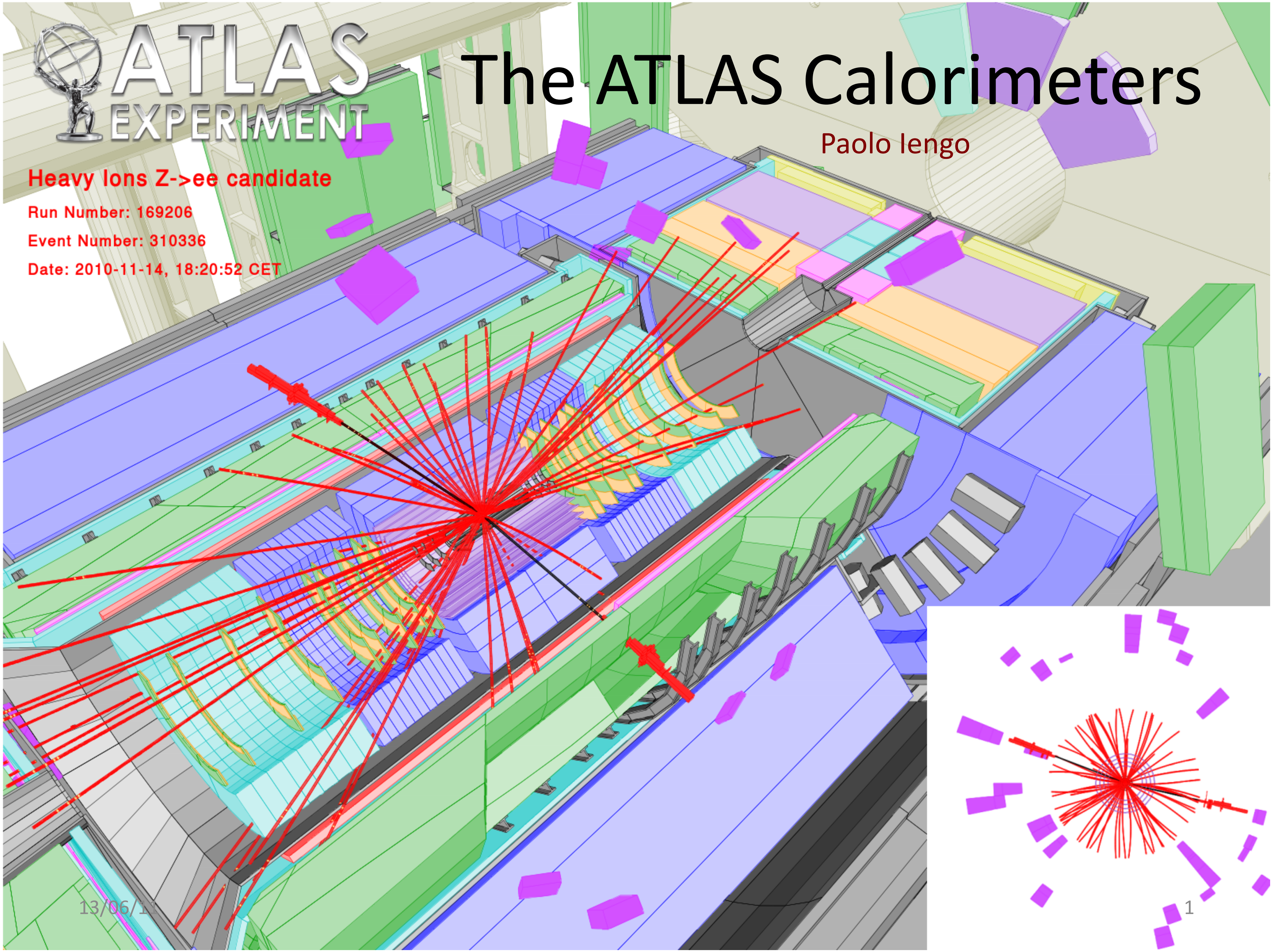
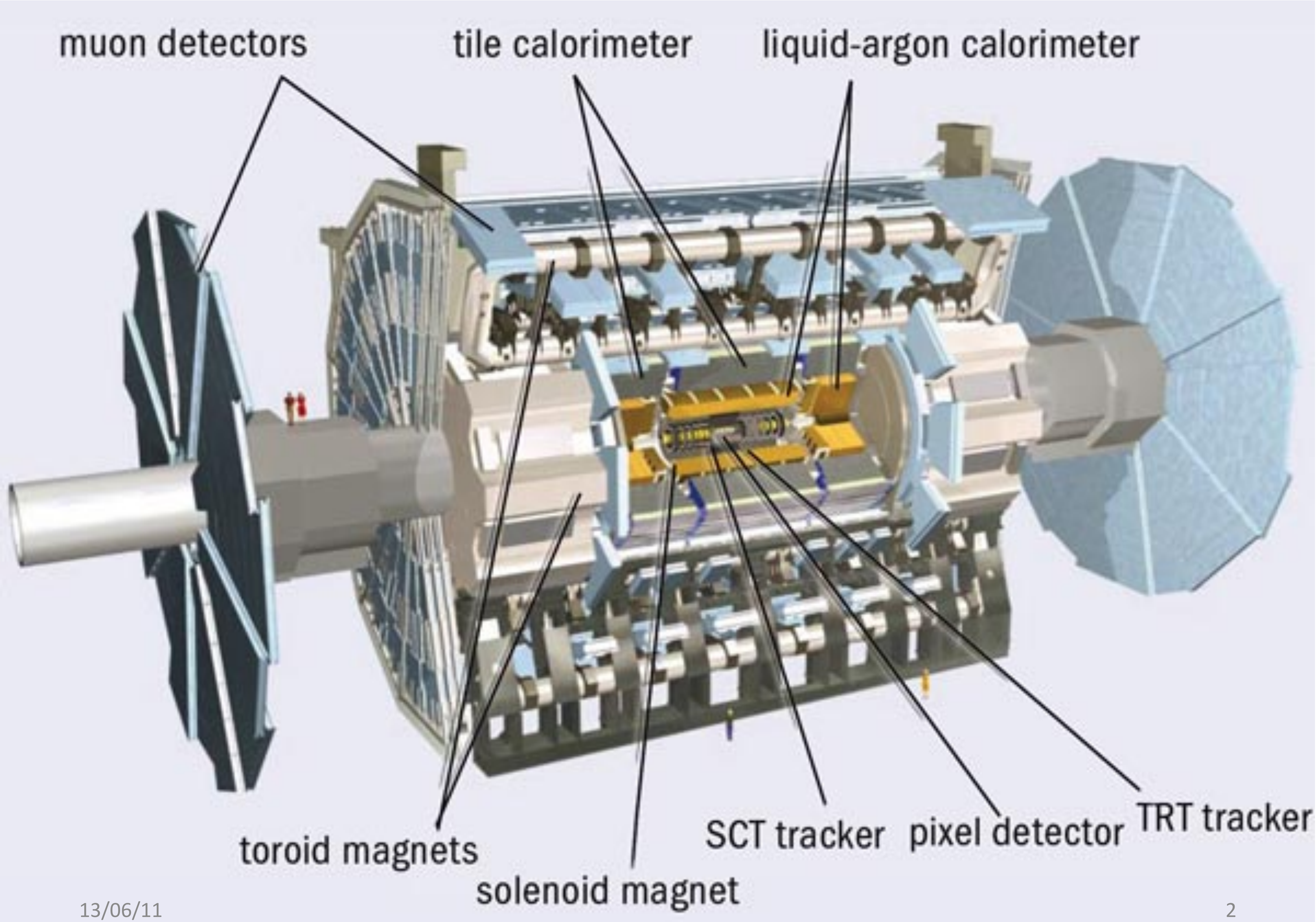
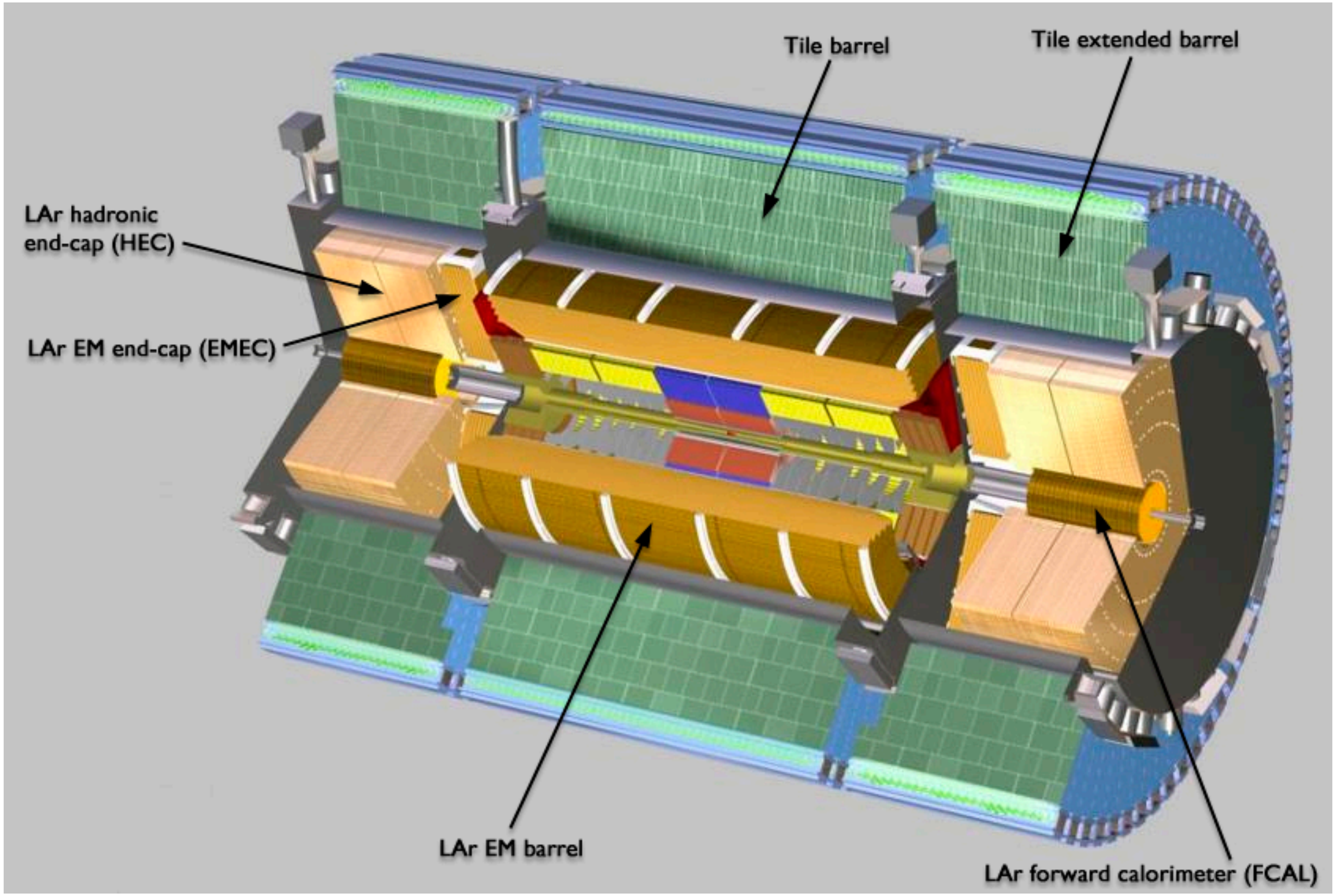
The ATLAS Calorimeters

Paolo Iengo




muon detectors
tile calorimeter
liquid-argon calorimeter
toroid magnets
solenoid magnet
SCT tracker
pixel detector
TRT tracker

The ATLAS Calorimeter System



- **A complex system**
- **Before going into details let's look to general and basic concepts of calorimetry**

Intoduction: calorimeters in a nutshell

- **Calorimeters in HEP experiments are designed to measure energy of incoming particles**
  - **Particles to be measured must be fully absorbed: disruptive measurement**
  - **Calorimeters measure energy of charged as well as neutral particles (n,γ,π^0…)**
  - **They can provide information on the direction of the particle: segmentation**
  - **They can measure ‘missing’ energy, i.e. energy carried by not interacting particles like neutrinos: hermiticity**
  - **Classification of calorimeters:**
  - **Depending on particles measured:**
    - **Electromagnetic (EM) – measure electrons and photons through their electromagnetic interactions**
    - **Hadronic (HCAL) – measure mainly hadrons through their strong and electromagnetic interactions**
  - **According to the construction technique:**
    - **Sampling – consisting of alternating layers of absorbers and active materials**
    - **Homogeneous – consisting of a single type of material**

Particle showers

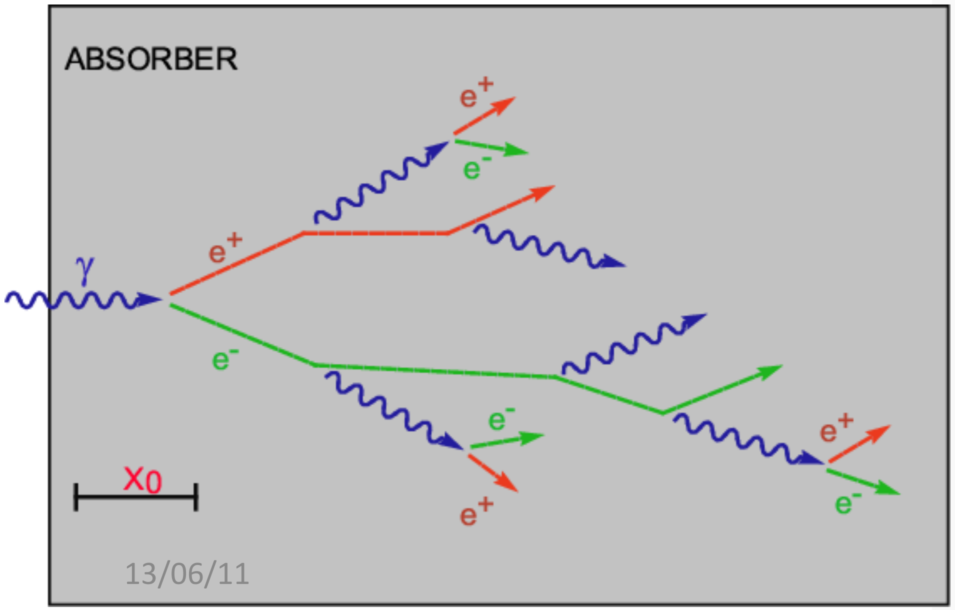
Calorimeters measure energy of charged secondary particles created by the interaction of the incoming particle with a block of material

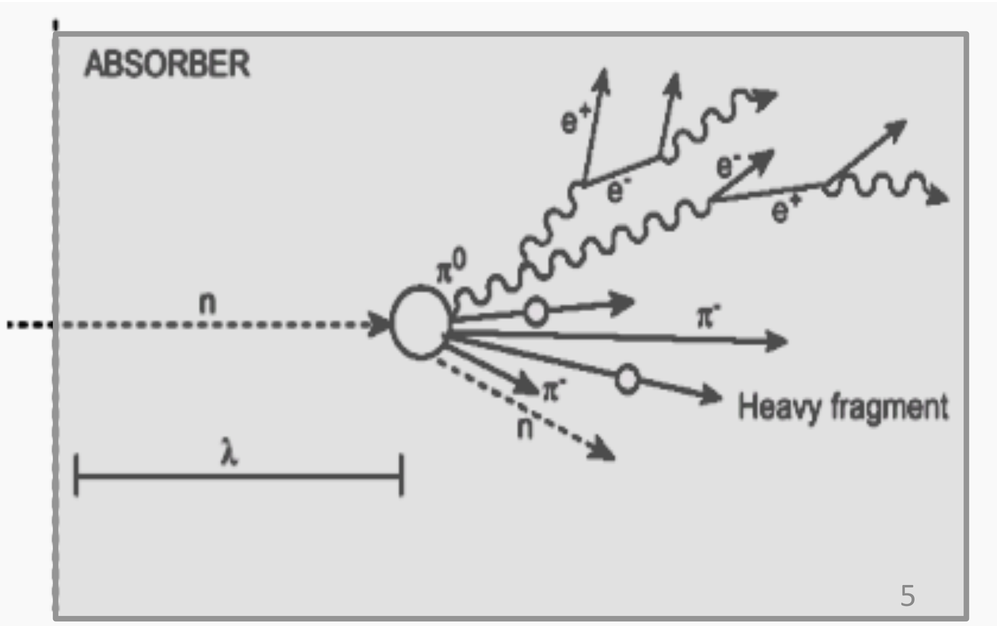
EM Calorimeter

- **EM shower initiated by e^+, e^- or γ**
- **Shower development based on two processes**
  - Bremsstrahlung
  - Pair creation
- **e^+, e^- and γ are the sole components of the shower**

Hadronic Calorimeter

- **Hadronic shower initiated by hadrons (p,n,π…)**
- **Hadronic showers have always an EM component too**
- **Shower development based on hadronic interacion and on electromagnetic one (for the EM part)**
- **Large variety of particle components**



