Status of Standard Model Higgs Searches ATLAS

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BNL

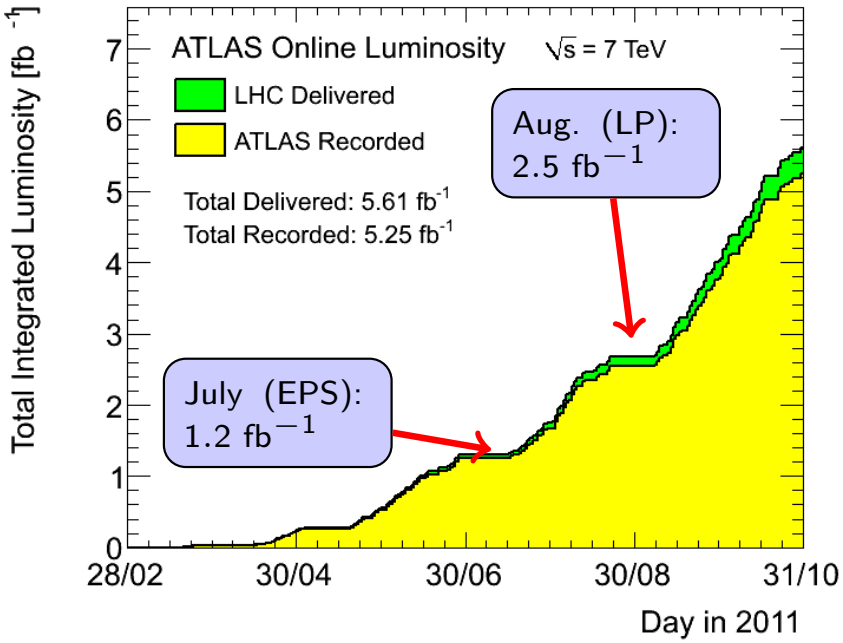
- Introduction
- SM Higgs search channels
  - $WW \to \ell\nu\ell\nu$
  - $\gamma\gamma$
  - $ZZ \to 4\ell$
- Combination
- Conclusions/outlook

LHC

LHC performance has greatly exceeded expectations!



Integrated luminosity:



Delivered: $5.6\ \text{fb}^{-1}$
Recorded: $5.3\ \text{fb}^{-1}$

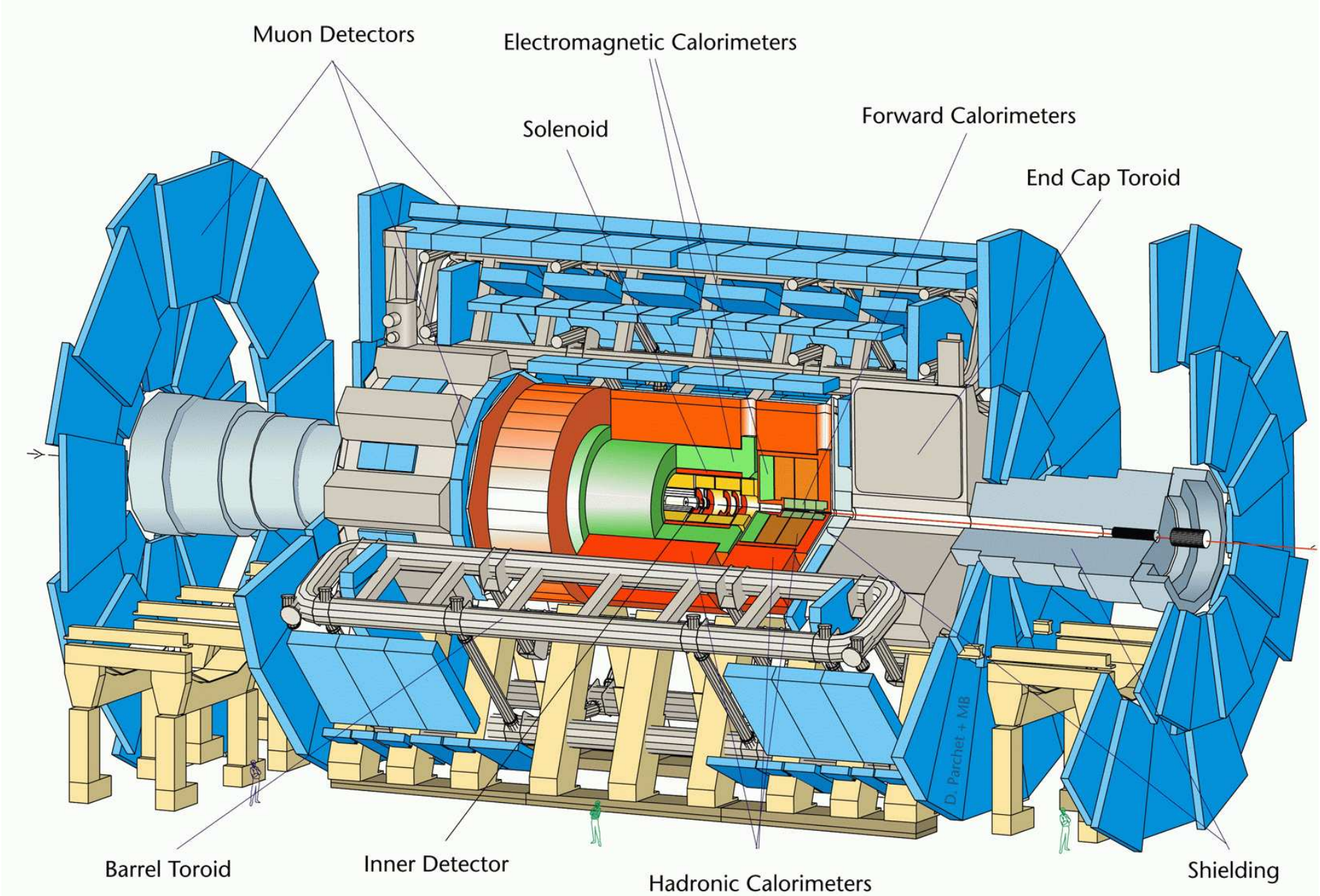
90%–96% of recorded data usable for analysis (depending on analysis).

2011 goal set in spring

Goal for 2011: $1\ \text{fb}^{-1}$
Accomplished: $\sim 5\ \text{fb}^{-1}$

Peak lumi at ATLAS: $3.6 \times 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$

ATLAS detector

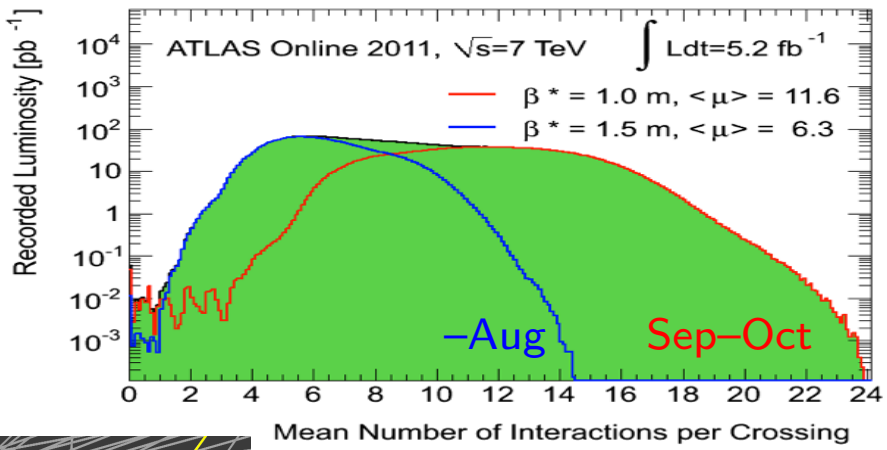


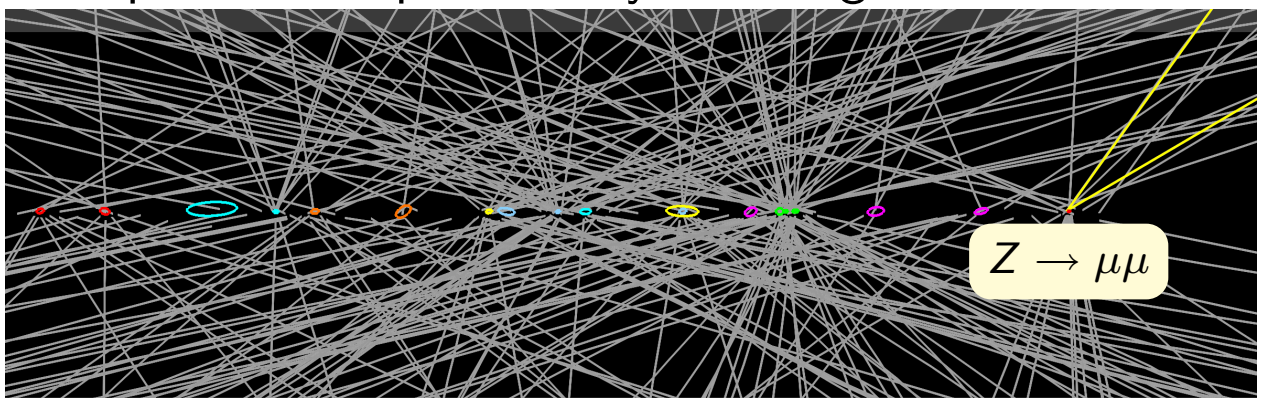
Pileup

Large luminosity means having many interactions in the same crossing ("pileup")

Up to ~ 20 — worse than expected for this luminosity.

- $\sim 2(20)$ events/crossing for $L = 10^{33}$ (10^{34}).
- 50 ns bunch spacing, other parameters pushed beyond design.





Event with 20 vertices. (Ellipses enlarged 20× for visibility.)

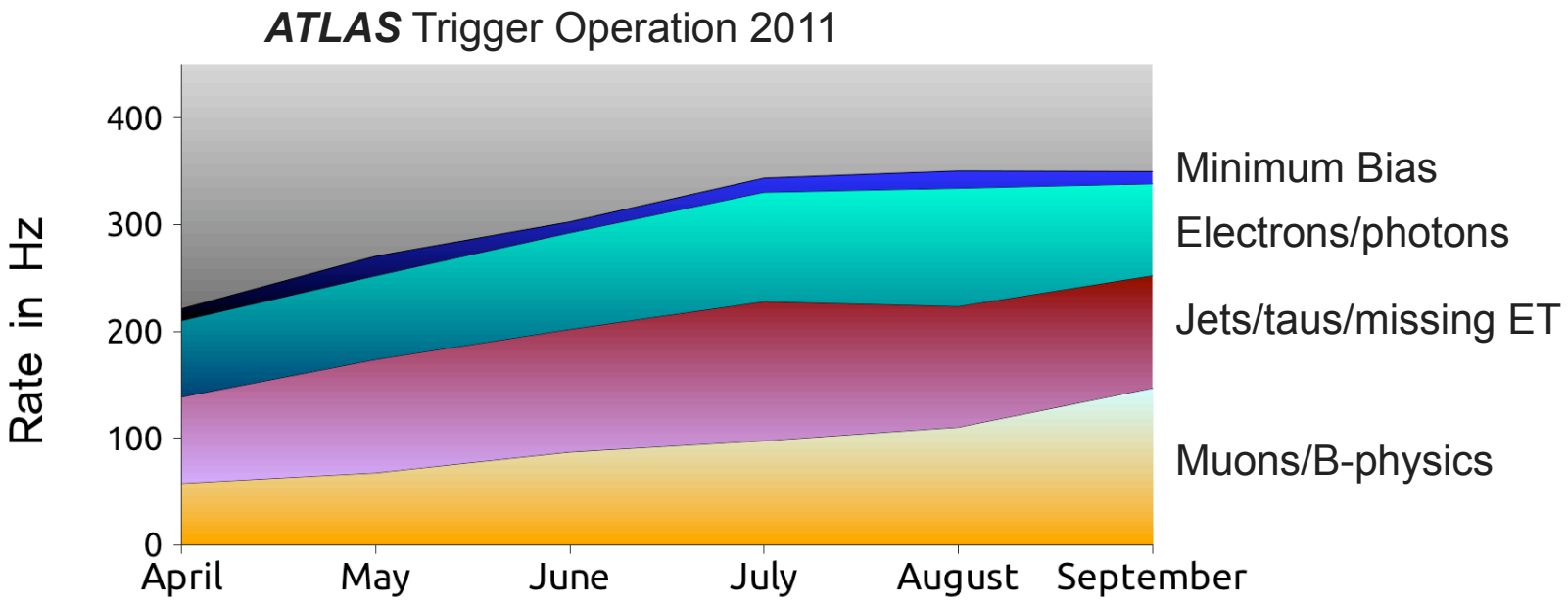
Challenges for reconstruction, trigger, and computing requirements.
Precise modeling of pileup is essential.

Trigger

Single-lepton triggers used where possible, augmented with others (eg, multi-lepton triggers) where needed.

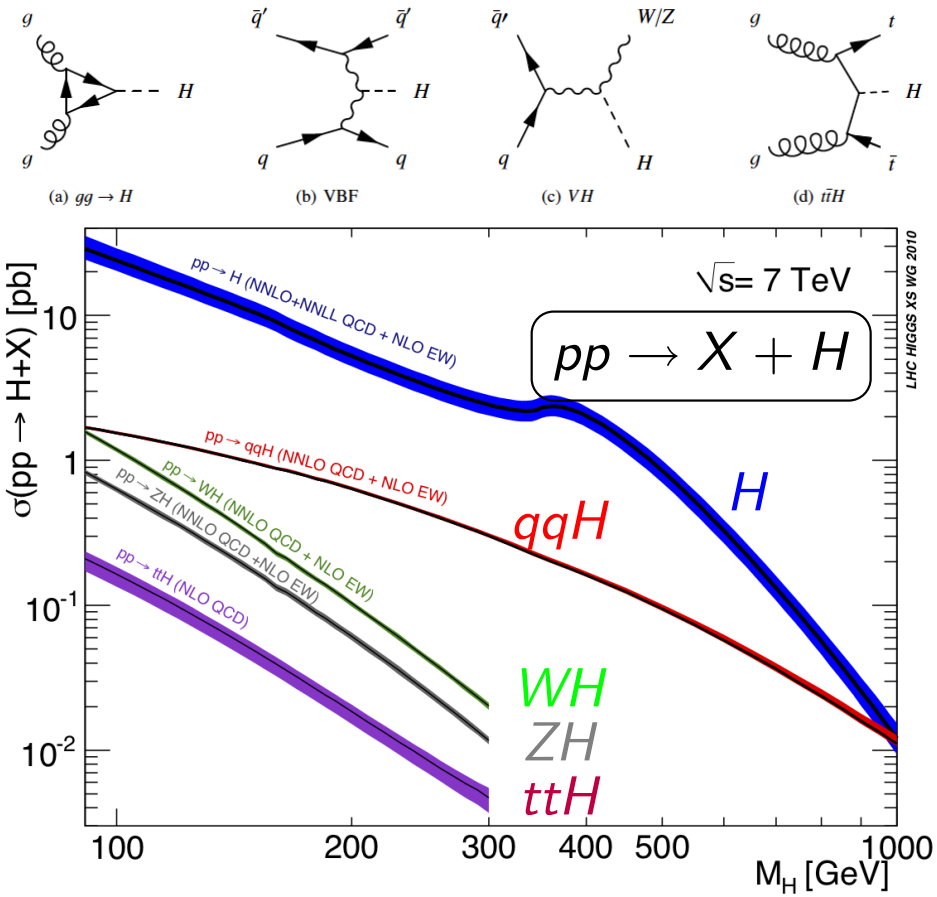
Triggers adjusted over the course of 2011 to adjust to the increasing luminosity.

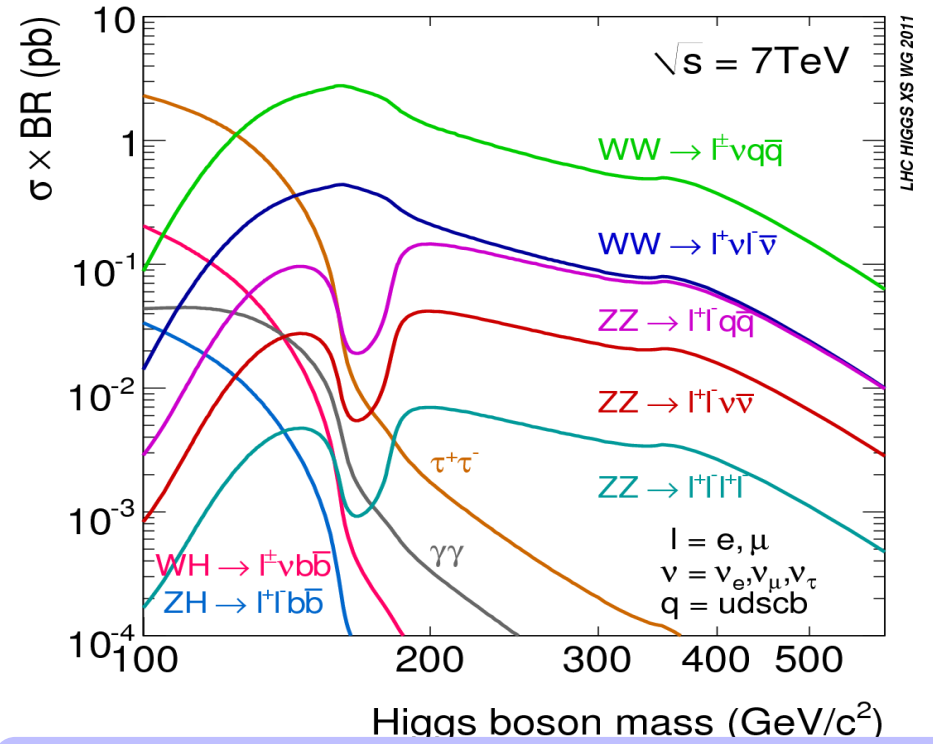
Triggers for Higgs analyses mostly stable, with a few increases of trigger threshold.



Typical recorded rates: e/γ: 100 Hz; Muons: 150 Hz; jets/τ/$\not{E}_T$: 100 Hz

SM Higgs production and decay



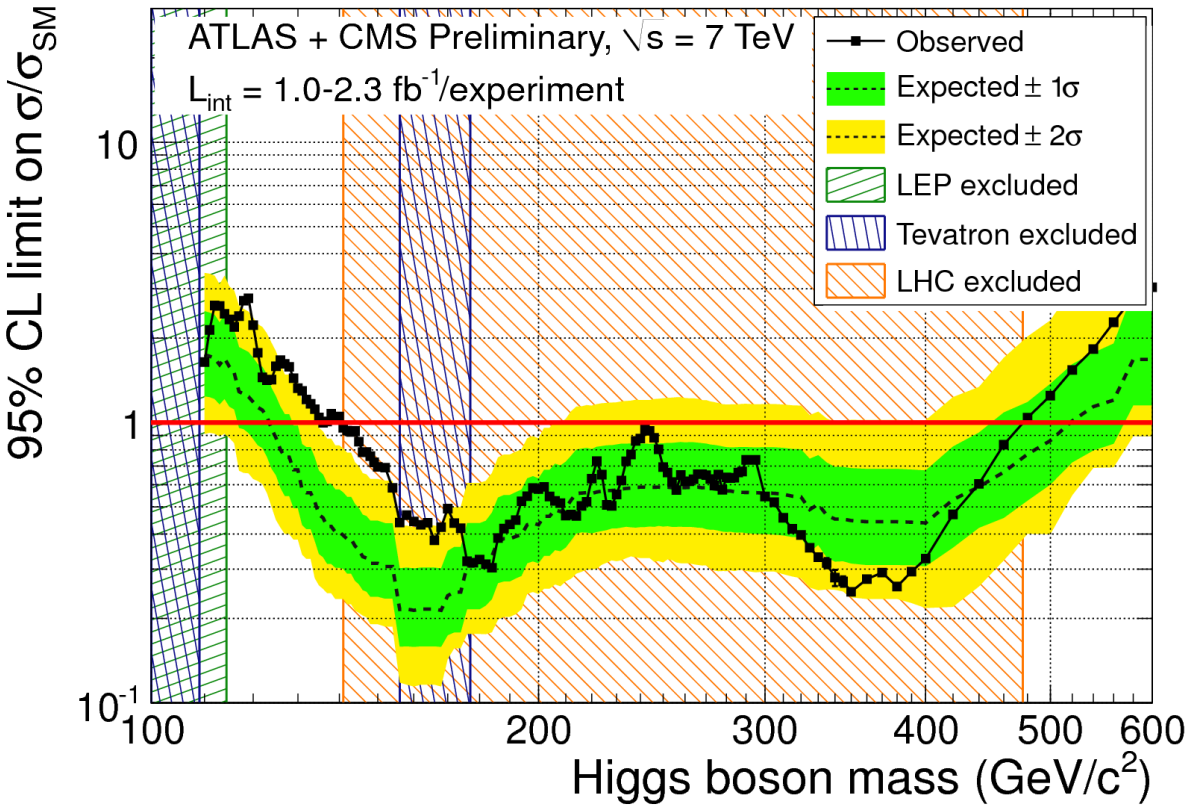


$\gamma\gamma$: < 130 $\quad$ $WW \to \ell\nu\ell\nu$: 125–180
$ZZ \to 4\ell$: 125–300 $\quad$ $ZZ \to \ell\ell\nu\nu$: 300–600

Much progress has been made in theoretical predictions (LHC xsect WG etc)
Calculations to NNLO in most cases; uncertainties $<\sim 20\%$

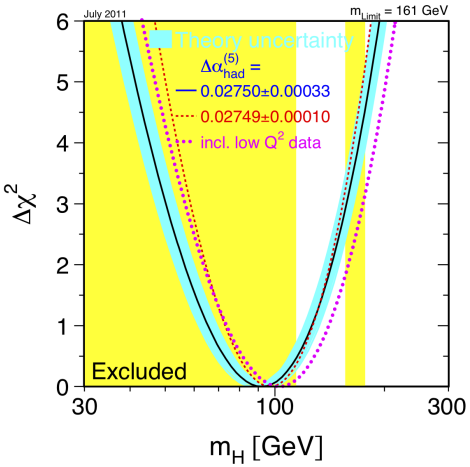
Previous ATLAS/CMS combination

Combination as of Nov., using data through Aug. 11 (~ 2.3 fb^{-1} each)



LEP 95% CL:

$m_H > 114.4$ GeV



Tevatron 95% exclusion:

$100 < m_H < 109$ GeV;

$156 < m_H < 177$ GeV

Excluded at 95% CL: 141–476 GeV

Excluded at 99% CL: 146-443 GeV (except a few small regions within 200-300 GeV).

