the hard-scattering vertex within \( \pm 300 \mu \text{m} \) of the true vertex position in \( z \). The hard-scattering vertex is selected as the primary vertex with the largest \( \sum p_T^2 \), summed over all its constituent tracks.

<table>
<thead>
<tr>
<th>Event type</th>
<th>x-y resolution (( \mu \text{m} ))</th>
<th>z resolution (( \mu \text{m} ))</th>
<th>Reconstruction efficiency (%)</th>
<th>Selection efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} ) (without beam constraint)</td>
<td>18</td>
<td>41</td>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>( t\bar{t} ) (with beam constraint)</td>
<td>11</td>
<td>40</td>
<td>100</td>
<td>99</td>
</tr>
<tr>
<td>( H \rightarrow \gamma \gamma ) (without beam constraint)</td>
<td>36</td>
<td>72</td>
<td>96</td>
<td>79</td>
</tr>
<tr>
<td>( H \rightarrow \gamma \gamma ) (with beam constraint)</td>
<td>14</td>
<td>66</td>
<td>96</td>
<td>79</td>
</tr>
</tbody>
</table>

efficiencies to reconstruct and select correctly these primary vertices in the presence of pile-up at a luminosity of \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) (the beam constraint in the transverse plane assumes the interactions occur at a fixed position with RMS of \( \sim 15 \mu \text{m} \)).

The resolutions for the reconstruction of the radial position of secondary vertices for three-prong hadronic \( \tau \)-decays in \( Z \rightarrow \tau \tau \) events, with a mean \( p_T \) of 36 GeV for the \( \tau \)-lepton, and for \( J/\psi \rightarrow \mu \mu \) decays in events containing \( B \)-hadron decays, with a mean \( p_T \) of 15 GeV for the \( J/\psi \), are shown respectively in figures 10.17 and 10.18. In the first more challenging example, the vertex resolutions are Gaussian in the central region, but have long tails as can be seen from the points showing 95\% coverage in figure 10.17. Finally, figure 10.19 shows the resolution as a function of decay radius for the reconstruction of the radial position of secondary vertices for \( K^0 \) decays with mean \( p_T \) of 6 GeV in events containing \( B \)-hadron decays. The reconstruction is performed in three dimensions and hence requires at least two silicon hits. Consequently, the efficiency falls rapidly
Figure 10.17: Resolution for the reconstruction of the radial position of the secondary vertex for three-prong hadronic $\tau$-decays in $Z \to \tau\tau$ events, as a function of the pseudorapidity of the $\tau$. The $\tau$-leptons have an average visible transverse energy of 36 GeV. The distributions are fitted to a Gaussian core with width $\sigma_{\text{fit}}$. The fractions of events found within $\pm 1\sigma$ (68.3% coverage) and $\pm 2\sigma$ (95% coverage) are also shown.

Figure 10.18: Resolution for the reconstruction of the radial position of the secondary vertex for $J/\psi \to \mu\mu$ decays in events containing $B$-hadron decays, as a function of the pseudorapidity of the $J/\psi$. The $J/\psi$ have an average transverse momentum of 15 GeV.

Figure 10.19: Resolution for reconstruction of radial position of secondary vertex for $K^0_s \to \pi^+\pi^-$ decays in events containing $B$-hadron decays, as a function of the $K^0_s$ decay radius.

Figure 10.20: Resolution for reconstruction of the invariant mass of the charged-pion pair for $K^0_s \to \pi^+\pi^-$ decays in events containing $B$-hadron decays, as a function of the $K^0_s$ decay radius.

for decay radii larger than 30 cm. The effect of crossing the three successive pixel layers is clearly visible as well as the degraded resolution for decays beyond the last pixel layer. Figure 10.20 shows the resolution as a function of decay radius for the reconstruction of the invariant mass of the charged-pion pair for the same $K^0_s \to \pi^+\pi^-$ decays.
10.2.5 Particle identification, reconstruction of electrons and photon conversions

The reconstruction of electrons and of photon conversions is a particular challenge for the inner detector, since electrons have lost on average between 20 and 50% of their energy (depending on $|\eta|$) when they leave the SCT, as illustrated in figure 10.21. In the same region, between 10% and 50% of photons convert into an electron-positron pair, as illustrated in figure 10.22.

The TRT plays a central role in electron identification, cross-checking and complementing the calorimeter, especially at energies below 25 GeV. In addition, the TRT contributes to the reconstruction and identification of electron track segments from photon conversions down to 1 GeV and of electrons which have radiated a large fraction of their energy in the silicon layers.

By fitting electron tracks in such a way as to allow for bremsstrahlung, it is possible to improve the reconstructed track parameters, as shown for $|\eta| > 1.5$ in figure 10.23 for two examples of bremsstrahlung recovery algorithms. These algorithms rely exclusively on the inner-detector information and therefore provide significant improvements only for electron energies below $\sim 25$ GeV (see section 10.4.2 for a discussion of bremsstrahlung recovery using also the position information of the electromagnetic calorimeter). The dynamic-noise-adjustment (DNA) method extrapolates track segments to the next silicon detector layer. If there is a significant $\chi^2$ contribution, compatible with a hard bremsstrahlung, the energy loss is estimated and an additional noise term is included in the Kalman filter [254]. The Gaussian-sum filter (GSF) is a non-linear generalisation of the Kalman filter, which takes into account non-Gaussian noise by modelling it as a weighted sum of Gaussian components and therefore acts as a weighted sum of Kalman filters operating in parallel [255]. Figure 10.24 shows the improvements from bremsstrahlung recovery for the reconstructed $J/\psi \rightarrow ee$ mass. Without any bremsstrahlung recovery, only 50% of events are reconstructed within $\pm 500$ MeV of the nominal $J/\psi$ mass, whereas with the use of the bremsstrahlung recovery, this fraction increases to approximately 60% for both algorithms.
Figure 10.23: Probability distribution for the ratio of the true to reconstructed momentum for electrons with $p_T = 25$ GeV and $|\eta| > 1.5$. The results are shown as probabilities per bin for the default Kalman fitter and for two bremsstrahlung recovery algorithms (see text).

Figure 10.24: Probability for reconstructed invariant mass of electron pairs from $J/\psi \rightarrow ee$ decays in events with $B^0_d \rightarrow J/\psi(ee)K^0_s$. The results are shown for the default Kalman fitter and for two bremsstrahlung recovery algorithms (see text). The true $J/\psi$ mass is shown by the dotted line.

Figure 10.25: Average probability of a high-threshold hit in the barrel TRT as a function of the Lorentz $\gamma$-factor for electrons (open squares), muons (full triangles) and pions (open circles) in the energy range 2–350 GeV, as measured in the combined test-beam.

Figure 10.26: Pion efficiency shown as a function of the pion energy for 90% electron efficiency, using high-threshold hits (open circles), time-over-threshold (open triangles) and their combination (full squares), as measured in the combined test-beam.

Using pion, electron and muon samples in the energy range between 2 and 350 GeV, the barrel TRT response has been measured in the CTB in terms of the high-threshold hit probability, as shown in figure 10.25. The transition-radiation X-rays contribute significantly to the high-threshold hits for electron energies above 2 GeV and saturation sets in for electron energies above 10 GeV. Figure 10.26 shows the resulting pion identification efficiency for an electron efficiency of 90%, achieved by performing a likelihood evaluation based on the high-threshold probability for electrons and pions for each straw. Figure 10.26 also shows the effect of including time-over-threshold information, which improves the pion rejection by about a factor of two when combined with
the high-threshold hit information. At low energies, the pion rejection (the inverse of the pion efficiency plotted in figure 10.26) improves with energy as the electrons emit more transition radiation. The performance is optimal at energies of \( \sim 5 \text{ GeV} \), and pion-rejection factors above 50 are achieved in the energy range of 2–20 GeV. At very high energies, the pions become relativistic and therefore produce more \( \delta \)-rays and eventually emit transition radiation, which explains why the rejection slowly decreases for energies above 10 GeV.

The electron-pion separation expected for the TRT in ATLAS, including the time-over-threshold information, is shown as a function of \( |\eta| \) in figure 10.27 as the pion identification efficiency expected for an electron efficiency of 90%. The shape observed is closely correlated to the number of TRT straws crossed by the track, which decreases from approximately 35 to a minimum of 20 in the transition region between the barrel and end-cap TRT, \( 0.8 < |\eta| < 1.1 \), and which also decreases rapidly at the edge of the TRT fiducial acceptance for \( |\eta| > 1.8 \). Because of its more efficient and regular foil radiator, the performance in the end-cap TRT is better than in the barrel TRT (see section 4.3.3).

Figure 10.28 shows the efficiency for reconstructing conversions of photons with \( p_T = 20 \text{ GeV} \) and \( |\eta| < 2.1 \) as a function of the conversion radius, using the standard tracking algorithm combined with the back-tracking algorithm described in section 10.2.1. At radii above 50 cm, the efficiency for reconstructing single tracks drops and that for reconstructing the pair drops even faster because the two tracks are merged. If both tracks from the photon conversion are reconstructed successfully, vertexing tools can be used to reconstruct the photon conversion with high efficiency up to radii of 50 cm. The overall conversion-finding efficiency can be greatly increased at large radii by defining single tracks as photon conversions under certain conditions. Only tracks which have no hits in the vertexing layer, are not associated to any fitted primary or secondary vertex, and pass a loose electron identification cut requiring more than 9% high-threshold hits on the TRT segment of the track, are retained. The resulting overall efficiency for finding photon conversions is almost uniform over all radii below 80 cm, as shown in figure 10.29.

10.3 Muon reconstruction and identification

10.3.1 Introduction

The collisions at the LHC will produce a broad spectrum of final-state muons, ranging from low-momentum non-isolated muons in \( b \)-jets to high-momentum isolated muons from \( W/Z \)-boson decays or from possible new physics. The experiment will detect and measure muons in the muon spectrometer and will also exploit the measurements in the inner detector and the calorimeters.
<table>
<thead>
<tr>
<th>Conversion radius (mm)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
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</tr>
<tr>
<td>200</td>
<td>0.4</td>
</tr>
<tr>
<td>300</td>
<td>0.6</td>
</tr>
<tr>
<td>400</td>
<td>0.8</td>
</tr>
<tr>
<td>500</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Figure 10.28:** Efficiency to reconstruct conversions of photons with $p_T = 20\text{ GeV}$ and $|\eta| < 2.1$, as a function of the conversion radius. Shown are the efficiencies to reconstruct single tracks from conversions, the pair of tracks from the conversion and the conversion vertex. The errors are statistical.

**Figure 10.29:** Efficiency to identify conversions of photons with $p_T = 20\text{ GeV}$ and $|\eta| < 2.1$, as a function of the conversion radius. The overall efficiency is a combination of the efficiency to reconstruct the conversion vertex, as shown also in figure 10.28, and of that to identify single-track conversions (see text). The errors are statistical.

to improve the muon identification efficiency and momentum resolution. Muon measurements are a combination of accurate measurements in the muon spectrometer and in the inner detector. The muon spectrometer also efficiently triggers on muons over a wide range of energies and over $|\eta| < 2.4$, as described in detail in section 6.6 for the detectors and in section 10.9 for the actual trigger performance. The inner detector provides the best measurement at low to intermediate momenta, whereas the muon spectrometer takes over above 30 GeV. The toroidal field guarantees excellent momentum resolution even at the highest values of $\eta$ (see section 2.2.3.2 and figure 2.12 for details about the mapping of the toroidal field).

This section describes the alignment results obtained in the combined test-beam (CTB), which have validated the overall alignment strategy for both the barrel and end-cap muon-chamber systems, and the expected muon reconstruction performance in terms of momentum resolution, track-finding efficiency and mass resolution for selected channels.

### 10.3.2 Calibration and alignment

In order to achieve the required performance for combined muon reconstruction, the inner detector and the muon spectrometer must be calibrated and aligned internally and with respect to each other. The alignment of the inner detector is described in section 10.2.2.

In the muon spectrometer, movements of most of the precision chambers (MDT and CSC) are monitored by a system of optical sensors with an accuracy of a few micrometres (see section 6.5). In principle, the optical system alone should provide the chamber positions with an accuracy such that the alignment contribution to the error on the sagitta measurement does not exceed 40 $\mu$m. Muon tracks, however, are required to align the chambers with no (or poor) optical connection, to align the end-caps with respect to the barrel, and to align the muon spectrometer with respect to the inner detector with an accuracy of approximately 200 $\mu$m in $z$ and 1 mm in $R\phi$. 

10.3.2.1 Performance of optical alignment system in test-beam

The optical alignment concept for the muon spectrometer underwent a final round of testing and validation with one full barrel sector and one full end-cap sector in the H8 muon beam line at CERN in 2002-2004 (see figures 10.1 and 10.3). Figures 10.30 and 10.31 show as examples the measured track sagittas, after applying the corrections obtained from the optical alignment system, for a specific displacement of the middle chamber of the barrel sector and for a specific rotation of the inner chamber of the barrel sector, respectively. Alignment accuracies of approximately 20 µm have been achieved in these tests, well within the design specifications of the alignment system (see section 6.5) [194, 195, 262, 263].

10.3.2.2 Alignment of the muon spectrometer with tracks

In the muon spectrometer (see section 6.3.2 and table 6.3), some chambers are not optically linked (BIS.8, BEE), or the optical connection does not have the required precision for the sagitta measurement (barrel chambers of the small sectors). During normal data-taking, these chambers can be aligned precisely using muon tracks passing through overlap regions with the optically aligned neighbouring chambers. Similarly, the alignment of the two end-caps with respect to the barrel will use tracks fully reconstructed in the barrel and passing through one end-cap chamber: one example of such an overlap is that between BIS-EIL-BML-BOL.

As an additional independent test of the achieved alignment accuracy, it is foreseen to run for some short periods without magnetic field in the toroids, while the solenoid is at full field. This will yield straight tracks in the muon spectrometer, which can be selected to have e.g., $p_T > 10$ GeV, using the matching track reconstructed in the inner detector to limit the impact of multiple scattering. If the chamber alignment were perfect, the measured sagittas would be centred around zero with...
a variance determined by multiple scattering and the position resolution of the chambers. Significant deviations from zero in certain \( \eta \)-\( \phi \) regions would point to errors of chamber positioning, as obtained from the optical alignment. A statistical accuracy of 30 \( \mu \)m on the average sagitta can be obtained with 15000 tracks with \( p_T \) > 10 GeV per chamber triplet. This corresponds to a less than one day of data-taking at a luminosity of \( 10^{33} \) cm\(^{-2} \) s\(^{-1} \). A similar procedure can be used during cosmic-ray data-taking to align parts of the spectrometer independently of LHC operation.

10.3.2.3 Overall calibration and alignment strategy

The drift-time measurements of the MDT’s are synchronised with an accuracy of 200 ps by measuring the minimum drift time from the raw drift-time spectra of the individual tubes. The space-to-drift-time relationships, \( R-t \), are iteratively determined from the residuals of reconstructed muon track segments in the chambers. The required \( R-t \) accuracy of 20 \( \mu \)m can be achieved with 2000 track segments per chamber.

Both the alignment constants obtained from tracks and the MDT calibrations will be produced on a daily basis and will have to be ready within 24 hours to be used in the reconstruction. In order to collect enough statistics for these tasks, a dedicated stream of high-\( p_T \) single muons will be provided at a rate of 1 kHz as a direct output of the L2 muon trigger [174].

10.3.3 Reconstruction strategies

Muons with momenta ranging from approximately 3 GeV to 3 TeV are identified and measured with optimal acceptance and efficiency through the use of a combination of three track-reconstruction strategies (see section 10.2.1 for a brief description of the tracking software common to inner-detector and muon-spectrometer reconstruction):

- Stand-alone: muon track reconstruction based solely on the muon spectrometer data over the range \( |\eta| < 2.7 \) (defined by the spectrometer acceptance).
- Combined: combination of a muon-spectrometer track with an inner-detector track over the range \( |\eta| < 2.5 \) (defined by the inner-detector acceptance).
- Segment tag: combination of an inner-detector track with a muon-spectrometer segment, i.e. a straight-line track, in an inner muon station.

Track reconstruction in the muon spectrometer is logically sub-divided into the following stages: pre-processing of raw data to form drift-circles in the MDT’s or clusters in the CSC’s and the trigger chambers (RPC’s and TGC’s), pattern-finding and segment-making, segment-combining, and finally track-fitting. Track segments are defined as straight lines in a single MDT or CSC station. The search for segments is seeded by a reconstructed pattern of drift-circles or clusters or by drift-circles or clusters lying in a region of activity, which is defined by the trigger chambers and has a size of the order of 0.4 \( \times \) 0.4 in \( \eta - \phi \) space.

Full-fledged track candidates are built from segments, starting from the outer and middle stations and extrapolating back through the magnetic field to the segments reconstructed in the other stations. Each time a reasonable match is found, the segment is added to the track candidate.
The final track-fitting procedure takes into account, in full detail, the geometrical description of the traversed material and the magnetic field inhomogeneities along the muon trajectory.

The muon-spectrometer track parameters are determined at the inner stations, which yield the first set of measurements in the muon spectrometer. The track is then propagated back to the interaction point and the momentum is corrected for the energy loss in the calorimeters (and in the inner detector). The energy lost by dE/dX in the calorimeters is estimated by an algorithm, which uses either the parametrised expected energy loss or the measured calorimeter energy. The measured energy is used only if it exceeds significantly the most probable energy loss and if the muon track is isolated.

The combination of the stand-alone tracks reconstructed in the muon spectrometer with tracks reconstructed in the inner detector is performed in the region $|\eta| < 2.5$, which corresponds to the geometrical acceptance of the inner detector. This combination will considerably improve the momentum resolution for tracks with momenta below 100 GeV, but will also suppress to a certain extent backgrounds from pion punch-through and from pion or kaon decays in flight.

In the case of segment tags, inner-detector tracks are extrapolated to the inner muon stations and either associated directly to reconstructed muon segments or used to select muon drift-circles and clusters in a cone with typically a size of 100 mrad, from which track segments are then reconstructed. The muons reconstructed through this procedure provide an important improvement to the stand-alone muon reconstruction for three main reasons:

- at momenta below typically 6 GeV, muon tracks do not always reach the middle and outer muon stations;
- in the barrel/end-cap transition region with $1.1 < |\eta| < 1.7$, the middle stations are missing for the initial data-taking (EES and EEL chambers in table 6.4) and the stand-alone reconstruction efficiency is reduced in this region;
- in the difficult regions at $\eta \approx 0$ and in the feet, the geometrical acceptance of the muon stations is considerably reduced.

10.3.4 Muon reconstruction performance for single muons

Three main quantities can be used to summarise the performance of the muon reconstruction and identification algorithms: the momentum resolution, the efficiency and the misidentification or fake rate. This section presents the expected performance of the three first strategies described above for single muons. Both the stand-alone and combined results shown here have been obtained using as an example the algorithms described in ref. [264]. Except where directly relevant to the performance (e.g. for estimates of the fake rates), the results presented here do not include any effects arising from cavern background or pile-up.

Figure 10.32 shows the expected fractional momentum resolution, averaged over $\phi$, for single muons with $p_T = 100$ GeV, as obtained for stand-alone and combined muon tracks. Over a large fraction of the acceptance, the stand-alone resolution is close to 3%, as shown in more detail in figure 10.33, which shows its variation as a function of $\phi$ in the region $0.3 < |\eta| < 0.65$. One clearly sees the degradation in resolution due to the feet which support the experiment and are situated close to $\phi = 240^\circ$ and $300^\circ$. In the region $1.1 < |\eta| < 1.7$, the large degradation of
Figure 10.32: For muons with $p_T = 100$ GeV, expected fractional momentum resolution as a function of $|\eta|$ for stand-alone and combined reconstruction. The degradation in the region with $1.1 < |\eta| < 1.7$ is due to the absence of the middle muon stations in the barrel/end-cap transition region for the initial data-taking, to the low bending power of the magnetic field in the transition region between the barrel and end-cap toroids and to the material of the coils of the end-cap toroids.

The stand-alone momentum resolution is due to several effects. In the region $1.1 < |\eta| < 1.3$, the degradation is due to the absence of the middle muon stations in the barrel/end-cap transition region for the initial data-taking, which results in a large degradation of the resolution since the measurement is limited to an angle-angle measurement between the inner and outer stations. At larger values of $|\eta|$, the degradation is due to the combination of the low bending power of the magnetic field in the transition region between the barrel and end-cap toroids and of the large amount of material in the coils of the end-cap toroid in limited regions in $\phi$. The contribution of the inner detector to the combined resolution is therefore more important in this $\eta$-region. In the barrel region, the contribution of the inner detector remains significant, whereas it basically vanishes for $|\eta| > 2.0$. This is due to the intrinsically worse momentum resolution in the inner detector because of the absence of any TRT measurements in this $\eta$-region, of the solenoidal field non-uniformity, and of the shorter length of the tracks in the inner-detector magnetic volume.

The stand-alone momentum resolution of muons with $p_T = 100$ GeV can be calculated based on the spatial resolution of the chambers, the material distribution, and the magnetic-field configuration in the muon spectrometer [265]. The result of this calculation is shown as a function of $\phi$ and $|\eta|$ in figure 10.34. No momentum measurement is possible at $|\eta| < 0.1$ and $|\eta| = 1.3$ because of holes in the acceptance of the muon spectrometer. The expected stand-alone momentum resolution is approximately 3% over most of the $\eta - \phi$ plane. It is degraded to 5% at $|\eta| = 0.2, 0.3$ and 0.7, due to support structures of the barrel toroid magnet coils. The degradation in the regions corresponding to $1.2 < |\eta| < 1.7$ and to $\phi$-values which are multiples of $22.5^\circ$ is caused by the
Figure 10.34: For muons with $p_T = 100$ GeV, expected fractional stand-alone momentum resolution as a function of $\phi$ and $|\eta|$. The results are based on a parametrisation using the material distribution in the muon spectrometer shown in figure 6.7, the magnetic field configuration in the muon spectrometer, and the spatial resolution of the muon chambers. No momentum measurement is possible at $|\eta| < 0.1$ over most of the azimuth, nor at $|\eta| = 1.3$ because of holes in the acceptance of the muon spectrometer (see text).

small bending power of the magnetic field in these regions. The resolution expectations from this analytical model are in good agreement with the results shown in figures 10.32 and 10.33, which are based on full simulation and reconstruction.

Figures 10.35 and 10.36 show the expected stand-alone and combined momentum resolutions as a function of $p_T$, excluding the $\eta$-region $1.1 < |\eta| < 1.7$, respectively for the barrel and end-cap muon spectrometer. The stand-alone resolution displays its characteristic behaviour with optimal resolution achieved at $\sim 100$ GeV. At lower transverse momenta, the stand-alone resolution is dominated by fluctuations in the energy loss in the calorimeters, whereas at higher transverse momenta, it is dominated by the intrinsic MDT tube accuracy, assumed to be $80 \mu$m in the case of a calibrated and aligned detector. At low transverse momenta, the combined resolution reflects directly the dominant performance of the inner detector, which is itself limited by multiple scattering for transverse momenta below $\sim 10$ GeV (see section 10.2.3).

