ICNFP 2014, Crete, Greece, 31 Jul-6 Aug 2014.

Measurement of the Higgs boson mass with the ATLAS detector.

Francisca Garay, on behalf of the ATLAS collaboration.

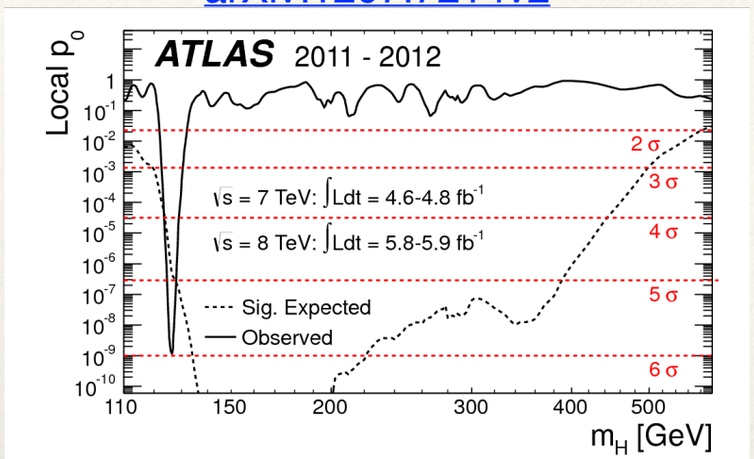
Some history

Observation

m_H= 126.0±0.4(stat)±0.4(sys) GeV

μ=1.4±0.3

arXiv:1207.7214v2

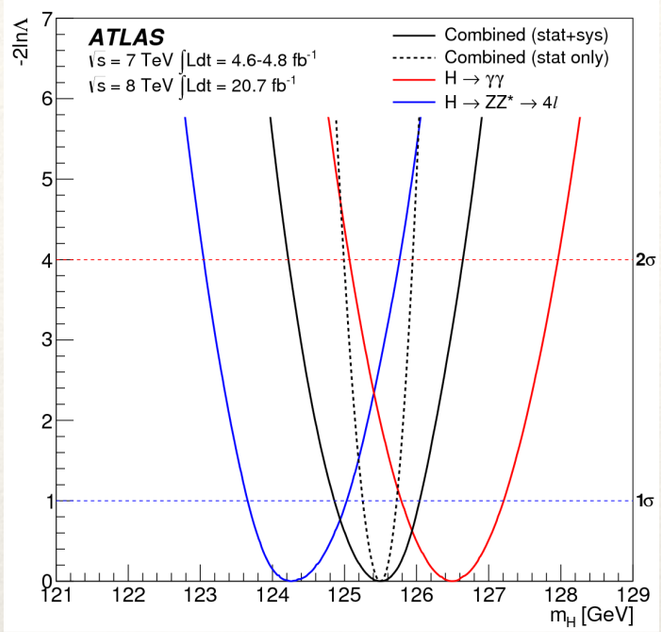


Paper Physics Letters B

m_H= 125.5±0.2(stat)$_{-0.6}^{+0.5}$(sys) GeV

μ=1.33$_{-0.18}^{+0.21}$

arXiv:1307.1427v1



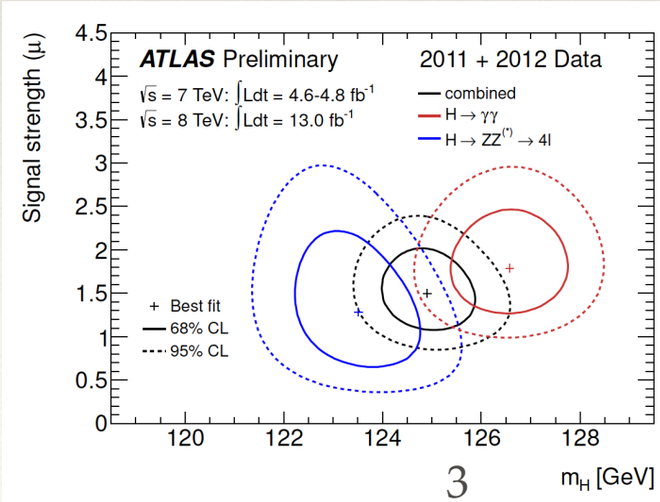
July 2012 | December 2012 | July 2013 | June 2014

