Measurement of the Higgs boson mass with the ATLAS detector

THE UNIVERSITY *of* EDINBURGH

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on behalf of the ATLAS Collaboration

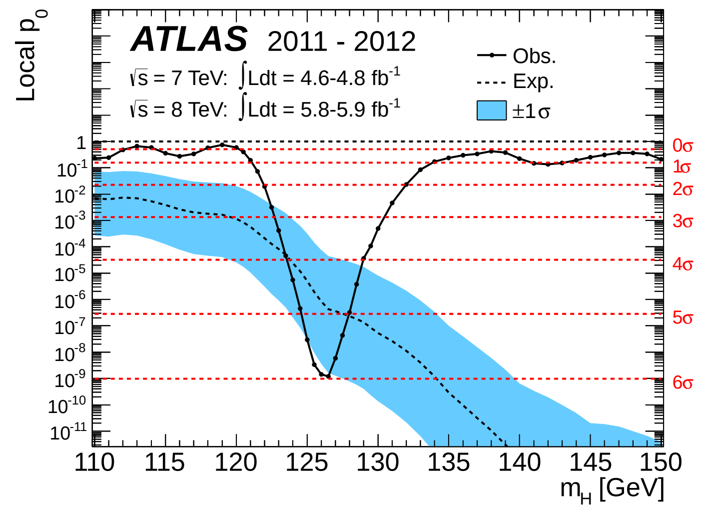
Overview

- Previous m_H measurements
- Improvements to electron and photon calibration
- $H \to \gamma\gamma$
  - Mass measurement
- $H \to ZZ^* \to 4l$
  - Changes since previous measurement
  - Mass measurement
- Combined result
- Direct limit on Higgs width
- Summary

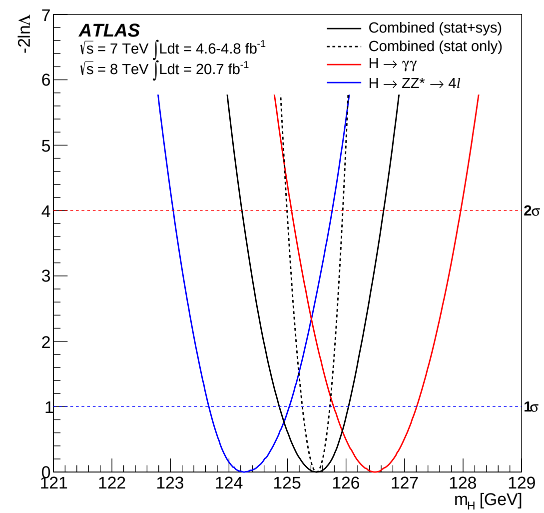
History of m_H measurements

- July 2012, PLB 716 (Observation paper) arXiv:1207.7214v2
  - 11 fb^{-1}
  - $m_H = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$ GeV
  - Signal strength: $\mu = 1.4 \pm 0.3$
- CERN Council, Dec 2012 ATLAS-CONF-2012-170
  - 18 fb^{-1}
  - $m_H = 125.2 \pm 0.3(\text{stat}) \pm 0.6(\text{sys})$ GeV
  - $\mu = 1.35 \pm 0.24$
- July 2013, PLB 726 (Higgs couplings) arXiv:1307.1427v1
  - 25 fb^{-1}
  - $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV
  - $\mu = 1.33^{+0.21}_{-0.18}$
- June, 2014, paper submitted to PRD arXiv:1406.3827v1
  - Final ATLAS measurement of Higgs boson mass using Run 1 data

July 2012



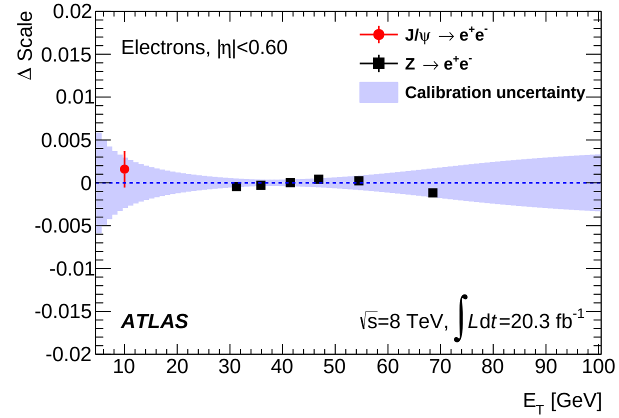
July 2013



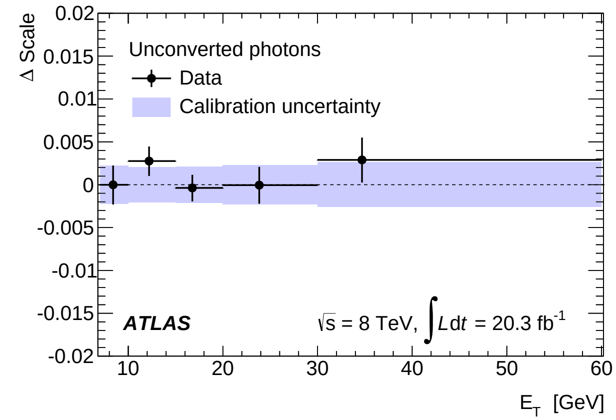
Improvements to electron and photon calibration

- From simulation: EM cluster energy correction via multivariate regression: resolution 10% better for $H \to \gamma\gamma$
- Corrections from data:
  - Intercalibration of calorimeter layers using $Z \to \mu\mu$ events: 1-2% for EM layers 1&2
  - Accurate knowledge of material in front of EM calorimeter: ~2-10% radiation lengths
- Calorimeter response verified to be stable w.r.t. time, pileup to $< 0.05\%$
- Energy scale accuracy from $Z \to ee$:
  - 0.03% for $|\eta| < 1.37$, 0.05% for $|\eta| > 1.82$ for e
  - 0.2% for $|\eta| < 1.37$, 0.3% for $|\eta| > 1.82$ for γ
- Resolution accuracy from $Z \to ee$:
  - 0.3 (0.5)% in barrel (endcap)
- Independent cross-checks using $J/\psi \to ee$ and $Z \to ll\gamma$