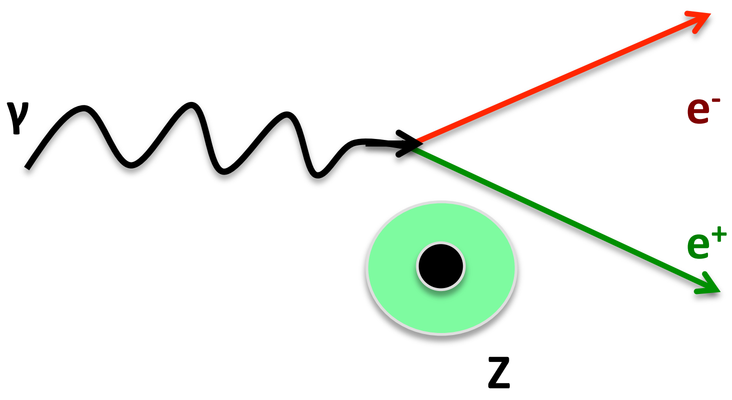


EM showers – Basic concepts

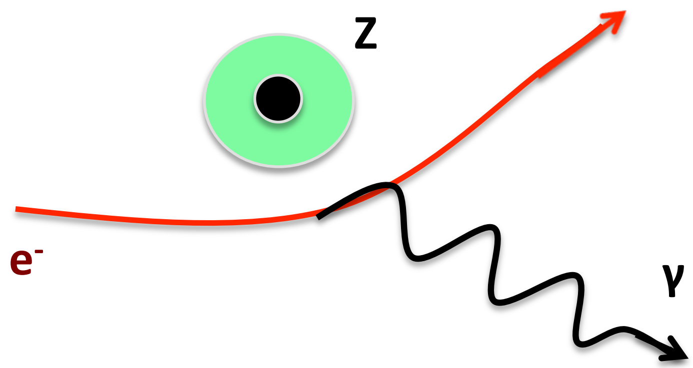
- Above ~1GeV energy loss by e/γ is dominated by radiative processes → we focus on these

- At lower energy other processes contribute
  - Ionization for electrons
  - Compton scattering and photoelectric effect for photons

Pair creation



Bremsstrahlung



- EM showers develop:
  - Longitudinally: direction of primary particle
  - Transversally: in the transverse plane

- Few parameters can discribe the development
  - We won't go to a detailed description

EM showers – Basic concepts

Radiation length

$$X_0 \approx \frac{180A}{Z^2} g \cdot cm^{-2}$$

- Material badget that reduces on average the energy of an electror by a factor e
- In 1 X_0 1 electron loses ~2/3 of its energy by emitting a photon
- In 1 X_0 a photon has a probability of ~7/9 to undergo a pair conversion

X_0 can be (approximately) assumed as generation length: at each generation (step) the number of particles in the shower doubles and the energy of the particles halves

Critical Energy

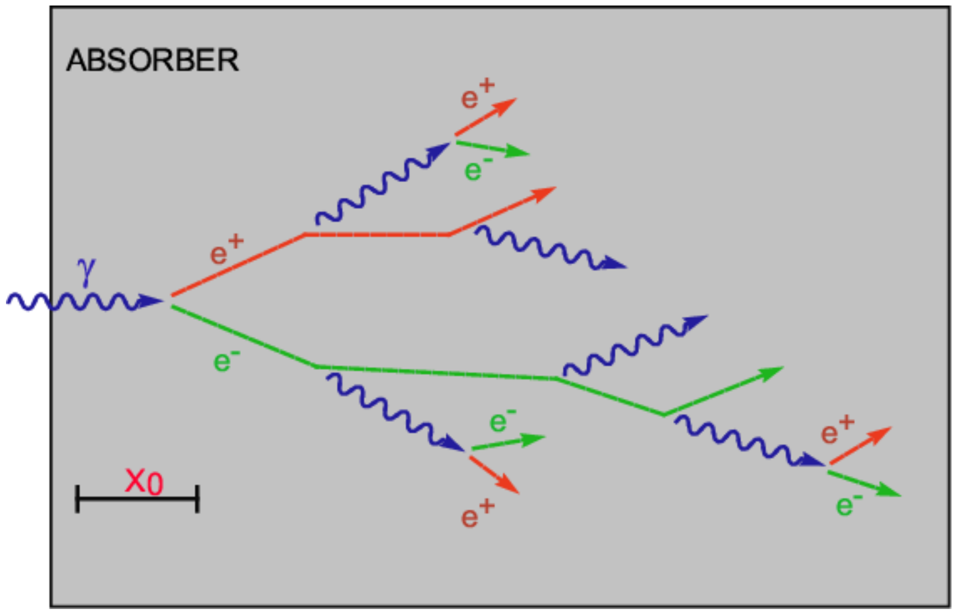
$$E_c \approx \frac{610MeV}{Z + 1.24}$$

Is the energy at which electrons start irradiating photons. At energy below Ec ionization dominates

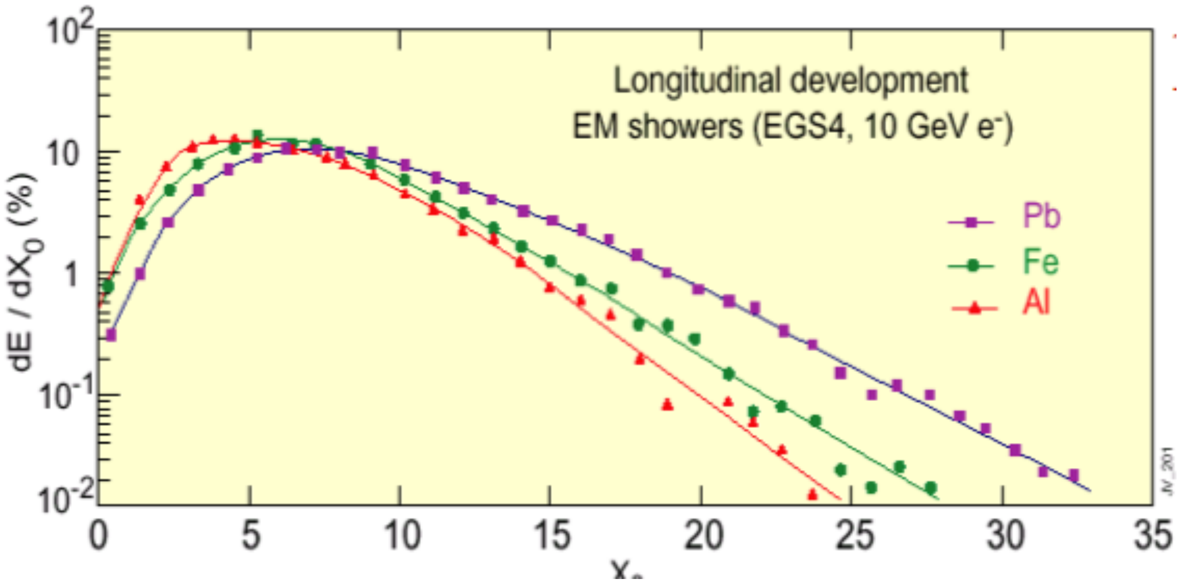
Moliere radius

$$R_M = \frac{21MeV}{E_c} X_0 \propto \frac{A}{Z}$$

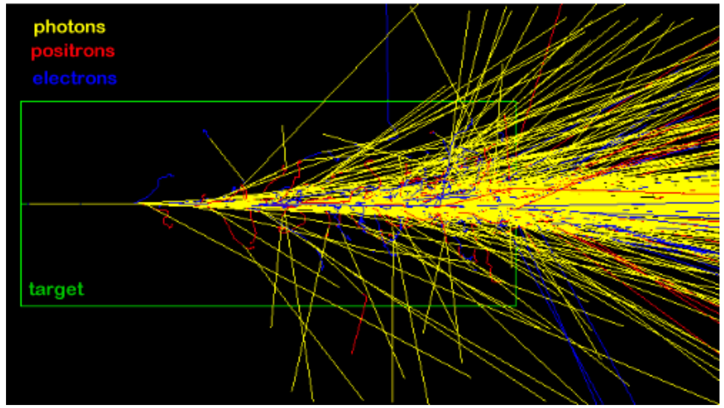
Measures the transverse shower size: average lateral deflection of electron with $E=E_c$ after $1X_0$



EM showers



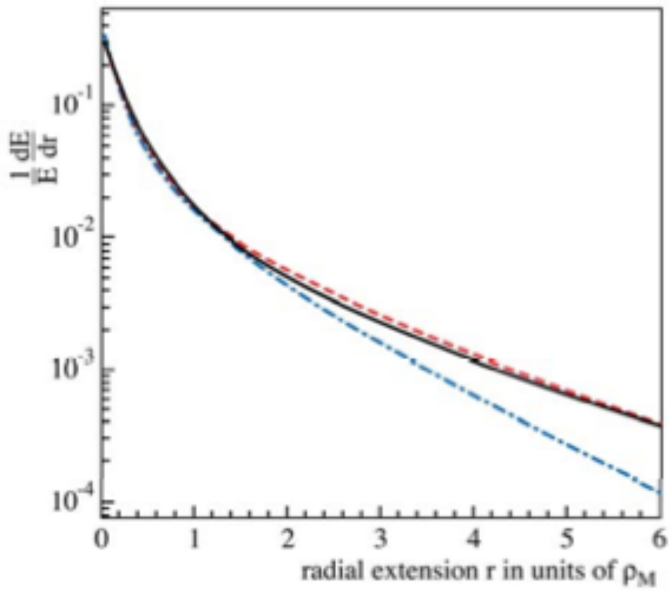
Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.



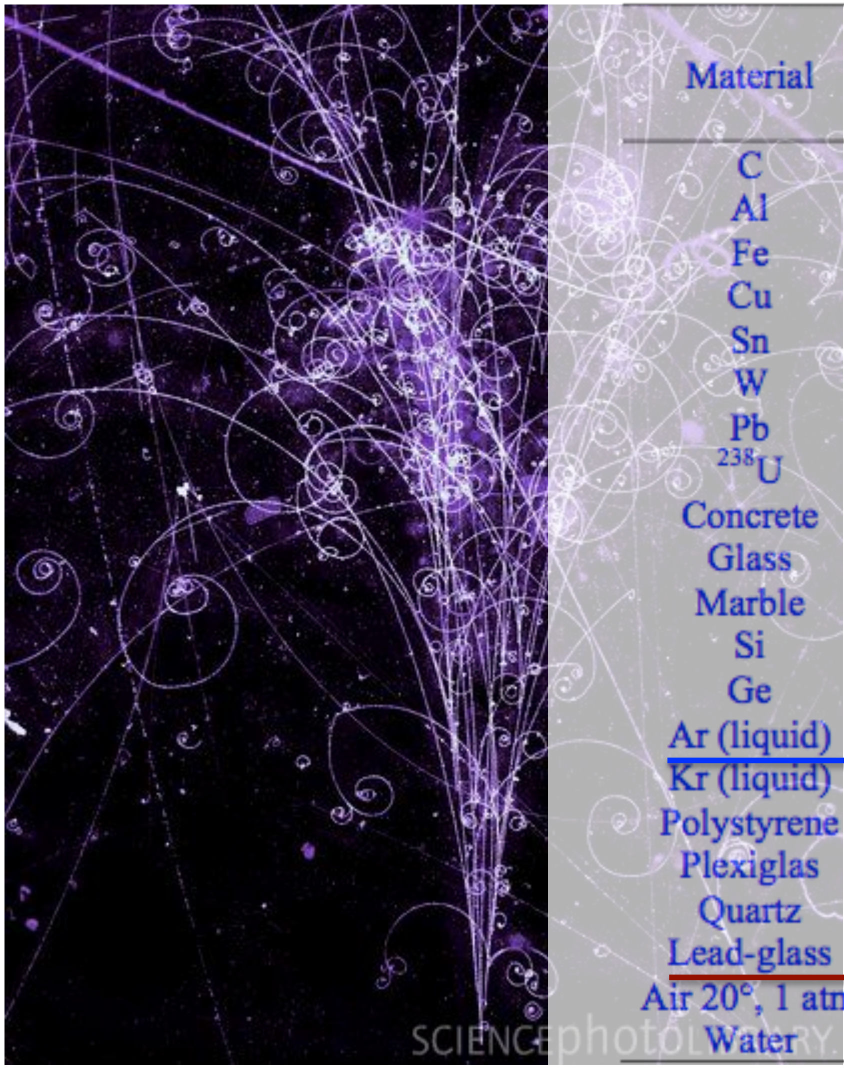
- **EM showers are contained (>99%) in 20 X_0 regardless the material (X_0 depends on ρ)**

Material tichness for containement ~ Ln(E)

Lateral shower developmen:
EM showers contained in
1 RM: ~87%
2 RM: ~96%
5 RM: >99%



Some numbers

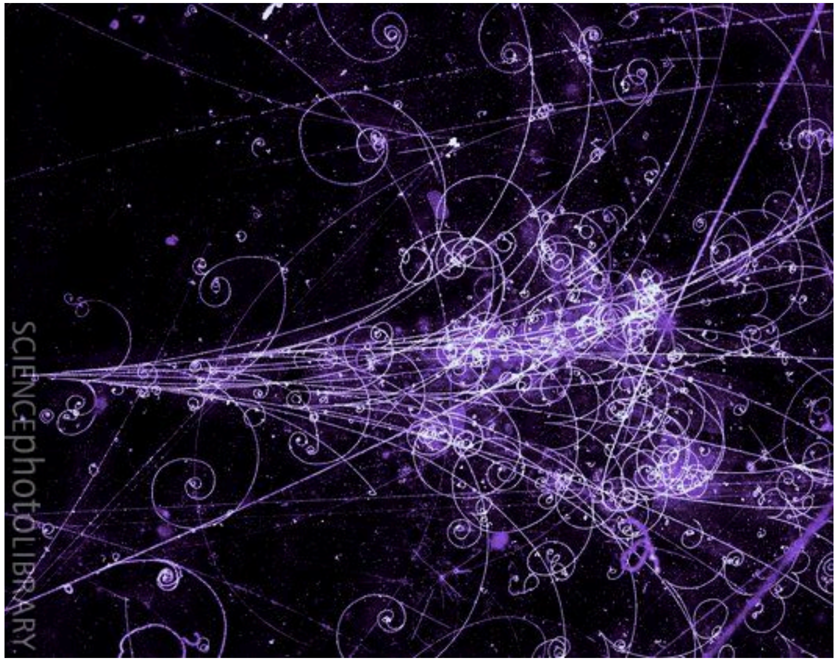


Material	Z	Density [g cm^{-3}]	E_c [MeV]	X_0 [mm]	ρ_M [mm]	λ_{int} [mm]	$(dE/dx)_{mip}$ [MeV cm^{-1}]
C	6	2.27	83	188	48	381	3.95
Al	13	2.70	43	89	44	390	4.36
Fe	26	7.87	22	17.6	16.9	168	11.4
Cu	29	8.96	20	14.3	15.2	151	12.6
Sn	50	7.31	12	12.1	21.6	223	9.24
W	74	19.3	8.0	3.5	9.3	96	22.1
Pb	82	11.3	7.4	5.6	16.0	170	12.7
^{238}U	92	18.95	6.8	3.2	10.0	105	20.5
Concrete	-	2.5	55	107	41	400	4.28
Glass	-	2.23	51	127	53	438	3.78
Marble	-	2.93	56	96	36	362	4.77
Si	14	2.33	41	93.6	48	455	3.88
Ge	32	5.32	17	23	29	264	7.29
Ar (liquid)	18	1.40	37	140	80	837	2.13
Kr (liquid)	36	2.41	18	47	55	607	3.23
Polystyrene	-	1.032	94	424	96	795	2.00
Plexiglas	-	1.18	86	344	85	708	2.28
Quartz	-	2.32	51	117	49	428	3.94
Lead-glass	-	4.06	15	25.1	35	330	5.45
Air 20°, 1 atm	-	0.0012	87	304 m	74 m	747 m	0.0022
Water	-	1.00	83	361	92	849	1.99

- $25X_0$ = { Lead-glass: 25*25.1 = 627.5 mm → homogeneous?
  Liquid Ar: 25*140 = 3500 mm → sampling

Energy resolution

- Measured energy in EM calorimeters is the energy of electrons and positrons interacting with the active detector material



$$\mathbf{E_0} \propto \mathbf{N_{tot}}$$

Multiplication process is stocastic
Poisson distribution

$$\sigma(\mathbf{E_0}) \propto \sigma(\mathbf{N_{tot}}) \propto \sqrt{\mathbf{N_{tot}}}$$

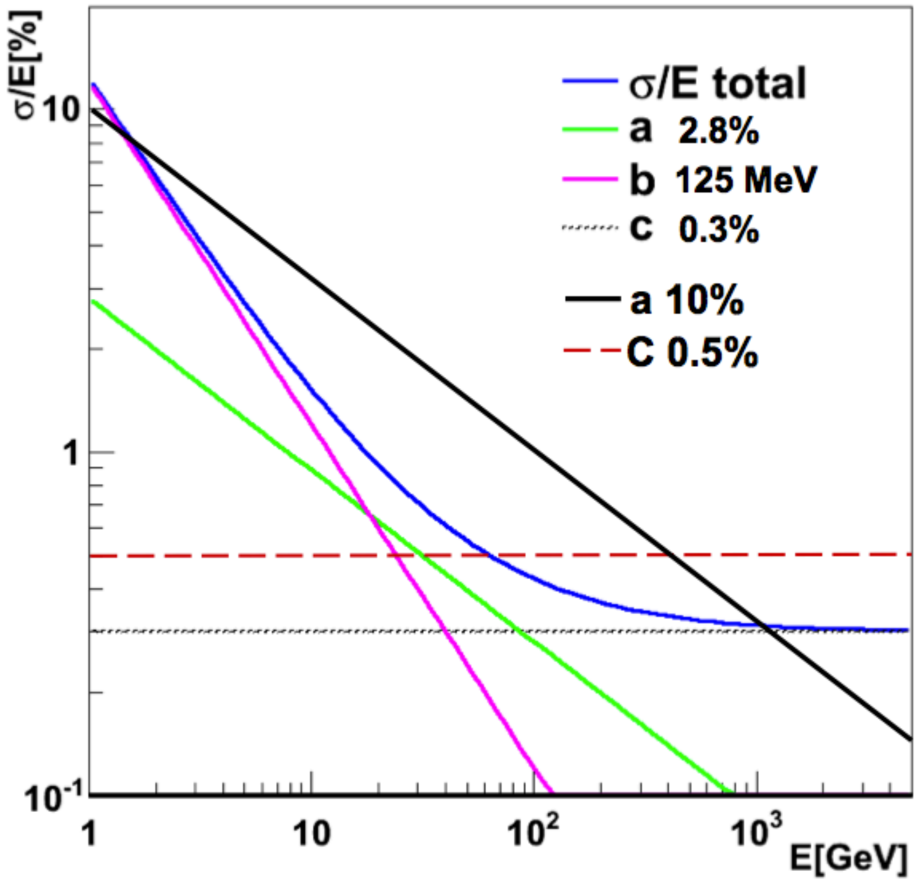
$$\frac{\sigma(\mathbf{E_0})}{\mathbf{E_0}} \propto \frac{\sigma(\mathbf{N_{tot}})}{\mathbf{N_{tot}}} \propto \frac{\sqrt{\mathbf{N}_{\mathbf{tot}}}}{\mathbf{N_{tot}}} \propto \frac{\mathbf{1}}{\sqrt{\mathbf{E_0}}}$$