Expected exclusion: 124–520 GeV. Max deviation from BG-only @ 144 GeV (3σ).

Summary of ATLAS SM Higgs searches

Substantial progress over the past year in understanding the detector and in improving reconstruction and simulation.

Channel	m_H range (GeV)	Int lum fb^{-1}	Major bkgs	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
$H \to \tau\tau \to \ell\ell + \nu$	110–140	1.1	$Z \to \tau\tau$, top	0.8	0.02	30–60
$H \to \tau\tau \to \ell\tau_{\text{had}}$	100–150	1.1	$Z \to \tau\tau$	10	5E-3	10-25
$W/ZH \to bb\ell(\ell)$	110–130	1.1	W/Z + jets, top	6	5E-3	15–25
$H \to WW^{(*)} \to \ell\nu\ell\nu$	110–300	2.1	WW, top, Z + jet	20 (@130)	0.3	0.3–8
$H \to ZZ^{(*)} \to 4\ell$	110–600	4.8	ZZ^*, top, Zbb	2.5 (@130)	1.5	0.7–10
$H \to ZZ^{(*)} \to \ell\ell\nu\nu$	200–600	2.1	ZZ, top, Z + jets	20 (@400)	0.3	0.8–4
$H \to ZZ \to \ell\ell qq$	200–600	2.1	Z + jets, top	2–20 (@400)	0.05–0.5	2–6
$H \to WW \to \ell\nu qq$	240–600	1.1	W + jets, top, jets	45 (@400)	1E-3	5–10

$\gamma\gamma$ and $ZZ \to 4\ell$ channels updated with full luminosity.
$WW \to \ell\nu\ell\nu$ also updated.
(Three channels with the best sensitivity in the allowed low-mass region.)

$H \to WW^{(*)} \to \ell\nu\ell\nu$

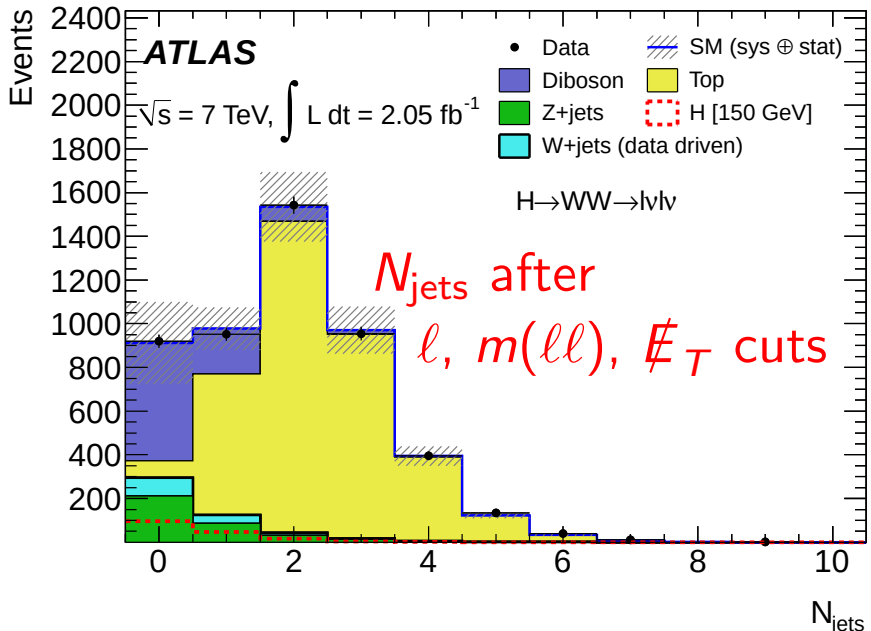
$\int \mathcal{L}\, dt = 2.1\ \text{fb}^{-1}$

- Covers $110 < m_H < 300$ GeV.
- Relatively large $\sigma \sim 200$ fb
  - Most sensitive channel over 125–180 GeV.
- But 2ν: no mass reconstruction.
- Initial selection: 2 opposite-charge leptons inconsistent with $Z/J/\psi$ decay, large $\not\!\!E_T$.
- 0- and 1-jet bins; b-jet veto.
- Additional selections to reduce WW: $p_T(\ell\ell)$, $m(\ell\ell)$, $\Delta\phi(\ell\ell)$.
- Final selection: $0.75 m_H < m_T(\ell\ell, \not\!\!E_T) < m_H$.

Backgrounds: WW, top, W/Z + jets

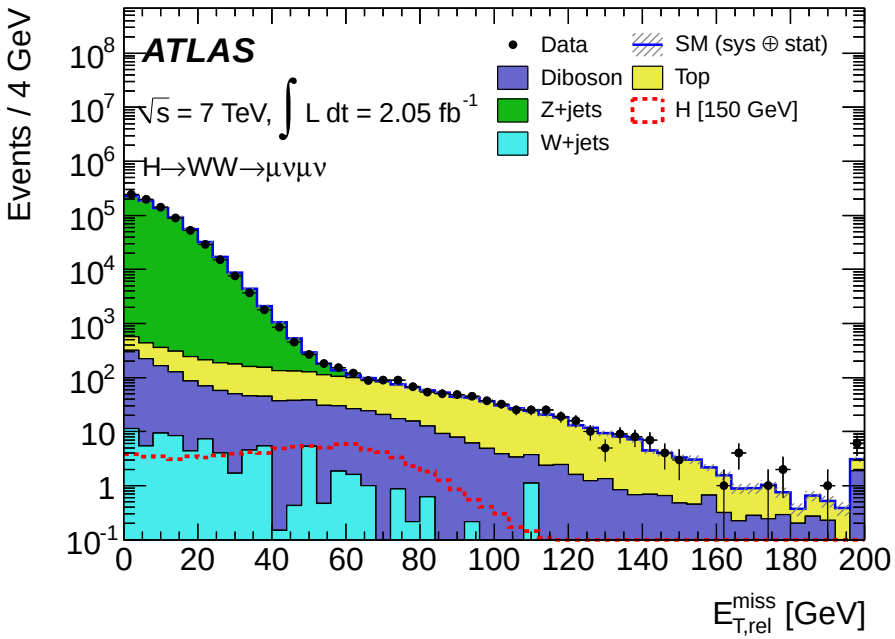
Compare data to background MC in signal-free control regions; derive scale factors by which MC should be corrected.

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



$H \to WW^{(*)} \to \ell\nu\ell\nu$

$\not\!\!E_T$ spectrum in data for $\mu\mu$ well-described by background model.

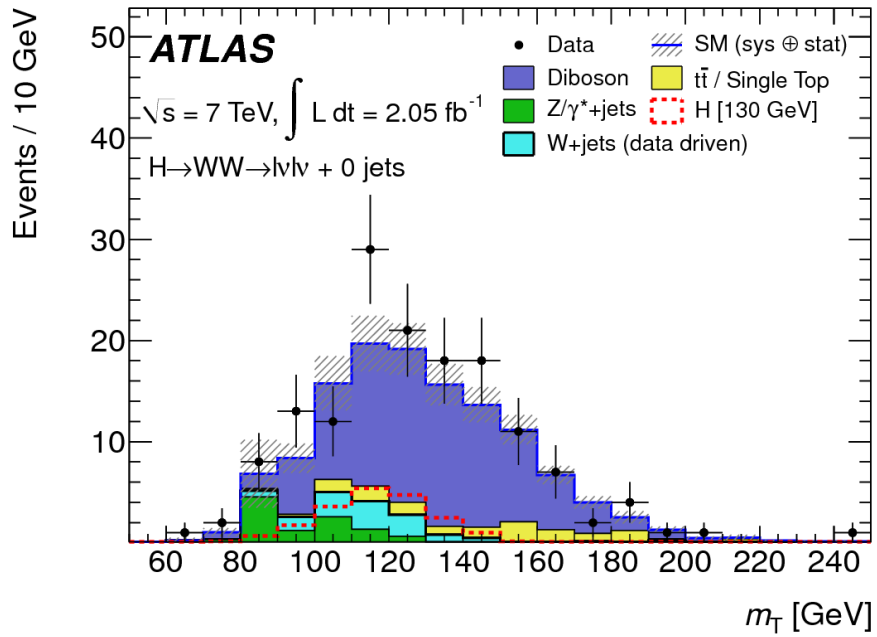


- For $\not\!\!E_T > 50$ GeV, mostly real ν's from top.
- For $\not\!\!E_T < 50$ GeV, a mixture of fakes and real ν's from $Z +$ jets.

After all cuts (for $m_H = 130$ GeV)

Observed in data	94 events
	10 ee, 42 $e\mu$, 42 $\mu\mu$
Expected BG	76 ± 11
Expected signal	19 ± 4

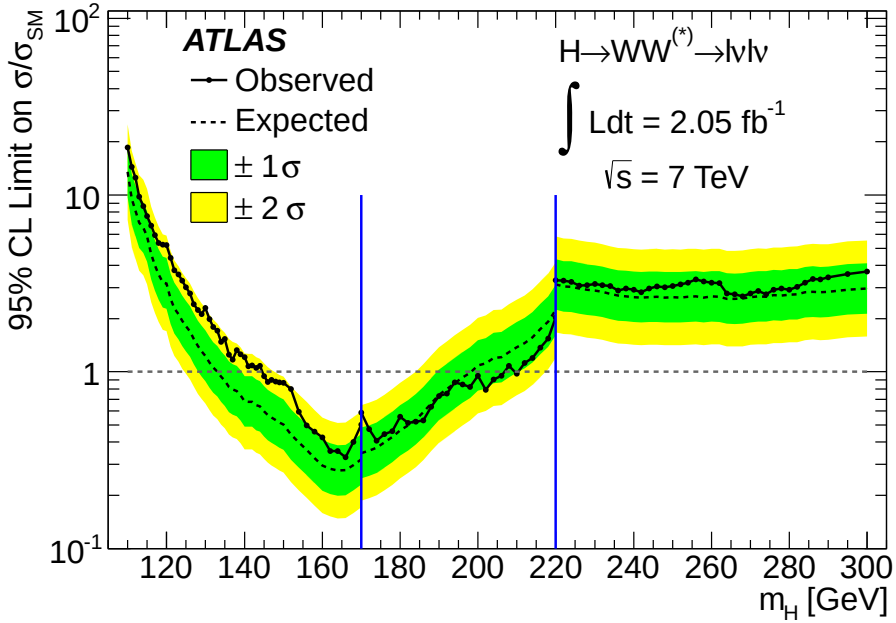
Transverse mass spectrum before m_T cut:



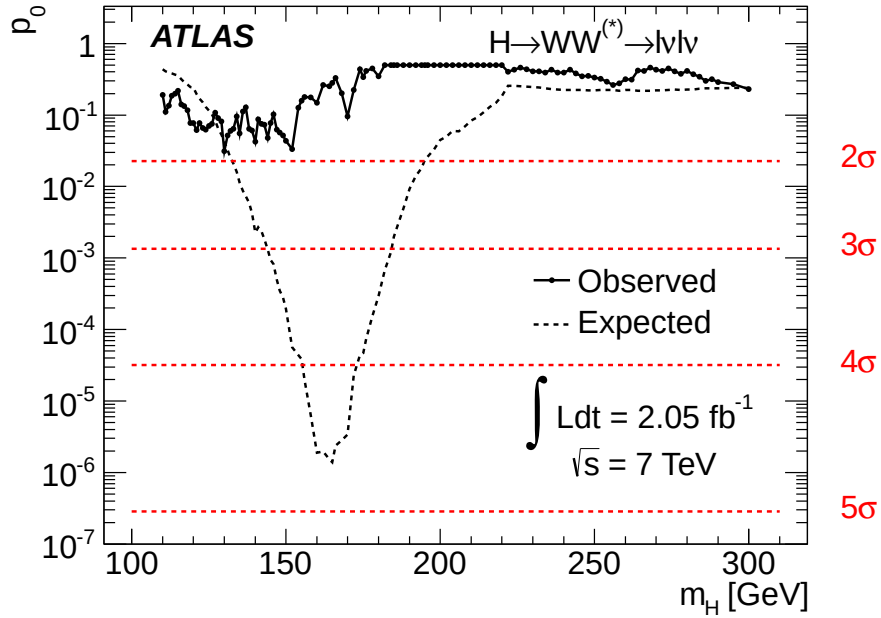
$$m_T = \sqrt{(E_T^{\ell\ell} + \not\!\!E_T)^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{\text{miss}})^2}$$

$H \to WW^{(*)} \to \ell\nu\ell\nu$

Exclusion limits:



Consistency with background-only hypothesis



Excluded at 95% CL: $145 < m_H < 206$ GeV (expected: 134–200 GeV)
Maximum deviation is 1.9σ at $m_H \sim 130$ GeV.

$H \to \gamma\gamma$

$\int \mathcal{L}\, dt = 4.9\ \text{fb}^{-1}$

- Covers $110 < m_H < 150$ GeV.
- $\gamma\gamma$ Higgs decay relatively rare
  - $\sigma \times BR \sim 40$ fb
- Simple final state: 2 high-p_T isolated photons.
  - Require $E_T(\gamma_1, \gamma_2) > (40, 25)$ GeV
- Events divided into 9 categories based on:
  - Photon η (central, crack, endcap).
  - Did photon convert?
  - $p_T(\gamma\gamma)$ perpendicular to $\gamma\gamma$ thrust axis.

Main background: continuum $\gamma\gamma$ production.

- Other backgrounds: γj, jj.

In 4.9 fb^{-1}, expect

- 70 signal events for $m_H = 125$ GeV.
- ~ 3000 background events in signal window.
- $S/B \sim 0.02$.

Analysis requires excellent $\gamma\gamma$ mass resolution and π^0 rejection.

$m(\gamma\gamma)$: opening angle $[m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)]$

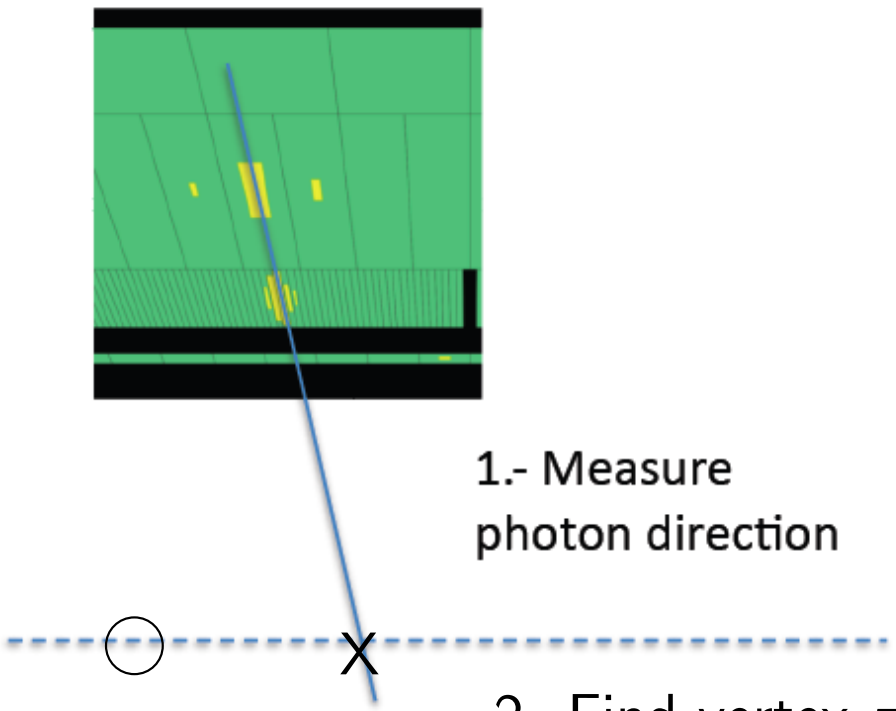
Fine EM calorimeter segmentation allows direct $\theta(\gamma)$ measurement.

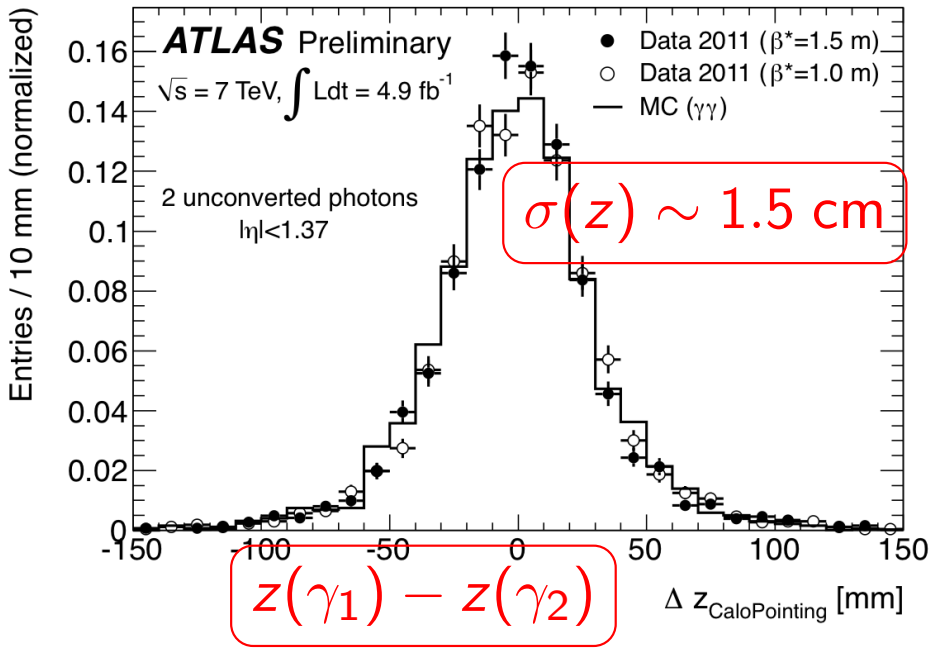
Calorimeter "pointing" reduces vertex uncertainty: $\sim 5.6 \rightarrow 1.5$ cm.

Crucial at high pileup with many vertices over the $\sim$ 5.6 cm LHC beam spot:
Which one produced the $\gamma\gamma$ pair?