CERN council

m_H= 125.2±0.3(stat)±0.6(sys) GeV

μ=1.35±0.24

ATLAS-CONF-2012-170



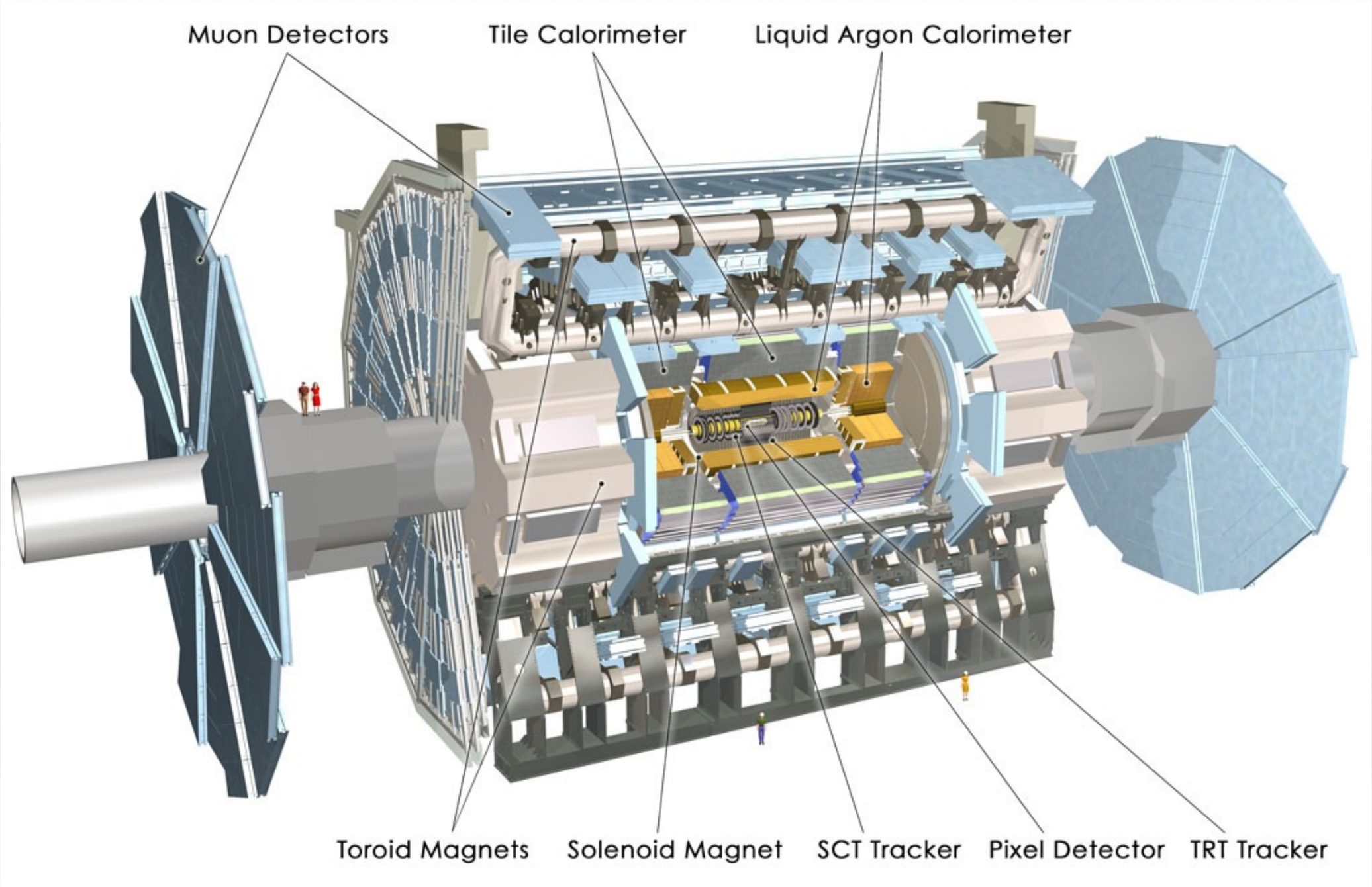
Paper Physical Review D

Will be presented in the next slides…

arXiv:1406.3827v1

Overview: ATLAS detector

ATLAS Detector

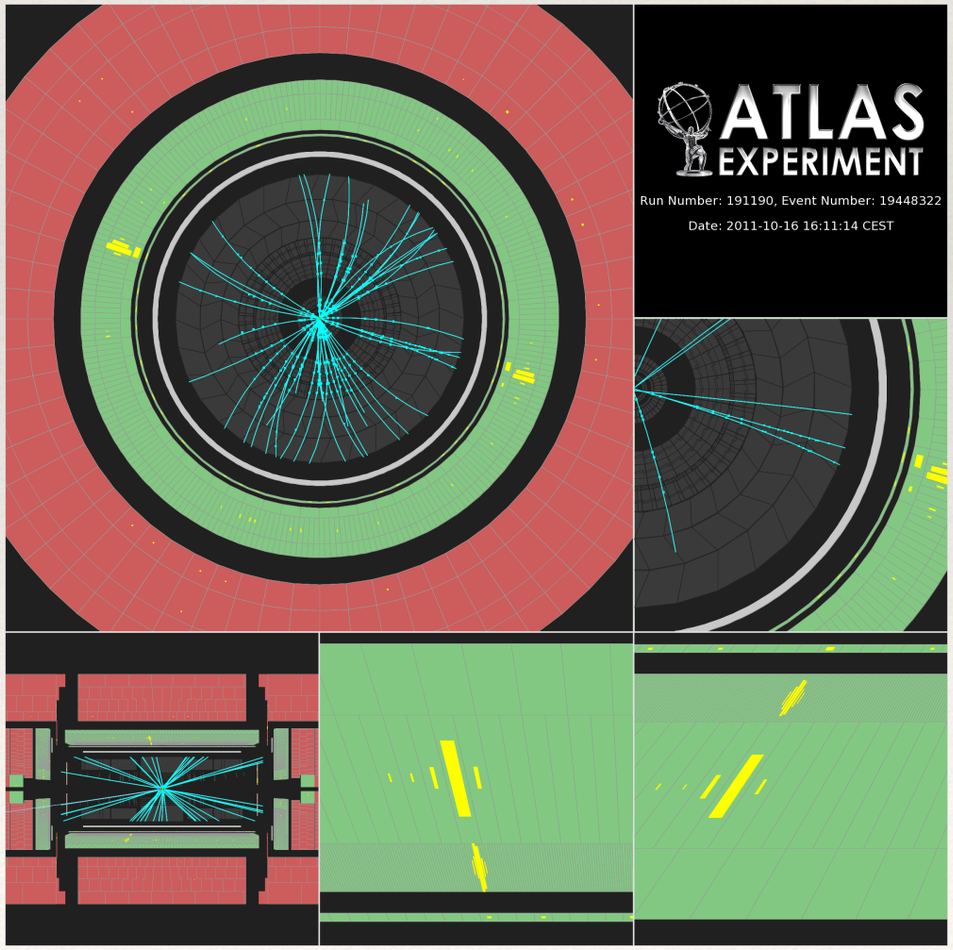


Improvements in photon and electron calibration

