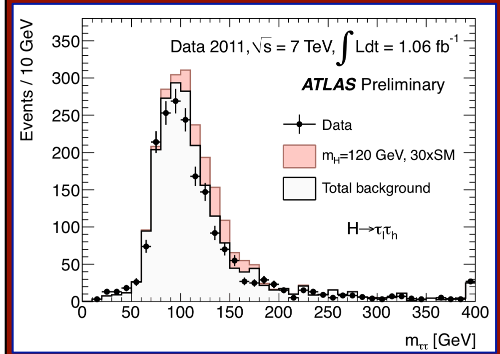
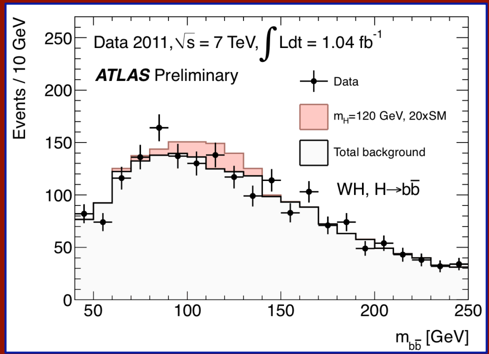
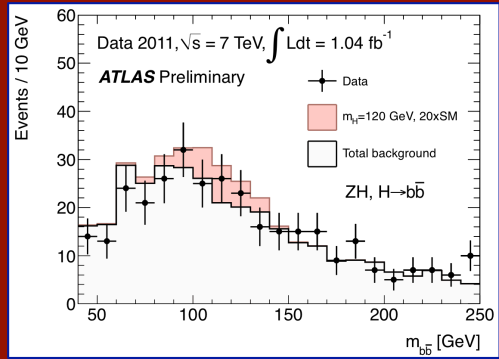
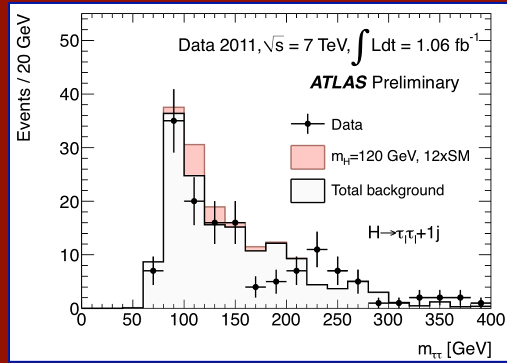


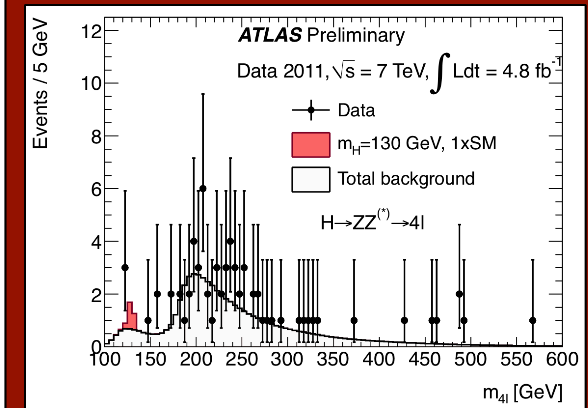


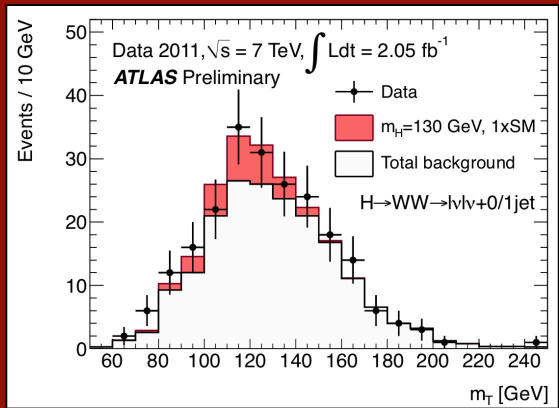


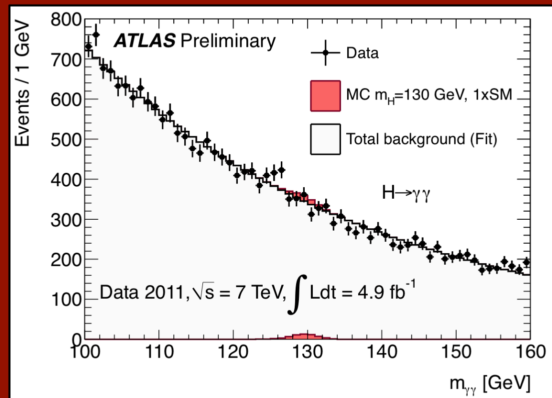


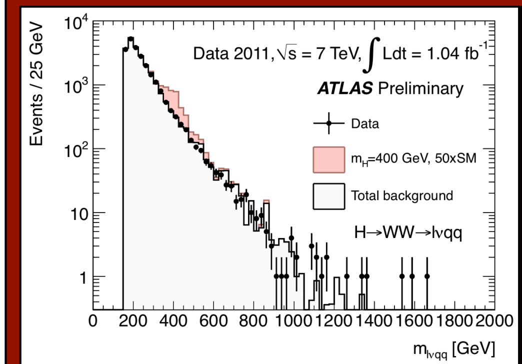
Update of Standard Model Higgs searches in ATLAS

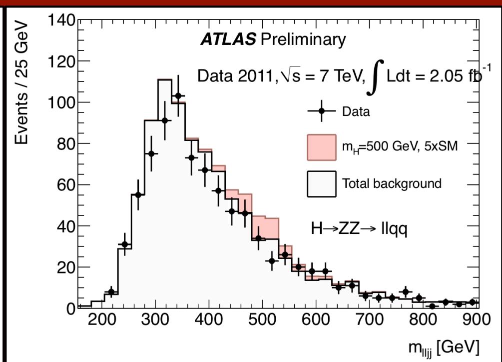
Fabiola Gianotti,
representing the
ATLAS Collaboration

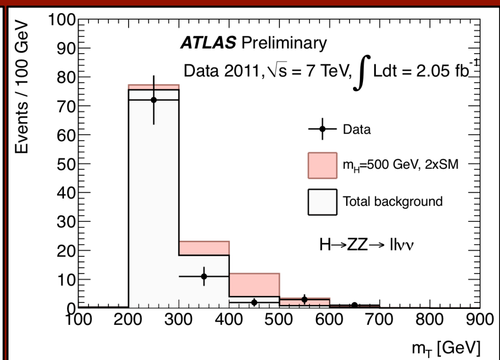


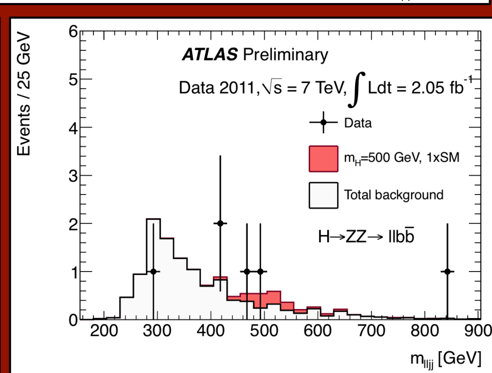












Higgs searches have guided the conception, design and technological choices of ATLAS and CMS:

- ❑ perhaps the primary LHC goal
- ❑ among the most challenging processes

→ have set some of the most stringent performance (hence technical) requirements: lepton identification, lepton energy/momentum resolution, b-tagging, E_T^{miss} measurement, forward-jet tagging, etc.

Proceedings of LHC Workshop (Aachen, 1990): H→ 4l signals
m_H=130, 150, 170 GeV
$\sqrt{s}$ = 16 TeV, 100 fb^{-1}

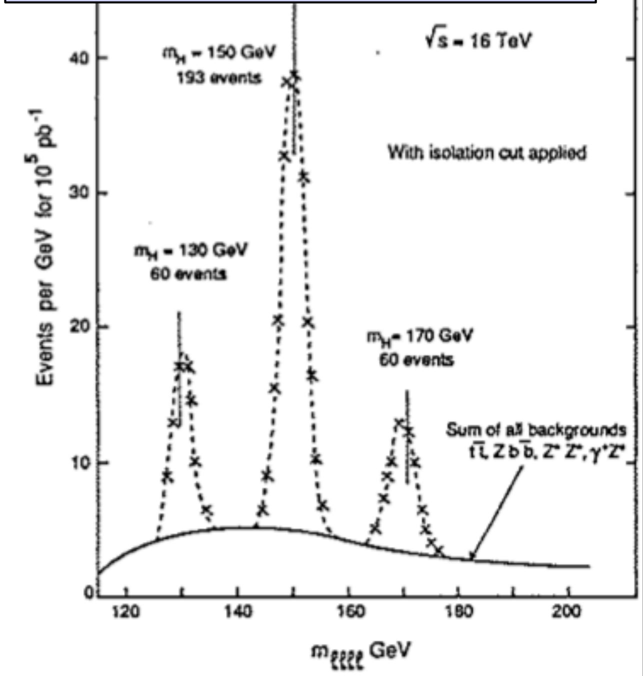
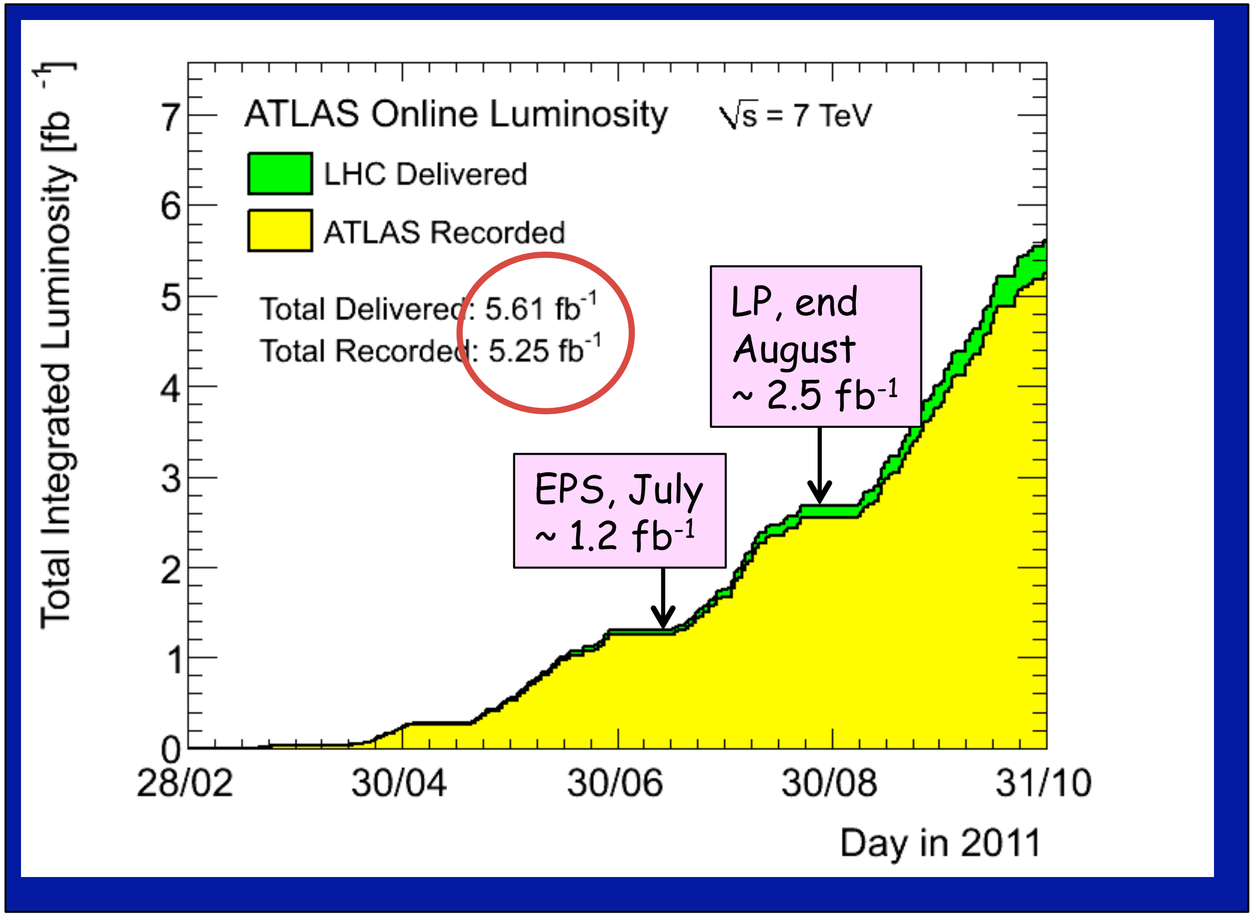


Fig. 10

After 2 years of LHC operation, ATLAS has achieved excellent sensitivity over a large part of the allowed mass range, thanks to:

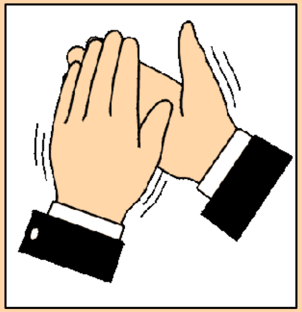
- ❑ outstanding LHC performance → > 5 fb^{-1}
- ❑ high detector operational efficiency and data quality
- ❑ excellent detector performance; mature understanding reflected in detailed modeling of several subtle effects included in the simulation
- ❑ huge numbers of physics results produced with the 2010-2011 data → the main SM processes and many backgrounds to Higgs searches studied in detail (and compared to theory)

→ Work of building solid foundations for (difficult) Higgs searches is well advanced



Peak luminosity seen by ATLAS: ~ 3.6 x10^{33} cm^{-2} s^{-1}

Many thanks to the LHC team for such a superb performance !



Fraction of non-operational detector channels:
(depends on the sub-detector)

few permil to 3.5%

Data-taking efficiency = (recorded lumi)/(delivered lumi):

~ 93.5%

Good-quality data fraction, used for analysis :
(depends on the analysis)

90-96%

Price to pay for the high luminosity: larger-than-expected pile-up

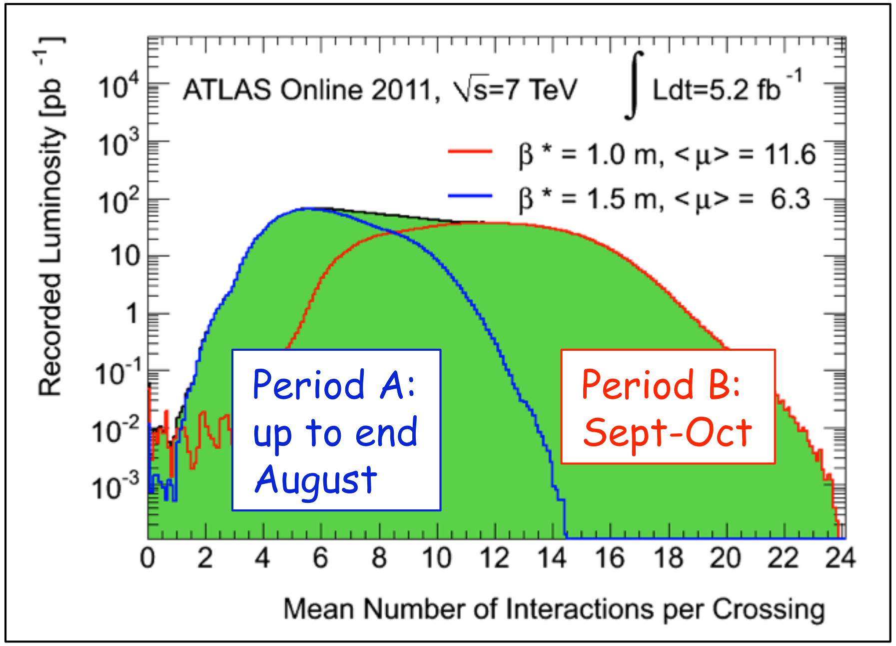
Pile-up = number of interactions per crossing

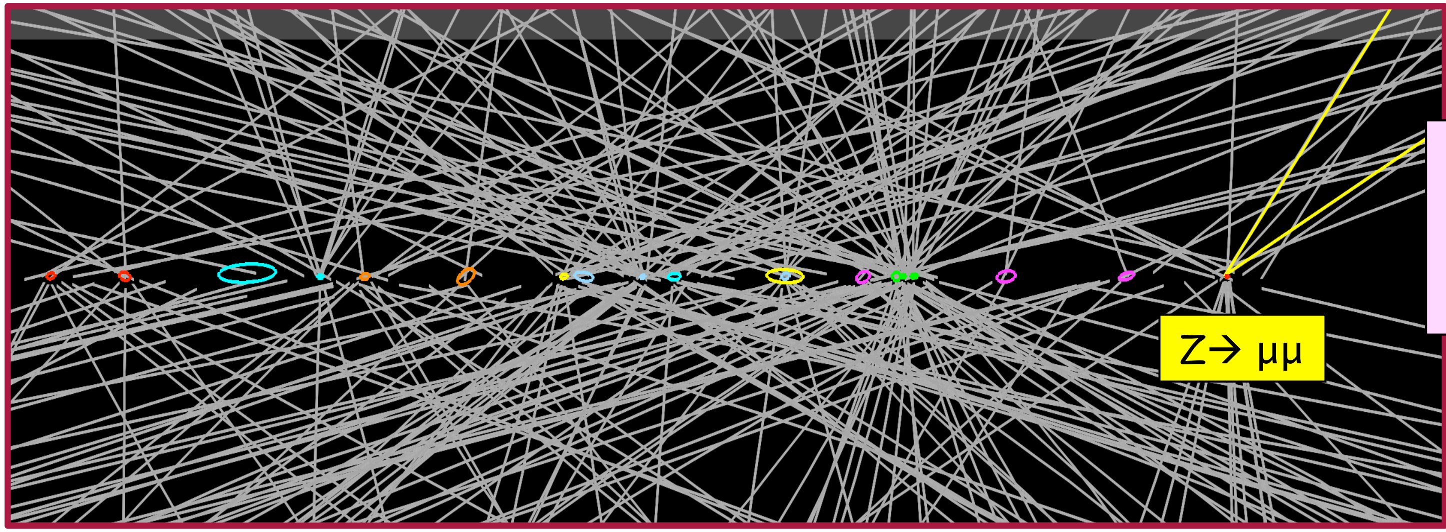
Tails up to ~20 → comparable to design luminosity

(50 ns operation; several machine parameters pushed beyond design)

LHC figures used over the last 20 years:

~ 2 (20) events/crossing at $L=10^{33}$ (10^{34})





Event with 20 reconstructed vertices

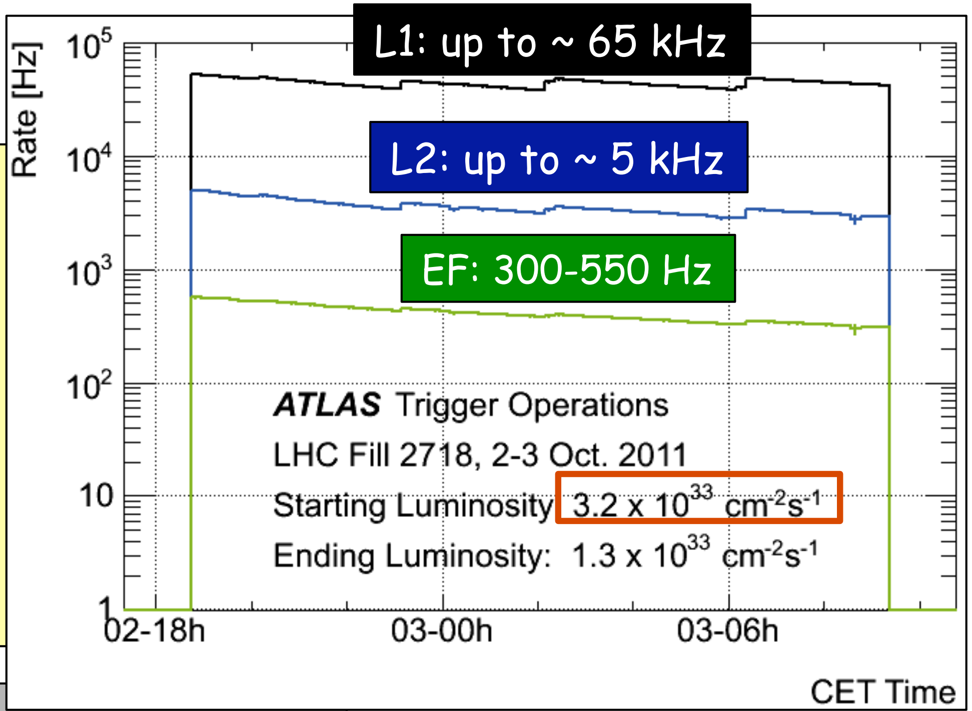
(ellipses have 20 σ size for visibility reasons)

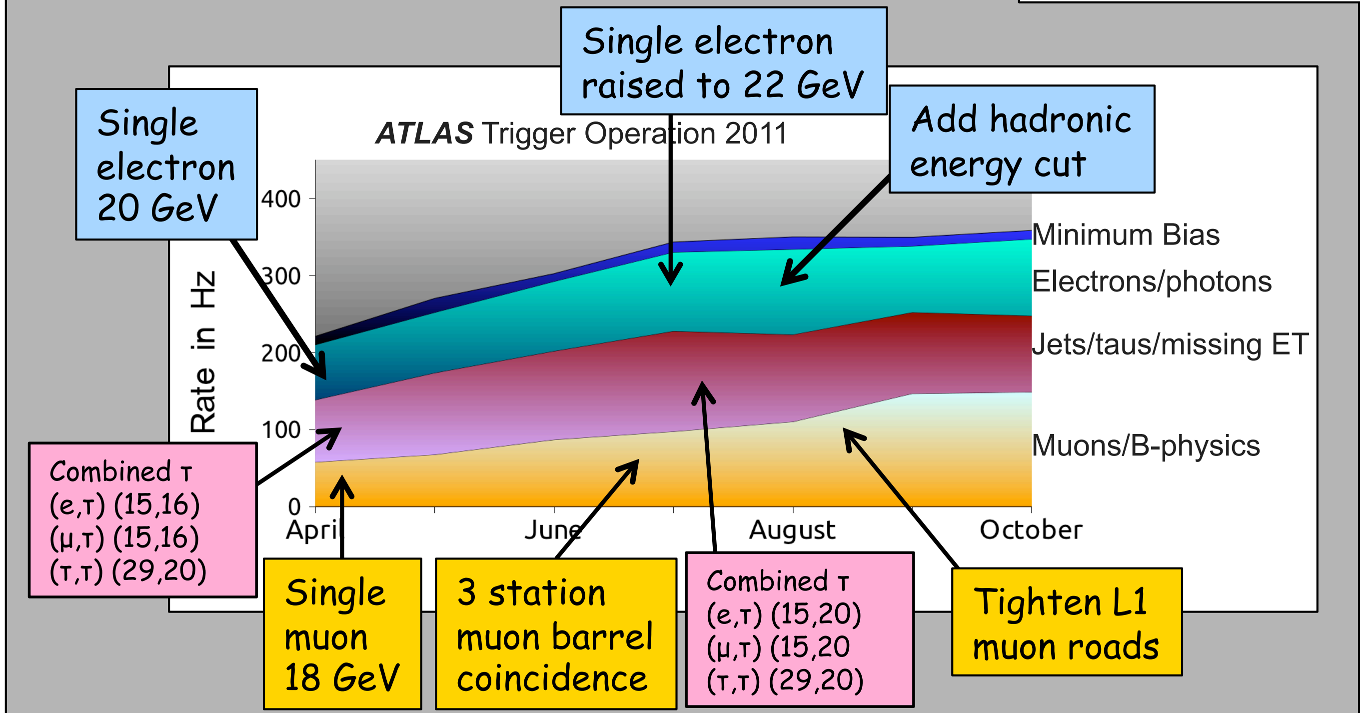
Challenging for trigger, computing resources, reconstruction of physics objects (in particular E_T^{miss}, soft jets, ..)

Precise modeling of both in-time and out-of-time pile-up in simulation is essential

Trigger

- Coping very well with rapidly-increasing luminosity (factor ~10 over 2011) and pile-up by adapting prescales, thresholds, menu.
- Strive to maximise physics (e.g. keeping low thresholds for inclusive leptons)
- Main menu complemented by set of calibration/support triggers: e.g. special $J/\psi \rightarrow ee$ stream (few Hz) for unbiased low-p_T electron studies



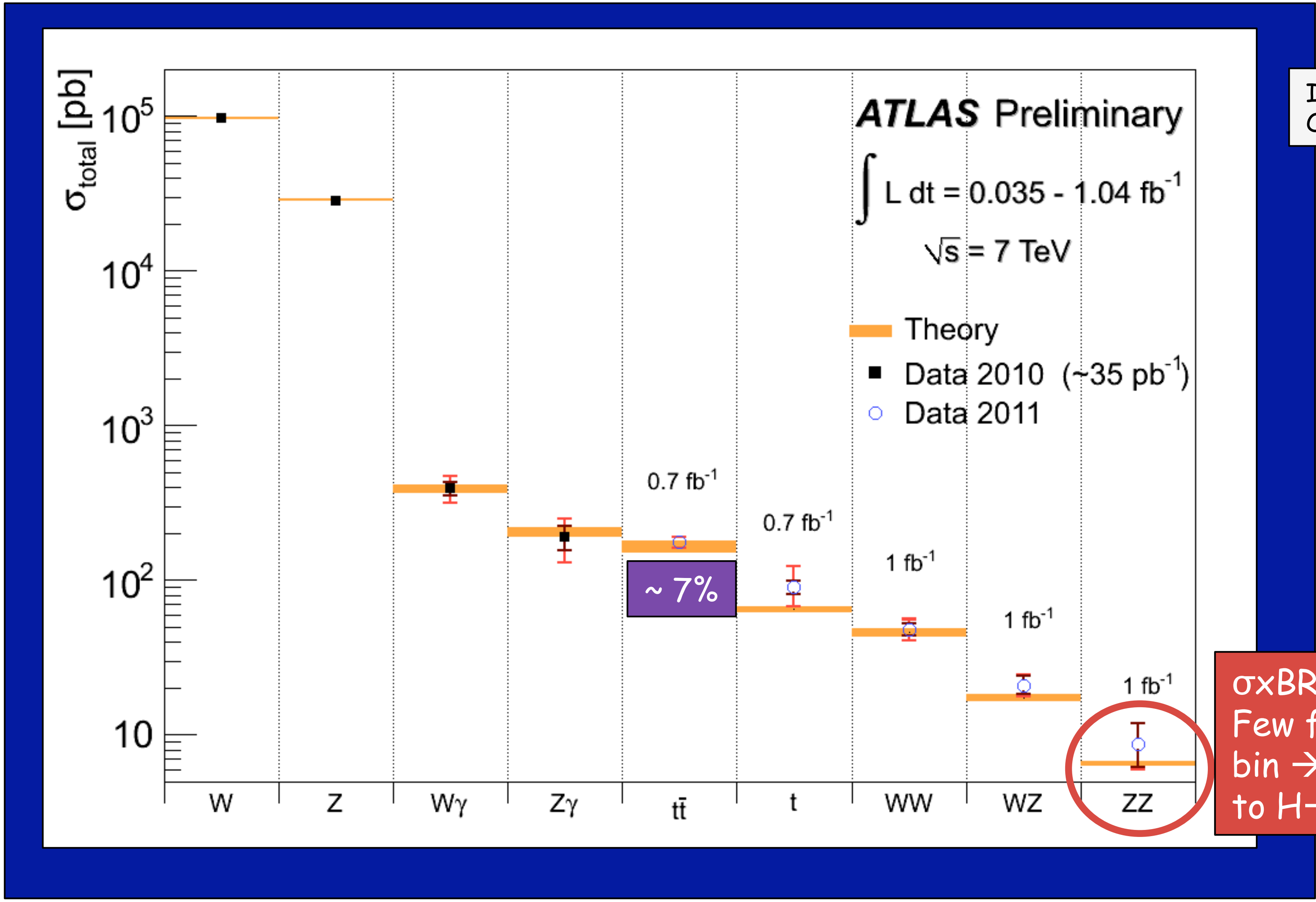


Typical recorded rates for main streams:

e/γ	~ 100 Hz
$Jets/\tau/E_T^{miss}$	~ 100 Hz
Muons	~ 150 Hz

Managed to keep inclusive lepton thresholds ~ stable during 2011

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

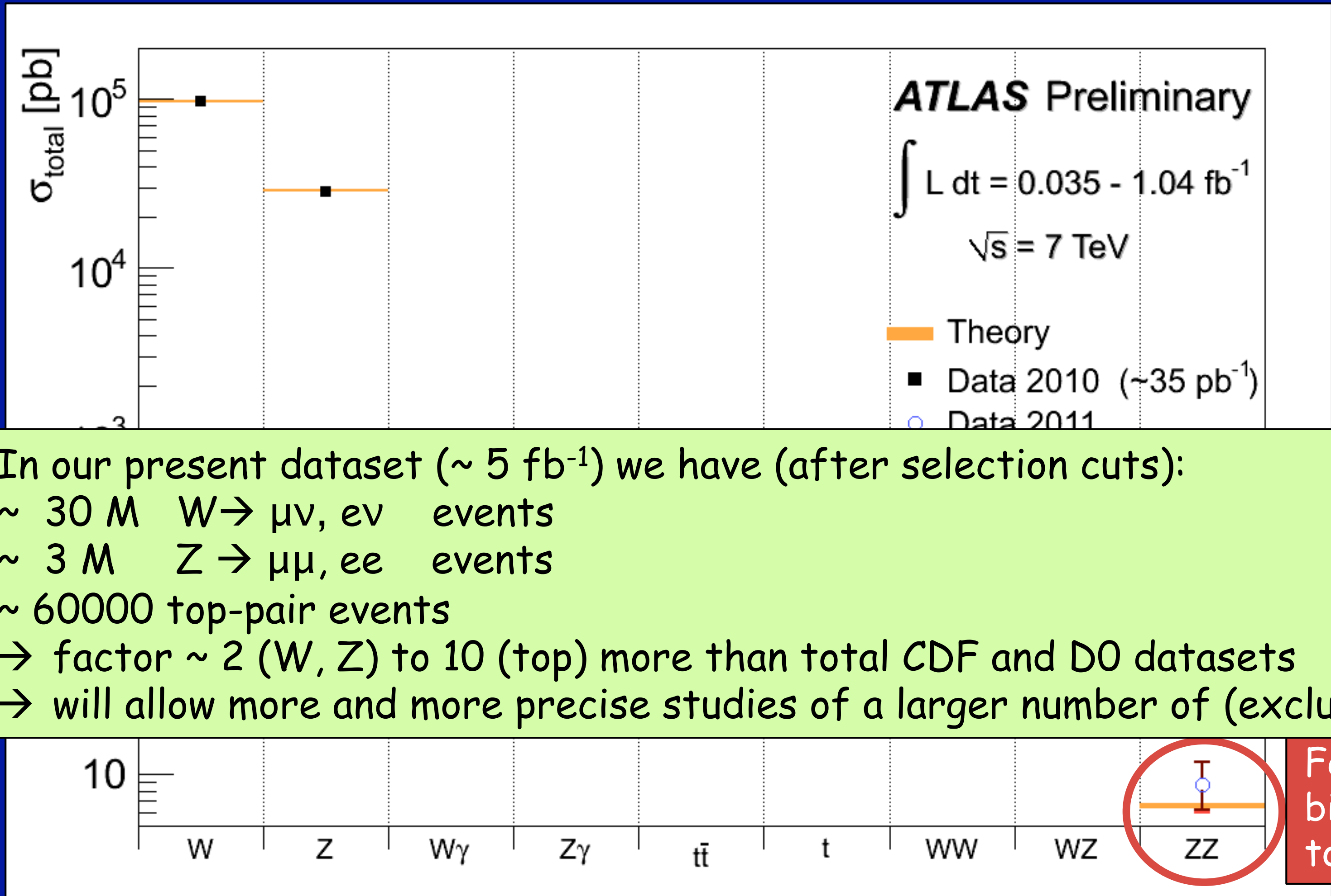
σxBR(ZZ→ 4l) ~ 40 fb
Few fb in narrow mass bin → comparable to H→ZZ$^{(*)}$→ 4l

Good agreement with SM expectations (within present uncertainties)

Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

Measuring cross-sections down to few pb (~ 40 fb including leptonic branching ratios)

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

In our present dataset (~ 5 fb^{-1}) we have (after selection cuts):
- ~ 30 M $W \rightarrow \mu\nu, e\nu$ events
- ~ 3 M $Z \rightarrow \mu\mu, ee$ events
- ~ 60000 top-pair events

→ factor ~ 2 (W, Z) to 10 (top) more than total CDF and D0 datasets
→ will allow more and more precise studies of a larger number of (exclusive) processes