With pointing (and conversion vertex location), angular term contributes negligible uncertainty to $m(\gamma\gamma)$.

Robust against pileup!

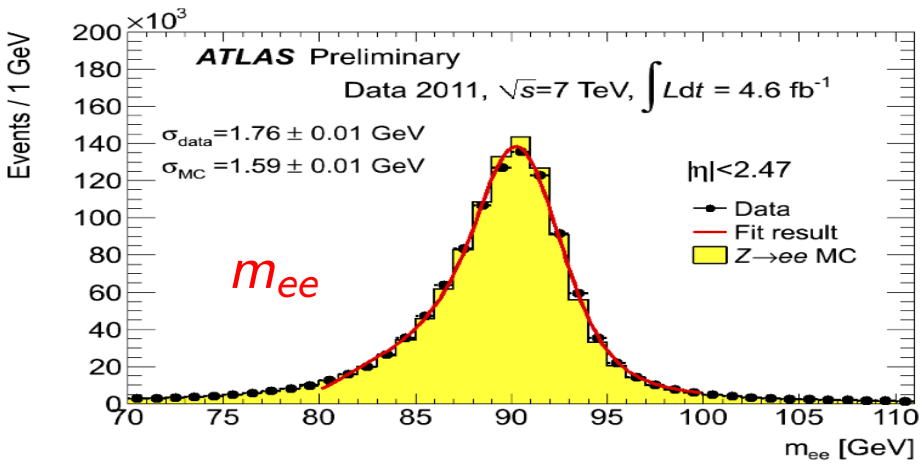




$m(\gamma\gamma)$: resolution

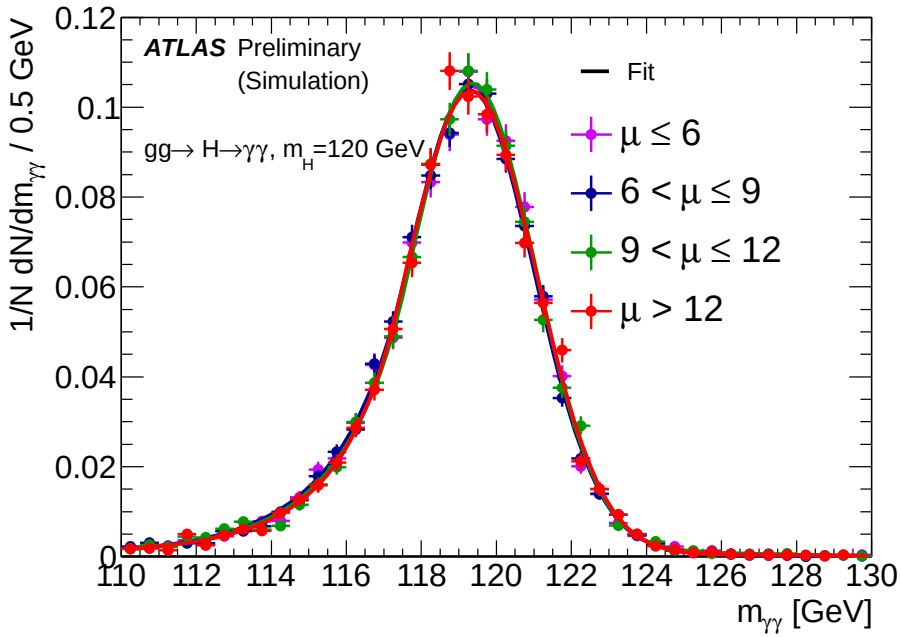
Calorimeter energy calibration:

- From Z, J/ψ, W data and MC
- Scale @m_Z known to 0.5%.
- Linearity better than 1%.
- Uniformity: $\sim 1\%$ (barrel), $\sim 1.7\%$ (endcap).
- e calibration converted to γ via MC (small systematics from upstream material).



Width of $m(\gamma\gamma)$:

- Overall: 1.7 GeV.
- Best: 1.4 GeV (unconverted central).
- Worst: 2.3 GeV ($\geq 1\gamma$ converted, $\geq 1\gamma$ in crack).

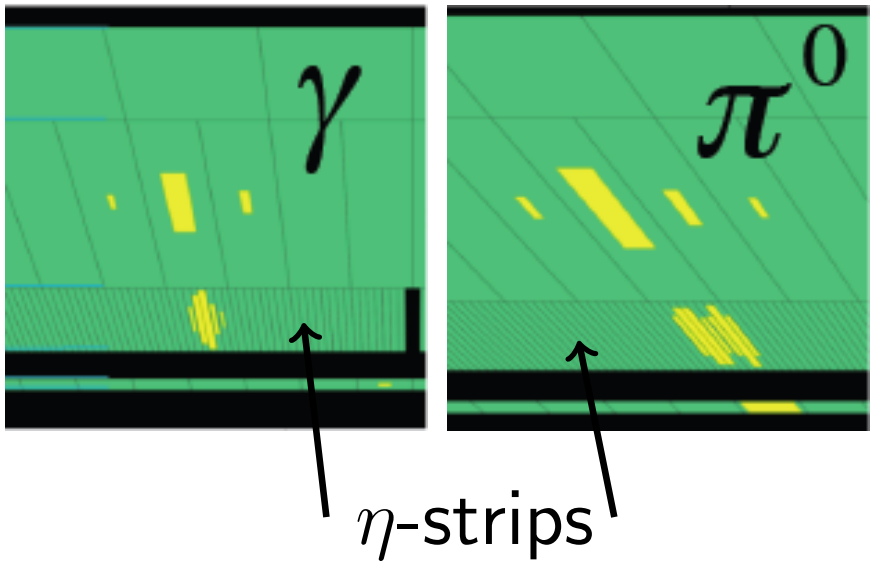


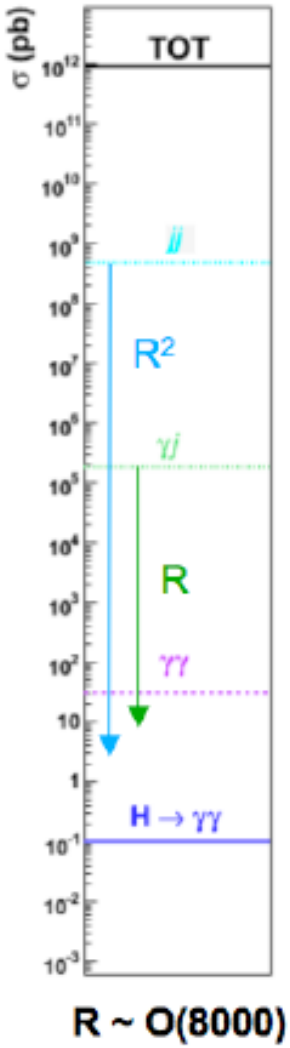
π^0 rejection

Important backgrounds are jj and γj with $j \to \pi^0$.

Need for π^0 rejection motivated fine η segmentation of first EM compartment.

($E_T \sim$ 20–30 GeV)





jj: $\sim 500\ \mu$b

γj: ~ 200 nb

$\gamma\gamma$: ~ 30 pb

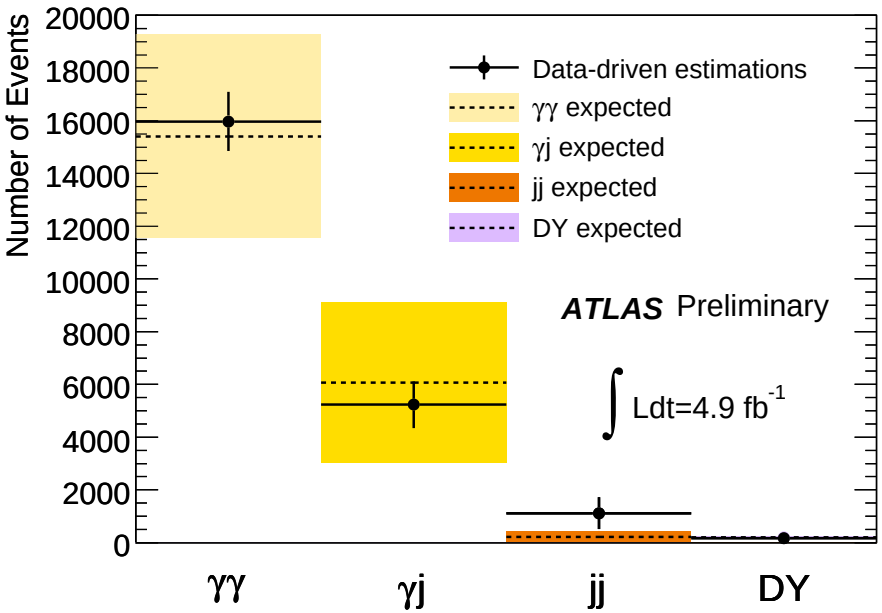
$H \to \gamma\gamma$: ~ 40 fb

Large uncertainties on $\sigma(\gamma j, jj)$: need to measure with data.

$H \to \gamma\gamma$ background composition

After all cuts: 22489 events in $100 < m_{\gamma\gamma} < 160$ GeV.

Estimate composition using control samples



	Nb. of events	Fraction
$\gamma\gamma$	16000 ± 1120	$(71 \pm 5)\%$
γj	5230 ± 890	$(23 \pm 4)\%$
jj	1130 ± 600	$(5 \pm 3)\%$
DY/Z	165 ± 8	$(0.7 \pm 0.1)\%$

Purity $\sim 70\%$

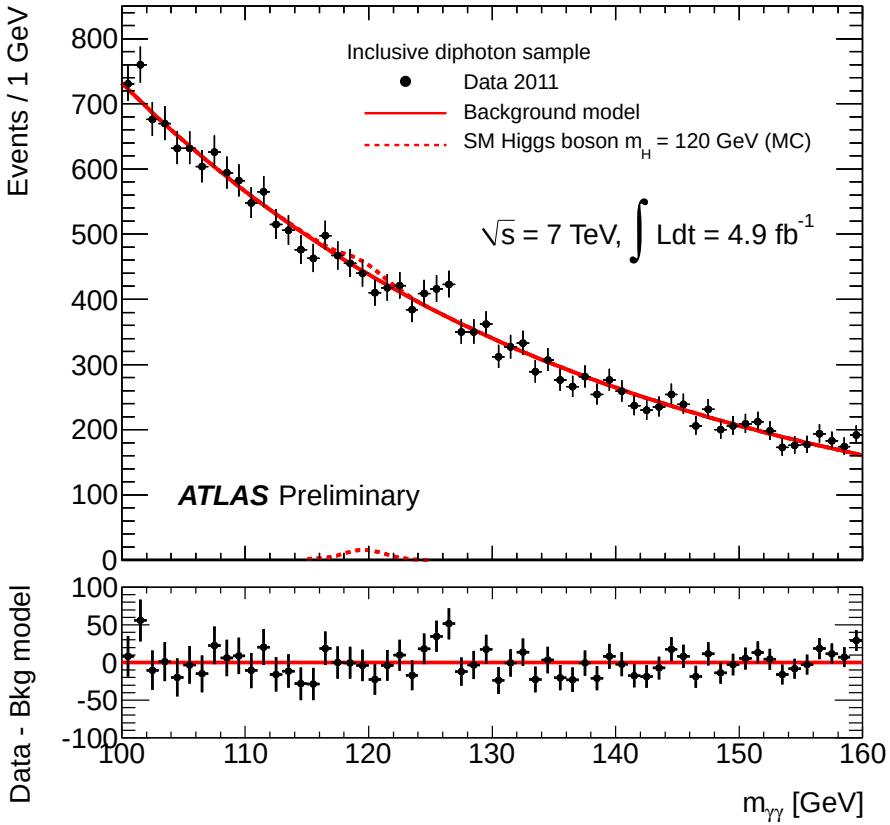
$\gamma j + jj \ll \gamma\gamma$

Photon identification efficiency: $85 \pm 5\%$

(From MC, cross-checked with data.)

$H \to \gamma\gamma$: results

Background in each category fit with an exponential.

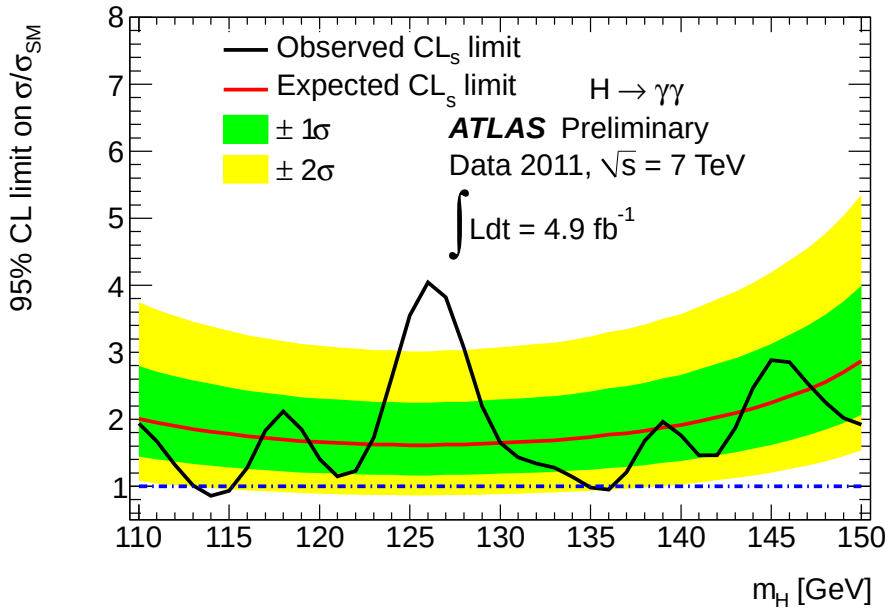


Dominant systematics:

- Signal yield: $\sim 20\%$
- $m_{\gamma\gamma}$ resolution: $\sim 14\%$
- $H \to \gamma\gamma$ p_T: $\sim 8\%$

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

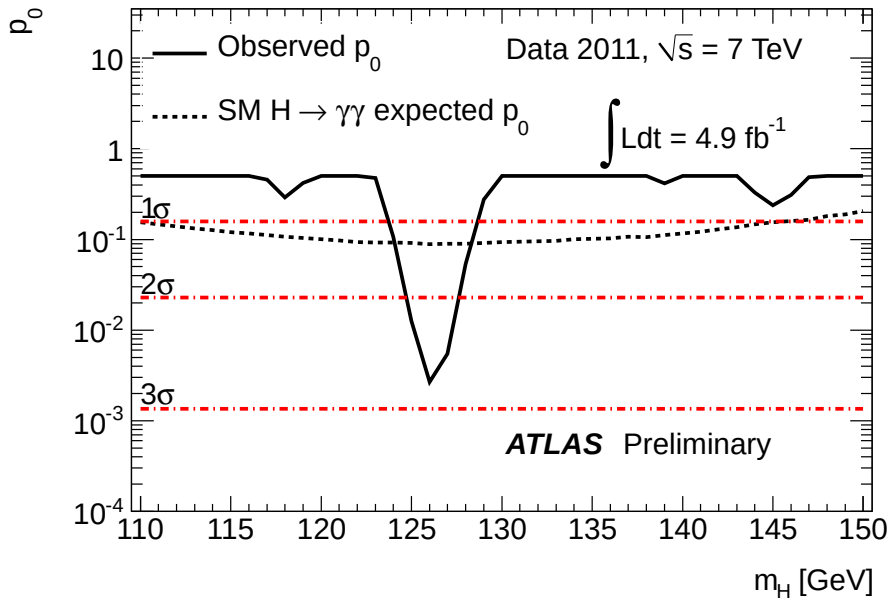
$H \to \gamma\gamma$: exclusion limits



Excluded at 95% CL:

$114 \leq m_H \leq 115$ GeV;
$135 \leq m_H \leq 136$ GeV

Consistency of data with background-only expectation:



Max. deviation from background: $m_H = 126$ GeV

- Local p_0: 0.27% (2.8σ)
- SM Higgs expectation: $\sim 1.4\sigma$
- Include "look-elsewhere" effect: p_0 (110–150 GeV): 7% (1.5σ)

$H \to ZZ^{(*)} \to 4\ell$ $(4e,\ 4\mu,\ 2e2\mu)$ $\int \mathcal{L}\, dt = 4.8\ \text{fb}^{-1}$

- Covers $110 < m_H < 600$
- Small $\sigma \sim 2$–5 fb. But:
  - Fully reconstructed mass.
  - Small background, $S/B \sim 1$.
- 2 opposite-sign, same-flavor lepton pairs.
- ${p_T}^{1,2,3,4} > 20, 20, 7, 7$ GeV.
- m_{12} within $m_Z \pm 15$ GeV
- $m_{34} > 15$–60 GeV (dep on m_H)

Backgrounds:

- $ZZ^{(*)}$ (irreducible)
- At lower masses: Zbb, $Z +$ jets, $t\bar{t}$.
- Reducible backgrounds suppressed with isolation and impact parameter cuts.

Analysis requirements

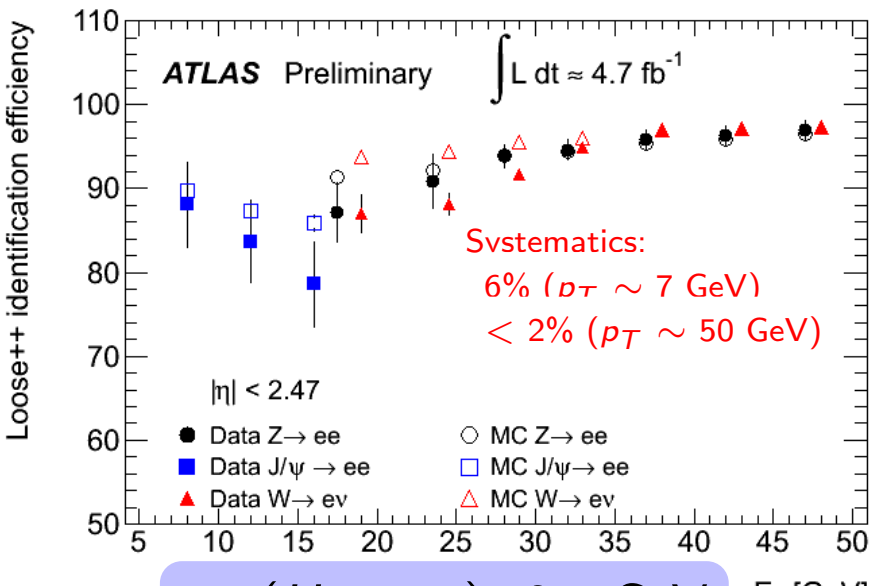
High lepton reconstruction/identification efficiencies across p_T spectrum.
Good lepton energy/momentum resolution.
Good control of reducible backgrounds for low m_H.
(Need to compare against background-enriched control regions.)

$H \to ZZ^{(*)} \to 4\ell$ ($4e$, 4μ, $2e2\mu$): Electron performance

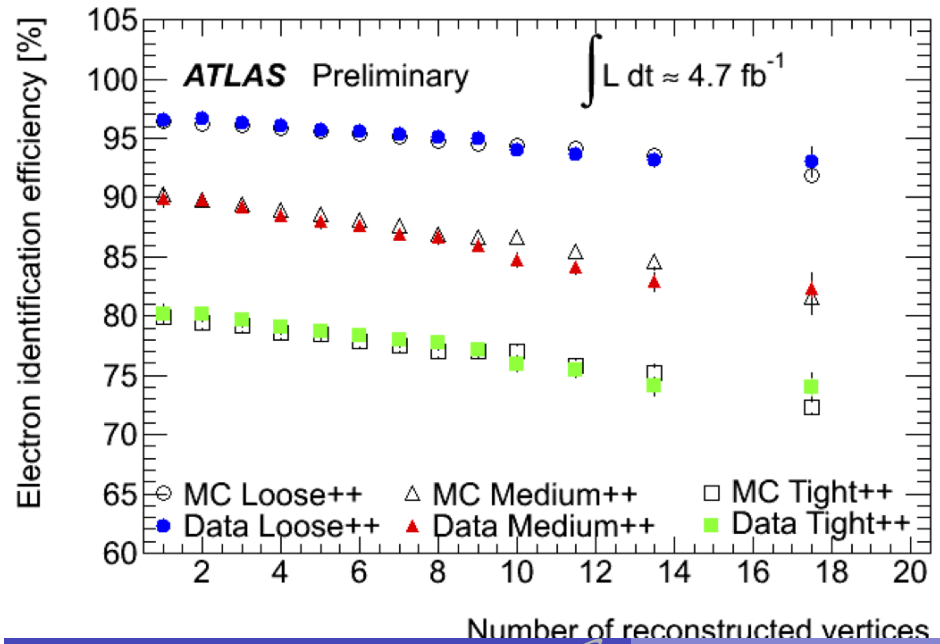
Electron efficiency measured with $J/\psi \to ee$, $W \to e\nu$, $Z \to ee$.