Improvements in photon and electron calibration

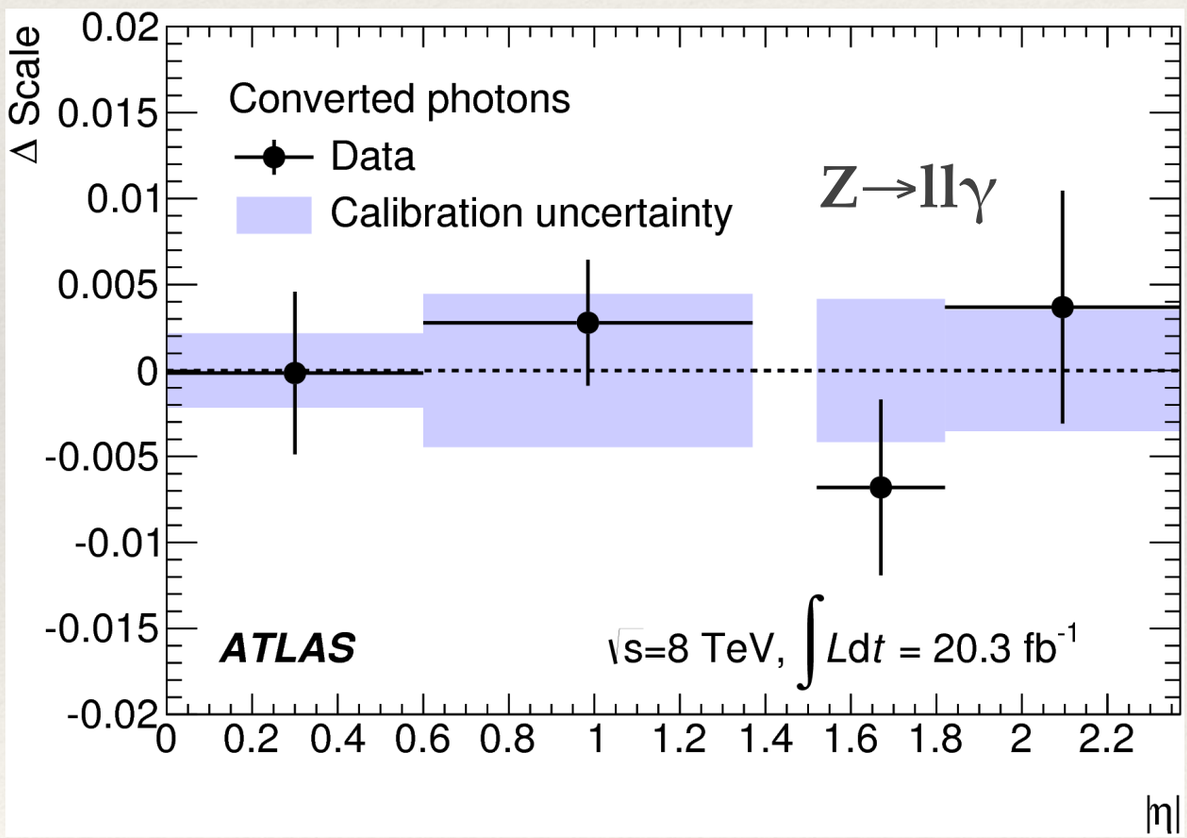
- Multivariate regression algorithm from simulation.
  10% improvement on mass resolution for $H \rightarrow \gamma\gamma$
- Calorimeter response is stable in time.
  better than 0.05%.
- Intercalibration of calorimeter layers (from data and simulation):
  - Uncertainty varies from 1%-2%
  - Presampler better than 5%.
- Determination of the material in front of the EM (from data):
  - To correct the energy lost upstream the calorimeter.
  - The material is well described by simulation. radiation length is accurate to 3-10%.
- An independent check was performed with $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow l^+l^-\gamma$.