In figures 10.37 and 10.38, the single muon reconstruction efficiency is shown, respectively as a function of $|\eta|$ for muons with $p_T = 100$ GeV and as a function of $p_T$. The efficiency is defined as the fraction of simulated muons which are reconstructed within a cone of size $\Delta R = 0.2$ of the...
Resolution (%)

Stand-alone
Combined

Resolution (%)

Stand-alone
Combined

Efficiency

Stand-alone
Combined

Efficiency

Stand-alone
Combined

Figure 10.35: Expected stand-alone and combined fractional momentum resolution as a function of $p_T$ for single muons with $|\eta| < 1.1$.

Figure 10.36: Expected stand-alone and combined fractional momentum resolution as a function of $p_T$ for single muons with $|\eta| > 1.7$.

Figure 10.37: Efficiency for reconstructing muons with $p_T = 100$ GeV as a function of $|\eta|$. The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.

Figure 10.38: Efficiency for reconstructing muons as a function of $p_T$. The results are shown for stand-alone reconstruction, combined reconstruction and for the combination of these with the segment tags discussed in the text.

The efficiency for stand-alone tracks drops to very low values in the region with $\eta \sim 0$ because of the large gap for services, in which there are very few muon stations. The stand-alone efficiency also drops substantially close to $\eta = 1.2$, which corresponds to a region in the barrel/end-cap transition region where several stations are missing. The efficiency for combining stand-alone muon tracks with the inner detector is very high in the central region, starts to drop for $|\eta| > 2.0$ and decreases rapidly to 0 for $|\eta| > 2.4$. The segment tags contribute only to a limited extent to the overall efficiency for $1.4 < |\eta| < 2.0$ for muons with high $p_T$, but figure 10.38 shows that, as expected, their contribution is substantial for lower $p_T$ values.
The efficiencies presented above must be compared to the expected fake rates, especially in the presence of cavern background, which permeates the whole muon spectrometer, and of pile-up, which affects mostly the high-|\eta| region. Electromagnetic showers triggered by energetic muons traversing the calorimeters and support structures lead to low-momentum electron and positron tracks, which accompany the muons in the muon spectrometer. These low-momentum tracks are an irreducible source of fake stand-alone muons. Most of them can be rejected by a cut on their transverse momentum. For example, a cut requiring \( p_T > 5 \text{ GeV} \) reduces the fake rate to a few percent per triggered event. Such fakes can be almost entirely rejected by requiring a match of the muon-spectrometer track with an inner-detector track.

The second source of fake stand-alone muons is the background of thermal neutrons and low-energy \( \gamma \)-rays in the muon spectrometer (the so-called "cavern background"). Most of these fakes also have transverse momenta smaller than 5 GeV. The expected fake rate with \( p_T > 5 \text{ GeV} \) from cavern background at \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \) is below 2% per triggered event. This rate is proportional to the background counting rate and can be reduced by almost an order of magnitude by requiring a match of the muon-spectrometer track with an inner-detector track.

### 10.3.5 Reconstruction of \( Z \rightarrow \mu\mu \) and \( H \rightarrow \mu\mu\mu\mu \) decays

The large expected rates of \( Z \rightarrow \mu\mu \) decays provide an excellent tool to untangle various effects which might lead to distortions of the measured dimuon invariant mass spectrum. One example is shown in figure 10.39 for stand-alone muon measurements, where the performance obtained with a misaligned layout is compared to that expected from a perfectly aligned layout. The misalignments introduced for this study were random displacements of typically 1 mm and random rotations of typically 1 mrad. These lead to a distribution of the difference between the dimuon reconstructed invariant mass and the true dimuon mass with a fitted Gaussian resolution of approximately 8 GeV. The fitted Gaussian resolution obtained for the same distribution in the case of the perfectly aligned layout is 2.5 GeV.

The muon reconstruction and identification efficiency will also be measured from data using \( Z \rightarrow \mu\mu \) decays and the tag-and-probe method described in section 10.9.7 with similar results in terms of accuracy of the measurement. These in situ measurements will be extended to lower-mass resonances, using \( J/\psi \) and \( \Upsilon \) decays at lower initial luminosities.

Finally, figures 10.40 and 10.41 show the four-muon invariant mass distributions from \( Z \rightarrow \mu\mu \) decays for an aligned layout of the chambers and for a misaligned layout, where all chambers are displaced and rotated randomly by typically 1 mm and 1 mrad.

**Figure 10.39:** For stand-alone muon reconstruction, reconstructed invariant mass distribution of dimuons from \( Z \rightarrow \mu\mu \) decays for an aligned layout of the chambers and for a misaligned layout, where all chambers are displaced and rotated randomly by typically 1 mm and 1 mrad.

The muon reconstruction and identification efficiency will also be measured from data using \( Z \rightarrow \mu\mu \) decays and the tag-and-probe method described in section 10.9.7 with similar results in terms of accuracy of the measurement. These in situ measurements will be extended to lower-mass resonances, using \( J/\psi \) and \( \Upsilon \) decays at lower initial luminosities.

Finally, figures 10.40 and 10.41 show the four-muon invariant mass distributions from respectively stand-alone and combined reconstruction without using any \( Z \)-mass constraint for \( H \rightarrow \mu\mu\mu\mu \) decays in the case of a Higgs-boson mass of 130 GeV. The stand-alone resolution is 3.3 GeV, whereas the combined resolution is 2.1 GeV. The non-Gaussian tails in the distribution
Figure 10.40: For $H \rightarrow \mu\mu\mu\mu$ decays with $m_H = 130$ GeV, reconstructed mass of the four muons using stand-alone reconstruction. The results do not include a $Z$-mass constraint.

Figure 10.41: For $H \rightarrow \mu\mu\mu\mu$ decays with $m_H = 130$ GeV, reconstructed mass of the four muons using combined reconstruction. The results do not include a $Z$-mass constraint.

amount to 29% (resp. 18%) of events which lie further than $2\sigma$ away from the peak for the stand-alone (resp. combined) reconstruction. They are partially due to radiative decays, but mostly to muons poorly measured in certain regions of the muon spectrometer, especially in the case of the stand-alone measurements.

10.4 Electrons and photons

Efficient and accurate reconstruction and identification of electrons and photons will be a task of unprecedented difficulty at the LHC, where the ratios of inclusive electrons and photons to jets from QCD processes are expected to be between one and two orders of magnitude worse than at the Tevatron (as an example, the electron-to-jet ratio is expected to be $\sim 10^{-5}$ at $p_T = 40$ GeV). In addition, the large amount of material in front of the electromagnetic calorimeters and the harsh operating conditions at the LHC design luminosity provide a difficult challenge in terms of preserving most of the electrons and photons with their energies and directions measured as well as would be expected from the intrinsic performance of the electromagnetic calorimeters measured in test-beams. This section is devoted to a summary of the calibration and expected performance of the electromagnetic calorimeter, of electron and photon identification in the energy range of interest for initial physics, and of the strategies under evaluation for the validation and certification of the performance in situ.

10.4.1 Calibration and performance of the electromagnetic calorimeter

The results presented in this section are based on detailed simulation studies, validated by extensive test-beam studies over the past years (see section 5.7) and using reconstruction procedures developed for test-beam data analysis. Compared to ref. [248], the material budget in front of the calorimeter has increased substantially. The large amount of material in front of the presampler and the electromagnetic calorimeter leads to substantial energy losses for electrons, as shown in figure 10.42 (see also figure 10.21 for more details on electron energy loss in the inner-detector...
Figure 10.42: Average energy loss in GeV as a function of $|\eta|$ for electrons with an energy of 100 GeV. The results are shown before the presampler (open circles) and the strip layer (crosses).

Figure 10.43: Fraction of photons converting at a radius of below 80 cm (115 cm) in open (full) circles as a function of $|\eta|$.

Material itself) and to a large fraction of photons converting, as shown in figure 10.43 (see also figure 10.22 for details on the photon conversion probability in the inner-detector material).

Electron and photon reconstruction is seeded using a sliding-window algorithm with a window size corresponding to $5 \times 5$ cells in the middle layer of the electromagnetic calorimeter (see table 1.3 for a detailed description of the granularity and $\eta$-coverage of the electromagnetic calorimeter). A cluster of fixed size is then reconstructed around this seed. For electrons, the energy in the barrel electromagnetic calorimeter is collected over an area corresponding to $3 \times 7$ cells in the middle layer or $0.075 \times 0.175$ in $\Delta \eta \times \Delta \phi$. This choice optimises the balance between the conflicting requirements of collecting all the energy even in the case of hard bremsstrahlung and of preserving the energy resolution by minimising the contributions from noise and pile-up. For unconverted photons, adequate performance is obtained by limiting the area to $3 \times 5$ cells in the middle layer, whereas converted photons are treated like electrons. Finally, for the end-cap electromagnetic calorimeters, an optimal area of $5 \times 5$ cells in layer 2 has been chosen for both electrons and photons.

Position corrections are applied as a first step in the precise reconstruction of the electromagnetic cluster. Corrections for modulations of the local energy response as a function of the extrapolated impact point of the electron in both $\eta$ and $\phi$ are shown in figures 10.44 and 10.45, respectively. These corrections do not modify the global energy scale and are rather small in terms of the relative response: typically, the $\eta$-variation is, minimum to maximum, around 1%, whereas the $\phi$-modulation correction due to the accordion structure of the absorbers is, minimum to maximum, around 0.4%. The parabolic component of this latter correction is smaller than the one in $\eta$ because of the energy sharing between adjacent cells in $\phi$.

The most important corrections to optimise at the same time the energy resolution and the linearity of the response are incorporated using $\eta$-dependent longitudinal weights, similarly to what is described for the electromagnetic calorimeter test-beam results in section 5.7.1:

$$E = s(\eta)[c(\eta) + w_0(\eta) \cdot E_{PS} + E_{strips} + E_{middle} + w_3(\eta) \cdot E_{back}],$$

(10.1)
where \( s \) is an overall scale factor, \( c \) is an offset, \( w_0 \) corrects for energy losses upstream of the presampler, and \( w_3 \) corrects for longitudinal leakage, while \( E_{\text{PS}} \), \( E_{\text{strips}} \), \( E_{\text{middle}} \) and \( E_{\text{back}} \) represent the energies measured in the successive layers of the electromagnetic calorimeter (presampler, strips, middle and back). The weights are determined as functions of \(|\eta|\), using simulated single-particle events (electrons and photons) with energies from 5 GeV to 200 GeV. The weights are calculated separately for electrons (matched track required) and photons (no matched track required) and applied to the corresponding cluster energies. In the future, this method will be replaced by a more complex algorithm, which corrects the different types of true energy loss one by one, by correlating each of them with measured observables.

In figures 10.46 and 10.47, the energy response, plotted as the difference between measured and true energy divided by the true energy, is shown for electrons with an energy of 100 GeV and for two illustrative \( \eta \)-values in the barrel electromagnetic calorimeter. The central value of the energy is reconstructed with excellent precision (\( \approx 3 \times 10^{-4} \)) if one assumes perfect knowledge of the material in front of the calorimeter. Both the Gaussian core and the non-Gaussian component of the tail of the energy distribution are significantly worse at the point with the larger \( \eta \) due to the larger amount of material in front of the calorimeter (see figure 4.46). As shown in figures 10.48 and 10.49, the resolution and non-Gaussian tails are better for photons than for electrons, but are somewhat worse for all photons than for unconverted photons, i.e. photons not converting before leaving the volume of the inner detector.

The energy resolution as a function of energy is shown in figures 10.50 and 10.51, respectively for electrons and photons and for three illustrative values of \(|\eta|\). The results shown here include the expected electronic noise contributions at 100 GeV of 190, 190 and 230 MeV (respectively 180, 180 and 230 MeV) for the three \( \eta \)-values for electrons (respectively photons).

As expected in the case of the points at the larger \( \eta \)-values, the resolution is degraded with respect to the one at the more central value of \( \eta \). Fits to these results similar to those described in section 5.7.1 and expressed in eq. (5.2) yield stochastic terms of respectively 10.0%, 15.1% and 14.5% for the electrons at the three \( \eta \)-values shown. The corresponding terms for photons are found to be 10.2%, 12.4% and 12.1%, once again showing that photons are less sensitive than...
electrons to the material in front of the calorimeter. This can also be clearly seen when comparing figures 10.52 and 10.53, which show for electrons and photons the expected relative energy resolution as a function of $|\eta|$ for a fixed energy of 100 GeV. The $\eta$-region between 1.37 and 1.52 corresponds to the difficult transition region between the barrel and end-cap cryostats, where the energy resolution degrades significantly despite the presence of scintillators in the crack between the barrel and end-cap cryostats to correct for the energy lost in the barrel cryostat flange (see section 5.5). This crack region is not used for photon identification nor for precision measurements with electrons.

In figure 10.54, the expected $\eta$-resolution is shown for the two main layers (strips and middle layer) of the barrel and end-cap calorimeters. The resolution is fairly uniform as function of $|\eta|$ and is $2.5 - 3.5 \times 10^{-4}$ for the strips (which have a size of 0.003 in $\eta$ in the barrel electromagnetic calorimeter) and $5 - 6 \times 10^{-4}$ for the middle-layer cells (which have a size of 0.025 in $\eta$). The regions with worse resolution correspond to the barrel/end-cap transition region and, for the
strips, to the region with $|\eta| > 2$, where the strip granularity of the end-cap calorimeter becomes progressively much coarser (see table 1.3). The results shown in section 5.7.1 are somewhat better because they correspond to a higher electron energy of 245 GeV.

Because of the fine lateral and longitudinal granularity of the electromagnetic calorimeter, these $\eta$-measurements can be used to determine the direction of the axis of the shower development in the $\eta$-direction (or polar angle $\theta$). To achieve the best performance, one requires an accurate parametrisation of the shower depth ($R$-coordinate in the barrel and $z$-coordinate in the end-caps), as determined by Monte-Carlo simulations for both layers. The resulting resolution on the polar angle of photon showers is shown in figure 10.55 for a representative sample of photons from $H \rightarrow \gamma\gamma$ decays. A resolution of 50–75 mrad / $\sqrt{E}$ (GeV) is obtained, which should be sufficient to e.g. measure accurately the invariant mass of photon pairs without using any primary vertex information.
In addition to the calorimeter-seeded electron and photon reconstruction, a second electron reconstruction and identification algorithm uses good-quality tracks as a seed and constructs a cluster around the extrapolated impact point in the calorimeter [266]. This algorithm relies more on the electron identification capabilities of the inner detector and has been developed to improve the efficiency for low-$p_T$ electrons (see section 10.4.3) as well as for electrons close to jets (see section 10.8.5). The algorithm matches good-quality inner-detector tracks to small clusters of electromagnetic energy. For a given track, only the energy contained in a small window along the track extrapolation is used and the contribution of neighbouring hadronic showers is therefore reduced. The identification procedure takes full advantage of the tracking and electron-identification capabilities of the TRT in the inner detector (over $|\eta| < 2.0$, as described in section 10.2.5), as well as of the granularity of the electromagnetic calorimeter. A likelihood ratio combines inner-detector information (measured track momentum and transition-radiation hits) with shower-shape variables from the calorimeter.

In the following, unless specified otherwise (as in section 10.4.3), only the results of the calorimeter-seeded algorithm will be discussed.

### 10.4.2 Electron and photon reconstruction and identification

For the standard reconstruction of electrons and photons, a seed cluster is taken from the electromagnetic calorimeter and a loosely matching track is searched for among all reconstructed tracks. Additionally, the candidate is flagged if it matches a photon conversion reconstructed in the inner detector. Electron and photon candidates are thus separated reasonably cleanly, by requiring the electrons to have an associated track but no associated conversion. In contrast, the photons are defined as having no matched track, or as having been matched to a reconstructed conversion.

For all electron and photon candidates, shower-shape variables (lateral and longitudinal shower profiles, etc.) are calculated using the fine granularity of the electromagnetic calorimeter, and typically more than 50 calorimeter cells are summed to collect the full cluster energy. Addition-
ally, combined reconstruction properties, such as the ratio of energy (calorimeter) to momentum (inner detector), the difference between the coordinates $\eta$ and $\phi$ reconstructed by the cluster and the track extrapolated into the calorimeter, and the ratio of high-threshold transition radiation hits to low-threshold hits on the track, are used to identify electrons.

The energy of high-$p_T$ electrons is obtained from the energy measured in the calorimeter (the inner-detector momentum measurement is not expected to improve the accuracy of the calorimeter energy measurement significantly for energies above 20–30 GeV). The $\eta$ and $\phi$ directions are, however, more precisely determined using the associated track. For photons, everything is derived from the calorimeter information, the energy, the $\phi$-direction using the precisely known average transverse position of the primary vertex, and the $\eta$-direction as described above.

### 10.4.2.1 Electrons

The standard identification for isolated high-$p_T$ electrons is based on cuts on the shower shapes, on information from the reconstructed track and on the combined reconstruction. Jet rejections are computed with respect to truth-particle jets reconstructed using particle four-momenta within a cone of size $\Delta R = 0.4$. Three sets of cuts have been studied depending on the signal efficiency and jet rejection requirements of the physics samples under study:

- "loose cuts" consisting of simple shower-shape cuts (longitudinal leakage, shower shape in the middle layer of the electromagnetic calorimeter) and very loose matching cuts between reconstructed track and calorimeter cluster;

- "medium cuts", which add shower-shape cuts using the important information contained in the first layer of the electromagnetic calorimeter and track-quality cuts similar to the standard reconstruction cuts quoted in section 10.2.3;

- "tight cuts", which tighten the track-matching criteria and the cut on the energy-to-momentum ratio. These cuts also explicitly require the presence of a vertexing-layer hit on the track (to further reject photon conversions) and a high ratio between high-threshold and low-threshold hits in the TRT detector (to further reject the background from charged hadrons), as shown in section 10.2.5. Additionally, further isolation of the electron may be required by using calorimeter energy isolation beyond the cluster itself. Two sets of tight selection cuts are used in this section to illustrate the overall performance of the electron identification. They are labelled as "tight (TRT)", in the case where a TRT cut with approximately 90% efficiency for electrons is applied, and as "tight (isol.)", in the case where a TRT cut with approximately 95% efficiency is applied in combination with a calorimeter isolation cut.

The performance of the cut-based analysis is summarised in table 10.3 and in figure 10.56 for electrons. As can be seen from table 10.3, the signal from prompt electrons is dominated by initially non-isolated electrons from heavy flavours, which explains the much lower efficiency observed for these electrons. Dedicated algorithms might improve this efficiency somewhat, but these electrons will nevertheless provide the most abundant initial source of isolated electrons and will be used for alignment of the electromagnetic calorimeters and the inner detector, for $E/p$ calibrations, and more generally to improve the understanding of the material of the inner detector. For tight cuts and
Table 10.3: Expected efficiencies for isolated and non-isolated electrons and corresponding jet background rejections for the three standard levels of cuts used for electron identification. The results are shown for simulated inclusive jet samples corresponding to $E_T$-thresholds of the electron candidates of 17 GeV (left) and 8 GeV (right). The three bottom rows show, for each of the inclusive jet samples, the fractions of all surviving candidates which originate from the different categories for the medium cuts and the two sets of tight cuts. The isolated electrons are prompt electrons from $W$, $Z$ and top-quark decay and the non-isolated electrons are from $b$, $c$ decay. The residual jet background is split into its two dominant components, electrons from photon conversions and Dalitz decays (first term in brackets) and charged hadrons (second term in brackets). The quoted errors include part of the systematics, but do not include the larger systematic uncertainties from the physics input and detector simulation.

<table>
<thead>
<tr>
<th>Cuts</th>
<th>$E_T &gt; 17$ GeV</th>
<th>$E_T &gt; 8$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>Jet rejection</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>87.9 ± 0.5</td>
<td>38 ± 1</td>
</tr>
<tr>
<td>$b, c \rightarrow e$</td>
<td>76.7 ± 0.5</td>
<td>27 ± 1</td>
</tr>
<tr>
<td>Tight (TRT)</td>
<td>61.3 ± 0.5</td>
<td>20 ± 1</td>
</tr>
<tr>
<td>Tight (isol.)</td>
<td>63.6 ± 0.5</td>
<td>16 ± 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative populations of surviving candidates (%)</th>
<th>Isolated</th>
<th>Non-isolated</th>
<th>Jets</th>
<th>Isolated</th>
<th>Non-isolated</th>
<th>Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>0.9</td>
<td>6.4</td>
<td>92.6 (1.5 + 91.1)</td>
<td>—</td>
<td>7.7</td>
<td>92.3 (2.2 + 90.9)</td>
</tr>
<tr>
<td>Tight (TRT)</td>
<td>10.5</td>
<td>56.1</td>
<td>33.4 (4.3 + 29.0)</td>
<td>—</td>
<td>63.2</td>
<td>36.8 (4.0 + 32.8)</td>
</tr>
<tr>
<td>Tight (isol.)</td>
<td>13.0</td>
<td>53.4</td>
<td>33.6 (4.6 + 29.0)</td>
<td>—</td>
<td>62.8</td>
<td>37.2 (4.4 + 30.3)</td>
</tr>
</tbody>
</table>

an electron $p_T$ of $\sim 20$ GeV, the isolated electrons from $W$, $Z$ and top-quark decays represent less than 20% of the total prompt electron signal and are only at the level of $\sim 30$–40% of the residual jet background. For the lower $E_T$-threshold of 8 GeV, the expected signal from isolated electrons is negligibly small. Not surprisingly, the tight TRT cuts are more efficient to select non-isolated electrons from heavy-flavour decay, while the tight isol. cuts are more efficient at selecting isolated electrons. After tight cuts, the signal-to-background ratio is close to 2:1, and depends only weakly on the $E_T$-threshold. The residual background is dominated by charged hadrons. Further rejection could be possible at the expense of loss of efficiency by stronger cuts (TRT and/or isolation) and by improving the photon conversion reconstruction (see section 10.2.5).

Figure 10.56 shows in more detail the overall reconstruction and identification efficiencies for the three sets of electron cuts discussed above: the $E_T$ dependence of the efficiencies is shown for single electrons of fixed $E_T$ as well as for physics processes containing isolated electrons from cascade decays of supersymmetric particles to illustrate the rather stable behaviour of the cuts when moving from the ideal case of single particles to a busy environment with many additional jets in the event. The somewhat worse efficiency observed in complex events is attributed to the fraction of cases when the electron candidate is close to or even within a high-$p_T$ jet. The overall efficiency of the cuts remains stable for even higher electron energies (the efficiency of the tight isol. cuts is 68% for electrons of $E_T = 500$ GeV).
Figure 10.56: Overall reconstruction and identification efficiency of various levels of electron cuts: loose, medium, and tight isol. as a function of $E_T$ for single electrons (open symbols) and for isolated electrons in a sample of physics events with a busy environment (full symbols).