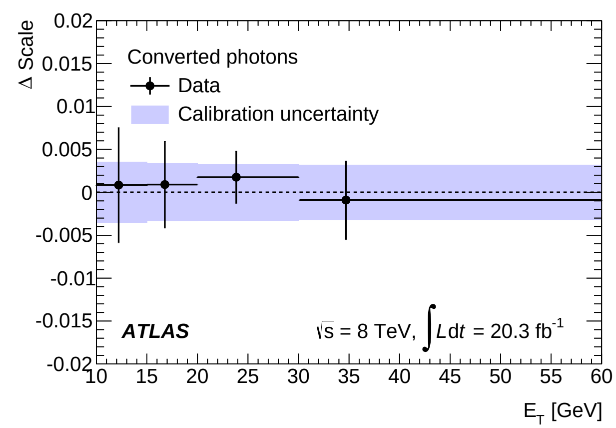
Electrons



Unconverted photons, $Z \to ll\gamma$



Converted photons, $Z \to ll\gamma$

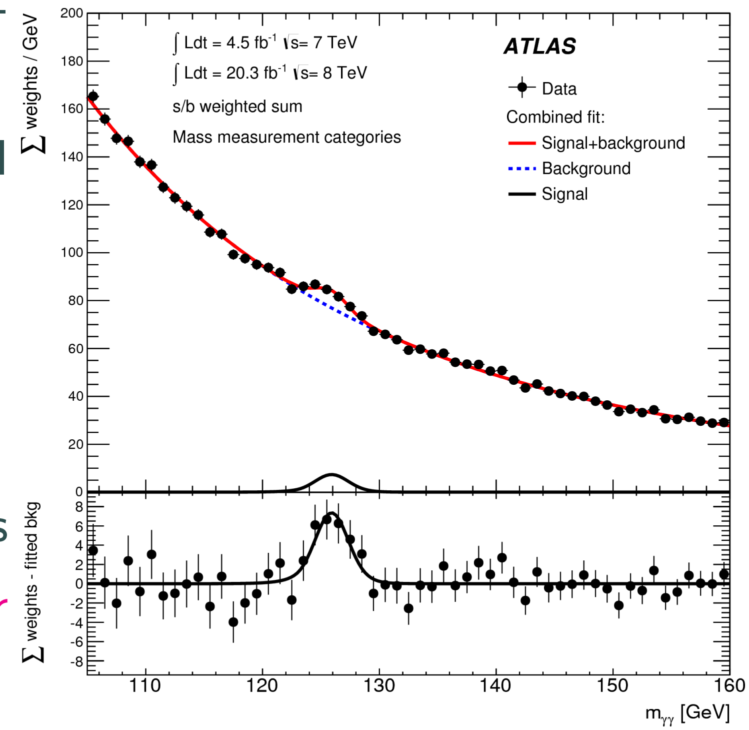


For more details, see dedicated talk: J-B. Blanchard

$H \to \gamma\gamma$ analysis

- Two isolated high-energy photons
- Excellent mass resolution 1.2-2.4 GeV, $\sim$ 1.7 GeV on average
- Good γ/e ID $\to$ 75% $\gamma\gamma$ purity after cuts
- Since summer 2013 conferences, analysis optimized w.r.t.:
  - Background modelling using analytical functions
  - 10 categories based on:
    - photon conversion status
    - photon η
    - p_{Tt}: di-photon p transverse to thrust axis
  - 20% improvement in exp. statistical error over inclusive analysis
- Analysis also takes advantage of improved electron and photon calibrations

- $m_{\gamma\gamma}$ for template fit:
  - photon energies
  - primary vertex
    - uses Neural Network algorithm
    - uses calorimeter pointing info
  - impact points in calorimeter



$H \to \gamma\gamma$ mass measurement

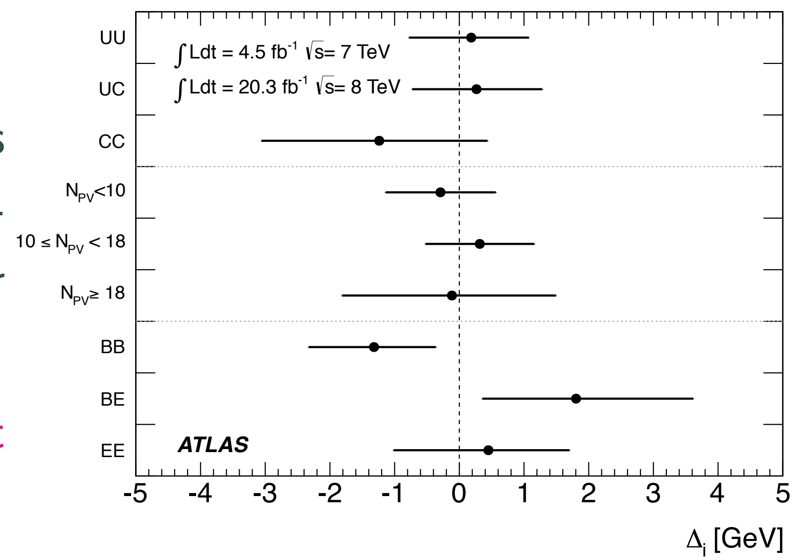
$$\boxed{\begin{aligned} m_H &= 125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{sys})\ \text{GeV} \\ &= 125.98 \pm 0.50\ \text{GeV} \\ \mu &= 1.29 \pm 0.30 \end{aligned}}$$

Previous result (Summer 2013, PLB 762):

$$m_H = 126.8 \pm 0.24(\text{stat}) \pm 0.7(\text{sys})\ \text{GeV}$$

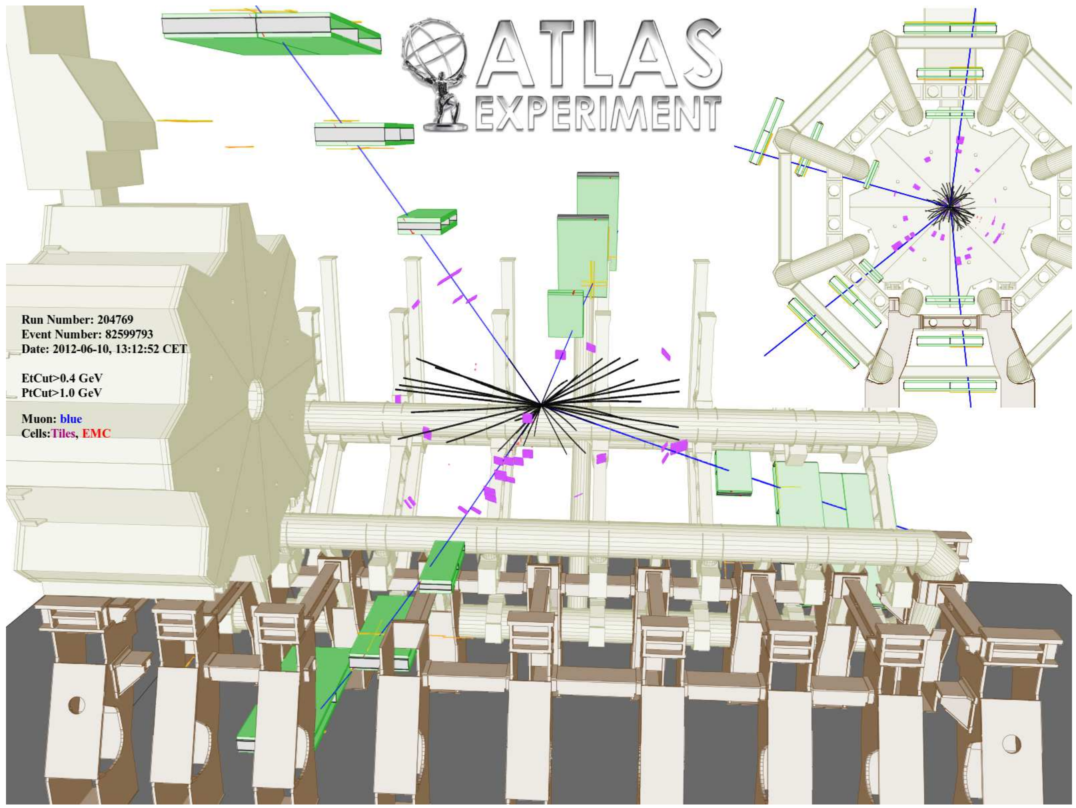
$$\mu = 1.55^{+0.33}_{-0.28}$$

- Systematic uncertainties dominated by γ energy scale, reduced by factor of 2.5
- Statistical error compatible with expectation: 0.35 (0.45) GeV for μ=1.3 (1.0), p-value=16% for $\mu = 1.3$
- Cross-checks:
  - Data divided into subsamples based on conversion status, number primary vertices and detector regions
  - No deviation above 1.5σ from fit of combined categories