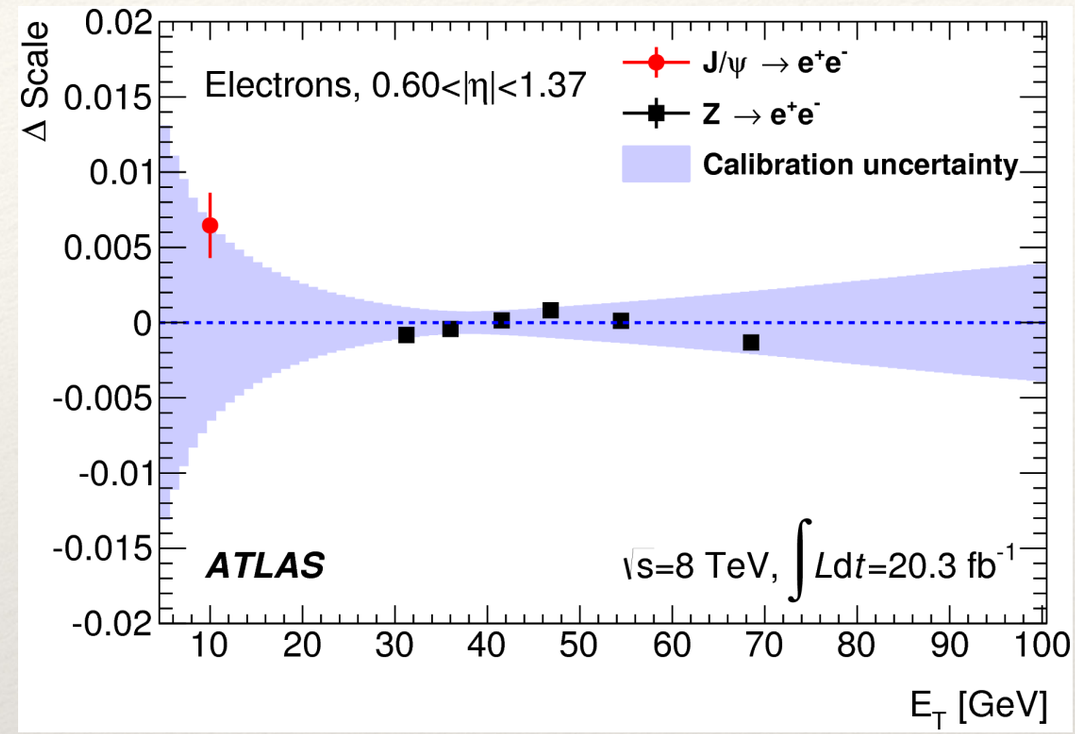
Electron candidate: matched to a track consistent with originating from an electron produced in the beam interaction region.
Unconverted photon: without a matching track or reconstructed vertex in the ID.
Converted photon: with a matching track and reconstructed vertex in the ID.