In addition to the traditional cut-based analysis, multivariate techniques have been developed, based on similar variables, and the performance of a likelihood technique is shown as an example in figure 10.57. Compared to the tight cuts described above, a gain of 4–8% in efficiency for the same fixed rejection against jets or of 40–60% in rejection for the same fixed efficiency can be obtained, using this likelihood method for isolated electrons with energies typical of those expected from $Z \rightarrow ee$ decays.

As discussed already to some extent in section 10.2.5, certain dedicated tracking algorithms improve the momentum reconstruction for electrons with transverse momenta up to 10 GeV. However, as shown in figure 10.58 for electrons with $p_T = 25$ GeV, a significant reduction of the tails due to bremsstrahlung can only be achieved at higher energies by combining the inner-detector measurements with the accurate measurement of the $\phi$-position of the electromagnetic shower. This latter constraint, when combined with the extrapolated track impact in the calorimeter, provides enough information to estimate with reasonable accuracy the origin and energy of a hard bremsstrahlung photon. As shown in figure 10.58, this combined bremsstrahlung

Figure 10.57: Jet rejection as a function of overall reconstruction and identification efficiency for electrons, as obtained using a likelihood method (full circles). The results obtained with the standard cut-based method are also shown in the case of tight TRT (open triangle) and tight isol. (open square) cuts.

Figure 10.58: For electrons with $p_T = 25$ GeV and $|\eta| > 1.5$, integral probability for ratio of true to reconstructed transverse momentum to exceed a given value. The various symbols represent different track-fitting algorithms (see section 10.2.5) and the bremsstrahlung recovery algorithm, which uses the accurate measurement of the shower position in $\phi$ in the electromagnetic calorimeter (see text).
recovery procedure will reduce considerably the tails in the $E/p$ distribution, which will be an important tool for studying the uniformity of calibration of the electromagnetic calorimeter, as well as material and alignment effects.

10.4.2.2 Photons

Photons are much harder to extract as a signal from the jet background than certain specific isolated electron signals, such as those expected from $Z \rightarrow ee$ or $W \rightarrow e\nu$ decays. A single set of photon identification cuts, equivalent to the "tight cuts" defined for electrons, has been optimised based on the shower shapes in the calorimeter with special emphasis on separating single $\pi^0$'s from photons using the very fine granularity in $\eta$ of the strip layer. In addition, a simple track-isolation criterion has been added to further improve the rejection while preserving the vast majority of converted photons. Using these criteria, an efficiency of 84% has been obtained for photons with an energy spectrum as expected from $H \rightarrow \gamma\gamma$ decay with $m_H = 120$ GeV. This efficiency is quite uniform over the whole $\eta$-range except for the crack between the barrel and end-cap calorimeters mentioned above. For this value of the photon efficiency, a jet rejection of $\sim 5000$ (without track isolation) to $9000$ (with track isolation) has been achieved, averaged over the parton flavours corresponding to the inclusive di-jet background sample used. The expected jet rejections are shown in table 10.4 separately for quarks and gluons and for two relevant values of the $E_T$-threshold applied to the photon candidates. The larger rejection expected against gluon jets is due to the softer fragmentation and therefore broader lateral extent of gluon jets compared to light jets which are dominant in the quark-jet sample. The residual background from jets is mostly composed of isolated $\pi^0$'s, so the fine-grained strip layer of the electromagnetic calorimeter is an important element to achieve such rejections. As for the electrons, the jet rejections are computed with respect to truth-particle jets reconstructed using particle four-momenta within a cone of size $\Delta R = 0.4$.

Multivariate methods have also been developed for the more difficult case of photon identification. These can be seen in figure 10.59, which shows as an example the expected performance for a likelihood technique compared to the standard cut-based analysis. For photon candidates with $E_T > 25$ GeV and a fixed efficiency of 84%, the rejection with respect to the cut-based selection is improved by 6% for the likelihood method.
Table 10.4: Jet rejections obtained before and after applying track-isolation cuts for photon candidates with $E_T > 25$ GeV and $E_T > 40$ GeV and for a photon efficiency of approximately 84%. The rejection values are shown with their statistical errors separately for quark and gluon jets.

<table>
<thead>
<tr>
<th>Selection cuts</th>
<th>$E_T &gt; 25$ GeV</th>
<th>$E_T &gt; 40$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quark jets</td>
<td>Gluon jets</td>
</tr>
<tr>
<td>Before isolation</td>
<td>1770±50</td>
<td>15000±700</td>
</tr>
<tr>
<td>After isolation</td>
<td>2760±100</td>
<td>27500±2000</td>
</tr>
<tr>
<td></td>
<td>Quark jets</td>
<td>Gluon jets</td>
</tr>
<tr>
<td>Before isolation</td>
<td>1610±100</td>
<td>15000±1600</td>
</tr>
<tr>
<td>After isolation</td>
<td>2900±240</td>
<td>28000±4000</td>
</tr>
</tbody>
</table>

10.4.2.3 Reconstruction of $H \rightarrow eeee$ and $H \rightarrow \gamma\gamma$ final states

The performance of the reconstruction, including calibration, with the identification criteria discussed above is shown in figure 10.60 for decays of a Higgs boson with a mass of 130 GeV to four electrons (loose electron cuts applied) and in figure 10.61 for decays of a Higgs boson with a mass of 120 GeV to two photons (tight photon cuts applied and barrel/end-cap transition region excluded). A global constant term of 0.7% has been included in the electromagnetic calorimeter resolution for these plots. In the case of $H \rightarrow \gamma\gamma$ decays, the photon directions are derived from a combination of the direction measurement in the electromagnetic calorimeter described above (see figure 10.55) with the primary vertex information from the inner detector (see table 10.2).

In the case of the Higgs-boson decay to four electrons, the central value of the reconstructed invariant mass is correct to $\sim 1$ GeV, corresponding to a precision of 0.7%, and the expected Gaussian resolution is $\sim 1.5\%$. The non-Gaussian tails in the distribution amount to 20% of events which lie further than 2σ away from the peak. They are mostly due to bremsstrahlung, particularly in the innermost layers of the inner detector, but also to radiative decays and to electrons poorly measured in the barrel/end-cap transition region of the electromagnetic calorimeter.

In the case of the Higgs-boson decay to two photons, the central value of the reconstructed invariant mass is correct to $\sim 0.2$ GeV, corresponding to a precision of 0.3%, and the expected resolution is $\sim 1.2\%$. Figure 10.61 also clearly shows that most of the non-Gaussian tails at low values of the reconstructed mass of the photon pair are due to photons which converted in the inner detector.

10.4.3 Assessment of performance in situ with initial data

One important ingredient in the calibration strategy for the electromagnetic calorimeter is the use of large-statistics samples of $Z \rightarrow ee$ decays to perform an accurate inter-calibration of regions with a fixed size of $\Delta\eta \times \Delta\phi = 0.2 \times 0.4$ [267]. It is expected that such a scheme will decrease the initial spread from region to region, conservatively assumed to be approximately 1.5–2%, to values comparable to the expected constant term of $\sim 0.5\%$ in each region. This however assumes an excellent knowledge of the material in front of the electromagnetic calorimeter. The material in the inner detector should be eventually mapped out very accurately using e.g. photon conversions, but other less sensitive but more robust methods will also be used, exploiting the high granularity of the electromagnetic calorimeter. The energy flow measured in the second layer of the electromagnetic calorimeter, for example in minimum-bias events, provides such a tool, as illustrated in figure 10.62. Only energy deposits more than 5σ above the electronic noise level are considered...
Figure 10.60: Expected distribution for the invariant mass of the four electrons from Higgs-boson decays with $m_H = 130$ GeV. The energies of the electrons are determined only from the electromagnetic calorimeter measurements. The results do not include a $Z$-mass constraint.

Figure 10.61: Expected distribution for the invariant mass of the two photons from Higgs-boson decays with $m_H = 120$ GeV. The shaded plot corresponds to events in which at least one of the two photons converted at a radius below 80 cm.

for these measurements. With approximately two million minimum-bias events, corresponding to roughly one day of data-taking, additional material inside the inner detector amounting to 20% $X_0$ would be identified in any region of size $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ [268]. Another more sensitive possibility is the study of the $\phi$-symmetry of the fraction of energy deposited in the first layer of the electromagnetic calorimeter by isolated electrons, as shown in figure 10.63. Combining this information with that from the other layers in the calorimeter and with the momentum measurement of the electrons will provide higher sensitivity (for example in $\eta$) than the minimum-bias results.

Figure 10.64 shows the result of such an inter-calibration procedure applied to simulated $Z \rightarrow ee$ decays with an initial 2% spread from region to region. Once the material in front of the electromagnetic calorimeter is sufficiently well understood, an inter-calibration accuracy of 0.7% could be achieved for a total of approximately 50,000 $Z \rightarrow ee$ decays, reconstructed with the medium set of identification cuts described above, and corresponding to an integrated luminosity of $\sim 150$ pb$^{-1}$.

As described in section 10.9.3 for initial luminosities of $10^{31}$ cm$^{-2}$ s$^{-1}$, a trigger on low-mass di-electron pairs (the 2e5 signature in table 10.7) should provide good statistics of $J/\psi \rightarrow ee$ and $\Upsilon \rightarrow ee$ decays. An example of the signal and background samples which will be provided by the low-mass pair di-electron trigger in early data is shown in figure 10.65. For this study, the track-seeded algorithm introduced in section 10.4.1 has been used with tight electron cuts as described above. The signal-to-background ratio obtained is larger than one at the $J/\psi$ and $\Upsilon$ peaks, but the extraction of electron pairs from Drell-Yan will require further studies (tighter identification or kinematic cuts). With an integrated luminosity of 100 pb$^{-1}$ and an efficient identification and reconstruction of these low-mass pairs, approximately 100,000 $J/\psi$ decays and 30,000 $\Upsilon$ decays could be isolated for detailed studies of the electron identification and reconstruction performance, in particular in terms of matching energy and momentum measurements at a scale quite different from that of the more commonly used $Z \rightarrow ee$ decays.
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Figure 10.62: Distribution of the transverse energy accumulated in $\Delta \eta \times \Delta \phi = 0.1 \times 0.025$ middle-layer regions with a few hours of minimum bias events. The full histogram corresponds to the hemisphere with a nominal amount of inner-detector material in the simulation for $1.8 < \eta < 1.9$, whereas the dotted histogram corresponds to the hemisphere with a 25% increase in the amount of material in the same $\eta$-region.

Figure 10.63: Distribution of the fraction of energy deposited in the strip layer by electrons from $W/Z$ decays corresponding to the statistics expected for an integrated luminosity of 50 pb$^{-1}$. The full histogram corresponds to the hemisphere with a nominal amount of inner-detector material in the simulation for $1.8 < \eta < 1.9$, whereas the dotted histogram corresponds to the hemisphere with a 25% increase in the amount of material in the same $\eta$-region.

Figure 10.64: Statistical accuracy expected from inter-calibration of the electromagnetic calorimeter as a function of the number of reconstructed $Z \rightarrow ee$ decays or of the integrated luminosity (see text). These results assume a perfect knowledge of the material in front of the electromagnetic calorimeter.

Figure 10.65: Expected differential cross-section for low-mass electron pairs using the 2e5 trigger menu item discussed in section 10.9.3. Shown is the invariant di-electron mass distribution reconstructed using tracks for $J/\psi \rightarrow ee$ decays (dotted histogram), $Y \rightarrow ee$ decays (dashed histogram) and Drell-Yan production (full histogram). Also shown is the expected background after the offline selection described in the text (full circles).
10.5 Jet reconstruction

The ATLAS calorimeters have very high lateral granularity and several samplings in depth over $|\eta| < 3.2$ (see table 1.3 for an overview of the properties of the various ATLAS calorimeters). The forward calorimeters, which cover the region $3.2 < |\eta| < 4.9$, also provide sufficient granularity to reconstruct jets with small polar angles with reasonable accuracy and efficiency. For the reconstruction of jets in the wide variety of physics processes of interest at the LHC, specific care has therefore been taken to devise a modular and generic design of the corresponding software. The implementation allows for the use of a variety of jet clustering algorithms using as input any reconstruction object having a four-momentum representation. These inputs can vary from calorimeter cells, or charged tracks, to Monte-Carlo truth objects, such as stable particles or final-state partons from the generator. It also supports easy implementation of jet-clustering algorithms different from the ones most commonly used, and has followed the guidelines collected for Run II at the Tevatron [269].

10.5.1 Jet clustering algorithms

The two default jet-clustering algorithms in ATLAS are a seeded fixed-cone algorithm and a successive recombination algorithm. Both algorithms are used in two different configurations, one producing narrow jets for e.g. $W$-mass spectroscopy in $t\bar{t}$ events or events containing large multiplicities of jets as in supersymmetric models, and the other producing wider jets for e.g. QCD studies of di-jet and multi-jet final states at luminosities below $10^{33}$ cm$^{-2}$ s$^{-1}$.

The seeded cone algorithm uses two parameters, the transverse energy threshold for a seed, $E_T = 1$ GeV for all cone jets, and the cone size, $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$, with $\Delta R = 0.4$ for narrow jets and $\Delta R = 0.7$ for wide jets. In all cases, a split-and-merge step follows the actual cone building, with an overlap fraction threshold of 50%. The cone algorithm in this particular implementation is fast and therefore also used in the high-level trigger (see section 10.9).

The $k_T$ algorithm in ATLAS is implemented following the suggestions in [270], which makes it efficient even for a rather large number of input objects and avoids the usual pre-clustering step. The distance parameter $R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$ is adjusted for narrow jets to $R = 0.4$ and for wide jets to $R = 0.6$. The physics performance is very similar to the one of the corresponding cone configurations. In all cases the full four-momentum recombination is used to calculate the jet kinematics after each clustering step.

10.5.2 Input to jet reconstruction

Typical inputs for jet-finding in ATLAS are final-state particles for truth-particle jets, and calorimeter signals for reconstructed or calorimeter jets. Naturally, truth-particle jets are only available in simulated data. They are formed by applying a jet algorithm to all stable neutral and charged particles in the final state within $|\eta| < 5$. These particles can emerge from the hadronisation of the hard-scattered parton, from initial- and final-state radiation, and from the underlying multiple interactions in the event. The kinematic properties of these particles are taken at their generation vertex, before any interaction with the detector and its magnetic field.
Figure 10.66 presents an overview of the reconstruction flow for calorimeter jets. Calorimeter jets are reconstructed by applying a jet-clustering algorithm to calorimeter signals, typically followed by a calibration step. Two different signals from the calorimeter are used for jet-finding, towers and topological clusters. Towers are formed by collecting cells into bins of a regular \( \Delta \eta \times \Delta \phi = 0.1 \times 0.1 \) grid, depending on their location, and summing up their signals, or a fraction of their signal corresponding to the overlap area fraction between the tower bin and the cell in \( \Delta \eta \) and \( \Delta \phi \). This summing stage is non-discriminatory, meaning all calorimeter cells are used in the towers. Towers with negative signals are dominated by noise, and cannot be used in jet-finding. They are recombined with nearby positive signal towers until the net signal is positive, i.e. the resulting towers have a valid physical four-vector and can directly be used by the jet finders. This approach can be understood as an overall noise cancellation rather than suppression, since the noisy cells still contribute to the jets at initial luminosities of \( 10^{31} \text{ cm}^{-2} \text{s}^{-1} \) to \( 10^{33} \text{ cm}^{-2} \text{s}^{-1} \).

Topological cell clusters represent an attempt to reconstruct three-dimensional energy depositions in the calorimeter [152, 271]. First, nearest neighbours are collected around seed cells with a significant absolute signal above the major seed threshold, i.e. \( |E_{\text{cell}}| > 4 \sigma_{\text{cell}} \) of the total noise (electronics plus pile-up). Energy equivalents of the \( \sigma \) of the electronic noise alone in the various calorimeter cells are shown in figure 5.27, while figure 10.67 shows estimates for the total \( \sigma \) when fluctuations from pile-up at a luminosity of \( 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) are included at the cell level. These neighbouring cells are collected independently of the magnitude of their own signal. If the absolute value of their signal significance is above a secondary seed threshold, typically such that \( |E_{\text{cell}}| > 2 \sigma_{\text{cell}} \), they are considered secondary seeds and their direct neighbours are also collected. Finally, all surrounding cells above a very low threshold (typically set to \( 0 \sigma \)) are added if no more secondary seeds are among the direct neighbours. A final analysis of the resulting cluster looks for multiple local signal maxima. In case of more than one maximum in a given cluster, it is split into smaller clusters, again in three dimensions, along the signal valleys between the maxima.

Contrary to the signal tower formation, topological cell clustering includes actual noise suppression, meaning that cells with no signal at all are most likely already not included in the cluster. This results in substantially less noise, as shown in figure 10.68, and less cells, as shown in figure 10.69, in these cluster jets than in tower jets. Topological cell clusters are under study for

Figure 10.66: Jet reconstruction flow for calorimeter jets from towers or clusters.
use as the basis for the local hadronic energy calibration, which attempts to correct for detector effects, such as calorimeter responses with $e/h > 1$ and dead-material energy losses, outside of the jet context itself. Although very promising in terms of noise suppression, the topological cell clustering will require careful validation with real data, in particular in terms of the possible impact of long-range noise correlations and of detailed studies of pile-up effects as the luminosity increases.

### 10.5.3 Jet calibration

The strategy currently adopted for calorimeter jet calibration in ATLAS is the application of cell signal weighting similar to the original approach developed for the H1 calorimeter [272]: all calorimeter cells with four-momenta $(E_i, \vec{p}_i)$, where $E_i = |\vec{p}_i|$, in tower or cluster jets are considered and re-summed with weighting functions, $w$, such that the resulting new jet four-momentum is:

$$ (E_{\text{rec}}, \vec{p}_{\text{jet}}) = \left( \sum_{i}^{N_{\text{cells}}} w(\rho_i, \vec{X}_i) E_i, \sum_{i}^{N_{\text{cells}}} w(\rho_i, \vec{X}_i) \vec{p}_i \right). $$

The weighting functions $w$ depend on the cell signal density, $\rho_i = E_i / V_i$, where $V_i$ is the volume of the cell considered, and on the cell location in the calorimeter, $\vec{X}_i$, consisting basically of module and layer identifiers. They are fitted using simulated QCD di-jet events, covering the whole kinematic range expected at the LHC, and matching calorimeter cone-tower jets, with $\Delta R = 0.7$, with
Figure 10.68: Average electronic noise contribution to cone jets with $\Delta R = 0.7$ in QCD di-jet events, reconstructed from towers (open circles) and topological cell clusters (full circles), as a function of $|\eta|$.

Figure 10.69: Average total number of cells contributing to cone jets with $\Delta R = 0.7$ in QCD di-jet events, reconstructed from towers (open circles) and topological cell clusters (full circles), as a function of the jet energy.

nearby truth-particle cone jets of the same size and with energy $E_{\text{truth}}$, and then constraining $E_{\text{rec}}$ in eq. (10.2) to $E_{\text{truth}}$ by:

$$
\frac{\partial \chi^2}{\partial w(\rho_i, \hat{X}_i)} = \frac{\partial}{\partial w(\rho_i, \hat{X}_i)} \left[ \sum_{\text{matched jets}} \frac{(E_{\text{rec}} + E_{\text{DM}} - E_{\text{truth}})^2}{E_{\text{truth}}} \right] = 0. 
$$

(10.3)

The weighting functions determined in this way absorb all detector effects, including missing signals from charged truth particles with less than $\sim 400$ MeV transverse momentum, which are bent away from the calorimeter by the solenoid magnetic field in the inner detector cavity. Implicitly included also are corrections for energy loss in inactive materials, except for losses between the electromagnetic barrel and tile barrel calorimeters, which are parametrised in eq. (10.3) as:

$$
E_{\text{DM}} = a \frac{E_{\text{EMB3}} E_{\text{TILE0}}}{E_{\text{TILE0}}},
$$

(10.4)

where $E_{\text{EMB3}}$ is the sum of the energies of the cells in the last layer of the barrel electromagnetic calorimeter belonging to the jet and $E_{\text{TILE0}}$ is the corresponding sum in the first layer of the hadronic tile calorimeter. Both quantities are reconstructed at the electromagnetic energy scale.

The parameter $a$ was assumed to be independent of energy and of $\eta$ and was determined together with $w(\rho_i, \hat{X}_i)$ in a combined fit according to eq. (10.3).

Naturally, the calibration applied in this way only corrects to the level of the truth-particle jet. The extracted weighting functions were obtained for cone-tower jets with $\Delta R = 0.7$ and are not universal, since they depend on the choice of calorimeter signals used, on the jet algorithm chosen and on its specific configuration, and on the choice of (simulated) physics calibration samples used to extract them. Residual mis-calibrations for all cluster cone and cluster $k_T$ jets are corrected for by functions depending on $|\eta|$ and $p_T$ of each measured jet. Similar corrections are applied to tower cone jets with $\Delta R = 0.4$ and to the tower $k_T$ jets. These corrections have been derived by comparing the calorimeter jets after applying the cell signal weights and dead-material corrections with the matching truth-particle jet in the simulated QCD di-jet events.
Figure 10.70: Signal linearity for cone-tower jets with $\Delta R = 0.7$, as expressed by the ratio of reconstructed tower jet energy to the matching truth-jet energy $E_{\text{rec}}/E_{\text{truth}}$, in two different regions of $|\eta|$ and as a function of $E_{\text{truth}}$. Jet signals calibrated at the electromagnetic energy scale are compared to the fully calibrated jets.

Figure 10.71: Fractional energy resolution for calibrated cone-tower jets reconstructed with $\Delta R = 0.7$ and $\Delta R = 0.4$ in two different regions of $|\eta|$ and as a function of $E_{\text{truth}}$.

10.5.4 Jet signal characteristics

All signal features discussed in the following are extracted from simulations including a model for the electronic noise in each calorimeter cell, tuned with parameters extracted from various test-beam measurements. The results shown here are, unless stated otherwise, based on the jet-calibration procedure described above, called from now on global calibration. Pile-up fluctuations are not included.

The most important requirements for the jet signal after global calibration are a linear response across all jet energies, a uniform response as independent as possible from the jet direction, and a fractional energy resolution within the specifications laid out in table 1.1.

10.5.4.1 Jet signal linearity and energy resolution

The signal linearity for calorimeter jets in ATLAS is expressed by the ratio of the reconstructed jet energy and the matched truth-jet energy, $E_{\text{rec}}/E_{\text{truth}}$, in simulated QCD di-jet events.