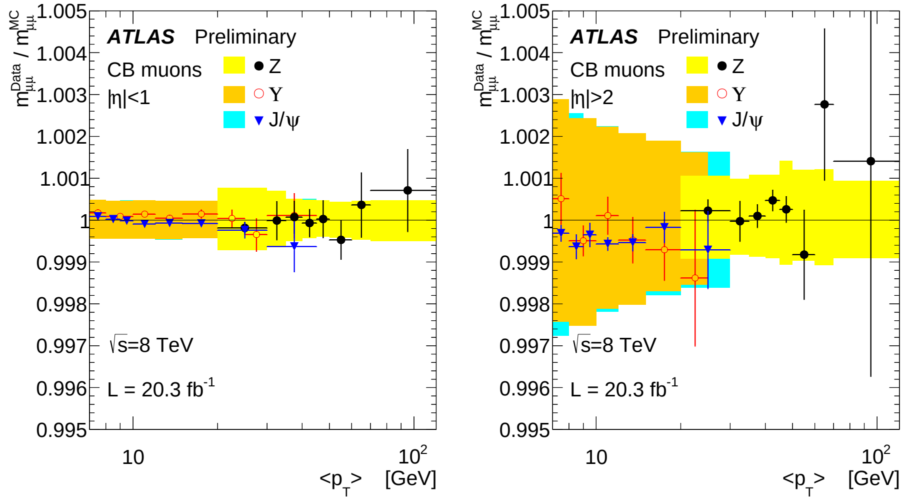
$H \to ZZ^* \to 4l$ analysis

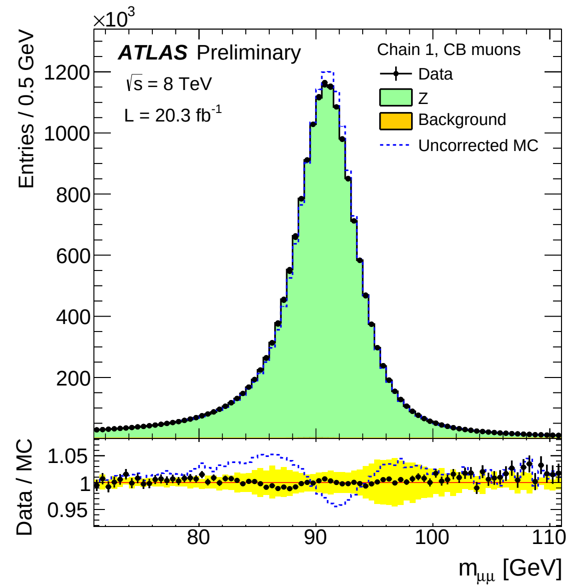
- High S/B: ~ 2 in m_{4l} range 120-130 GeV
- Excellent mass resolution: 1.6 (2.2) GeV in 4μ ($4e$) channel
- Small rates: $\sigma \times BR \sim 2.9$ fb @ 125.5 GeV at 8 TeV
- 4 categories based on final state: 4μ, $2e2\mu$, $2\mu2e$, $4e$
- Z-mass constraint applied
- m_{4l} modelling and expected number of events:
  - signal and ZZ^* background from MC
  - reducible Z+jets and $t\bar{t}$ from data-driven estimations



Changes to $H \to ZZ^* \to 4l$ (since July 2013)

- For 8 TeV, e ID changed from cut-based to likelihood method $\to$ factor 2 rejection of light flavor jet and γ conversion
- Updated EM calibration
- Combined fit of track momentum and calorimeter cluster energy for electrons with $E_T < 30$ GeV
- Multivariate discriminant used to separate signal and ZZ^* background
- Muon p_T MC corrections:
  - Determined using 9M $Z \to \mu\mu$ and 6M $J/\psi \to \mu\mu$ events
  - Checked with $\Upsilon \to \mu\mu$
- Momentum scale uncertainties: 0.05% in barrel, up to 0.2% for $|\eta| > 2$

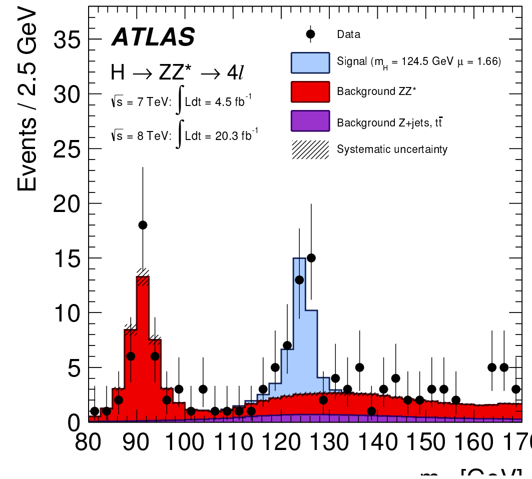


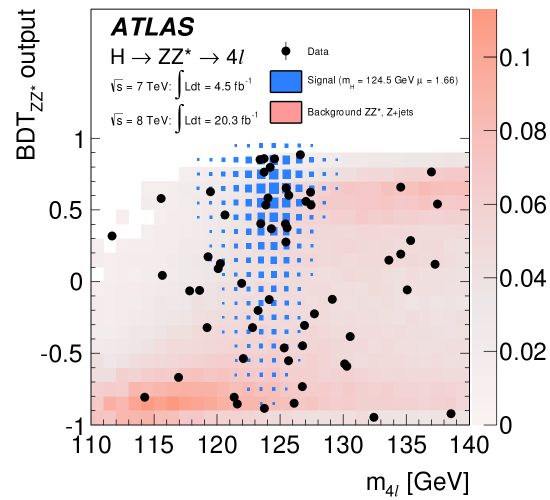


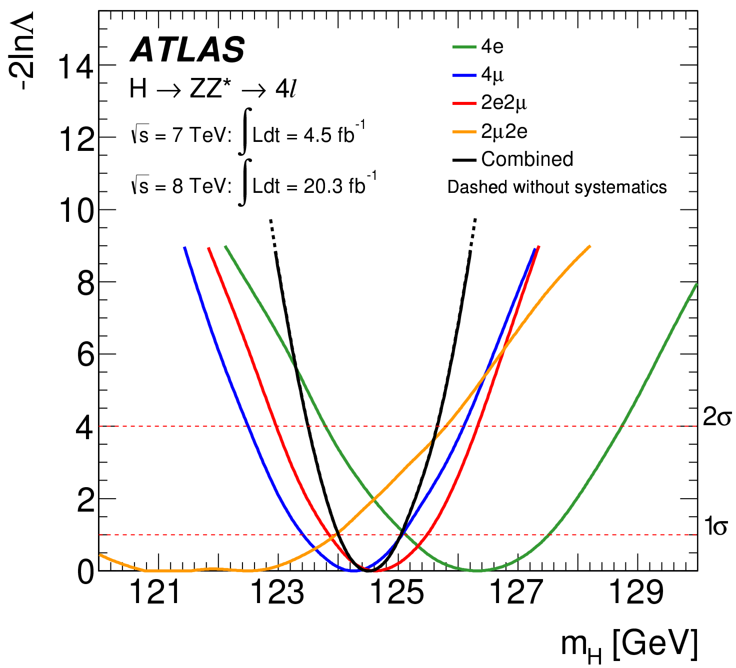
N.B.: see 2 posters in poster session for more information.