Intrinsic energy resolution improve with E

Energy resolution

Generic parametrization of calorimeter energy resolution:

$$\frac{\sigma(E_0)}{E_0} = \frac{a}{\sqrt{E_0}} \oplus \frac{b}{E_0} \oplus c$$

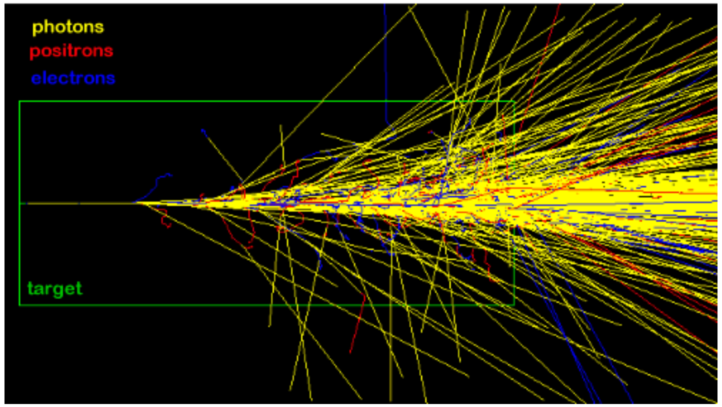


- a: Stocastic term
  - intrinsic limit due to statistical processes
- b: noise term
  - important at low energy
  - Electronic noise, pileup etc.
- c: constant term
  - Dominates at high energy
  - Due to inhomogeneities in materials, calibration imperfections, leakage

Sampling vs homogeneous

- Homogeneous

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

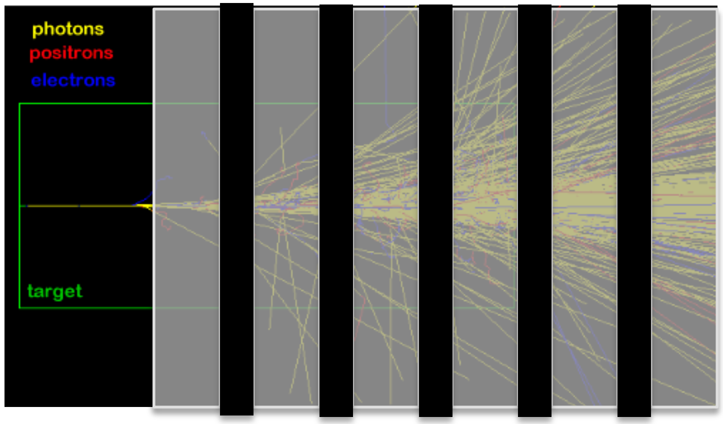


Active medium (with high X_0) coincides with absorber
Very good energy resolution (small a)
No information on longitudinal development of the shower
Cost effective

a ~ 1-10 %

- Sampling

Massive shower in a tungsten cylinder (outlined in green) produced by a single 10 GeV incident electron.

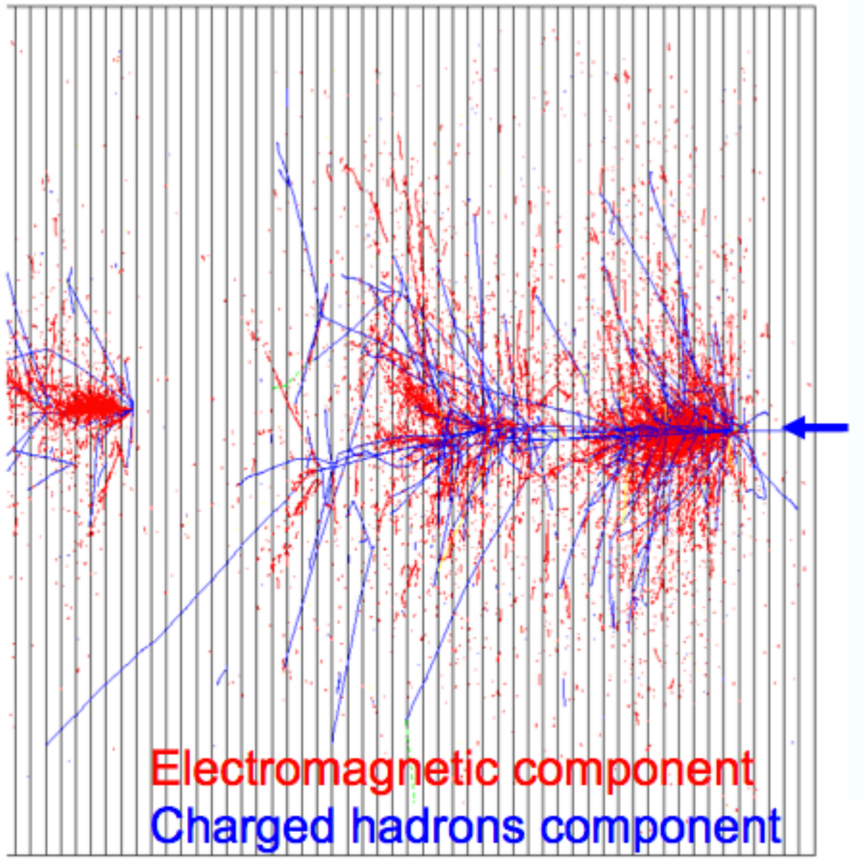


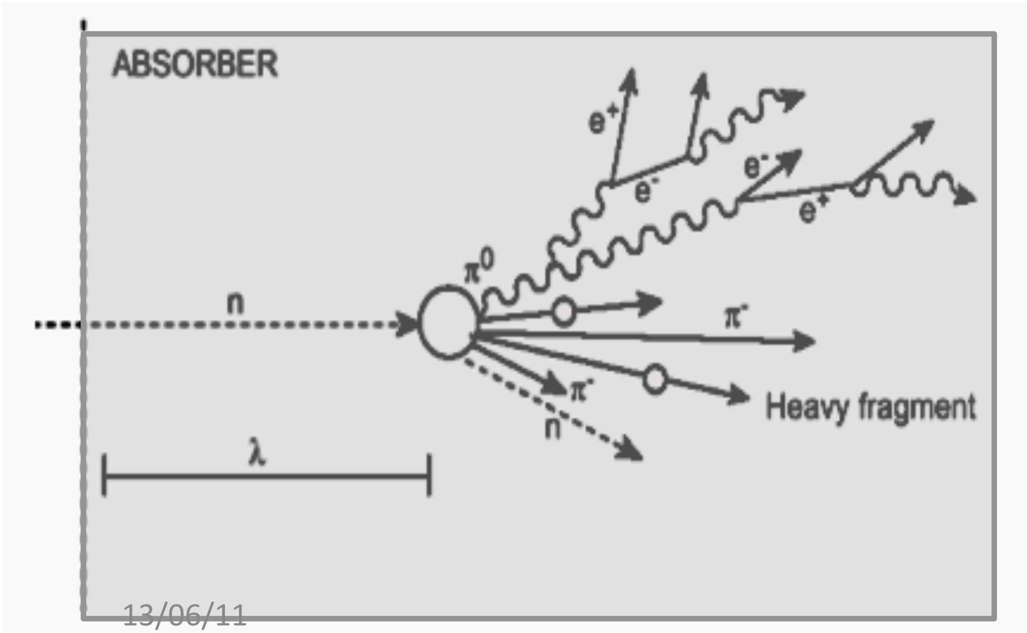
Alternating layers of active medium (smaller X_0) and absorber (larger X_0: Pb, Cu, Fe)
Energy is sampled: sampling fraction introduces an additional contribution to the stocastic term
Shower shape information
Normally cheaper than homogeneous

a ~ 10-20 %

Hadron shower

- Description of hadron shower development is rather complicated
- It preceeds via strong and EM interactions
- Strong interaction of a single hadron with matter can lead to production of many secondaries
- $\pi^0 \rightarrow \gamma\gamma$ generate EM component of the shower
- Nuclei can breakup leading to spallation of n and p
- Energy threshold is the production of π: $E_{th} \sim 2m_\pi$ =2 80 MeV





Energy deposited by hadron components:

Ionizing particle (p, pi+-, etc)	~60%
Neutron	~10%
Invisible energy (nuclear binding)	~30%

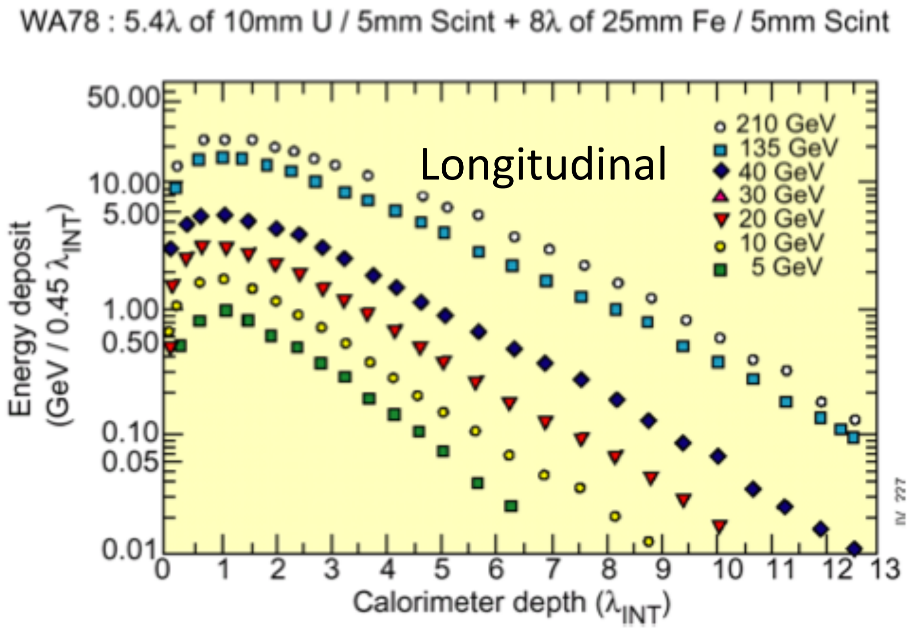
Huge fluctuations → poor energy resol.

a ~ 20-40%

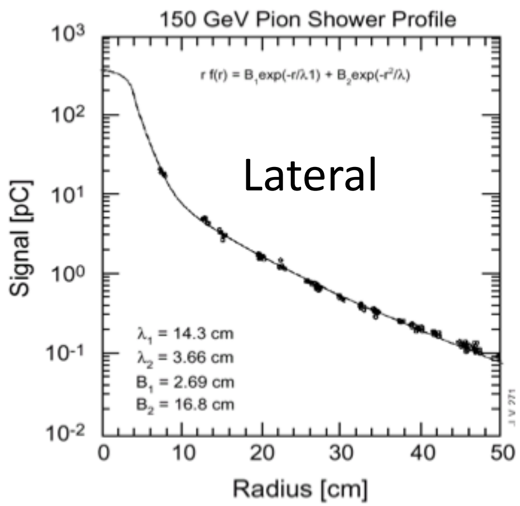
Hadron shower

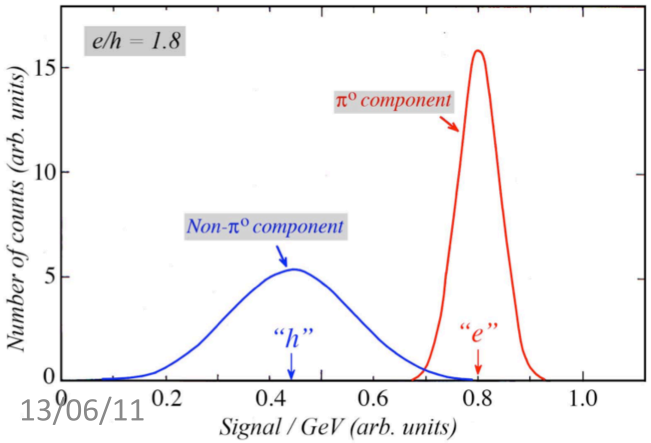
- Hadron showers development is parametrized with interaction length

$$\lambda_{\mathrm{int}} \sim 35 A^{1/3} \mathrm{g} \cdot \mathrm{cm}^{-2}$$



~10 λ_{int} to contain a shower ~ 1-2 m (heavy absorber) → HCAL always sampling





Moreover: response of active layer to HAD and EM shower components is different (e/h ≠ 1)

Concept of calorimeter compensation, not described here.
ATLAS calorimeter is not compensating

Recap

- Calorimeters
  - ElectroMagnetic
  - Hadronic
  - Homogeneous
  - Sampling

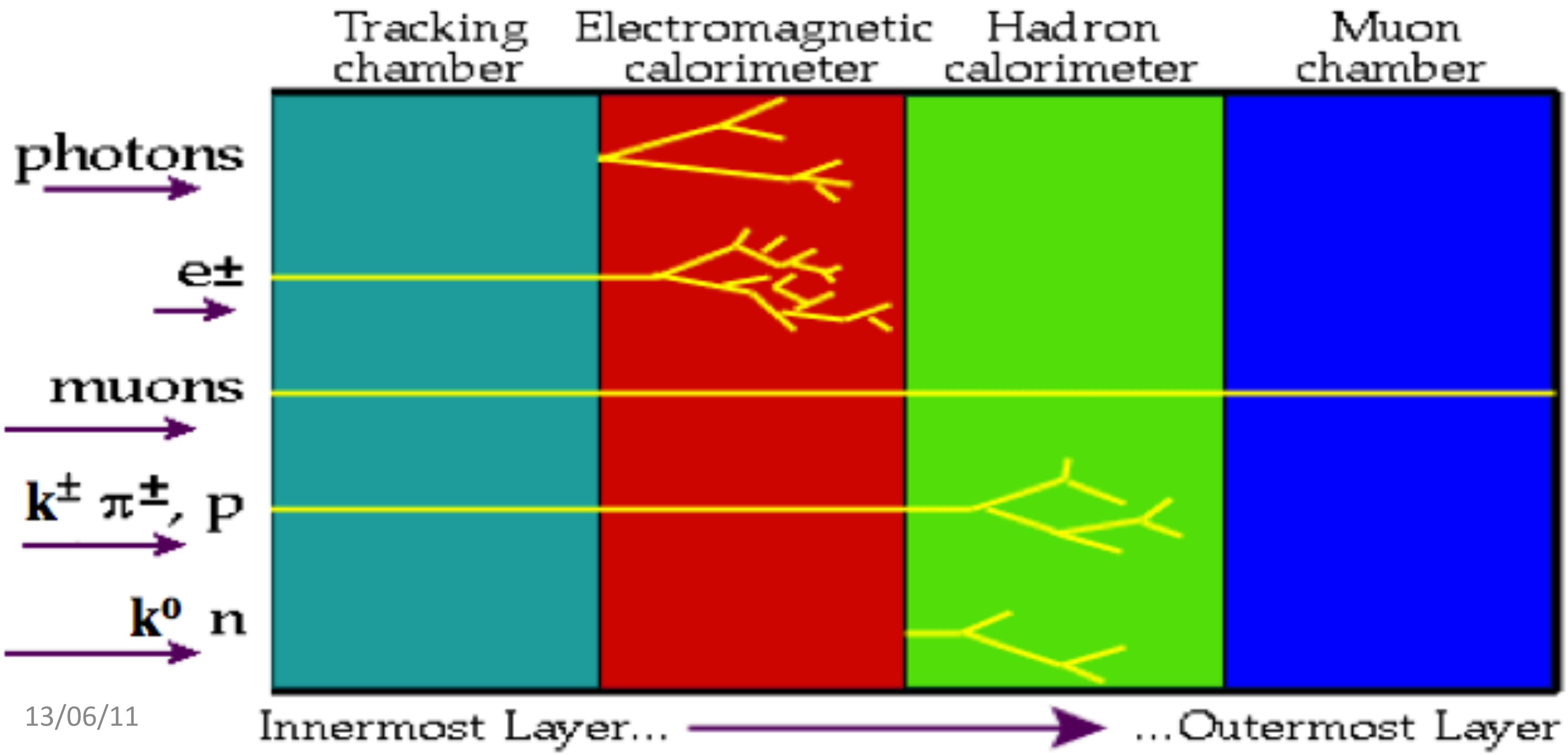
$$\frac{\sigma(E_0)}{E_0} = \frac{a}{\sqrt{E_0}} \oplus \frac{b}{E_0} \oplus c$$