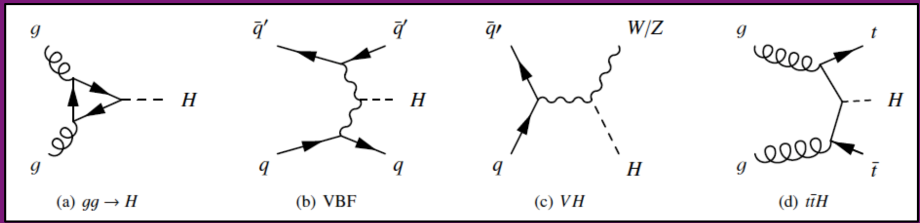
fb
Few fb in narrow mass bin → comparable to $H \rightarrow ZZ^{(*)} \rightarrow 4l$

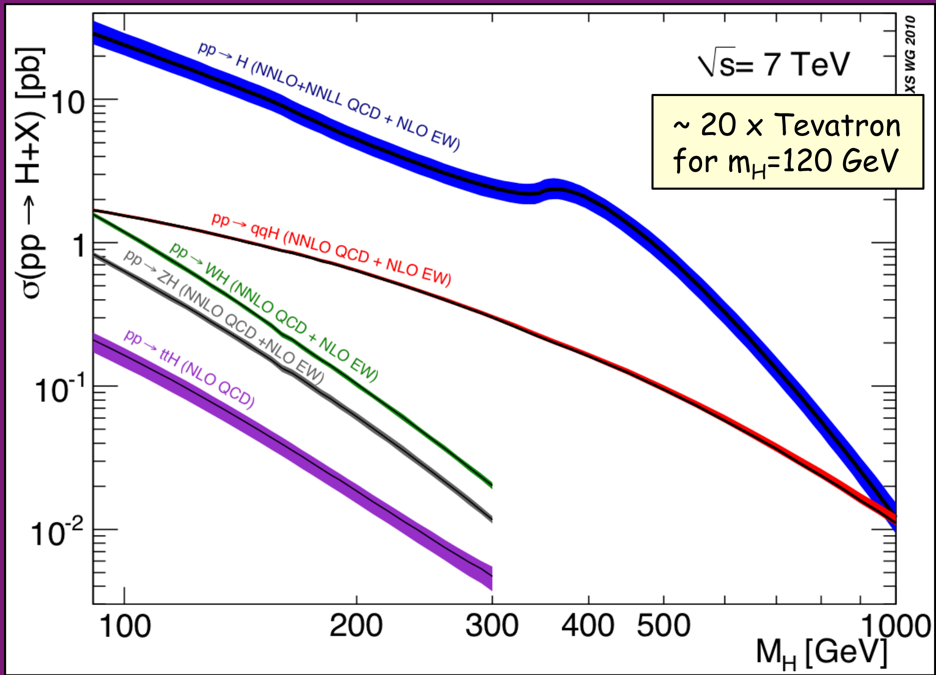
Good agreement with SM expectations (within present uncertainties)

Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

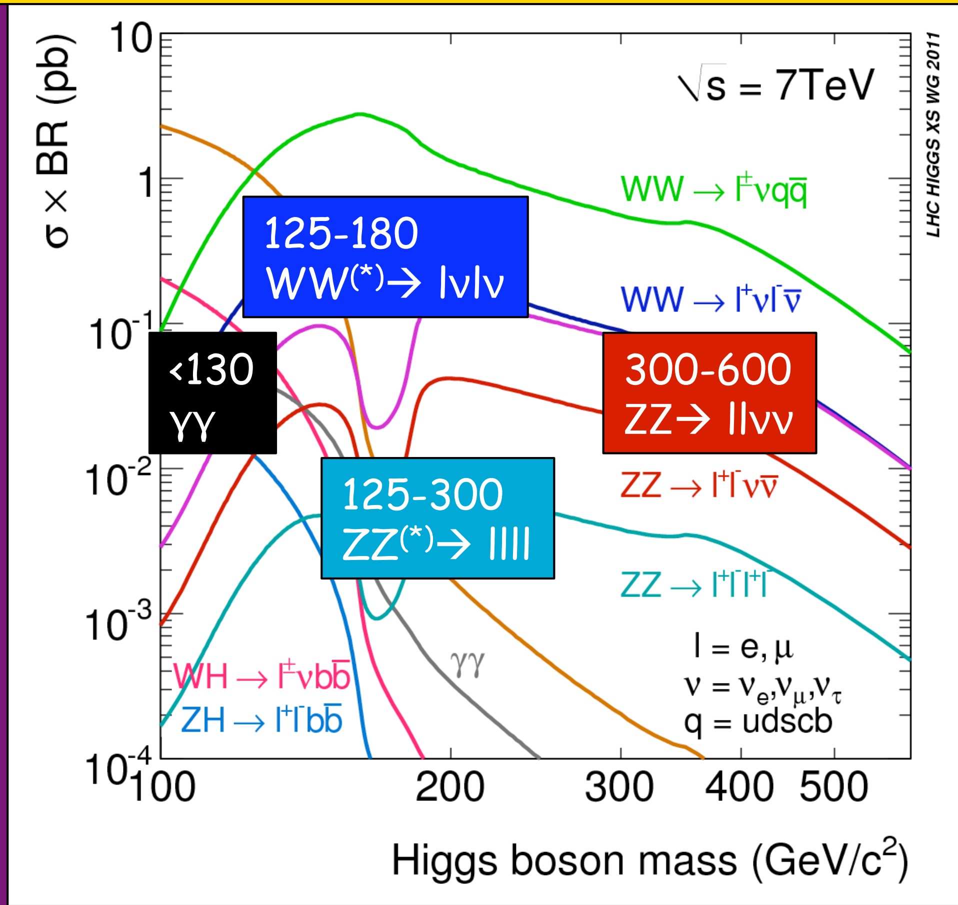
Measuring cross-sections down to few pb (~ 40 fb including leptonic branching ratios)

SM Higgs production cross-section and decay modes





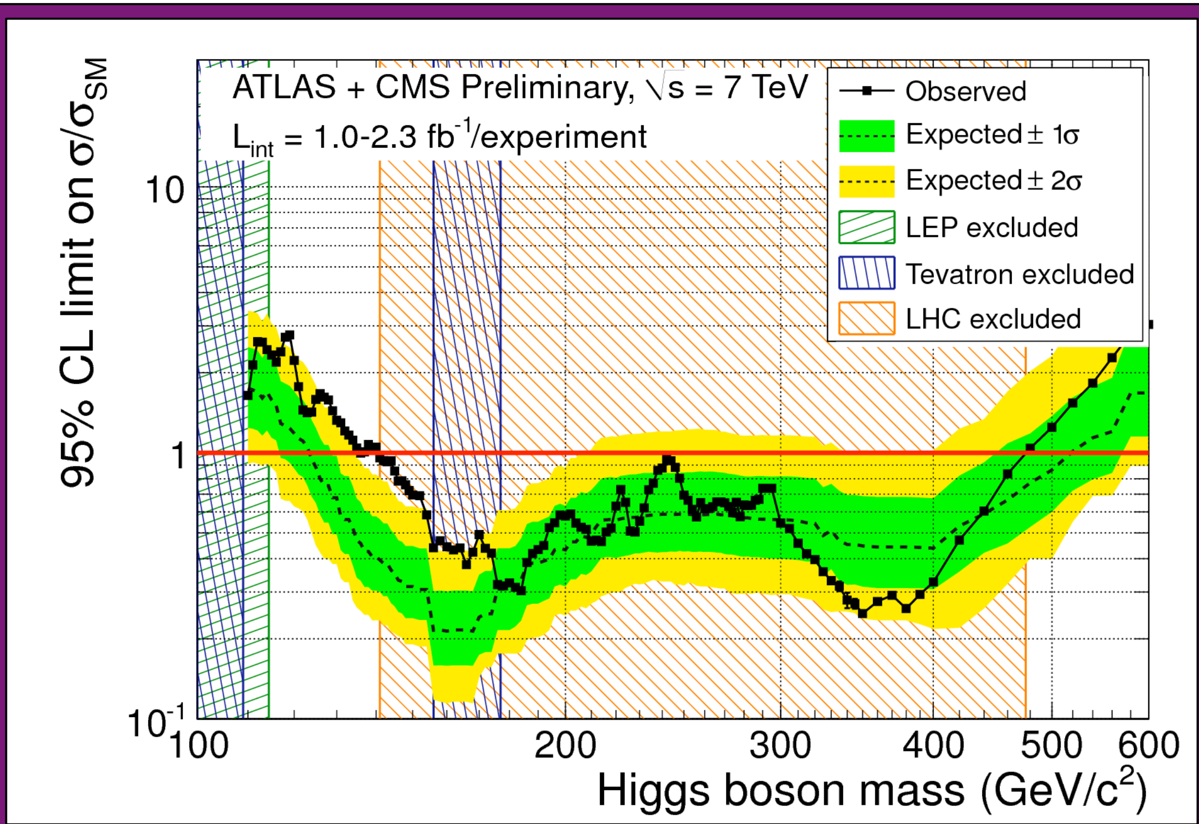
Experimentally most sensitive channels vs m_H



- ❑ Cross-sections computed to NNLO in most cases → theory uncertainties reduced to < 20%
- ❑ Huge progress also in the theoretical predictions of numerous and complex backgrounds

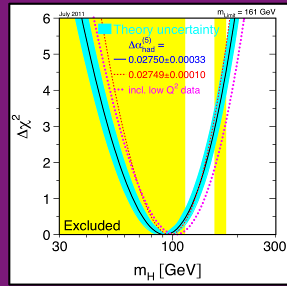
→ Excellent achievements of the theory community; very fruitful discussions with the experiments (e.g. through LHC Higgs Cross Section WG, LPCC, etc.)

Present status (as of this morning …)



November 2011
CMS PAS HIG-11-023,
ATLAS-CONF-201-157

LEP (95%CL)
m_H > 114.4 GeV



Tevatron exclusion (95%CL):
100 < m_H < 109 GeV
156 < m_H < 177 GeV

First ATLAS+CMS combination: based on data recorded until end August 2011: up to ~2.3 fb^{-1} per experiment

Excluded 95% CL : 141-476 GeV
Excluded 99% CL : 146-443 GeV (except ~222, 238-248, ~295 GeV)
Expected 95% CL : 124-520 GeV → max deviation from background-only: ~ 3σ (m_H~144 GeV)

Over the last months …

Huge efforts to improve understanding of detector performance:

- 2011 data recorded with very different conditions compared to 2010, in particular the latest period with higher pile-up
- several measurements with 2010 data already dominated by systematic uncertainty → need to dismantle systematics

→ Improved knowledge (of many subtle effects…) propagated to simulation and reconstruction: detailed simulation of in- and out-of-time pile-up including bunch-train structure; new alignment; accurate simulation of absorber plates in the EM calorimeter (→ better agreement data-MC for e/γ showers); modeling varying detector conditions in MC; etc. etc.

Necessary, high-priority work for the full ATLAS physics programme based on the 2011 data

Higgs searches:
We updated the most sensitive channels in the best motivated (EW fit) and not-yet-excluded low-mass region: $H \rightarrow \gamma\gamma$ (4.9 fb^{-1}), $H \rightarrow 4l$ (4.8 fb^{-1}), $H \rightarrow WW \rightarrow l\nu l\nu$ (2.1 fb^{-1})

Micro-summary of present Higgs searches in ATLAS

Channel	m_H range (GeV)	Int. lumi fb^{-1}	Main backgrounds	Number of signal events after cuts	S/B after cuts	Expected σ/σ_{SM} sensitivity
$H \to \gamma\gamma$	110-150	4.9	$\gamma\gamma$, γj, jj	~70	~0.02	1.6-2
$H \to \tau\tau \to ll+\nu$	110-140	1.1	$Z \to \tau\tau$, top	~0.8	~0.02	30-60
$H \to \tau\tau \to l\tau_{had}$	100-150	1.1	$Z \to \tau\tau$	~10	~5 10^{-3}	10-25
$W/ZH \to bbl(l)$	110-130	1.1	W/Z+jets, top	~6	~5 10^{-3}	15-25
$H \to WW^{(*)} \to l\nu l\nu$	110-300	2.1	WW, top, Z+jet	~20 (130 GeV)	~0.3	0.3-8
$H \to ZZ^{(*)} \to 4l$	110-600	4.8	ZZ*, top, Zbb	~2.5 (130 GeV)	~1.5	0.7-10
$H \to ZZ \to ll\,\nu\nu$	200-600	2.1	ZZ, top, Z+jets	~20 (400 GeV)	~0.3	0.8-4
$H \to ZZ \to ll\,qq$	200-600	2.1	Z+jets, top	2-20 (400 GeV)	0.05-0.5	2-6
$H \to WW \to l\nu qq$	240-600	1.1	W+jets,top,jets	~45 (400 GeV)	10^{-3}	5-10

- ❑ Based on (conservative) cut-based selections
- ❑ Large and sometimes not well-known backgrounds estimated mostly with data-driven techniques using signal-free control regions

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ ($e\nu e\nu$, $\mu\nu\mu\nu$, $e\nu\mu\nu$)

$110 < m_H < 300$ GeV

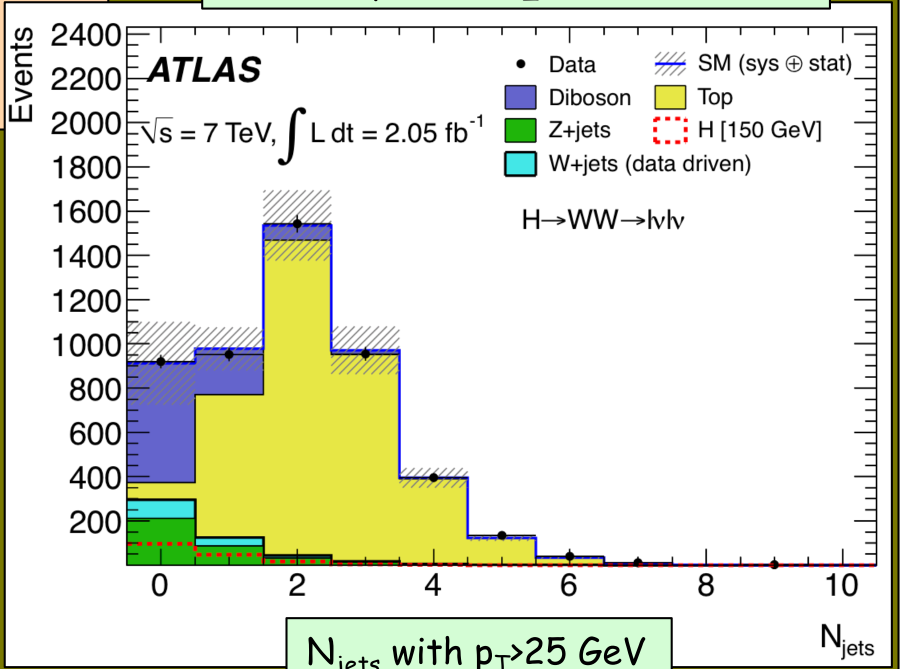
- Most sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- However: challenging: $2\nu \rightarrow$ no mass reconstruction/peak $\rightarrow$ "counting channel"
- 2 isolated opposite-sign leptons, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
  $\rightarrow m_{ll} \neq m_Z$, b-jet veto, …
  $\rightarrow$ Topological cuts against "irreducible" WW background:
  p_{Tll}, m_{ll}, $\Delta\phi_{ll}$ (smaller for scalar Higgs), m_T (ll, E_T^{miss})

Crucial experimental aspects:
- understanding of E_T^{miss} (genuine and fake)
- excellent understanding of background in signal region $\rightarrow$ use signal-free control regions in data to constrain MC $\rightarrow$ use MC to extrapolate to the signal region

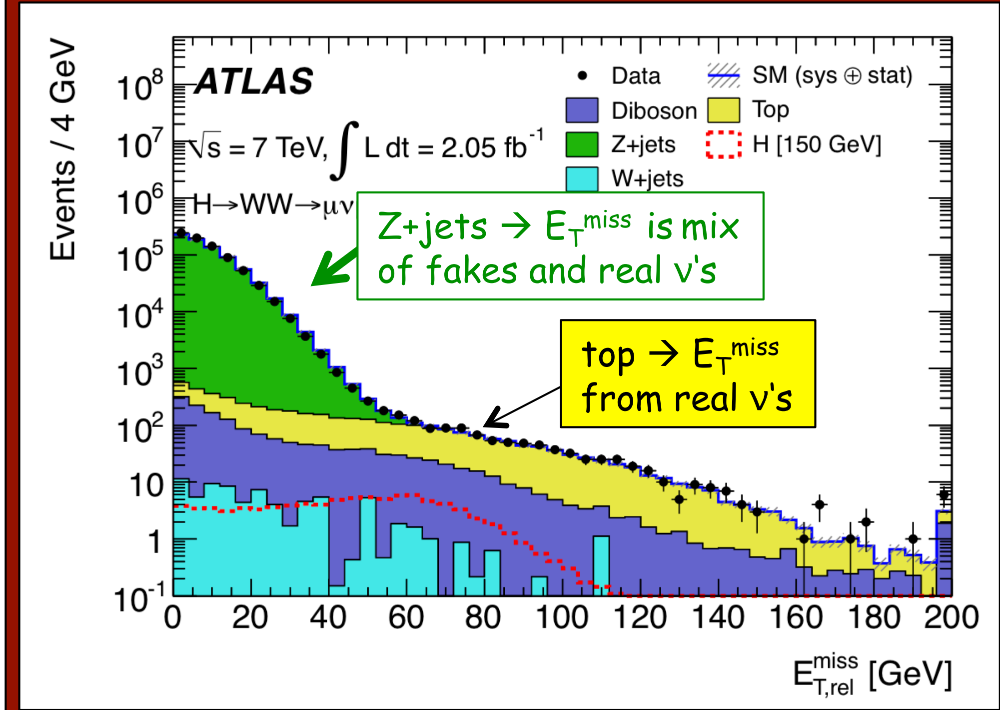
2.1 fb^{-1}

Control region	MC expectation	Observed in data
WW 0-jet	296±36	296
WW 1-jet	171±21	184
Top 1-jet	270±69	249

After leptons, m_Z and E_T^{miss} cuts



N_{jets} with p_T>25 GeV



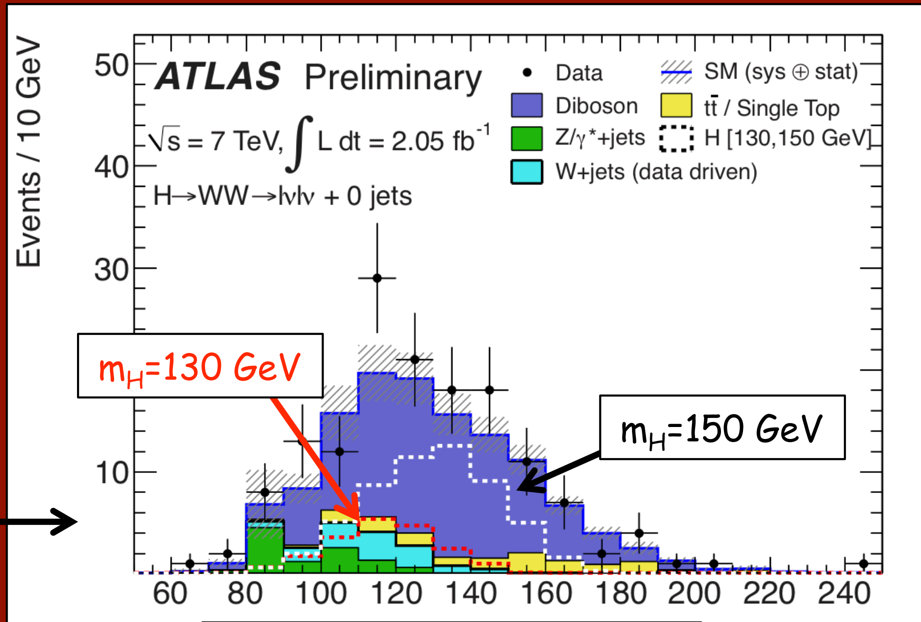
E_T^{miss} spectrum in data for inclusive events with $\mu^+\mu^-$ pair well described (over 5 orders of magnitude) by the various background components.
Dominated by real E_T^{miss} from ν's starting at E_T^{miss} ~ 50 GeV
→ little tails from detector effects

E_T^{miss} spectrum and resolution very sensitive to pile-up → we will include Period-B data when understanding at similar level as Period A

2.1 fb^{-1}

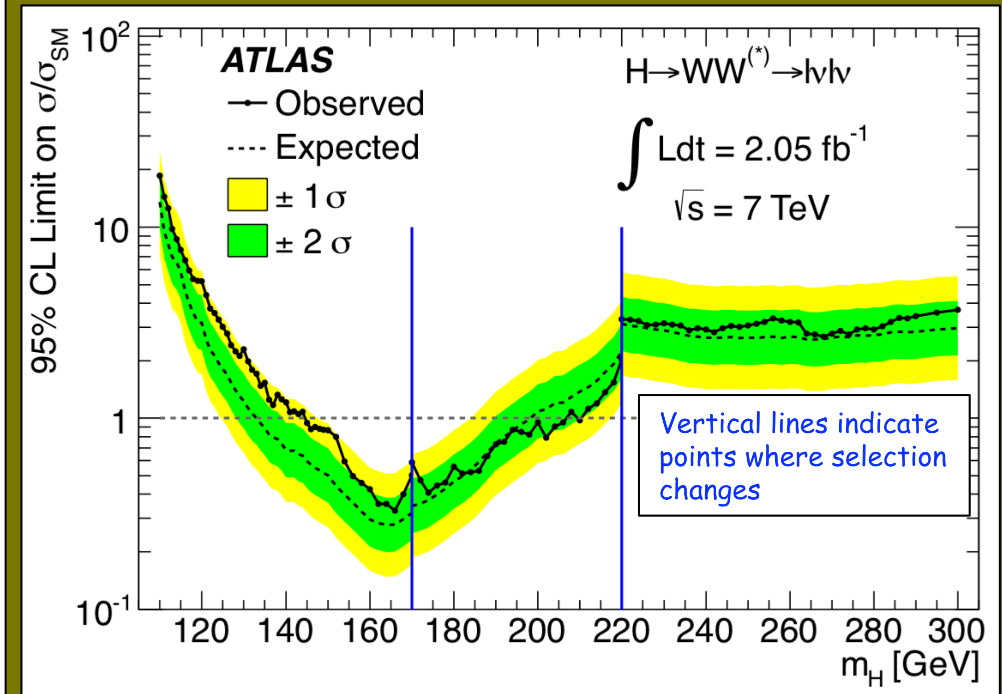
After all cuts (selection for m_H=130 GeV)	
Observed in data	94 events 10 ee, 42 eμ, 42 μμ
Expected background	76 (±11)
Expected signal m_H=130 GeV	19 (±4)

Transverse mass spectrum after all cuts (except M_T) →

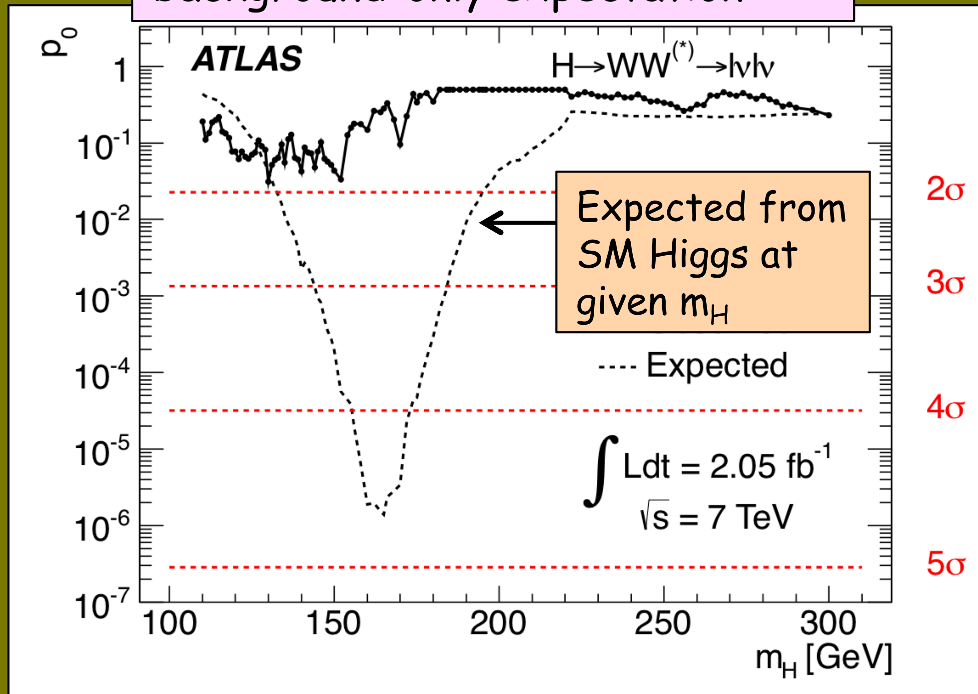


$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

After all cuts (selection for m_H=130 GeV)	2.1 fb^{-1}
Observed in data	94 events 10 ee, 42 eμ, 42 μμ
Expected background	76 (±11)
Expected signal m_H=130 GeV	19 (±4)



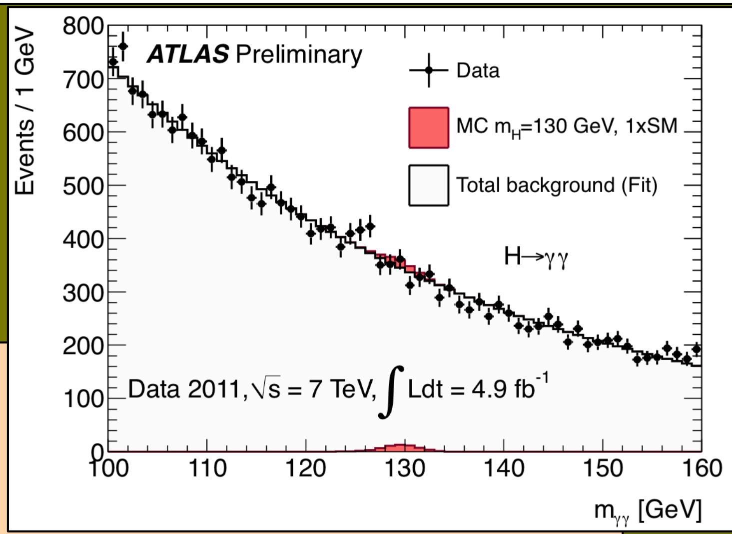
Consistency of the data with the background-only expectation



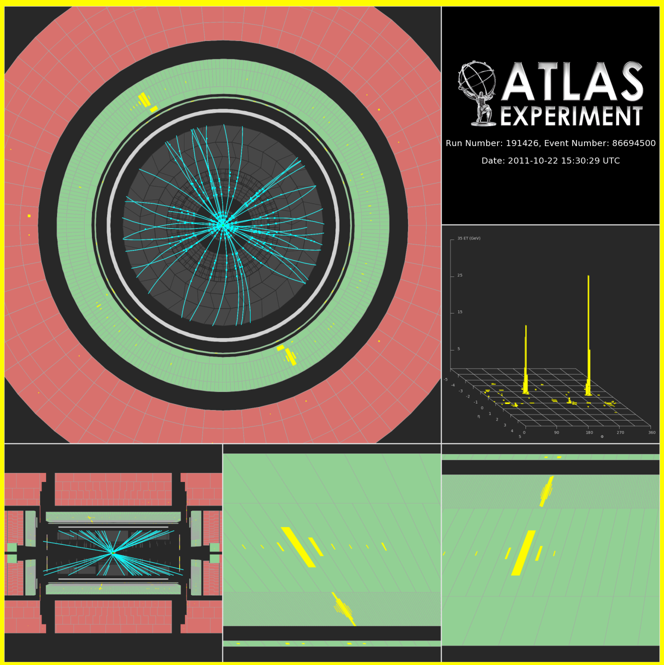
- Excluded (95% CL): 145 < m_H < 206 GeV (expected: 134-200 GeV)
- Observed limit within 2σ of expected: max deviation 1.9 σ for m_H ~ 130 GeV

$H \rightarrow \gamma\gamma$

$110 \leq m_H \leq 150$ GeV



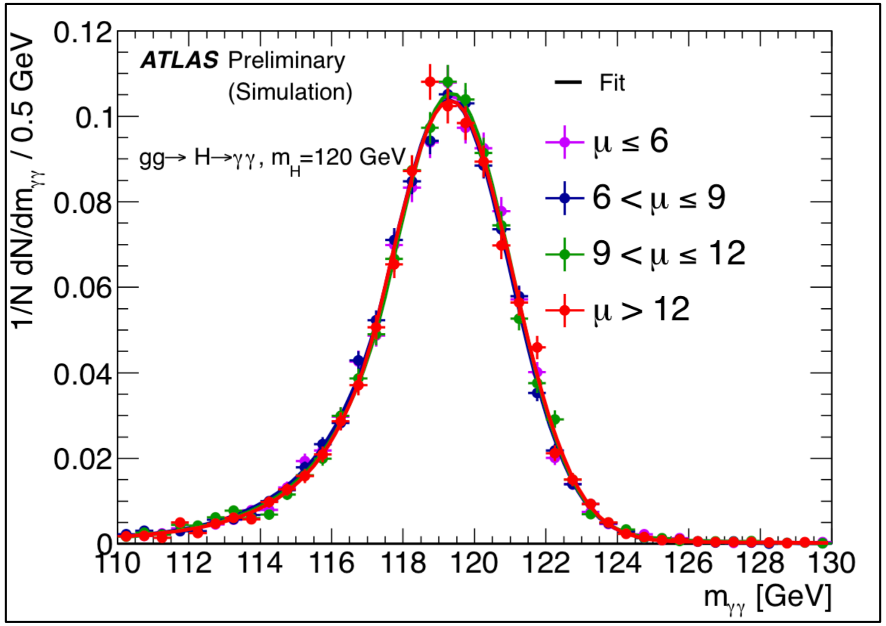
- Small cross-section: $\sigma \sim 40$ fb
- Simple final state: two high-p_T isolated photons
  $E_T(\gamma_1, \gamma_2) > 40, 25$ GeV
- Main background: $\gamma\gamma$ continuum (irreducible, smooth, ..)
- Events divided into 9 categories based on η-photon (e.g. central, rest, …), converted/unconverted, $p_T^{\gamma\gamma}$ perpendicular to $\gamma\gamma$ thrust axis
- ~70 signal events expected in 4.9 fb^{-1} after all selections for m_H=125 GeV
  ~ 3000 background events in signal mass window → S/B ~ 0.02

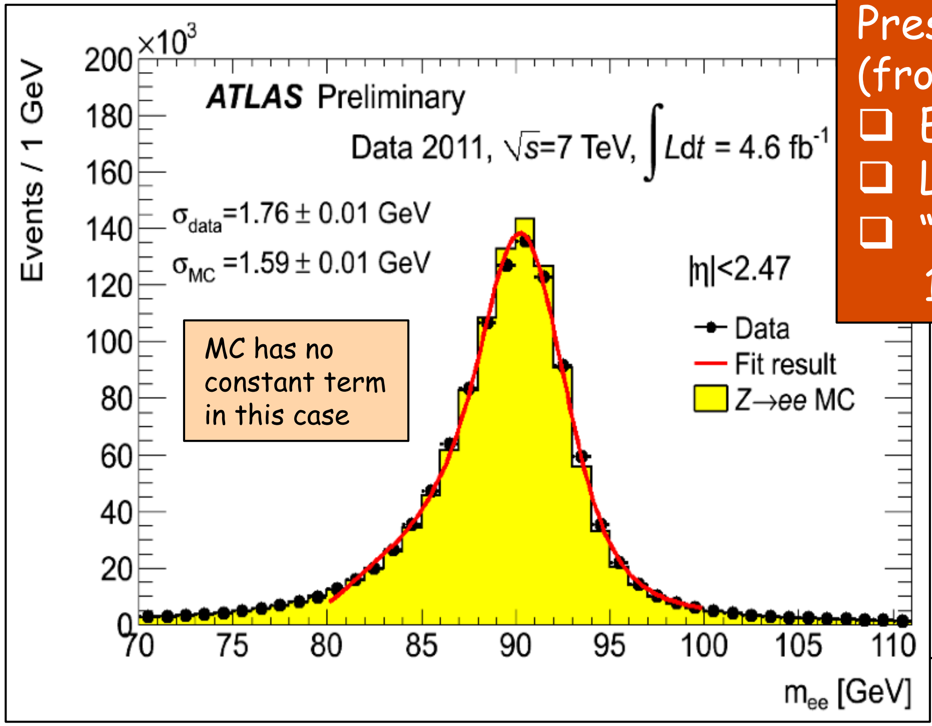


Crucial experimental aspects:
- excellent $\gamma\gamma$ mass resolution to observe narrow signal peak above irreducible background
- powerful γ/jet separation to suppress γj and jj background with jet → π^0 faking single γ

$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

m_H=120 GeV	σ ($m_{\gamma\gamma}$) GeV	Event fraction in $\pm$ 1.4 σ ($m_{\gamma\gamma}$)
All	1.7	80 %
Best category (unconverted central)	1.4	84%
Worst category (~10%) ($\geq$ 1 γ converted, $\geq$ 1 γ near barrel/end-cap transition)	2.3	70%