Figure 10.70 shows, for two different regions in $|\eta|$, that the signal linearity for cone jets made from towers with $\Delta R = 0.7$ is reasonable over the whole energy range after the global calibration is applied. Figure 10.70 also shows the deviations from signal linearity expected for jets reconstructed at the electromagnetic energy scale, i.e. without any hadronic calibration applied. In this case, the reconstructed jet signals correspond to only $\sim 65\%$ (at the lowest energies) to $\sim 80\%$ (at the highest energies) of the true jet energy.

The fractional energy resolution for the same jets, again after global calibration, is shown as a function of $E_{\text{truth}}$ and for two different $\eta$-regions in figure 10.71. In addition, the resolution for a smaller cone size $\Delta R = 0.4$ is shown. The curves show the results of a three-parameter fit to the
Figure 10.72: For cone-tower jets reconstructed with $\Delta R = 0.7$, distribution of $\Delta R$ between reconstructed and matched particle jet axes for two different transverse energy and $\eta$-ranges.

Figure 10.73: For cone-cluster jets reconstructed with $\Delta R = 0.7$, distribution of $\Delta R$ between reconstructed and matched particle jet axes for two different transverse energy and $\eta$-ranges.

energy resolution function:

$$\frac{\sigma}{E} = \sqrt{\frac{a^2}{E} + \frac{b^2}{E^2} + c^2} \quad (10.5)$$

For central jets in the region $0.2 < |\eta| < 0.4$, the stochastic term is $\approx 60\% \sqrt{\text{GeV}}$, while the high-energy limit of the resolution, expressed by the constant term $c$, is $\approx 3\%$ with the current global calibration. One important contribution to the $\eta$-dependence of the jet energy resolution is the noise, which varies quite rapidly due to the increasing readout-cell size and the change in calorimeter technology in the hadronic calorimeters from the low-noise tile calorimeter to the (higher-noise) LAr calorimeter with increasing $\eta$. The noise term $b$ in the energy resolution function is found to increase from 0.5 GeV to 1.5 GeV when going from the barrel to the end-cap $\eta$-ranges shown in figure 10.71.

10.5.4.2 Jet direction measurement

The highly granular ATLAS calorimeters provide a precise measurement not only of the jet energy, but also of the jet direction together with the knowledge of the primary vertex position from the inner detector (see section 10.2.4). Figures 10.72 and 10.73 show very similar distributions of the distance $\Delta R$ between reconstructed and matched truth-particle jet directions for tower and cluster cone jets with $\Delta R = 0.7$ in two different pseudo-rapidity regions and two different transverse energy ranges. The choice of calorimeter signal obviously does not significantly affect the direction reconstruction of the jet. The general conclusion is that for both tower and cluster jets with transverse energies above 100 GeV, basically all reconstructed jets fall within the default matching cuts, $\Delta R < 0.2$. At lower transverse energies, however, it is clear that the precision with which the jet axis is reconstructed is degraded and a non-negligible fraction of reconstructed jets will fall outside the default matching cut. This issue is rediscussed below in section 10.5.5 with wider matching cuts to assess the efficiency and purity of reconstruction of low-$p_T$ jets.
10.5.4.3 Jet signal uniformity

The variation of the jet energy response as a function of the jet direction is a measure of the uniformity of the jet signal across the full rapidity coverage of the calorimeters. Figure 10.74 shows for tower jets the ratio of reconstructed to matching truth-particle energy as a function of $|\eta|$ for jets in two different bins of $E_T$. The dips in response, corresponding to the two transition regions, $1.2 < |\eta| < 2.0$ and $2.8 < |\eta| < 3.4$, are much more apparent at low transverse energies. The dip in response in the last $\eta$-bin is a reflection of the limited fiducial coverage of jet reconstruction for $|\eta| > 4.4$. The $\eta$-dependence of the corresponding fractional energy resolution in figure 10.75 can be understood: the energy $E_{\text{jet}}$ of jets with $30 < p_T < 40$ GeV increases from $E_{\text{jet}} = 30$ GeV at $|\eta| = 0$ to $E_{\text{jet}} \approx 1.8$ TeV at $|\eta| = 4.5$. Following the parametrisation in eq. (10.5), the fractional energy resolution, $\sigma/E$, improves dramatically over this energy range. The energy-dependent stochastic, $a/\sqrt{E}$, and noise, $b/E$, terms dominate over a large part of the kinematic regime. For jets with $480 < p_T < 640$ GeV, the jet energy range is $480 \leq E_{\text{jet}} < 7000$ GeV from $|\eta| = 0$ up to $|\eta| \approx 3.1$, which is the kinematic limit at the LHC. In this region, $\sigma/E$ is essentially independent of $E_{\text{jet}}$, i.e. dominated by the constant term, $c \gg a/\sqrt{E} \gg b/E$.

10.5.5 Jet reconstruction performance

The evaluation of the jet reconstruction performance includes not only the required signal features discussed above, but also parameters which are more oriented towards physics analysis, such as jet-finding efficiency and purity, jet vetoing, and jet tagging.

The jet reconstruction efficiency is defined as:

$$\epsilon(\Delta R_m) = \frac{\text{# matches of truth particle jets with reconstructed jets}}{\text{# truth particle jets}} = \frac{N_{\text{jets}}(\Delta R_m)}{N_{\text{jets}}^{\text{truth}}} ,$$

(10.6)

where $\Delta R_m = \sqrt{(\eta_{\text{reco}} - \eta_{\text{truth}})^2 + (\phi_{\text{reco}} - \phi_{\text{truth}})^2}$ is the chosen matching radius (typically

\textbf{Figure 10.74}: Signal uniformity for QCD di-jets in two different $E_T$ ranges, as a function of $|\eta|$ of the matched truth-particle jet. The results are shown for cone-tower jets with $\Delta R = 0.7$ and $\Delta R = 0.4$.

\textbf{Figure 10.75}: Jet energy resolution for QCD di-jets in two different $E_T$ ranges, as a function of $|\eta|$ of the matched truth-particle jet. The results are shown for cone-tower jets with $\Delta R = 0.7$ and $\Delta R = 0.4$. 

...
The purity $\pi$ of the jet reconstruction can be expressed as:

$$\pi(\Delta R_m) = \frac{\text{# matches of truth particle jets with reconstructed jets}}{\text{# reconstructed jets}} = \frac{N^\text{jets}(\Delta R_m)}{N^\text{reco}}.$$  \hspace{1cm} (10.7)

The fake jet reconstruction rate $f$ is then simply $f = 1 - \pi(\Delta R_m)$. In all cases, only one match is allowed for each reference jet. In case of two or more nearby jets, the one closest to the chosen reference is taken.

The two different calorimeter signal definitions used for jet reconstruction (towers and clusters) are expected to produce different efficiencies and purities. This is particularly important for searches for specific exclusive final states, where the requirement that no additional jet be present in the event is often used as a powerful tool to reject certain backgrounds. For example, one of the interesting production channels for the Higgs boson is vector-boson fusion (VBF), which has a very characteristic final state with two forward-going quark jets (often called tag jets) and, for non-hadronic Higgs-boson decay modes, no jets from the hard-scattering process itself in the central region of the detector. In this specific case, the efficiency of the jet-finding in the forward region, as defined in eq. (10.6), is a measure of the jet-tagging probability. The purity of the jet reconstruction in the central region then measures the efficiency for vetoing low-$p_T$ jets.

The resulting efficiencies and purities are shown for cone-tower and cone-cluster jets with $\Delta R = 0.7$, respectively, as a function of $p_T$ and $\gamma$ in figures 10.76, 10.77, 10.78 and 10.79 for the specific case of VBF produced $H \rightarrow \tau \tau$ decays with $m_H = 120$ GeV and for a looser matching radius $\Delta R_m = 0.5$ (see eq. (10.6) and (10.7)). These results show that for $p_T > 40$ GeV, the performances of the tower and cluster jets are very similar. For lower values of $p_T$, however, the cluster jets are found with both higher efficiency and purity than tower jets.

For jets reconstructed with $p_T > 10$ GeV, the fake rates in the central region are quite high, ranging from 30% for cluster jets to 45% for tower jets. In the forward regions, the jet-tagging efficiencies are close to 90% for cluster jets while they are only around 50% for tower jets with,
Figure 10.78: Efficiency of jet reconstruction in VBF-produced Higgs-boson events as a function of the rapidity $y$ of the truth-particle jet for $p_T^{\text{jet}} > 10$ GeV and $p_T^{\text{jet}} > 20$ GeV and for cone-tower and cone-cluster jets with $\Delta R = 0.7$.

Figure 10.79: Purity of jet reconstruction in VBF-produced Higgs-boson events as a function of the rapidity $y$ of the reconstructed jet for $p_T^{\text{jet}} > 10$ GeV and $p_T^{\text{jet}} > 20$ GeV and for cone-tower and cone-cluster jets with $\Delta R = 0.7$.

However, significantly higher fake rates of $\sim 10\%$ for the cluster jets. These results are clearly also quite sensitive to pile-up, so it is important to stress here that the numbers above apply only for initial data-taking at luminosities between $10^{31}$ cm$^{-2}$ s$^{-1}$ and $10^{33}$ cm$^{-2}$ s$^{-1}$.

10.5.6 Validation of jet calibration with in-situ measurements

There are several final states at the LHC which provide signals for validation of the jet energy calibration, and, in some cases, even the extraction of further corrections. In general, final states with a well measured electromagnetic object balancing one or more jets in transverse momentum, such as in $\gamma + \text{jet(s)}$ and $Z + \text{jet(s)}$ events, are good choices for this task. The $\gamma + \text{jet(s)}$ process provides high statistics in the transverse momentum range from 40 to 400 GeV, but lower purity than the $Z + \text{jet(s)}$ process, which should, however, cover precisely the lower edge of the transverse momentum range, up to 100 GeV.

As an example, one approach to measure the jet response using $\gamma + \text{jet(s)}$, which has been developed at the Tevatron, is the missing transverse momentum projection fraction. The basic idea of this method is to project the hadronic transverse-momentum vectors onto the transverse-momentum vector of the photon and to measure the apparent $E_T^{\text{miss}}$ fraction. In events where the photon is back-to-back with the jet (to better than approximately ten degrees in $\phi$), the jet response $R_{\text{jet}}$ can then be determined by

$$R_{\text{jet}} = -\frac{\sum \text{signals} \cdot \vec{p}_T^{\text{had}} \cdot \vec{\hat{n}}_\gamma}{p_{T,\gamma}}.$$  

(10.8)

Here $\vec{\hat{n}}_\gamma = \vec{p}_{T,\gamma}/p_{T,\gamma}$ is the direction of the photon in the transverse event plane. The hadronic transverse momentum can be calculated using the reconstructed jet(s) ($\vec{p}_{T,\text{had}} = \vec{p}_{T,jet}$), or just using the sum of cluster signals without the jet context ($\vec{p}_{T,\text{had}} = \vec{p}_{T,\text{calo}}$). Figure 10.80 shows the jet response for cone-tower jets with $\Delta R = 0.4$ at the electromagnetic energy scale, as a function of the jet energy, for simulated $\gamma + \text{jet}$ events. This variable can be measured directly and can thus become...
the basis for a global jet energy scale calibration derived from collision data. The $\eta$-dependence of the jet response for the same jets and events is shown in figure 10.81. The shape of the response clearly indicates the effect of the crack regions of the ATLAS calorimeter system on the jet energy measurement.

The other important final state for jet calibration are hadronically decaying $W$ bosons ($W \to qq$), which in ATLAS can only be used with high purity in $t\bar{t}$ production. Here, $m_W$ constrains the energy scale of the two quark jets. Figure 10.82 shows the ratio between the reconstructed di-jet mass from $W \to jj$ decays and the nominal $W$-boson mass as a function of the true transverse momentum, $p_T^W$, of the $W$-boson. For the nominal selection cuts used to reconstruct $t\bar{t}$ events, this ratio departs significantly from unity at low values of $p_T^W$ because of the high $p_T$-threshold of 40 GeV applied to the jets, as illustrated in figure 10.82. With further in-situ corrections aimed at re-scaling jet energies as a function of $|\eta|$ to obtain a uniform response, e.g. as shown in figure 10.81, a linearity of better than 2% can be achieved up to values of $p_T^W$ as high as 200 GeV.

![Figure 10.80: Jet response for seeded cone-tower jets ($\Delta R = 0.4$) in $\gamma +$ jet events, averaged over $\eta$ and calculated by the missing transverse momentum fraction method, as a function of the jet energy. The calorimeter signals are reconstructed at the electromagnetic energy scale.](image1)

![Figure 10.81: Jet response for seeded cone-tower jets ($\Delta R = 0.4$), in $\gamma +$ jet events, averaged over jet energy and calculated by the missing transverse momentum fraction method, as a function of the jet direction, $|\eta_{\text{jet}}|$. The calorimeter signals are reconstructed at the electromagnetic energy scale. The degraded response in the calorimeter crack regions is clearly visible.](image2)

![Figure 10.82: Ratio of the reconstructed di-jet mass from $W \to jj$ decays and the nominal $W$-boson mass as a function of the true transverse momentum of the $W$-boson, $p_T^W$, for globally calibrated cone-tower jets with $\Delta R = 0.7$. Shown are the results for the nominal jet-selection cuts, $p_T > 40$ GeV (open circles), for jets reconstructed with $p_T > 10$ GeV (open squares) and for jets re-scaled to obtain a more uniform response as a function of $|\eta|$ (full triangles).](image3)
10.6 Missing transverse energy

A very good measurement of the missing transverse energy, $E_{\text{miss}}^T$, is a critical requirement for the study of many physics channels in ATLAS, in particular in the search for signals from new physics such as supersymmetry or extra dimensions. A good $E_{\text{miss}}^T$ measurement in terms of linearity and accuracy is also important for the reconstruction of the top-quark mass from $t\bar{t}$ events with one top quark decaying semi-leptonically. It is crucial for the efficient and accurate reconstruction of the Higgs-boson mass when the Higgs boson decays to a pair of $\tau$-leptons, the most prominent example being the supersymmetric Higgs boson $A$. Another important requirement on the measurement of $E_{\text{miss}}^T$ is to minimise the impact of tails induced by imperfections in the detector coverage or detector response. The $\eta$-coverage of the forward calorimeters minimises by design any tails from particles escaping at very large $\eta$, but there are several transition regions in the calorimetry, which will lead to incorrect measurements of $E_{\text{miss}}^T$ in a certain fraction of the cases. This could significantly enhance for example the backgrounds from QCD multi-jet events to a possible signal from supersymmetry or the backgrounds from $Z \rightarrow ll$ decays accompanied by high-$p_T$ jets to a possible signal from Higgs-boson decay into two leptons and two neutrinos. This section describes briefly the reconstruction and calibration of $E_{\text{miss}}^T$ in ATLAS, illustrates the expected performance with a few examples, and finally concludes with a discussion of the possible sources of fake $E_{\text{miss}}^T$.

10.6.1 Reconstruction and calibration of $E_{\text{miss}}^T$

The $E_{\text{miss}}^T$ reconstruction in ATLAS is based in a first step on the calibrated calorimeter cell energies (following the global calibration scheme described in section 10.5.3) and on the reconstructed muons. The $E_{\text{miss}}^T$ muon term is calculated from the momenta of the muons measured using the stand-alone muon-spectrometer reconstruction (see section 10.3). Energy lost by muons in the calorimeter is thus not double-counted, since it is only taken into account in the calorimeter term. Only good-quality muons with a matched track in the inner detector are considered, which reduces considerably possible contributions from fake muons, sometimes created from high hit multiplicities in the muon spectrometer in events with very energetic jets.

In a second step, the $E_{\text{miss}}^T$ reconstruction accounts for the so-called cryostat term, which corrects for the energy lost in the cryostat between the barrel LAr electromagnetic and tile calorimeters. This correction is applied following the recipe described in section 10.5.3 and eq. (10.4) and is found to be non-negligible for high-$p_T$ jets: it represents a $5\%$ contribution per jet with $p_T$ above 500 GeV.

In a final step, a refined calibration of $E_{\text{miss}}^T$ is performed through the association of each high-$p_T$ object in the event to its globally calibrated cells. Starting from the reconstructed identified objects in a carefully chosen order, namely electrons, photons, hadronically decaying $\tau$-leptons, $b$-jets, light jets and muons, each calorimeter cell is associated to its parent high-$p_T$ object. The refined calibration of $E_{\text{miss}}^T$ then replaces the initial contribution from globally calibrated cells by the contribution from the corresponding calibrated high-$p_T$ objects themselves. The cells which survive a noise cut optimised in terms of $E_{\text{miss}}^T$ measurements and which do not contribute to any reconstructed object are also calibrated using the global calibration scheme and accounted for in the $E_{\text{miss}}^T$ calculation.
Figure 10.83: Linearity of response for reconstructed $E_T^{\text{miss}}$ as a function of the average true $E_T^{\text{miss}}$ for different physics processes covering a wide range of true $E_T^{\text{miss}}$ and for the different steps of $E_T^{\text{miss}}$ reconstruction (see text). The points at average true $E_T^{\text{miss}}$ of 20 GeV are from $Z \to \tau\tau$ events, those at 35 GeV are from $W \to e\nu$ and $W \to \mu\nu$ events, those at 68 GeV are from semi-leptonic $t\bar{t}$ events, those at 124 GeV are from $A \to \tau\tau$ events with $m_A = 800$ GeV, and those at 280 GeV are from events containing supersymmetric particles at a mass scale of 1 TeV (left). Linearity of response for reconstructed $E_T^{\text{miss}}$ as a function of the true $E_T^{\text{miss}}$ for $A \to \tau\tau$ events with $m_A = 800$ GeV (right).

10.6.2 Evaluation of $E_T^{\text{miss}}$ performance

The $E_T^{\text{miss}}$ performance is evaluated by comparing the final reconstructed and calibrated value of $E_T^{\text{miss}}$ with the true $E_T^{\text{miss}}$, calculated using all stable and non-interacting particles in the final state, for a number of physics processes of interest, involving a variety of topologies and final states over a wide range of energies. Although this evaluation focuses primarily on the linearity of response and on resolution, other features, such as the direction of the $E_T^{\text{miss}}$ vector (in the transverse plane) and tails in the measurement of $E_T^{\text{miss}}$ have also been carefully studied.

The expected performance in terms of $E_T^{\text{miss}}$ linearity of response as a function of true $E_T^{\text{miss}}$ is shown for a number of physics processes of interest in figure 10.83. The evolution of the linearity of response is illustrated for each of the major steps in the $E_T^{\text{miss}}$ reconstruction described above:

- the uncalibrated $E_T^{\text{miss}}$ corresponds to the use of cell energies at the electromagnetic scale, which therefore creates a large systematic bias of 10–30% in the response (the bias is smaller for events containing little hadronic activity on average, such as $W \to e\nu$ and $W \to \mu\nu$ decays);
- the reconstructed $E_T^{\text{miss}}$ based on globally calibrated cell energies and reconstructed muons provides a correct response to within 5%;
- the reconstructed $E_T^{\text{miss}}$ including in addition the cryostat correction provides excellent linearity of response for all processes except $W \to e\nu$;
- the refined $E_T^{\text{miss}}$ calibration in the specific case of $W \to e\nu$ events amounts to correcting the globally calibrated cells of the electron shower back to the electromagnetic scale and the linearity of response is then also restored in this case.
Figure 10.84: Resolution $\sigma$ of the two components $(x, y)$ of the $E_T^{\text{miss}}$ vector after refined calibration as a function of the total transverse energy, $\Sigma E_T$, measured in the calorimeters for different physics processes corresponding to low to medium values of $\Sigma E_T$ (left) and to higher values of $\Sigma E_T$ (right). The curves correspond respectively to the best fit, $\sigma = 0.53 \sqrt{\Sigma E_T}$, through the points from $Z \rightarrow \tau\tau$ events (left) and to the best fit, $\sigma = 0.57 \sqrt{\Sigma E_T}$, through the points from $A \rightarrow \tau\tau$ events (right). The points from $A \rightarrow \tau\tau$ events are for masses $m_A$ ranging from 150 to 800 GeV and the points from QCD jets correspond to di-jet events with $560 < p_T < 1120$ GeV.

Figure 10.84 shows that the $E_T^{\text{miss}}$ resolution $\sigma$ follows an approximate stochastic behaviour over a wide range of values of the total transverse energy deposited in the calorimeters. A simple fit to a function $\sigma = a \cdot \sqrt{\Sigma E_T}$ yields values between 0.53 and 0.57 for the parameter $a$, for $\Sigma E_T$ values between 20 and 2000 GeV. The refined $E_T^{\text{miss}}$ calibration yields somewhat better results for the $E_T^{\text{miss}}$ resolution for e.g. $W \rightarrow e\nu$ decays. Departures from this simple behaviour are expected and observed for low values of $\Sigma E_T$ where noise plays an important contribution and for very high values of $\Sigma E_T$ where the constant term in the jet energy resolution dominates.

10.6.3 Measurement of $E_T^{\text{miss}}$ direction

Figure 10.85 shows the $E_T^{\text{miss}}$ azimuthal angular resolution as a function of the true $E_T^{\text{miss}}$ for three different physics processes. The measurement of the $E_T^{\text{miss}}$ azimuth is clearly more accurate for $W \rightarrow e\nu$ events, which contain in general one high-$p_T$ electron and moderate hadronic activity in addition, than for $t\bar{t}$ events, which contain much more hadronic activity. Figure 10.85 also shows that, for values of the true $E_T^{\text{miss}}$ below 40 GeV, the accuracy on the measurement of the direction of a $E_T^{\text{miss}}$ vector with small modulus degrades rapidly. In contrast, for high values of the true $E_T^{\text{miss}}$, azimuthal accuracies below 100 mrad can be achieved.

Figure 10.85: Accuracy of the measurement of the azimuth of the $E_T^{\text{miss}}$ vector as a function of the true $E_T^{\text{miss}}$ for three different physics processes: semi-leptonic $t\bar{t}$ events, $Z \rightarrow \tau\tau$ and $W \rightarrow e\nu$ events.
Figure 10.86: Expected distributions for the reconstructed invariant mass of $\tau$-lepton pairs, with one $\tau$-lepton decaying to a lepton and the other one decaying to hadrons. The results are shown for $Z \rightarrow \tau\tau$ decays (left) and for $A \rightarrow \tau\tau$ decays with $m_A = 450$ GeV (right).

As discussed in section 10.6.5, large fluctuations in the jet energy measurements, due in particular to cracks in the fiducial acceptance of the calorimeters, may lead to fake $E_T^{\text{miss}}$ with a vector of large modulus pointing in the same direction as the mis-measured jet in the azimuthal plane. A good accuracy on the measurement of the $E_T^{\text{miss}}$ azimuth will therefore be needed to apply a cut, requiring that the measured $E_T^{\text{miss}}$ vector be isolated from all high-$p_T$ jets in the event, with a high efficiency for signal events with large true $E_T^{\text{miss}}$.