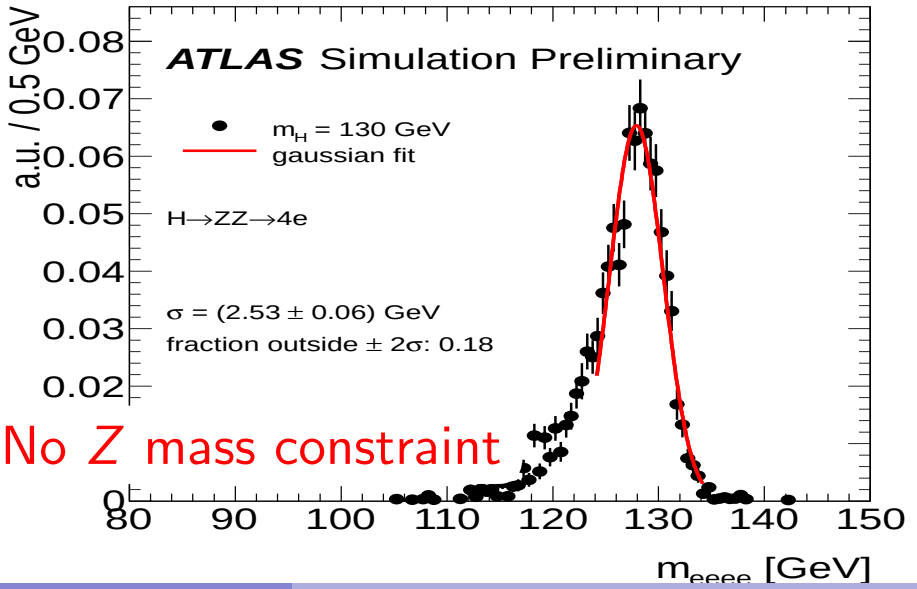
Crucial to use data in the low-p_T region, where material effects are most significant.

Variation of electron efficiency with pileup well modeled by simulation: $Z \to ee$ data/MC



$\sigma m(H \to 4e)$: 2.5 GeV





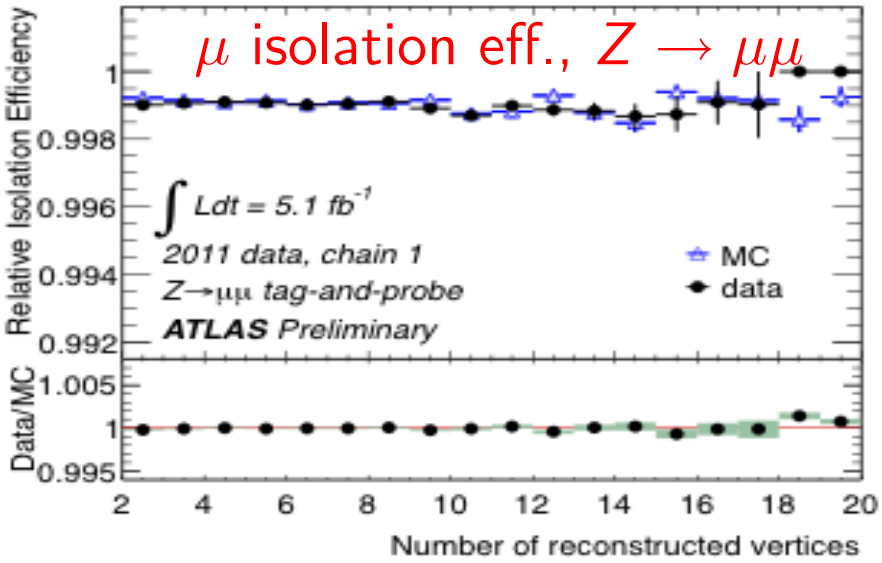
No Z mass constraint

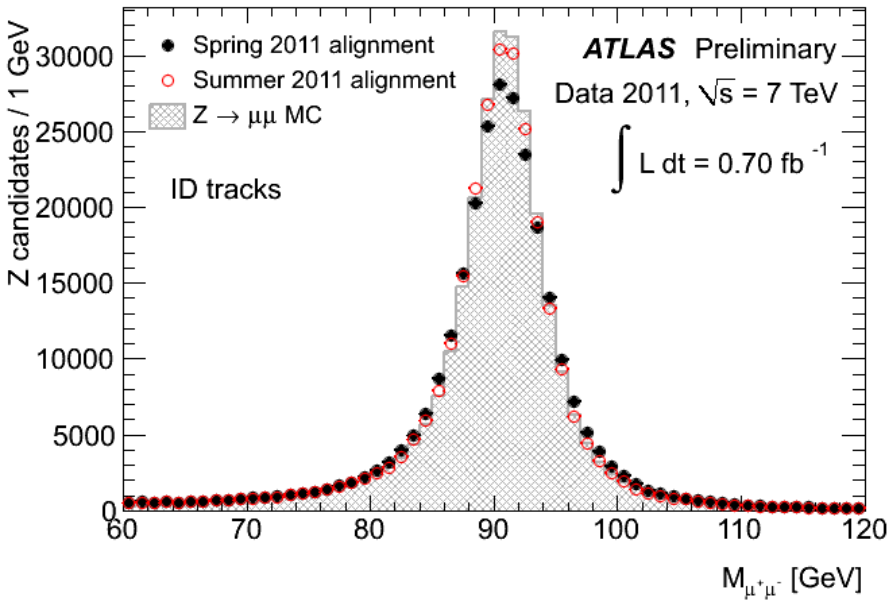
$H \to ZZ^{(*)} \to 4\ell$ ($4e$, 4μ, $2e2\mu$): Muon performance

μ reconstruction efficiency $> 95\%$ over $4 < p < 100$ GeV.

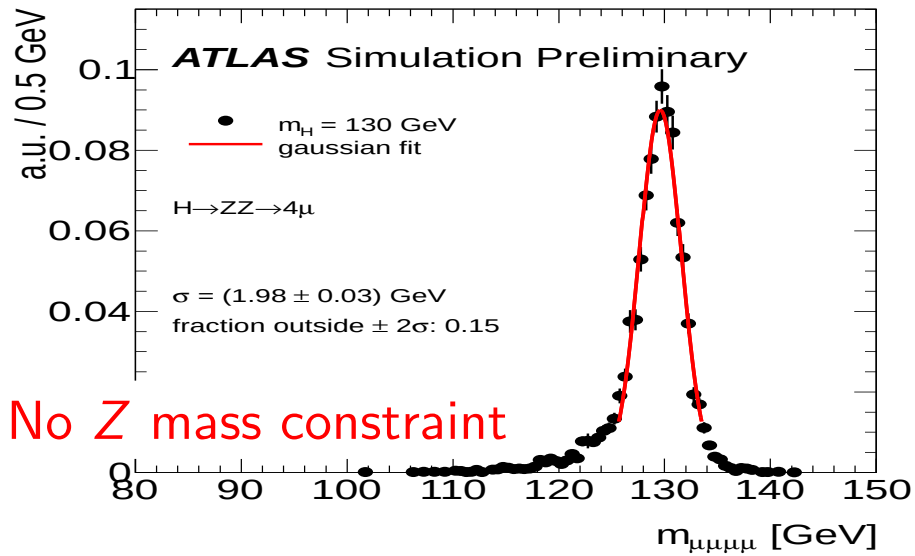
Recently improved μ alignment:

MC (perfect): 2.31 ± 0.01 GeV
Data Spring 2011: 2.89 ± 0.01 GeV
Data Summer 2011: 2.45 ± 0.01 GeV





$\sigma m(H \to 4\mu)$: 2 GeV



No Z mass constraint

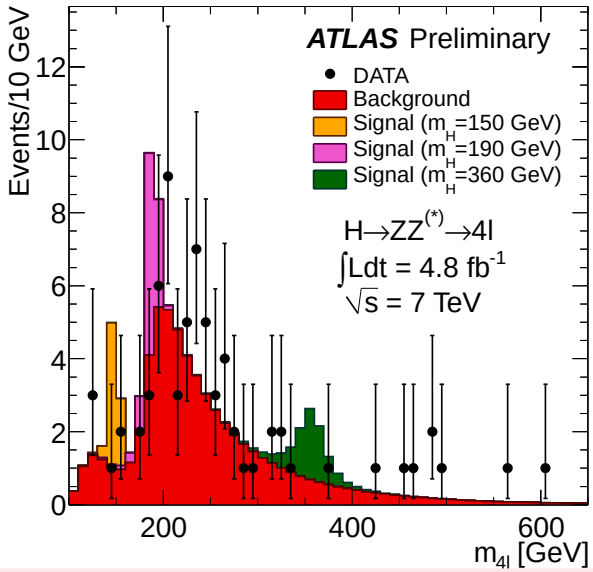
$H \to ZZ^{(*)} \to 4\ell$ ($4e$, 4μ, $2e2\mu$): After all selections

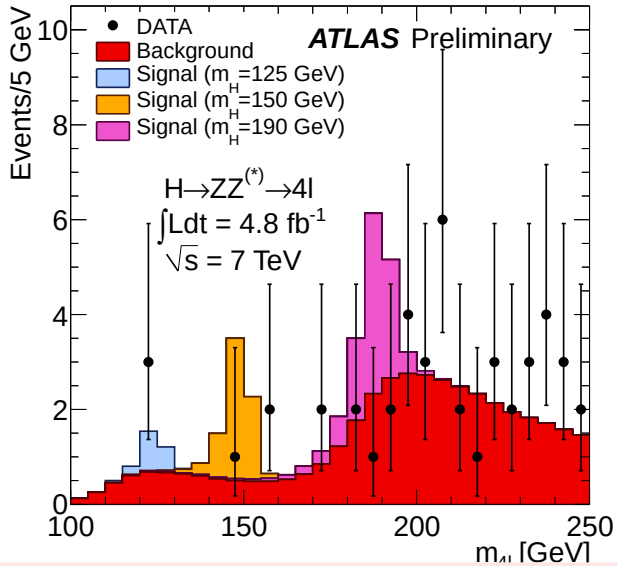
Full mass range

Observe 71 (24 4μ, 30 $2e2\mu$, 17 $4e$)
Expect from background: 62 ± 9

$m(4\ell) < 180$ GeV

Observe 8 (3 4μ, 3 $2e2\mu$, 2 $4e$)
Expect from background: 9.3 ± 1.5





For $m_H < 141$ GeV (not already excluded), observe 3 events:
two $2e2\mu$ ($m = 123.6$ GeV, $m = 124.3$ GeV), one 4μ ($m = 124.6$ GeV)

In $117 < m(4\ell) < 128$ GeV
(around $m_H = 125$ GeV):

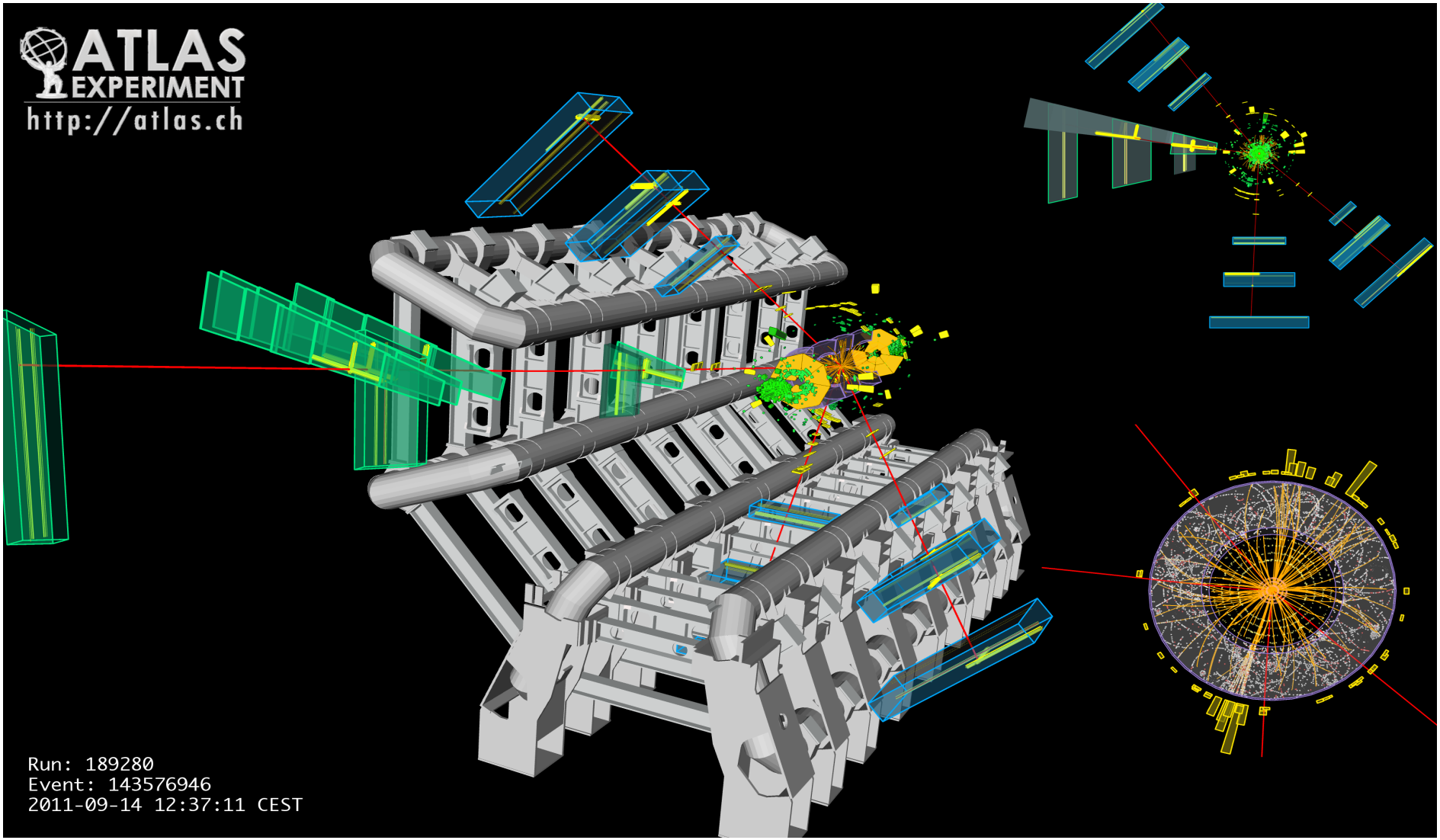
Expect 1.5 events from both signal and BG
$S/B \sim 2$ (4μ), 1 ($2e2\mu$), 0.3 ($4e$)
Background: $ZZ^{(*)}$, Z + jets ($4e$ only)

Main systematics:

Higgs cross section: $\sim 15\%$
Electron efficiency: $\sim$ 2–8%
$ZZ^{(*)}$ background: $\sim$ 15%
Zbb,Z + jets backgrounds: $\sim 40\%$

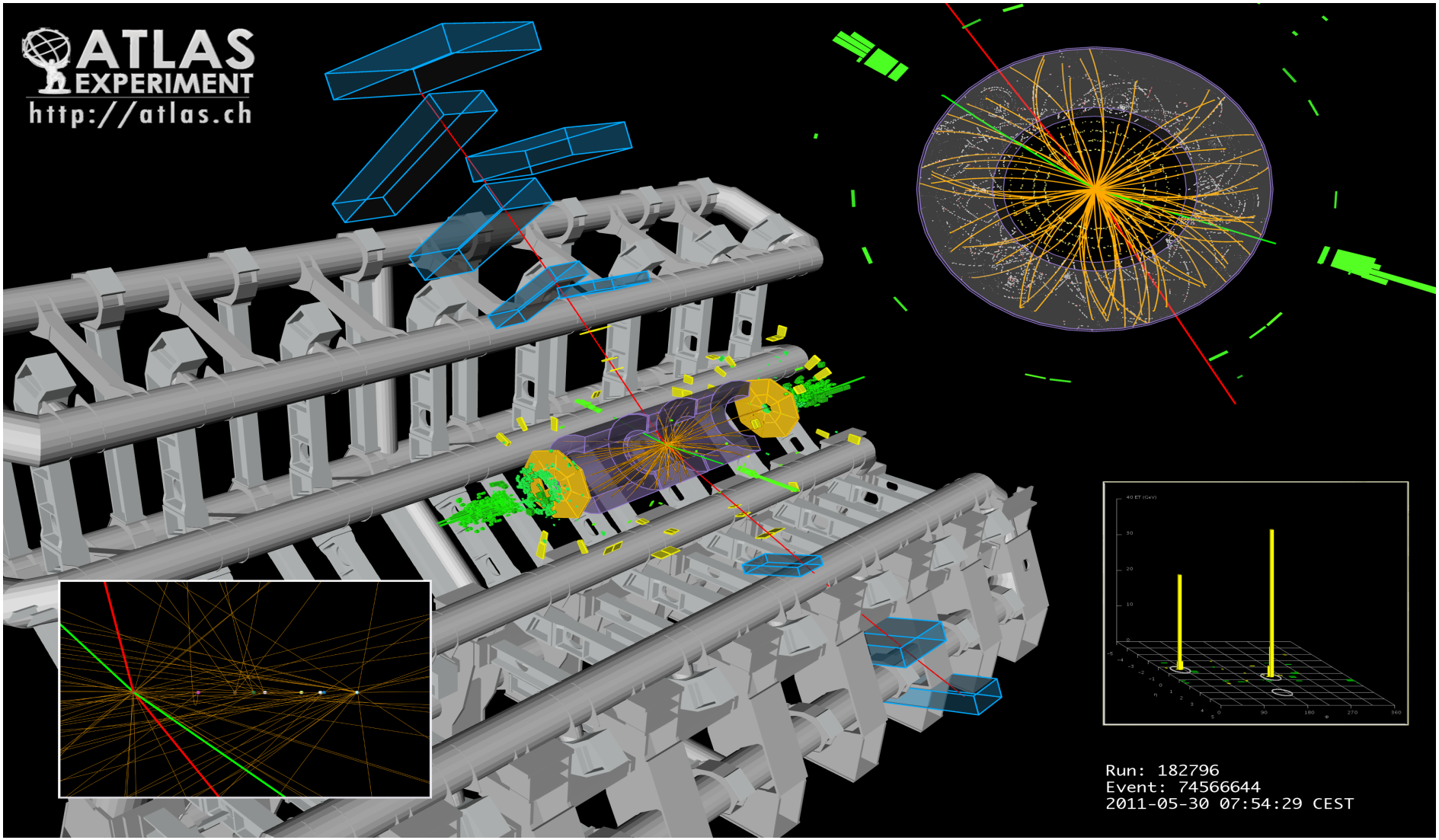
4μ candidate with $m(4\mu) = 124.6$ GeV

$p_T(\mu^-, \mu^+, \mu^+, \mu^-) = 61.2, 33.1, 17.8, 11.6$ GeV; $\quad m_{12} = 89.7$ GeV, $m_{34} = 24.6$ GeV



$2e2\mu$ candidate with $m(4\ell) = 124.3$ GeV

$p_T(e^+, e^-, \mu^-, \mu^+) = 41.5, 26.5, 24.7, 18.3$ GeV; $\quad m_{ee} = 76.8$ GeV, $m_{\mu\mu} = 45.7$ GeV