Resolution increase with E

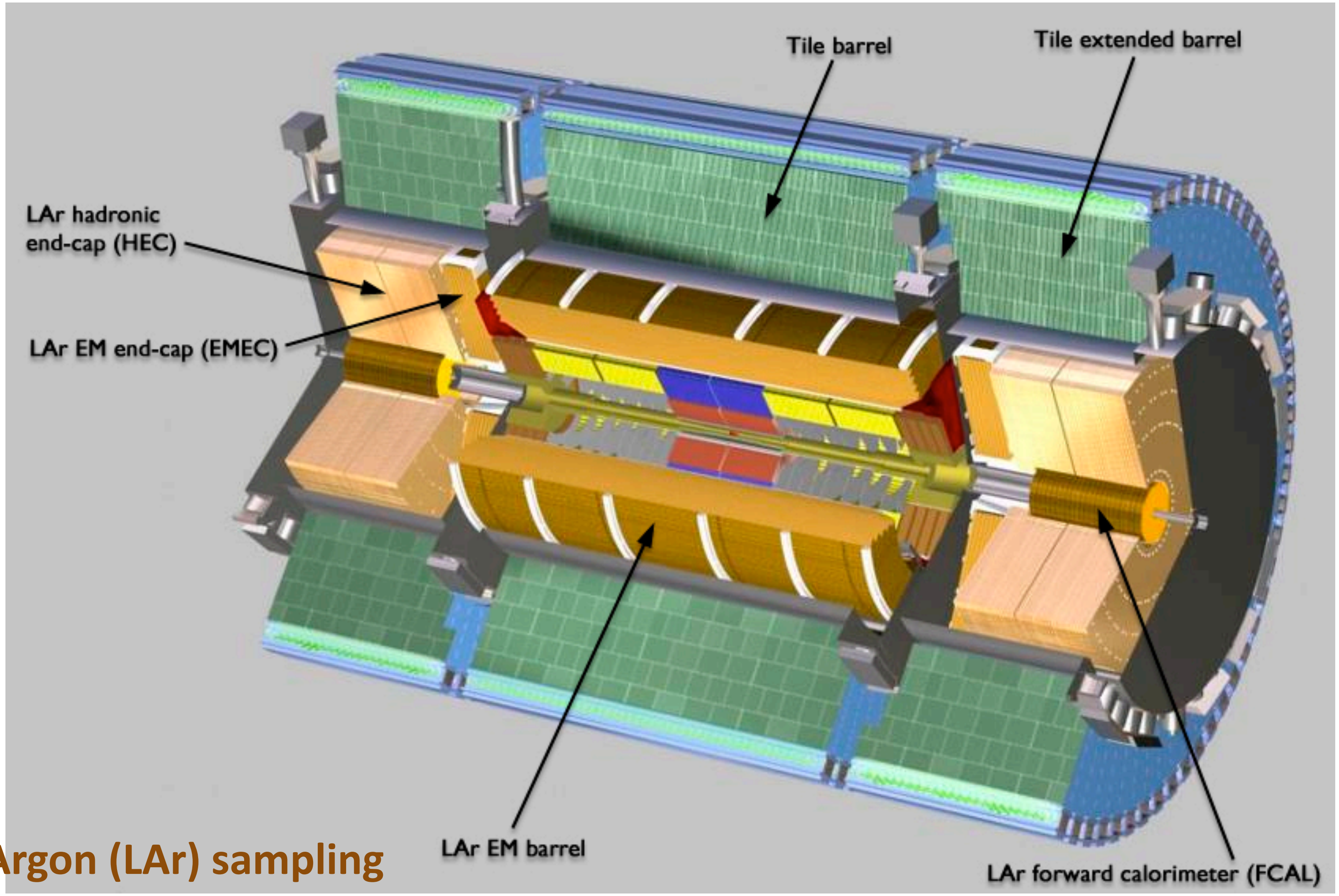
Sower size (containement) ~ Ln(E)

Calorimeters can be based on different detection techniques

Scintillators, ionization, cerenkov etc.



The ATLAS Calorimeter System



Liquid Argon (LAr) sampling

- **EM Barrel (|η|<1.475 - Pb)**
- **EM EndCap (1.4<|η|<3.2 - Pb)**
- **HAD EndCap (1.5<|η|<3.2 - Cu)**
- **Forward (3.2<|η|<4.9 – Cu/W)**

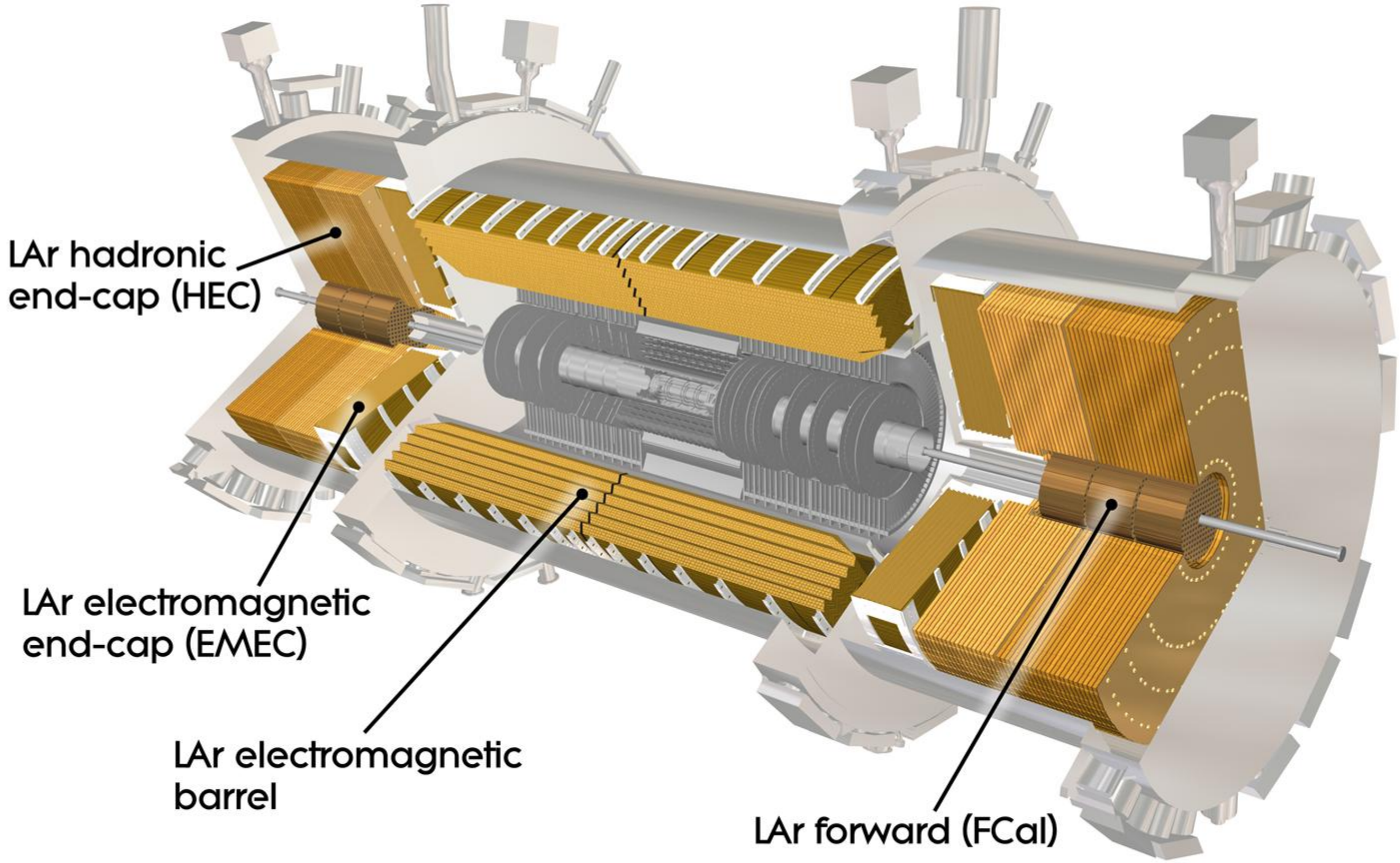
Scintillator Tiles/Steel sampling

- **HAD Barrel (||<1.0)**
- **HAD Extended Barrel (0.8<||<1.7)**

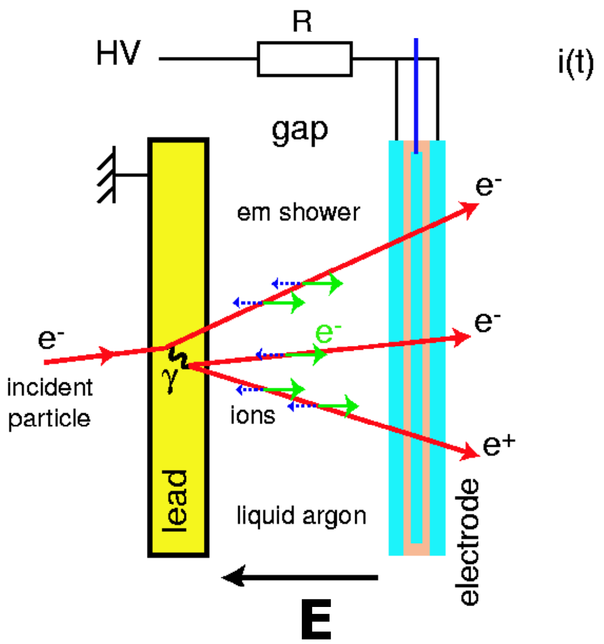
ATLAS LAr Calorimeter

Active material: Liquid Argon
Absorber: Pb (EMB)

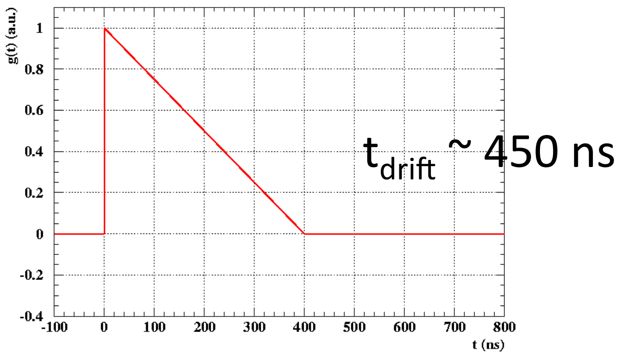
To keep argon in liquid phase the detector is kept at 88K by three big cryostats

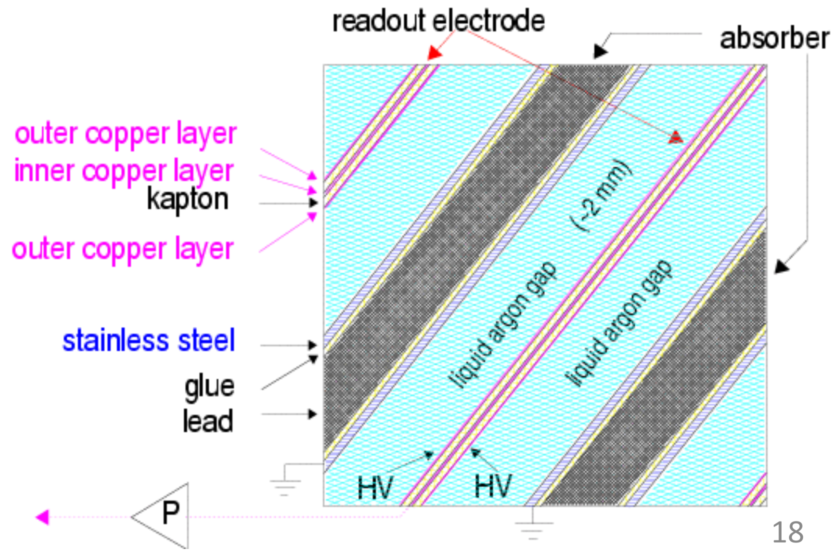


Principle of LAr/Pb calorimeter



- Interactions mainly in lead absorber
- Charged particles ionize Ar atoms
- Elecrons drift in the LAr gap where an electric field is applied
- Signal is induced on the read-out electrodes by the moving electrons
- Induced signals have a caracteristic triangular shape current peak ~ energy lost by particles



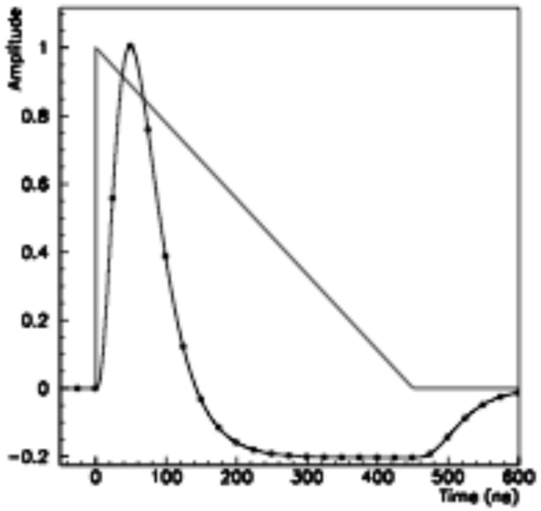


$$I(t) = \frac{dQ(t)}{dt} \propto Q_0\left(1 - \frac{v_d}{d}t\right)$$

ATLAS LAr EM Calorimeter

- Advantages of LAr as active material
  - Detector uniformity (easier calibration)
  - Linearity of the response (LAr high density → no electron amplification needed)
  - Stability with time
  - Radiation hard
  - High granularity possible (shaping)

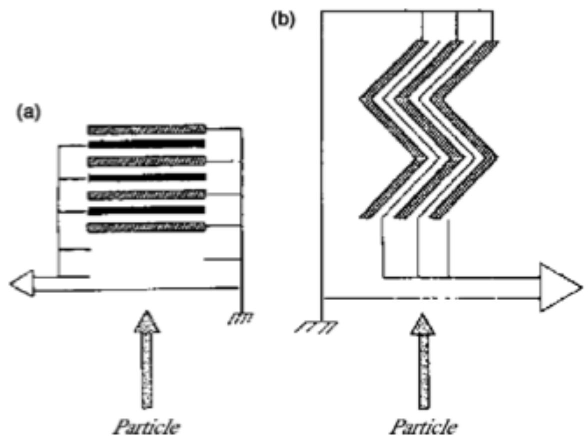
- Drawbacks
  - Sampling (but longitudinal segmentation possible)
  - Criogenics → difficult operation, additional dead material
  - 'Slow' charge collection: 450ns >> 25ns = LHC BC frequency



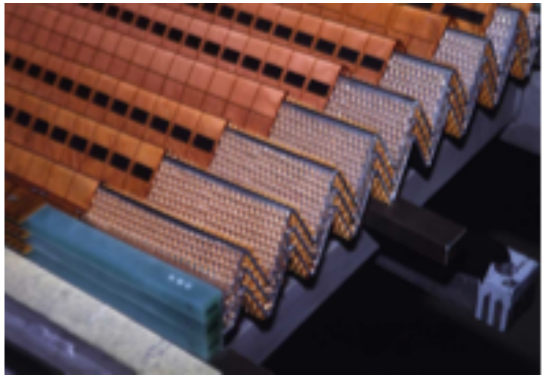
$t_d \gg \tau_{BC}$ but the energy information is given by the current peak
→ intergration of the signal over ~ 50ns
→ degradation of S/N
→ fast signal extraction (from RO electrode to FE elx) needed

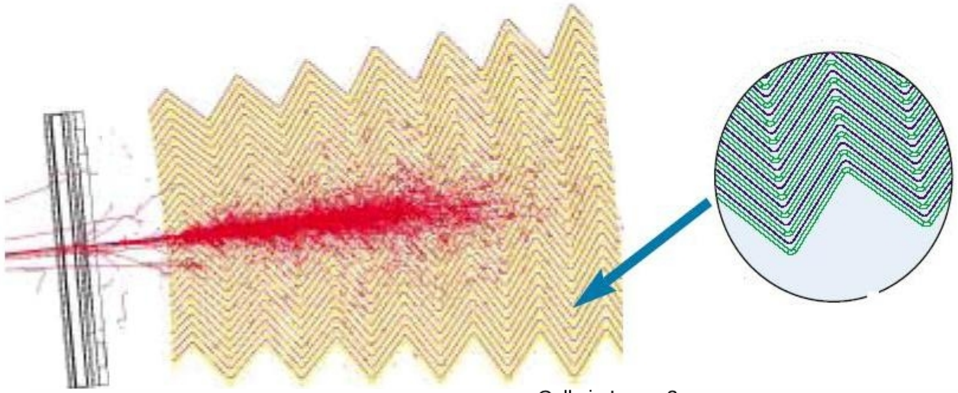
Solution: the accordion geometry

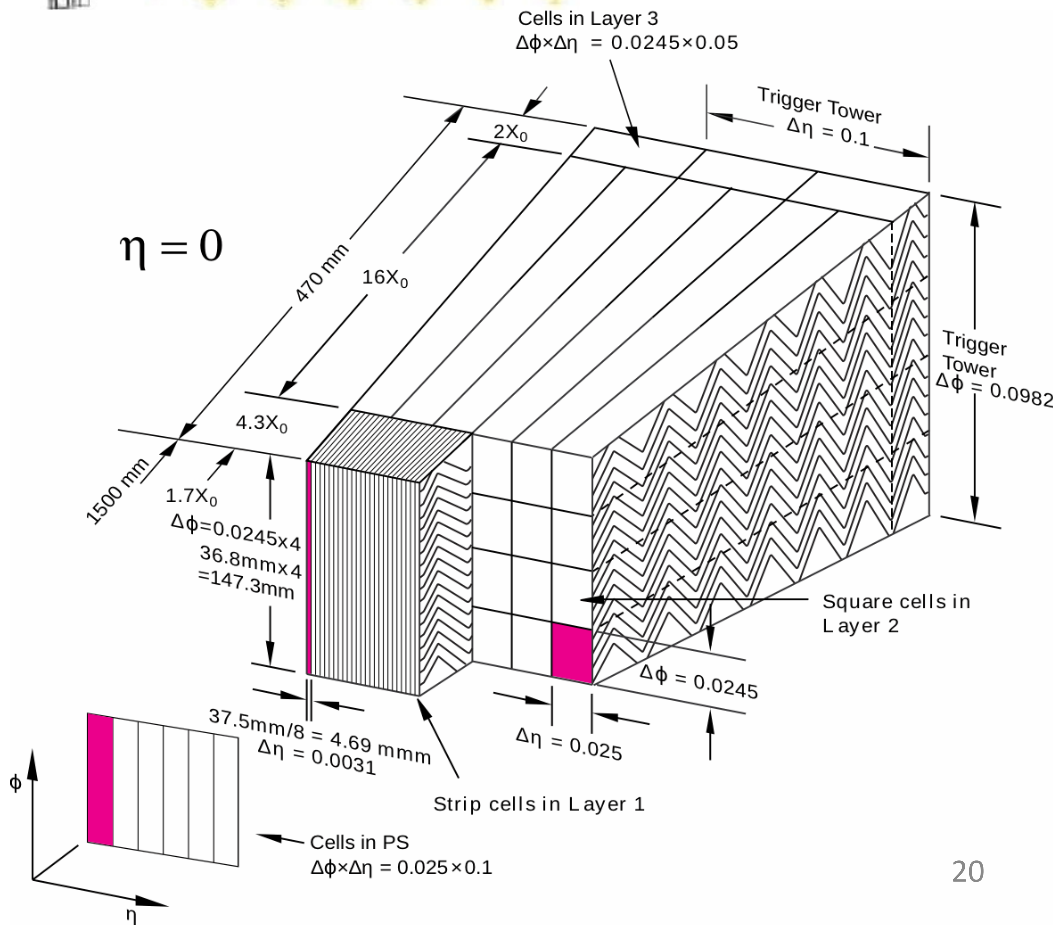
Additional advantages:
Ermiticity in phi: no cracks
High granularity
Capacitance reduction