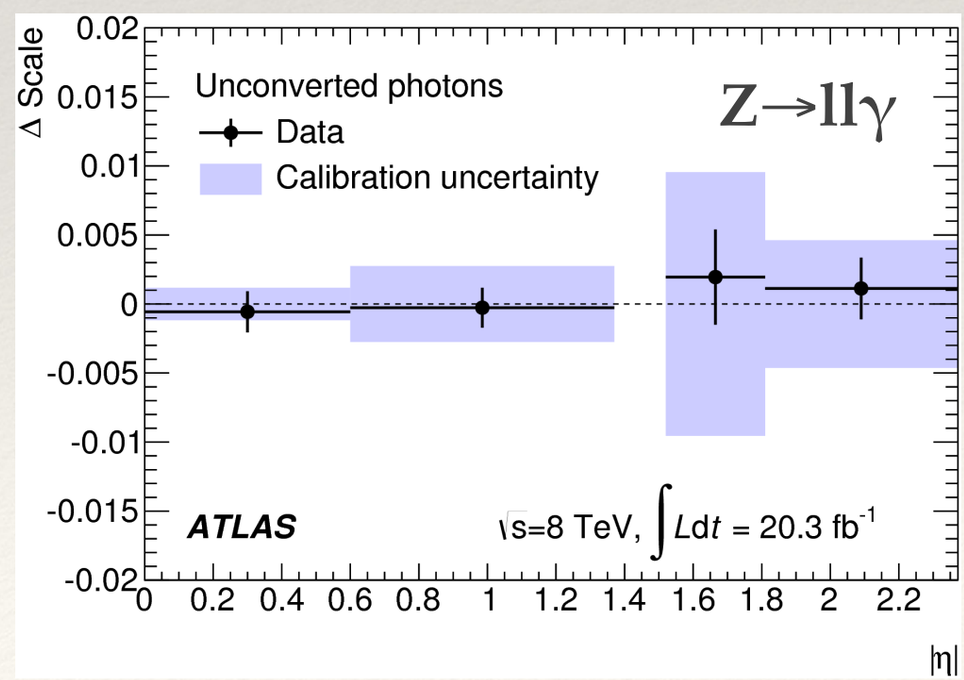


Improved photon and electron calibration

- Energy scale uncertainty from $Z \rightarrow e^+e^-$ (depending on η) ranges from:
  - electrons (E_T=40 GeV): 0.03% to 0.2%.
  - converted photons (E_T=60 GeV): 0.18% to 1%.
  - unconverted photons (E_T=60 GeV): 0.19% to 1.35%.