10.6.4 Use of $E_T^{\text{miss}}$ for mass reconstruction

The reconstructed $E_T^{\text{miss}}$ vector can be used to improve the overall reconstruction of final-state topologies with only one neutrino in the final state (e.g. in $t\bar{t}$ events with one hadronic and one semi-leptonic top-quark decay). But, under certain simplifying assumptions and only for pairs which are not back-to-back [273, 274], one can even use the reconstructed $E_T^{\text{miss}}$ vector in $Z \rightarrow \tau\tau$ and $A \rightarrow \tau\tau$ decays, despite the presence of several neutrinos in the final state, to reconstruct the invariant mass of the $\tau\tau$ pair. The results of such a procedure are shown in figure 10.86 for the reconstruction of $Z \rightarrow \tau\tau$ and $A \rightarrow \tau\tau$ decays with $m_A = 450$ GeV, where $A$ is a supersymmetric Higgs boson. The reconstructed masses are correct to $\sim 2\%$ and the mass resolution is approximately $11\%$. Nevertheless, significant tails remain in the distributions because of the highly non-Gaussian effects induced by mis-measurements of $E_T^{\text{miss}}$ and by the approximations used.

10.6.5 Fake $E_T^{\text{miss}}$

Fake $E_T^{\text{miss}}$, defined simply as the difference between reconstructed and true $E_T^{\text{miss}}$, can arise at a significant level from a number of different sources: beam-gas scattering and other machine backgrounds, displaced interaction vertices, hot/dead/noisy cells (or regions) in the calorimeters, and mis-measurements in the detector itself, due to high-$p_T$ muons escaping outside the fiducial acceptance of the detector (see also section 10.3) and to large losses of deposited energy in cracks or inactive materials (see also section 10.5.4.3). These latter two effects might effectively limit the performance of the $E_T^{\text{miss}}$ reconstruction in the longer term and have therefore been studied in detail.
Figure 10.87: For QCD di-jet events containing at least one jet with 560 < $E_T$ < 1120 GeV, distribution of fake $E_T^{miss}$ (circles), calculated as the difference between reconstructed and true $E_T^{miss}$, compared to the true $E_T^{miss}$ (triangles) expected in this di-jet sample (left). Also shown is the distribution of fake $E_T^{miss}$ due to muons (squares), calculated as the difference between the fake $E_T^{miss}$ and the residual fake $E_T^{miss}$ obtained using only the true muons in the event. The fake and true $E_T^{miss}$ distributions are shown (right) after applying an isolation cut on the azimuth of the reconstructed $E_T^{miss}$ vector. This cut requires that the distance in azimuth between the reconstructed $E_T^{miss}$ vector and the direction of any high-$p_T$ jet reconstructed in the event be larger than 17°.

Figure 10.88: For QCD di-jet events containing at least one jet with 560 < $E_T$ < 1120 GeV and with a fake $E_T^{miss}$ larger than 100 GeV, distribution of $|\eta|$ of the mis-measured jet.
response). As already shown in figure 10.87, these excesses can be significantly reduced with simple topological cuts, but other tools can also reduce them further if required, such as the use of jets reconstructed from tracks to further improve the isolation in azimuth of the reconstructed $E_T^{\text{miss}}$.

10.7 Hadronic $\tau$-decays

Hadronic decays of $\tau$-leptons will play an important role at the LHC, especially as probes for new phenomena spanning a wide range of theoretical models. Based on this motivation, two complementary approaches, one track-based and the other calorimeter-based (see section 10.7.3), have been developed to efficiently reconstruct and identify these decays, whilst providing the required large rejection against the otherwise overwhelming backgrounds from hadronic jets. The equally difficult task of triggering on these decays as inclusively as possible is addressed in section 10.9.

In general, hadronically decaying $\tau$-leptons are reconstructed by matching narrow calorimeter clusters with a small number of tracks. Specific analyses may require exactly one or three tracks with total charge consistent with the charge of a $\tau$-lepton, and, if more than one, the tracks may be required to be quite collimated and to be consistent with originating from a common secondary vertex. The visible reconstructed energy of the hadronically decaying $\tau$-lepton is concentrated in a narrow cone around the leading (highest-$p_T$) track (typically a cone of half-angle $\Delta R = 0.2$ is sufficient to collect this energy). It can be estimated using only the calorimeter information or using a more refined scheme (often called energy flow), which combines the reconstructed track momenta with the energy of localised electromagnetic clusters within the chosen narrow cone.

Several key variables, which are characteristic of the properties of hadronic $\tau$-decays, are used for the purpose of identification: the profile of the shower in the electromagnetic calorimeter, the isolation of the narrow calorimeter cluster used to identify the $\tau$-candidate, the number and energy-weighted width of strips, the ratio between the transverse energy deposited in the calorimeter and the transverse momentum of the leading track, the number of associated tracks (passing some quality criteria), the momentum-weighted width and invariant mass of the track system and the signed impact parameter significance. Both traditional cut-based selections and multi-variate discrimination techniques (likelihood, neural networks, etc.) have been applied to this set of identification variables (see section 10.7.3).

Two specific performance aspects of particular interest for the reconstruction of hadronic $\tau$-decays are first discussed in this section and are followed by the more general discussion of the overall performance in terms of reconstruction and identification efficiency versus rejection of the large backgrounds from QCD jets expected at the LHC.

10.7.1 Track reconstruction in hadronic $\tau$-decays

The efficiency and quality of the track reconstruction in the inner detector are discussed in some detail in section 10.2. For hadronic $\tau$-decays from a representative sample of $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ decays studied with the track-based algorithm, particular attention has been given to minimise the amount of charge misidentification and of migration between the single- and three-prong categories in the reconstruction. In the low-$p_T$ range, the performance is degraded due to hadronic interactions in the inner-detector material (see for example figure 10.12). For hadronic
Figure 10.89: Reconstruction efficiency for charged-pion tracks as a function of the pion transverse momentum for single- and three-prong hadronic \( \tau \)-decays from \( W \rightarrow \tau \nu \) and \( Z \rightarrow \tau \tau \) signal samples.

Figure 10.90: Reconstruction efficiency for the charged-pion track as a function of \(|\eta|\) for three different ranges of pion \( p_T \), for single-prong hadronic \( \tau \)-decays from \( W \rightarrow \tau \nu \) and \( Z \rightarrow \tau \tau \) signal samples.

\( \tau \)-decays with high energy, the performance for three-prong decays will be degraded due to the strong collimation of the tracks. Figures 10.89 and 10.90 show the efficiency for reconstructing tracks from single-prong and three-prong \( \tau \)-decays for \( \tau \)-leptons from \( W/Z \)-boson decays as a function of the track transverse momentum and pseudorapidity. The quality criteria used are the standard ones discussed in section 10.2.3 and the results shown in figure 10.90 are in agreement with those shown for single particles in figure 10.13, except for three-prong \( \tau \)-decays at high energy for which a degradation in efficiency is observed.

The charge of the identified hadronic \( \tau \)-decay is determined as the sum of the reconstructed track charges. For the leading track, which is required e.g. by the track-based algorithm to have a transverse momentum larger than 9 GeV, charge misidentification is limited to \( \sim 0.2\% \) with the standard quality cuts. The overall charge misidentification probability for the \( \tau \)-lepton is, however, dominated by combinatorial effects: single-prong decays may migrate to the three-prong category due to photon conversions or the presence of additional tracks from the underlying event, or a three-prong decay may be reconstructed as a single-prong decay due to inefficiencies of the track reconstruction and selection. This overall misidentification is estimated to be below \( \sim 3\% \) without requiring further quality cuts.

The rejection of leptonic \( \tau \)-decays misidentified as single-prong hadronic \( \tau \)-candidates is based on dedicated algorithms optimised to veto electrons and muons in the kinematic configurations of interest here. The rejection obtained against electron tracks from \( W \rightarrow e\nu \) decays is approximately 50 for a \( \tau \)-efficiency of 95\%. Using only information from the calorimeter combined with the inner detector, the rejection obtained against muons from \( W \rightarrow \mu\nu \) decays is sufficient, reaching a value of approximately 30 for a \( \tau \)-efficiency of 99\%.

10.7.2 Electromagnetic clusters in single-prong decays

Because of the very fine granularity of the electromagnetic calorimeter, electromagnetic clusters created by showers from photons from \( \pi^0 \) decays can be identified and measured with reasonable
Table 10.5: Expected probabilities for observing a specific multiplicity of localised clusters in the electromagnetic calorimeter within the narrow cone ($\Delta R = 0.2$) used to identify the $\tau$-candidate, for inclusive and exclusive single-prong hadronic $\tau$-decays from $W \rightarrow \tau \nu$ and $Z \rightarrow \tau \tau$ signal samples.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>No cluster</th>
<th>One cluster</th>
<th>More than one cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td>All single-prong $\tau$-decays</td>
<td>32%</td>
<td>35%</td>
<td>33%</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^\pm \nu$</td>
<td>65%</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho^\pm (\rightarrow \pi^0 \pi^\pm) \nu$</td>
<td>15%</td>
<td>50%</td>
<td>35%</td>
</tr>
<tr>
<td>$\tau \rightarrow a_1^\pm (\rightarrow 2\pi^0 \pi^\pm) \nu$</td>
<td>9%</td>
<td>34%</td>
<td>57%</td>
</tr>
</tbody>
</table>

efficiency and accuracy within the narrow cone used to reconstruct hadronic $\tau$-decays. The results reported in this section have been obtained using the three-dimensional topological clustering described in more detail in section 10.5 applied only to the first two layers of the electromagnetic calorimeter.

As an example, in the case of single-prong decays, the reconstructed charged track in the inner detector and the reconstructed isolated clusters in the electromagnetic calorimeter may be used to obtain the energy and invariant mass of the visible products of the hadronic $\tau$-decay. The resulting performance has been evaluated for $W \rightarrow \tau \nu$ decays and is shown in table 10.5 for inclusive single-prong decays and also for exclusive decays containing a $\rho$ or $a_1$ meson compared to decays containing only one single charged pion. Figure 10.91 shows the response and resolution obtained by this algorithm for reconstructing the visible transverse energy from the $\tau$-decay, in the cases where one such isolated electromagnetic cluster is identified: the response is correct to $\sim 2.5\%$ and the fractional energy resolution is $\sim 5\%$, i.e. far better than that obtained for normal hadronic jets in the same energy range of 20–50 GeV. In the cases where several such clusters are identified, their energy-weighted barycentre is calculated and the fractional energy resolution is somewhat degraded to $\sim 7\%$. Finally, in the cases where at least one such cluster is identified, figure 10.92 shows the reconstructed invariant mass of the system for three single-prong final states. The use of certain specific final states in hadronic $\tau$-decays will be of great interest in polarisation and spin analyses in searches for new particles decaying into $\tau$-leptons.

10.7.3 Identification of hadronic $\tau$-decays and rejection of QCD jets

Two complementary algorithms for $\tau$-identification and reconstruction have been studied, as outlined above:

- a track-based algorithm [275], which relies on tracks reconstructed in the inner detector and adopts an energy-flow approach. This algorithm has been optimised for visible transverse energies in the 10–80 GeV range, which corresponds to hadronic $\tau$-decays from $W \rightarrow \tau \nu$ and $Z \rightarrow \tau \tau$ processes;

- a calorimeter-based algorithm [276], which relies on clusters reconstructed in the calorimeter and has been optimised for visible transverse energies above 30 GeV, which corresponds to hadronic $\tau$-decays from heavy Higgs-boson production and decay.
Figure 10.91: Energy response, expressed as the ratio $(E_{\text{rec}} - E_{\text{truth}})/E_{\text{truth}}$, where $E_{\text{rec}}$ (resp. $E_{\text{truth}}$) are the reconstructed (resp. true) visible energies (see text), for single-prong hadronic $\tau$-decays from a $W \to \tau\nu$ signal sample with one reconstructed electromagnetic cluster.

Figures 10.93 and 10.94 show the expected performance of the two algorithms, expressed as curves describing jet rejection versus efficiency for single- and three-prong hadronic $\tau$-decays separately and for different ranges of the visible transverse energy. The jet rejections are computed with respect to truth jets reconstructed using particle four-momenta within a cone of size $\Delta R = 0.4$. The behaviour of the respective rejection versus efficiency curves reflects the different optimisations performed for the two algorithms. Whereas the track-based algorithm has been tuned to preserve similar performance for single- and three-prong decays, the calorimeter-based algorithm has been tuned to provide the best possible rejection at medium-to-high energies and is therefore more performant for single-prong decays than the track-based algorithm. For an overall efficiency of 30% for single-prong decays, the rejection against jets is typically between 700 and 6000, as is illustrated more quantitatively and as a function of the visible transverse energy in table 10.6.

The track-based algorithm requires a good-quality track system, in which the leading track has transverse momentum above 9 GeV, as a seed for building a hadronic $\tau$-candidate. This provides already after reconstruction considerable rejection against QCD jets with high track multiplicities. This is illustrated in figures 10.95 and 10.96, which show respectively the normalised track-multiplicity spectra for hadronic $\tau$-candidates, with visible transverse energy above 20 GeV, from $Z \to \tau\tau$ decays and from QCD jets. The distributions are shown after the reconstruction step, after a cut-based identification algorithm and finally after applying a multi-variate discrimination technique using a neural network. The track multiplicity in the QCD jet sample is quite different from that in the signal sample, for any of the cuts applied. At the same time, figure 10.95 shows that the fractions of single-prong and three-prong decays in the signal sample approach those expected from an ideal signal sample: for single-prong (respectively three-prong) candidates, the fractions of correctly assigned decays improve from 87% (respectively 74%) after reconstruction to 91% (respectively 86%) after cut-based identification and to 92% (respectively 93%) after applying the neural-network discrimination technique.
Figure 10.93: Expected rejection against hadronic jets as a function of the efficiency for hadronic $\tau$-decays for the track-based algorithm using a neural-network selection. The results are shown separately for single- and three-prong decays and for two ranges of visible transverse energy.

Figure 10.94: Expected rejection against hadronic jets as a function of the efficiency for hadronic $\tau$-decays for the calorimeter-based algorithm using a likelihood selection. The results are shown separately for single- and three-prong decays and for two ranges of visible transverse energy.

Figure 10.95: Track multiplicity distributions obtained for hadronic $\tau$-decays with visible transverse energy above 20 GeV using the track-based $\tau$-identification algorithm. The distributions are shown after reconstruction, after cut-based identification and finally after applying the neural network (NN) discrimination technique for an efficiency of 30% for the signal.

Figure 10.96: Track multiplicity distributions obtained for the background from QCD jets with visible transverse energy above 20 GeV using the track-based $\tau$-identification algorithm. The distributions are shown after reconstruction, after cut-based identification and finally after applying the neural network (NN) discrimination technique for an efficiency of 30% for the signal.
Table 10.6: Rejection of track-based and calorimeter-based \( \tau \)-identification algorithms over the range of visible transverse energy in which they have been optimised. The values are given separately for single- and three-prong decays and for an efficiency of 30%. The quoted errors are statistical.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>( E_T = 10\text{-}30 \text{ GeV} )</th>
<th>( E_T = 30\text{-}60 \text{ GeV} )</th>
<th>( E_T = 60\text{-}100 \text{ GeV} )</th>
<th>( E_T &gt; 100 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-based (neural network)</td>
<td>1-prong 740±70</td>
<td>1030±160</td>
<td>2240±140</td>
<td>4370±280</td>
</tr>
<tr>
<td></td>
<td>3-prong 590±50</td>
<td>590±70</td>
<td>310±7</td>
<td>423±8</td>
</tr>
<tr>
<td>Calorimeter-based (likelihood)</td>
<td>1-prong 1130±50</td>
<td>2240±140</td>
<td>4370±280</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-prong 187±3</td>
<td>310±7</td>
<td>423±8</td>
<td></td>
</tr>
</tbody>
</table>

Figures 10.95 and 10.96 also show that the candidates with track multiplicity above three may be used to normalise the QCD background. This would allow a reasonably precise calibration of the performance of the \( \tau \)-identification algorithms using real data, provided the rejection against QCD jets is proven to be sufficient to extract a clean signal in the single-prong and three-prong categories. The sensitivity of such a method can be enhanced by also studying the track multiplicity outside the narrow cone used for \( \tau \)-identification and combining this information with that presented in figure 10.96.

10.8 Flavour tagging

The ability to tag hadronic jets arising from heavy flavours is an important asset for many physics analyses, such as precision measurements in the top-quark sector and searches for Higgs bosons or other new physics signatures. This section describes the \( b \)-tagging performance which can be achieved using different methods [277]. In the results presented in this section, the impact of possible residual misalignments on the \( b \)-tagging performance has not been taken into account.

10.8.1 Ingredients of \( b \)-tagging algorithms

Except when explicitly stated otherwise, the results presented in this section are based on simulations without pile-up and with a perfect alignment of the inner detector. Jets are reconstructed in the calorimeters using standard algorithms (see section 10.5.1) and the jets with \( p_T > 15 \text{ GeV} \) and \(|\eta| < 2.5\) are considered for \( b \)-tagging. Only reconstructed tracks within a distance \( \Delta R < 0.4 \) from the jet axis are used for \( b \)-tagging.

To assess quantitatively the \( b \)-tagging performance, the Monte-Carlo truth is used to determine the type of parton from which a jet originates. This labelling procedure is somewhat ambiguous. For the results presented here, a quark-based labelling has been used: a jet is labelled as a \( b \)-jet if a \( b \)-quark with \( p_T > 5 \text{ GeV} \) is found in a cone of size \( \Delta R = 0.3 \) around the jet direction. A jet is labelled as a \( c \)-jet (or \( \tau \)-jet) if a \( c \)-quark (or \( \tau \)-lepton) with \( p_T > 5 \text{ GeV} \) is found in the cone instead of a \( b \)-quark. When no heavy quark nor \( \tau \)-lepton satisfies these requirements, the jet is labelled as a light jet. No attempt is made to distinguish between \( u-, d-, s \)-quarks and gluons. It is important to note that this labelling procedure defines as \( b \)-jets most gluon jets splitting to a \( b \bar{b} \) pair in the parton-shower process.
10.8.1.1 Track selection and track impact parameters

The track selection for $b$-tagging is designed to select well-measured tracks and to reject fake tracks in jets and secondary tracks from $K^0_s$, $\Lambda$ and hyperon decays, as well as electrons from photon conversions. Only tracks with transverse momentum above 1 GeV are considered. At least seven precision hits (pixels and strips) are required, of which at least two must be in the pixel detector and one in the pixel vertexing layer. The transverse ($d_0$) and longitudinal ($z_0$) impact parameters at the point of closest approach to the vertex must fulfil respectively, $|d_0| < 1$ mm and $|z_0 - z_v| \sin \theta < 1.5$ mm, where $z_v$ is the reconstructed primary vertex position in $z$ and $\theta$ is the measured polar angle of the track. The efficiency of these cuts and the resulting fake-track rate in jets are discussed in section 10.2.3 (see in particular figure 10.14).

For the $b$-tagging algorithms, the impact parameters of tracks are computed with respect to the primary vertex (see section 10.2.4). The transverse impact parameter is signed using the jet direction as measured by the calorimeters: tracks crossing the jet axis behind the primary vertex have a negative impact parameter. The distribution of the signed transverse impact parameter, $d_0$, is shown in figure 10.97 for tracks reconstructed in $b$-jets, $c$-jets and light jets. Figure 10.98 shows the corresponding significance distribution, $d_0/\sigma_{d_0}$, which gives more weight to precisely measured tracks.

10.8.1.2 Secondary vertices

To further increase the discrimination between $b$-jets and light jets, the inclusive vertex formed by the decay products of the $B$-hadron, including the products of the subsequent charm hadron decay, can be reconstructed. The search starts by combining all track pairs which form a good vertex, using only tracks with a high impact-parameter significance in order to remove the tracks which are compatible with the primary vertex. The invariant mass of the particles originating from
Figure 10.99: Properties of secondary vertices reconstructed in $b$-jets and light jets: invariant mass of all tracks originating from the vertex (left), the ratio of the sum of the energies of the tracks originating from the vertex to the sum of the energies of all tracks in the jet (middle) and number of two-track vertices (right).

the secondary vertex candidate and the location of this vertex candidate are used to reject vertices which are likely to come from $K^0_S$ decays and photon conversions or from secondary interactions in material such as the beam-pipe or the vertexing layer. All tracks from the remaining two-track vertices are combined into a single vertex and three of its properties are exploited: the invariant mass of all the tracks originating from the vertex, the ratio of the sum of the energies of the tracks originating from the vertex to the sum of the energies of all tracks in the jet, and the number of two-track vertices. These properties are illustrated in figure 10.99 for $b$-jets and light jets. The secondary-vertex reconstruction efficiency depends quite strongly on the event topology and the typical efficiencies achieved are higher than 60% for the $t\bar{t}$ and $WH$ events studied here.

10.8.2 Likelihood-ratio tagging algorithms

For both the impact-parameter tagging and the secondary-vertex tagging, a likelihood-ratio method is used: the discriminating variables are compared to pre-defined smoothed and normalised distributions for both the $b$- (signal) and light- (background) jet hypotheses. Multi-dimensional probability density functions are used as well for some $b$-tagging algorithms. The ratio of the probabilities defines the track or vertex weight, which can be combined in a jet weight as the sum of the logarithms of the individual weights. The distribution of such a weight is shown in figures 10.100 and 10.101 for $b$-, $c$- and light jets for two different $b$-tagging algorithms: the first one combines only the transverse impact parameter significance of tracks, while the second one combines in two dimensions the transverse and longitudinal impact parameter significances of tracks as well as the three variables from the secondary vertex search discussed above. The former algorithm is simpler and more robust than the latter which will require more time to commission. Currently, no use is made of probability density functions for $c$-jets, and these are not considered when creating the reference distributions for the signal and background hypotheses.
**Figure 10.100:** Jet $b$-tagging weight distribution for $b$-jets, $c$-jets and purified light jets (see section 10.8.3). The $b$-tagging algorithm is based on the transverse impact parameter significance of tracks.

**Figure 10.101:** Jet $b$-tagging weight distribution for $b$-jets, $c$-jets and purified light jets (see section 10.8.3). The $b$-tagging algorithm uses the transverse and longitudinal impact parameter significances of tracks as well as the properties of the secondary vertex found in the jet.

### 10.8.3 Jet activity and jet purification

A difficulty arises as soon as the jet multiplicity is high and various jet flavours are present in the same event: a light jet close in $\Delta R$ to a $b$-jet will sometimes be labelled as a light jet, even though tracks from $B$-hadron decay with high lifetime content may be associated with it. This leads to an artificial degradation of the estimated performance, which is not related to the $b$-tagging algorithm itself but to the labelling procedure which strongly depends on the activity in the event. In order to obtain a more reliable estimation of the $b$-tagging performance, a purification procedure has been devised: light jets for which a $b$-quark, a $c$-quark or a $t$-lepton are found within a cone of size $\Delta R = 0.8$ around the jet direction are not used to assess the $b$-tagging performance.