ATLAS LAr EM calorimeter







Segmentation in (eta, phi)

Segmentation in depth, 3 layers:

- Strips, Middle, Back
- Strips highly segmented: good rejection π^0/γ

24 X_0 in total

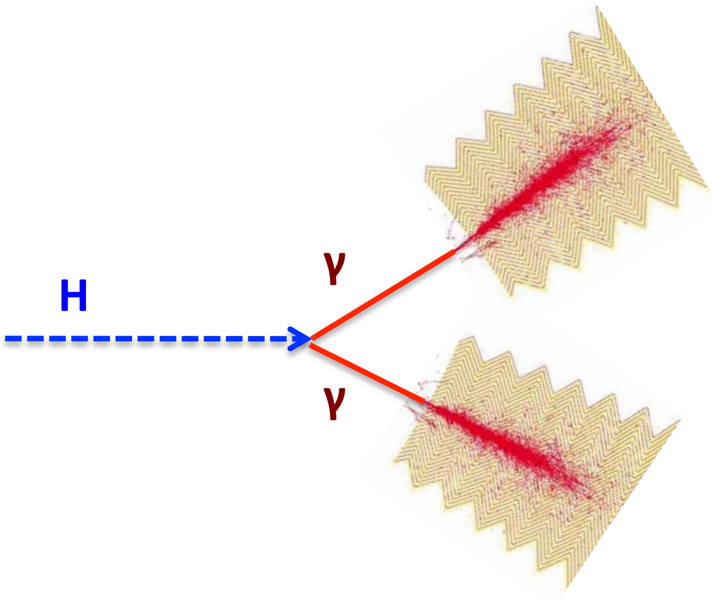
Presampler up to |eta| =1.8

Energy resolution:

$$\frac{\sigma(\mathbf{E})}{\mathbf{E}} = \frac{10\%}{\sqrt{\mathbf{E}}} \oplus 0.7\%$$

EM calo benchmarg: H→gg

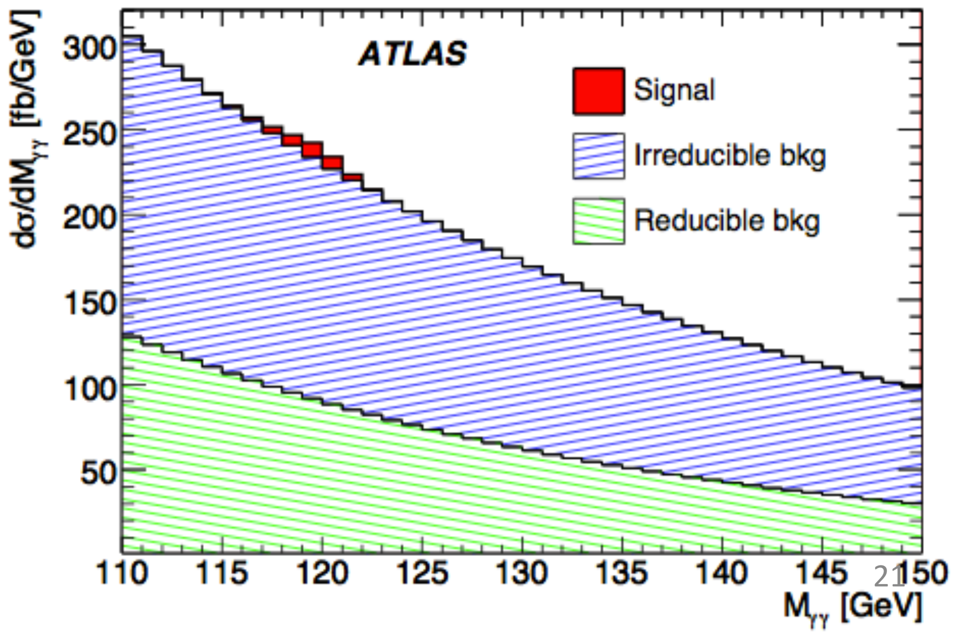
- BR(H→gg) ≈ 2•10^{-3}at m_H=120GeV
- But a very clean channel (and possibly the best one at small masses)



$$m_{\gamma\gamma} = 2E_1E_2(1 - \cos\theta_{\gamma\gamma})$$

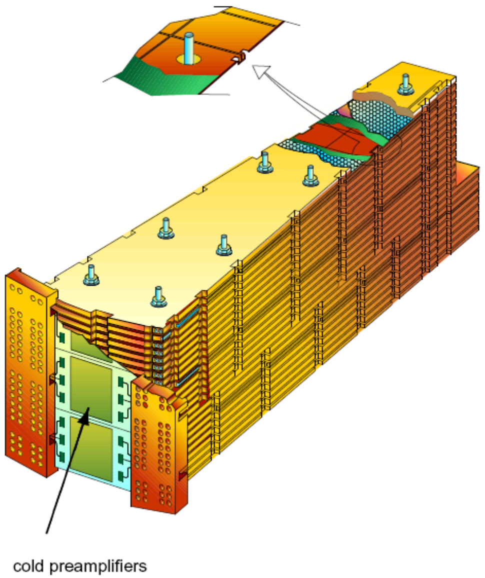
$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{1}{2}\sqrt{\left(\frac{\sigma_1}{E_1}\right)^2 + \left(\frac{\sigma_2}{E_2}\right)^2 + \left(\frac{\sigma_\theta}{\tan(\theta/2)}\right)^2}$$

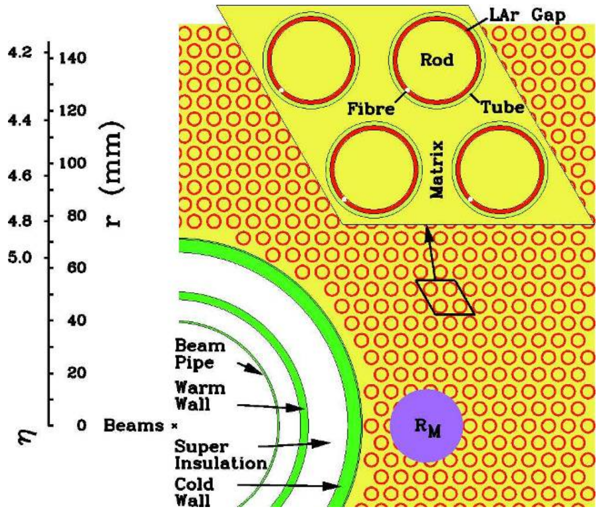
To achieve a good invariant mass resolution on $m_{\gamma\gamma}$ good energy and angular resolutions are needed

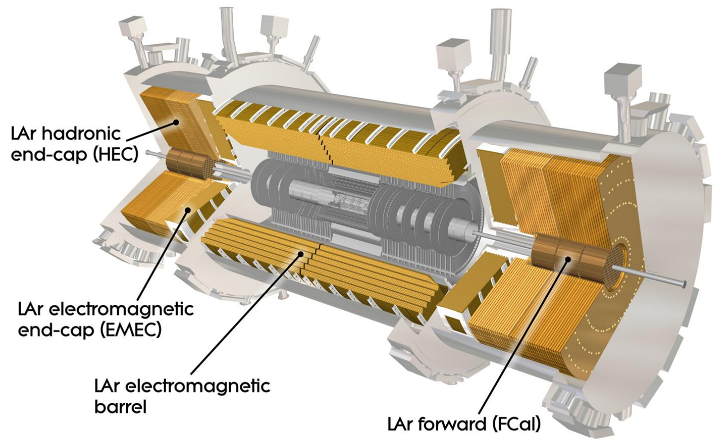


Lar HCAL and FCAL

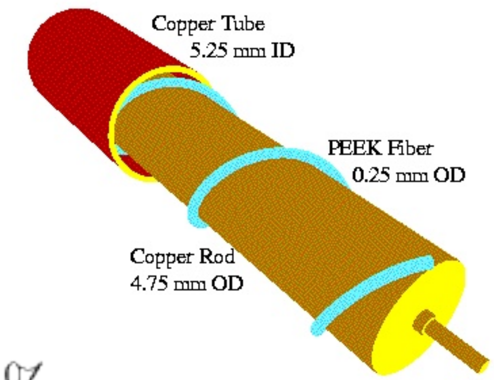
- Same principle as EM but different geometries and absorbers





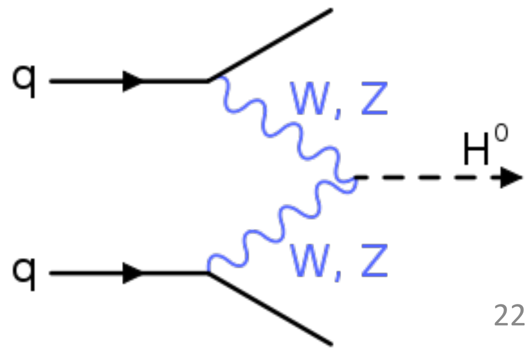


HEC $$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$$

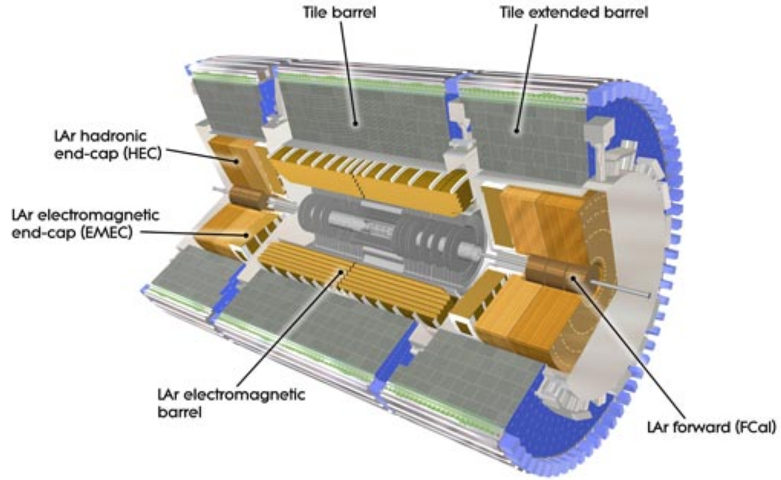


FCAL: important for detection of forward 'jets', e.g. in VBF higgs production

FCAL $$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$$



ATLAS Tile Calorimeter

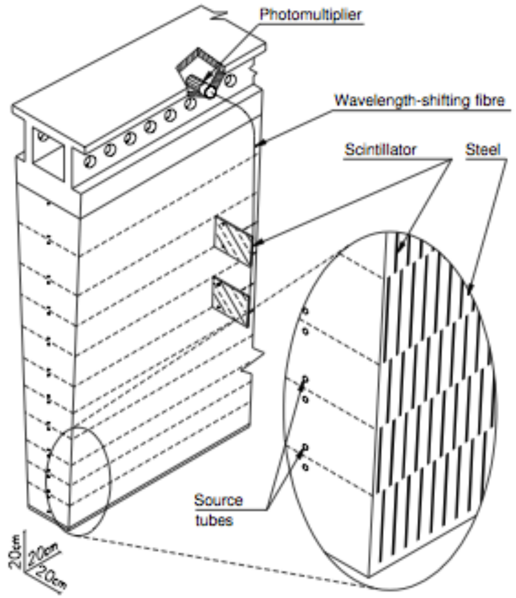


Unconventional geometry: absorber plates (steel) and scintillating tiles oriented along the direction of the incident particles:

→ homogeneous sensitivity

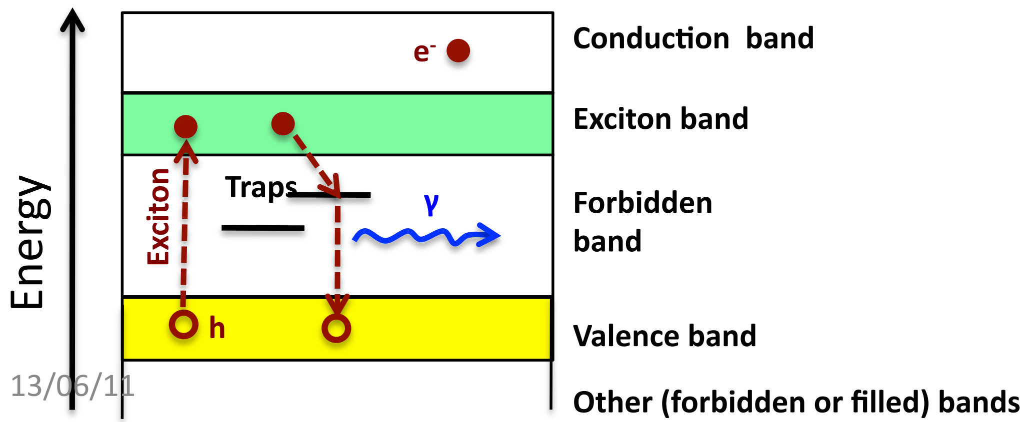
→ hermiticity in phi

→ economic construction



Scintillators (crystals):

- incident charged particles create electron-hole pairs
- photons are emitted when electrons return to the valence band
- the incident electron or photon is completely absorbed
- the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors



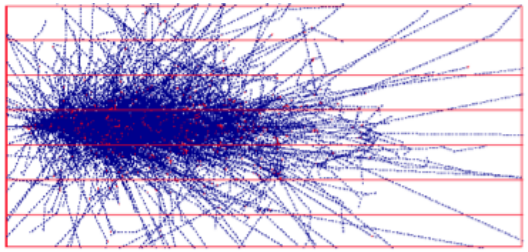
$$\frac{\sigma(\mathrm{E})}{\mathrm{E}} = \frac{53\%}{\sqrt{\mathrm{E}}} \oplus 6\%$$

Measured objects

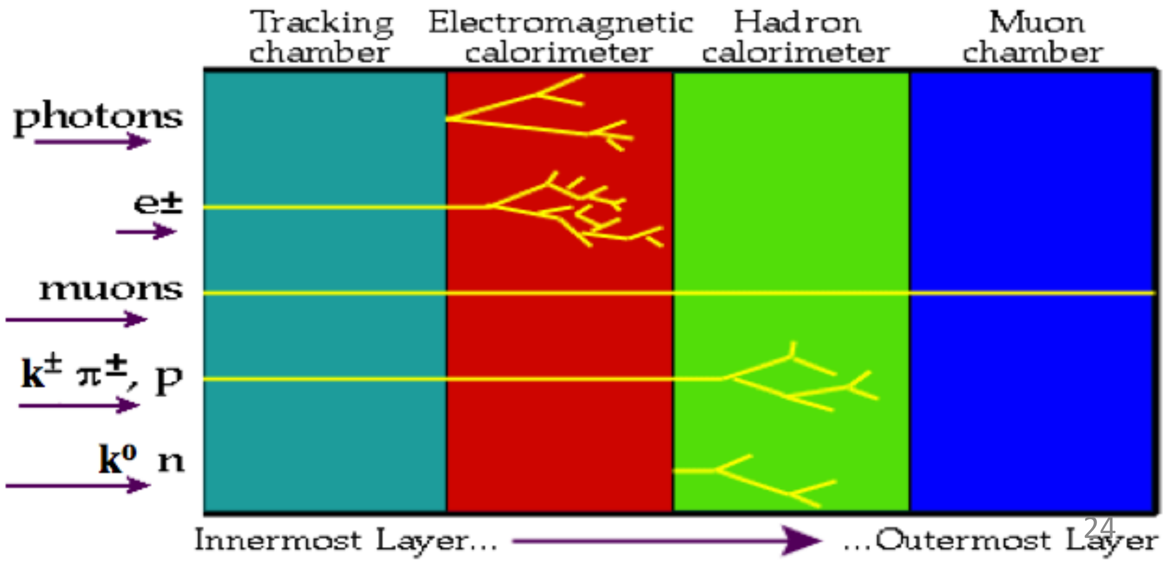
- So far we have discussed about e^+, e^-, γ, n, p, π…
- From the point of view of the detected quantities we should rather talk of measured objects