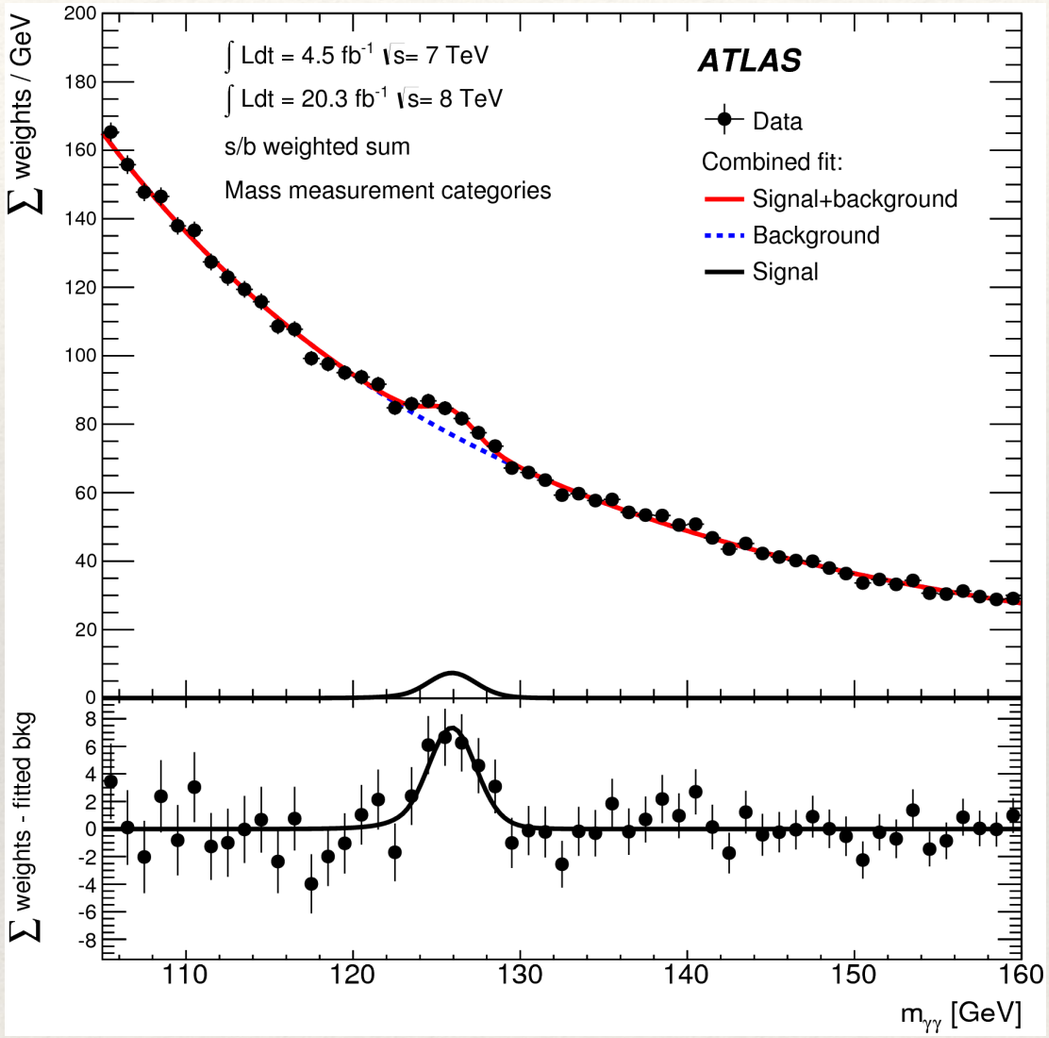
See details in: arXiv:1207.7214v2

Talk on Wednesday: Parallel session number 5.

$H \rightarrow \gamma\gamma$ mass measurement

H→γγ mass measurement

- Good sensitivity to the Higgs boson mass.
  - Mass resolution of 1.7 GeV on average.
- Main background: continuum γγ production (20% from γ+jets).
- Event selection:
  - Two isolated high energy photons.
  - $m_{\gamma\gamma}$: photon energies, primary vertex (calorimeter pointing info) and impact points in the calorimeter.
- Improvements since summer 2013:
  - Event categorisation (10 groups) to improve the accuracy of the mass measurement.
  - Background modelling from analytical function.
  - Improved electron and photon calibration used.
- 20% reduction on the expected statistical uncertainty compared with the inclusive measurement.