$H \to ZZ^* \to 4l$ mass measurement

- Input for BDT variable: matrix-element kinematic discriminant, Higgs p_T and $|\eta|$
  - 8% improvement to m_H uncertainty over 1D m_{4l} fit
- 26.5 events expected, 37 observed



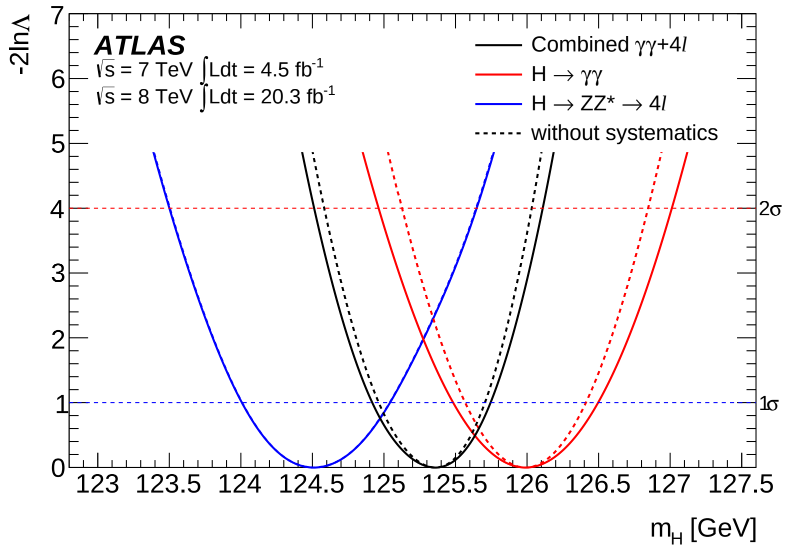


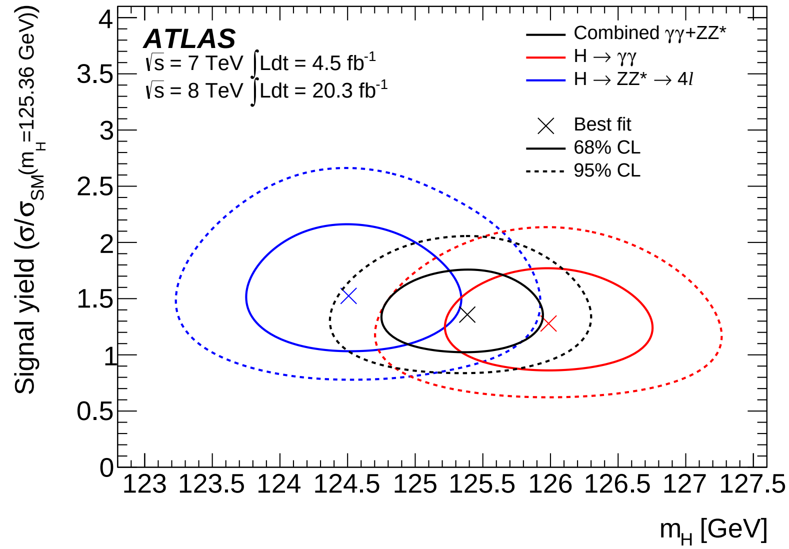


$$m_H = 124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{sys})\ \text{GeV}$$
$$= 124.51 \pm 0.52\ \text{GeV}$$
$$\mu = 1.66^{+0.45}_{-0.38}$$

Previous result (PLB 726): $m_H = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(sys)GeV$, $\mu = 1.43^{+0.40}_{-0.35}$

Combination





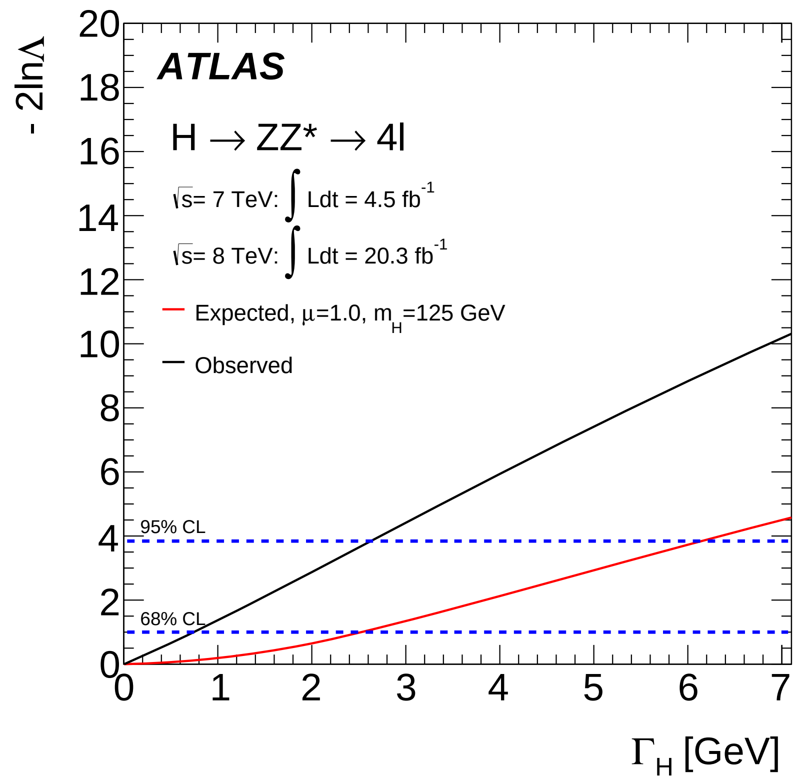
$$m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}$$

Previous result: $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(sys)\ GeV$

- Total uncertainty reduced by $\sim 40\%$
- Systematic uncertainties reduced by factor ~ 3
- Compatibility between channels: 2.0σ (4.8%) for observed μ_{4l} and $\mu_{\gamma\gamma}$, 1.6σ for $\mu = 1$ (previous compatibility 2.5σ)

Direct Higgs width measurement

- *N.B.: see earlier talk in this session for indirect width measurement.*
- Analytical m_{4l} (non-relativistic Breit-Wigner) model convoluted with detector resolution with width Γ_H (m_H and μ free parameters) ($\Gamma_H = 4$ MeV at 125 GeV)
- Analysis assumes no interference with background processes
- $H \to ZZ^* \to 4l$:
  - Event-by-event modelling of detector resolution
  - Per-lepton resolution functions use sums of 2(3) Gaussians for muons (electrons)
  - Validated by fitting mass peak for $Z \to 4l$ using convolution of detector response with BW for Z mass
  - 95% CL: $\Gamma_H < 2.6$ GeV (exp. limit 3.5 GeV for $\mu = 1.7$, 6.2 GeV for $\mu = 1$)
- $H \to \gamma\gamma$:
  - 95% CL: $\Gamma_H < 5.0$ GeV (expected limit 6.2 GeV for $\mu = 1$)