The performance estimated after purification represents the intrinsic power of the $b$-tagging algorithms and should be similar for different kinds of physics events; in contrast, results obtained using all the light jets, regardless of their environment, are more dependent on the underlying activity in the event. These latter results are, however, more representative of the actual $b$-tagging performance to be expected for a given physics analysis. This is illustrated in figures 10.102 and 10.103 for two types of physics processes. The $WH$ events correspond to events in which the $W$ decays leptonically and the Higgs boson decays to a $b\bar{b}$ pair (signal case) or is forced to decay to a $u\bar{u}$ or $c\bar{c}$ pair (background case). Such events therefore usually have only two high-$p_T$ and well-separated jets and the light-jet rejection obtained is similar with and without jet purification, as shown in figure 10.102. For semi-leptonic $t\bar{t}$ events, the jet activity is quite high and therefore the two performance curves with and without purification shown in figure 10.103 differ in the region...
of $b$-jet efficiencies below 80%, where the lifetime content dominates over resolution effects. It is also important to note that the purification procedure discards jets coming from gluon-splitting to heavy quarks.

### 10.8.4 Expected $b$-tagging performance

As shown in figures 10.102 and 10.103, a light-jet rejection higher than 100 can be achieved for a $b$-jet efficiency of 60%. The performance depends strongly on the jet momentum and pseudorapidity. This is illustrated in figures 10.104 and 10.105 for the two $b$-tagging algorithms described above. At low $p_T$ and/or high $|\eta|$, the performance is degraded mostly because of the increase of multiple scattering and secondary interactions. At high $p_T$, some dilution arises because the fraction of fragmentation tracks in the fixed-size cone increases, and more $B$-hadrons decay outside the vertexing layer: some gain should therefore be achieved by changing the track selection. At very high $p_T$, the performance degradation arises from pattern-recognition deficiencies in the core of very dense jets.

### 10.8.5 Soft-lepton tagging

Soft-lepton tagging relies on the semi-leptonic decays of bottom and charm hadrons. It is therefore intrinsically limited by the branching ratios to leptons: at most 21% of $b$-jets will contain a soft lepton of a given flavour, including cascade decays of bottom to charm hadrons. However, when a soft lepton is present, $b$-tagging algorithms based on soft leptons can exhibit high purity. More importantly, they have only small correlations with the track-based $b$-tagging algorithms, which is very important for checking and cross-calibrating performance with data.
Figure 10.104: Rejection of purified light jets as a function of the jet transverse momentum for two different $b$-tagging algorithms operating at a fixed $b$-tagging efficiency of 60% in each bin.

Figure 10.105: Rejection of purified light jets as a function of the jet pseudorapidity for two different $b$-tagging algorithms operating at a fixed $b$-tagging efficiency of 60% in each bin.

Soft muons are reconstructed using two complementary reconstruction algorithms (see section 10.3): combined muons, which correspond to a track fully reconstructed in the muon spectrometer and matched with a track in the inner detector, and muons with a low momentum, typically below $\sim 5$ GeV, which cannot reach the muon middle and outer stations and are identified by matching an inner-detector track with a segment in the muon spectrometer inner stations only. Muons reconstructed in this way and satisfying some basic selection criteria, $p_T > 4$ GeV and $|d_0| < 4$ mm, are associated to the closest jet provided their distance to the jet axis satisfies $\Delta R < 0.5$. Finally, the kinematic properties of the jet-muon system, such as the relative transverse momentum of the muon with respect to the jet axis, are used in order to reject the background caused by punch-through particles and decays in flight in light jets. As shown in figure 10.106 for $t\bar{t}$ events, the soft-muon $b$-tagging algorithm yields an efficiency of 10% (including branching ratios and identification efficiency) and a light-jet rejection of 200 for jets with $p_T > 15$ GeV and $|\eta| < 2.5$. The rejection against light jets decreases by approximately 30% when the expected contributions from pile-up and especially cavern background at $10^{33}$ cm$^{-2}$ s$^{-1}$ are included.

Reconstructing soft electrons in jets in the electromagnetic calorimeter is more difficult because of the overlap of hadronic showers with the electron shower itself. This is achieved using the soft-electron algorithm [266] which matches an inner-detector track to an electromagnetic cluster, as described in section 10.4.1. The performance of this algorithm is, however, highly dependent on the track density in the jets as well as on the amount of material in front of the electromagnetic calorimeter (photon conversions). As shown in figure 10.107, a light-jet rejection of 90 can be achieved for an efficiency of 7% in $WH$ events. Currently, for a 7% (respectively 10%) $b$-tagging efficiency, about 75% (respectively 40%) of the surviving light jets are tagged by electrons originating from photon conversions: the performance would therefore substantially improve if these conversions could be rejected further.
10.9 Trigger performance

10.9.1 Overview

This section gives an overview of the performance achieved on simulated raw data using the online physics selection strategy of ATLAS. As already mentioned in section 8.1, components of the reconstruction and analysis software, implemented mostly in the offline environment in previous experiments, have had to be embedded within the trigger system to achieve the required rejection power while retaining excellent sensitivity to the various physics signatures of interest. A great deal of flexibility is provided by the three-level trigger system to adapt to changes in the luminosity (from fill-to-fill and even during a single fill), to variations in the background conditions, and to new requirements which will undoubtedly arise as the understanding of the physics, trigger performance and detector develops.

The approach taken to guarantee good acceptance for as broad a spectrum of physics as possible is to use mainly inclusive criteria for the online selection, i.e. signatures mostly based on single- and di-object high-p_T triggers. The choice of the thresholds is made to have a good overlap with the reach of the Tevatron and other colliders, and to ensure good sensitivity to new particles over a wide range of masses and decay channels. This high-p_T inclusive selection is complemented where necessary with more focussed signatures, such as the presence of several different physics objects or the use of topological criteria.

10.9.2 Selection strategy

The architecture of the trigger and data acquisition system is described in section 8.3 (see in particular figure 8.1) and is based on a three-level trigger system, with a first level (L1) using hardware based on ASIC’s and FPGA’s, and the other two (L2 and EF or event filter, collectively also called
high-level triggers or HLT) using software algorithms running on farms of commercial computers. At L2, the event selection is based on specialised algorithms, optimised for speed, whereas the EF uses more complex algorithms, basically identical to those used in the offline reconstruction software.

The L2 and EF algorithms are usually "seeded", meaning that reconstruction is normally guided by the previous trigger level to access and process data only in a "Region-of-Interest" (RoI) containing particle candidates. This significantly reduces the processing time (and also data movement from the holding buffers to the L2 processors), without degrading the selection performance. For the EF, and even for L2 where necessary, data can be accessed and processed from the full detector, within the constraints of available data-movement and processing resources. This applies for example to scans of the complete inner detector for low-\(p_T\) tracks for the \(B\)-physics selection or to the processing of all calorimeter cells for an improved calculation of missing transverse energy. At L2, this can only be done in special cases and for a small fraction of the events due to bandwidth limitations, whereas in the EF the full event data are available in memory. It is also possible to use so-called secondary RoI's which did not contribute to the L1 selection, but provide the coordinates of lower-\(p_T\) objects which can be included in the L2 selection.

In the HLT, "feature-extraction" algorithms are used to identify objects (such as electrons or jets) and determine their properties or to determine global characteristics of the event. The sequence of execution of the algorithms (e.g. ordered according to complexity) is chosen to maximise the physics potential and retain adequate flexibility within the available data-movement and processing resources of the HLT. After each step in the sequence, hypothesis algorithms determine whether a given signature is satisfied or not. The processing of any given RoI is stopped as soon as it is clear that it cannot contribute to the selection of the event. The event itself is rejected if none of the signatures in the trigger menu is satisfied.

The initial implementation and capabilities of the DAQ/HLT system are described in section 8.4, where it is stated that the system should handle a L1 trigger rate of \(\sim 40\) kHz, i.e. approximately 50% of the design specification. Clearly, only the availability of real data will allow the whole strategy to be finalised. However, it is important to be able to face this initial phase with the most complete set of tools possible and with a versatile selection architecture, in order to cope with the surprises which are likely to appear at the time of LHC start-up.

### 10.9.3 Trigger menus

Trigger menus are tables which specify thresholds and selection criteria at each of the three trigger levels to address the physics-analysis requirements of ATLAS. The process of preparing the menus takes into account an assessment of the rejection capabilities at each selection stage and for each signature, and the rate capabilities of each level of the trigger and of the offline computing system. This procedure is iterative and makes use of earlier studies of the L1 trigger and HLT, as documented in [204, 237].

Trigger items, defined as entries in the trigger menu corresponding to selected physics objects, are identified using a notation where a symbol representing a particle type is preceded by a multiplicity value and followed by a \(E_T\)-threshold value, e.g. 2e5 corresponds to a requirement of two or more electrons, each with \(E_T\) above 5 GeV. The threshold value quoted for L1 is the
Table 10.7: Subset of items from an illustrative trigger menu at $10^{31}$ cm$^{-2}$ s$^{-1}$.

<table>
<thead>
<tr>
<th>Signature</th>
<th>L1 rate (Hz)</th>
<th>HLT rate (Hz)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>Up to 10000</td>
<td>10</td>
<td>Pre-scaled trigger item</td>
</tr>
<tr>
<td>$e10$</td>
<td>5000</td>
<td>21</td>
<td>$b, c \to e, W, Z, Drell-Yan, \bar{t}t$</td>
</tr>
<tr>
<td>$2e5$</td>
<td>6500</td>
<td>6</td>
<td>Drell-Yan, $J/\psi, \Upsilon, Z$</td>
</tr>
<tr>
<td>$\gamma 20$</td>
<td>370</td>
<td>6</td>
<td>Direct photons, $\gamma$-jet balance</td>
</tr>
<tr>
<td>$2\gamma 15$</td>
<td>100</td>
<td>$&lt; 1$</td>
<td>Photon pairs</td>
</tr>
<tr>
<td>$\mu 10$</td>
<td>360</td>
<td>19</td>
<td>$W, Z, \bar{t}t$</td>
</tr>
<tr>
<td>$2\mu 4$</td>
<td>70</td>
<td>3</td>
<td>$B$-physics, Drell-Yan, $J/\psi, \Upsilon, Z$</td>
</tr>
<tr>
<td>$\mu 4 + J/\psi(\mu \mu)$</td>
<td>1800</td>
<td>$&lt; 1$</td>
<td>$B$-physics</td>
</tr>
<tr>
<td>$j120$</td>
<td>9</td>
<td>9</td>
<td>QCD and other high-$p_T$ jet final states</td>
</tr>
<tr>
<td>$4j23$</td>
<td>8</td>
<td>5</td>
<td>Multi-jet final states</td>
</tr>
<tr>
<td>$\tau 20i + xE30$</td>
<td>5000 (see text)</td>
<td>10</td>
<td>$W, \bar{t}t$</td>
</tr>
<tr>
<td>$\tau 20i + e10$</td>
<td>130</td>
<td>1</td>
<td>$Z \to \tau \tau$</td>
</tr>
<tr>
<td>$\tau 20i + \mu 6$</td>
<td>20</td>
<td>3</td>
<td>$Z \to \tau \tau$</td>
</tr>
</tbody>
</table>

raw $E_T$ cut applied in the hardware, and high efficiency is only achieved for particles or jets of somewhat higher $E_T$; this differs from the definition used in previous documents [237]. For inclusive selections, the multiplicity requirement of one is implicit. An "i" following the threshold indicates that an isolation requirement is made in addition. For example, $\tau 20i$ requires at least one hadronic $\tau$ candidate with transverse energy above 20 GeV and with a specific calorimeter isolation requirement in addition. The term "xE" is a short form for $E_T^{\text{miss}}$.

The steering and configuration of the trigger (see section 8.3.6) support the description of both straightforward RoI-based triggers like single electrons, muons, $\tau$-leptons and jets along with more complex triggers like $E_T^{\text{miss}}$ and triggers for $B$-physics. For each trigger level, items in the menu can be pre-scaled to reduce their rates, or "pass-through" flags can be raised, where events are accepted irrespective of the HLT selection decision for the purpose of systematic studies.

The initial start-up luminosity at the LHC is expected to be around $10^{31}$ cm$^{-2}$ s$^{-1}$. This provides convenient conditions for commissioning the trigger and the detector sub-systems, validating the trigger and offline software algorithms, and ensuring that basic Standard Model signatures can be observed. The trigger menu for this start-up scenario reflects these requirements and allows for low $p_T$-thresholds on final-state leptons and photons, without any pre-scaling at L1, and for higher $p_T$-thresholds, for which most of the HLT algorithms are executed in "pass-through" mode.

Table 10.7 presents an example of a sample of the triggers which will be used at start-up. The rates shown have been estimated using non-diffractive minimum-bias events with a total assumed cross-section of 70 mb. Triggering on single and di-leptons should be possible with quite low $p_T$-thresholds and without applying isolation or other complex criteria, which must be validated with real data at turn-on. With the exception of the minimum-bias selection, the items indicated are those which should be operable without pre-scaling at $10^{31}$ cm$^{-2}$ s$^{-1}$. The full menu contains a number of additional components, including many pre-scaled items with lower thresholds.
The rates for combined triggers which require two or more final-state leptons or photons are expected to be low in most instances, allowing them to be run without pre-scaling with very low thresholds. Significant bandwidth will be devoted to collecting large samples of minimum-bias data for use in physics analysis and for detector and trigger performance studies. Multi-jet triggers will be run at a comparatively high rate to test b-jet tagging in the HLT which is discussed in section 10.9.6. A small amount of bandwidth is allocated for inclusive $E_T^{\text{miss}}$ and scalar sum-$E_T$ triggers, as well as using the $E_T^{\text{miss}}$ signature in combination with other criteria. Note that for the item $\tau_{20i} + x\text{E}30$ in table 10.7, the $E_T^{\text{miss}}$ selection is made only at the EF level, in case the corresponding L1 selection takes time to commission. The rate of the $\tau_{20i}$ item at L1 is approximately 5 kHz.

The quoted trigger rates are subject to large uncertainties on the cross-sections for QCD processes in proton-proton collisions at LHC energies, and on the modelling of the performance of the detector. The rates indicated assume that the selection cuts will already have been reasonably well tuned to achieve high background rejection with good signal efficiency. There is still scope to use tighter cuts and more delicate variables such as isolation after extensive optimisation and thorough validation. Should the rates turn out to be higher than estimated, the inclusive thresholds could be raised substantially without compromising much of the main initial physics programme, but nevertheless to the detriment of an efficient collection of large data samples required for the initial understanding of the detector performance.

10.9.4 Examples of trigger performance

The expected trigger performance at an initial luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$ is illustrated in the following with representative examples from the menu discussed above. As documented in ref. [237] and discussed briefly in section 10.9.6, the trigger also meets the physics requirements up to a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$.

The performance results presented here were obtained using an exact simulation of the algorithms which are implemented in the L1 hardware and using the same HLT algorithms as those which are run online. The full HLT chain was used to obtain the performance results. As described in section 10.1, these studies have also been made for data simulated with a misaligned and mis-calibrated detector to verify, and improve if necessary, the robustness of the selection.

10.9.4.1 Electrons and photons

The performance of the electron and photon triggers has been evaluated for a luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$, using simulations of single particles and selected physics channels. The trigger efficiencies are quoted with respect to events containing electrons and photons identified with loose offline particle identification cuts (see section 10.4). Inefficiency in the trigger selection arises mainly from tighter selection requirements needed to reduce the background rate to an acceptable level. There are also small losses due to the coarser calorimeter granularity used at L1 and the simpler (and faster) selection algorithms applied at L2 compared to the offline reconstruction.

Figure 10.108 shows the L1, L2 and EF efficiencies as a function of $E_T$ for the signature $e10$, the menu item selecting electrons with $E_T > 10$ GeV, as estimated using simulations of single electrons. The efficiency reaches a plateau value for $E_T$ above $\sim 15$ GeV and is quite uniform as a function of $|\eta|$, except for a 10–20% dip in the transition region between the barrel and the end-cap.
Figure 10.108: Trigger efficiencies at L1, L2 and EF as a function of the true electron $E_T$ for the e10 menu item. The efficiencies are obtained for single electrons and are normalised with respect to the medium set of offline electron cuts discussed in section 10.4.

Figure 10.109: Relative rates versus $|\eta|$ for jets passing the L1, L2 and EF trigger selections for the e10 menu item. The relative rates are shown for each of the seven $\eta$-ranges used to optimise the offline selection of isolated electrons and are normalised as described in the text.

Figure 10.110: Trigger efficiencies at L1, L2 and EF as a function of the true photon $E_T$ for the $\gamma$20i menu item. The efficiencies are obtained for single photons and normalised with respect to loose offline photon identification cuts.

Figure 10.111: Normalised relative rates versus $|\eta|$ for jets passing the L1, L2 and EF trigger selections for the $\gamma$20i menu item. The relative rates are shown for each of the six $\eta$-ranges used to optimise the offline selection of isolated photons and are normalised as described in the text. The bin corresponding to the barrel/end-cap transition region is not shown because the offline selection excludes it.

calorimeters. Figure 10.109 shows the normalised relative rates expected from QCD jets satisfying the e10 signature as a function of $|\eta|$ for the successive trigger levels. These relative rates are normalised for each trigger level to the total number of events selected and then the rate in each bin is rescaled to that expected for a bin of fixed size $\Delta \eta = 0.5$. The rates are quite sensitive to the result of the trigger efficiency optimisation and their non-uniformity reflects the lower efficiency in the regions where the electromagnetic calorimeter performance is not optimal, as in the barrel/end-cap transition region with $1.37 < |\eta| < 1.52$. Similar results are obtained for photons and shown for the signature $\gamma$20i, the menu item selecting isolated photons with $E_T > 20$ GeV, in figures 10.110 and 10.111.
10.9.4.2 \( \tau \)-leptons and \( E_T^{\text{miss}} \)

The performance of the trigger for selecting high-\( p_T \) \( \tau \)-leptons is illustrated with the \( \tau 20i \) signature selecting hadronic \( \tau \)-decays with true visible \( E_T \) of the hadronic \( \tau \)-decay (defined as the summed transverse energy of all the decay products which are not neutrinos) larger than 20 GeV. Figure 10.112 shows the trigger efficiency after each trigger level, normalised to an offline selection with loose requirements (see section 10.7), for hadronic \( \tau \)-decays from \( W \to \tau \nu \) and \( Z \to \tau \tau \) decays. The efficiency exhibits a drop of approximately 15% after L2, mostly because of the \( \tau \)-identification cuts applied. The efficiency turn-on rises more slowly than for the electron and photon triggers, especially at L1, reflecting the poorer resolution obtained for hadronic showers. Figure 10.113 shows the efficiency turn-on curves for various \( \tau \)-trigger thresholds as a function of the true visible \( E_T \) of the hadronic \( \tau \)-decay. The overall efficiency with respect to the offline selection is typically 85% on the plateau.

A somewhat special case is that of \( E_T^{\text{miss}} \) triggers which can be used either inclusively or in combination with other objects, in particular with jets or hadronic \( \tau \)-triggers. Because \( E_T^{\text{miss}} \) is a global property of the event, the RoI-driven L2 trigger is not capable of substantially improving the L1 trigger. However, the \( E_T^{\text{miss}} \) algorithm in the EF improves substantially on L1 by accessing the precision readout of the entire calorimeter and performing a simplified version of the offline algorithm.

A challenging goal of the \( \tau \)-selection during the low-luminosity period is to collect a large sample of \( W \to \tau \nu \) decays. This can be achieved using a \( \tau \)-trigger in combination with a requirement (potentially only at the level of the EF) of substantial \( E_T^{\text{miss}} \) (see table 10.7). Such events are obviously interesting for physics analyses, but are also needed to monitor the hadronic energy scale using single charged pions, and for other performance studies. An additional goal is to provide triggers with low \( p_T \)-thresholds and loose trigger requirements, in addition to the single high-\( p_T \) electron and muon triggers, for collecting efficiently Z-bosons decaying into two \( \tau \)-leptons, where one \( \tau \)-lepton decays to an electron or muon and the other to hadrons. The background rates for these \( e/\mu+\tau \) triggers are estimated to be in the range of one Hz or less at the initial luminosity of \( 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \), with rather loose HLT cuts applied to the trigger objects.
Table 10.8: Summary of L1 single-jet and multi-jet menu items, of L1 pre-scale factors and expected L1 and EF rates at a luminosity of $10^{31} \text{ cm}^{-2} \text{s}^{-1}$.

<table>
<thead>
<tr>
<th>Trigger item</th>
<th>j10</th>
<th>j18</th>
<th>j23</th>
<th>j35</th>
<th>j42</th>
<th>j70</th>
<th>j120</th>
<th>3j10</th>
<th>3j18</th>
<th>4j10</th>
<th>4j18</th>
<th>4j23</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-scale factor at L1</td>
<td>42000</td>
<td>6000</td>
<td>2000</td>
<td>500</td>
<td>100</td>
<td>15</td>
<td>1</td>
<td>150</td>
<td>1</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>L1 rate (Hz)</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>9</td>
<td>40</td>
<td>140</td>
<td>40</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>EF rate (Hz)</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>4</td>
<td>9</td>
<td>0.05</td>
<td>1</td>
<td>0.04</td>
<td>0.1</td>
<td>5</td>
</tr>
</tbody>
</table>

10.9.4.3 Jets

The inclusive jet trigger j120 presented in table 10.7 is complemented by a series of pre-scaled items chosen to give an approximately uniform rate across the jet $E_T$-spectrum. Collecting sufficient statistics over the entire jet $E_T$-spectrum is important for differential cross-section measurements and also for the measurement of detector, trigger and physics algorithm efficiencies. The set of threshold and pre-scale combinations is expected to be stable with rising luminosity for the first few years of data-taking. The strategy adopted to optimise the jet trigger menu for different luminosities is then primarily to modify the pre-scale factors associated with each jet-trigger threshold, rather than to change the set of thresholds on an ad-hoc basis.

Table 10.8 summarises a set of L1 jet-trigger items, L1 pre-scale factors and L1 and EF rates for a luminosity of $10^{31} \text{ cm}^{-2} \text{s}^{-1}$. Since the jet rates cannot be reduced much by the HLT, the EF rates quoted in table 10.8 are obtained through additional pre-scale factors applied wherever necessary. Figure 10.114 shows the corresponding reconstructed differential $E_T$ spectrum of the leading jet after the L1 trigger accept. The differential distribution thus obtained is almost uniform over the range of L1 single-jet triggers run with different pre-scale factors, yielding about $10^8$ leading jets with $E_T$ in the range between 10 and 100 GeV for an integrated luminosity of 100 pb$^{-1}$. Figure 10.115 shows that over this range of jet $E_T$, the efficiency at threshold of the various pre-scaled jet trigger menu items turns on much more slowly than the corresponding curves for leptons because of the poorer resolution of the jet $E_T$ reconstructed at L1.