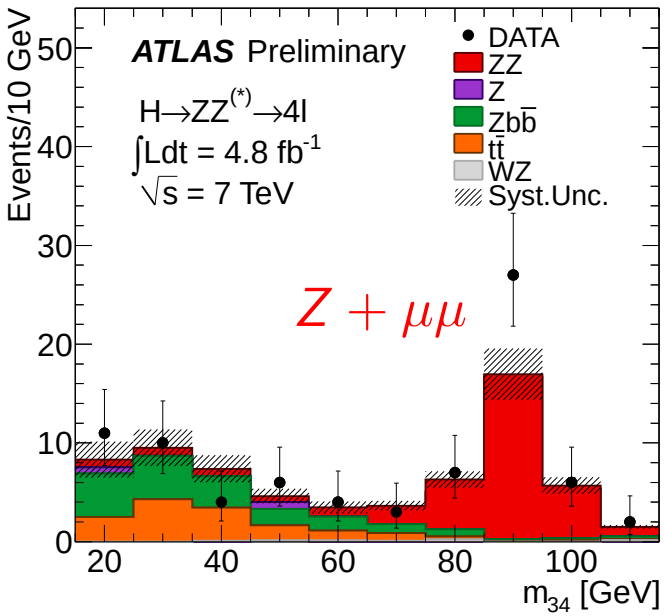


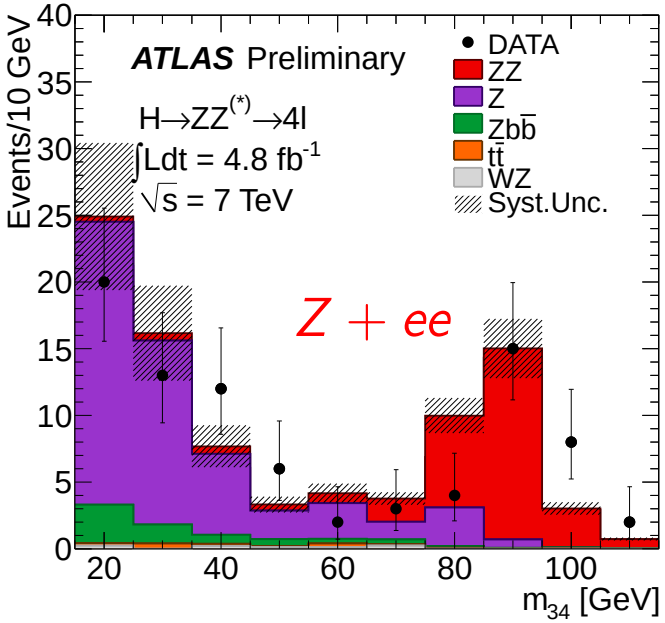
$H \to ZZ^{(*)} \to 4\ell$ backgrounds

Check reducible backgrounds with background-enriched control samples:

2 opposite-sign, same-flavor leptons near m_Z;

2 additional same-flavor leptons passing all selections except isolation and impact parameter

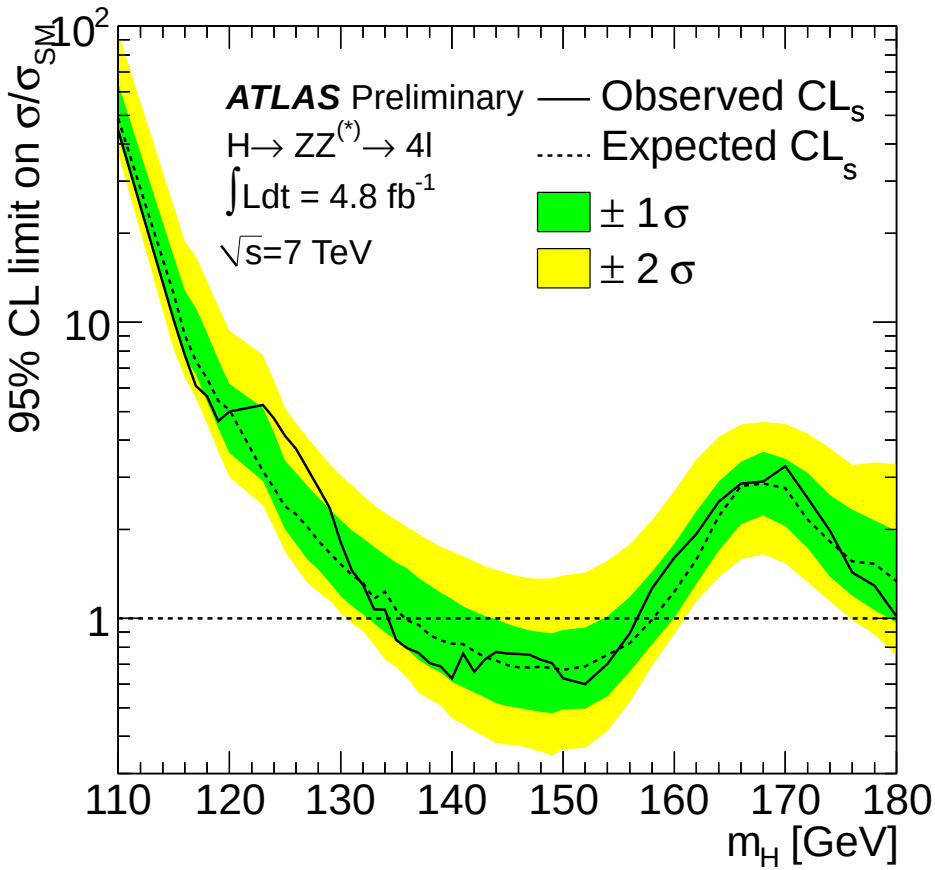


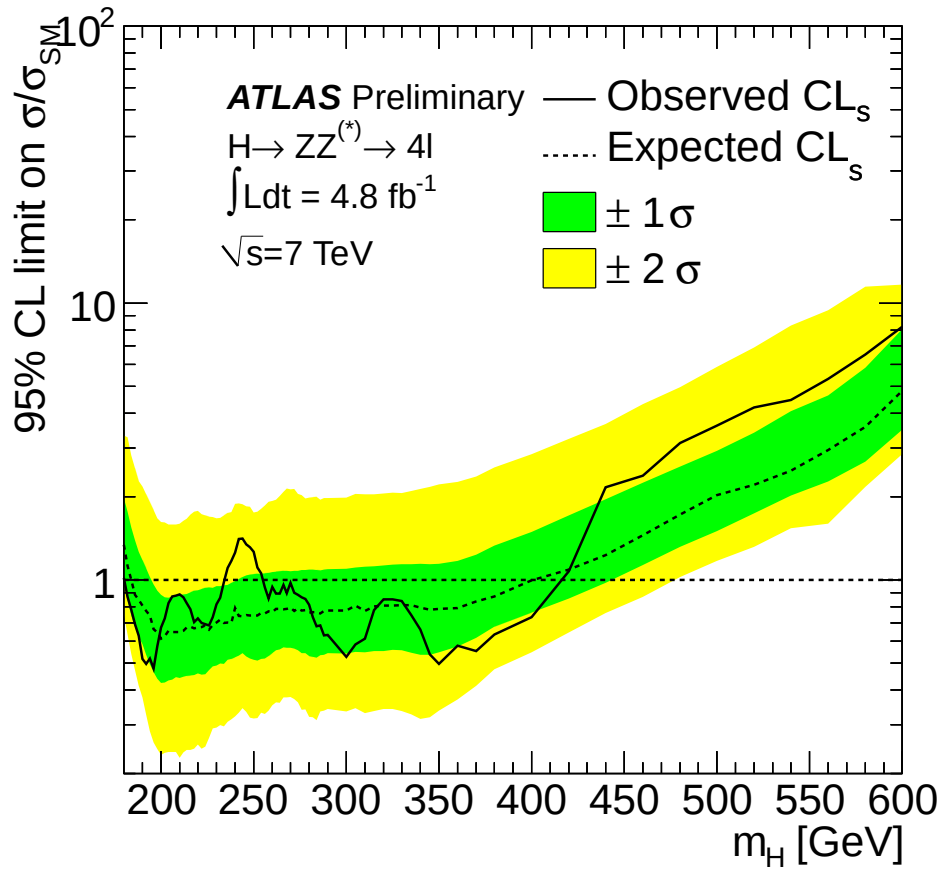


Low-mass regions dominated by Zbb (muons) and Z + jets (electrons).
MC reproduces data well (within uncertainties)
$Z + e/Z + \mu$ samples used to compare selection efficiencies between data and MC.
Good agreement $\to$ MC used to estimate background in signal region.

$H \to ZZ^{(*)} \to 4\ell$ exclusion limits

Fit signal and background expectations to mass spectrum.

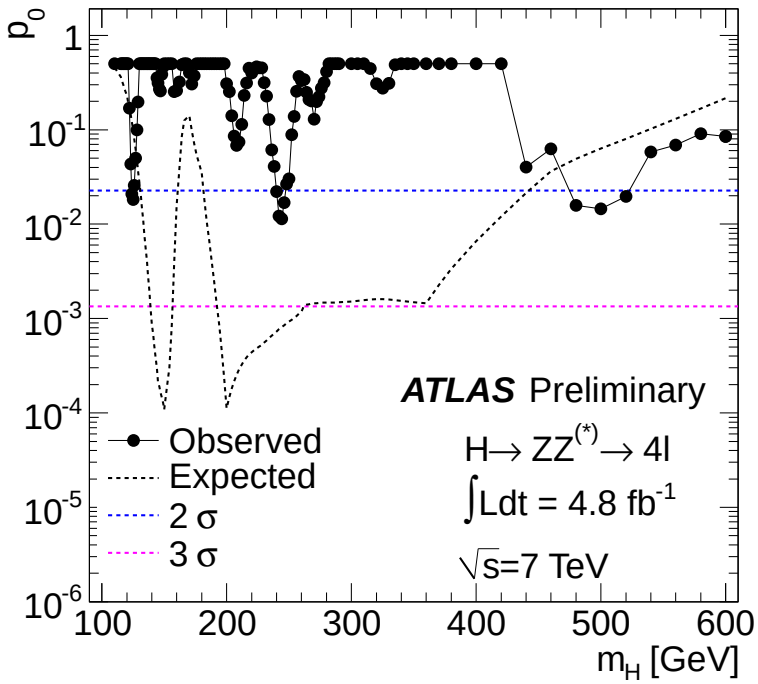


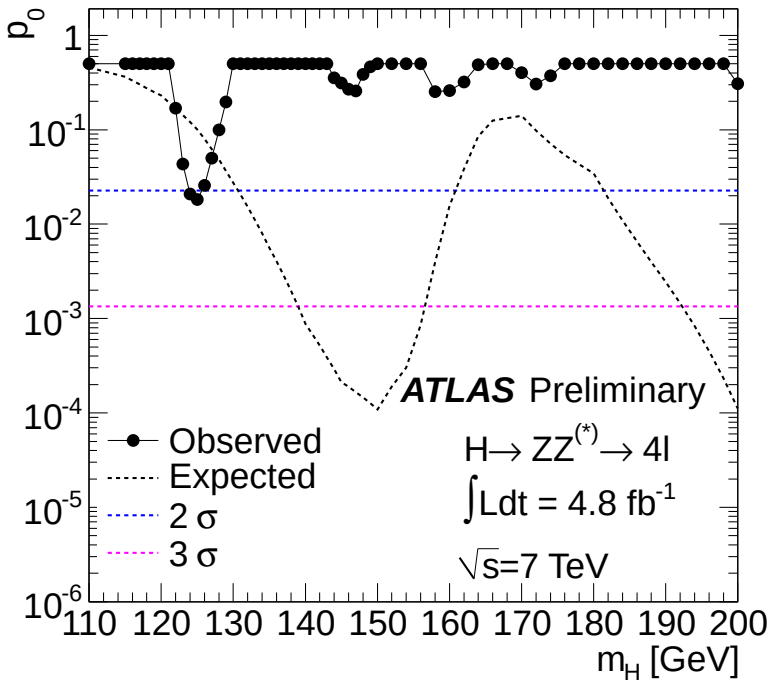


Excluded (95% CL): $135 < m_H < 156$ GeV and $181 < m_H < 415$ GeV (except 234–255 GeV)

Expected exclusion: $137 < m_H < 158$ GeV and $185 < m_H < 400$ GeV

$H \to ZZ^{(*)} \to 4\ell$: consistency with BG-only hypothesis





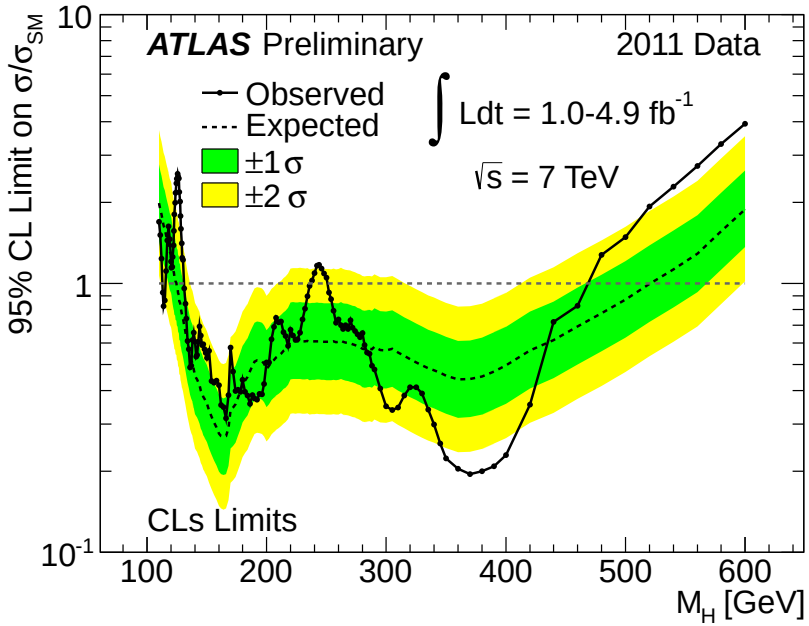
Maximum deviations from background-only expectations

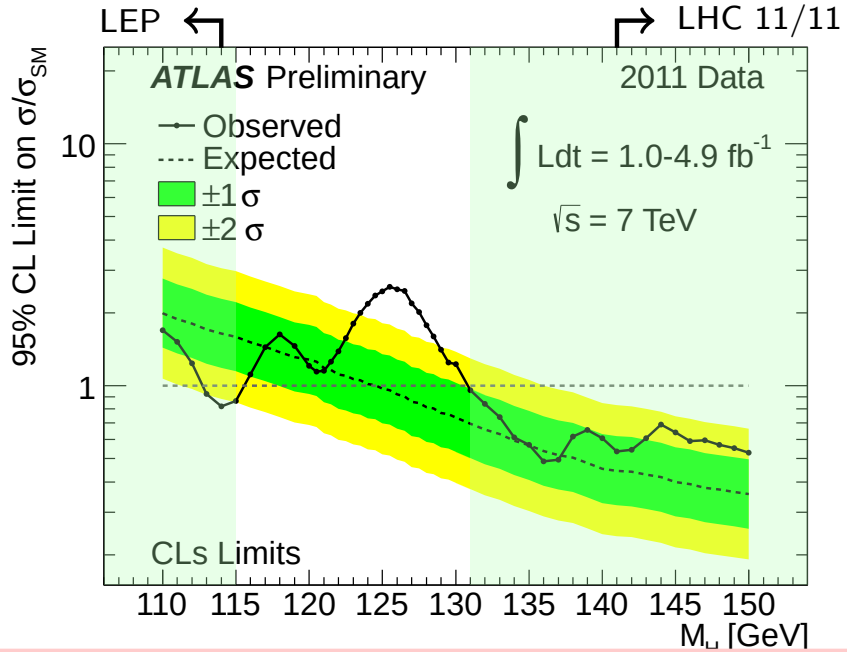
m_H (GeV)	Local p_0	LEE corrected	Local signif	Expected from SM Higgs
125	1.8%	$\sim 50\%$	2.1σ	1.4σ
244	1.1%	$\sim 50\%$	2.3σ	3.2σ
500	1.4%	$\sim 50\%$	2.2σ	1.5σ

Look-elsewhere effect (LEE) estimated over $110 < m_H < 600$ GeV

Combined exclusion limits

Channels: $\gamma\gamma$; $\tau\tau$; $WW^{(*)} \to \ell\nu(\ell\nu, qq)$; $ZZ^{(*)} \to \ell\ell(\ell\ell, \nu\nu, qq)$
Not included: $W/ZH \to \ell bb + X$



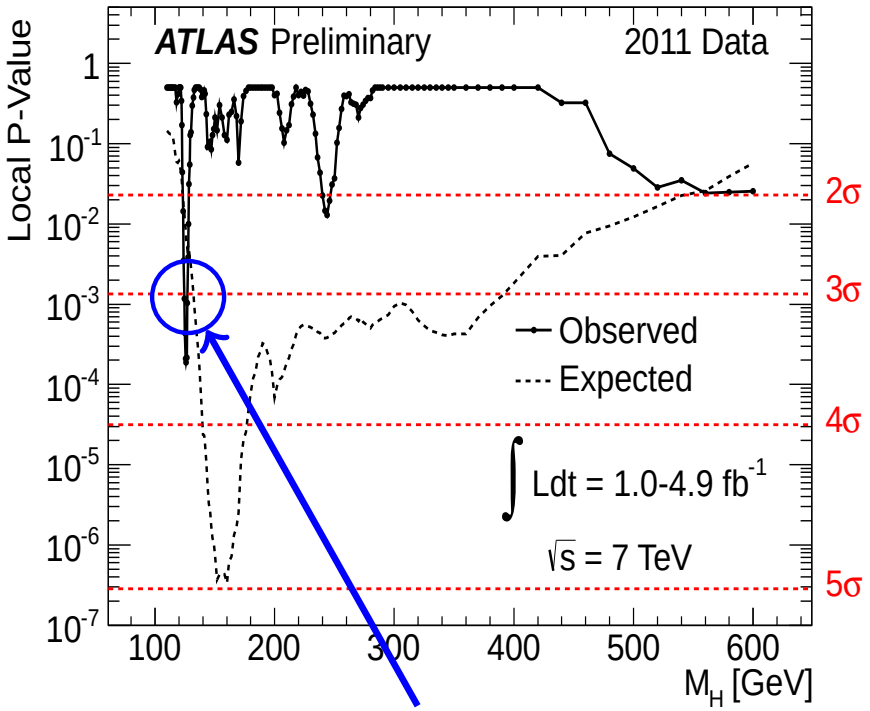


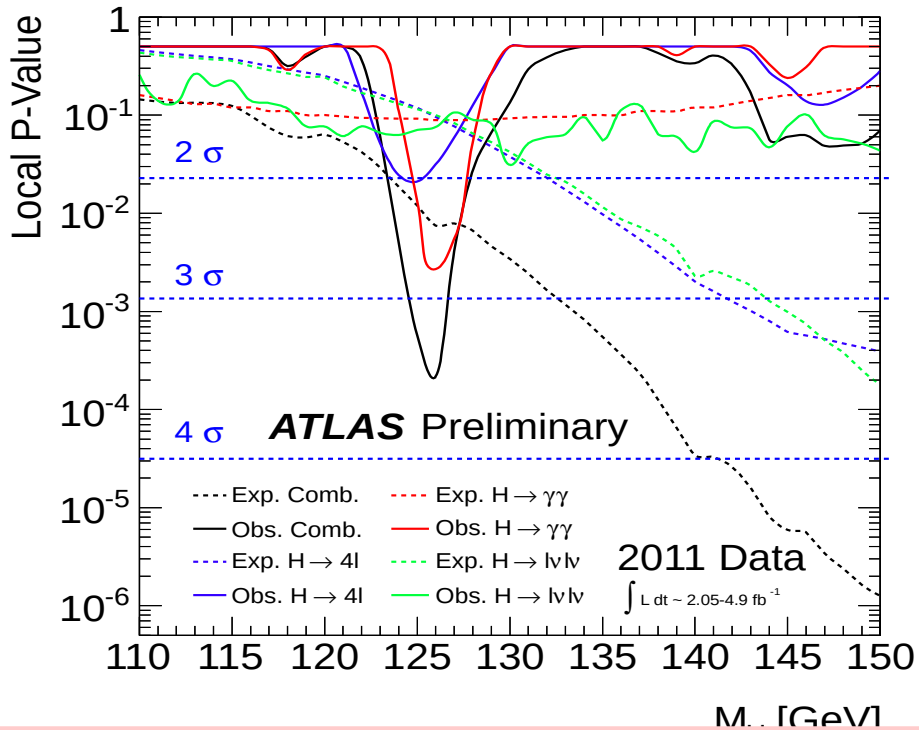
Excluded at 95% CL

$112.7 < m_H < 115.5$ GeV; $131 < m_H < 453$ GeV, except 237–251 GeV

Expected exclusion if no signal: 124.6–520 GeV
Excluded at 99% CL: $133 < m_H < 230$ GeV; $260 < m_H < 437$ GeV

Consistency with background-only expectations





Biggest inconsistency with expected background at $m_H \sim 126$ GeV

SM Higgs: Expect 2.4σ (1.4σ per channel).