Present understanding of calorimeter E response (from Z, J/ψ → ee, W→ eν data and MC):

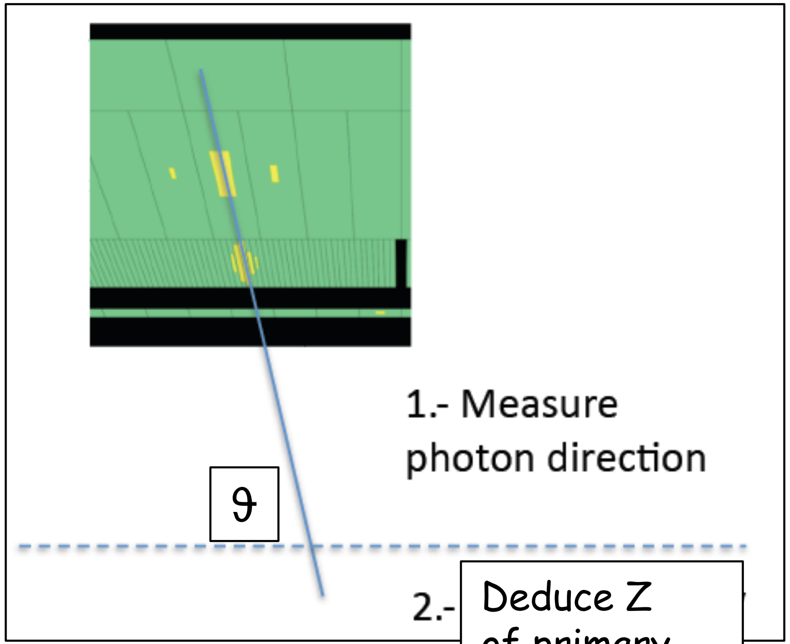
- Energy scale at m_Z known to ~ 0.5%
- Linearity better than 1% (over few GeV-few 100 GeV)
- "Uniformity" (constant term of resolution): 1% (barrel) -1.7 % (end-cap)

Electron scale and resolution transported to photons using MC
(systematics few from material effects)

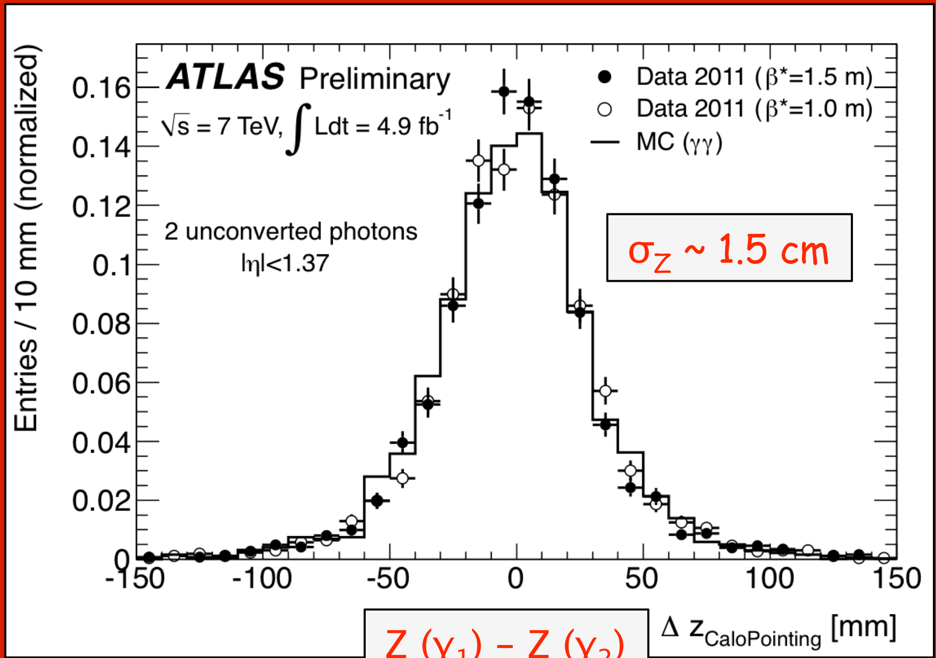
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1 - \cos\alpha)$

α=opening angle of the two photons

Use longitudinal (and lateral) segmentation of EM calorimeter to measure photon polar angle ϑ crucial at high pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5.6 cm → difficult to know which one produced the γγ pair



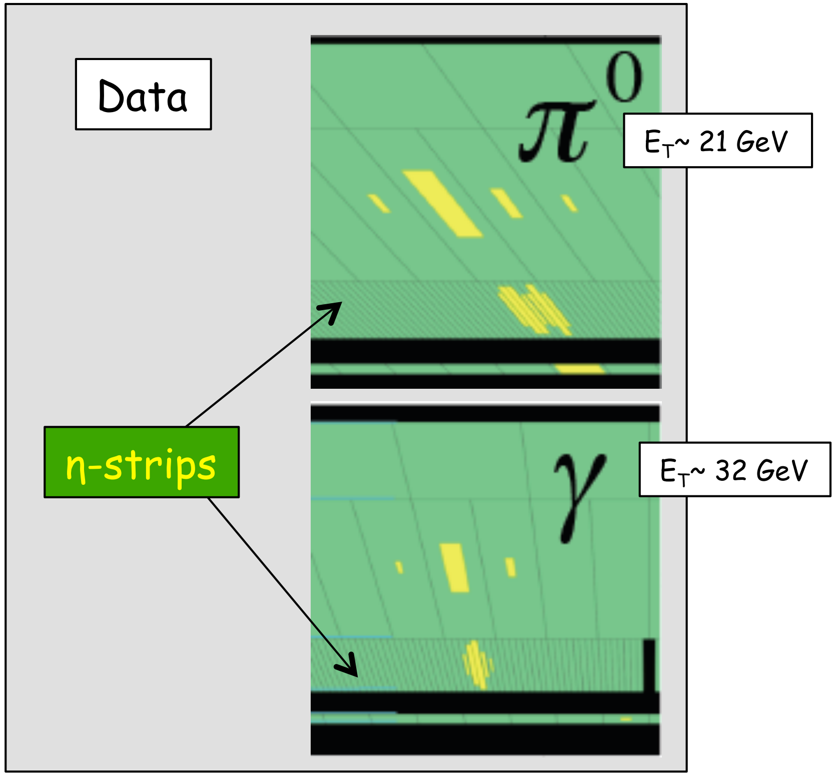
Z-vertex as measured in γγ events after selection from calorimeter "pointing"

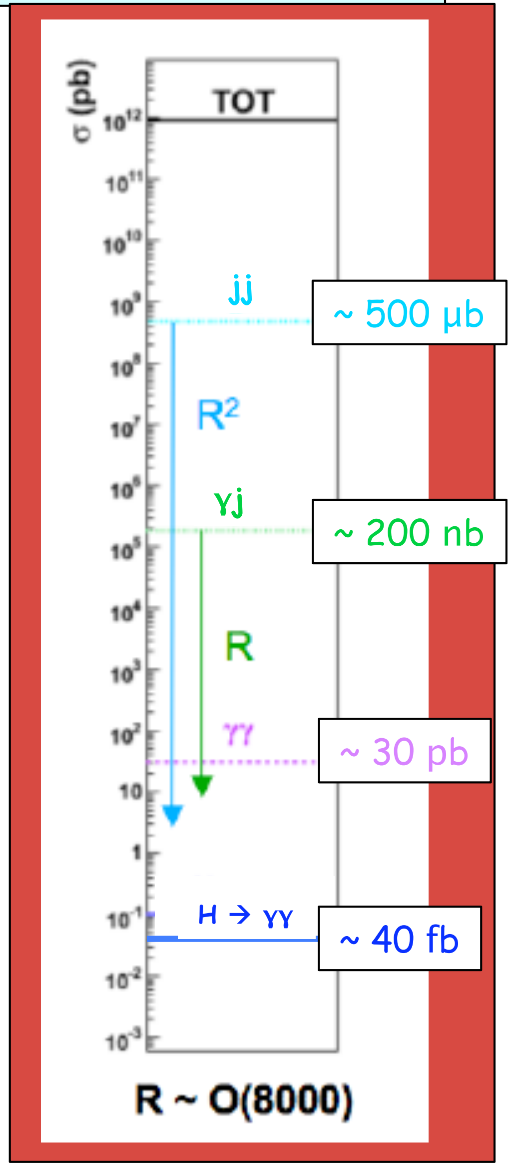


- Calorimeter pointing capability reduces vertex uncertainty from ~ 5.6 cm (LHC beam spot) to ~ 1.5 cm
- → Contribution to mass resolution from angular term is negligible with calo pointing (γ →ee vertex also used)
- Robust against pile-up

Potentially huge background from γj and jj production with jets fragmenting into a single hard π^0 and the π^0 faking single photon

Determined choice of fine lateral segmentation (4mm η-strips) of the first compartment of ATLAS EM calorimeter

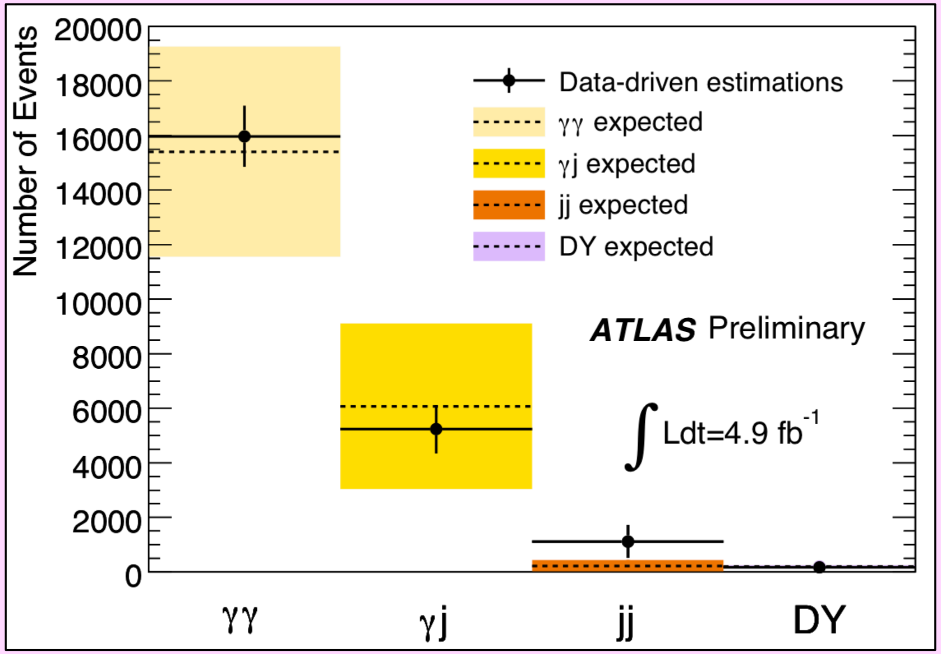




However: huge uncertainties on σ (γj, jj) !! → not obvious γj, jj could be suppressed well below irreducible γγ until we measured with data

After all cuts: 22489 events with $100 < m_{\gamma\gamma} < 160$ GeVobserved in the data

Sample composition estimated from data using control samples



	Number of events	Fraction
γγ	16000 ± 1120	71 ±5 %
γj	5230 ± 890	23 ±4 %
jj	1130 ± 600	5 ±3 %
DY/Z	165 ± 8	0.7 ±0.1 %

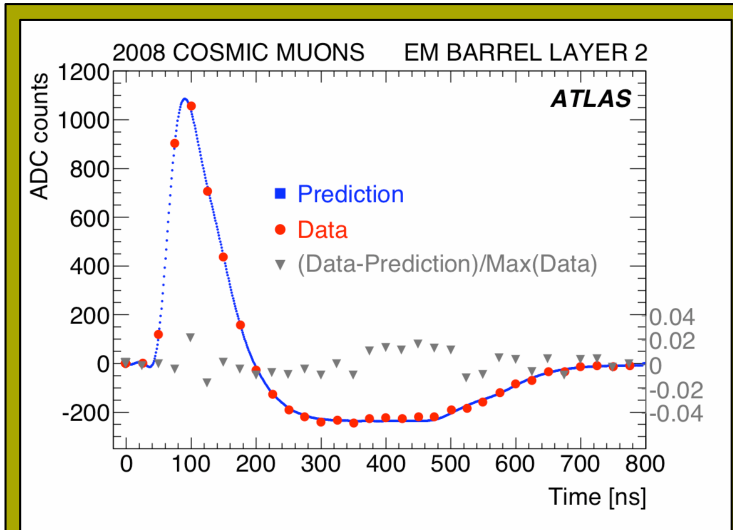
γj + jj << γγ irreducible (purity ~ 70%)

Photon identification efficiency: ~ 85±5% from MC, cross-checked with data (Z→ ee, Z→ eeγ, μμγ)

Photon identification efficiency: ~ 85±5% from MC, cross-checked with data ($Z \to ee$, $Z \to ee\gamma$, $\mu\mu\gamma$)

Photon isolation requirement: $E_T < 5$ GeV inside a cone $\Delta R < 0.4$ around γ direction. Underlying event and pile-up contribution subtracted using an "ambient energy density" determined event-by-event.

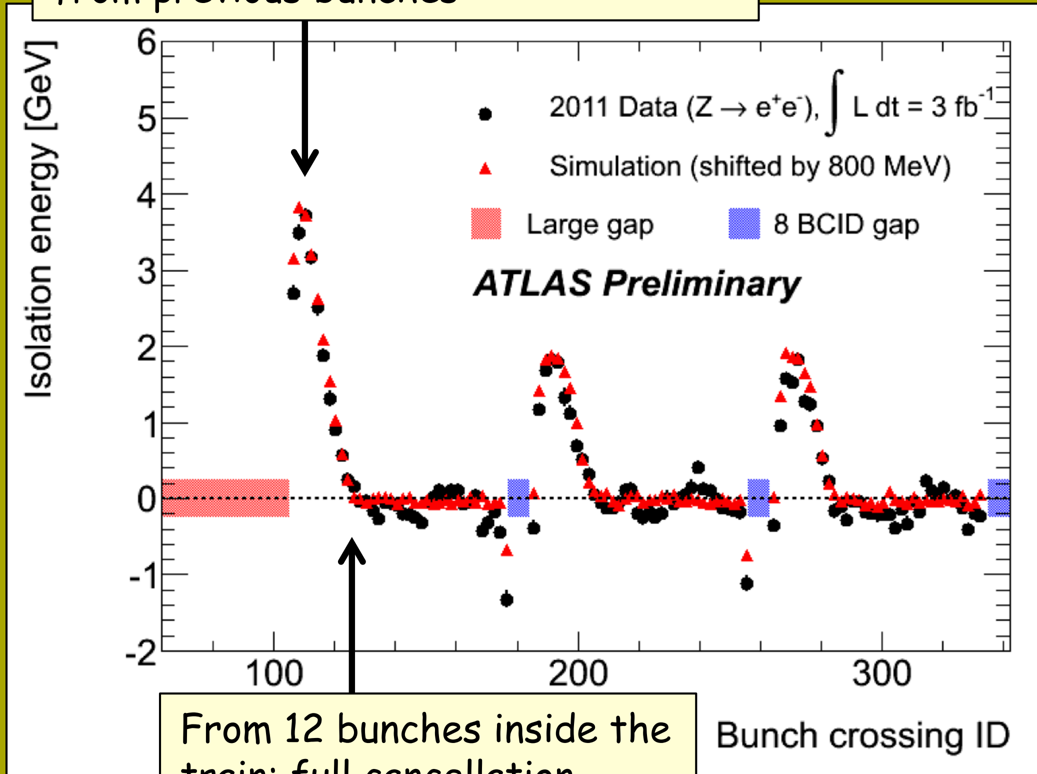
If the subtraction is not perfect, a residual dependence of the corrected isolation energy on the bunch position in the train is observed, due to the impact of pile-up from neighbouring bunches convolved with the LAr calorimeter pulse shape.



Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (~12 bunches)

Effect well described by the (detailed !) ATLAS simulation

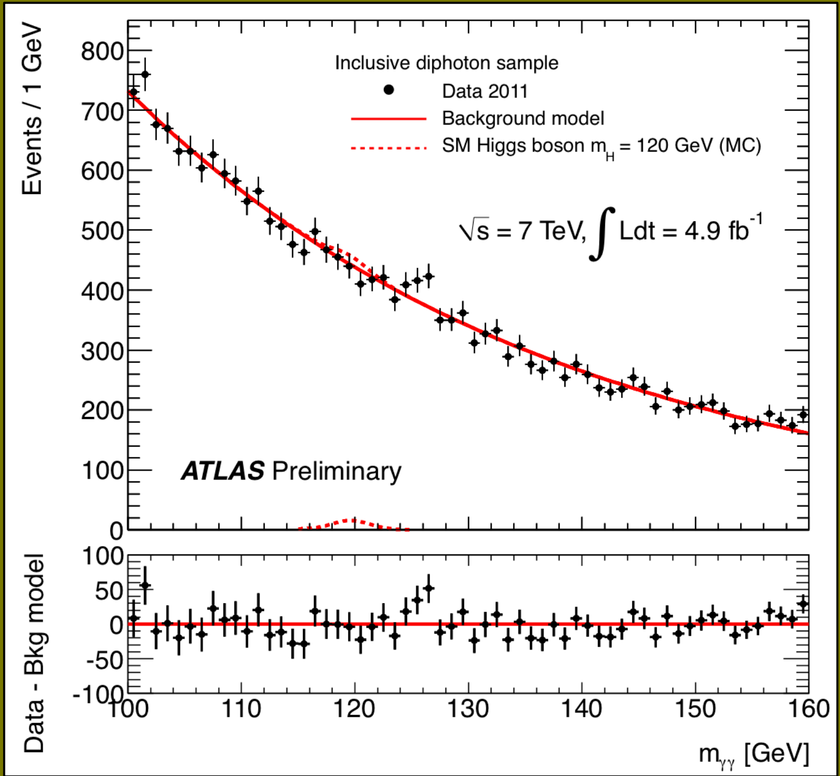
Beginning of the train: no cancellation from previous bunches



From 12 bunches inside the train: full cancellation

After all selections: kinematic cuts, γ identification and isolation

- 22489 events with $100 < m_{\gamma\gamma} < 160$ GeV observed in the data
- expected signal efficiency: ~ 35% for m_H=125 GeV



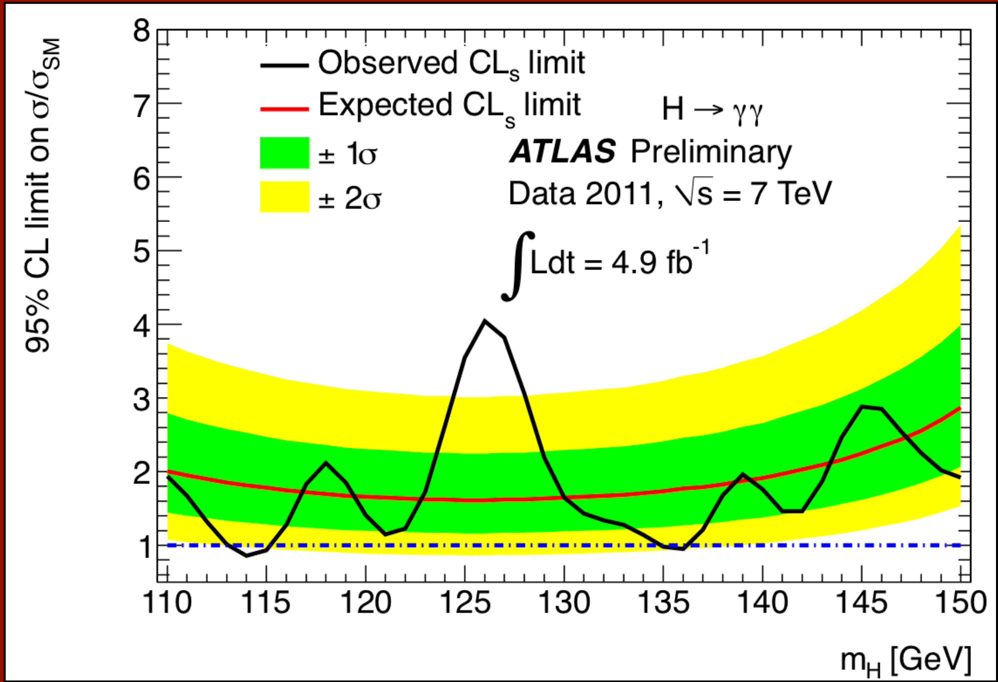
$m_{\gamma\gamma}$ spectrum fit with exponential function for background plus Crystal Ball + Gaussian for signal
→ background determined directly from data

Main systematic uncertainties

Expected signal yield : ~ 20%
H→ γγ mass resolution : ~ 14%
H→ γγ p_T modeling : ~ 8%
Background modeling : ±0.1-5.6 events

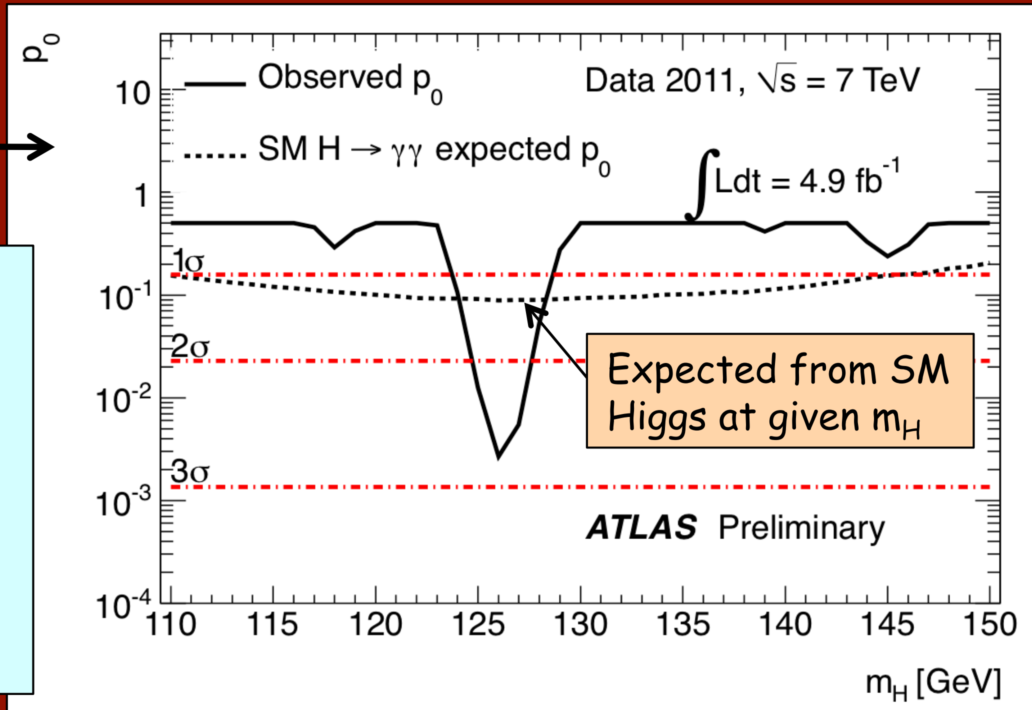
Systematic uncertainties on signal expectation

Event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section	+15%/ − 11%
Higgs boson p_T modeling	±1%
Luminosity	±3.9%
Mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Migration	
Higgs boson p_T modeling	±8%
Conversion reconstruction	±4.5%



Excluded (95% CL):
$114 \leq m_H \leq 115$ GeV, $135 \leq m_H \leq 136$ GeV

Consistency of the data with the background-only expectation



Maximum deviation from background-only expectation observed for m_H~126 GeV:

- local p_0-value: 0.27% or 2.8σ
- expected from SM Higgs: ~ 1.4σ local
- global p_0-value: includes probability for such an excess to appear anywhere in the investigated mass range (110-150 GeV) ("Look-Elsewhere-Effect"): ~7% (1.5σ)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

$110 < m_H < 600$ GeV

- $\sigma \sim$ 2-5 fb
- However:
  -- mass can be fully reconstructed → events would cluster in a (narrow) peak
  -- pure: S/B ~ 1
- 4 leptons: $p_T^{1,2,3,4} > 20,20,7,7$ GeV; $m_{12} = m_Z \pm 15$ GeV; $m_{34} > 15\text{-}60$ GeV (depending on m_H)
- Main backgrounds:
  -- $ZZ^{(*)}$ (irreducible)
  -- $m_H < 2m_Z$: Zbb, Z+jets, tt with two leptons from b/q-jets → l

→ Suppressed with isolation and impact parameter cuts on two softest leptons
- Signal acceptance x efficiency: ~ 15 % for $m_H \sim 125$ GeV

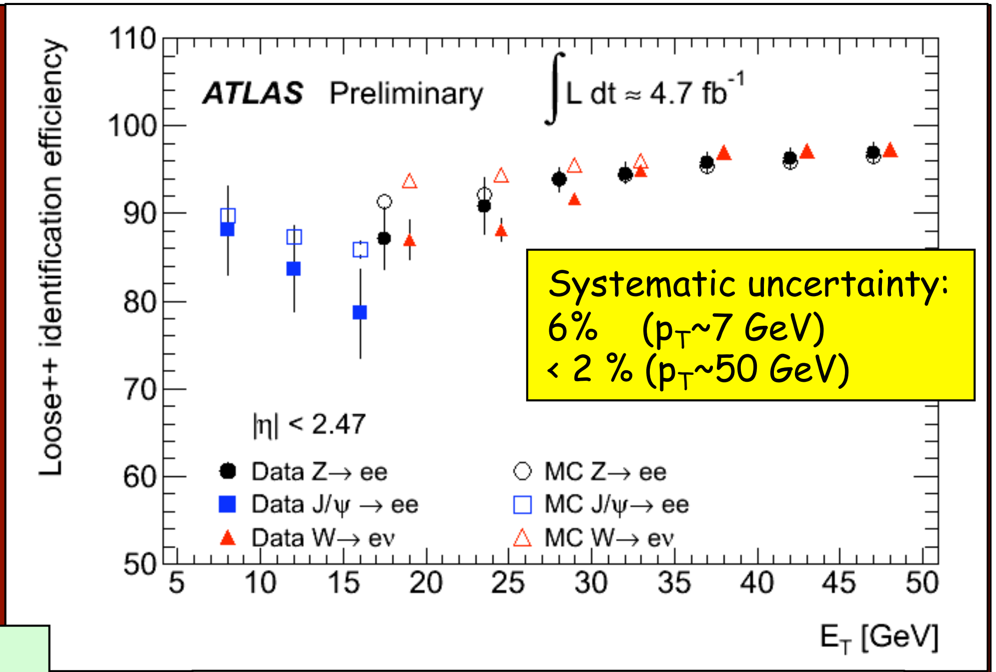
Crucial experimental aspects:
- High lepton reconstruction and identification efficiency down to lowest p_T
- Good lepton energy/momentum resolution
- Good control of reducible backgrounds (Zbb, Z+jets, tt) in low-mass region:
  → cannot rely on MC alone (theoretical uncertainties, b/q-jet → l modeling, ..)
  → need to compare MC to data in background-enriched control regions (but: low statistics ..)

→ Conservative/stringent p_T and m(ll) cuts used at this stage

Identification efficiency from
J/ψ → ee, W → eν, Z→ ee data samples

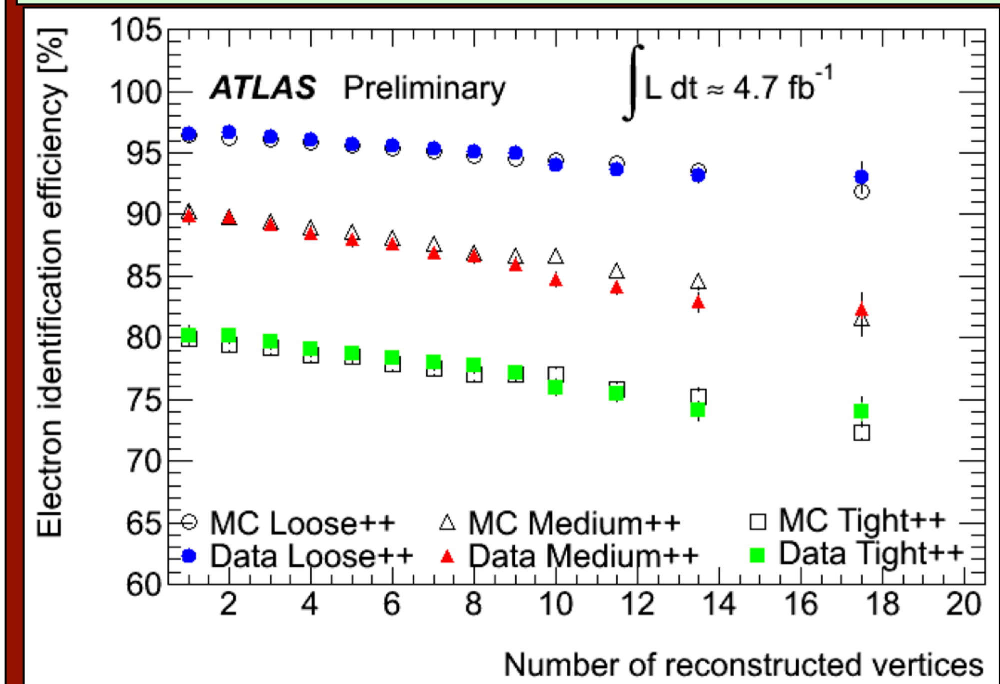
Crucial to understand low-p_T electrons (affected by material) with data

Electron performance

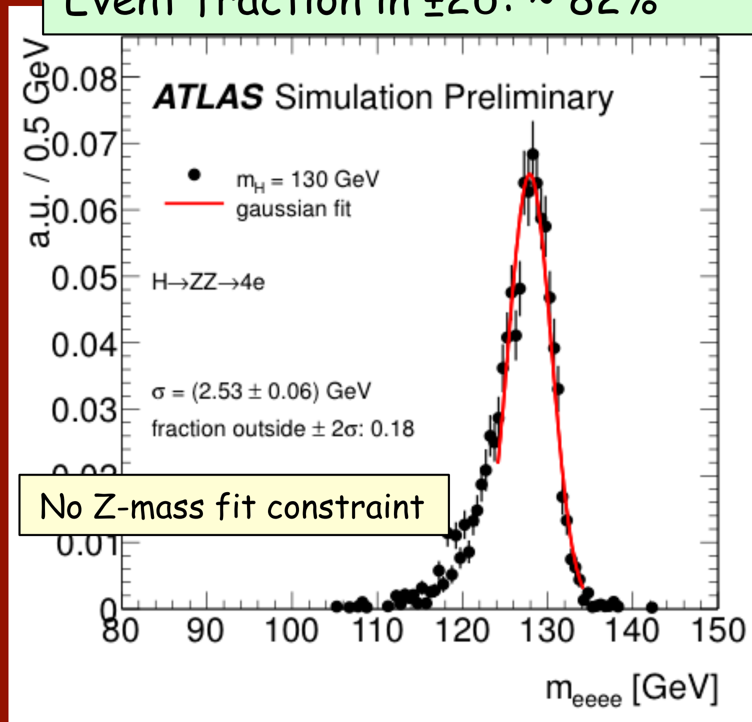


Systematic uncertainty:
6% (p_T~7 GeV)
< 2 % (p_T~50 GeV)

Variation of electron efficiency with pile-up (cuts not re-tuned yet) well modeled by simulation: from Z→ ee data and MC samples