Electromagnetic objects   Jets   MET

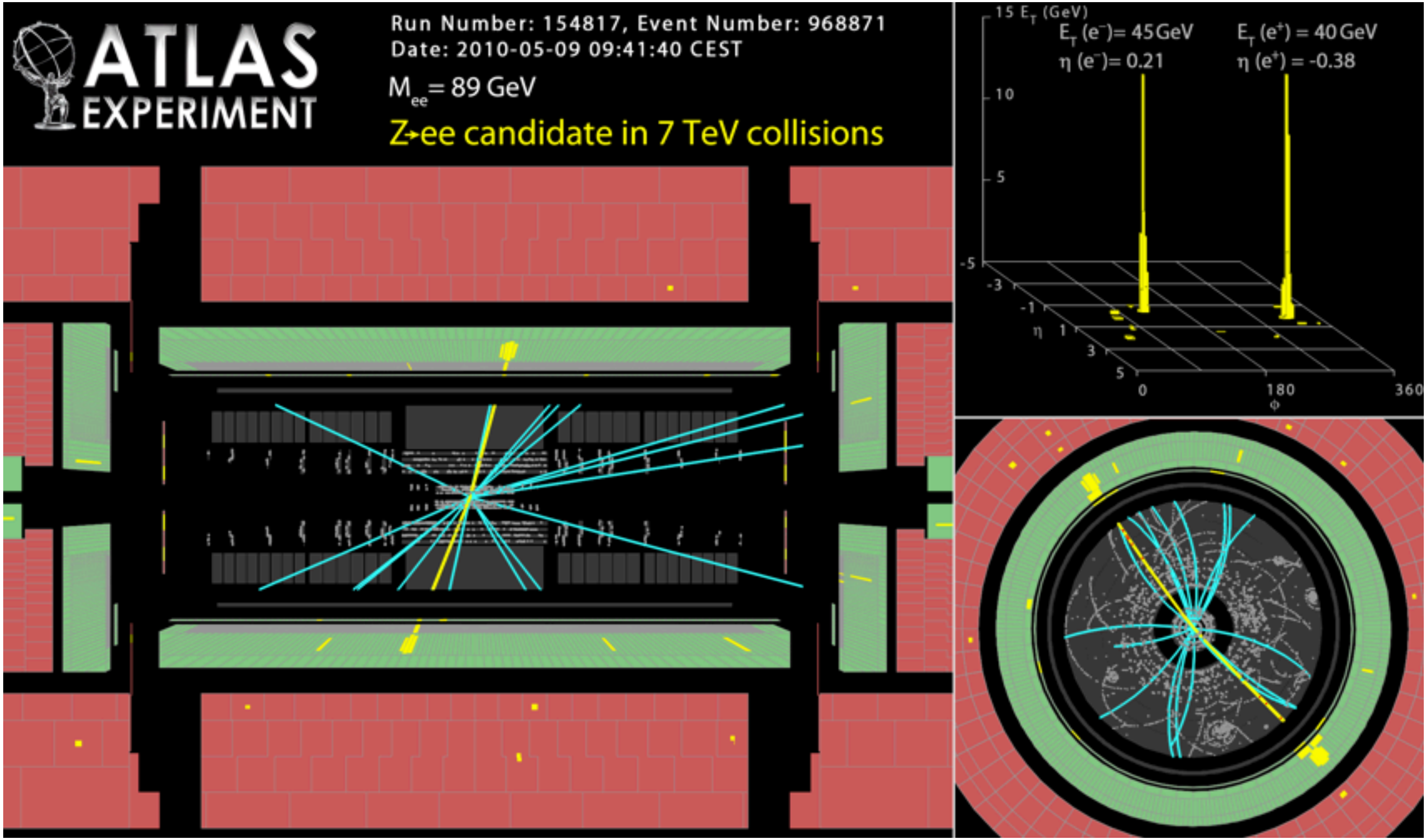
Electromagnetic objects:
- Measured by EM calo
- Electrons or photon
- EM calo cannot distinguish electrons from photons
- Need a match with ID charged tracks



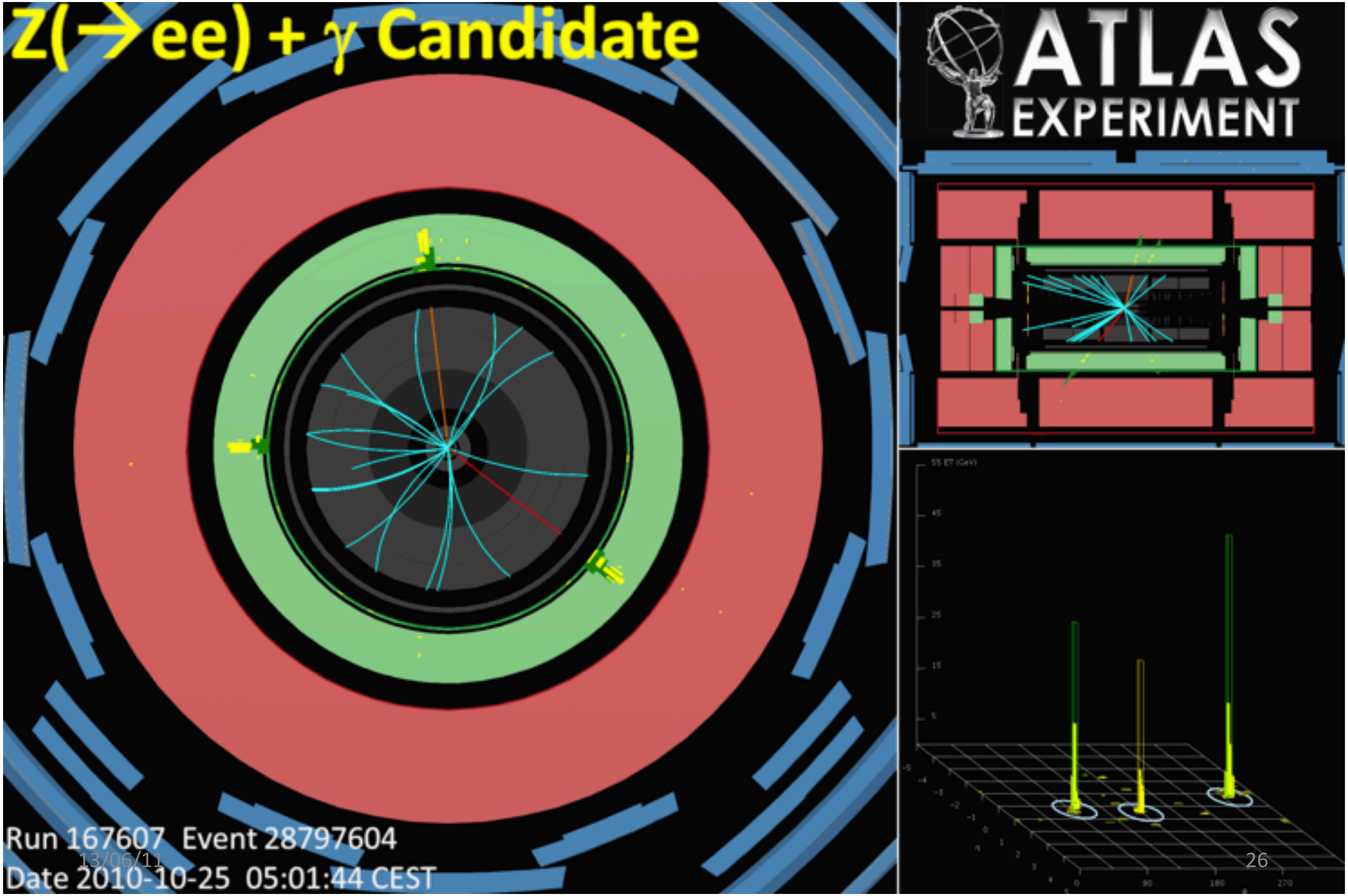
EM objects



$Z \rightarrow e^+e^-$



$Z(\rightarrow e^+e^-) + \gamma$

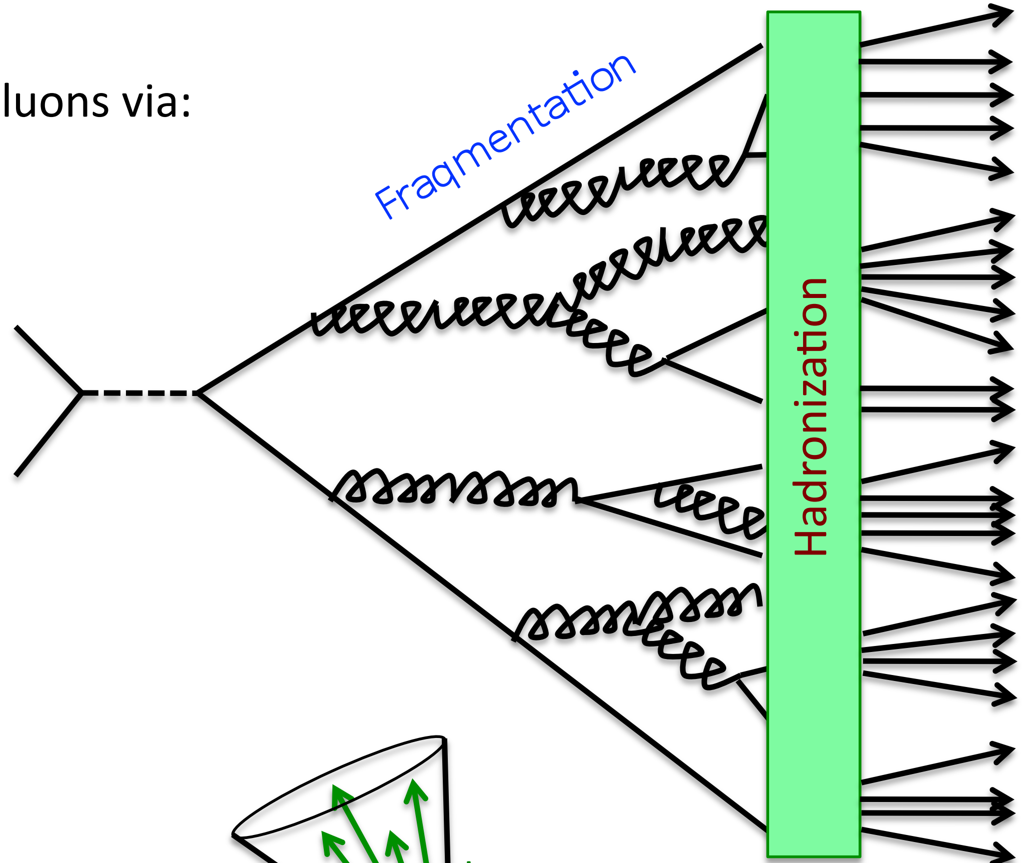


Jets

- Cluster of multiparticles generated by a quark or gluon
- Measured by HAD calo
- Hadrons are formed from quarks or gluons via:

Fragmentation

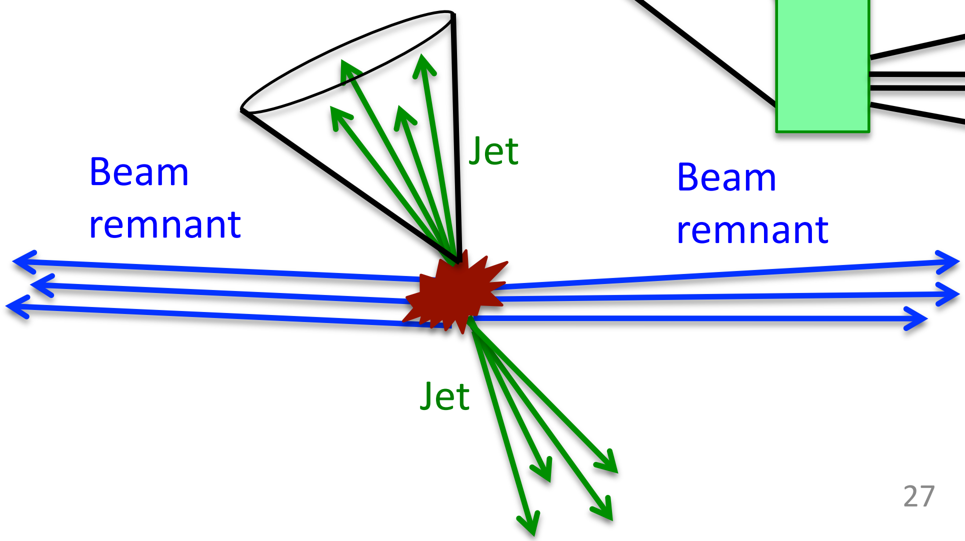
QCD radiation q→gq, g→gg and g→qq
Almost collinear



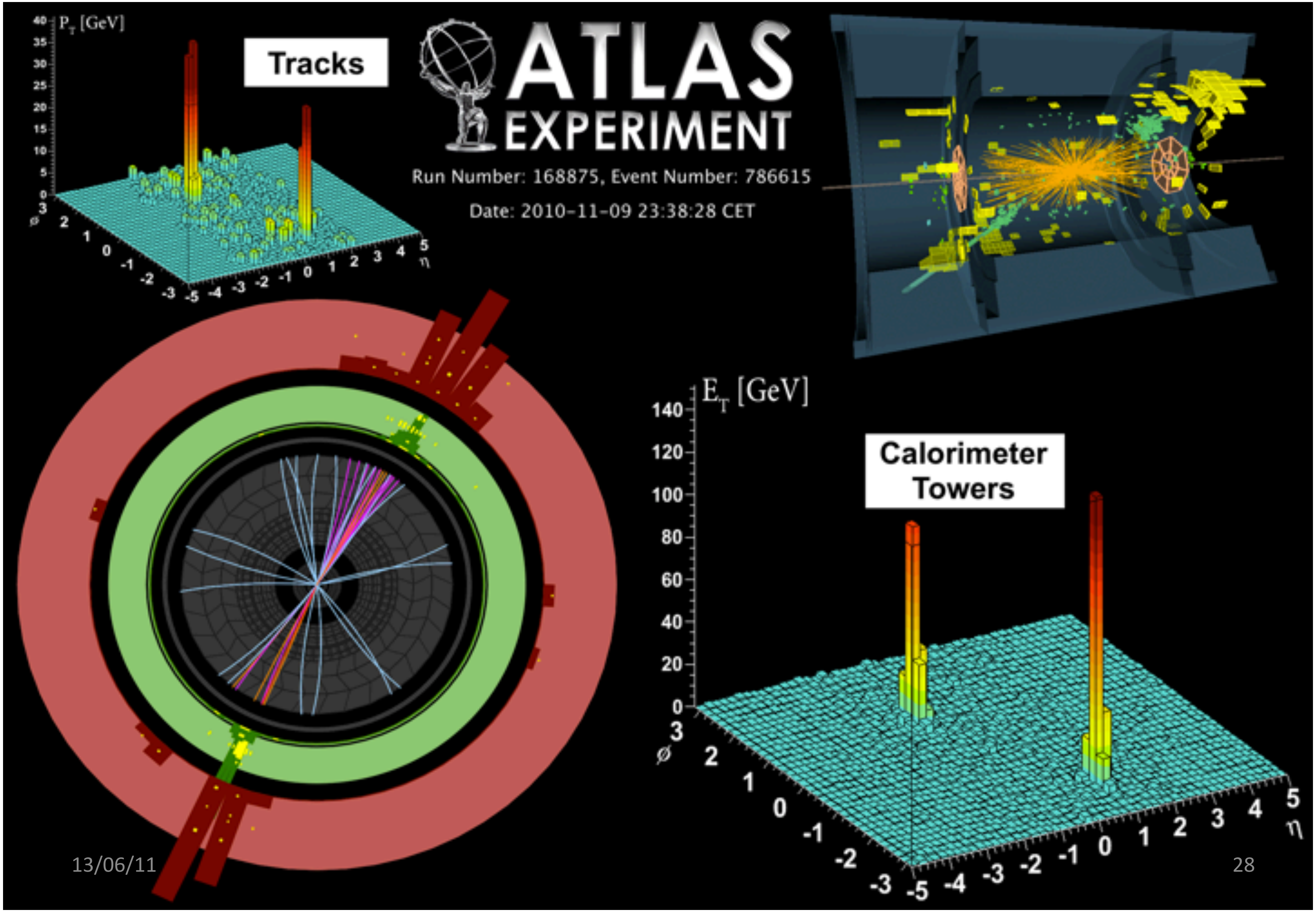
Hadronization

Final step of hardons (colorless) formation
Real QCD radiation becomes disfavuored

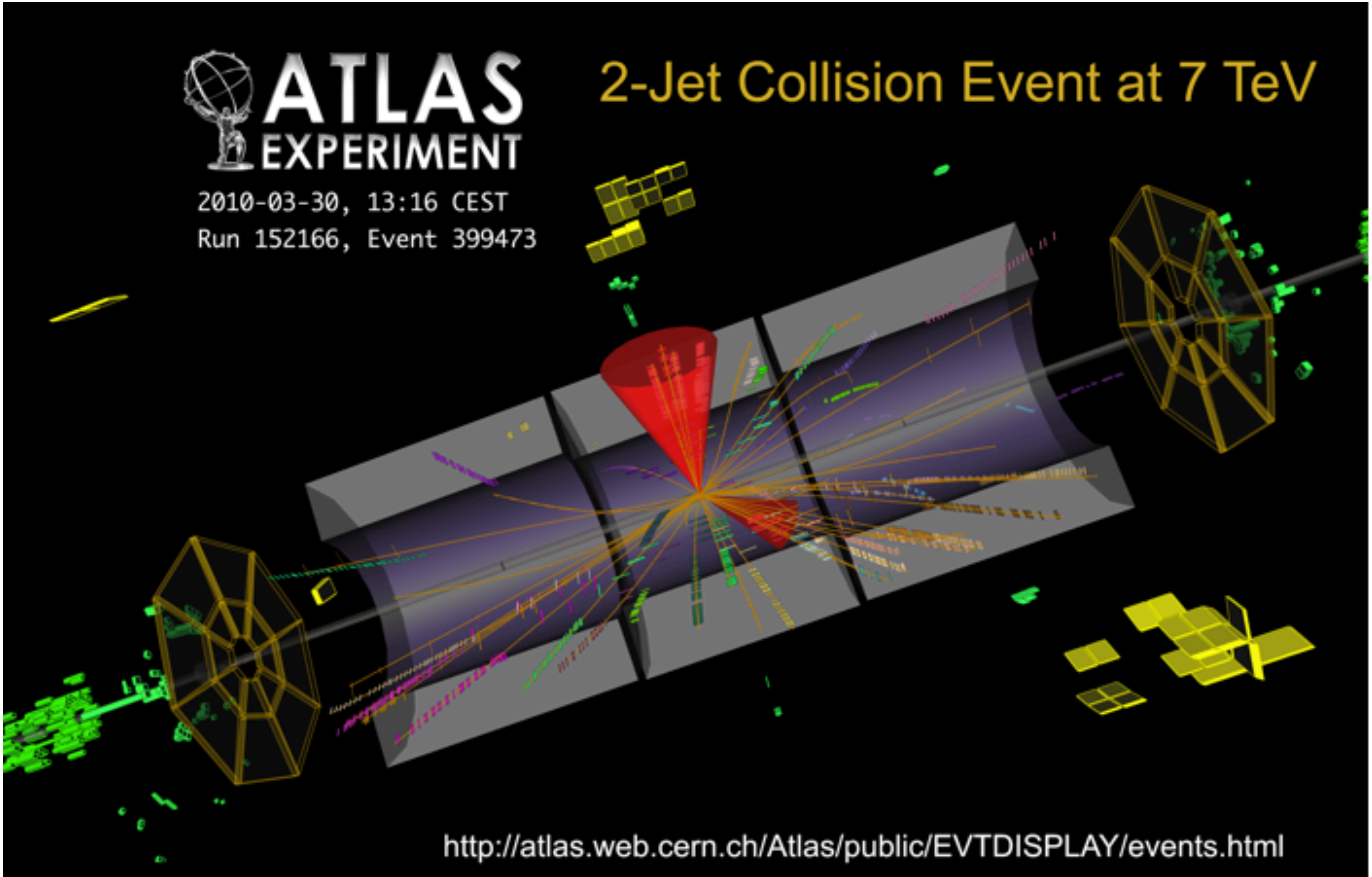
Hadrons created from single q or g are almost collinear → jet
Jets are reconstructed as energy deposit in a 'small' cone