Local significance of excess

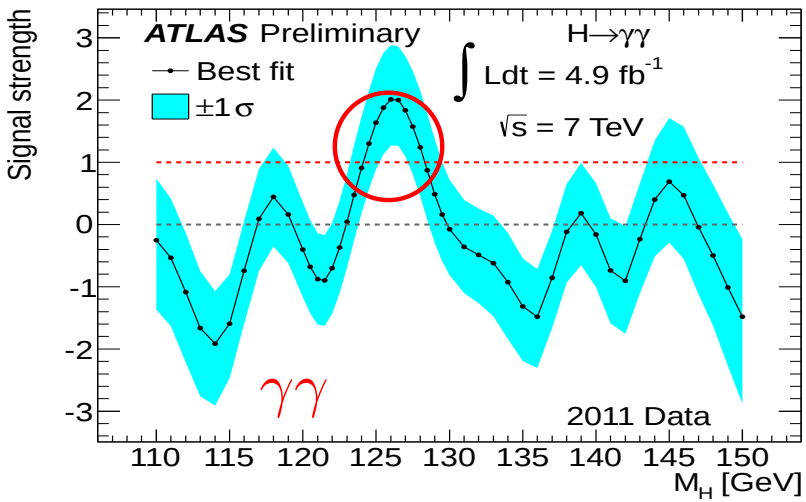
1.9×10^{-4} (3.6σ)

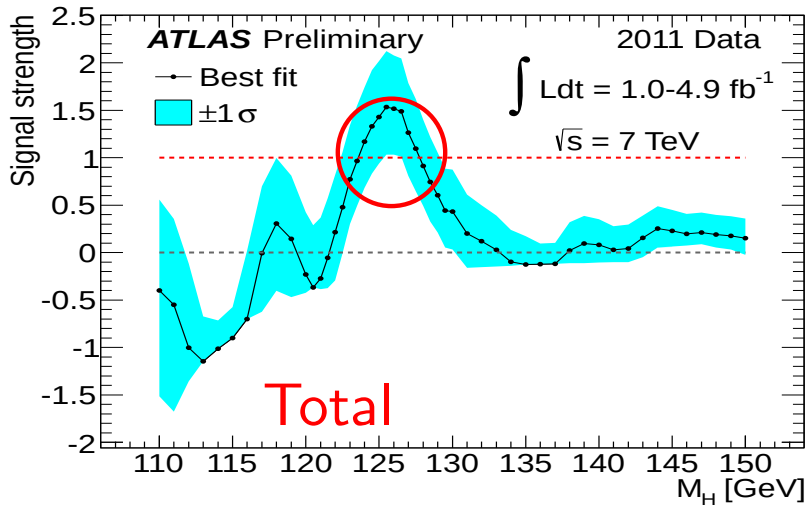
$\gamma\gamma$: 2.8σ; 4ℓ: 2.1σ; $\ell\nu\ell\nu$: 1.4σ

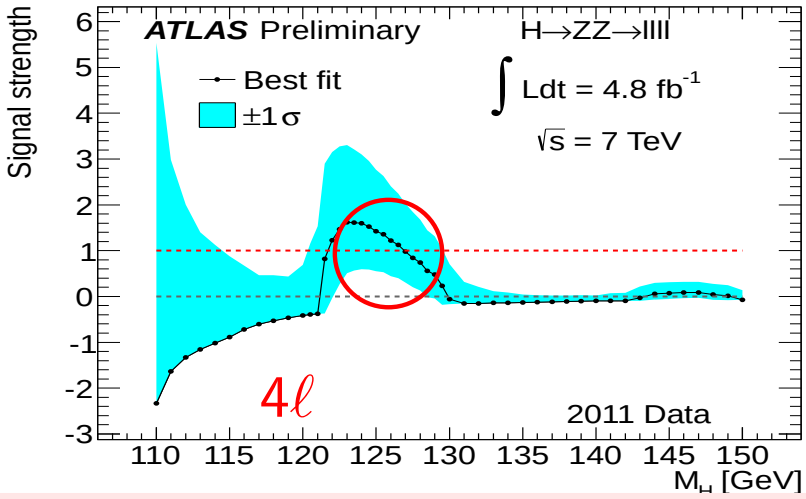
Corrected for look-elsewhere effect

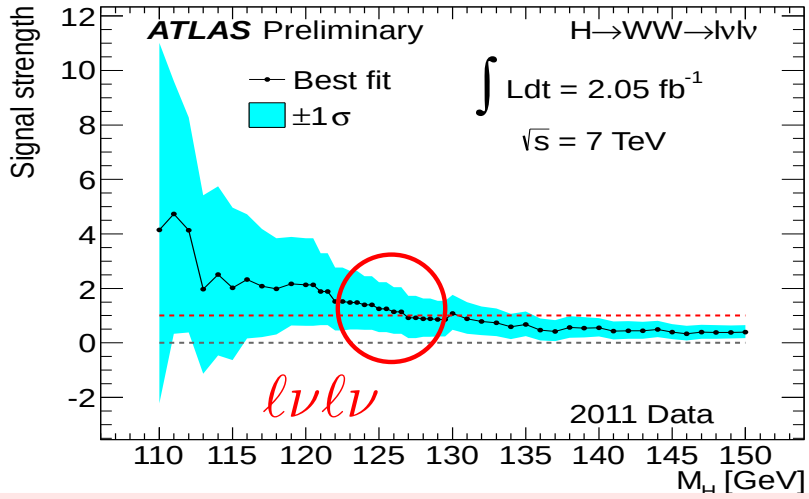
110–146 GeV: 2.5σ (0.6%); 110–600 GeV: 2.2σ (1.4%)

Consistency with SM Higgs









Excess 2 ± 0.8 times larger than expected in $\gamma\gamma$ channel; within 1σ for others and combined.

Still to come

On timescale of winter conferences:

- Update all channels to full luminosity.
- Relax kinematic cuts to increase acceptance at low m_H.
- Better S/B discrimination:
  - Multivariate techniques, more analysis bins, etc.
- Ongoing improvements to object reconstruction and detector modeling.

Combination with CMS under discussion.

2012 run:

With ~ 20 fb^{-1} additional luminosity per experiment:

- 5σ discovery at $m_H \sim 125$ (ATLAS alone)
- $\sim 3\sigma$ per channel
- Combining ATLAS+CMS: 5σ down to ~ 116 GeV

Doesn't include:

- Analysis improvements.
- Possible increase in energy to $\sqrt{s} = 8$ TeV. (10% gain)

Conclusions

The LHC and ATLAS have performed wonderfully over the past year!

We have searched for a SM Higgs boson at the LHC using up to 4.9 fb^{-1} of integrated luminosity in many distinct channels over 110–600 GeV;

Small excess observed around $m_H \sim 126$ GeV

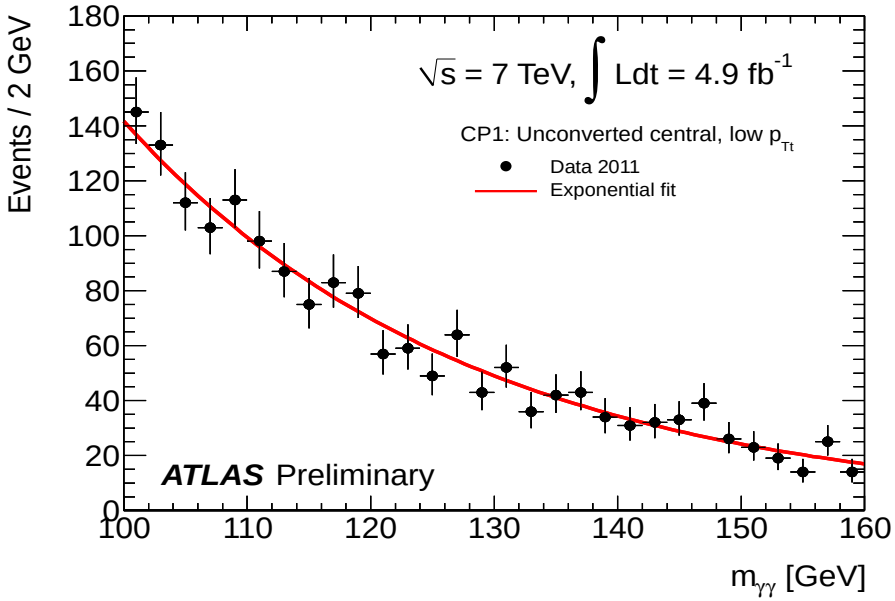
- Local significance 3.6σ from the $H \to \gamma\gamma$ (2.8σ), $H \to ZZ^{(*)} \to 4\ell$ (2.1σ), $H \to WW^{(*)} \to \ell\nu\ell\nu$ (1.4σ) channels.
- SM Higgs expectation: 2.4σ (local). Observed excess compatible within 1σ.
- Significance corrected for look-elsewhere effect: $\sim 1\%$ (2.3σ)

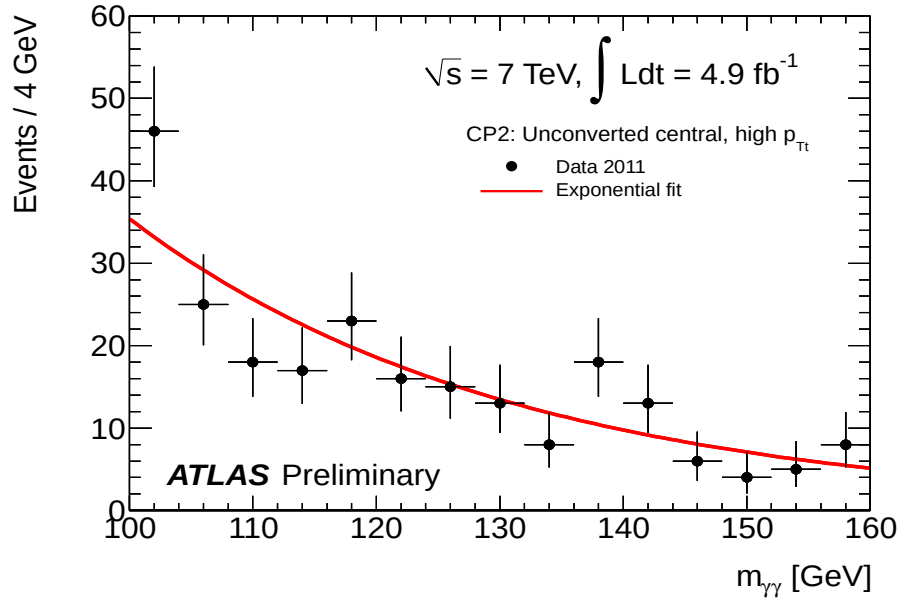
More data are needed to draw any definite conclusions.
We're well-positioned for the year to come!

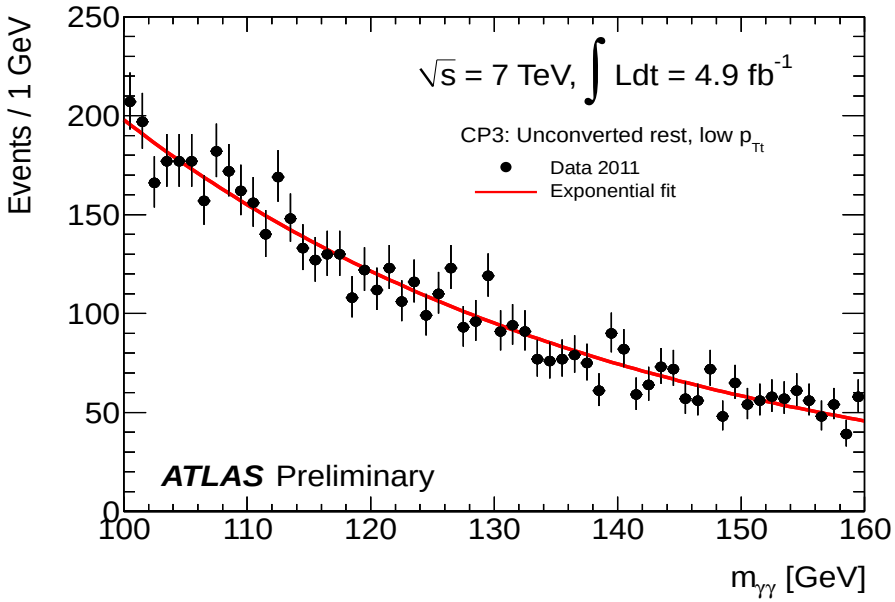
More info: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-163 (+references)