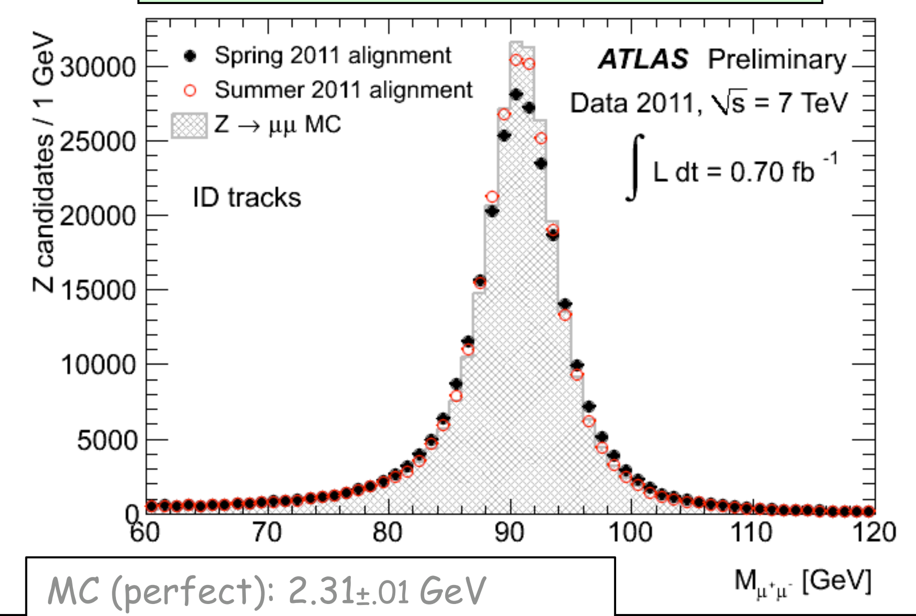


H→ 4e mass resolution: 2.5 GeV
Event fraction in ±2σ: ~ 82%



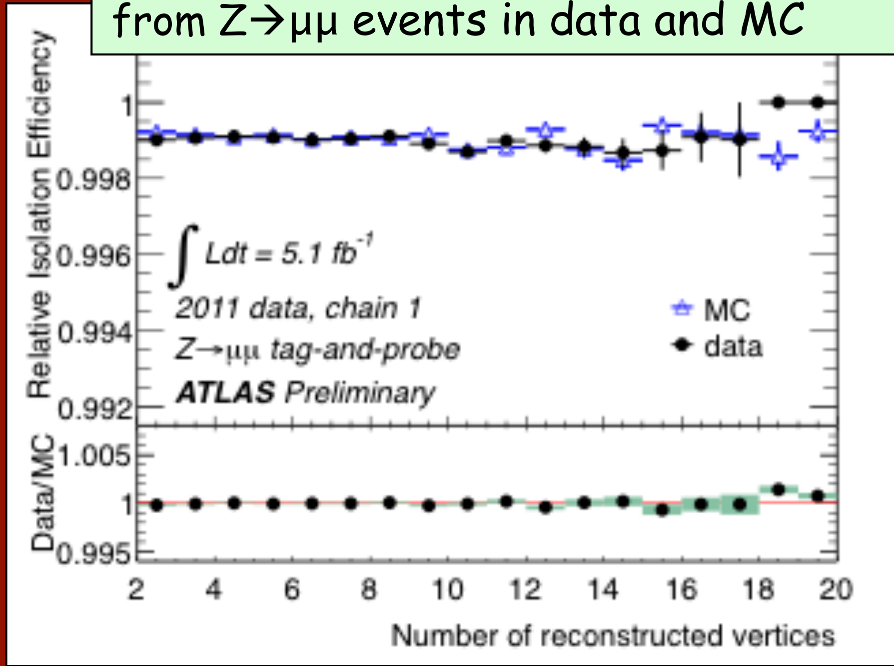
No Z-mass fit constraint

Improving Z→μμ mass resolution



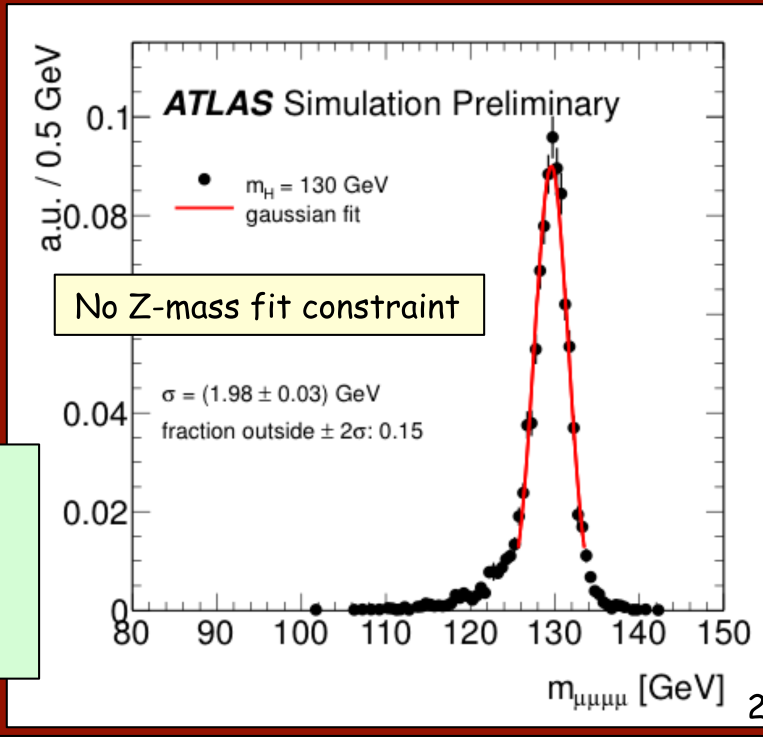
MC (perfect): 2.31±.01 GeV
Data Spring 2011 : 2.89±.01 GeV
Data Summer 2011: 2.45±.01 GeV

Muon (calorimetric) isolation efficiency from Z→μμ events in data and MC



Muon performance

Muon reconstruction efficiency > 95% over 4 < p < 100 GeV



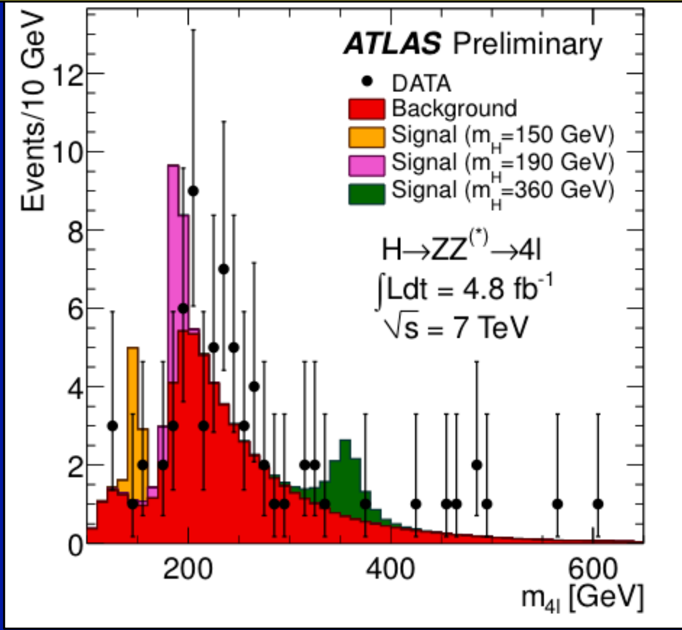
No Z-mass fit constraint

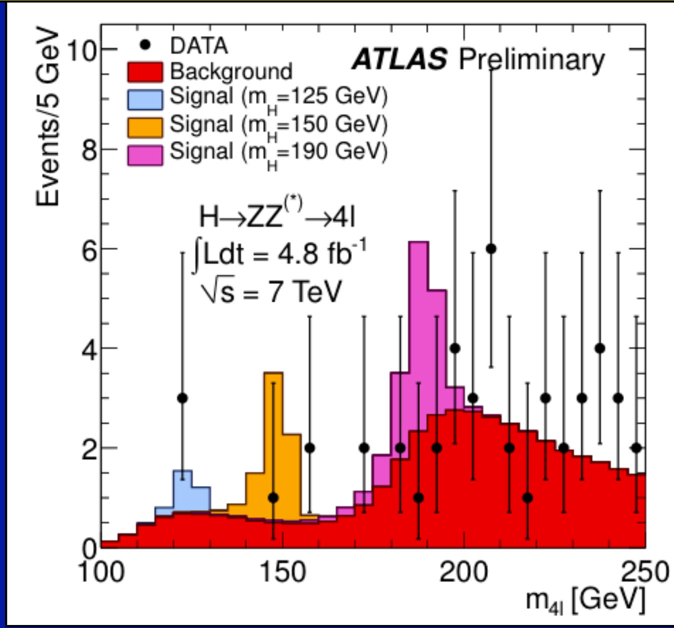
H→ 4μ mass resolution: ~2 GeV
Event fraction in ±2σ: ~ 85%

After all selections: kinematic cuts, isolation, impact parameter

Full mass range
Observed: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9

m(4l) < 180 GeV
Observed: 8 events: 3 4μ + 3 2e2μ + 2 4e
Expected from background: 9.3±1.5





In the region m_H < 141 GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

In the region 117< m_{4l} <128 GeV
(containing ~90% of a m_H=125 GeV signal):

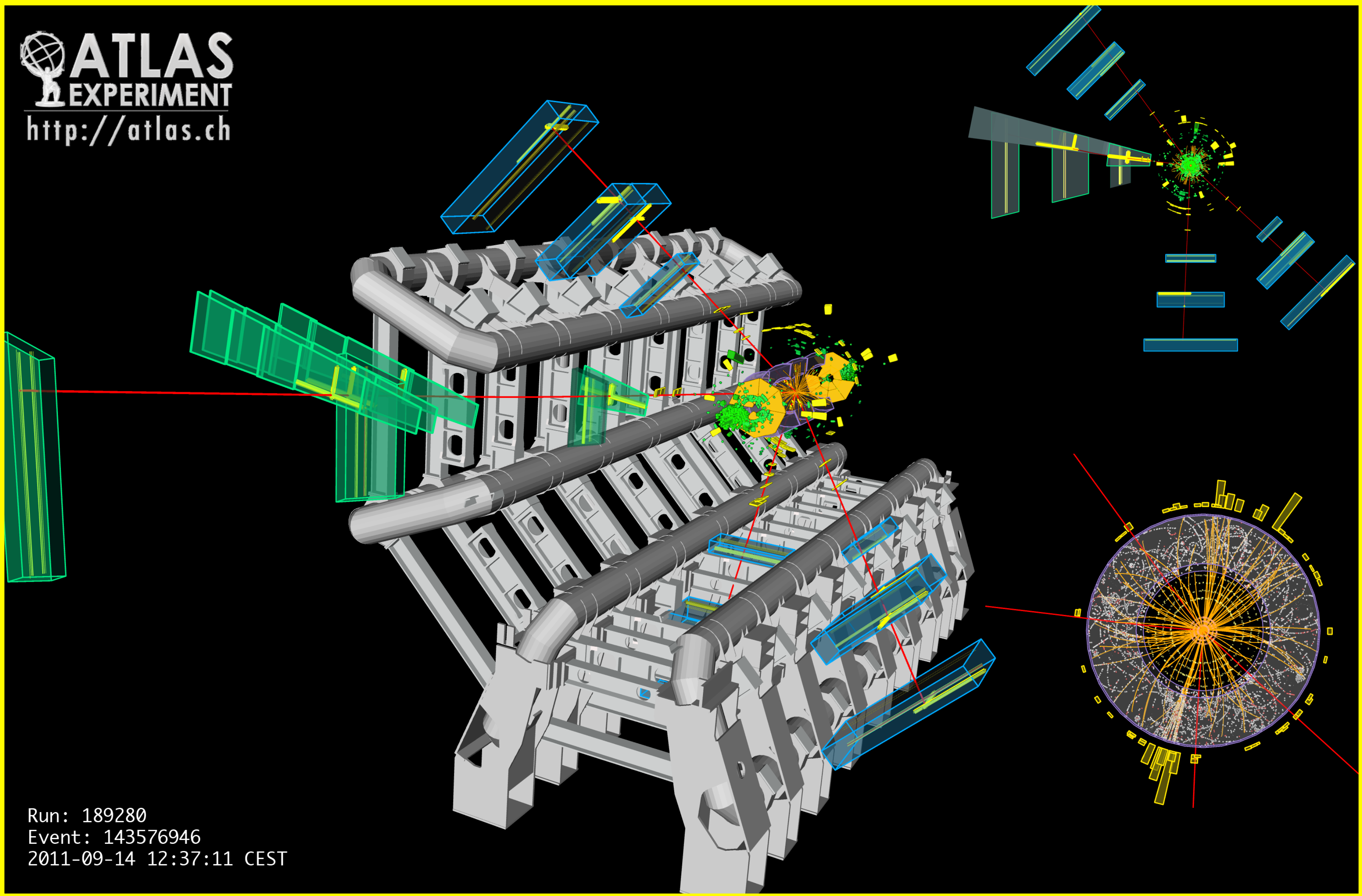
- similar contributions expected from signal and background: ~ 1.5 events each
- S/B ~ 2 (4μ), ~ 1 (2e2μ), ~ 0.3 (4e)
- Background dominated by ZZ* (4μ and 2e2μ), ZZ* and Z+jets (4e)

Main systematic uncertainties

Higgs cross-section	: ~ 15%
Electron efficiency	: ~ 2-8%
ZZ* background	: ~ 15%
Zbb, +jets backgrounds	: ~ 40%

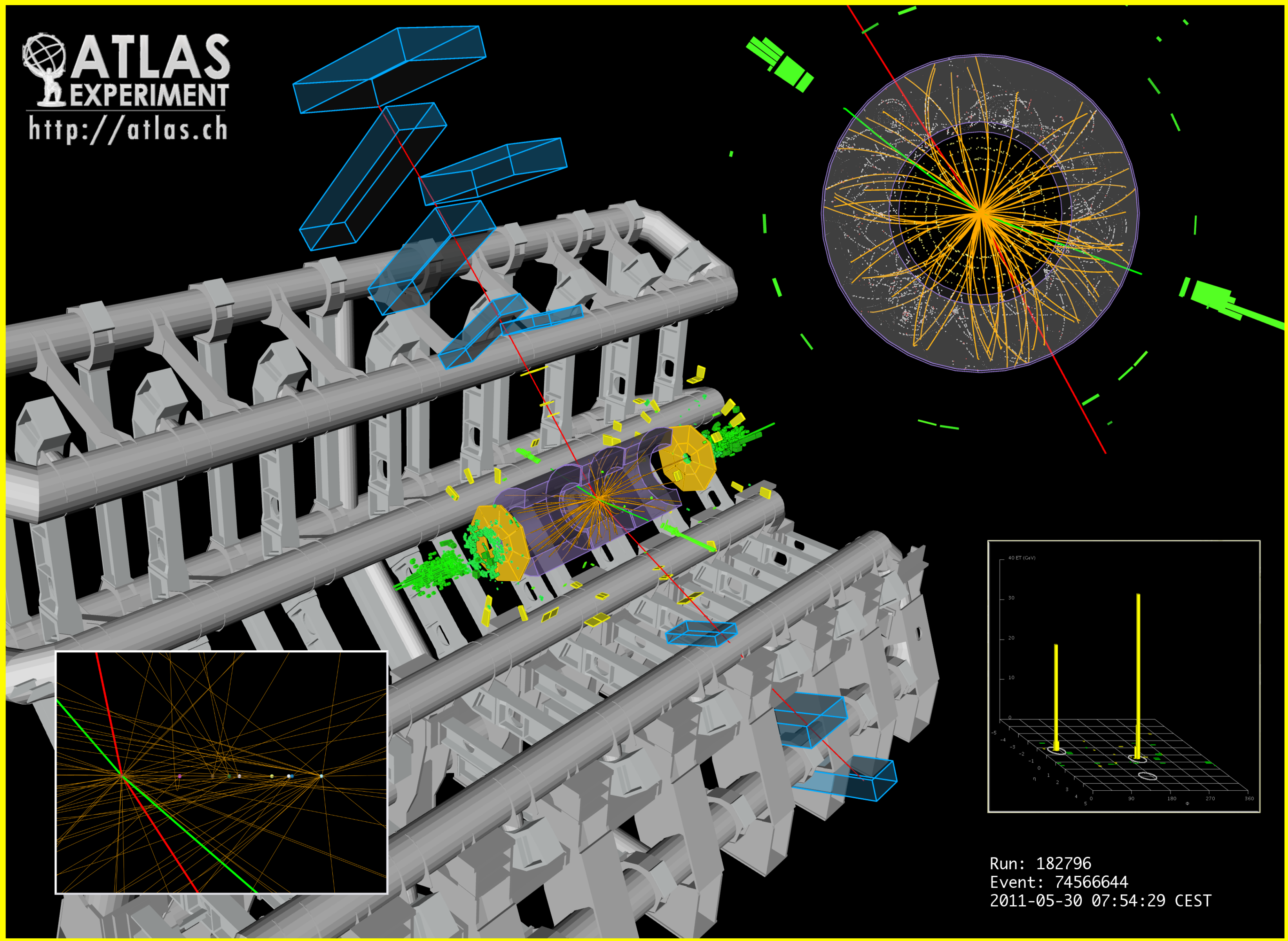
4μ candidate with $m_{4\mu}$= 124.6 GeV

p_T (μ^-, μ^+, μ^+, μ^-)= 61.2, 33.1, 17.8, 11.6 GeV
m_{12}= 89.7 GeV, m_{34}= 24.6 GeV



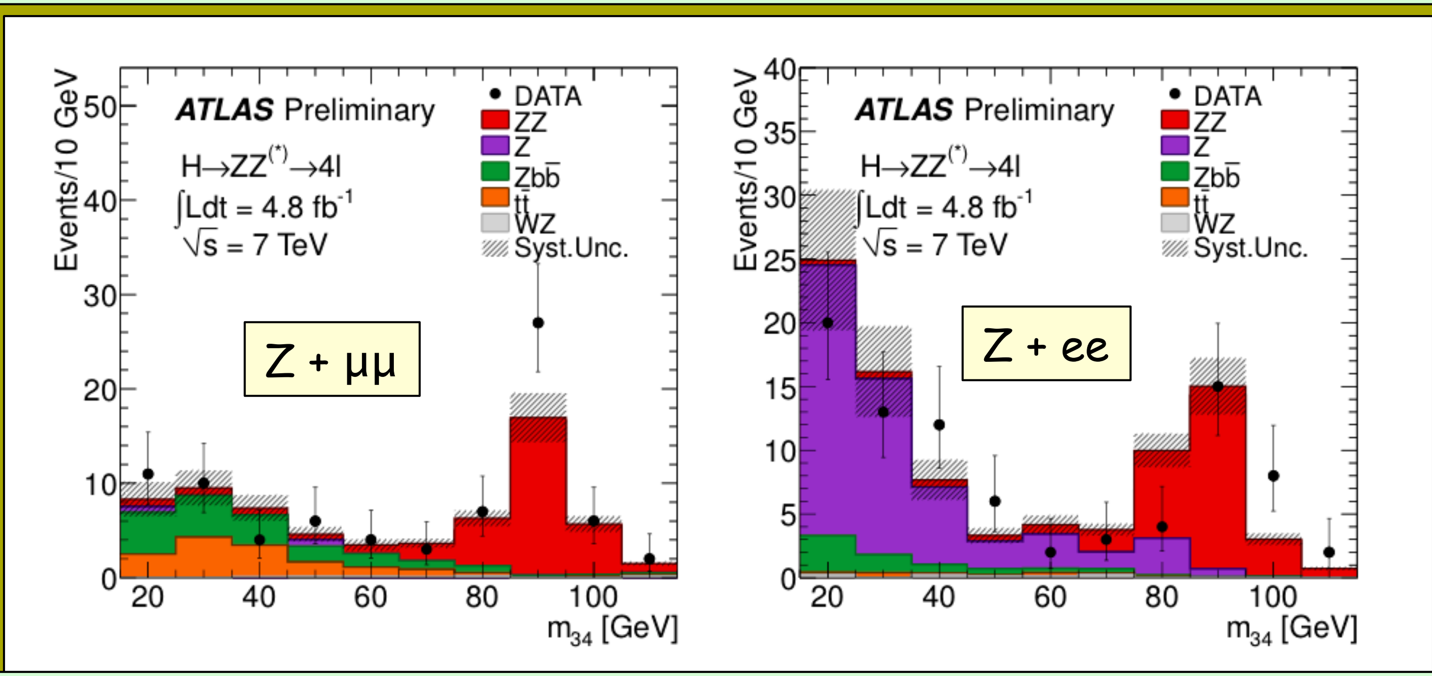
2e2μ candidate with $m_{2e2\mu}$= 124.3 GeV

p_T (e^+, e^-, μ^-, μ^+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e^+e^-)= 76.8 GeV, m($\mu^+\mu^-$) = 45.7 GeV



Reducible backgrounds from Zbb, Z+jets, tt giving 2 genuine + 2 fake leptons measured using background-enriched-signal-depleted control regions in data mimicking as much as possible the kinematics of the signal region → compromise between statistics and "purity"

Zbb+Z+jets control regions: events with:
- 2 opposite-sign same-flavour leptons, $m_{ll}=m_Z \pm 15$ GeV
- 2 additional same-flavour leptons passing all cuts but isolation and impact parameter
  → below plots of their invariant mass (m_{34})

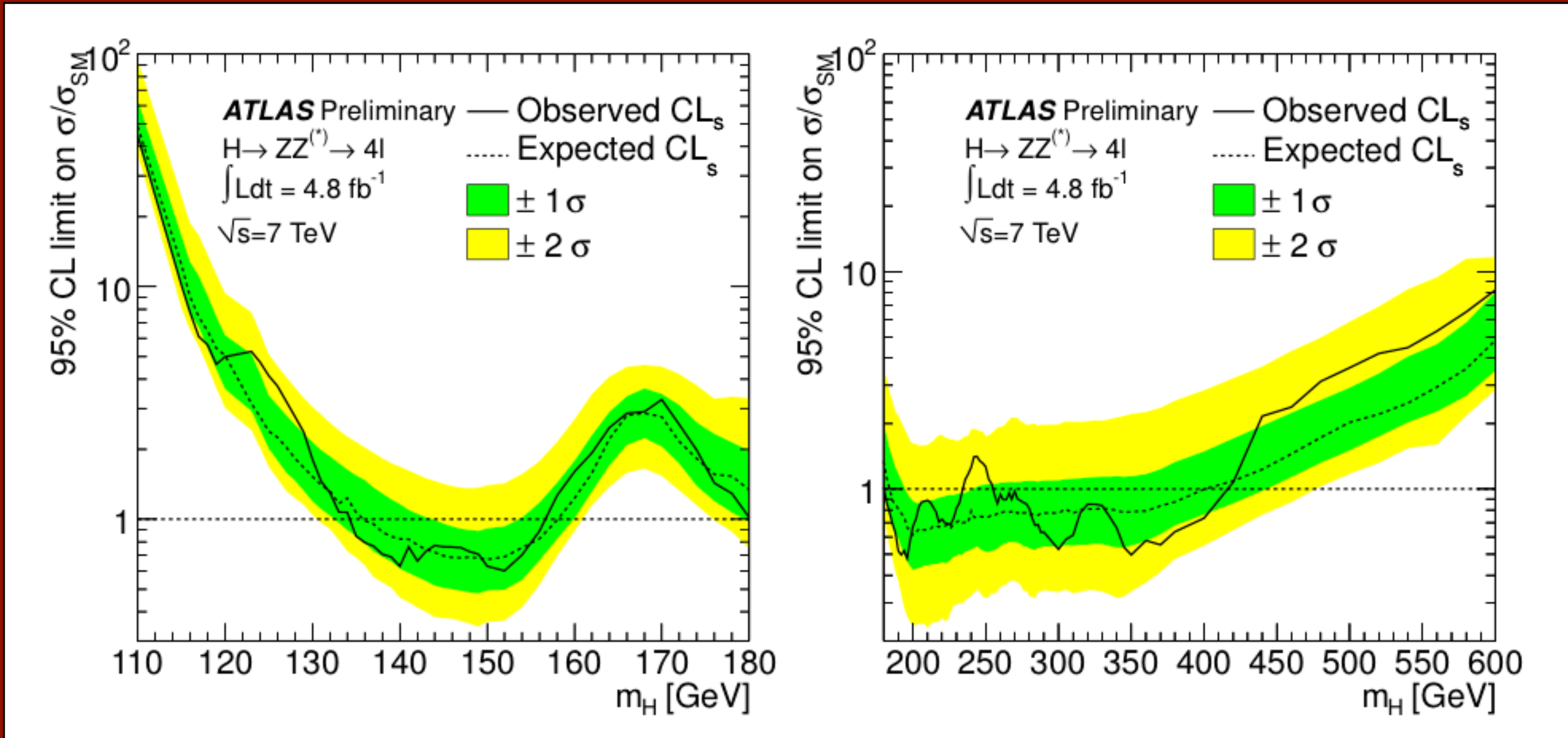


- Low-mass regions dominated by Zbb ($Z+\mu^+\mu^-$ sample) and Z+jet ($Z+e^+e^-$ sample)
- Data well reproduced by MC (within uncertainties)
- Samples of Z+μ and Z+e then used to compare efficiencies of isolation and impact parameter cuts between data and MC → Good agreement

	Data	MC
Z+μ	20±1%	20.3± 0.4%
Z+e	29.9±0.6%	30.4± 0.4%

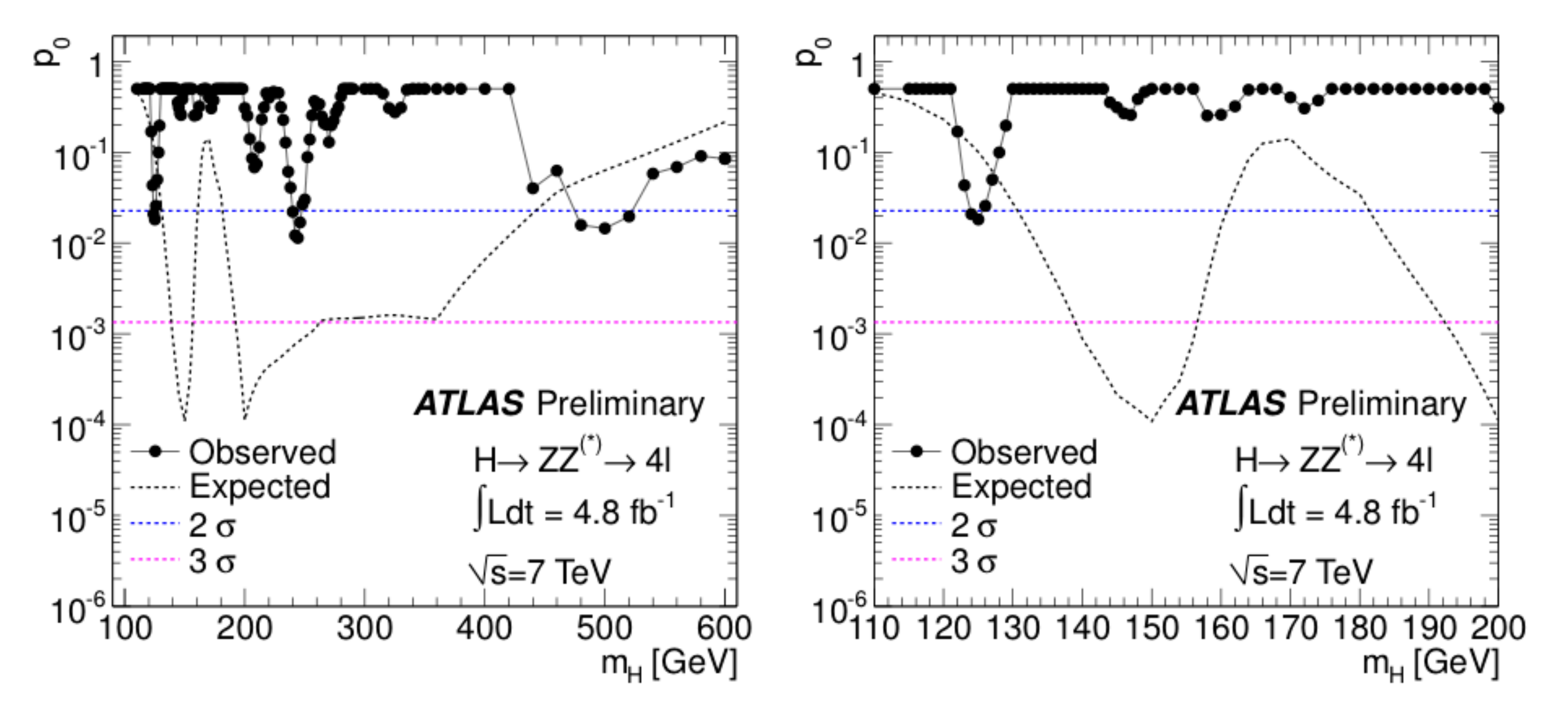
→ MC used to estimate background contamination in signal region

From fit of signal and background expectations to 4l mass spectrum



Excluded (95% CL): $135 < m_H < 156$ GeV and $181 < m_H < 415$ GeV (except 234-255 GeV)
Expected (95% CL): $137 < m_H < 158$ GeV and $185 < m_H < 400$ GeV

Consistency of the data with the background-only expectation



Maximum deviations from background-only expectations

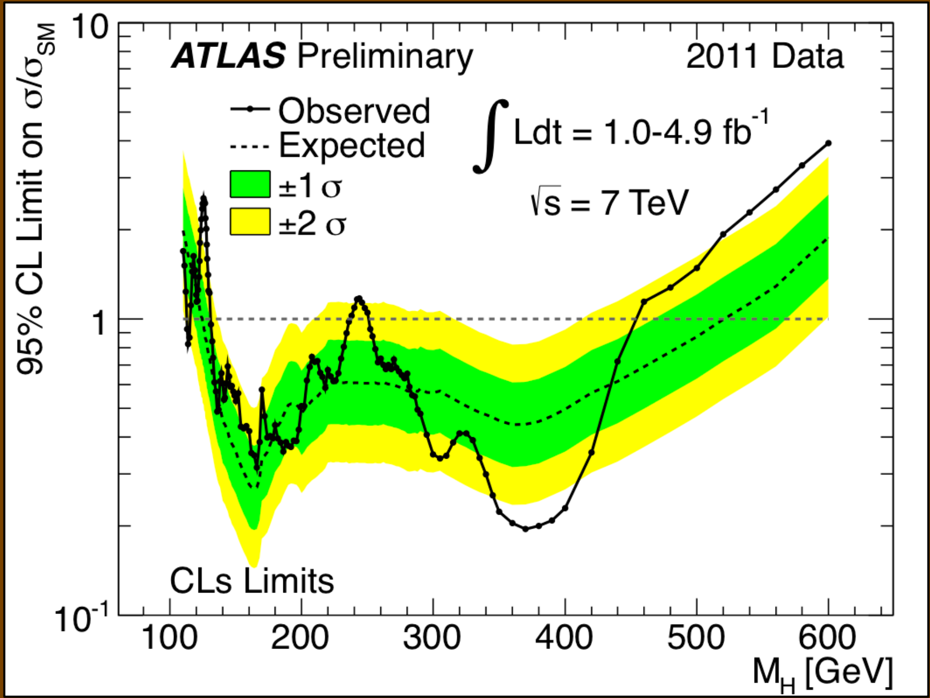
Excluded at 95% C.L. by ATLAS+CMS combination

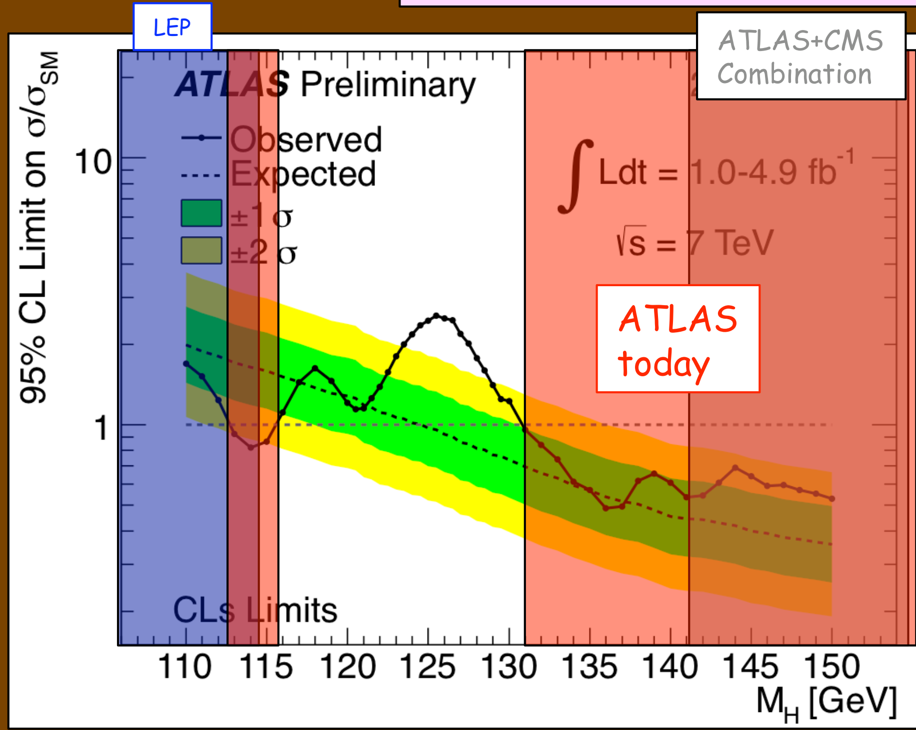
m_H (GeV)	Local (global) p_0	Local significance	Expected from SM Higgs
125	1.8% (~50%)	2.1 σ	1.4σ
244	1.1% (~50%)	2.3 σ	3.2σ
500	1.4% (~50%)	2.2 σ	1.5σ