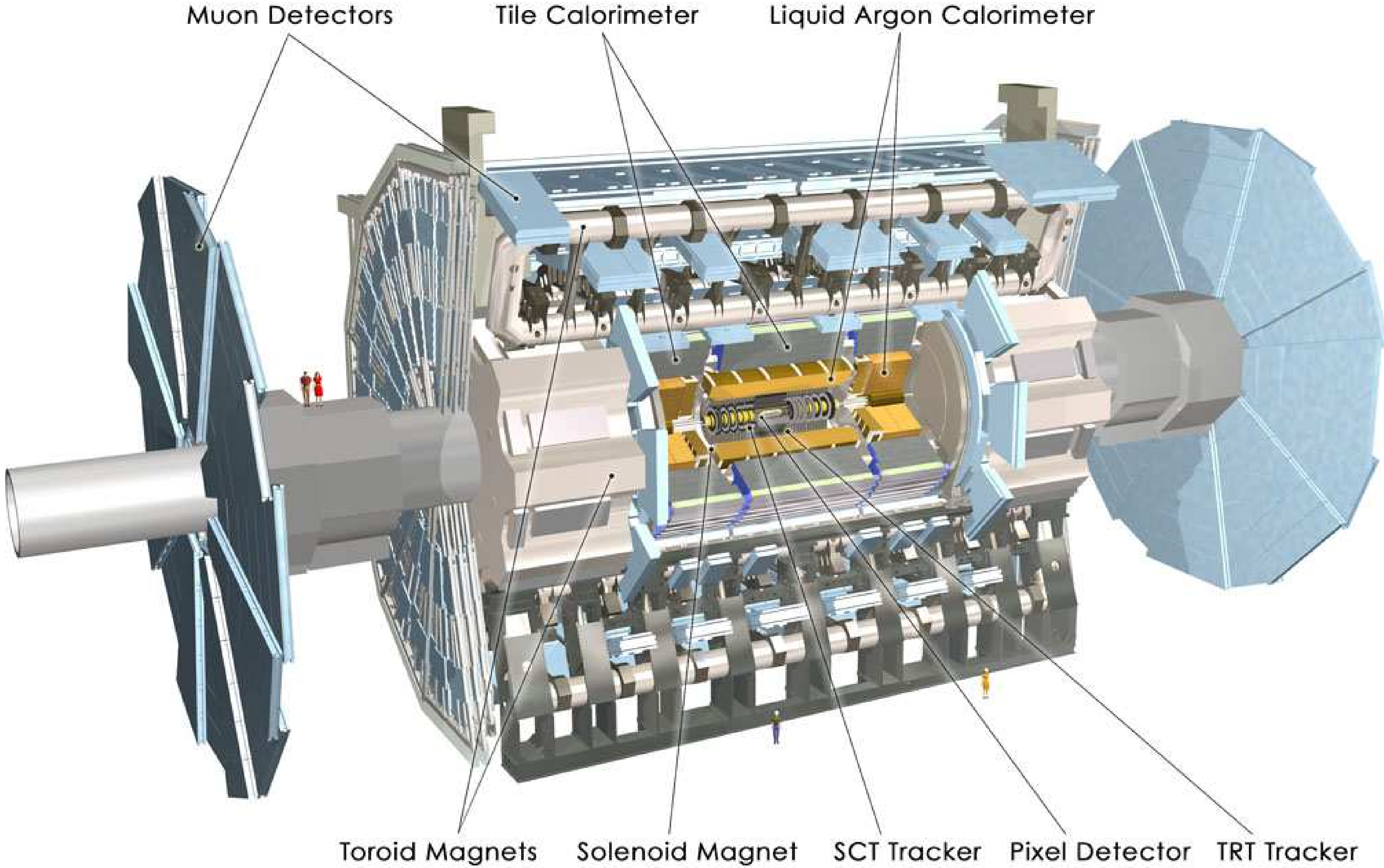


Summary

- Final result: $m_H = 125.36 \pm 0.37(\mathrm{stat}) \pm 0.18(\mathrm{sys})$ GeV
- Better electron and photon calibrations, better understanding of systematic uncertainties $\rightarrow$ improved Higgs boson mass measurement in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels since previous measurement
- Compared to previous result, total uncertainty reduced by 40% and systematic uncertainty reduced by factor 3
- Channels compatible with each other to within 2.0σ
- Direct limits on Γ_H set using $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels (5.0 and 2.6 GeV, respectively)

Backup Slides

ATLAS detector



$H \to \gamma\gamma$ selection

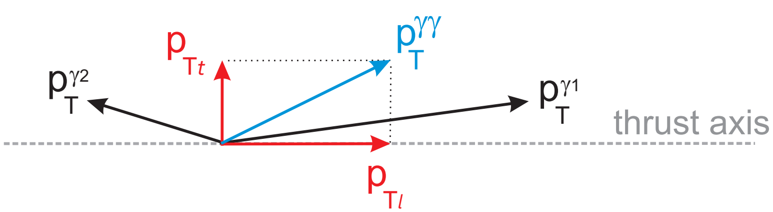
- Diphoton trigger (loose photon ID applied at trigger level): $E_T > 20$ GeV for both photons in 7 TeV data, $E_T > 35$ and 25 GeV in 8 TeV data
- $|\eta| < 2.37$, transition region $(1.37 < |\eta| < 1.56)$ removed (reduced calorimter granularity, signifiant additional inactive material)
- Both photons pass tight ID criteria based on shower shapes in EM calorimeter
- For 7 TeV, NN discriminant used to suppress jets misidentified as photons; for 8 TeV, cuts optimised to reduce effects of pile-up
- Isolation required to reduce jets misidentified as photons:
  - Calorimeter isolation: energy in area of size $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ centered on photon subtracted from $\Delta R = 0.4$ cone, must be $< 5.5(6)$ GeV for 7(8) TeV
  - Track isolation: scalar sum of p_T of tracks in $\Delta R = 0.2$ cone around photon, track $p_T > 0.4(1.0)$ GeV for 7(8) TeV data, originating from primary vertex, must be $< 2.2(2.6)$ for 7(8) TeV data
- Primary vertex determination:
  - Important for mass reconstruction and to avoid pile-up contribution to track isolation
  - EM calorimeter used to determine photon pointing direction, this information used with the beam spot position and tracking information to create a NN discriminant to select best primary vertex (15 mm resolution in z with 93% efficiency for average pile-up conditions in 8 TeV data)
- $E_T > 0.35(0.25) \times m_{\gamma\gamma}$ for photon with highest (lowest) E_T
- Signal reconstruction and selection efficiency at 125 GeV: $\sim$ 40%

$H \to ZZ^* \to 4l$ selection

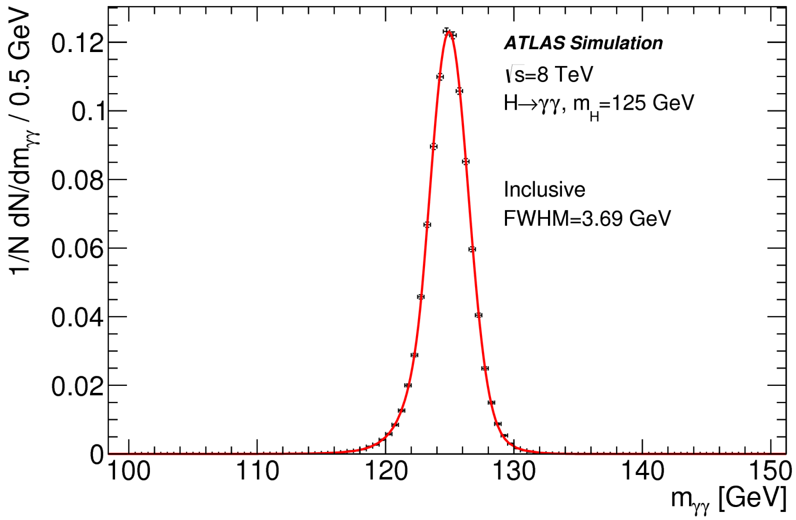
- Single-lepton and dilepton triggers:
  - Single-muon (single-electron) triggers from 18-24 (20-25) GeV between 7 and 8 TeV datasets
  - Dilepton triggers start at 6 (10) GeV for muons (electrons) for 7 TeV, 13 (12) GeV for muons (electrons) for 8 TeV (with an asymmetric threshold of (8,18) GeV)
- For 7 TeV, electrons use cut-based selection. For 8 TeV, use improved likelihood-based electron ID
- Only 1 standalone or calorimeter-tagged muon per event allowed. Muon tracks require minimum number of hits in ID, or hits in all muon stations for standalone muons
- Each lepton required to have longitudinal IP $<$ 10 mm w.r.t PV
- Muons required to have transverse IP $<$ 1 mm to reject cosmics
- All muons (electrons) must have $p_T > 6$ ($E_T > 7$) GeV
- Highest p_T lepton must have $p_T > 20$ GeV, 2nd (3rd) lepton $p_T >$ 15 (10) GeV
- $\Delta R > 0.1$ (0.2) for same (different) flavour leptons
- Multiple quadruplets allowed, only keep 1 per channel.
- Lepton pair with m closest to Z mass is "on-shell", $50 < m_{12} < 106$ GeV.
- $m_{\min} < m_{34} < 115$ GeV ($m_{\min}$ increases from 24-50 GeV for m_{4l} increase from 140-190 GeV)
- IP significance $|d_0|/\sigma_{d_0} < 3.5$ (6.5) for muons (electrons)
- Normalised track isolation < 0.15, normalised calorimeter isolation < 0.2 (0.3) for electrons in 7 (8) TeV data, < 0.3 for muons
- FSR recovery: at most 1 photon allowed to be added to invariant mass per event