2 symmetric jets in Pb-Pb collision

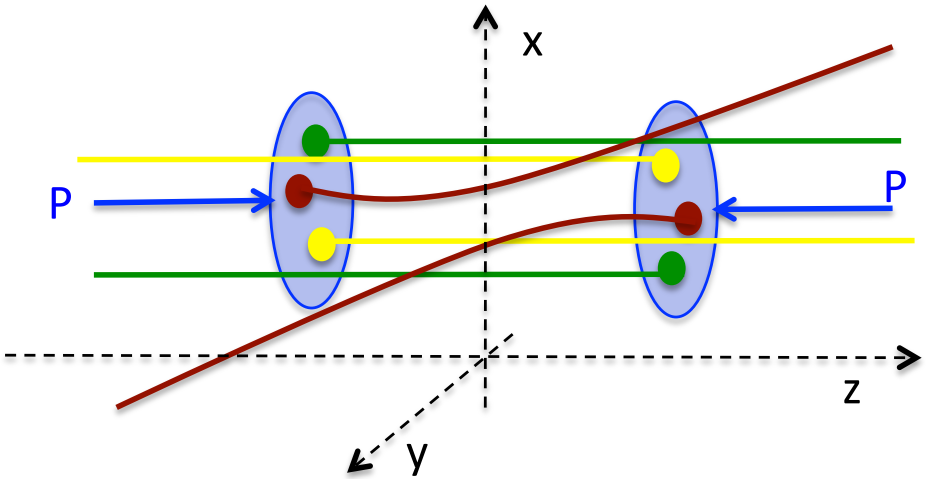


2-jet event in p-p collision



MET (Missing E_T)

- By measuring the 'visible' energy of the event one can reconstruct the energy carried by invisible objects (neutrinos, but also LSP in SUSY etc.)
- In hadron colliders we don't know the initial energy of the interacting partons
- We do know that in transverse plane (to the protons momentum) the initial energy is negligible (on average p_T^{parton} < ~300MeV)
- We can balance the energy of the event in the transverse plane (x-y in ATLAS convention)



$$E_x^{missCalo} = -\sum_{i=1}^{N_{cell}} E_i \sin\theta_i \cos\phi_i$$

$$E_y^{missCalo} = -\sum_{i=1}^{N_{cell}} E_i \sin\theta_i \sin\phi_i$$

$$E_{x(y)}^{miss} = E_{x(y)}^{missCalo} + E_{x(y)}^{missMuon}$$

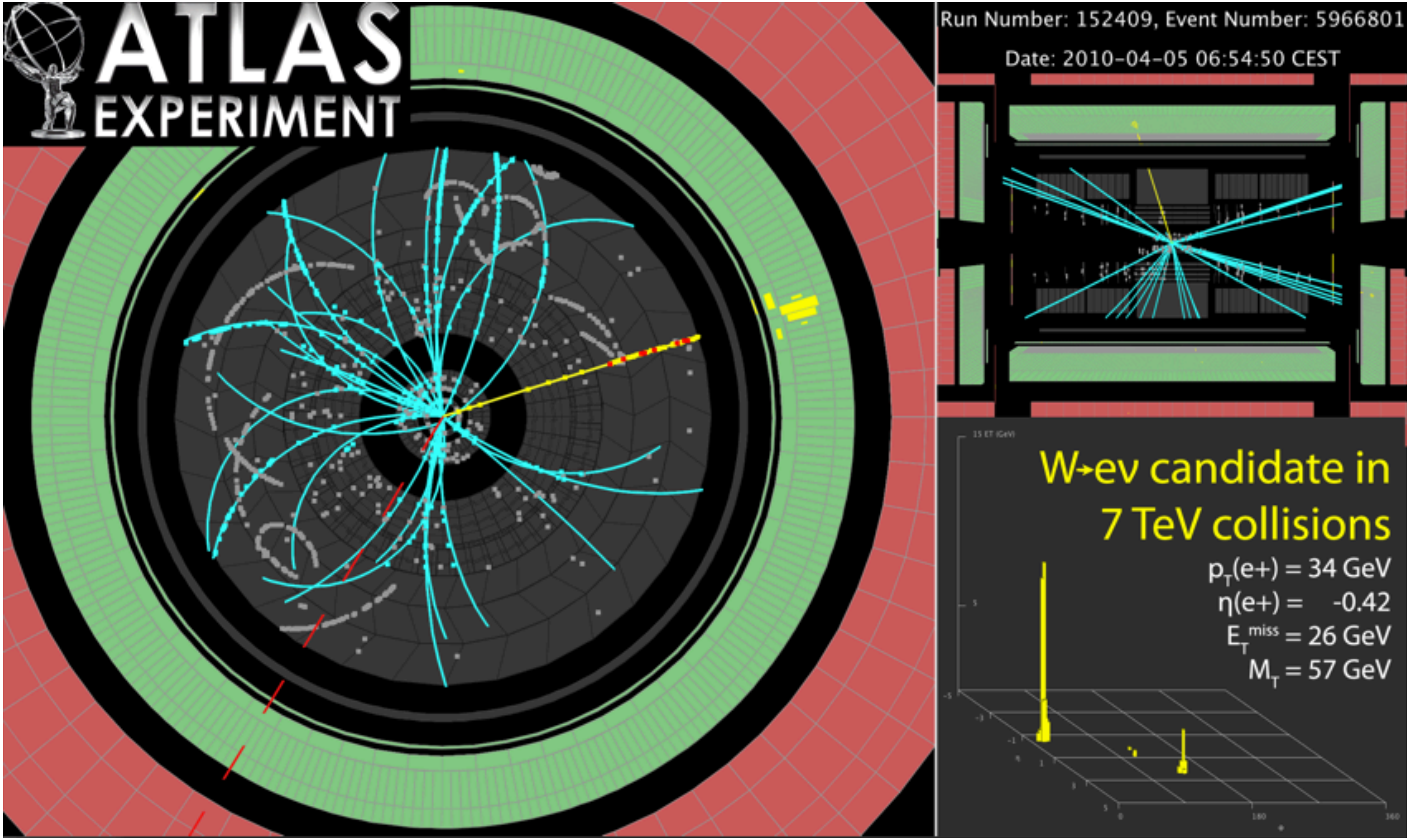
$$E_T^{miss} = \sqrt{(E_x^{miss})^2 + (E_y^{miss})^2}$$

E_x^{miss} and E_y^{miss} are normally distributed

E_T^{miss} follows a Rayleigh distribution:

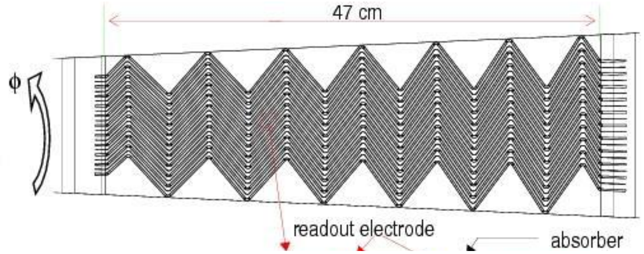
$$f(r) = \frac{r}{\sigma^2}\exp(-\frac{r^2}{2\sigma^2})$$

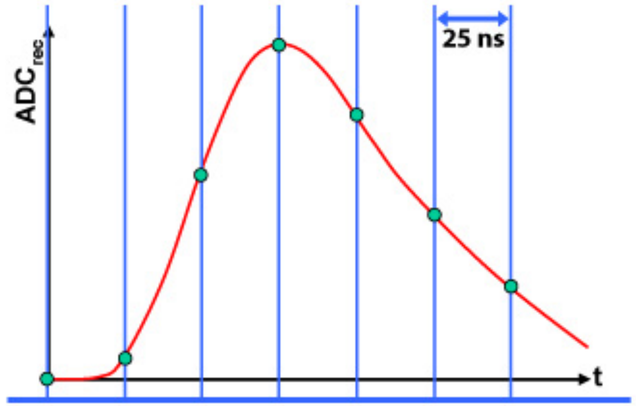
W→eν

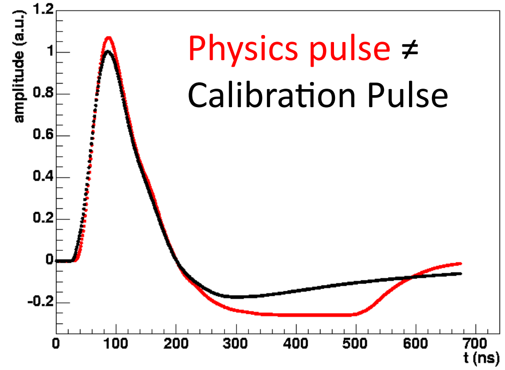

ATLAS
EXPERIMENT
Run Number: 152409, Event Number: 5966801
Date: 2010-04-05 06:54:50 CEST
W→eν candidate in
7 TeV collisions
p_T(e+) = 34 GeV
η(e+) = -0.42
E_T^miss = 26 GeV
M_T = 57 GeV

From digit to raw cell energy

- Signal pulse of the ATLAS calormeters are sampled every 25ns (LHC bunch crossing frequency)
- Normally 5 samples around the peak are stored
- Peak is reconstructed from ADC value of the samples → Optimal Filtering
- From peak value to current induced in the detector → calibration
- From measured current to deposited energy → sampling fraction



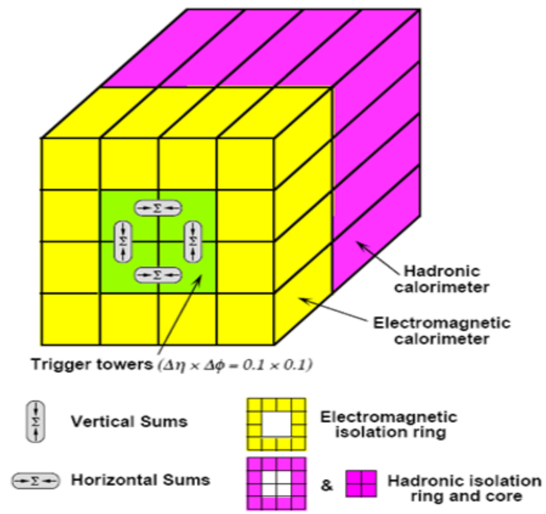




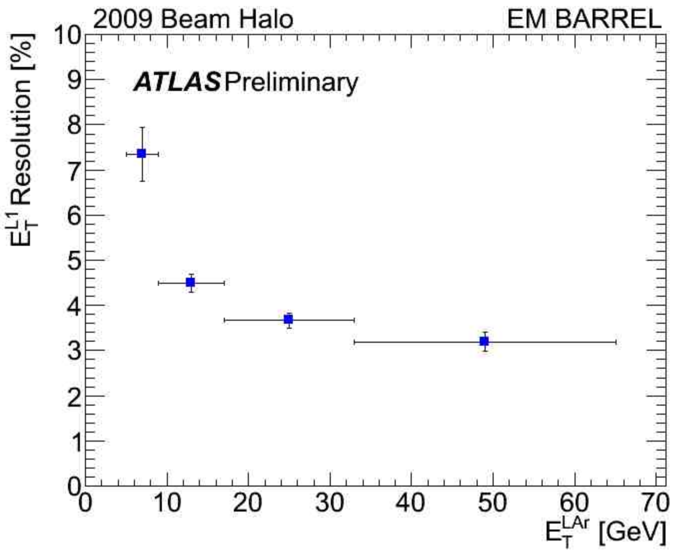
$$E_{\text{cell}} = F_{\mu\text{A}\to\text{MeV}} \cdot F_{DAC\to\mu\text{A}} \cdot \frac{1}{\frac{\text{M}_{\text{phys}}}{\text{M}_{\text{cali}}}} \sum_{i=1}^{M_{\text{ramps}}} R_i \left[\sum_{j=1}^{N_{\text{samples}}} a_j \left(s_j - p \right) \right]^i$$

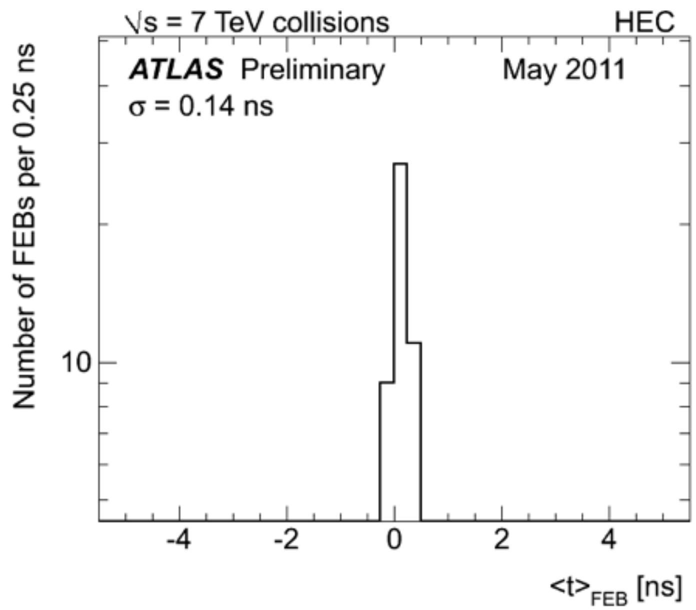
Trigger

- Calorimeters provide a fast and precise signal
- Suited to be used for trigger information
- Time resolution of ATLAS LAr calo: O(100ps)



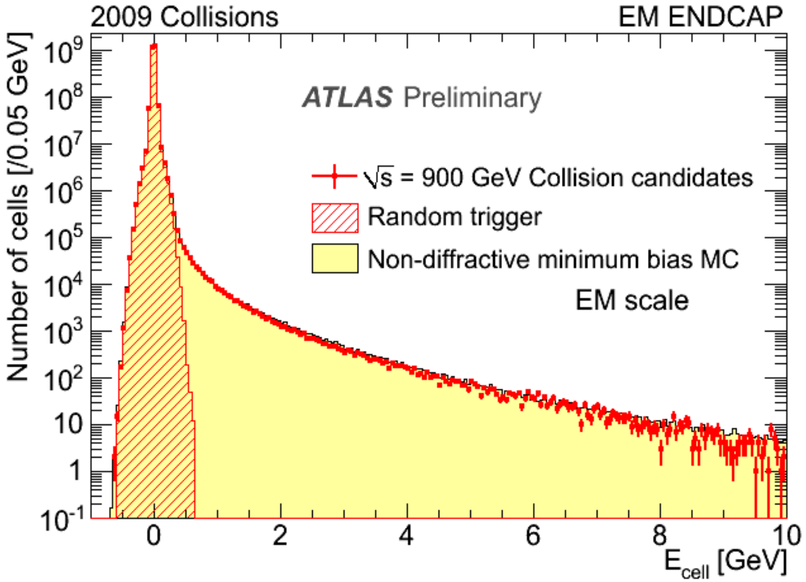
LVL1 Calo trigger based on the energy sum of cells belonging to a trigger tower reconstructed online
1TT = $0.1\times0.1\ \eta\times\varphi$