LEE estimated over mass range: 110-600 GeV

Putting all channels together → combined constraints

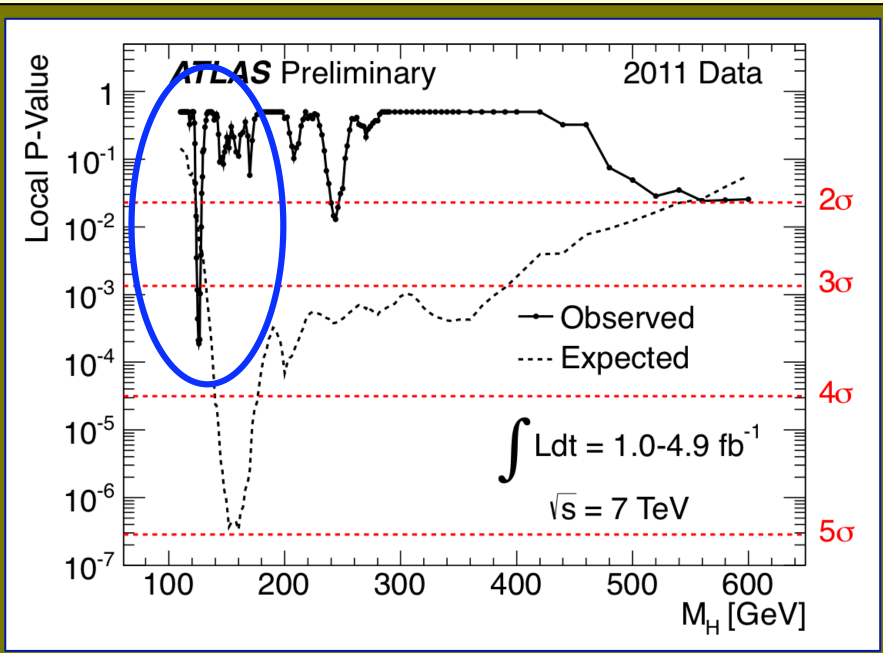
$H \to \gamma\gamma$, $H \to \tau\tau$
$H \to WW^{(*)} \to l\nu l\nu$
$H \to ZZ^{(*)} \to 4l$, $H \to ZZ \to ll\nu\nu$
$H \to ZZ \to llqq$, $H \to WW \to l\nu qq$
$W/ZH \to lbb+X$ not included

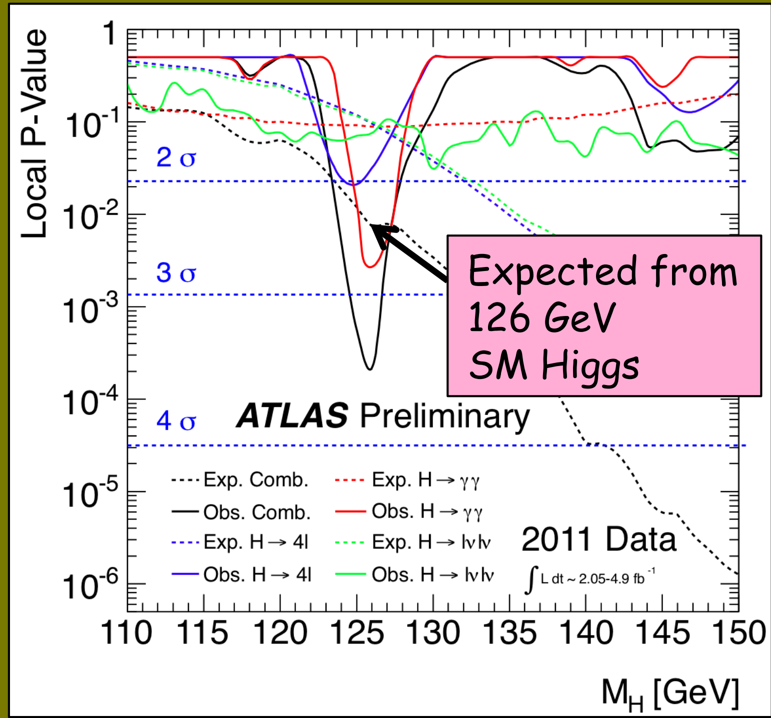




Excluded at 95% CL	$112.7 < m_H < 115.5$ GeV $131 < m_H < 453$ GeV, except 237-251 GeV
Expected if no signal	124.6-520 GeV
Excluded at 99% CL	$133 < m_H < 230$ GeV, $260 < m_H < 437$ GeV

Consistency of the data with the background-only expectation





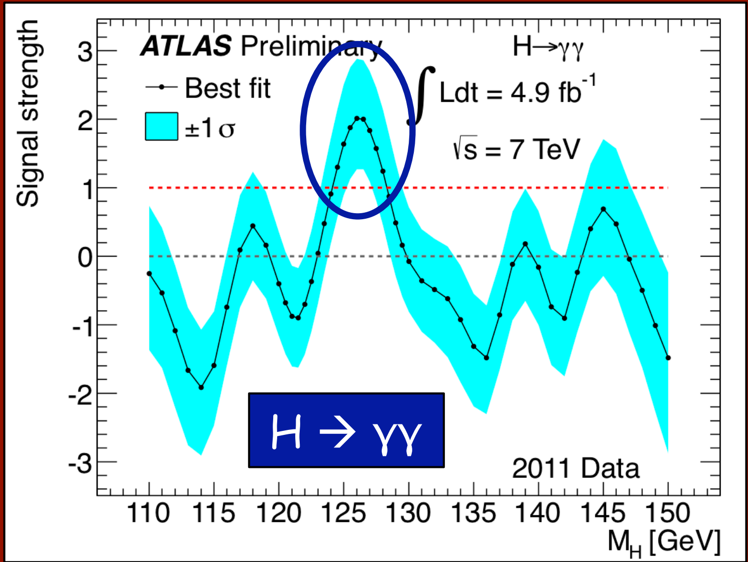
Maximum deviation from background-only expectation observed for m_H~126 GeV

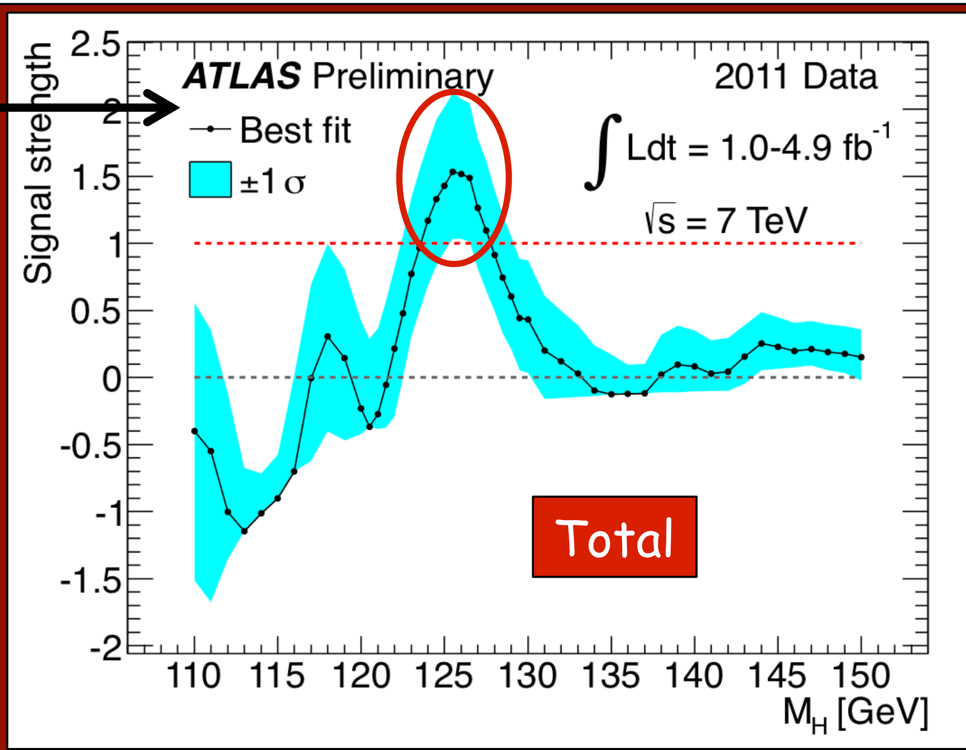
Local p_0-value: 1.9 10^{-4}
→ local significance of the excess: 3.6σ
~ 2.8σ H→ γγ, 2.1σ H→ 4l, 1.4σ H→ lνlν

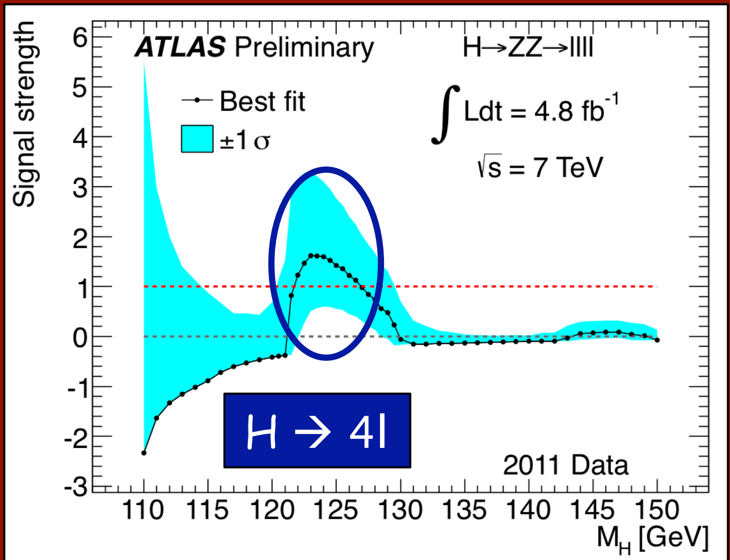
Expected from SM Higgs: ~2.4σ local (~1.4σ per channel)

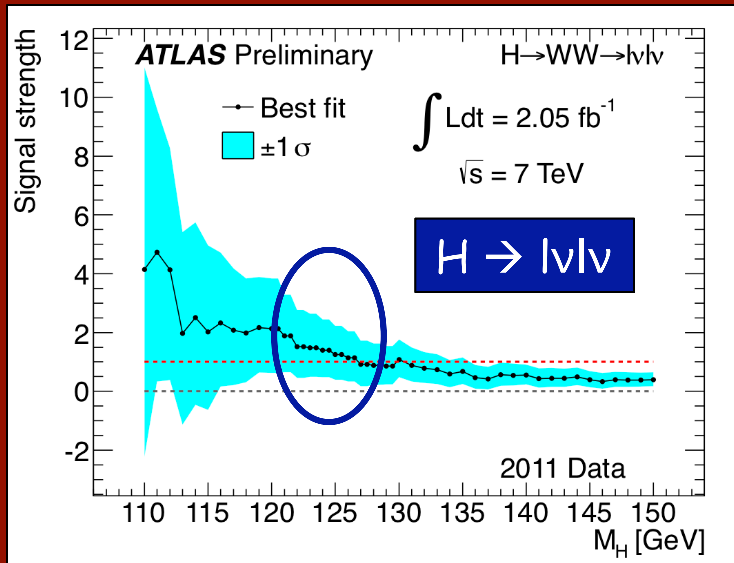
Global p_0-value : 0.6% →2.5σ LEE over 110-146 GeV
Global p_0-value : 1.4% →2.2σ LEE over 110-600 GeV

Compatibility of the observation with the expected strength of a SM Higgs signal









The observed excess is slightly larger (2±0.8) than expected in the H→γγ channel and compatible within 1σ for the other channels and the combined result

La suite …

Improve analysis sensitivities:

- update $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$, $W/ZH \rightarrow bb$ and $H \rightarrow \tau\tau$ to ~5 fb^{-1}
- relax kinematic cuts (e.g. lepton p_T) to increase acceptance at low masses
- multivariate techniques, exclusive channels (e.g $H \rightarrow \gamma\gamma$ + 0/1/2 jets), additional discriminating variables beyond mass spectra (p_T, angular distributions, etc.)

In parallel: improvements of the detector performance and modeling (a never-ending feat …)

One of the numerous lessons and outstanding achievements of the Tevatron:
how much better than expectation experiments can do with data and ingenuity !

Combine with CMS: being discussed …
Not before results from individual experiments are published

MORE DATA → 2012 run:

~ 20 fb^{-1} more per experiment of delivered luminosity needed for:

- 5σ discovery at m_H~ 125 GeV with ~ 3σ per channel (ATLAS alone)
- 5σ discovery down to ~ 116 GeV (ATLAS+CMS combined)

"Contingency": analysis improvements; $\sqrt{s}$=8 TeV (brings ~ 10% sensitivity gain)

Conclusions

It has been a wonderful year for the LHC and ATLAS → THANKS LHC TEAM !

We have looked for a SM Higgs boson
- over the mass region 110-600 GeV
- in 11 distinct channels
- using up to 4.9 fb^{-1} of integrated luminosity

→

We have restricted the most likely mass region (95% CL) to

115.5-131 GeV

We observe an excess of events around $m_H \sim 126$ GeV:
- local significance 3.6 σ, with contributions from the $H \to \gamma\gamma$ (2.8 σ), $H \to ZZ^* \to 4l$ (2.1 σ), $H \to WW^{(*)} \to l\nu l\nu$ (1.4 σ) analyses
- SM Higgs expectation: 2.4 σ local → observed excess compatible with signal strength within +1σ
- the global significance (taking into account Look-Elsewhere-Effect) is **~2.3σ**

It would be a <u>very nice</u> region for the Higgs to be → accessible at LHC in γγ, 4l, lνlν, bb, ττ

It's too early to draw definite conclusions
More studies and more data are needed
We have built solid foundations for the (exciting !) months to come

What an extraordinary time !

Argentina
Armenia
Australia
Austria
Azerbaijan
Belarus
Brazil
Canada
Chile
China
Colombia
Czech Republic
Denmark
France
Georgia
Germany
Greece
Israel
Italy
Japan
Morocco
Netherlands
Norway
Poland
Portugal
Romania
Russia
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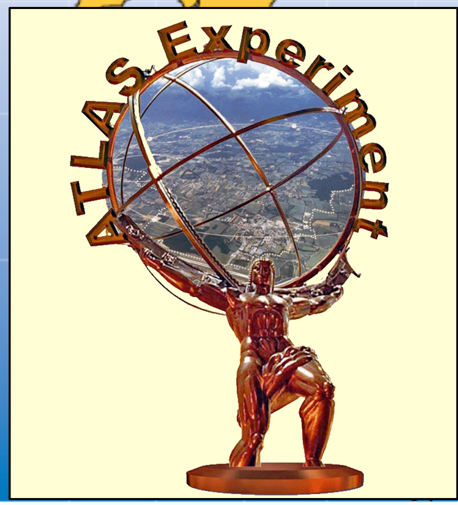
South Africa
Spain
Sweden
Switzerland
Taiwan
Turkey
UK
USA
CERN
JINR

ATLAS Collaboration



SPARES

ATLAS-CONF-2011-161 (13 December 2011)
Search for the Standard Model Higgs boson in the diphoton decay channel with 4.9 fb^{-1} of ATLAS data at $\sqrt{s}$=7 TeV

ATLAS-CONF-2011-162 (13 December 2011)
Search for the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^{(*)} \rightarrow 4l$ with 4.8 fb^{-1} of pp collisions at $\sqrt{s}$=7 TeV

ATLAS-CONF-2011-163 (13 December 2011)
Combination of Higgs Boson searches with up to 4.9 fb^{-1} of pp collisions data taken at a center-of-mass energy of 7 TeV with the ATLAS experiment at the LHC

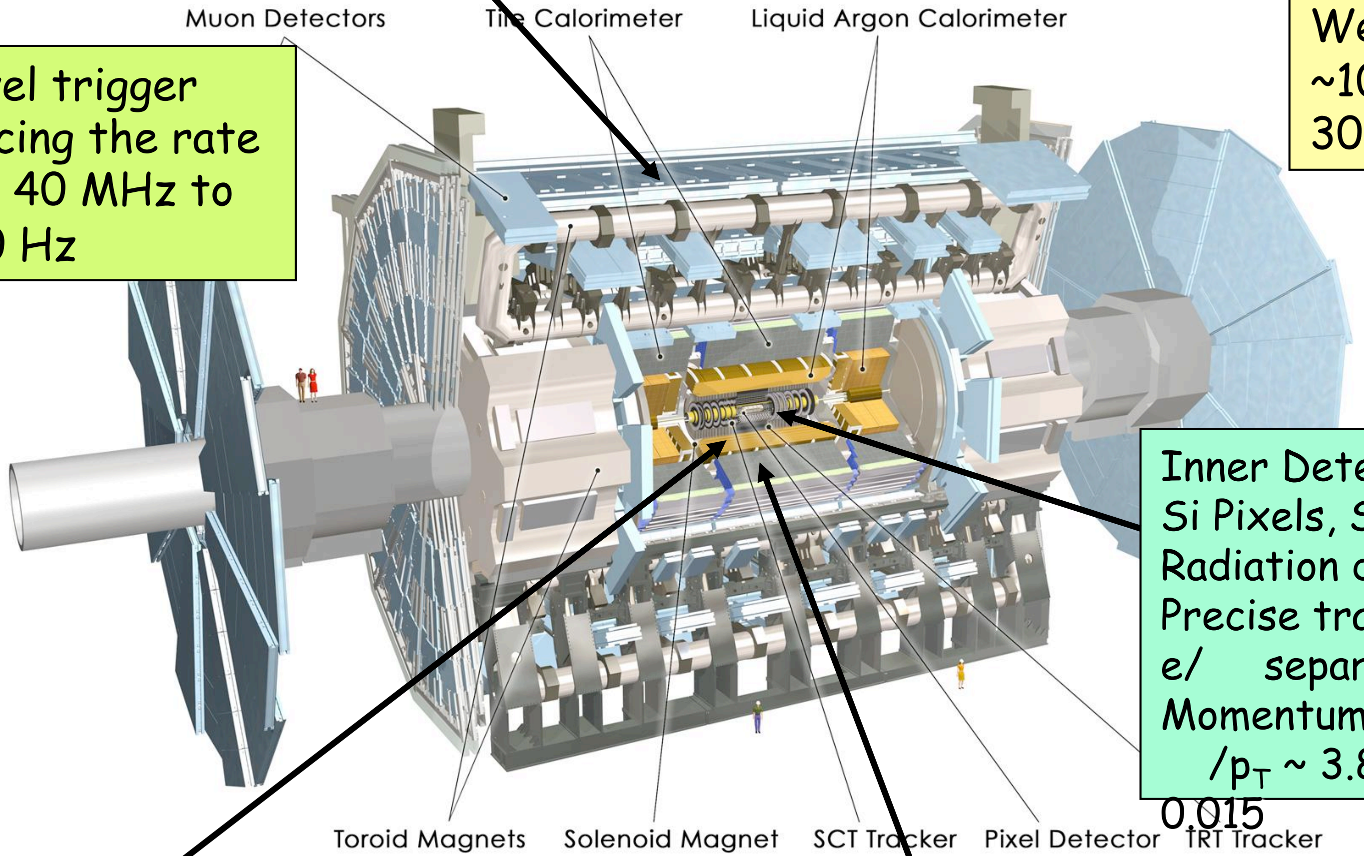
Submitted to PRL (12 December 2011)
Search for the Higgs boson in the $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$ decay channel in pp collisions at $\sqrt{s}$=7 TeV with the ATLAS detector

CONF notes available after the seminar at:
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/

Muon Spectrometer (|η|<2.7) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector (| |<2.5, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/ separation
Momentum resolution:
$/p_T \sim 3.8\times10^{-4}\, p_T\,(\mathrm{GeV})$
0.015

EM calorimeter: Pb-LAr Accordion
e/ trigger, identification and measurement
E-resolution: /E ~ 10%/ E

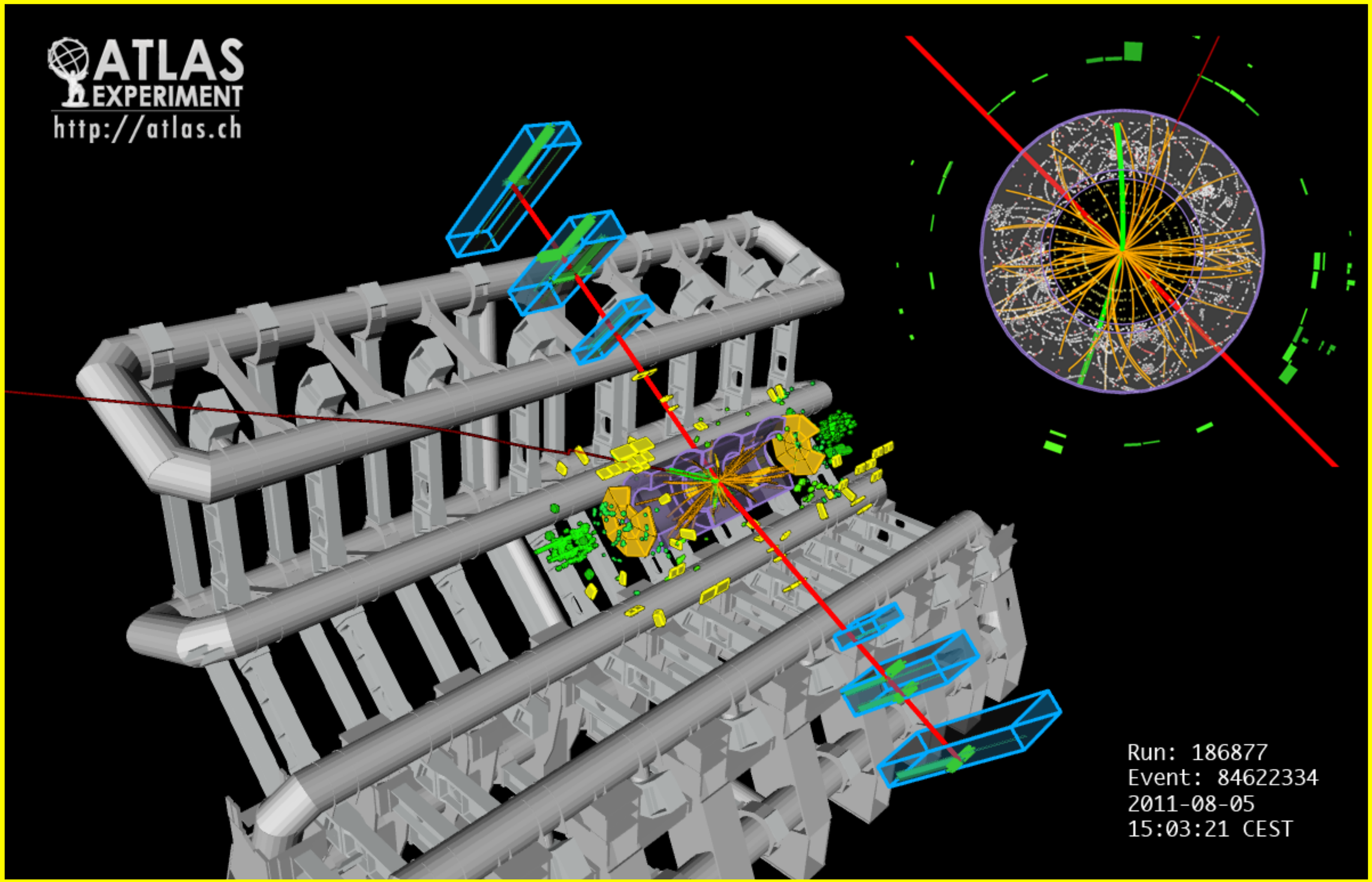
HAD calorimetry (|η|<5): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: σ/E ~ 50%/√E ⊕ 0.03

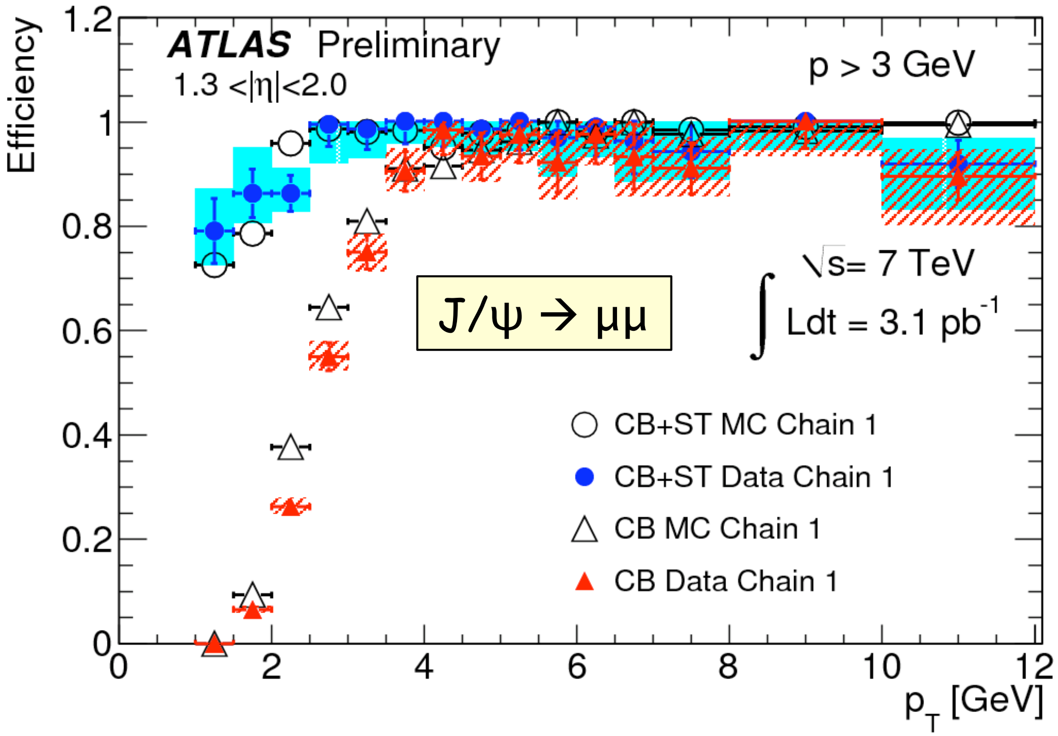
2011 Physics Proton Trigger Menu (end of run $L = 3.3\ 10^{33}\ cm^{-2}s^{-1}$)

	Offline Selection	Trigger Selection		L1 Rate (kHz) at 3e33	EF Rate (Hz) at 3e33
		L1	EF		
Single leptons	Single muon > 20GeV	11 GeV	18 GeV	8	100
	Single electron > 25GeV	16 GeV	22 GeV	9	55
Two leptons	2 muons > 17, 12GeV	11GeV	15,10GeV	8	4
	2 electrons, each > 15GeV	2x10GeV	2x12GeV	2	3
	2 taus > 45, 30GeV	15,11GeV	29,20GeV	7.5	15
Two photons	2 photons, each > 25GeV	2x12GeV	20GeV	3.5	5
Single jet plus MET	Jet pT > 130 GeV & MET > 140 GeV	50 GeV & 35 GeV	75GeV & 55GeV	0.8	18
MET	MET > 170 GeV	50 GeV	70GeV	0.6	5
Multi-jets	5 jets, each pT > 55 GeV	5x10GeV	5x30GeV	0.2	9
TOTAL				**<75**	**~400 (mean)**

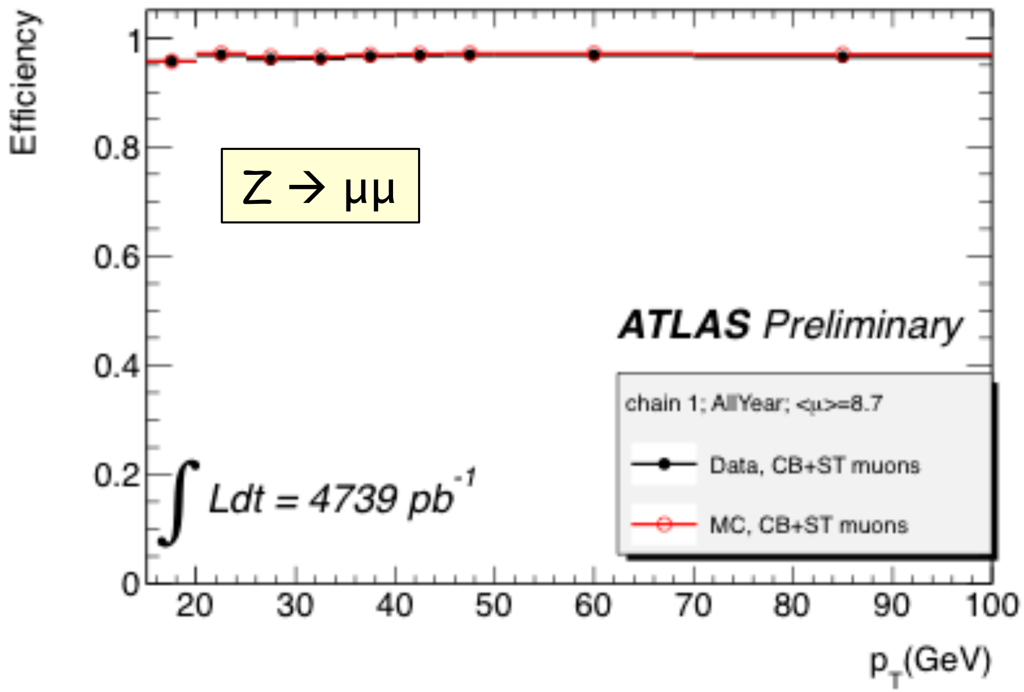
2μ2e candidate with $m_{2\mu 2e}$= 123.6 GeV

p_T (μ^-, μ^+, e^-, e^+)= 43.9, 43.5, 11.2, 9.9 GeV
m($\mu^+\mu^-$) = 89.3 GeV, m (e^+e^-)= 30 GeV





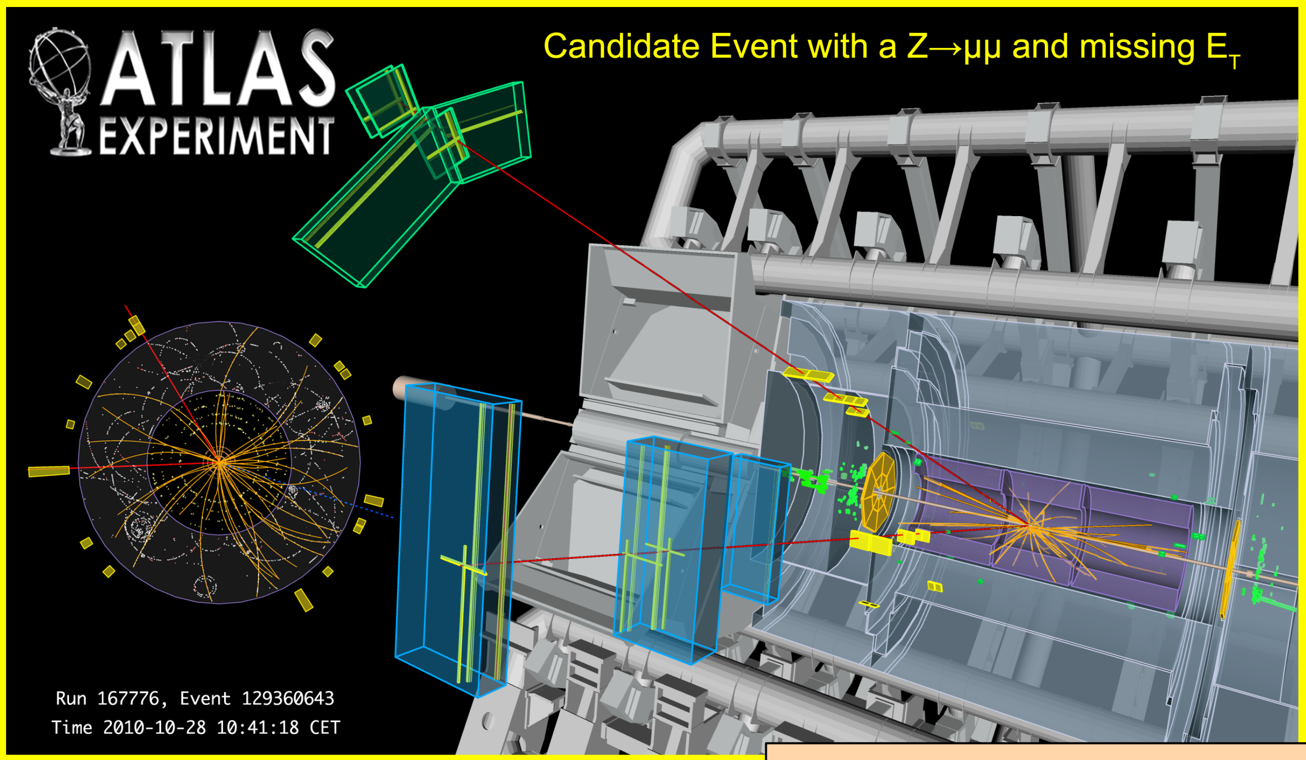
Muon reconstruction efficiency from Tag & Probe



$H \rightarrow ZZ \rightarrow ll\nu\nu$ (l=e,μ)