10.9.4.4 Muons

The geometrical coverage of the muon trigger detector system (see section 6.6 for a detailed description) limits the overall acceptance for triggering on muons at L1, as illustrated in figure 10.116. The barrel trigger system covers approximately 80% of the $\eta$-$\phi$ plane (over $|\eta| < 1.0$), while the end-cap trigger extends over approximately 96% of the relevant $\eta$-$\phi$ space. The limitations of the barrel system can be seen in figure 10.116, and are dominated by the crack at $\eta < 0.1$ (largely to accommodate inner-detector and calorimeter services), by the regions occupied by the feet of the experiment and by the space taken by the barrel toroid ribs. The end-cap trigger coverage is limited only by the detector supports and by the holes needed for the optical alignment system. Within the fiducial acceptance of the trigger detectors, the L1 trigger efficiency for muons with $p_T$ larger than the selection thresholds exceeds 99%. The L2 trigger then provides a first reduction of the L1 rates by confirming the muon candidates with a more precise measurement of their momentum and by matching them to inner-detector tracks.
Figure 10.114: Expected differential spectrum for single jets as a function of the reconstructed $E_T$ of the leading jet. The solid line shows the distribution after applying the L1 trigger thresholds and pre-scale factors presented in table 10.8, while the dashed line represents the distribution expected without any trigger requirements.

Figure 10.115: Efficiency as a function of the true jet $E_T$ (as defined for a cone of size $\Delta R = 0.4$) for each of the single-jet L1 menu items shown in table 10.8.

Figure 10.116: Acceptance map in $\eta$-$\phi$ space for the L1 muon trigger, which covers the $\eta$-range $|\eta| < 2.4$. The black points represent regions not instrumented with L1 trigger detectors because of the presence of various supports and services.

Figure 10.117: Estimated EF output rates for muons as a function of $p_T$-threshold at a luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$, integrated over the full $\eta$-range covered by the L1 trigger, $|\eta| < 2.4$.

The rates of muons at the output of the EF have been computed at a luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$, by summing the contributions from the barrel and end-cap regions of the muon spectrometer. As shown in figure 10.117, several physics processes contribute significantly to the rate. The rates given as a function of the $p_T$-threshold are for an inclusive muon selection, without applying an isolation requirement. The largest contributions to the total rate in the $p_T$-range from 4 to 6 GeV are from charm, beauty and in-flight decays of charged pions and kaons. Isolation, as well as refined matching requirements between the tracks in the inner detector and muon spectrometer, can be used to further reduce the rates.
10.9.4.5 B-physics

The trigger for B-physics is initiated by a single- or di-muon selection at L1. At $10^{31} \text{ cm}^{-2} \text{s}^{-1}$, a threshold $p_T > 4 \text{ GeV}$ will be used, rising to about 6 GeV at $10^{33} \text{ cm}^{-2} \text{s}^{-1}$ to match the rate capabilities of the HLT.

At the initial expected luminosity of $10^{31} \text{ cm}^{-2} \text{s}^{-1}$, the dimuon final states are selected by the $2\mu 4$ trigger which is expected to have a rate of a few Hz. For single-muon triggers, searches can be made in the HLT for additional features using information from the inner detector and calorimeters, as well as from the muon spectrometer. Mass cuts and secondary-vertex reconstruction are used to select the B-decay channels of interest. Channels, such as $B_d \rightarrow J/\psi (\mu \mu) K^0_s$ and $B_{s,d} \rightarrow \mu \mu$, are triggered by requiring two muons fulfilling $J/\psi$ or $B_{s,d}$ invariant-mass cuts. Identification of the second muon can either originate from a separate L1 RoI, or from the HLT in an enlarged RoI around the first muon. For other channels containing muons, such as $B_d \rightarrow K^{*0} \mu \mu$ or $B_s \rightarrow \phi \mu \mu$, inner-detector tracks are combined to first reconstruct the $K^{*0}$ or $\phi$ and then the muon tracks are added to reconstruct the $B_{s,d}$.

For hadronic final states like $B_s \rightarrow D^- \pi^+$ and $B_s \rightarrow D^- a_1^+$, inner-detector tracks are combined to reconstruct first the $\phi$-meson from the $D_s$ decay, then the $D_s$ and finally the $B_s$. Two different strategies are used for finding the tracks, depending on luminosity. Full reconstruction over the whole inner detector can be performed at $10^{31} \text{ cm}^{-2} \text{s}^{-1}$, since the L1 muon rate is comparatively modest, while at higher luminosities reconstruction will be limited to L1 jet RoI’s with $E_T > 5 \text{ GeV}$. This latter approach has lower efficiency for selecting the signal, as shown in figure 10.118, but requires fewer HLT resources for a fixed L1 rate. If one combines triggers for hadronic final states and pre-scaled single muon triggers needed for trigger efficiency measurements, the overall rate for B-physics triggers is approximately 10 Hz at $10^{31} \text{ cm}^{-2} \text{s}^{-1}$.

10.9.5 Trigger commissioning

A detailed strategy for commissioning the trigger during initial running with beam is being developed. It is assumed that the luminosity will be significantly less than $10^{33} \text{ cm}^{-2} \text{s}^{-1}$ during this period. A first step will be to establish a time reference for bunches of protons colliding at the interaction point in ATLAS. Signals from passive beam pick-ups will be used to form a filled-bunch trigger with known latency. This will be combined with the minimum-bias trigger, based on scintillation counters which are mounted in front of the end-cap cryostats (see section 5.5), which will...
be used to signal inelastic proton-proton collisions. The resulting interaction trigger will be used in setting up the timing of the experiment for the detector readout and of the calorimeter and muon L1 trigger systems.

Once the timing-in of the detector is completed, the minimum-bias trigger will be used to collect data for initial physics studies, in parallel with continuing work on commissioning the rest of the trigger. Since the calorimeter and muon L1 trigger systems are digital, commissioning tasks such as calibration using real (minimum-bias) data can be done offline, comparing the results read out from the trigger systems with corresponding quantities from the detector readout. It is anticipated that the trigger system will be brought on-line progressively. A first step will be to use, in parallel with a pre-scaled minimum-bias selection, the L1 trigger with loose and simple selection criteria, with relaxed requirements in the muon trigger and not using calorimeter quantities such as isolation and global energy sums, which are sensitive to low-energy detector behaviour. Tighter and more complicated selections will be brought in progressively after thorough offline validation of their performance.

Once the calorimeter and muon L1 triggers are operational, work will ramp up on commissioning the HLT. Many aspects can be addressed offline, using exactly the same algorithms as online, but running on data recorded previously. Then the L2 and EF algorithms will be used online in passive mode, while still recording all events selected by L1. The highest-priority physics channels will initially be covered by high-threshold L1 triggers which are passed through the HLT without further selection, while using the HLT actively elsewhere. Analysis of the recorded data will provide further optimisation of the algorithms and cross-checks on the efficiency of the HLT. As the luminosity increases towards $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the full power of the trigger will be required to limit the event rate, while retaining high efficiency for the physics channels of interest.

As an example, one can consider in more detail the commissioning of the L1 muon trigger. Given the low luminosity assumed for initial data-taking ($10^{31} \text{ cm}^{-2} \text{ s}^{-1}$), the related low cavern-background rates expected and the large bunch spacing foreseen (75 ns or more), the configuration parameters of the muon trigger system can initially be relaxed while maintaining acceptable rates. The data collected will be used to check and complete the commissioning of the muon trigger, which has already started using cosmic-ray data. In particular, large samples of muons will be needed to fine-tune the time calibration of the full system, with a required accuracy of about 3 ns in the barrel system. Initial coincidence roads will have been prepared based on simulation and will be available for several $p_T$-thresholds from about 4 GeV to 40 GeV. Once real data are available with large statistics, these roads will be checked and optimised with muons reconstructed over the full acceptance of the detector, using the $p_T$-measurement obtained with the inner detector. The commissioning of the muon trigger will use data collected with wide coincidence roads and also with other triggers (minimum bias, jets). The information recorded from the L1 muon trigger will be examined together with the results of the offline reconstruction, allowing measurements of the trigger efficiency for muons as a function of $p_T$.

In a similar way, the start-up menu for the electron and photon selection must provide data samples needed to commission trigger and detectors, as well as for physics analyses. Relevant physics processes include $J/\psi \rightarrow ee$, $\Upsilon \rightarrow ee$, Drell-Yan, $Z \rightarrow ee$, $W \rightarrow ev$ and direct photon production. The menu discussed above selects such events with single electrons with $E_T$ above $\sim 10 \text{ GeV}$ or single photons with $E_T$ above $\sim 20 \text{ GeV}$, in addition to the selection with double-object triggers at significantly lower thresholds.
Table 10.9: Subset of items from two illustrative trigger menus at L1 (left) and at the HLT (right) for a luminosity of $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$. The capital letters designate L1 trigger objects, whereas the small letters designate HLT trigger objects. The examples given are more to illustrate the evolution of the rates and thresholds as a function of luminosity, when comparing to table 10.7, than to provide accurate predictions of the expected rates.

<table>
<thead>
<tr>
<th>L1 signature</th>
<th>Rate (kHz)</th>
<th>HLT signature</th>
<th>Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM18I</td>
<td>12.0</td>
<td>e22i</td>
<td>40</td>
</tr>
<tr>
<td>2EM11I</td>
<td>4.0</td>
<td>2e12i</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>MU20</td>
<td>0.8</td>
<td>γ55i</td>
<td>25</td>
</tr>
<tr>
<td>2MU6</td>
<td>0.2</td>
<td>2γ17i</td>
<td>2</td>
</tr>
<tr>
<td>J140</td>
<td>0.2</td>
<td>μ20i</td>
<td>40</td>
</tr>
<tr>
<td>3J60</td>
<td>0.2</td>
<td>2μ10</td>
<td>10</td>
</tr>
<tr>
<td>4J40</td>
<td>0.2</td>
<td>j370</td>
<td>10</td>
</tr>
<tr>
<td>J36+XE60</td>
<td>0.4</td>
<td>4j90</td>
<td>10</td>
</tr>
<tr>
<td>TAU16I+XE30</td>
<td>2.0</td>
<td>j65+xE70</td>
<td>20</td>
</tr>
<tr>
<td>MU10+EM11I</td>
<td>0.1</td>
<td>τ35i+xE45</td>
<td>5</td>
</tr>
<tr>
<td>Others</td>
<td>5.0</td>
<td>2μ6 for B-physics</td>
<td>10</td>
</tr>
</tbody>
</table>

10.9.6 Evolution to higher luminosities

Building on the experience gained during the start-up phase, the trigger algorithms and parameters will be optimised to provide a trigger selection for use at higher luminosities. As the LHC luminosity ramps up towards its design value, tighter selections will be needed to control the rate. These will include using complex signatures involving multiple observables, higher $p_T$-thresholds, tighter selection criteria and requiring a more precise matching between different detector systems.

The trigger reconstruction and selection software must be robust against higher detector occupancies, pile-up and cavern backgrounds, which may affect the performance significantly at luminosities above $10^{33}$ cm$^{-2}$ s$^{-1}$. Many studies have been made to assess the performance of the trigger and data-acquisition system at high luminosities. Table 10.9 [237] shows an illustrative sample of L1 and HLT signatures, which could be used under stable operating conditions at luminosities around $2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$.

The triggers should guarantee coverage of the full physics programme, including searches for new physics and precision measurements of Standard Model parameters. The signatures include single- and di-lepton, photon and jet triggers, similar to those used at $10^{31}$ cm$^{-2}$ s$^{-1}$, but with higher $p_T$-thresholds and tighter selection criteria. Requirements on lepton and photon isolation, large $E_T^{miss}$, and possibly other complex criteria such as flavour tagging, which will have been operated only in a passive or loose mode during the start-up phase, will surely play an important role to achieve a sufficient rate reduction.

As an example, one can consider the case of $b$-jet tagging at the HLT. The performance of the proposed HLT $b$-tagging algorithms is based on transverse and longitudinal impact parameters of charged tracks in jets. The L2 and EF $b$-tagging efficiencies are strongly correlated with the offline $b$-tagging efficiency. To preserve full acceptance for an offline analysis with its $b$-tagging
selection criteria set for a given offline $b$-jet efficiency, the L2 and EF $b$-tagging algorithms must operate at an efficiency which is higher. Since most of the offline $b$-tagging results are obtained for $b$-jet efficiencies of $\sim 60\%$, the results quoted here for $b$-tagging in the HLT are given for $b$-jet efficiencies of approximately $80\%$ for L2 and $70\%$ for EF. Figure 10.119 shows that light-jet rejection factors larger than ten can be achieved, both at L2 and EF for a $b$-jet efficiency of $70\%$ and $b$-jet tagging could thus allow a more flexible operation of the L1 multi-jet trigger menus. To illustrate this, the rate reduction which could be achieved at L2 or EF by requesting two or more $b$-jets, is shown as a function of $E_T$ in figure 10.120.

Far more accurate projections of the rates given in table 10.9 will become possible once real data from the start-up phase have been accumulated and analysed. The total output rate of the trigger system at luminosities above $10^{33}$ cm$^{-2}$ s$^{-1}$ should remain fixed at approximately 200 Hz, a rate defined by the capabilities of the offline computing system.

### 10.9.7 Measurements of trigger efficiency from data

Since the trigger efficiency represents a basic element of any physics analysis, it is essential to have several independent methods for estimating it. It is important to depend as little as possible on Monte-Carlo models of LHC physics and on the detector operating conditions, particularly at the start-up of the LHC programme, given the large extrapolation from lower-energy measurements. Techniques under study include the "tag-and-probe" method, e.g. triggering events with the electron in $Z \rightarrow ee$ decays and measuring the efficiency to trigger on the positron in addition, and the "bootstrap" method, e.g. using minimum-bias events to measure the efficiency to trigger on low-$p_T$ jets, then triggering on low-$p_T$ jets and using them to measure the efficiency to trigger on higher-$p_T$ jets, etc. Redundant selections can also be used, in which one or more of the steps in the selection are skipped, thereby providing the possibility of determining the corresponding contributions to the inefficiency.
Figure 10.121: Trigger efficiencies as expected to be measured from data using the tag-and-probe method for electrons from approximately 25,000 $Z \rightarrow ee$ decays corresponding to an integrated luminosity of 100 pb$^{-1}$. The efficiencies are normalised with respect to a reference loose offline selection. The points with error bars show the measured efficiencies after L1 (full circles), L2 (open triangles) and the EF (full squares). Also shown as histograms are the corresponding distributions obtained using as a reference the Monte-Carlo truth information.

Figure 10.122: Difference between trigger efficiency as expected to be measured from data (using the tag-and-probe method for muons from $Z \rightarrow \mu\mu$ decays) and true efficiency (obtained using as a reference the Monte-Carlo truth information) normalised to true efficiency as a function of $\eta$. The efficiencies are normalised with respect to a reference loose offline selection. The results are shown after L1 (top), L2 (middle) and EF (bottom), and correspond to a sample of approximately 50,000 $Z \rightarrow \mu\mu$ decays for an integrated luminosity of 100 pb$^{-1}$.

As an example, studies have been made for the $Z \rightarrow ee$ tag-and-probe method, using events satisfying the e22i single-electron trigger selection, in which an opposite-charge electron pair has been identified by the offline reconstruction with an invariant mass near the $Z$ peak. Using the second lepton in these events as the probe which was not required to pass any trigger selection, the efficiency (relative to the offline selection) of a given trigger signature can be measured. Figure 10.121 shows the efficiency of the e22i trigger as a function of $p_T$ of the electron, as measured without any reference to Monte-Carlo truth information in the simulated sample of $Z \rightarrow ee$ events. The shape of the trigger-threshold curves in figure 10.121, obtained using as a reference the Monte-Carlo truth information, are accurately reproduced by the tag-and-probe measurements, and the values agree to better than 1% on the plateau for a sample of $Z \rightarrow ee$ decays corresponding to an integrated luminosity of 100 pb$^{-1}$. It is estimated that with such an integrated luminosity, the e22i trigger efficiency can be evaluated with a statistical accuracy of approximately 0.2%. Obviously, more data will be needed to study the trigger efficiency with much higher granularity, in particular as a function of $\eta$ and $\phi$. An example of such a study is shown in figure 10.122 for a sample of reconstructed $Z \rightarrow \mu\mu$ decays also corresponding to an integrated luminosity of 100 pb$^{-1}$. The results are plotted as the relative difference between the trigger efficiency measured using the tag-and-probe method and the true trigger efficiency as obtained from the Monte-Carlo truth information. The statistical accuracy achieved per bin is at the percent level.
A similar method can be used to measure the efficiency for triggering on hadronic $\tau$-decays, which can be measured using $Z \rightarrow \tau\tau$ samples collected with single electron and muon triggers (as shown in table 10.7), where one of the $\tau$-leptons decayed leptonically. In events where the second $\tau$-lepton decays to hadrons, one can measure the fraction of $\tau$-leptons reconstructed offline, which also pass the $\tau$-trigger. This will be done by correlating the detailed information recorded from the trigger with the results of the offline reconstruction and will require more integrated luminosity than in the case of the electron and muon triggers.
Chapter 11

Outlook

The broad range of physics opportunities and the demanding experimental environment of high-luminosity 14 TeV proton-proton collisions have led to unprecedented performance requirements and hence technological challenges for the general-purpose detectors at the LHC. The overall ATLAS detector design is the result of a complex optimisation process between conflicting requirements. These requirements can be expressed tersely as a set of four basic criteria over a large acceptance in pseudorapidity and basically full azimuthal coverage for all of the major detector systems (see chapter 1 for details):

- very good electromagnetic calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and $E_T^{\text{miss}}$ measurements;
- high-precision muon momentum measurements with the capability to guarantee accurate measurements at the highest luminosity using the muon spectrometer alone;
- efficient tracking at high luminosity for high-$p_T$ lepton momentum measurements, electron and photon identification, $\tau$-lepton and heavy-flavour identification, and full event reconstruction capability;
- efficient triggering with low $p_T$-thresholds on electrons, photons, muons and $\tau$-leptons, thereby providing high data-taking efficiencies for most physics processes of interest at the LHC.

After approximately fifteen years of detector design, construction, integration and installation, the ATLAS detector is now completed and almost entirely installed in the cavern (see chapter 9). All detector teams, together with the ATLAS performance and physics working groups, have developed detailed commissioning strategies using cosmic rays, single-beams, and initial data with colliding beams. As more and more detector components become operational, detector calibrations and extensive stand-alone and combined studies with cosmic-ray events are being carried out. These commissioning periods also exercise the full data acquisition chain, including the online and offline data-quality assessment tools and the streaming of events into several physics streams based
on the trigger decision. During the spring of 2008, calibration tests and cosmic-ray data-taking are ramping up, while the few remaining components of the detector are being installed and commissioned. The ATLAS detector will be ready for the first LHC collisions in summer 2008.

11.1 Detector installation and hardware status

The status of the ATLAS detector systems at the time of final submission of this paper in April 2008 is summarised below and in Table 11.1.

As described in chapter 2, the superconducting magnet system comprises the central solenoid, the barrel toroid, two end-cap toroids, and their services. Both the central solenoid and the barrel toroid magnets have been successfully commissioned at full current, and their safety systems have been tested in situ. Their mechanical behaviour as well as the magnetic-field measurements have confirmed the design expectations (see section 2.2). The magnetic field in the inner-detector cavity has been carefully mapped and the residual fractional bending-power uncertainties are well within specifications, i.e. below $5 \times 10^{-4}$. In the muon spectrometer, a preliminary analysis of B-sensor readings in a quarter of the field volume yields systematic uncertainties a few times larger than the ultimate desired precision. The end-cap toroids have been tested successfully in stand-alone mode at 50% field. An extensive field-reconstruction campaign over the entire spectrometer volume will be carried out during the full ATLAS magnet-system test which is scheduled just before the start of LHC operation.

As described in chapter 4, the inner tracking detector combines three concentric detector systems, namely the pixel detector, the SCT and the TRT. Substantial parts of the integrated barrel and end-cap TRT and SCT systems as well as parts of the pixel detector have been successfully operated on the surface in cosmic-ray tests before these systems were installed in the cavern. The tests of the installed inner-detector components are ongoing in parallel with completing the connection of the inner-detector services (cables and pipes). The TRT and SCT systems are already operational in cosmic-ray runs. The completion of the pixel service connections and subsequent stand-alone and cosmic-ray testing will follow next.

As described in Chapter 5, all three calorimeter cylinders, the barrel and the two end-caps, with the tile calorimeter surrounding the LAr cryostats, are installed in the cavern. The three cryostats are cold and filled with LAr. Now that all the calorimeter channels are part of the regular readout chain, the main activities are focused on the overall system commissioning.

As described in Chapter 6, the muon spectrometer is instrumented with precision chambers for momentum measurements (MDT’s and CSC’s) and with fast chambers for triggering (RPC’s and TGC’s). The construction of the various types of chambers has been completed for the initial detector configuration. The installation of the barrel stations and of the small and big end-cap wheels has also been completed. In parallel with the completion of the installation of the end-wall chambers (MDT’s) over the next months, the commissioning with cosmic rays is ongoing for both the barrel and end-cap regions, gradually increasing the number of sectors involved in these tests.

As described in Chapter 8, the components of the L1 trigger, of the DAQ/HLT system, and of the detector control systems are in an advanced stage of installation. The L1 trigger system (with its calorimeter, muon and central trigger processor sub-systems) is in its final production and installation phase for both the hardware and the software. The calorimeter trigger installation is
Table 11.1: Hardware status summary of the major ATLAS detector systems. Depending on the installation and commissioning status, the results are based on measurements on the surface prior to installation and/or measurements after installation in the main cavern, as described in the last column.