$H \to \gamma\gamma$ categories

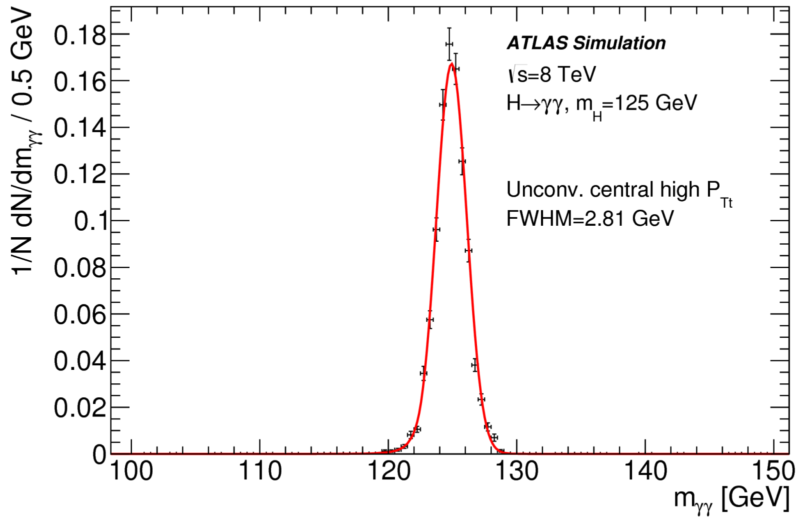
- 10 categories optimised to minimize expected mass measurement uncertainty:
  - converted and unconverted - energy resolution better for unconverted photons, energy scale systematic uncertainties different
  - photon η:
    * *central* region: both photons in central region, has best mass resolution and S-B ratio, smallest energy scale uncertainties
    * *transition* region: at least 1 photon in transition region, has worse energy resolution due to material in front of calorimeter, larger E-scale uncertainties
    * the *rest*
- p_T transverse variable: component of diphoton transverse momentum orthogonal to diphoton thrust axis in the transverse plane; high p_{Tt}: better S-B ratio and mass resolution, but small yield



All categories



Category with best photon resolution



$H \to \gamma\gamma$ categories summary

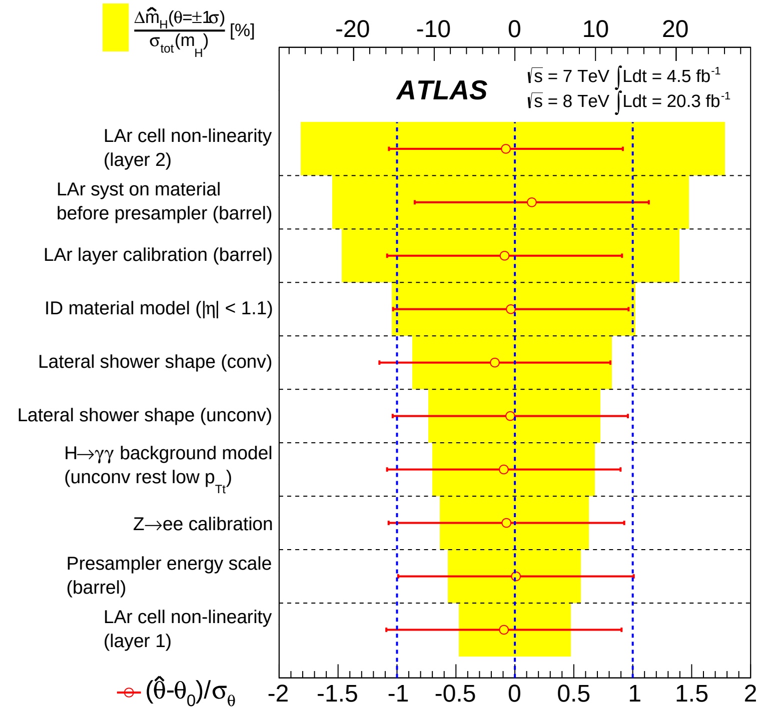
Table 1: Summary of the expected number of signal events in the 105–160 GeV mass range $n_{\rm sig}$, the FWHM of mass resolution, $\sigma_{\rm eff}$ (half of the smallest range containing 68% of the signal events), number of background events b in the smallest mass window containing 90% of the signal ($\sigma_{\rm eff90}$), and the ratio s/b and $s/\sqrt{b}$ with s the expected number of signal events in the window containing 90% of signal events, for the $H \to \gamma\gamma$ channel. b is derived from the fit of the data in the 105–160 GeV mass range. The value of m_H is taken to be 126 GeV and the signal yield is assumed to be the expected Standard Model value. The estimates are shown separately for the 7 TeV and 8 TeV datasets and for the inclusive sample as well as for each of the categories used in the analysis.

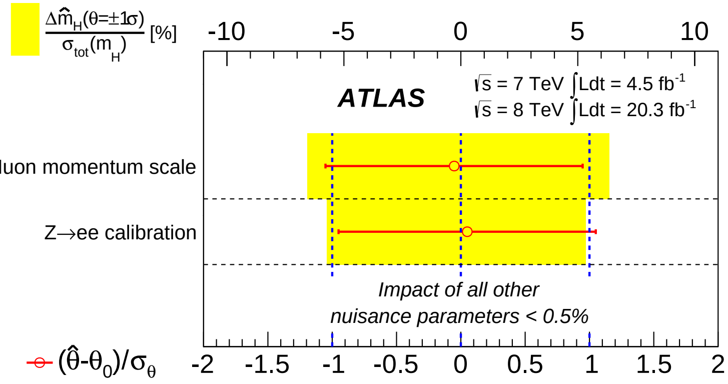
Category	$n_{\rm sig}$	FWHM [GeV]	$\sigma_{\rm eff}$ [GeV]	b in $\pm\sigma_{\rm eff90}$	s/b [%]	$s/\sqrt{b}$
			$\sqrt{s}$=8 TeV			
Inclusive	402.	3.69	1.67	10670	3.39	3.50
Unconv. central low $p_{\rm Tt}$	59.3	3.13	1.35	801	6.66	1.88
Unconv. central high $p_{\rm Tt}$	7.1	2.81	1.21	26.0	24.6	1.26
Unconv. rest low $p_{\rm Tt}$	96.2	3.49	1.53	2624	3.30	1.69
Unconv. rest high $p_{\rm Tt}$	10.4	3.11	1.36	93.9	9.95	0.96
Unconv. transition	26.0	4.24	1.86	910	2.57	0.78
Conv. central low $p_{\rm Tt}$	37.2	3.47	1.52	589	5.69	1.38
Conv. central high $p_{\rm Tt}$	4.5	3.07	1.35	20.9	19.4	0.88
Conv. rest low $p_{\rm Tt}$	107.2	4.23	1.88	3834	2.52	1.56
Conv. rest high $p_{\rm Tt}$	11.9	3.71	1.64	144.2	7.44	0.89
Conv. transition	42.1	5.31	2.41	1977	1.92	0.85
			$\sqrt{s}$=7 TeV			
Inclusive	73.9	3.38	1.54	1752	3.80	1.59
Unconv. central low $p_{\rm Tt}$	10.8	2.89	1.24	128	7.55	0.85
Unconv. central high $p_{\rm Tt}$	1.2	2.59	1.11	3.7	30.0	0.58
Unconv. rest low $p_{\rm Tt}$	16.5	3.09	1.35	363	4.08	0.78
Unconv. rest high $p_{\rm Tt}$	1.8	2.78	1.21	13.6	11.6	0.43
Unconv. transition	4.5	3.65	1.61	125	3.21	0.36
Conv. central low $p_{\rm Tt}$	7.1	3.28	1.44	105	6.06	0.62
Conv. central high $p_{\rm Tt}$	0.8	2.87	1.25	3.5	21.6	0.40
Conv. rest low $p_{\rm Tt}$	21.0	3.93	1.75	695	2.72	0.72
Conv. rest high $p_{\rm Tt}$	2.2	3.43	1.51	24.7	7.98	0.40
Conv. transition	8.1	4.81	2.23	365	2.00	0.38