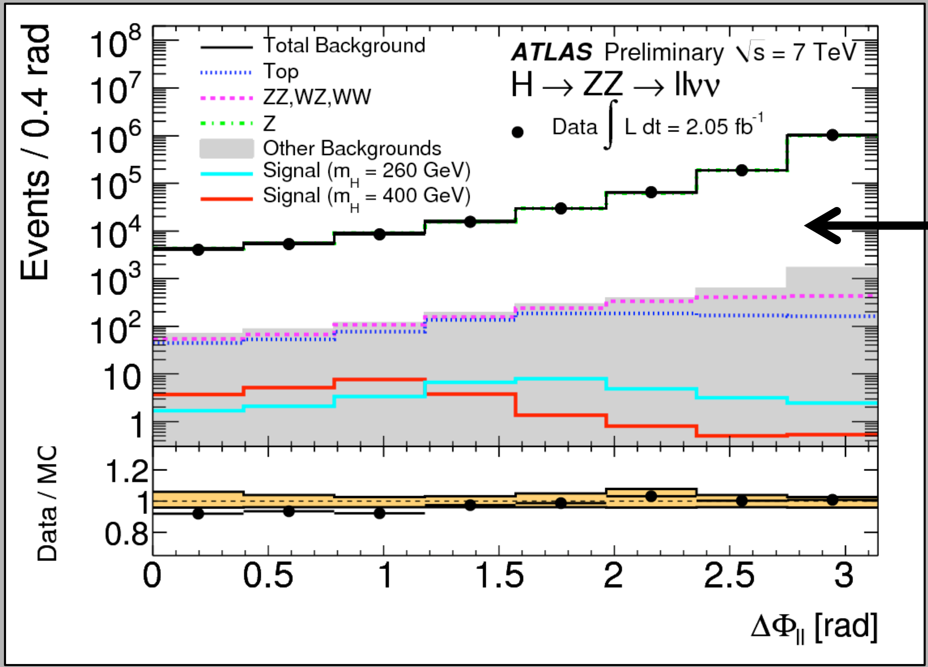
$200 \leq m_H \leq 600$ GeV

- Larger BR than $H \rightarrow 4l$: → $\sigma \sim 20$ fb
  Good S/B
  → most sensitive channel for $m_H > 300$ GeV
- Signature is $Z \rightarrow ll$ + large E_T^{miss} (both Z's are boosted for large m_H)
- Main backgrounds: ZZ (irreducible), top, Z+jets
  → reject with E_T^{miss} cut (> 66-82 GeV), b-jet veto, topology (small $\Delta\phi_{ll}$, m_T shape)



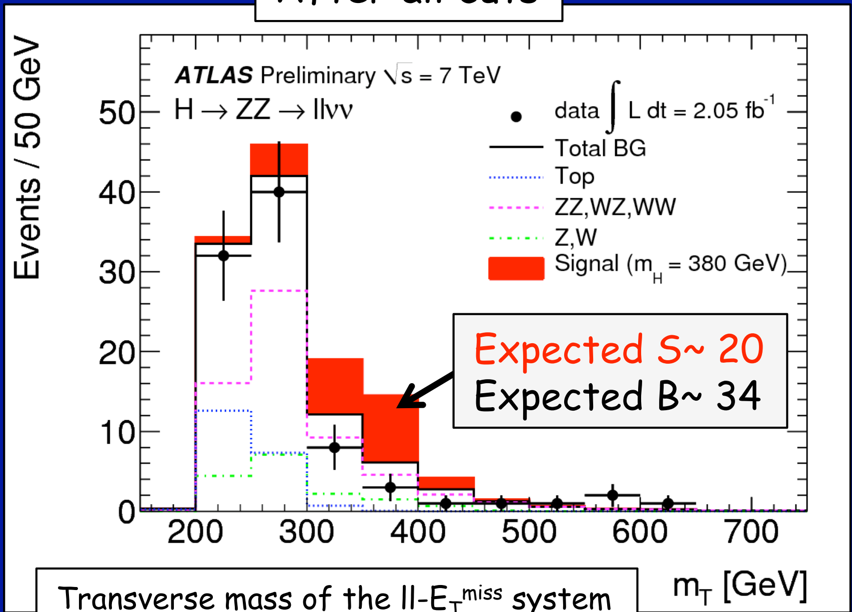
$ZZ \rightarrow \mu\mu\nu\nu$ candidate:
$m(\mu^+\mu^-) = 93.8$ GeV
$p_T(Z)=156$ GeV
$E_T^{miss} = 161$ GeV

Crucial experimental aspects:
- understand E_T^{miss} spectrum, in particular tails from mis-measured jets (Z+jets is 10^5 larger than signal !)
- understand shape of (irreducible) ZZ background



Δφ between leptons from Z→ ll decays
→ exploit to distinguish boosted Z from Higgs decays from Z+jets and other backgrounds

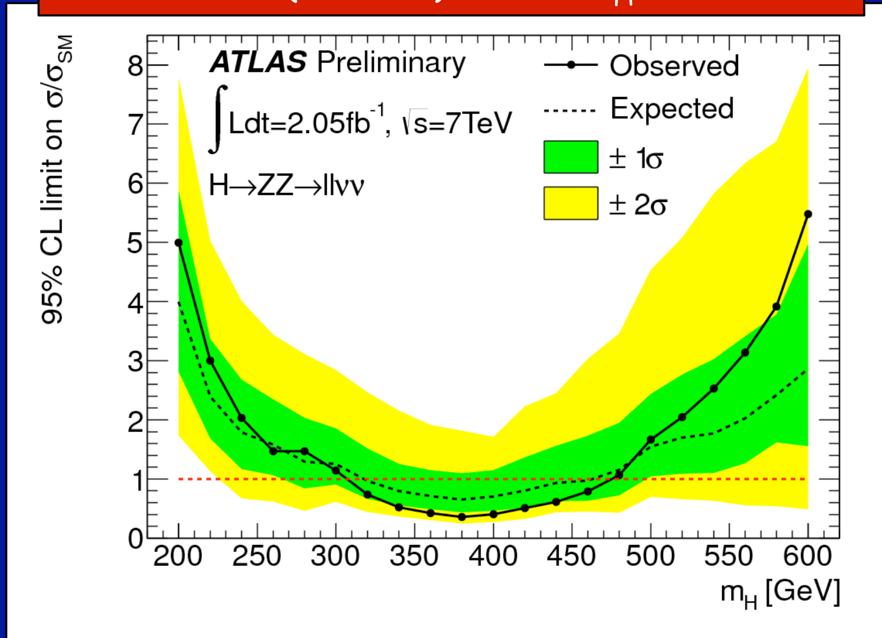
After all cuts



Expected S~ 20
Expected B~ 34

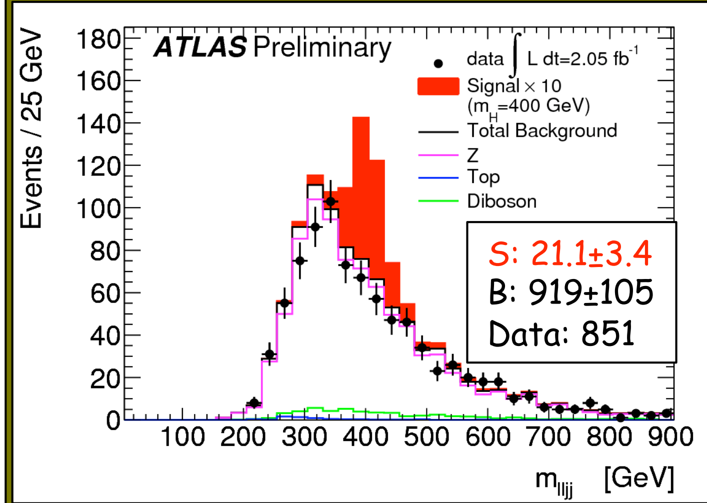
Transverse mass of the ll-E_T^{miss} system

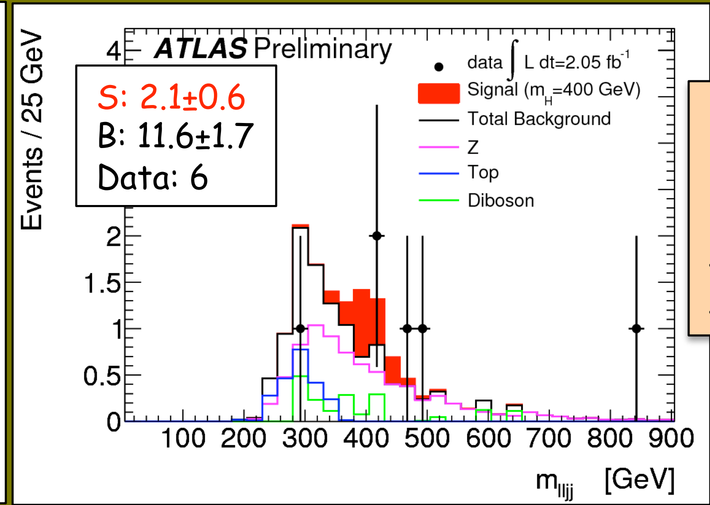
Excluded (95% CL): 310 ≤ m_H ≤ 470 GeV



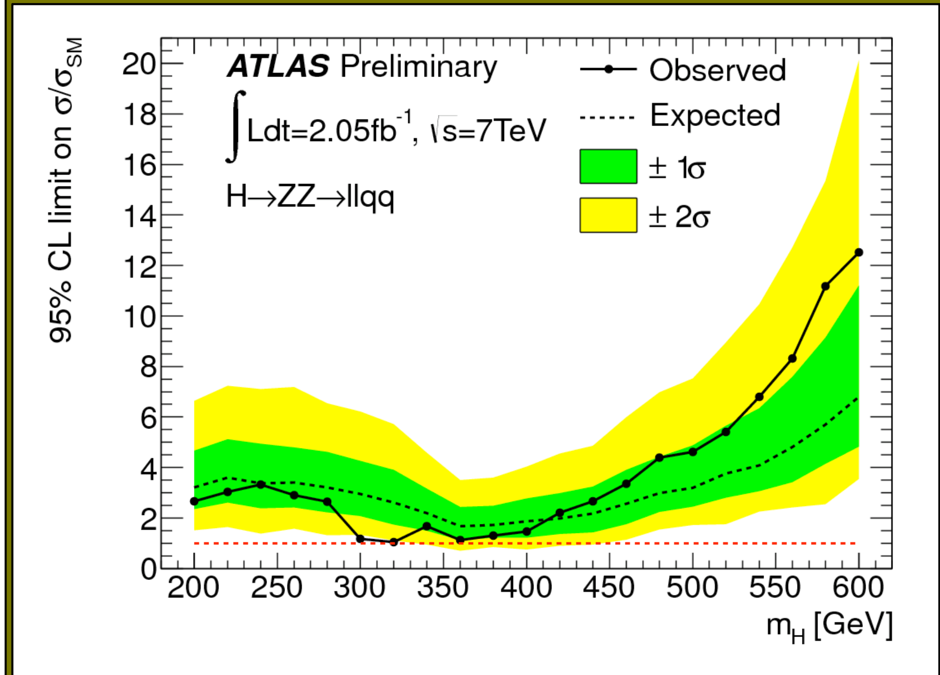
$H \rightarrow ZZ \rightarrow llqq$ ($l=e,\mu$)

$200 \leq m_H \leq 600$ GeV





lljj invariant mass for the untagged (left) and b-tagged (right) selections. The Higgs signal in the untagged plot is scaled by x 10.

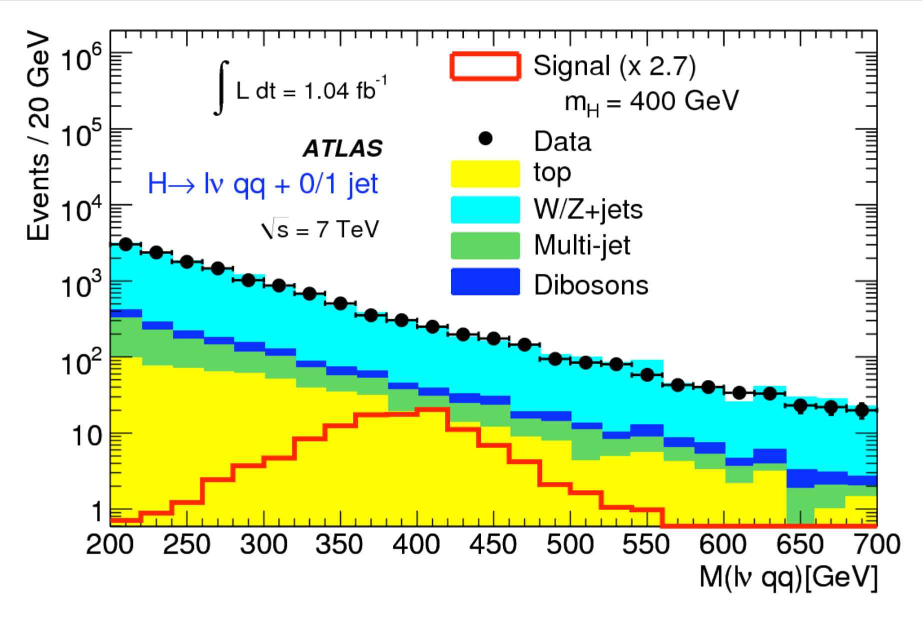


Helpful channel in the Higgs mass range $m_H > 2m_Z$
$\sigma \times BR \sim 10$ fb
Signature: $Z \rightarrow ll$+2 jets

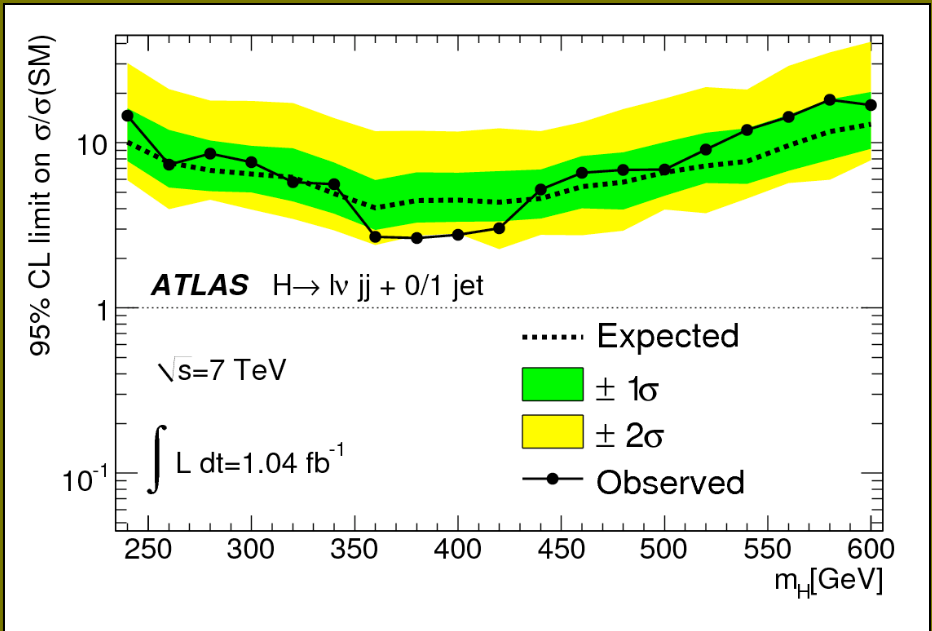
- Reconstruct a $Z \rightarrow ll$ and a second $Z \rightarrow jj$
- $E_T^{miss} < 50$ GeV against top background
- Reconstruct m_{lljj} (with m_{jj} scaled to m_Z)
- Z+jets background: MC normalised to data in the sidebands of the m_{jj} distribution
- Sample with b-tagged jets gives x10 smaller signal (~ 1 evt) but x10 larger S/B (~0.2)

$H \rightarrow WW \rightarrow l\nu qq$ (l=e,μ)

$240 \leq m_H \leq 600$ GeV

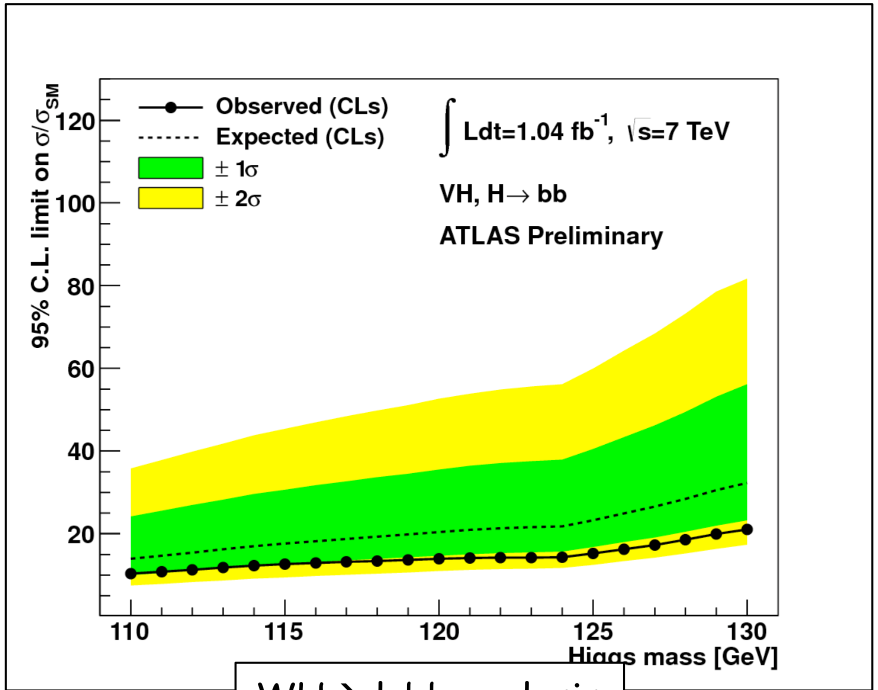


- $\sigma \times BR \sim 200$ fb
- 1 lepton p_T>30 GeV, E_T^{miss} > 30 GeV, 2-3 jets p_T > 25 GeV, no b-tagged jets
- m_{jj} compatible with m_W, constrain $m_{l\nu}=m_W$
- fit $m_{l\nu jj}$ mass spectrum with exponential function plus expected signal
- W+jets and multijet background from data (control samples with relaxed lepton identification or low E_T^{miss}), though not needed for limits extraction

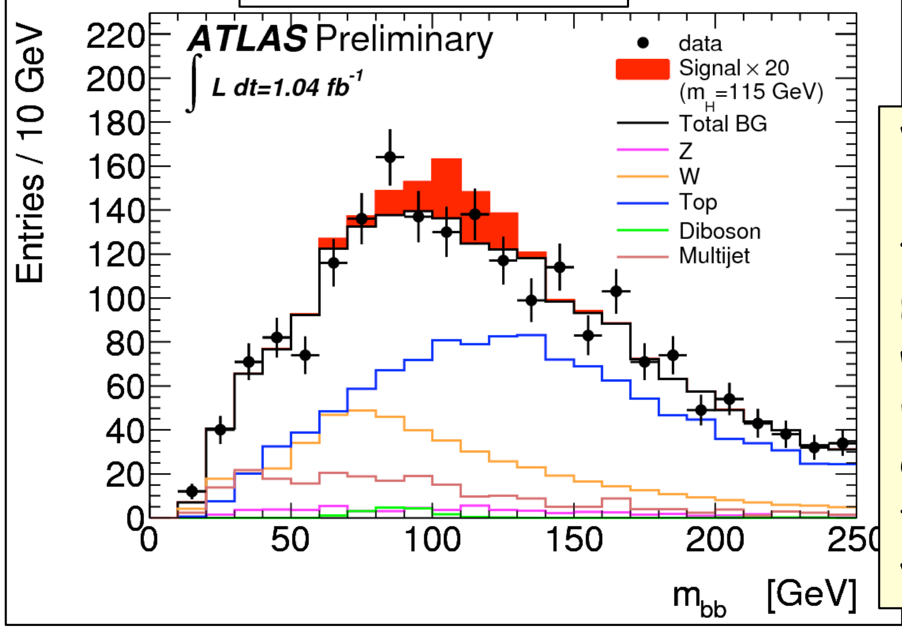


Data: 22161 events
Expected background: 22630 events
Expected signal (m_H=400 GeV): 43±12 events

WH → lνbb, ZH → ll bb (l=e,μ)



WH→ lνbb analysis



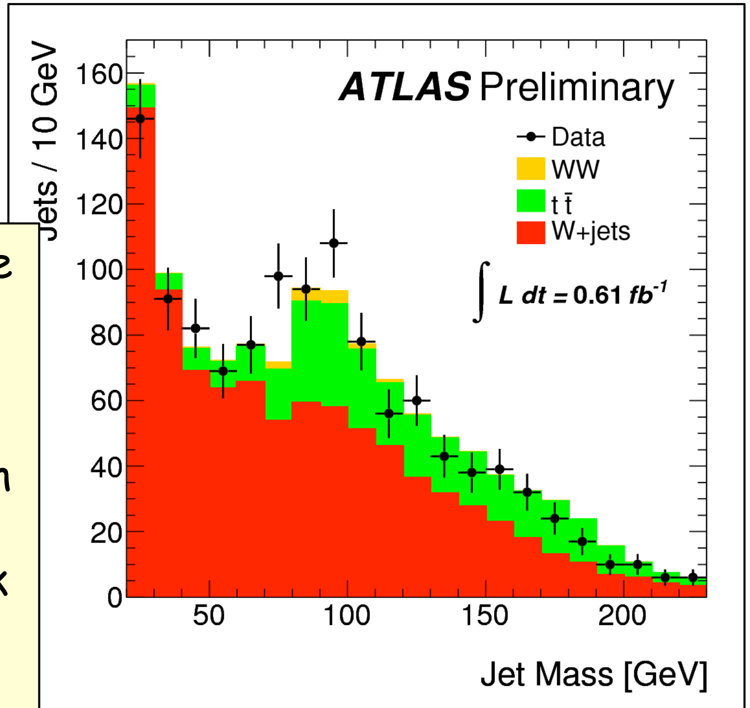
$110 \le m_H \le 130$ GeV

WH→ lνbb
- σ x BR ~ 80 fb
- 1 lepton p_T >25 GeV, E_T^{miss} > 25 GeV, $m_T(l\nu)$> 40 GeV, 2 b-tagged jets, no other jets
- Main backgrounds: Wbb, top

ZH→ llbb
- σ x BR ~ 15 fb
- 2 leptons p_T > 20 GeV, m_{ll}~m_Z, E_T^{miss} < 50 GeV, 2 b-tagged jets
- Main backgrounds: Zbb, top

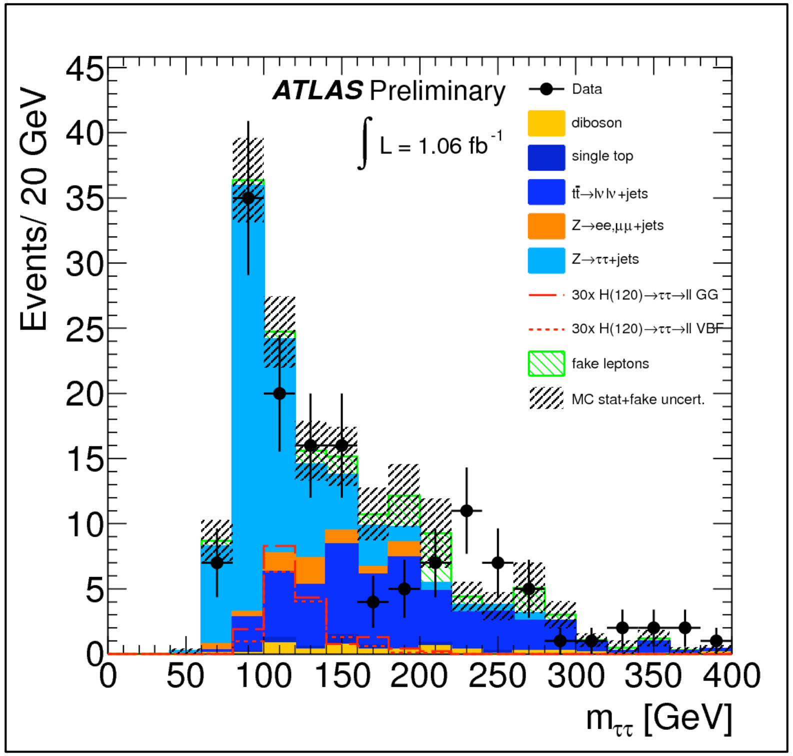
Backgrounds: from data (mainly from sidebands of m_{bb} distribution)

"Engineering" the boosted H→ bb technique: jet mass in events with W → lν with p_T>200 GeV
Clear W→jj peak from top events visible



$H \to \tau\tau \to ll$ + neutrinos (l=e,μ)

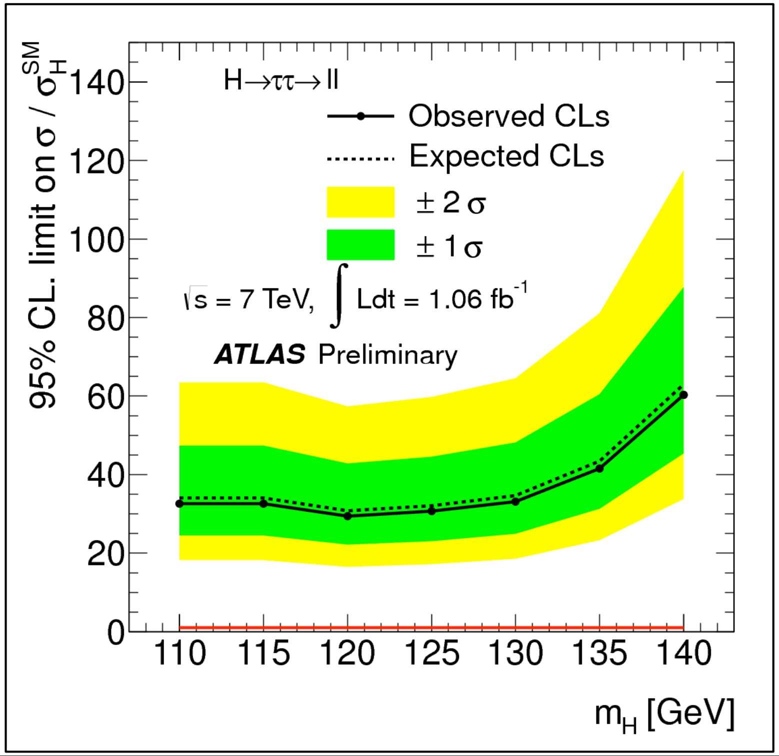
$110 \le m_H \le 140$ GeV

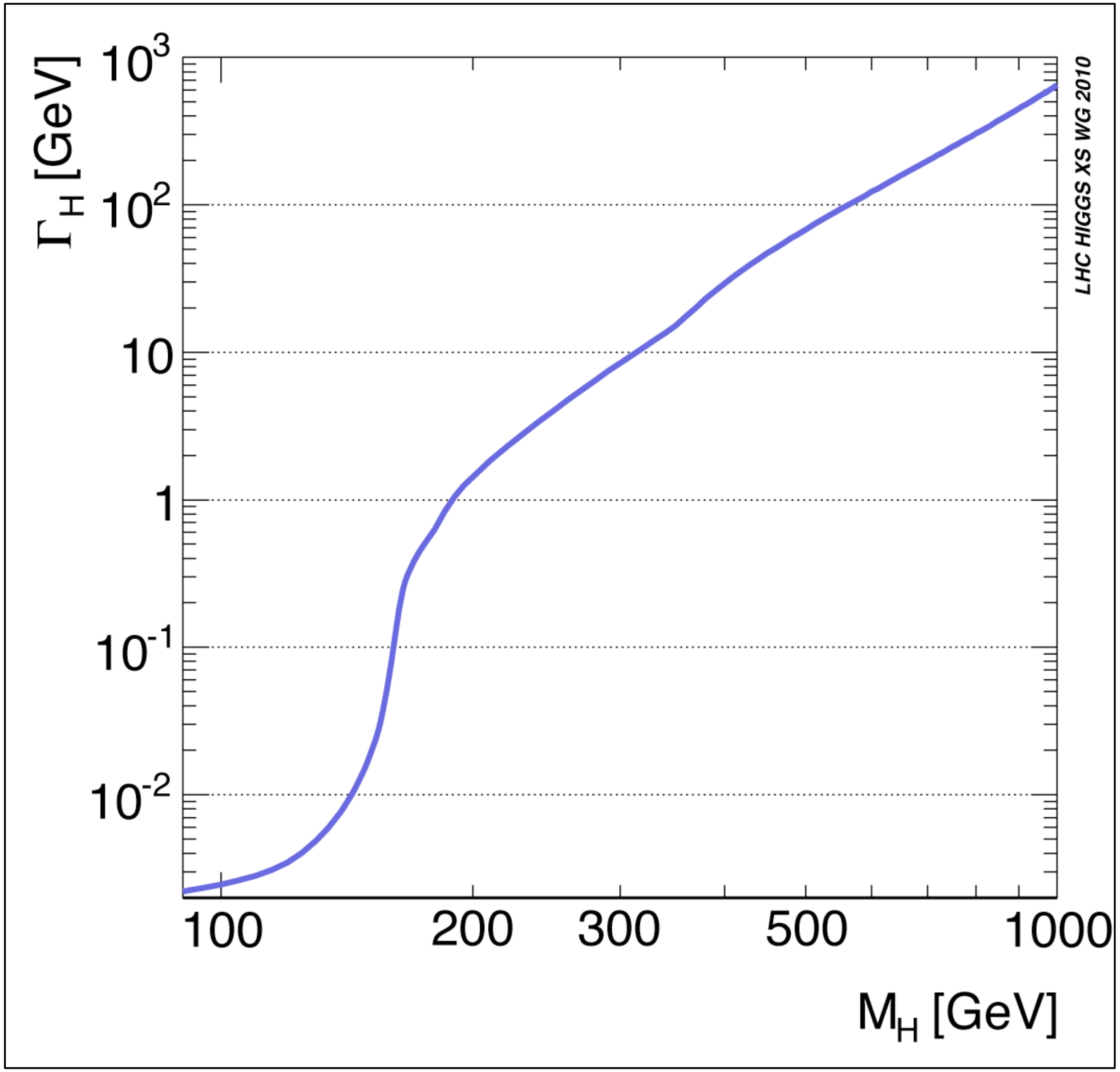


- $\sigma \times BR \sim 150$ fb
- $p_T(l) > 15\text{-}10$ GeV, $E_T^{miss} > 25\text{-}30$ GeV, $p_T(jet) > 40$ GeV (enhances S/B), topological cuts
- $m_{\tau\tau}$ from collinear approximation: 100-150 GeV
- Main backgrounds: $Z \to \tau\tau$, top

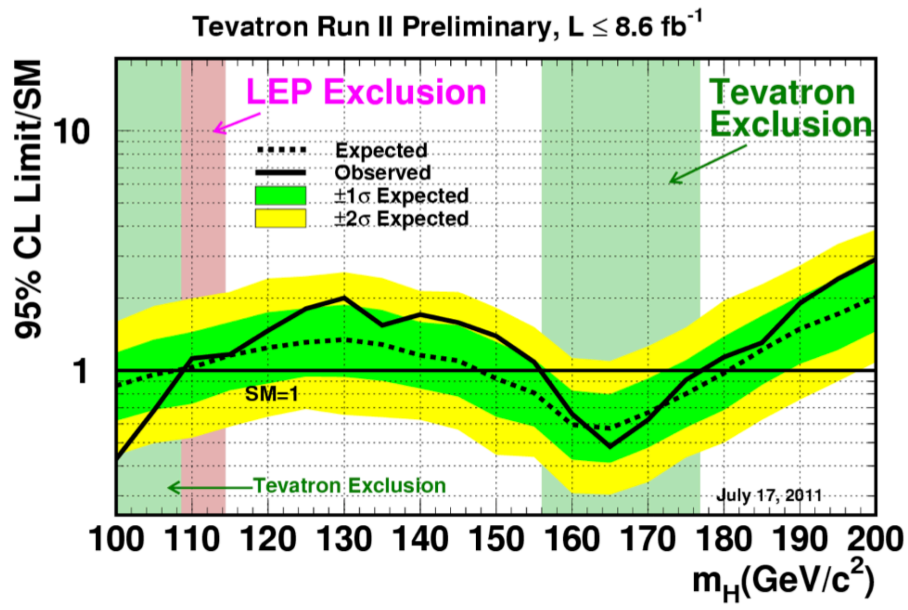
$Z \to \tau\tau$ from replacing μ in $Z \to \mu\mu$ events with simulated τ

	Events
Observed	46
Expected	47.4±3.9
gg→H(120 GeV)	0.44±0.05
VBF H(120 GeV)	0.38±0.02