<table>
<thead>
<tr>
<th>Component</th>
<th>Operational readiness</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Solenoid</td>
<td>Residual RMS values</td>
<td>Solenoid and barrel toroid tested at nominal field. End-cap toroids tested at 50% field.</td>
</tr>
<tr>
<td></td>
<td>between mapping and</td>
<td></td>
</tr>
<tr>
<td></td>
<td>model</td>
<td></td>
</tr>
<tr>
<td>- Barrel toroid</td>
<td>~ 0.4 mT for all field components. 1–6 mT depending on position. Analysis in progress.</td>
<td>Nominal field: 2T Preliminary analysis in one sector. Goal is 2 mT.</td>
</tr>
<tr>
<td>- End-cap toroids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner detector</td>
<td>Fraction of fully functional channels</td>
<td>Mechanical installation complete. In situ cabling almost complete.</td>
</tr>
<tr>
<td>- Pixel</td>
<td>99.7%</td>
<td>After final integration of system on surface.</td>
</tr>
<tr>
<td>- SCT</td>
<td>99.8%</td>
<td>After integration with TRT system on surface.</td>
</tr>
<tr>
<td>- TRT</td>
<td>98.4%</td>
<td>Measured in situ.</td>
</tr>
<tr>
<td>LAr calorimeters</td>
<td>Fraction of fully functional channels</td>
<td>Installed and operational. Electronics tuning ongoing.</td>
</tr>
<tr>
<td>- EM barrel/end-cap</td>
<td>99.98%</td>
<td>Tested cool on surface.</td>
</tr>
<tr>
<td>- HEC</td>
<td>99.91%</td>
<td>Tested cool on surface.</td>
</tr>
<tr>
<td>- FCAL</td>
<td>99.77%</td>
<td>Tested cool on surface.</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>Fraction of fully functional channels</td>
<td>Installed and operational. Electronics/power supply tuning on-going.</td>
</tr>
<tr>
<td>- Barrel/extended</td>
<td>99.2%</td>
<td>Measured in situ for part of detector.</td>
</tr>
<tr>
<td>barrel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>Fraction of fully functional channels</td>
<td>Installed except for some end-wall chambers.</td>
</tr>
<tr>
<td>- MDT</td>
<td>99.9%</td>
<td>Tested on surface and partly in situ.</td>
</tr>
<tr>
<td>- RPC</td>
<td>99.5%</td>
<td>Tested on surface and partly in situ.</td>
</tr>
<tr>
<td>- TGC</td>
<td>99.9%</td>
<td>Tested on surface and partly in situ.</td>
</tr>
<tr>
<td>- CSC</td>
<td>99.9%</td>
<td>Tested on surface.</td>
</tr>
<tr>
<td>Trigger and data</td>
<td>System used for cosmic-ray tests and performance verified in stand-alone and commissioning tests.</td>
<td>Readout system installed and operational. Trigger processing-power limited to 40 kHz L1 rate.</td>
</tr>
<tr>
<td>acquisition</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

completed and the central trigger processor sub-system is in place and routinely used during detector commissioning runs. The readout system, the event builder, and the output to mass storage have been demonstrated in technical runs to deliver the required performance and data through-put rates. The HLT processing power, sufficient to handle a 40 kHz L1 acceptance rate, is planned to be installed for the run in 2008. The HLT algorithms have been successfully tested with physics events pre-loaded in the readout system, and also with cosmic-ray muons. Besides their own commissioning, these systems are used extensively and routinely for the commissioning of specific detector systems and of the overall ATLAS experiment.
The ATLAS control room is fully operational and heavily used. It has become the centre of one of the most prominent activities in the collaboration over the past months, namely periods of global commissioning runs during which, in particular, cosmic-ray events are recorded with the components of the detector already installed and operational in the cavern.

11.2 Outlook on commissioning with data

Chapter 10 summarises the expected performance of the ATLAS experiment. Many of the results are supported by test-beam measurements, in particular for the single-particle response of the detector elements to electrons, photons, pions and muons at various benchmark energies. Other results on the expected performance rely solely on the simulation of the detector geometry, of the detector response, and of the underlying physics processes. These include jets, $E_T^{\text{miss}}$, hadronic $\tau$-decays, $b$-tagging and trigger performance. Most of these results, particularly the expected trigger rates, are subject to large uncertainties because of the hitherto unexplored energy range for QCD processes at the LHC. At the LHC design luminosity, simulation uncertainties affecting the estimated detector performance also arise from pile-up of $p$-$p$ interactions (mostly in the triggered bunch-crossing), and from background in the ATLAS cavern consisting predominantly of slow neutrons (see chapter 3).

In all detector systems, calibration runs of various types are used to map noisy and dead channels. The tile calorimeter also performs dedicated laser and caesium-source calibration runs. These initial calibration data, combined with test-beam measurements performed over the past years, are critical to achieve a sufficient quality of the first collision data. The cosmic-ray data will provide important additional information for aligning the detectors relative to each other. As an example, these data will define an absolute geometry for most of the octants of the barrel muon spectrometer, and will be used as a reference for the alignment based on optical sensors. These data will also be used to define an initial alignment of the major components of the inner detector relative to each other. As shown in chapter 10, cosmic-ray data are considered as an important ingredient in the overall alignment strategy of the inner detector.

The combination of the results of the detector-specific calibration and commissioning runs with those from the analysis of future large-scale cosmic-ray data will define to a large extent the expected calibration and alignment accuracies for the major ATLAS detector components at the LHC start-up. These ATLAS start-up goals and the ultimate design goals of the experiment, in terms of tracking and calorimeter performance, are summarised in table 11.2.

At the start-up of the LHC, after timing-in the detector systems with the colliding LHC bunches and the trigger signals, minimum-bias triggers from scintillator counters will provide large event statistics for initial physics studies at luminosities of $10^{31}$ cm$^{-2}$ s$^{-1}$ or less. All the triggered events will be used to perform a thorough shake-down of the ATLAS detector systems, thereby refining and completing the dead, noisy and faulty channel maps. The large rates of rather high-$p_T$ isolated tracks (leptons or pions) will be used to refine the inner-detector alignment. High- and low-threshold transition radiation hits from isolated electron and pion tracks will be compared to the expectations from simulation studies.

Minimum-bias events will help to monitor the azimuthal uniformity of the calorimeter response and, to a certain extent, the amount of material in the inner detector. In this initial phase,
Table 11.2: Expected calibration and alignment accuracies at the LHC start-up and the ultimate design goals. Examples of physics channels or measurements driving the requirements are indicated in the last column.

<table>
<thead>
<tr>
<th></th>
<th>Start-up of LHC</th>
<th>Ultimate goal</th>
<th>Physics goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic energy uniformity</td>
<td>1–2%</td>
<td>0.5%</td>
<td>$H \rightarrow \gamma \gamma$</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>$\sim 2%$</td>
<td>0.02%</td>
<td>$W$ mass</td>
</tr>
<tr>
<td>Hadronic energy uniformity</td>
<td>2–3%</td>
<td>&lt; 1%</td>
<td>$E_T^{miss}$</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>&lt; 10%</td>
<td>1%</td>
<td>Top-quark mass</td>
</tr>
<tr>
<td>Inner-detector alignment</td>
<td>50–100 $\mu$m</td>
<td>&lt; 10 $\mu$m</td>
<td>$b$-tagging</td>
</tr>
<tr>
<td>Muon-spectrometer alignment</td>
<td>&lt; 200 $\mu$m</td>
<td>30 $\mu$m</td>
<td>$Z' \rightarrow \mu \mu$</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>$\sim 1%$</td>
<td>0.02%</td>
<td>$W$ mass</td>
</tr>
</tbody>
</table>

it will also be crucial to validate the ATLAS calorimeter simulation by comparing shower shapes for isolated lepton and hadron tracks. The statistics corresponding to a few days of low-luminosity data-taking without toroid field should provide enough straight muon tracks to calibrate the muon optical alignment system to less than 100 $\mu$m. This will be improved to 30 $\mu$m at higher luminosity, which is required to take full benefit from the spatial resolution of 40 $\mu$m per muon chamber. These steps are all necessary to achieve the goal of measuring 1 TeV muon tracks with approximately 10% accuracy.

The commissioning of the overall trigger system will be a gradual process (see section 10.9.5). Simple inclusive L1 calorimeter and muon triggers will be included first, followed by more complex L1 triggers, involving for example $E_T^{miss}$. At the same time, the HLT system will begin to operate, initially in pass-through mode in order to test the algorithms, and later using the full power of the HLT. The data collected with the complete low-luminosity trigger menu will contain copious quantities of low-energy leptons from heavy quark decays and also from direct $J/\psi$ and $\Upsilon$ production. The data will contain approximately $5 \times 10^5 W \rightarrow \mu \nu$ and $5 \times 10^4 Z \rightarrow \mu \mu$ decays reconstructed per 100 pb$^{-1}$ of integrated luminosity (the expected rates are somewhat lower for electrons). The low-luminosity trigger menu will also provide abundant samples of high-$p_T$ jets, of prompt photons, mainly from $\gamma$-jet events, and of hadronic $\tau$-decays.

All these events will be crucial for an initial validation of the ATLAS performance. More specifically, the inner-detector material can be mapped with photon conversions to an accuracy of 1% $X_0$ with the statistics available after several months of data-taking. Inclusive electrons can be used to test bremsstrahlung recovery in the inner detector. The inner-detector alignment is expected to converge to the required accuracy of approximately 10 $\mu$m soon after the full detector commissioning has started, allowing the constant term in the tracking resolution to be kept below 20% of the overall resolution. Residual inner-detector misalignments can be studied with the use of resonances of known mass and lifetime using their decays to lepton pairs, with $E/p$ comparisons for well-measured electrons in the electromagnetic calorimeter, and with high-$p_T$ muons in combined track fits with the muon spectrometer.
A preliminary electromagnetic inter-calibration can be obtained at low luminosity using the azimuthal symmetry of inclusive isolated electrons from various sources. The next phase of the electromagnetic inter-calibration will use $Z \rightarrow ee$ events. If the inner-detector material is well understood at that point, data corresponding to an integrated luminosity of 100 pb$^{-1}$ would be sufficient to significantly improve the expected initial uniformity of 1–2% to a statistical precision of approximately 0.7%. Further improvements will require the use of $E/p$ distributions from inclusive electrons and/or $W \rightarrow ev$ decays.

Jet calibration will use $E_T$-balancing in di-jet, $\gamma$-jet and also $Z$-jet events. The latter two channels will be important to determine the global jet-energy scale with an expected precision of better than 5% after a few months of data taking. The expected number of $\sim 500$ fully reconstructed $t\bar{t}$ events for 100 pb$^{-1}$ with one $W$ decaying hadronically and the other one leptonically, will allow a calibration of the jet-energy scale using invariant mass fits to $W \rightarrow jj$ decays.

The most widely studied method to measure with data the performance of $b$-tagging algorithms at the LHC relies on the selection of $t\bar{t}$ events. However, recent developments show that the techniques extensively used by the Tevatron experiments, combining track-based and soft-muon $b$-tagging algorithms in di-jet events, could also be used at the LHC. Once large-statistics samples of $t\bar{t}$ events become available, $b$-jet samples with very high purity will be extracted and used to calibrate, for example, the $b$-tagging likelihoods directly, thereby reducing the reliance on Monte-Carlo simulation.

One of the most difficult detector observables to measure accurately is $E_{T}^{\text{miss}}$. Because it is sensitive to many new physics signatures, the tails of its distribution must be precisely calibrated with data before $E_{T}^{\text{miss}}$ measurements can be used for discrimination and especially reconstruction purposes. A reliable measurement of $E_{T}^{\text{miss}}$ requires the removal from the data sample of beam-halo muons, beam-gas collisions, cavern background and cosmic rays. Moreover, all calorimeter cells must be calibrated (for both electromagnetic and hadronic showers), and noise levels and deficient cells must be mapped and corrected for. Initial data-driven $E_{T}^{\text{miss}}$ studies will use minimum-bias and di-jet events, analysing the missing $E_{T}$ resolution as a function of the summed transverse energy. With larger statistics, the use of $W \rightarrow l\nu$ decays, of mass-constrained $t\bar{t}$ events and of $Z \rightarrow \tau\tau$ decays should lead to a calibration of the $E_{T}^{\text{miss}}$-scale to about 5%.

Initial physics measurements will primarily focus on Standard Model processes with high cross-sections. The most prominent among these will be the production of hadronic jets, of $W$ and $Z$ bosons, and also of $b\bar{b}$ and $t\bar{t}$ pairs. Analyses aiming at searches for new phenomena will first concentrate on the understanding of the detector performance and on these Standard Model processes. The ATLAS performance and physics working groups will exploit to the full the rich variety of known physics processes at the LHC to calibrate the analysis tools and thus to prepare for the exciting searches for new physics, which have been the driving motivation of large numbers of physicists during the many years of work which have brought the collaboration this far.

11.3 Future changes to the ATLAS detector system

As the luminosity of the LHC machine reaches its design value of $10^{34}$ cm$^{-2}$ s$^{-1}$, the detector parts which have been staged due to budgetary constraints need to be completed. The main items falling into this category are a significant part of the HLT processing farm, some parts of the muon spec-
trometer including in particular the monitored drift-tube chambers in the transition region between the barrel and end-cap toroids, and also some of the shielding elements in the forward region. During this phase, the performance of the ATLAS detector will be continuously evaluated and optimised, in particular as physics samples are used to further study and improve the calibration and alignment procedures. Pile-up effects will also need to be understood and dealt with as the luminosity increases.

After reaching design luminosity, the challenge will be to operate and optimise the ATLAS detector, its multi-faceted trigger system and the various physics analyses over several years of data-taking. The detector parts are generally designed for ten years of operation (conservatively estimated to correspond to an integrated luminosity of up to 700 fb$^{-1}$). The most critical element is the innermost layer of the pixel detector or vertexing layer, which is located at a radial distance of only 5 cm from the beam-pipe. This layer is designed to survive a 1 MeV neutron equivalent fluence of approximately $10^{15}$ cm$^{-2}$, which corresponds to less than half the integrated luminosity mentioned above. Changes in the pixel system may therefore be needed earlier than for other parts of the detector.

If the LHC luminosity were to be increased significantly beyond the current estimates, as suggested in some studies for the LHC machine upgrade on a time-scale not earlier than 2015, several detector components are likely to need substantial changes. In particular, the inner-detector system would need to be completely replaced, and certain calorimeter, muon and shielding elements in the forward directions would also require significant changes and improvements. Research and development work has started in earnest within the collaboration in several of the areas mentioned above. However, a decision about the necessity, scope and time-scale of such an upgrade can only be made after a few years of LHC and detector operation, considering both the physics results and the performance of the machine and the status of the experiments at that point.
Acknowledgements

We are greatly indebted to all CERN’s departments and to the LHC project for their immense efforts not only in building the LHC, but also for their direct contributions to the construction and installation of the ATLAS detector and its infrastructure. We acknowledge equally warmly all our technical colleagues in the collaborating institutions without whom the ATLAS detector could not have been built. Furthermore we are grateful to all the funding agencies which supported generously the construction and the commissioning of the ATLAS detector and also provided the computing infrastructure.

We acknowledge the support of ANPCyT, Argentina; Yerevan Physics Institute, Armenia; ARC and DEST, Australia; Bundesministerium für Wissenschaft und Forschung, Austria; National Academy of Sciences of Azerbaijan; State Committee on Science & Technologies of the Republic of Belarus; CNPq and FINEP, Brazil; NSERC, NRC, and CFI, Canada; CERN; NSFC, China; Ministry of Education, Youth and Sports of the Czech Republic, Ministry of Industry and Trade of the Czech Republic, and Committee for Collaboration of the Czech Republic with CERN; Danish Natural Science Research Council; IN2P3-CNRS and Dapnia-CEA, France; Georgian Academy of Sciences; BMBF, DESY, and MPG, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT, Japan; JINR; CNRST, Morocco; FOM and NWO, Netherlands; The Research Council of Norway; Ministry of Science and Higher Education, Poland; GRICES and FCT, Portugal; Ministry of Education, Research and Youth, Romania; Ministry of Education and Science of the Russian Federation, Russian Federal Agency of Science and Innovations, and Russian Federal Agency of Atomic Energy; Ministry of Science, Serbia; Department of International Science and Technology Cooperation, Ministry of Education of the Slovak Republic; Slovenian Research Agency, Ministry of Higher Education, Science and Technology, Slovenia; Ministerio de Educación y Ciencia, Spain; The Swedish Research Council, The Knut and Alice Wallenberg Foundation, Sweden; State Secretariat for Education and Science, Swiss National Science Foundation, and Cantons of Bern and Geneva, Switzerland; National Science Council, Taiwan; TUBITAK, Turkey; The Science and Technology Facilities Council, United Kingdom; DOE and NSF, United States of America.

The ATLAS detector design and construction has taken about fifteen years, and our thoughts are with all our colleagues who sadly could not see its final realisation.
Annex

We are greatly indebted to all our colleagues who, together with the authors of this paper, have worked hard for years on the installation and we extend to all of them our heartfelt thanks for their invaluable contribution to this tremendous task.

### ATLAS acronym list

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADC</td>
<td>Analogue-to-Digital Converter</td>
</tr>
<tr>
<td>ALFA</td>
<td>Absolute Luminosity for ATLAS</td>
</tr>
<tr>
<td>ASD</td>
<td>Amplifier/Shaper/Discriminator</td>
</tr>
<tr>
<td>ASDBLR</td>
<td>Amplifier/Shaper/Discriminator/BaseLine Restoration</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>ASM</td>
<td>Amplification, Sampling, (digitization) and Multiplexing</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC ApparatuS</td>
</tr>
<tr>
<td>BC</td>
<td>Bunch Crossing</td>
</tr>
<tr>
<td>BCID</td>
<td>Bunch-Crossing IDentification</td>
</tr>
<tr>
<td>BCM</td>
<td>Beam Conditions Monitor</td>
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<tr>
<td>BC-mux</td>
<td>Bunch-Crossing MUltipleXing</td>
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<tr>
<td>BEE</td>
<td>Barrel End-cap Extra</td>
</tr>
<tr>
<td>BIL</td>
<td>Barrel Inner Large</td>
</tr>
<tr>
<td>BIR</td>
<td>Barrel Inner Rail</td>
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<td>BIS</td>
<td>Barrel Inner Small</td>
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<tr>
<td>BM</td>
<td>Barrel Middle</td>
</tr>
<tr>
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<tr>
<td>BO</td>
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</tr>
<tr>
<td>BOC</td>
<td>Back Of Crate</td>
</tr>
<tr>
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<td>BiPhase Mark</td>
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<td>Barrel Toroid</td>
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<td>Controller Area Network bus</td>
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<td>CALbus</td>
<td>Calibration bus</td>
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<td>CDD</td>
<td>CERN Drawing Directory</td>
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<td>European Organization for Nuclear Research</td>
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<td>Central File Server</td>
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<td>Common Infrastructure Control</td>
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<td>Charge Injection System</td>
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<td>CMA</td>
<td>Coincidence Matrix chip</td>
</tr>
<tr>
<td>CM</td>
<td>Coincidence Matrix</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>CMM</td>
<td>Common Merger Module</td>
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<td>CMOS</td>
<td>Complementary Metal-Oxide Semiconductor</td>
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<td>COMbus</td>
<td>Common Timing and Trigger Bus</td>
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<tr>
<td>COOL</td>
<td>ATLAS-wide conditions database</td>
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<td>Cluster Processor</td>
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<td>Cluster Processor Module</td>
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<td>CRC</td>
<td>Cyclic Redundancy Check</td>
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<td>Cathode Strip Chambers</td>
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<td>Central Solenoid</td>
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<td>Chamber Service Module</td>
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<td>Central Trigger Processor</td>
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<tr>
<td>DAC</td>
<td>Digital-to-Analogue Converter</td>
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<tr>
<td>DAQ</td>
<td>Data AcQuision system</td>
</tr>
<tr>
<td>DCS</td>
<td>Detector Control System</td>
</tr>
<tr>
<td>DFM</td>
<td>Data Flow Manager</td>
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<tr>
<td>DMILL</td>
<td>Durci Mixte sur Isolant Logico-Lineaire (a radiation-hard ASIC technology)</td>
</tr>
<tr>
<td>DORIC</td>
<td>Digital Opto-Receiver Integrated Circuit</td>
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<td>DSP</td>
<td>Digital Signal Processors</td>
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<td>Detector Safety System</td>
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<td>EB</td>
<td>Extended Barrel</td>
</tr>
<tr>
<td>EC</td>
<td>End-Cap</td>
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<tr>
<td>ECT</td>
<td>End-Cap Toroid</td>
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<td>EDMS</td>
<td>Engineering Data Management System</td>
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<td>End-cap Extra Large</td>
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<td>ELMB</td>
<td>Embedded Local Monitor Board</td>
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<td>EMB</td>
<td>ElectroMagnetic Barrel calorimeter</td>
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<tr>
<td>EMD</td>
<td>Equipment Management Database</td>
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<tr>
<td>EMEC</td>
<td>ElectroMagnetic End-cap Calorimeter</td>
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<td>ElectroMagnetic</td>
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<td>Flash ADC</td>
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<td>Forward Calorimeter</td>
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<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>FEB</td>
<td>Front-End Board</td>
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<tr>
<td>FECcont</td>
<td>Front-End Crate controller board</td>
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<td>Front-End Crate</td>
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<td>FE</td>
<td>Front-End</td>
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<td>FIFO</td>
<td>First-In/First-Out</td>
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<td>Forward Inner wheel</td>
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<td>fLVPS</td>
<td>finger Low Voltage Power Supply</td>
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<td>FPGA</td>
<td>Field-Programmable Gate Array</td>
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<td>FPIAA</td>
<td>Find Persons Inside ATLAS Area</td>
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<td>Gain-SELector chip</td>
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<td>HADron calorimeter</td>
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<td>HEC</td>
<td>Hadronic End-cap Calorimeter</td>
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<td>HF</td>
<td>Steel structures below access shafts</td>
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<td>HLT</td>
<td>High-Level Trigger</td>
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<td>Blue support structure on ends of ATLAS cavern</td>
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<tr>
<td>HS</td>
<td>Blue support structure on sides of ATLAS cavern</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
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<td>HVPS</td>
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<td>Integrated Circuit</td>
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<td>Information Server</td>
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<td>Inter TileCal scintillators</td>
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<td>Inner Warm Vessel</td>
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<td>Jet/Energy Module</td>
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<tr>
<td>JEP</td>
<td>Jet/Energy-sum Processor</td>
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<td>Joint Task Action Group</td>
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<td>Level-1 Calorimeter trigger</td>
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<td>Level-2 trigger</td>
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<td>L2SV</td>
<td>Level-2 SuperVisor</td>
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<td>Long barrel</td>
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<td>MDT</td>
<td>Monitored Drift Tubes</td>
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<td>MIP</td>
<td>Minimum Ionising Particle</td>
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<td>Message Reporting Service</td>
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<td>Manufacturing and Test Folder database</td>
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<td>MUCTPI</td>
<td>MUon-to-Central-Trigger-Processor-Interface</td>
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<td>NEF</td>
<td>Neutron Equivalent Fluence</td>
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<td>Non-Evaporable Getter</td>
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<td>NRZ</td>
<td>Non Return to Zero</td>
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<td>ODH</td>
<td>Oxygen Deficiency Hazard</td>
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<td>Optimal Filtering Coefficients</td>
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<td>Online Histogramming Service</td>
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<td>Optical Multiplexer Board</td>
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<td>Optical Transmitter</td>
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<td>PolyEther-Ether-Ketone</td>
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<td>Pre-Processor Module</td>
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<td>Pre-Processor</td>
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<td>PS</td>
<td>Presampler</td>
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<td>PST</td>
<td>Pixel Support Tube</td>
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<td>Processor Unit</td>
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<td>Prozessvisualisierungs und Steuerungs System</td>
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<td>Quarter Service Panel</td>
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<td>QUADrupole</td>
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<td>Single Event Upset</td>
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<td>Event building node</td>
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<td>SFO</td>
<td>Event filter output node</td>
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