m_H systematics

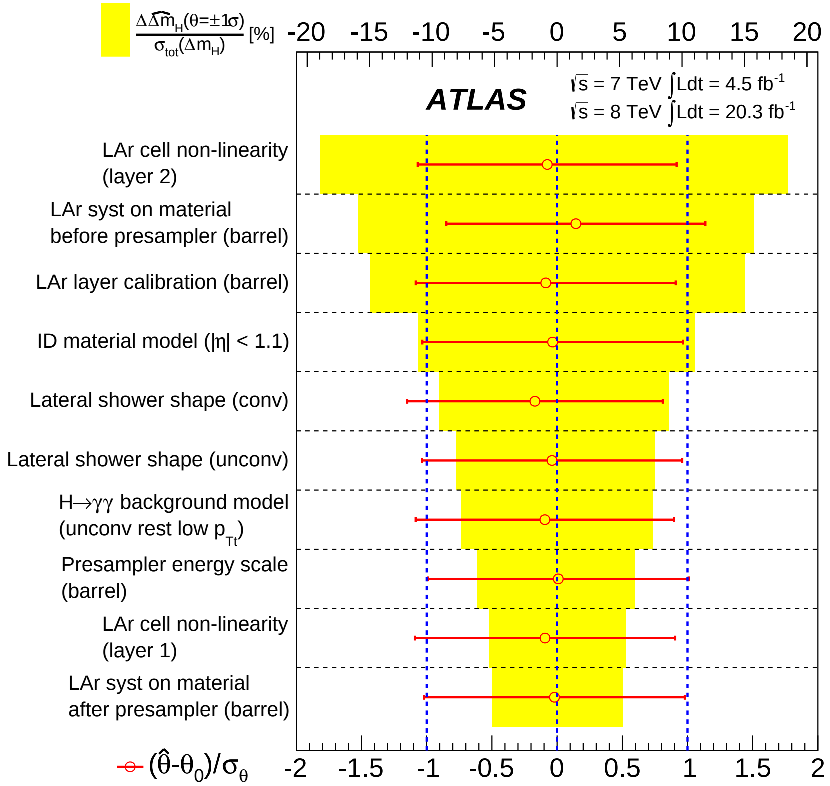
Table 4: Principal systematic uncertainties on the combined mass. Each uncertainty is determined from the change in the 68% CL range for m_H when the corresponding nuisance parameter is removed (fixed to its best fit value), and is calculated by subtracting this reduced uncertainty from the original uncertainty in quadrature.

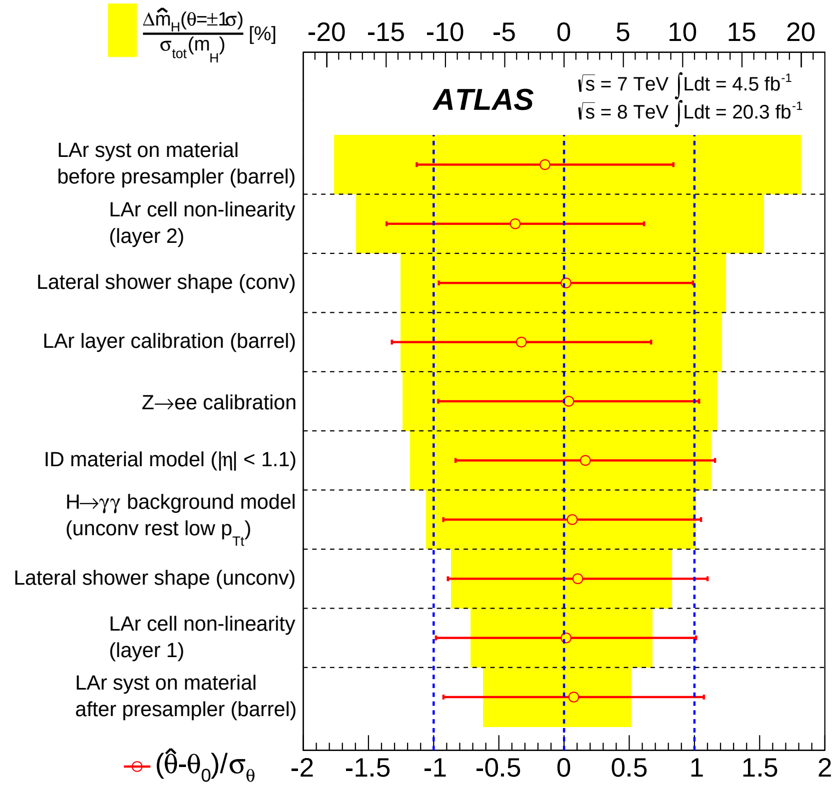
Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell non-linearity (layer 2)	60
LAr cell non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \to \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \to ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180