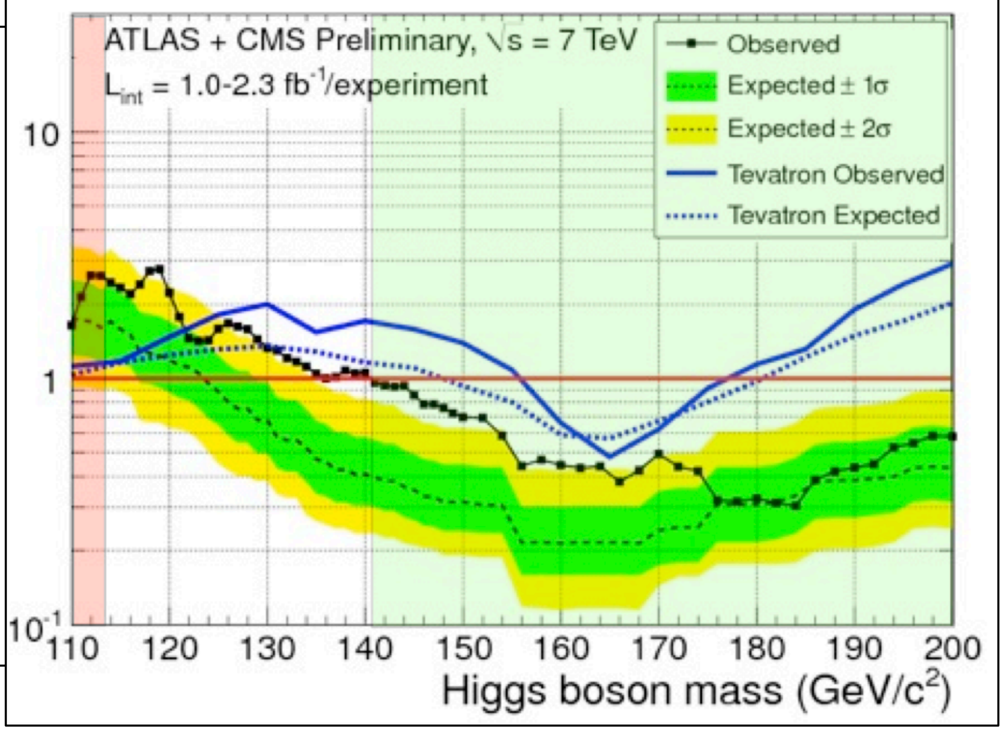


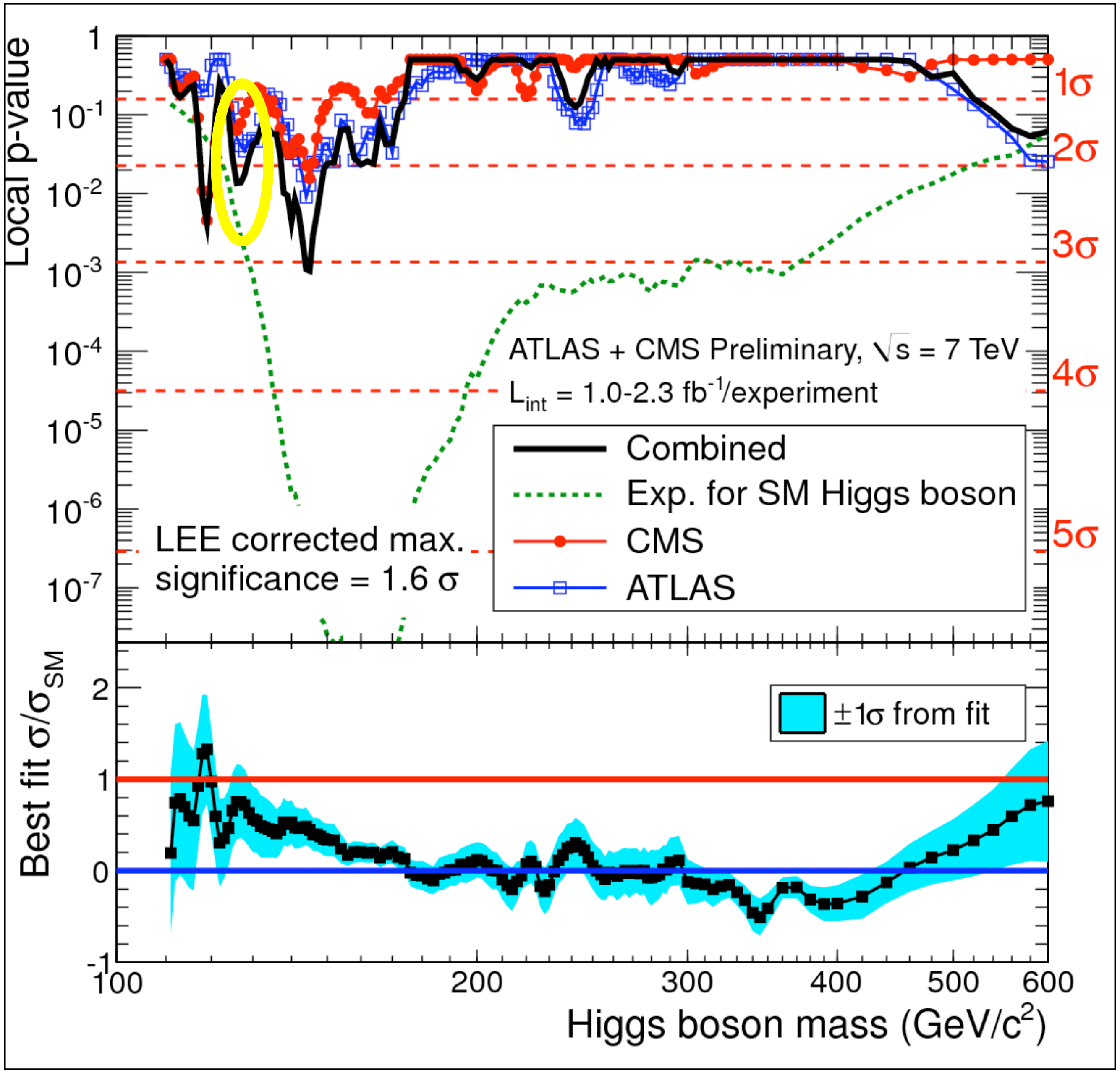
Γ_H [GeV]
10^3
10^2
10
1
10^{-1}
10^{-2}
100
200
300
500
1000
M_H [GeV]
LHC HIGGS XS WG 2010



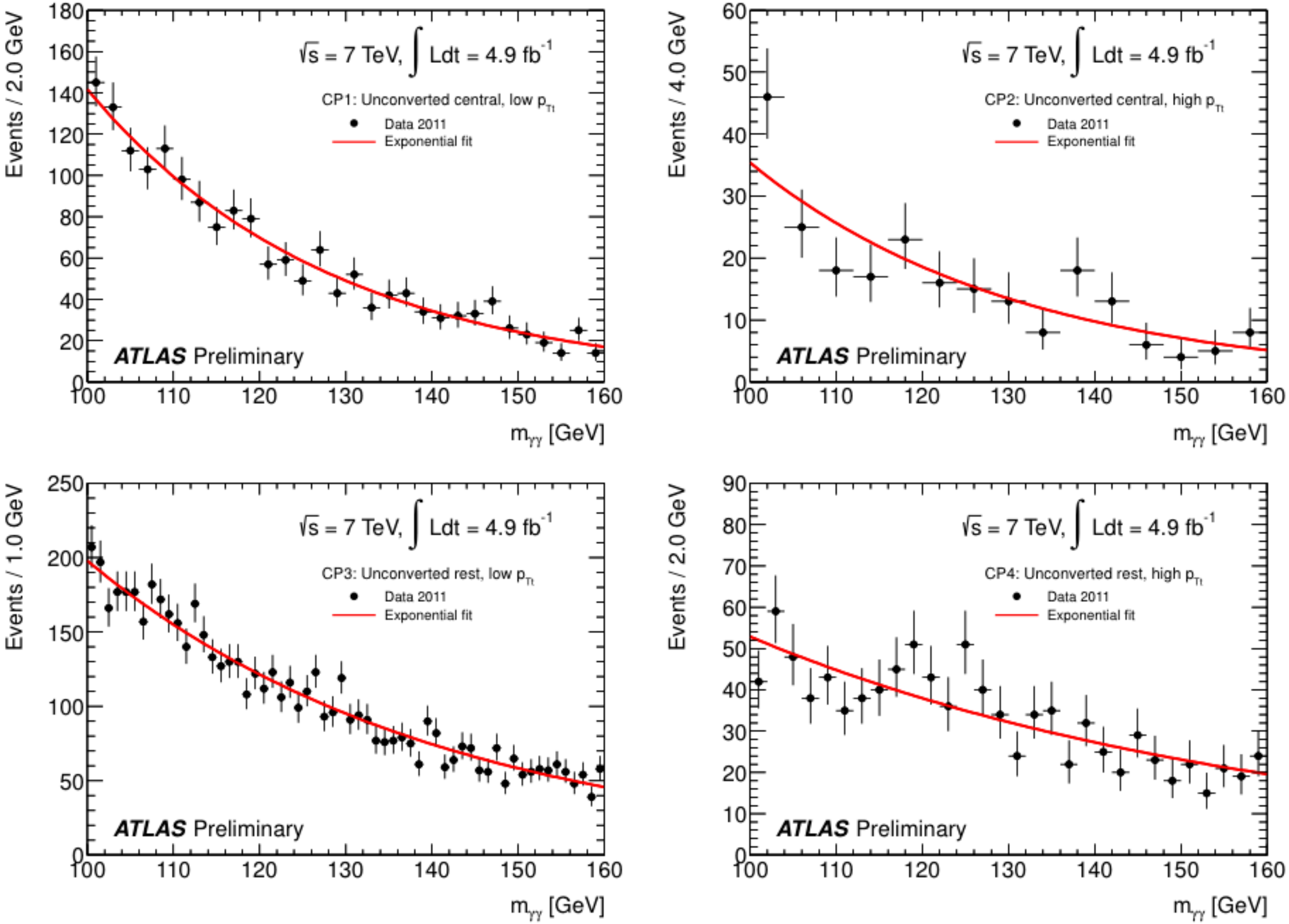
Observed Exclusion : 100-109 and 156-177 GeV/c^2

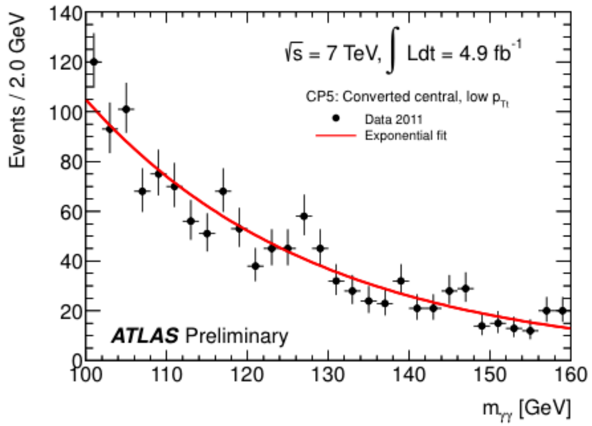
Expected Exclusion : 100-108 and 148-181 GeV/c^2



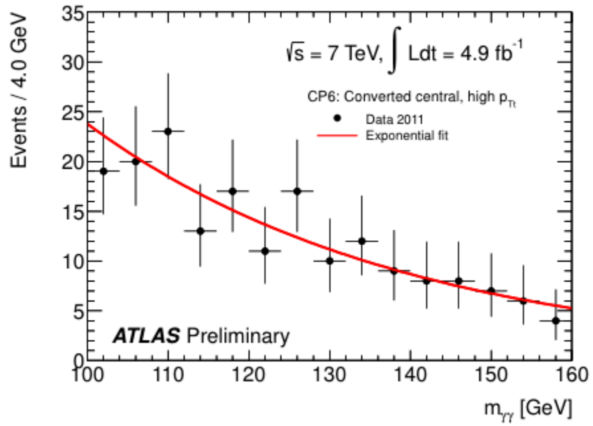


Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
1σ
2σ
3σ
4σ
5σ
ATLAS + CMS Preliminary, $\sqrt{s}$ = 7 TeV
L_{int} = 1.0-2.3 fb^{-1}/experiment
Combined
Exp. for SM Higgs boson
CMS
ATLAS
LEE corrected max. significance = 1.6 σ
Best fit σ/σ_{SM}
2
1
0
-1
±1σ from fit
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

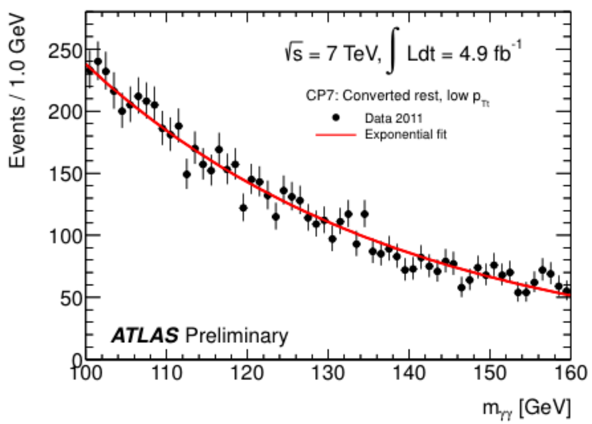

Events / 2.0 GeV
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
CP1: Unconverted central, low p_Tt
Data 2011
Exponential fit
ATLAS Preliminary
m_γγ [GeV]
Events / 4.0 GeV
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
CP2: Unconverted central, high p_Tt
Data 2011
Exponential fit
ATLAS Preliminary
m_γγ [GeV]
Events / 1.0 GeV
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
CP3: Unconverted rest, low p_Tt
Data 2011
Exponential fit
ATLAS Preliminary
m_γγ [GeV]
Events / 2.0 GeV
√s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
CP4: Unconverted rest, high p_Tt
Data 2011
Exponential fit
ATLAS Preliminary
m_γγ [GeV]



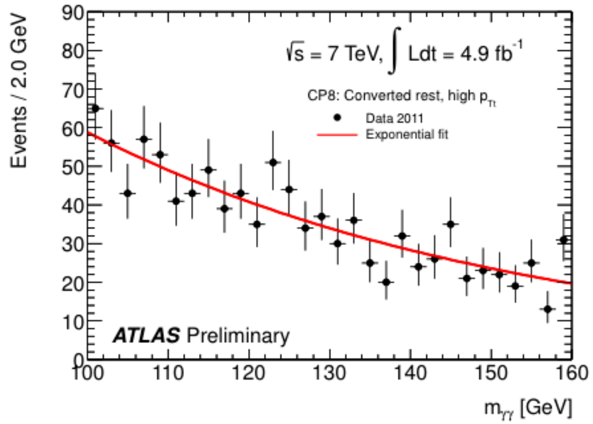
$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.9 fb^{-1}
CP5: Converted central, low p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 2.0 GeV
$m_{\gamma\gamma}$ [GeV]



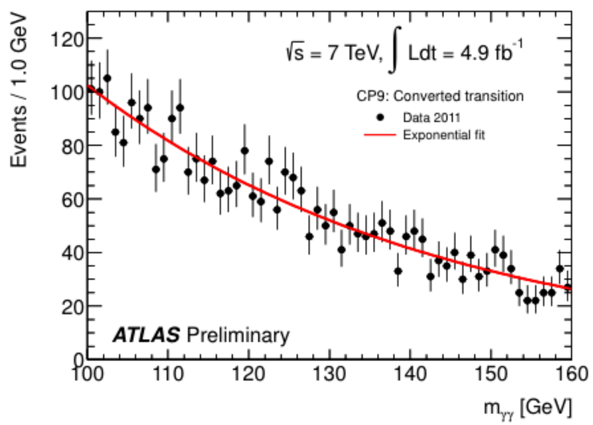
$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.9 fb^{-1}
CP6: Converted central, high p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 4.0 GeV
$m_{\gamma\gamma}$ [GeV]



$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.9 fb^{-1}
CP7: Converted rest, low p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 1.0 GeV
$m_{\gamma\gamma}$ [GeV]



$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.9 fb^{-1}
CP8: Converted rest, high p_{Tt}
Data 2011
Exponential fit
ATLAS Preliminary
Events / 2.0 GeV
$m_{\gamma\gamma}$ [GeV]



$\sqrt{s}$ = 7 TeV, $\int$ Ldt = 4.9 fb^{-1}
CP9: Converted transition
Data 2011
Exponential fit
ATLAS Preliminary
Events / 1.0 GeV
$m_{\gamma\gamma}$ [GeV]

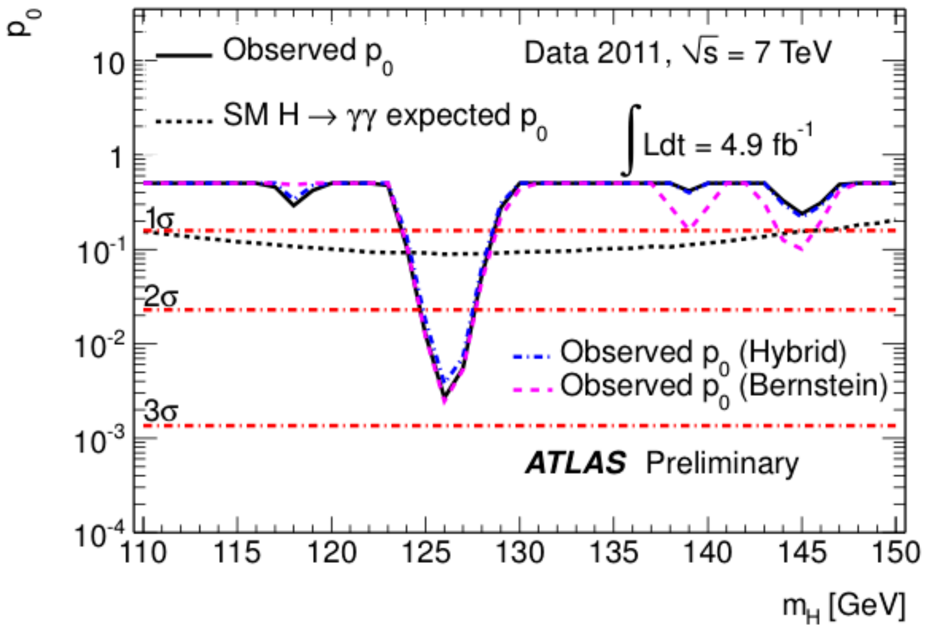
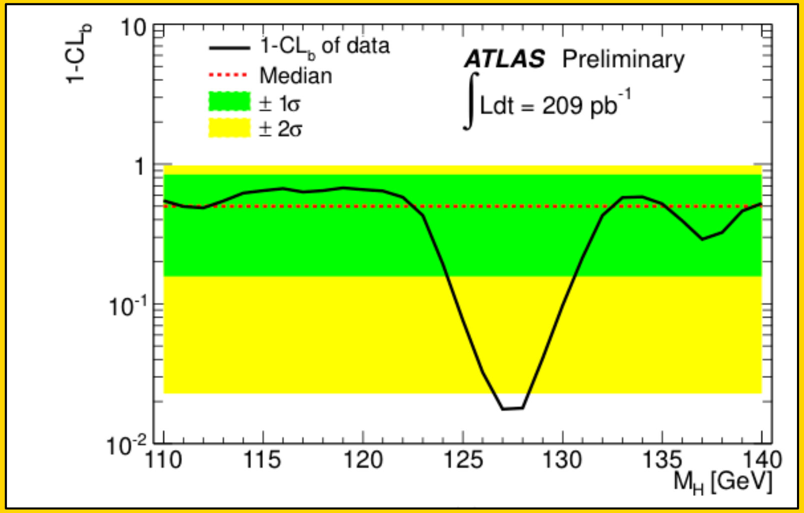
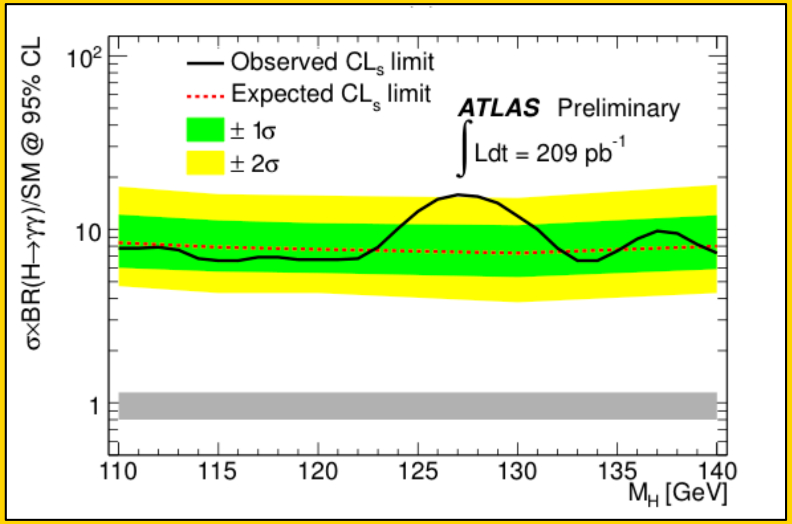


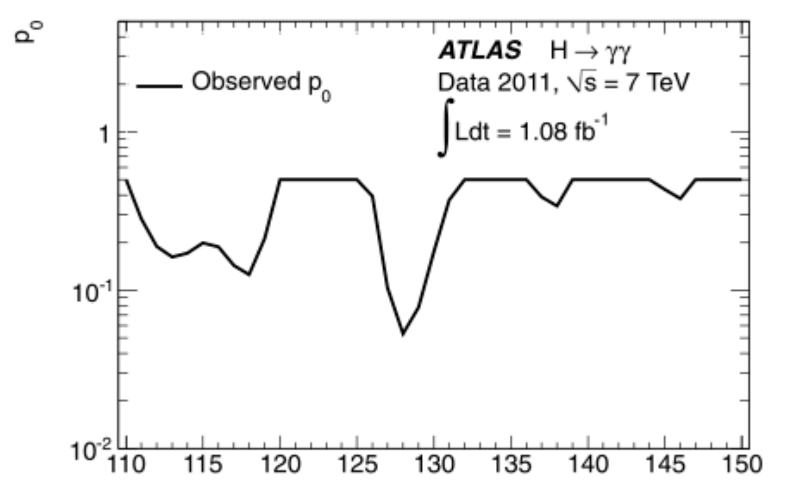
Figure 12: The observed and expected local p_0-value as a function of m_H for three different background models without taking the *look-elsewhere effect* into account. The black solid line is the result described in detail in this note, using single exponential functions in all categories. In the *Hybrid* model the high p_{Tt} categories are fitted with the 2[nd] order Bernstein polynomials, the other categories with the single exponential. In the model *Bernstein* all categories are fitted with the Bernstein function. The p_0-values near the minima at 126 GeV are very similar in all cases: p_0=0.38% using the *Hybrid* model, and p_0=0.25% using the *Bernestein* function.

June 2011: PLHC conference

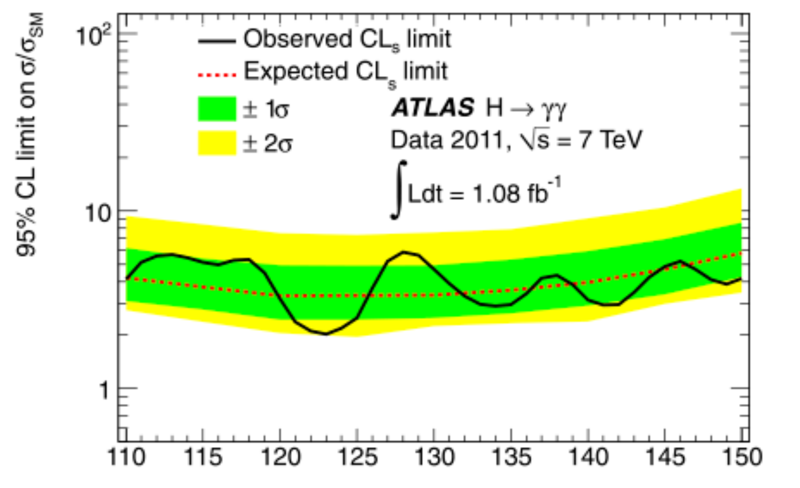




July 2011: EPS conference



(a)



(b)

Table 5: Systematic uncertainty on the background modelling in different categories.

Category	CP1	CP2	CP3	CP4	CP5	CP6	CP7	CP8	CP9
Events	±4.3	±0.2	±3.7	±0.5	±3.2	±0.1	±5.6	±0.6	±2.3

Table 3: Expected Higgs boson signal yields in 4.9 fb^{-1} integrated over a mass range of 100-160 G
for various values of m_H in each category and the sum.

m_H [GeV]	110	115	120	125	130	135	140	145	150
CP1: Unconverted Central, low p_{Tt}	8.9	8.9	8.7	8.2	7.5	6.7	5.7	4.6	3.5
CP2: Unconverted Central, high p_{Tt}	2.5	2.6	2.6	2.5	2.3	2.1	1.8	1.5	1.2
CP3: Unconverted Rest, low p_{Tt}	16.3	16.7	16.6	16.0	15.0	13.6	11.9	9.8	7.4
CP4: Unconverted Rest, high p_{Tt}	4.4	4.6	4.6	4.5	4.3	4.0	3.5	2.9	2.2
CP5: Converted Central, low p_{Tt}	5.9	5.9	5.8	5.5	5.1	4.6	4.0	3.3	2.4
CP6: Converted Central, high p_{Tt}	1.6	1.7	1.6	1.6	1.6	1.4	1.3	1.1	0.8
CP7: Converted Rest, low p_{Tt}	17.5	18.1	17.9	17.1	15.8	14.1	12.0	9.7	7.2
CP8: Converted Rest, high p_{Tt}	4.6	4.7	4.7	4.6	4.4	4.1	3.6	2.9	2.2
CP9: Converted Transition	8.2	8.4	8.4	8.1	7.6	6.9	6.0	4.9	3.7
Total	69.9	71.5	70.9	68.3	63.7	57.5	49.8	40.8	30.6

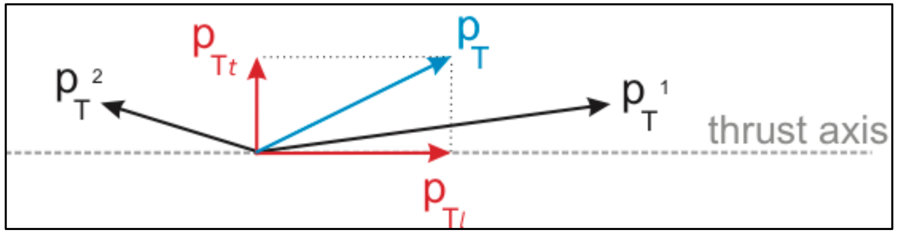
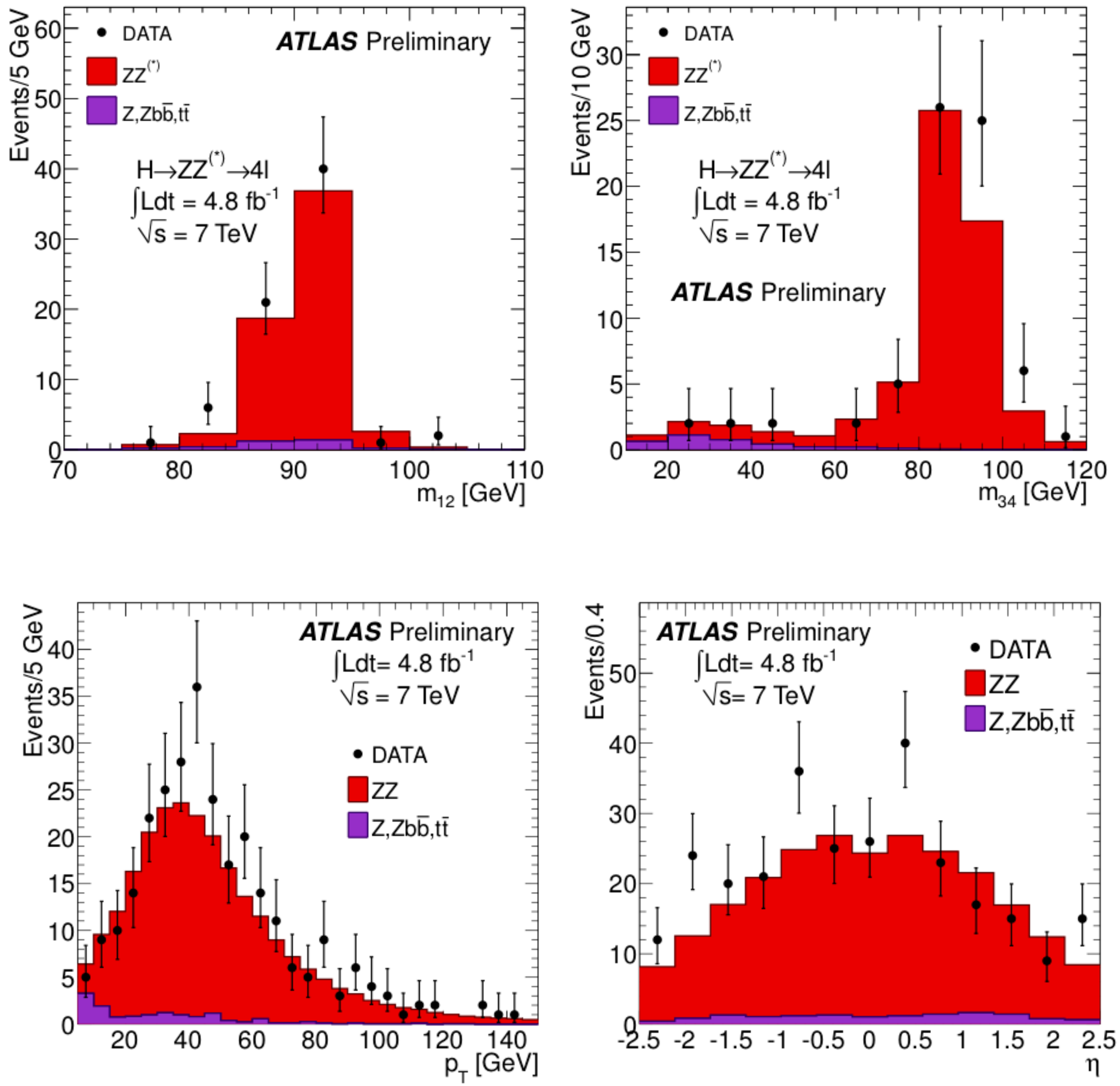
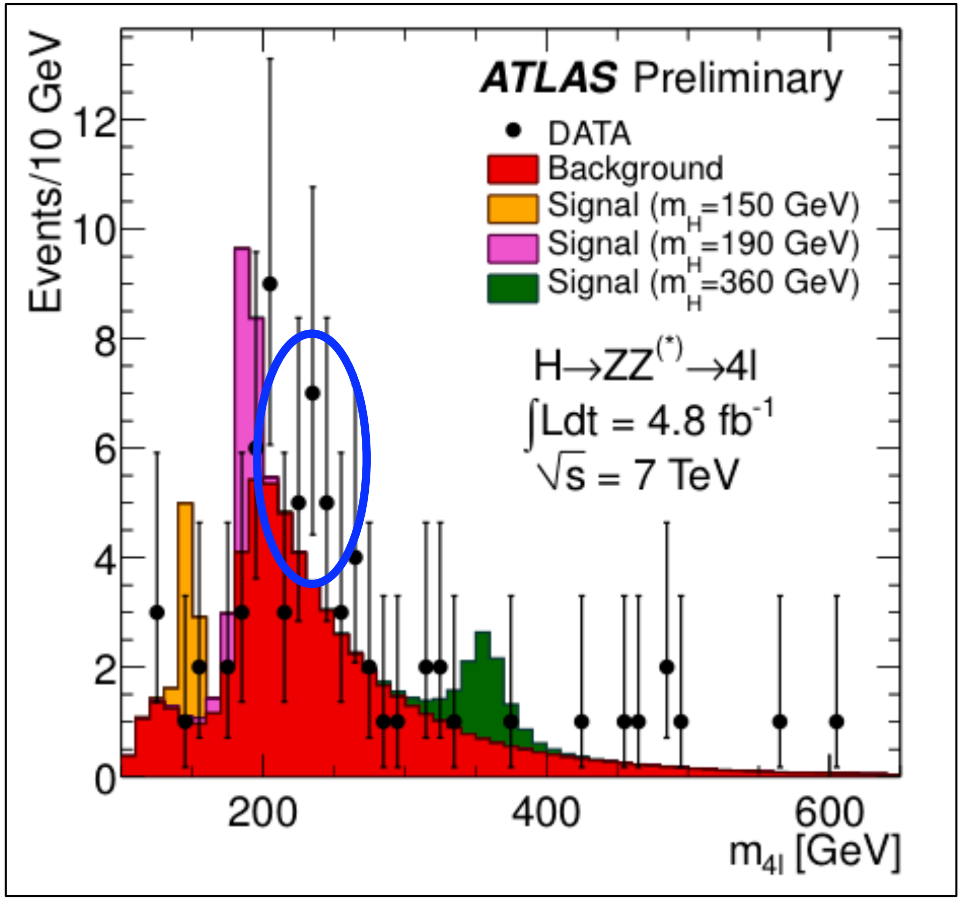


Table 2: The number of events found in $4.9\,\mathrm{fb}^{-1}$ of data for the nine categories.