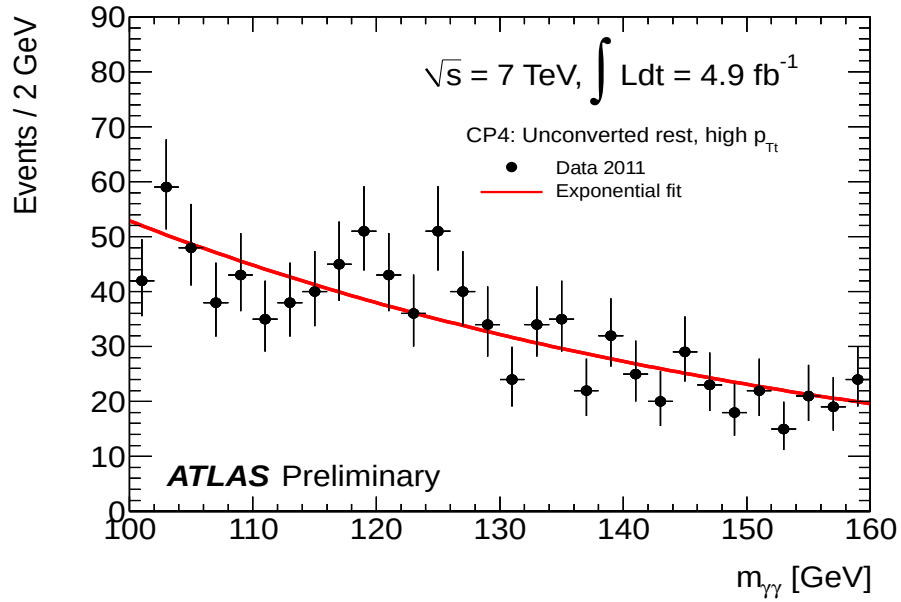
Backup

$H \to \gamma\gamma$ by category 1

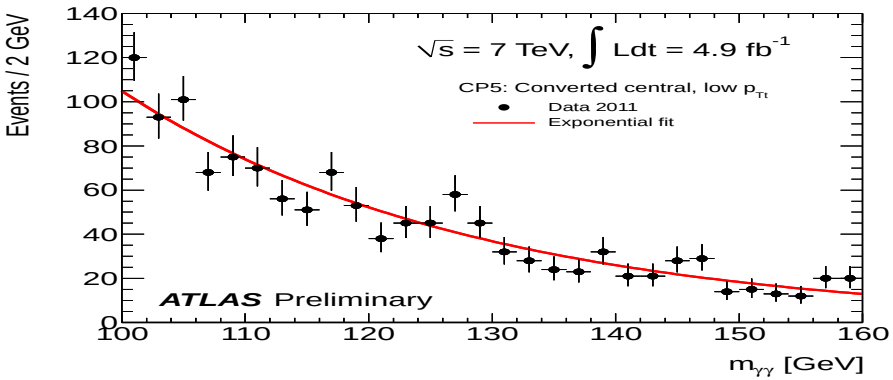


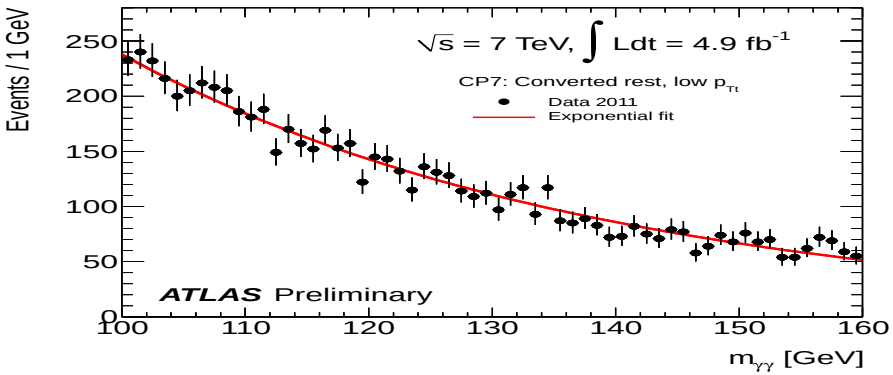


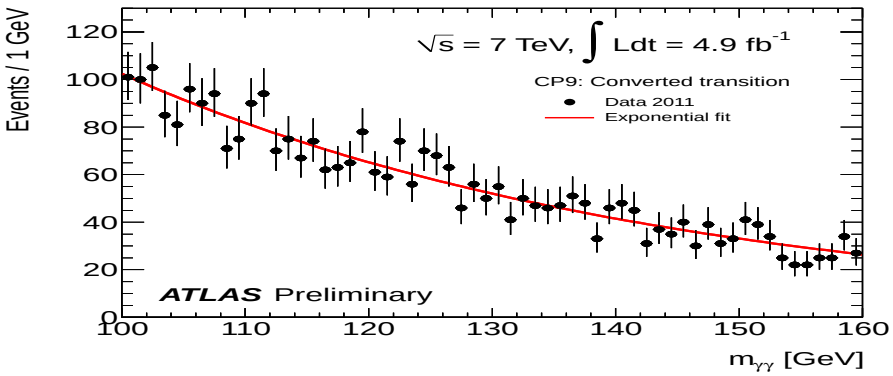


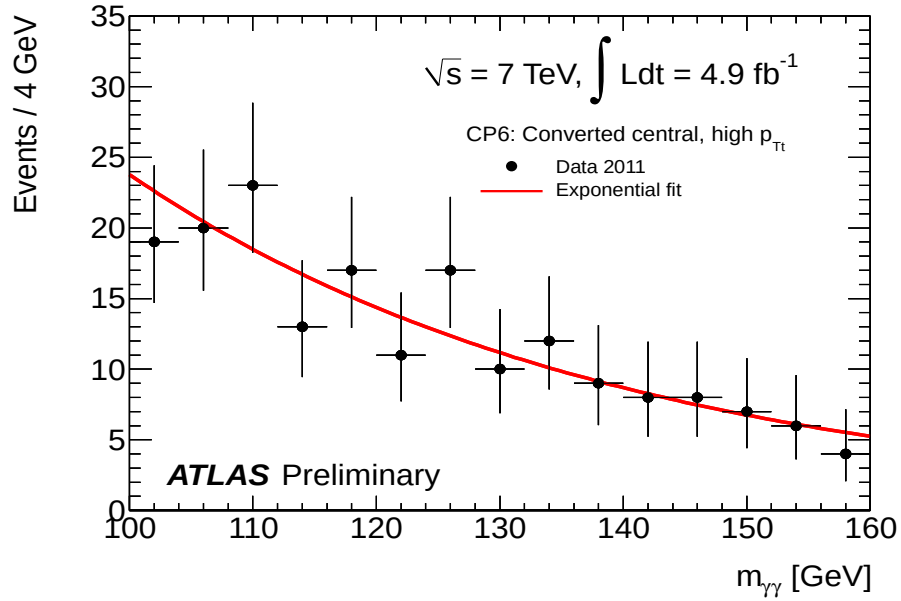


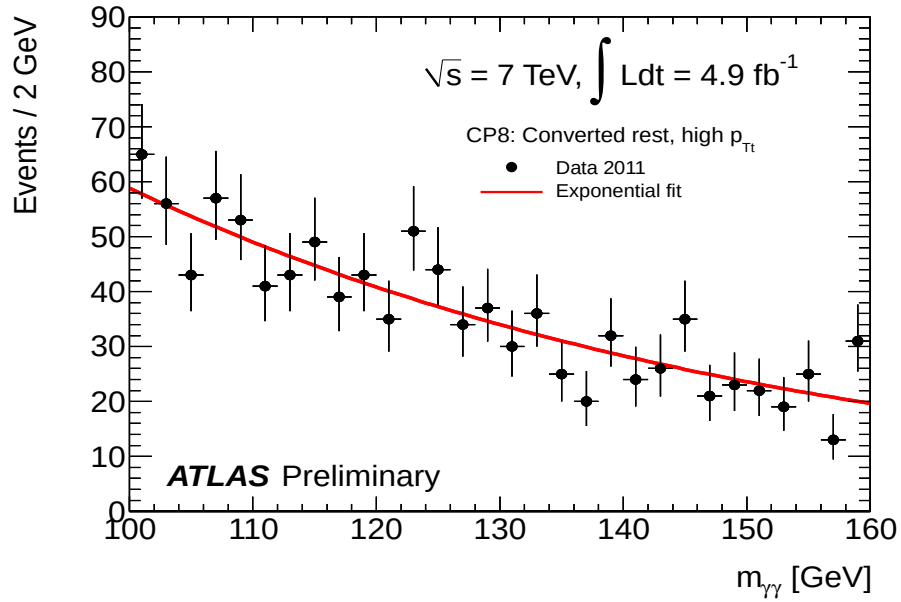
$H \to \gamma\gamma$ by category 2











$H \to \gamma\gamma$: Background model

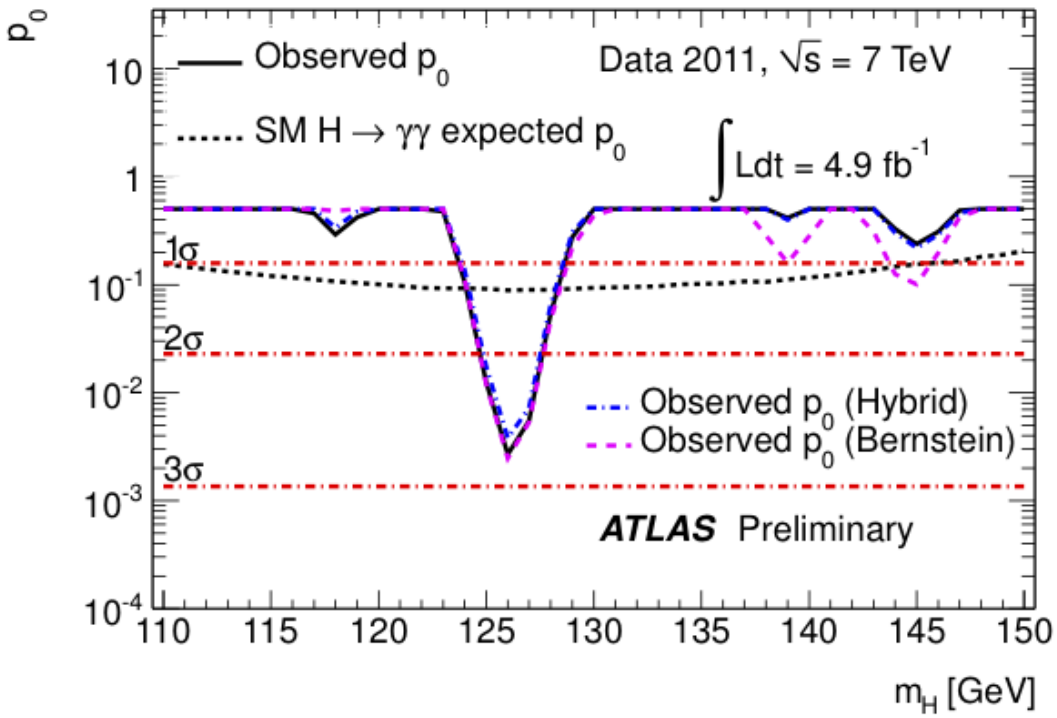
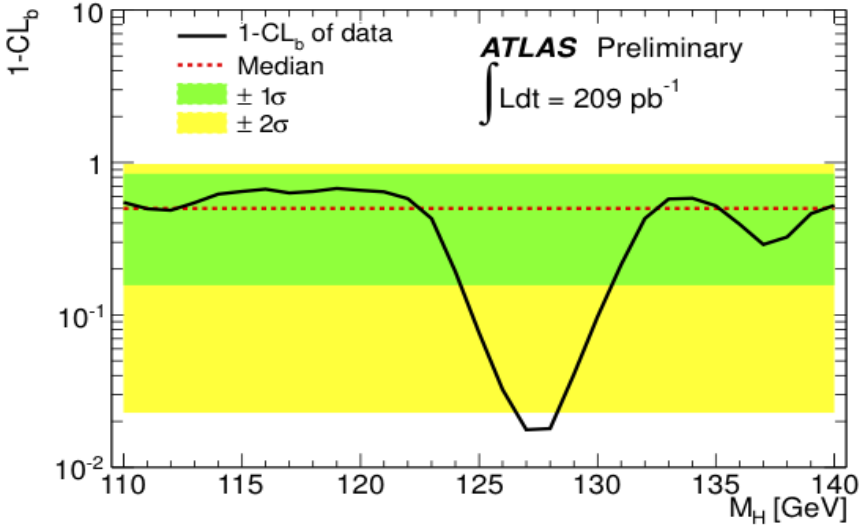
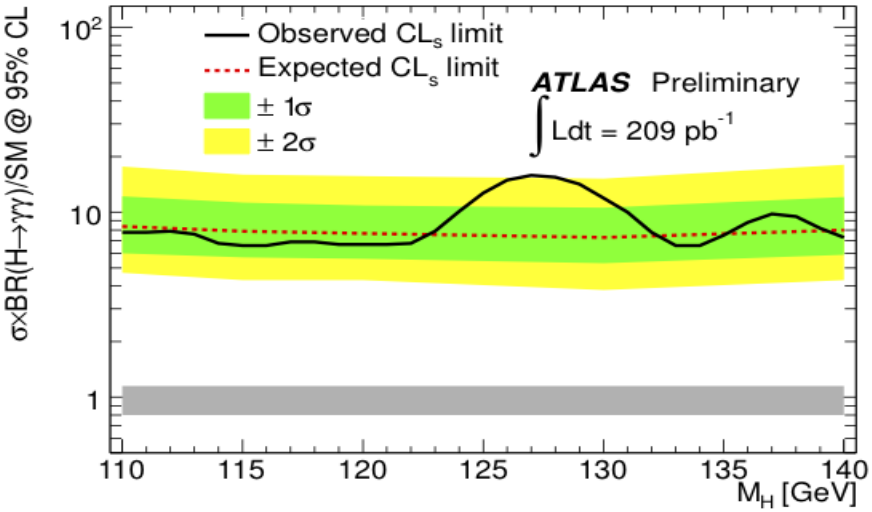


Figure 12: The observed and expected local p_0-value as a function of m_H for three different background models without taking the *look-elsewhere effect* into account. The black solid line is the result described in detail in this note, using single exponential functions in all categories. In the *Hybrid* model the high p_{Tt} categories are fitted with the 2nd 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.

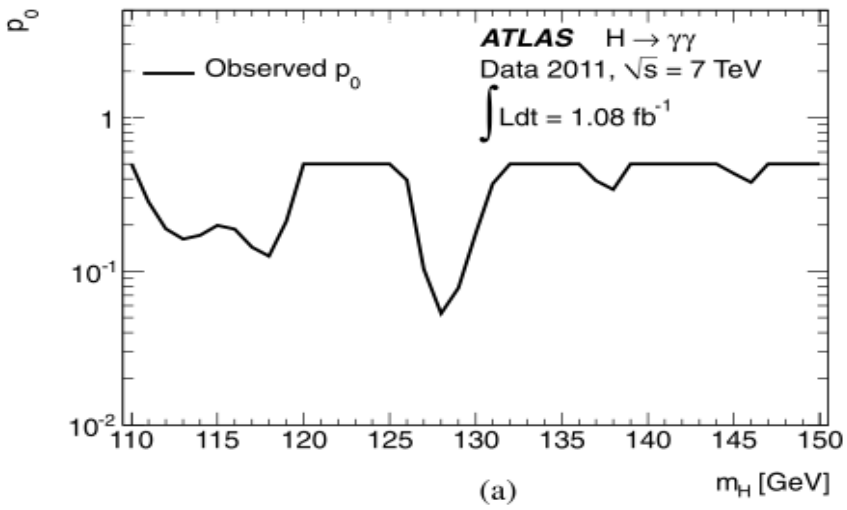
$H \to \gamma\gamma$: Previous results

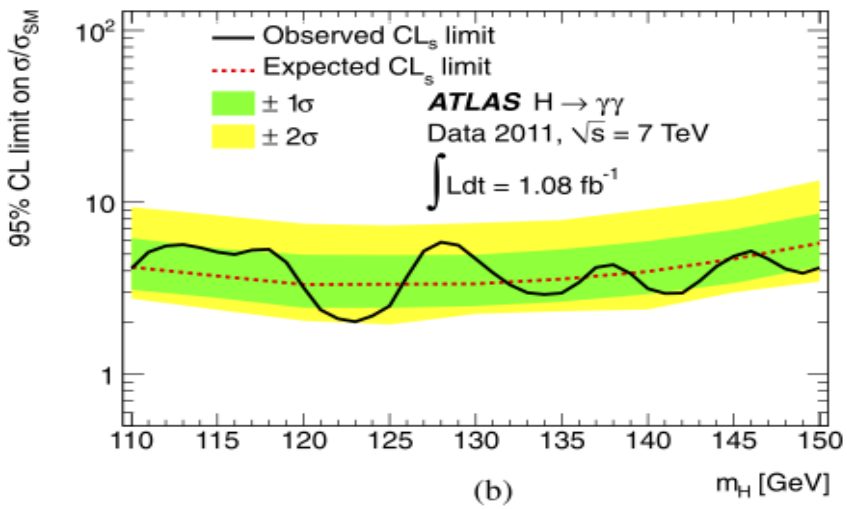
June 2011: PLHC





July 2011: EPS





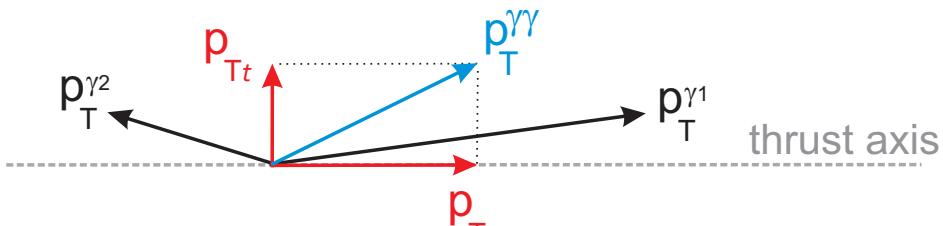
$H \to \gamma\gamma$

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



$H \to \gamma\gamma$: Events per category

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

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

$m(\gamma\gamma)$: opening angle $[m^2_{\gamma\gamma} = 2E_1E_2(1-\cos\alpha)]$

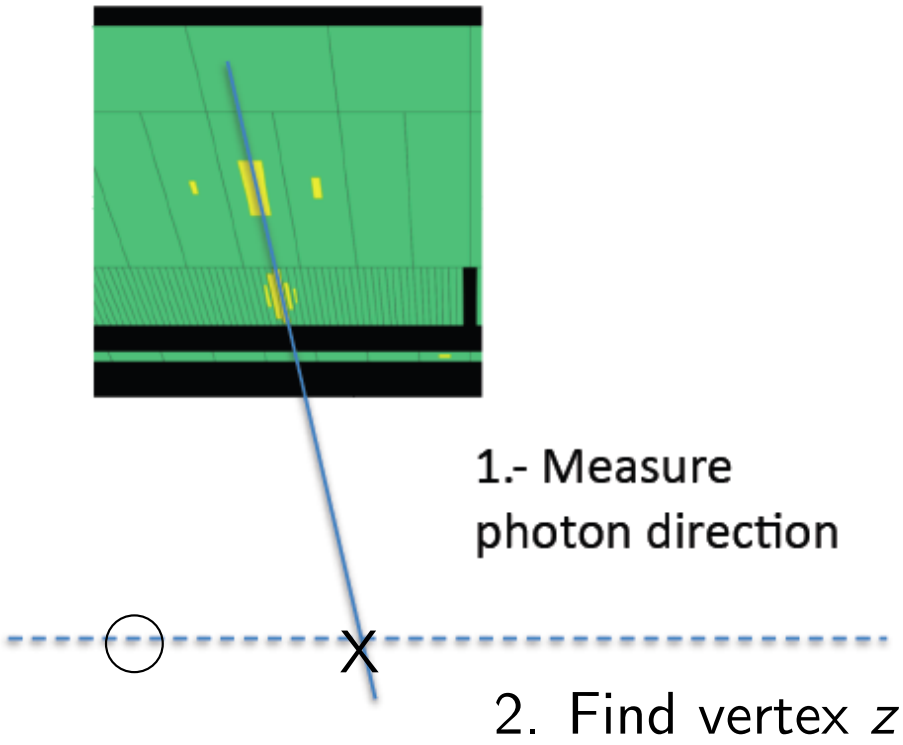
Fine EM calorimeter segmentation allows direct $\theta(\gamma)$ measurement.

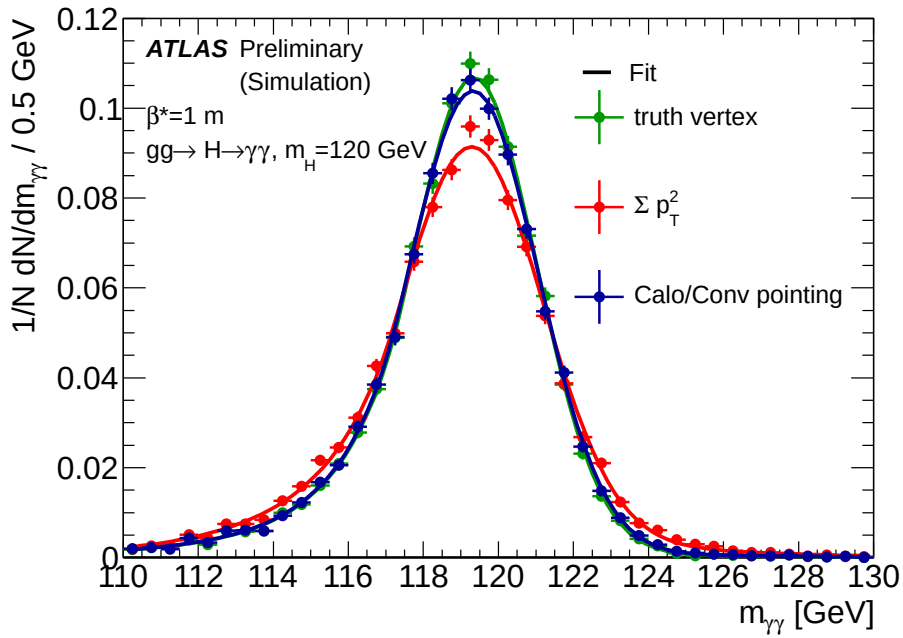
Calorimeter "pointing" reduces vertex uncertainty: $\sim 5.6 \rightarrow 1.5$ cm.

Crucial at high pileup with many vertices over the $\sim$ 5.6 cm LHC beam spot:
Which one produced the $\gamma\gamma$ pair?

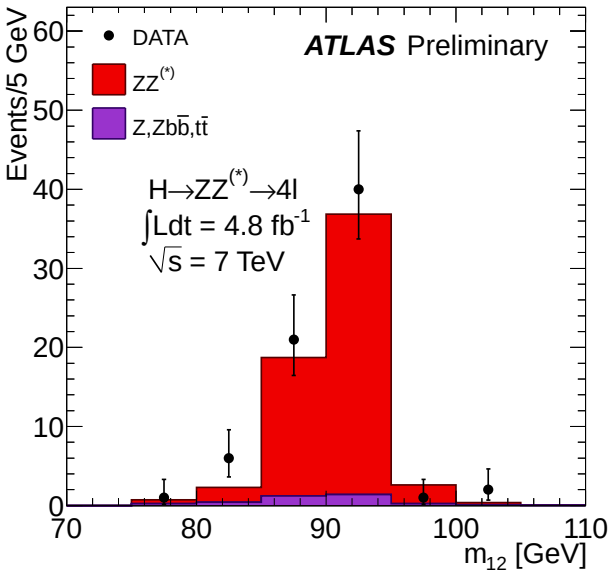
Robust against pileup!

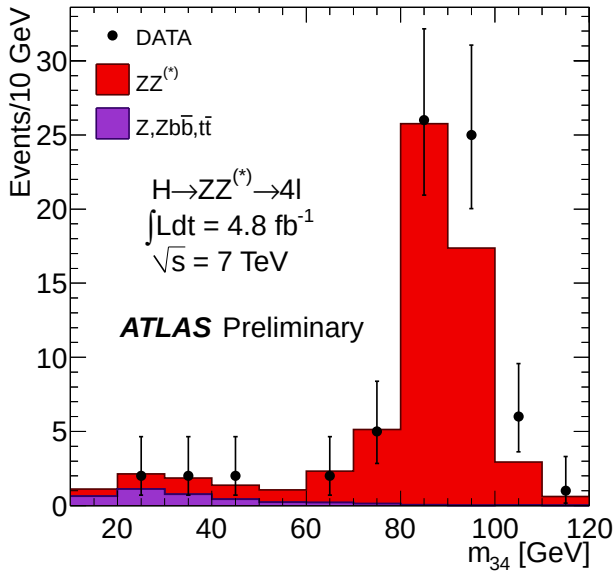
Without pointing, mass resolution would be $\sim$ 20% worse with $>$ 10 pileup events.

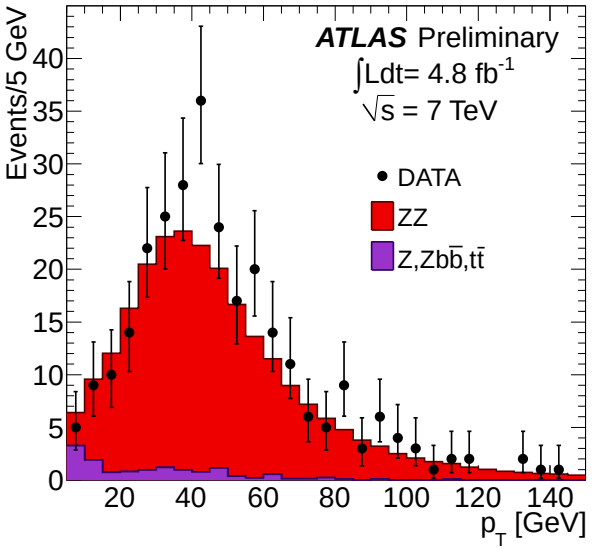


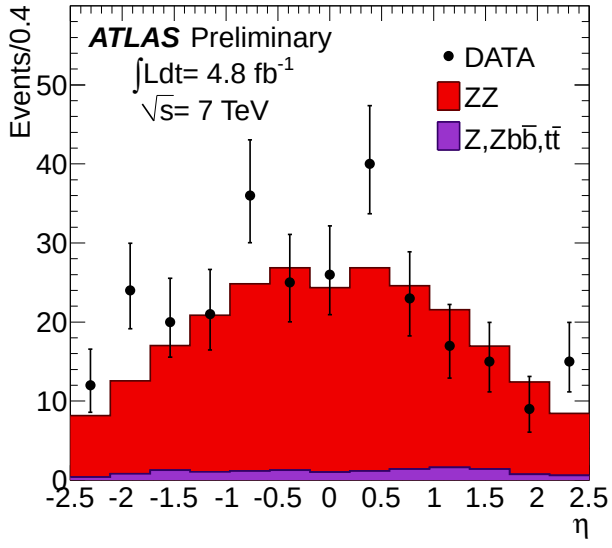


$H \to ZZ^{(*)} \to 4\ell$ kinematics









$H \to ZZ^{(*)} \to \ell\ell\nu\nu$

$\int \mathcal{L}\, dt = 2.1\ \text{fb}^{-1}$

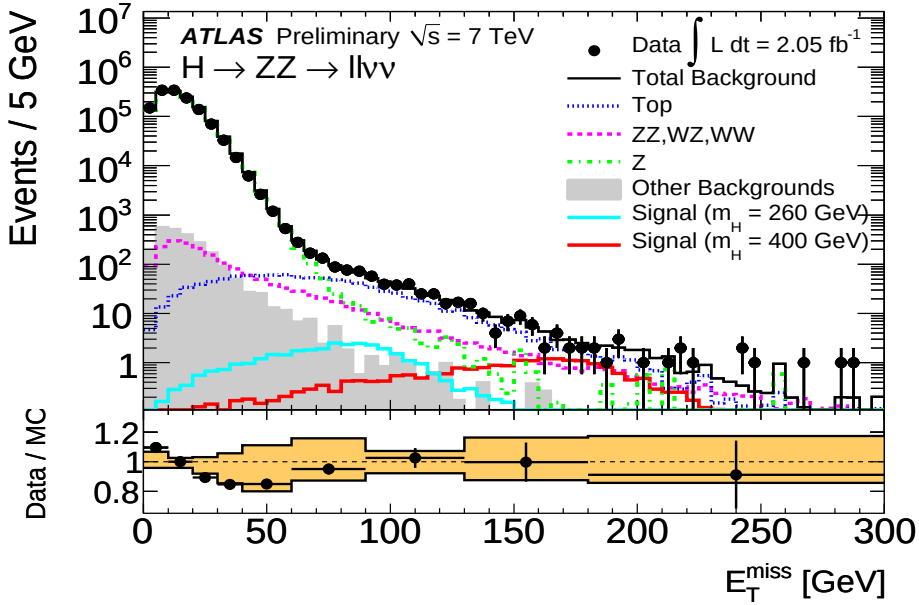
- Covers $200 < m_H < 600$ GeV.
- $\sigma \sim 20$ fb larger than 4ℓ.
  - But larger background.
  - Still most sensitive channel for $m_H > 300$ GeV.
- Selection:
  - Opposite-sign ee or $\mu\mu$ pair with $|m_{\ell\ell} - M_Z| < 15$ GeV.
  - No b-tagged jets.
  - $\not\!\!E_T$ not pointing along a jet.
  - Further cuts on $\not\!\!E_T$ and $\Delta\phi_{\ell\ell}$ dep. on hypothesized m_H.