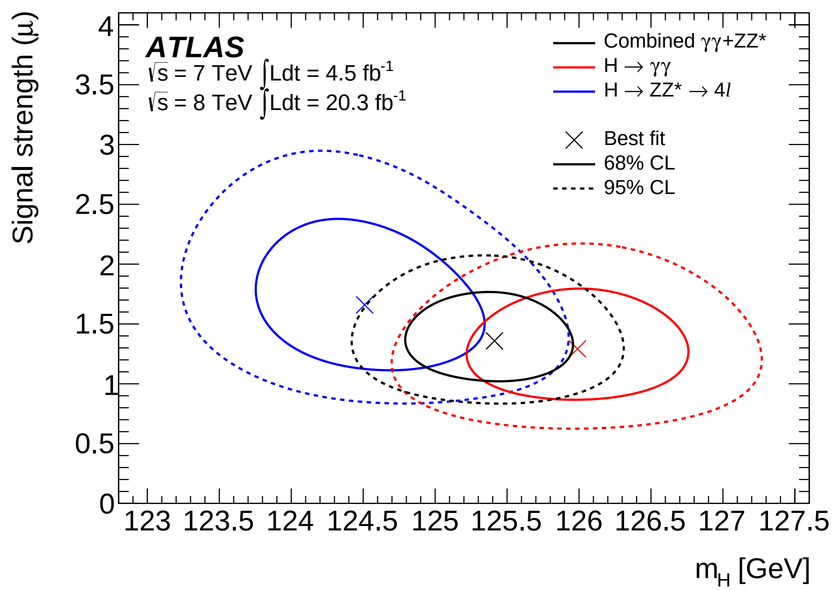


m_H systematics

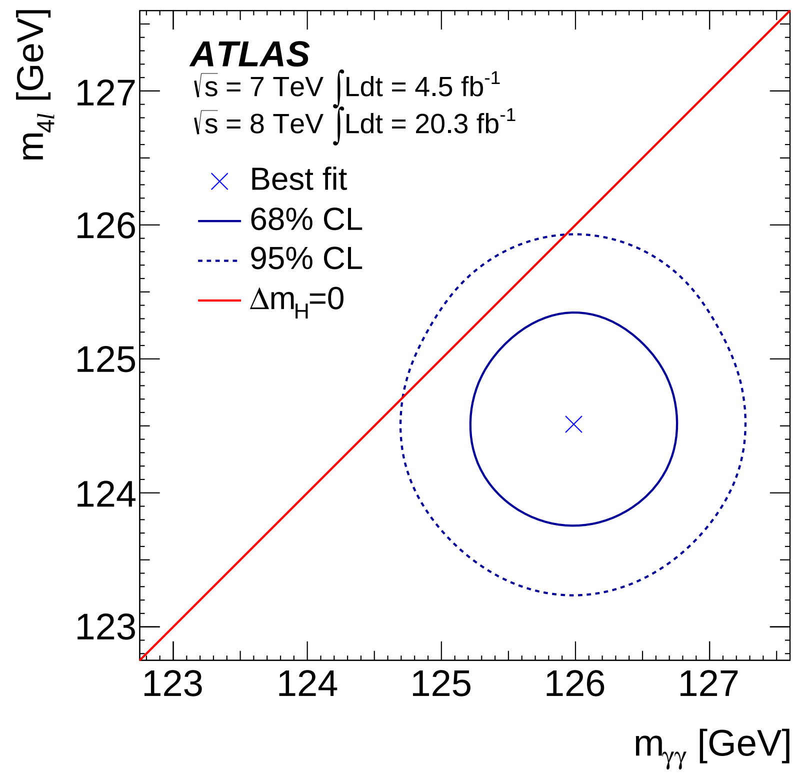




m_H plots

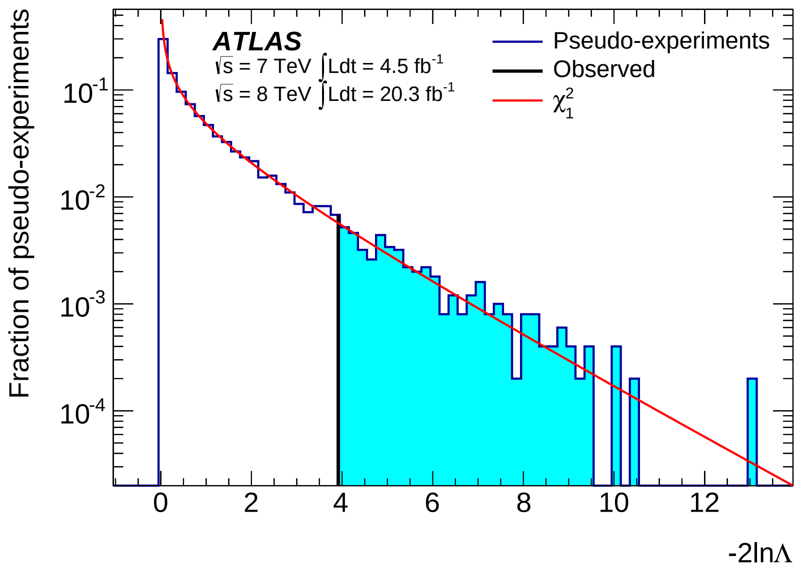


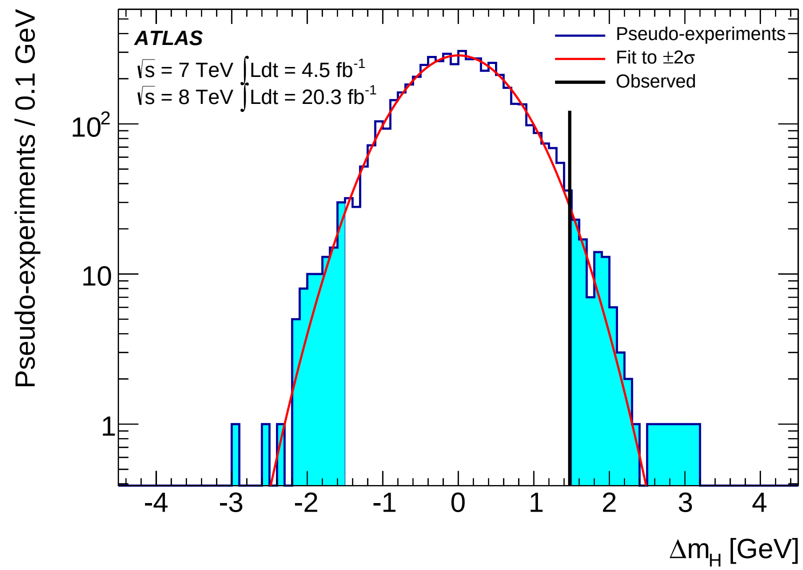
$\Delta \hat{m_H}$ **with** m_H **profiled**



$\hat{m_H}$ **with** $\Delta m_H = 0$

Results of pseudoexperiments



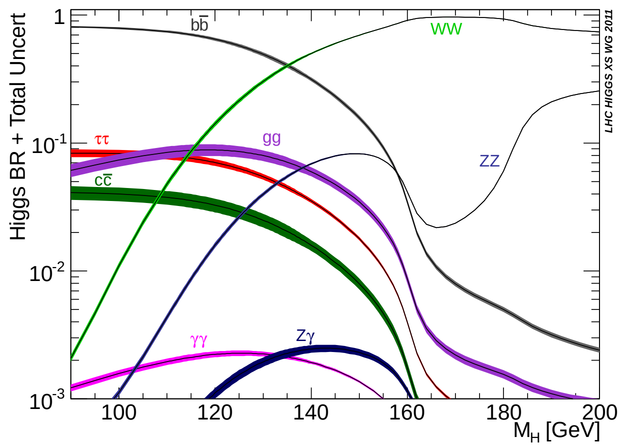


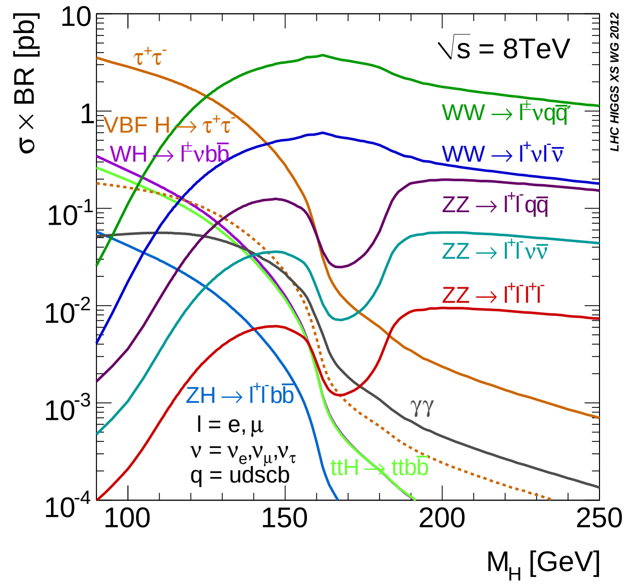
$\hat{m_H}$ **with** $\Delta m_H = 0$

Plots assume common m_H with separate signal strengths (μ).

Measurement channels

- $H \to \gamma\gamma$:
  - Excellent mass reconstruction ($\sim$ 3 GeV)
  - Small S/B (3%), but background easy to model
  - Excellent photon ID allows reduction of jets/electrons misidentified as photons $\to$ 75% of background is $\gamma\gamma$
- $H \to ZZ^{(*)} \to 4l$:
  - $llll$ has small branching ratio, but large S/B and excellent mass resolution





γ/e reconstruction

- Multivariate regression algorithm used to correct for following:
  - Energy deposited in front of calorimeter (a few to 20% of energy for 100 GeV electrons)
  - Energy outside of cluster (around 5%)
  - Variation of energy response as function of impact point in calorimeter
- MVA used Inputs to MVA:
  - Measured energy per calorimeter layer (including pre-sampler)
  - Pseudorapidity (η) of cluster
  - Local position of shower within 2nd-layer cell corresponding to cluster centroid
  - Converted photons: track transverse momenta and conversion radius
- Associated tracks fitted with Gaussian-Sum Filter to account for bremsstrahlung losses
- For $H \rightarrow ZZ^* \rightarrow 4l$ candidate electrons, track momentum combined with energy measured in calorimeter