Category	Conversion and η	p_{Tt} cut	Number of data events
CP1	Unconverted Central	$p_{\mathrm{Tt}} \leq 40$ GeV	1763
CP2	Unconverted Central	$p_{\mathrm{Tt}} > 40$ GeV	235
CP3	Unconverted Rest	$p_{\mathrm{Tt}} \leq 40$ GeV	6234
CP4	Unconverted Rest	$p_{\mathrm{Tt}} > 40$ GeV	1006
CP5	Converted Central	$p_{\mathrm{Tt}} \leq 40$ GeV	1318
CP6	Converted Central	$p_{\mathrm{Tt}} > 40$ GeV	184
CP7	Converted Rest	$p_{\mathrm{Tt}} \leq 40$ GeV	7311
CP8	Converted Rest	$p_{\mathrm{Tt}} > 40$ GeV	1072
CP9	Converted Transition	No cut	3366
Total			22489

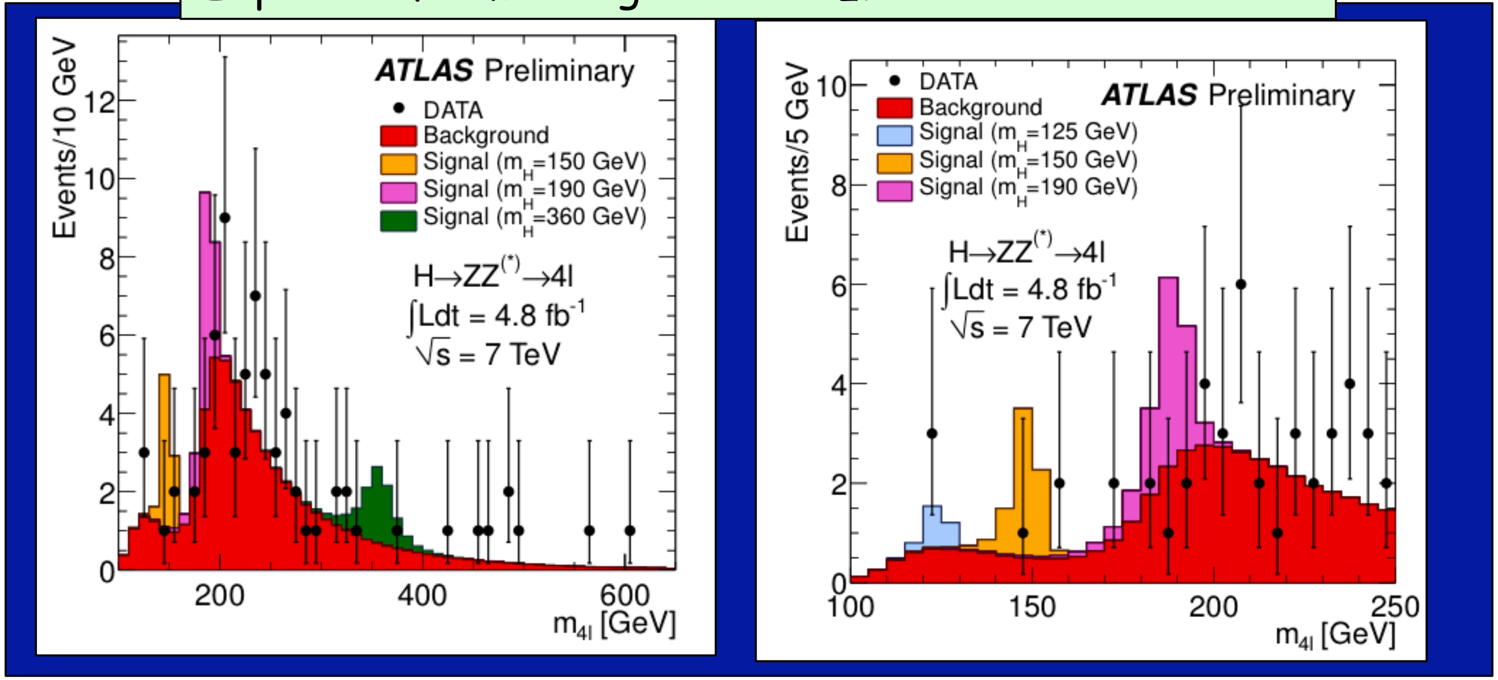

ATLAS Preliminary
DATA
ZZ(*)
Z,Zbb̄,tt̄
H→ZZ(*)→4l
∫Ldt = 4.8 fb-1
√s = 7 TeV
Events/5 GeV
m12 [GeV]
Events/10 GeV
m34 [GeV]
ATLAS Preliminary
∫Ldt= 4.8 fb-1
√s = 7 TeV
DATA
ZZ
Z,Zbb̄,tt̄
Events/5 GeV
pT [GeV]
Events/0.4
η



In the region 212-255.5 GeV, containing ~ 90% of the signal for m_H=244 GeV, 22 events are observed in the data, with a background expectation of 16 events. The signal expectation is 11 events.

After all selections: kinematic cuts, isolation, impact parameter

Observed in data: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9



In the region m_H < 141 GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

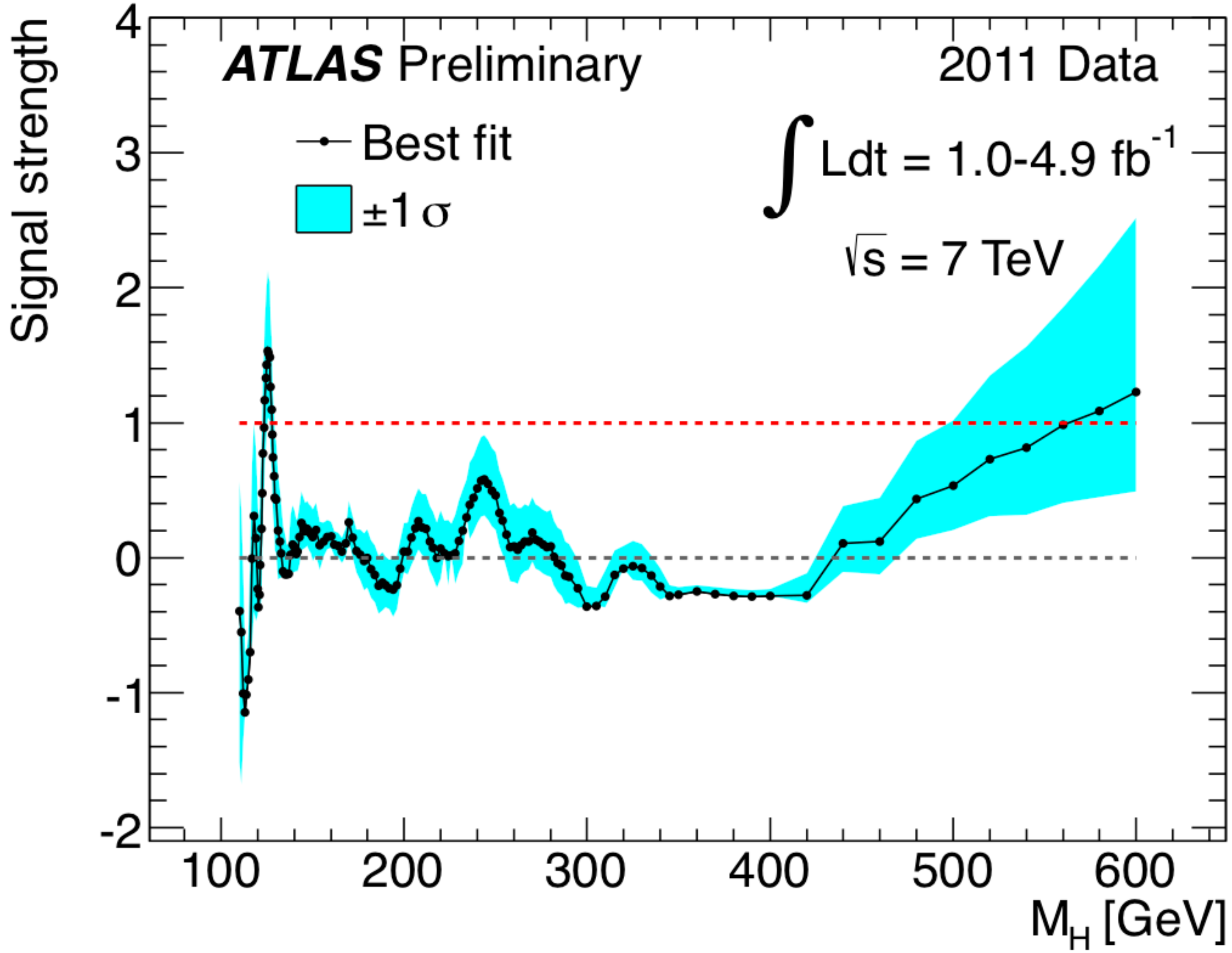
In the region 117< m_{4l} <128 GeV (containing ~90% of a m_H=125 GeV signal) expect:

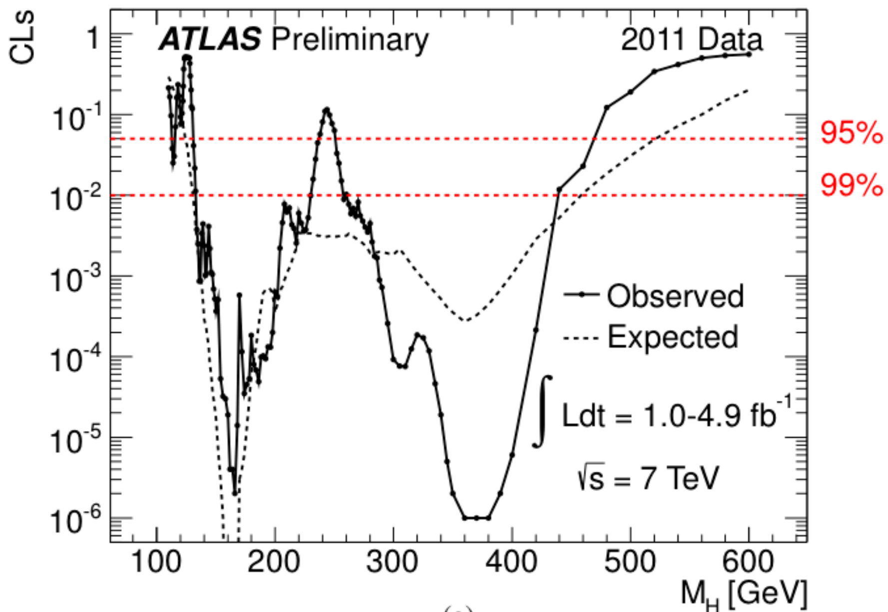
~1.5 events background: 0.26 4μ + 0.86 2e2μ + 0.64 4e
~1.4 events signal: 0.53 4μ + 0.66 2e2μ + 0.23 4e

Background dominated by ZZ* (4μ and 2e2μ), ZZ* and Z+jets (4e)

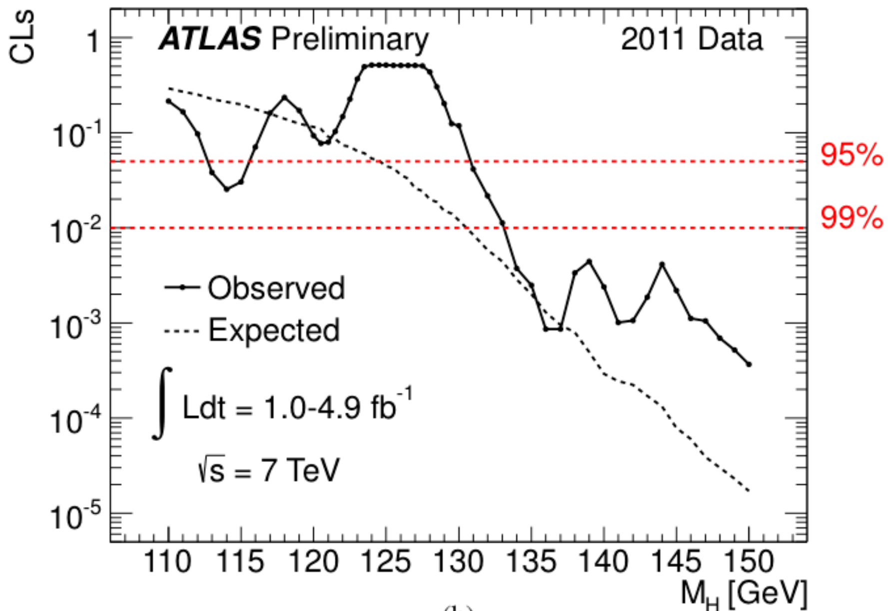
Main systematic uncertainties

Higgs cross-section	: ~ 15%
Electron efficiency	: ~ 2-8%
Zbb, +jets backgrounds	: ~ 40%
ZZ* background	: ~ 15%

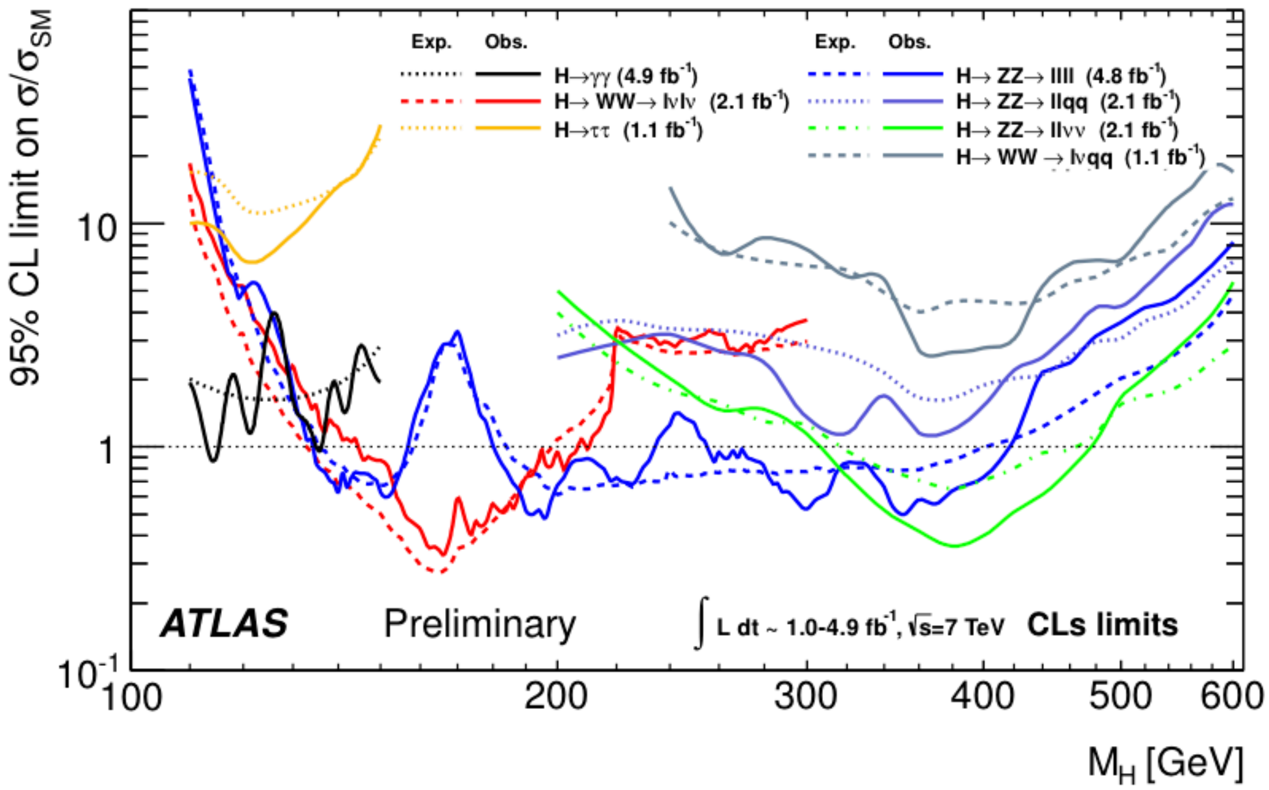

ATLAS Preliminary
2011 Data
Best fit
±1 σ
∫Ldt = 1.0-4.9 fb-1
√s = 7 TeV
Signal strength
M_H [GeV]
4
3
2
1
0
-1
-2
100
200
300
400
500
600


CLs
ATLAS Preliminary
2011 Data
95%
99%
Observed
Expected
∫Ldt = 1.0-4.9 fb^-1
√s = 7 TeV
M_H [GeV]

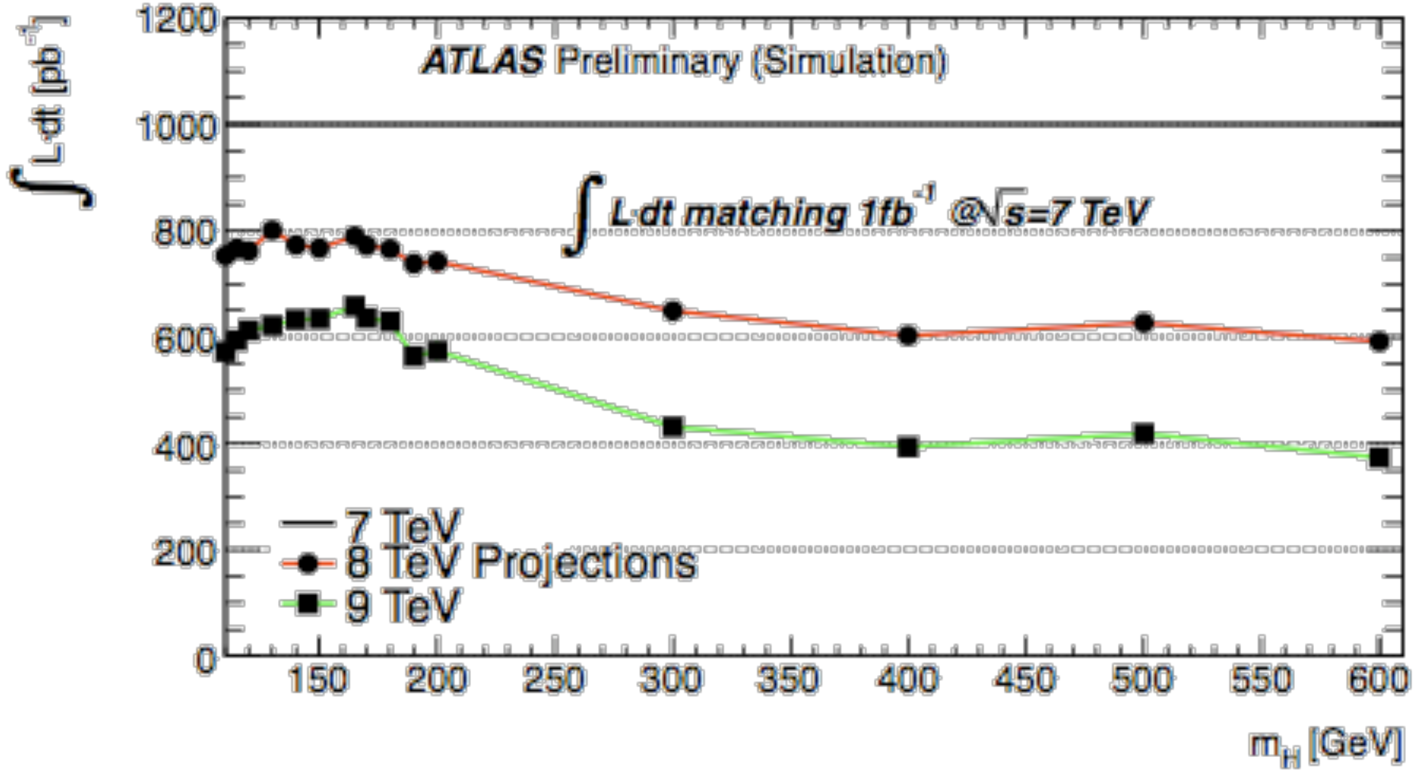
(a)

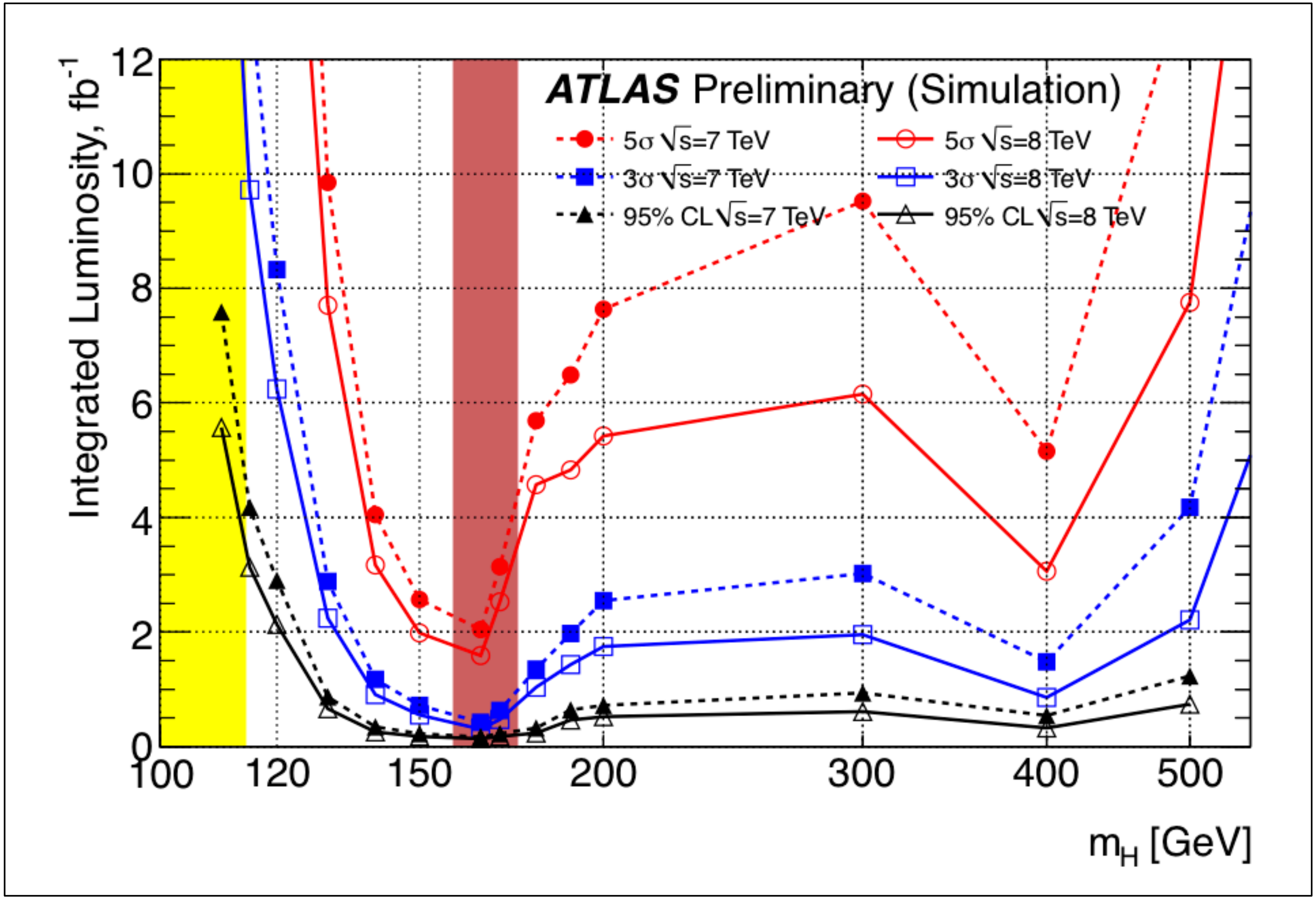

CLs
ATLAS Preliminary
2011 Data
95%
99%
Observed
Expected
∫Ldt = 1.0-4.9 fb^-1
√s = 7 TeV
M_H [GeV]

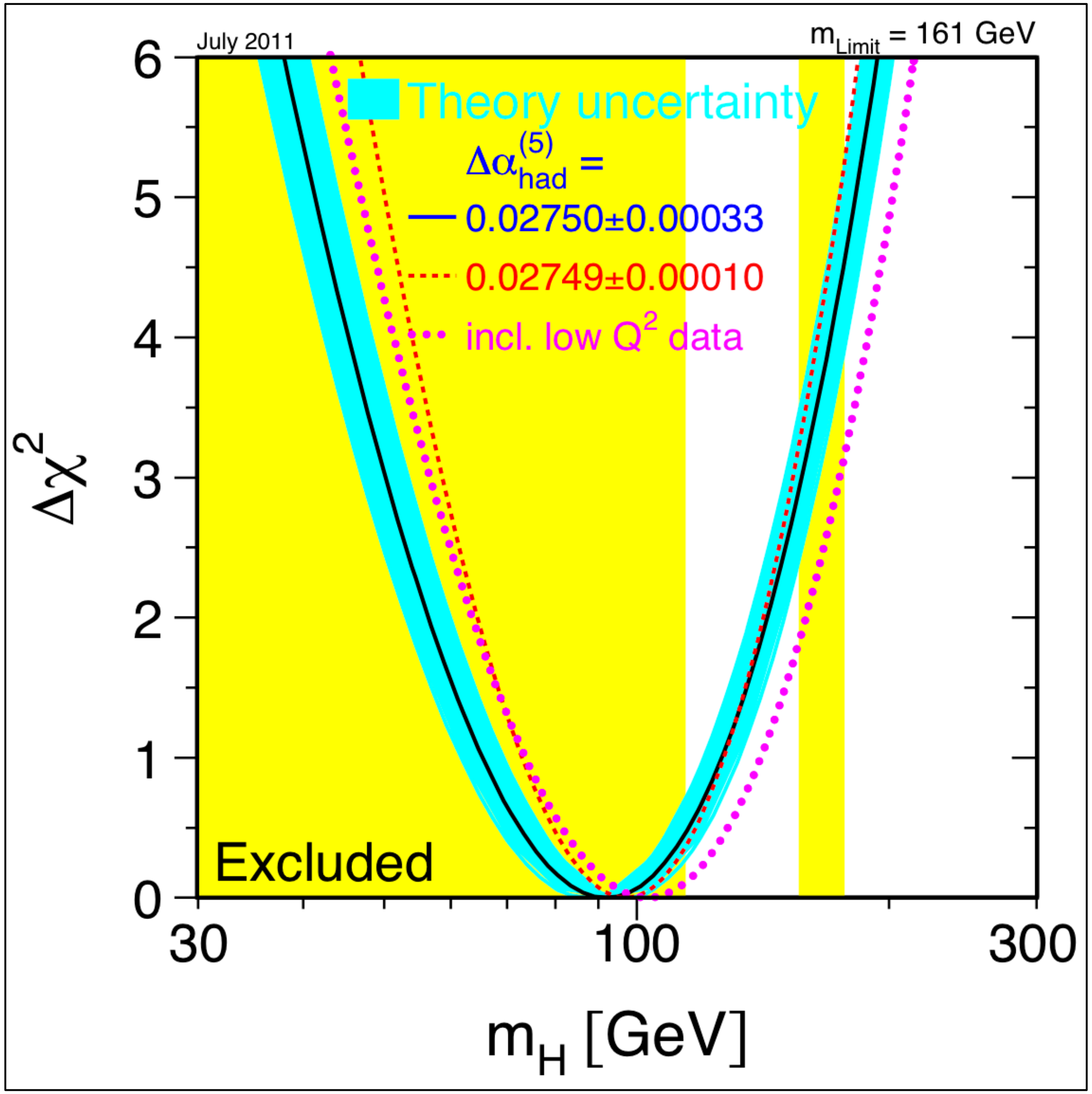
(b)



95% CL limit on σ/σ_SM
Exp. Obs.
H→γγ (4.9 fb⁻¹)
H→ WW→ lνlν (2.1 fb⁻¹)
H→ττ (1.1 fb⁻¹)
Exp. Obs.
H→ ZZ→ llll (4.8 fb⁻¹)
H→ ZZ→ llqq (2.1 fb⁻¹)
H→ ZZ→ llνν (2.1 fb⁻¹)
H→ WW → lνqq (1.1 fb⁻¹)
10
1
10⁻¹
100
200
300
400
500
600
ATLAS
Preliminary
∫ L dt ~ 1.0-4.9 fb⁻¹, √s=7 TeV
CLs limits
M_H [GeV]


ATLAS Preliminary (Simulation)
$\int L \cdot dt$ matching 1fb^{-1} @$\sqrt{s}$=7 TeV
7 TeV
8 TeV Projections
9 TeV
$\int L \cdot dt$ [pb^{-1}]
m_H [GeV]
0
200
400
600
800
1000
1200
150
200
250
300
350
400
450
500
550
600

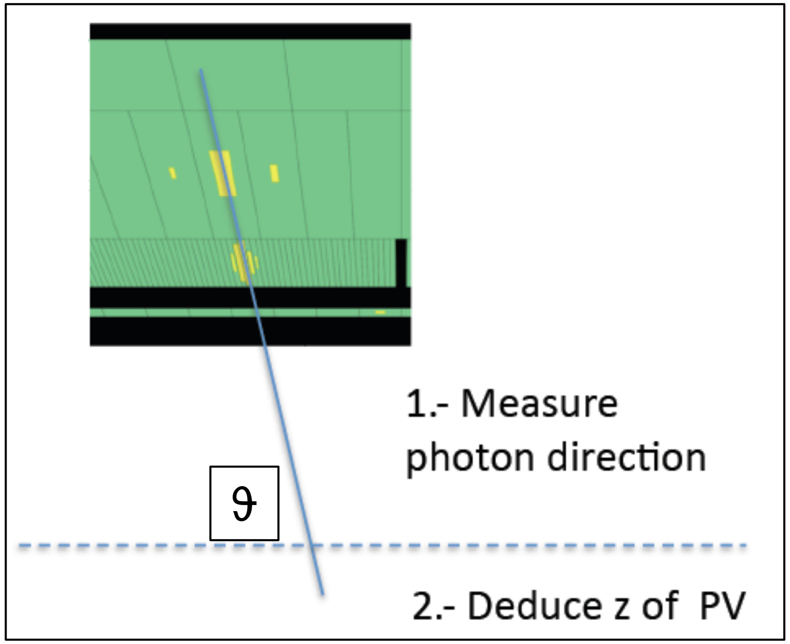

ATLAS Preliminary (Simulation)
5σ √s=7 TeV
3σ √s=7 TeV
95% CL √s=7 TeV
5σ √s=8 TeV
3σ √s=8 TeV
95% CL √s=8 TeV
Integrated Luminosity, fb⁻¹
m_H [GeV]
0
2
4
6
8
10
12
100
120
150
200
300
400
500

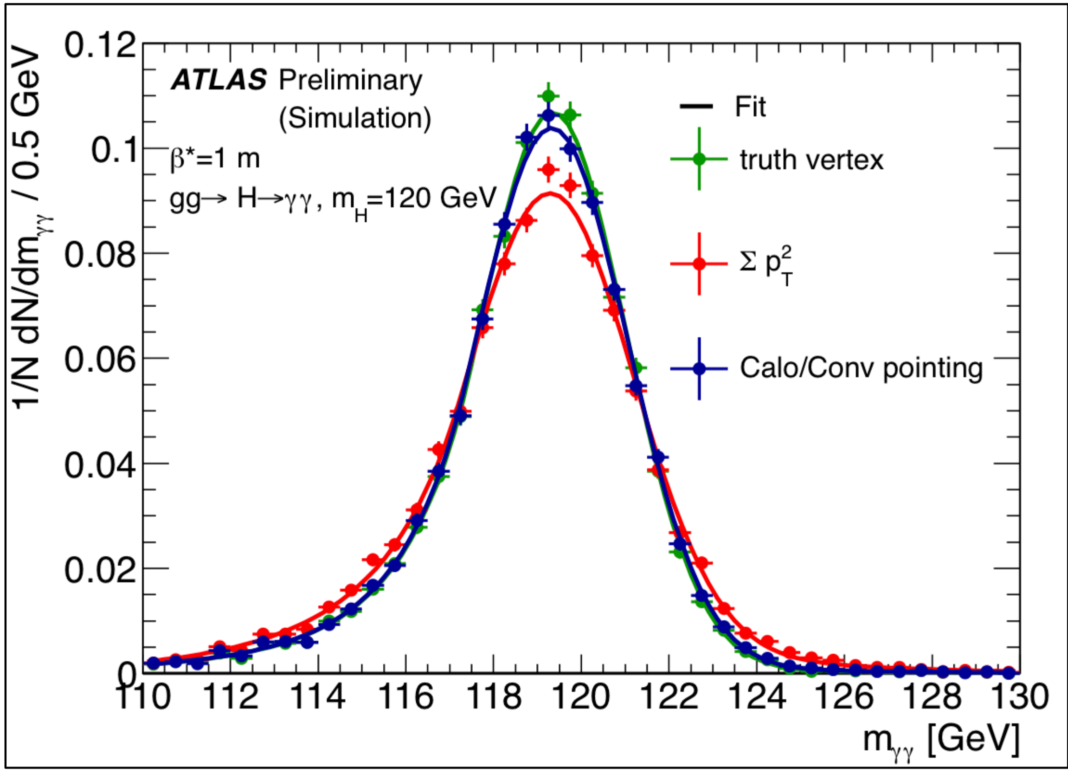


July 2011
m_{Limit} = 161 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02750±0.00033
0.02749±0.00010
incl. low Q^2 data
Excluded
$\Delta\chi^2$
m_H [GeV]
30
100
300
0
1
2
3
4
5
6

$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$

Use longitudinal segmentation of EM calorimeter to measure photon polar angle ϑ
Crucial at high pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5.6 cm → difficult to know which one produced the $\gamma\gamma$ pair





- Calorimeter pointing capability reduces vertex uncertainty from ~ 5.6 cm (LHC beam spot) to ~ 1.5 cm
- Robust against pile-up

→ Contribution to mass resolution from angular term is negligible with calo pointing (γ →ee vertex also used)

Without calo-pointing the mass resolution would deteriorate by ~ 20% when running with > 10 pile-up events