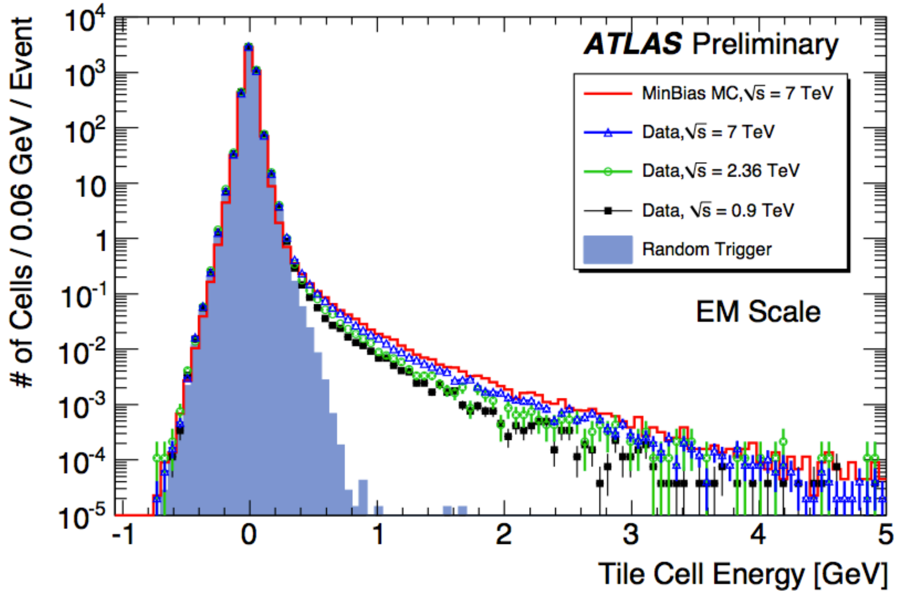




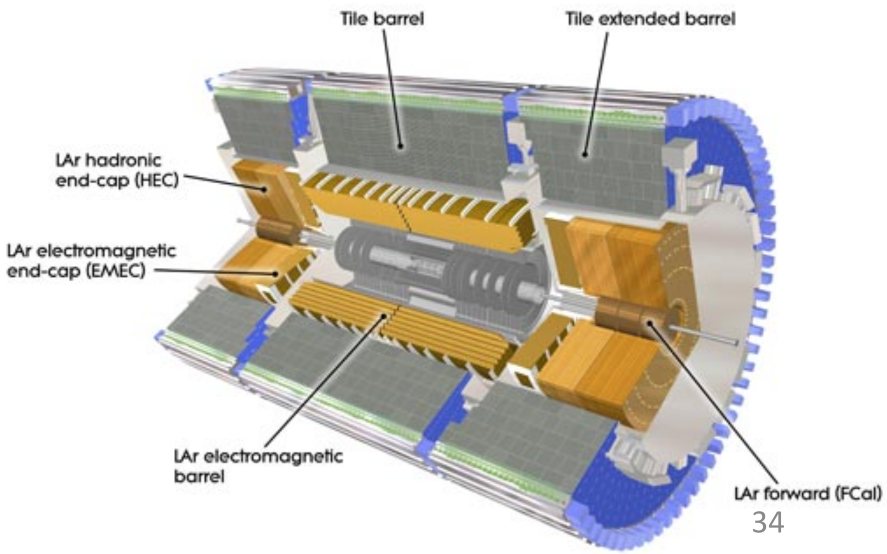
E^{L1}_T resolution as function of E^{LAr}_T
Requirement of <5% resolution at E>10 GeV

Calo cell energy distribution





- Good agreement between data and MC
- No correction for dead material applied on the individual cells



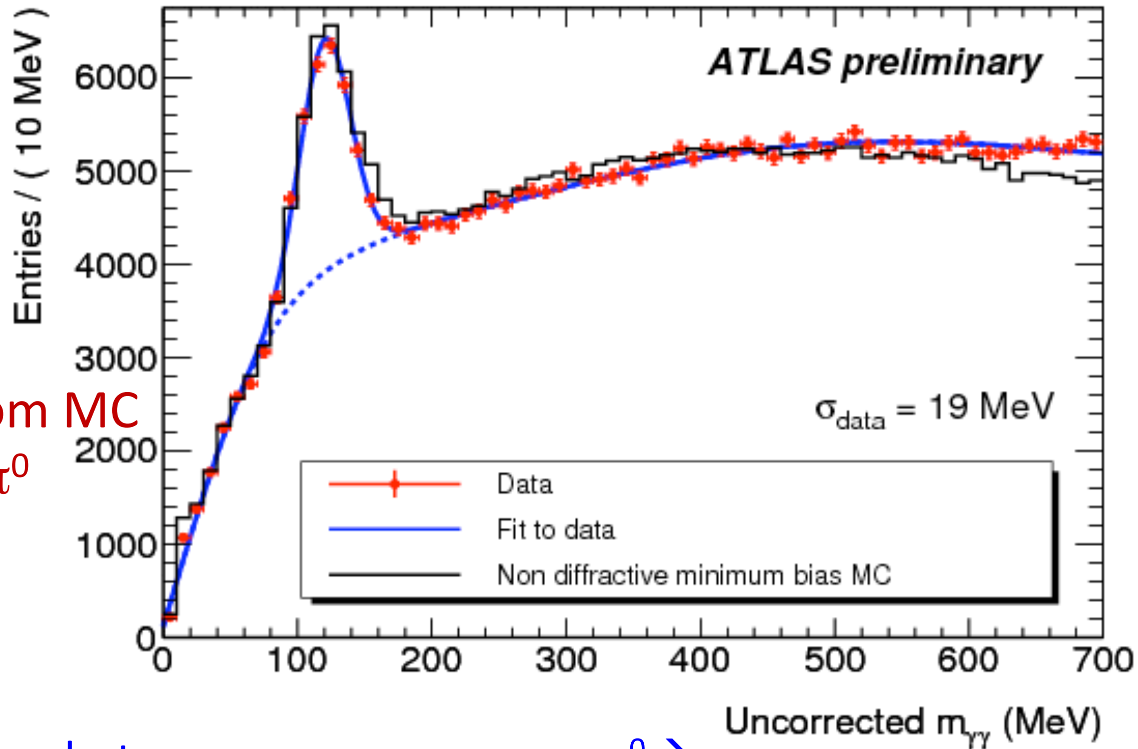
π^0 signal

$\pi^0 \rightarrow \gamma\gamma$

E_T(EM cluster) > 300 MeV

E_T(π^0 candidate) > 900 MeV

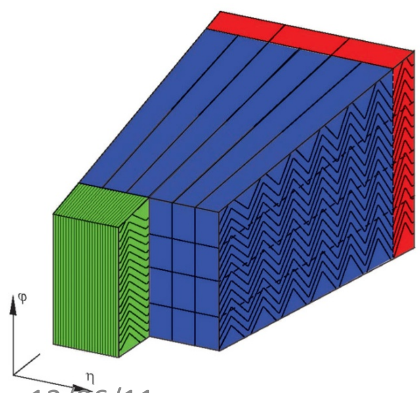
No correction for dead material



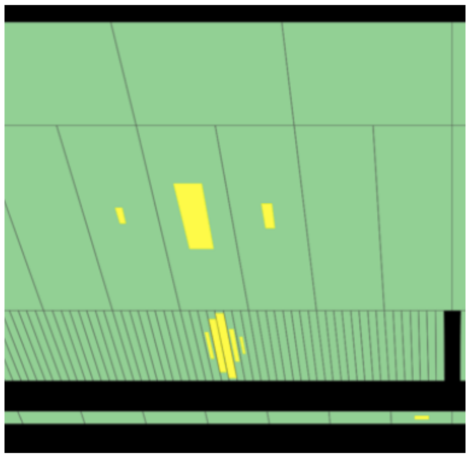
Resolution 19 MeV as expected from MC

LAr performs well in separating γ/π^0

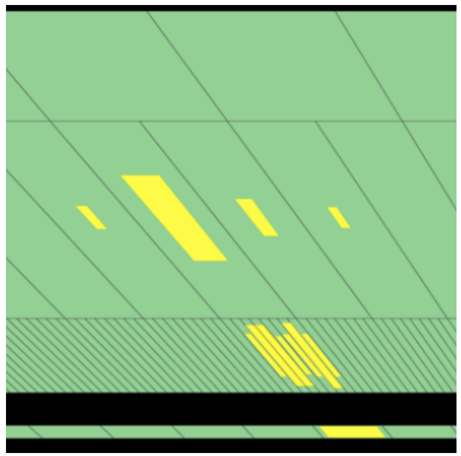
First EM layer highly segmented important for γ/π^0 separation



photon

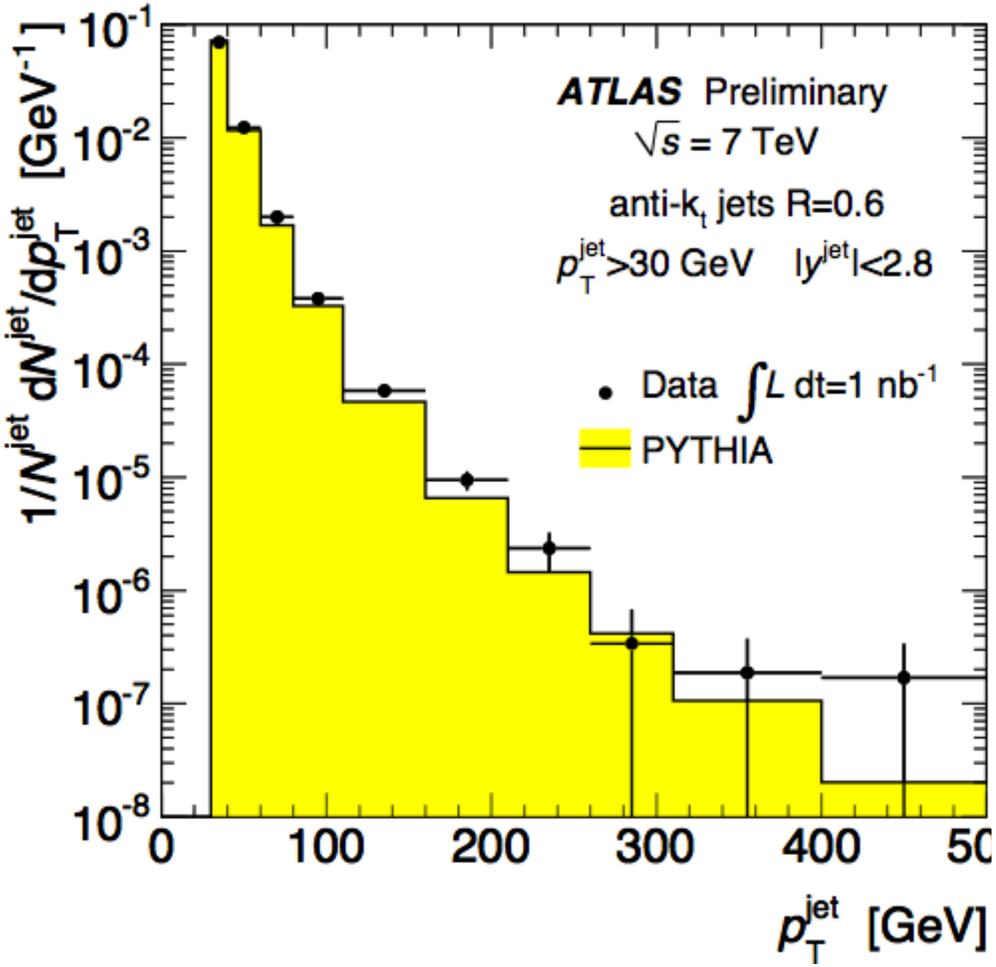


$\pi^0 \rightarrow \gamma\gamma$



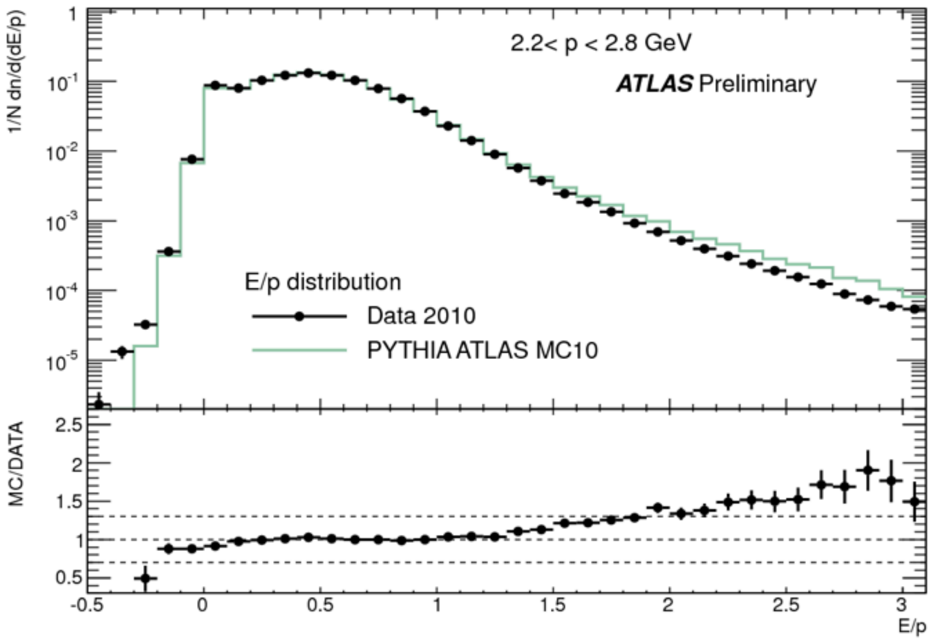
Jets

Jet transverse momentum distribution

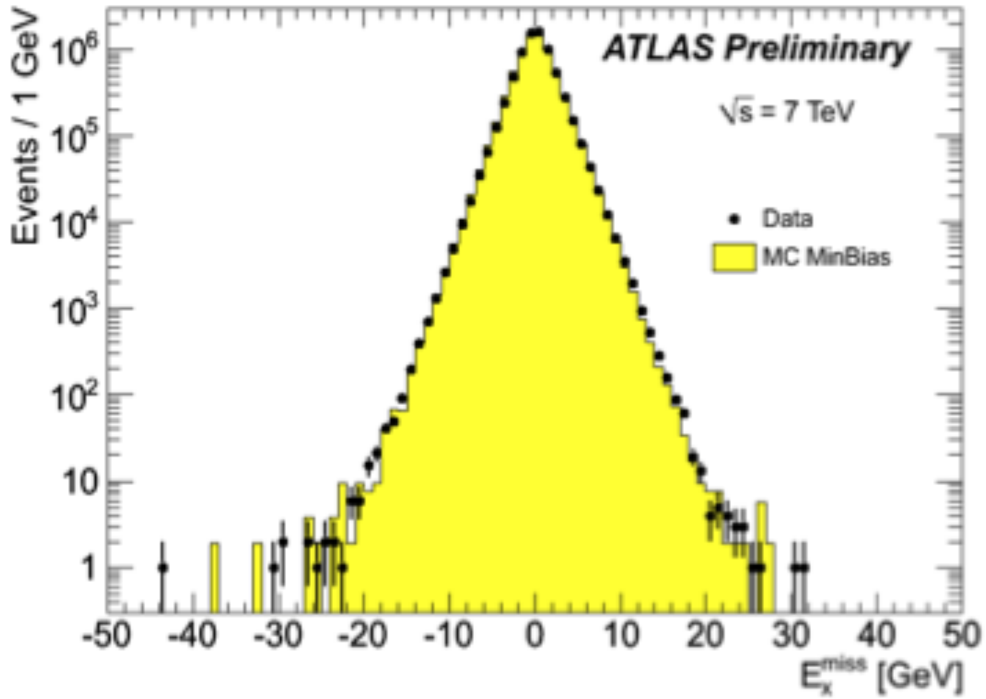


Jet reconstructed from clusters using AntiKt alg.
No calibration applied
Only cells in clusters are used (noise suppression)

E/p for isolated track (cone R<0.4)
With 0.5<pt<10 GeV
Only cells in clusters are used (noise suppression)



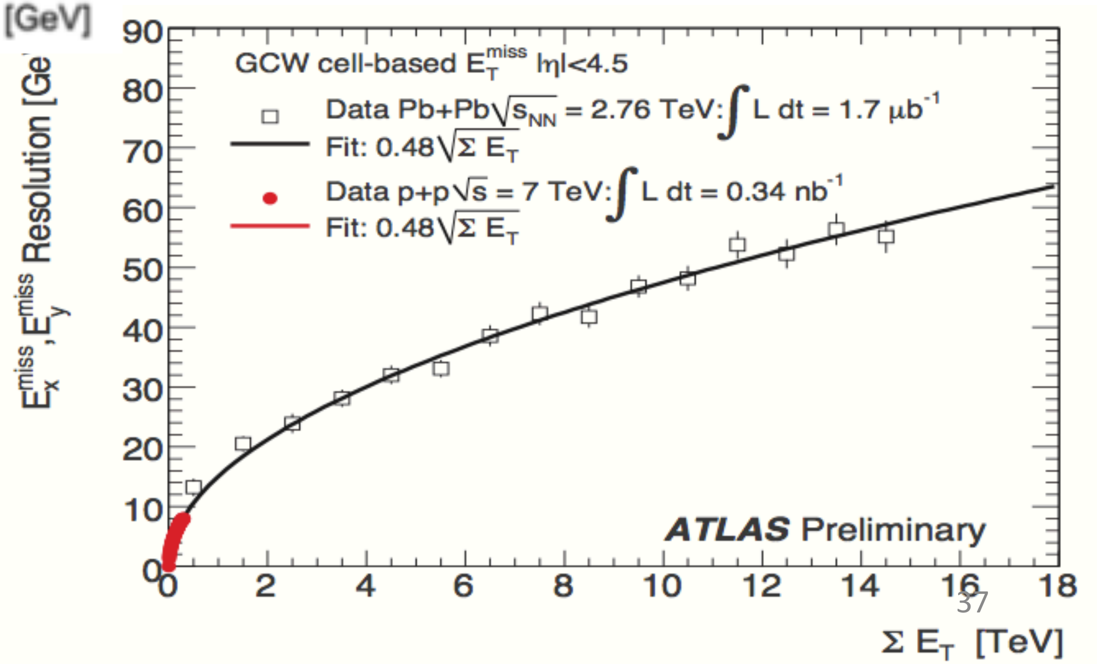
Missing E_T



Missing x-component transverse energy in collision data

No calibration applied
Only cells in clusters are used
(noise suppression)

MET resolution vs ∑Et



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- C. W. Fabjian and F. Giannotti «Calorimetry for particle physics», Reviews of Modern Physics, Vol. 75, Oct. 2003
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- ATLAS LAr TDR: http://atlas.web.cern.ch/Atlas/GROUPS/LIQARGEXT/TDR/Welcome.html
- ATLAS Tile TDR: http://atlas.web.cern.ch/Atlas/SUB_DETECTORS/TILE/TDR/TDR.html
- M. Diemoz, D. Fournier, R. Wigmans
  - Lectures at EDIT 2001: http://indico.cern.ch/conferenceDisplay.py?confId=124299