$m_H < 280$ GeV	$m_H > 280$ GeV
$\not\!\!E_T > 66$ GeV	$\not\!\!E_T > 82$ GeV
$1 < \Delta\phi_{\ell\ell} < 2.64$	$\Delta\phi_{\ell\ell} < 2.25$
	$\Delta\phi_{\not\!\!E_T,\ell\ell} < 1$

Backgrounds:

- ZZ: modeled from MC.
- Z + jets, top: modeled from MC, checked against data control samples.
- Multijet BG calculated from data.

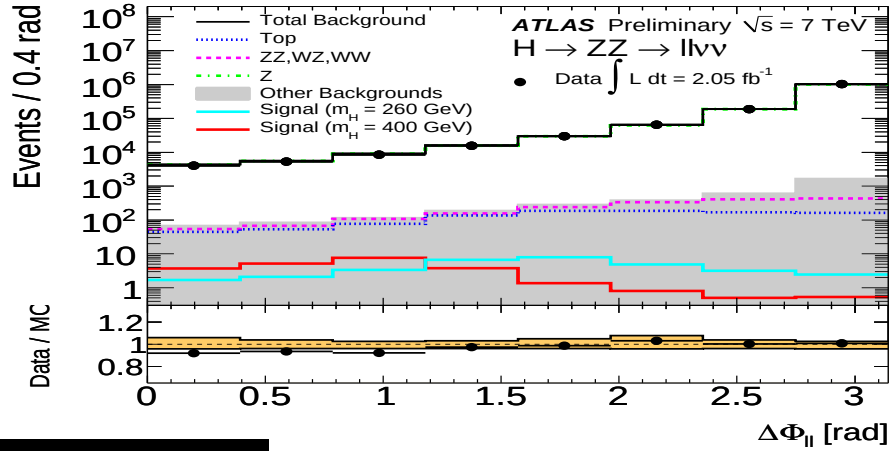
Missing E_T distribution:

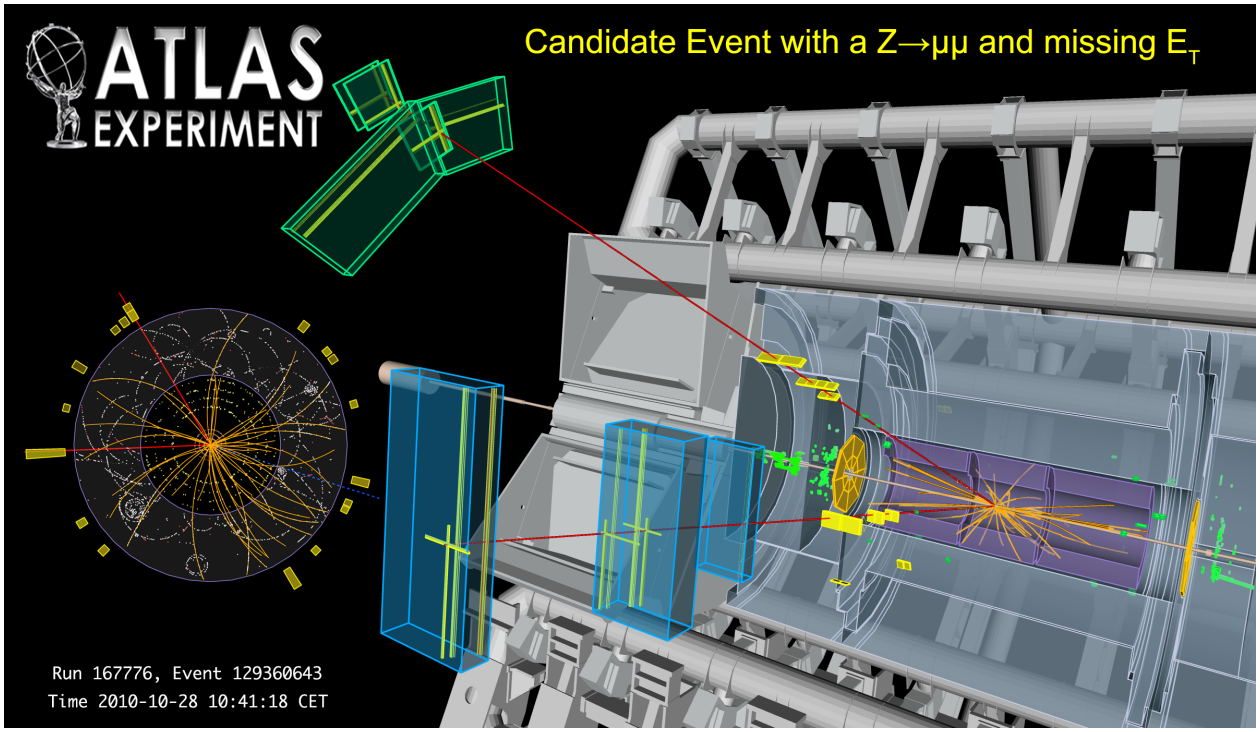


Background modeled using ALPGEN. Small disagreement at low end goes away if PYTHIA used instead. Difference taken as a systematic.

$H \to ZZ^{(*)} \to \ell\ell\nu\nu$

$\Delta\phi$ between leptons from Z decay: smaller for boosted Zs.

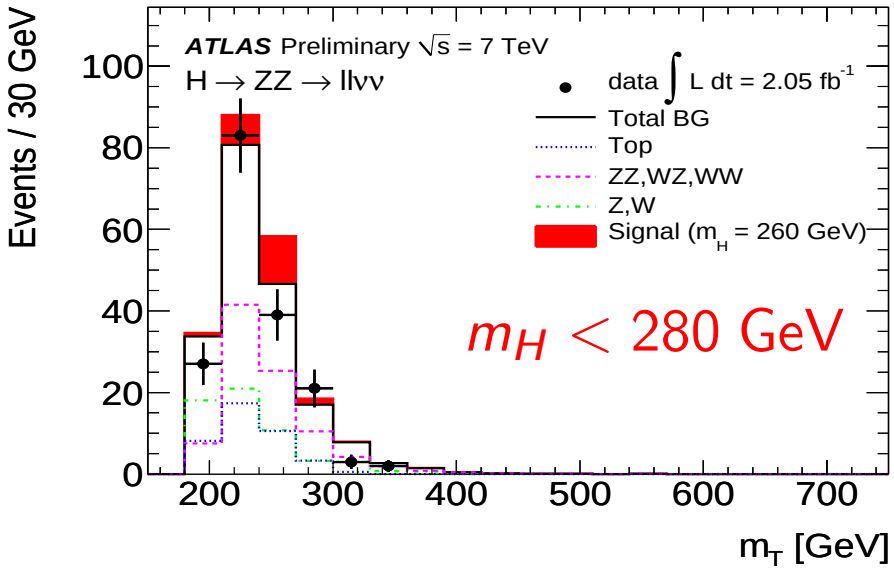


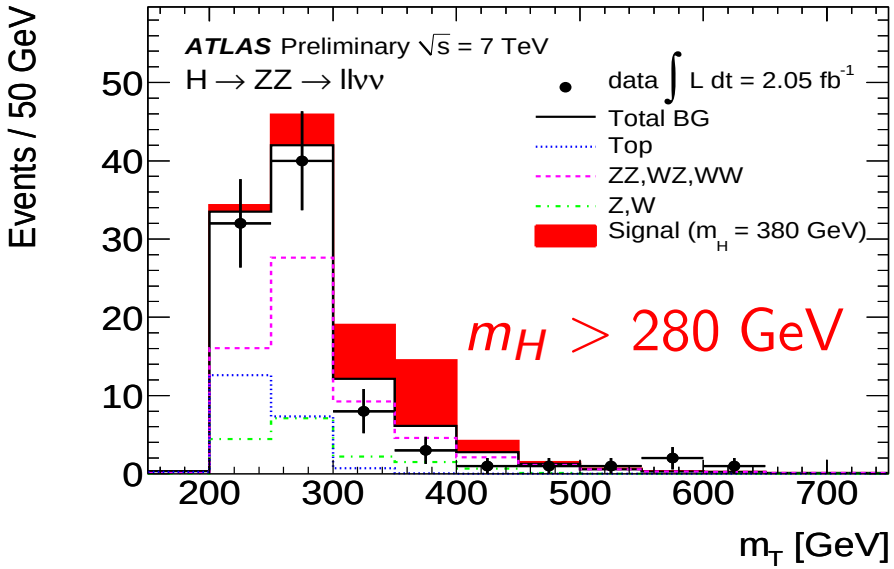


$Z \to \mu\mu$ candidate
$m(\mu\mu) = 93.8$ GeV
$p_T(Z) = 156$ GeV
$\not{E}_T = 161$ GeV

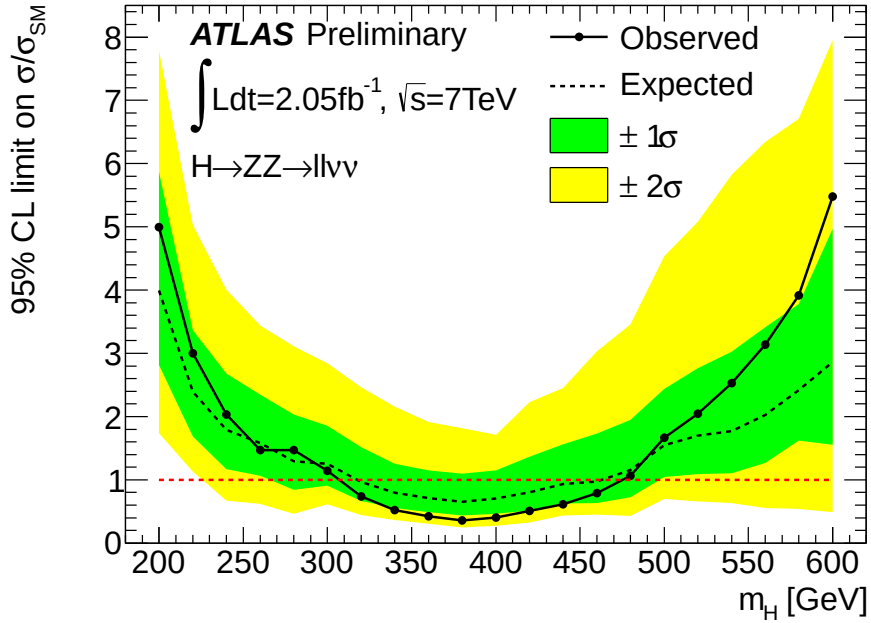
$H \to ZZ^{(*)} \to \ell\ell\nu\nu$

Transverse mass of $\ell\ell\not{E}_T$ system:





Final exclusion limit:



Excluded at 95% CL

$310 < m_H < 470$ GeV

$H \to ZZ^{(*)} \to \ell\ell qq$

$\int \mathcal{L}\, dt = 2.1\ \text{fb}^{-1}$

- Covers $200 < m_H < 600$ GeV
- $\sigma \sim 10$ fb
  - Large Z + jets background.

Selection:

- Reconstruct $Z \to \ell\ell$ and $Z \to jj$.
- $\not{E}_T < 50$ GeV to reject $t\bar{t}$.
- For $mH \geq 300$ GeV, additional requirements on $\Delta\phi(\ell\ell)$, $\Delta\phi(jj)$, and $p_T(j)$.

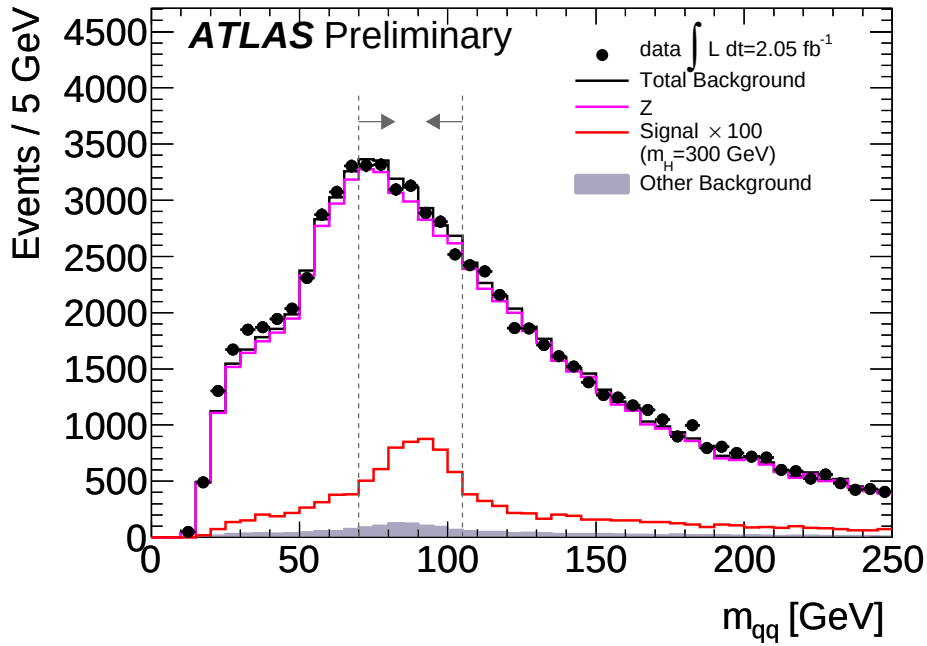
Sample divided into two bins: two b-tags ("tagged"), and < 2 b-tags ("untagged").

- Tagged sample has $\sim 10\times$ smaller signal but $\sim 10\times$ larger S/B.
- Tagged/untagged contribute about evenly to final result.

Backgrounds:

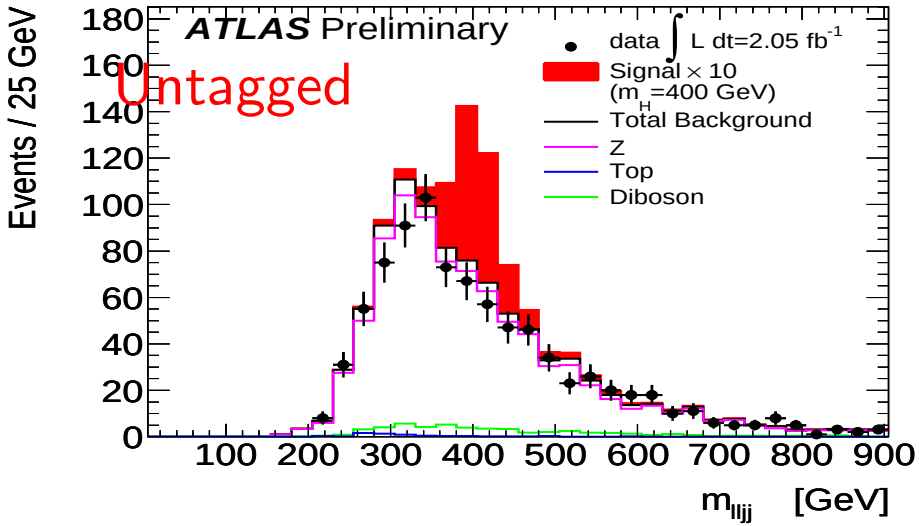
- ZZ: modeled from MC.
- Z + jets, top: modeled from MC, normalized using data control samples.
- Multijet BG calculated from data.

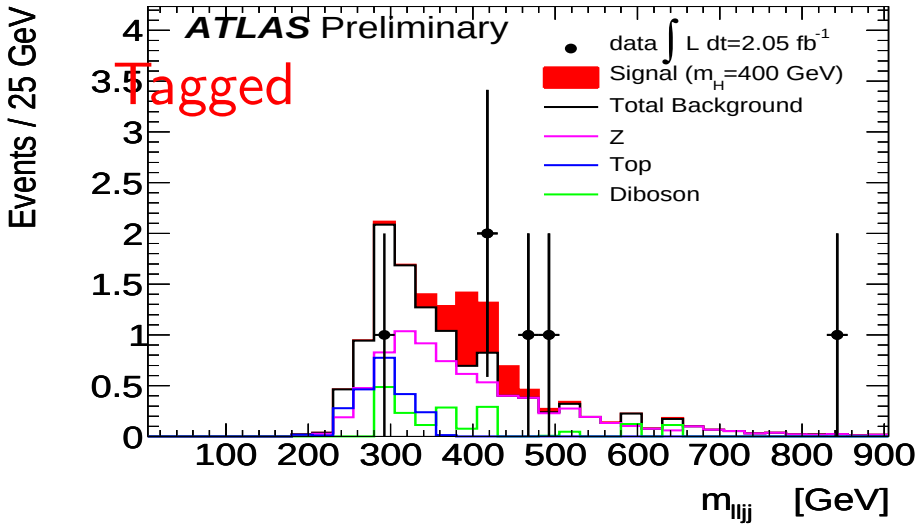
Dijet mass spectrum (untagged selection):



$H \to ZZ^{(*)} \to \ell\ell qq$

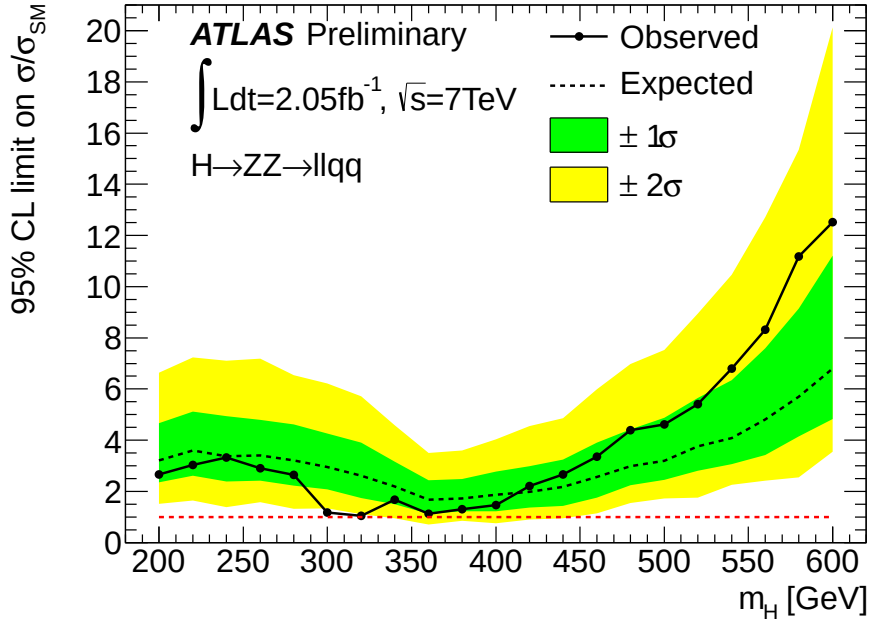
$m(\ell\ell jj)$ for $m_H = 400$ GeV





(Signal in untagged channel scaled up by $\times 10$.)

Exclusion limits:



Close to excluding SM Higgs around $m_H = 300$ GeV.