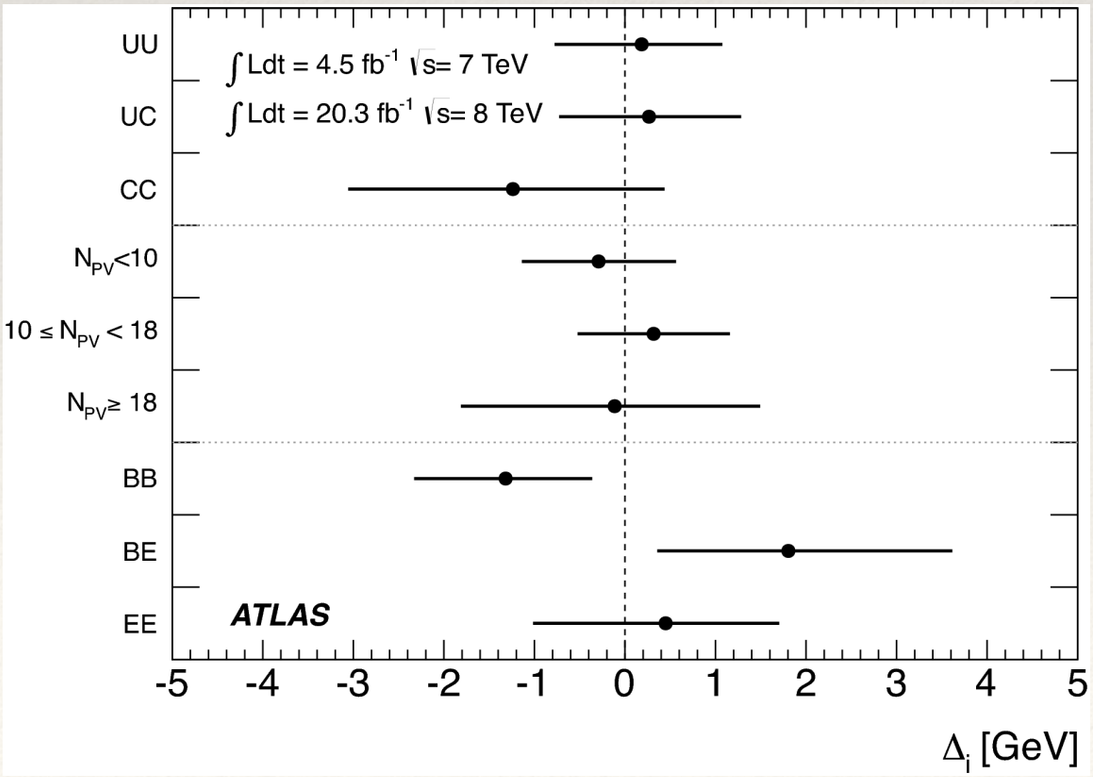


- **Mass measurement method:** Simultaneous fit of all categories at 7 and 8 TeV using an unbinned maximum likelihood fit.

Result for H→γγ

m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV
= 125.98 ± 0.50 GeV
μ = 1.29 ± 0.30

Previous result:
m_H= 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
μ = 1.55 +0.33(-0.28)
arXiv:1307.1427v1



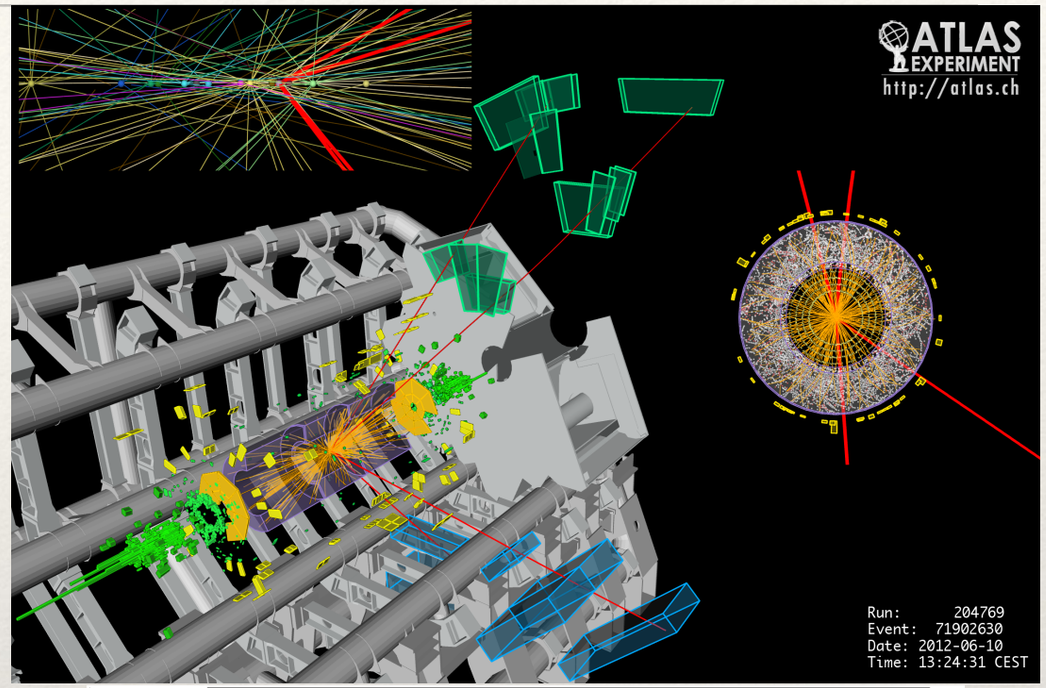
- Change in the central value is consistent with the expected change (updated photon energy scale calibration.)
- Statistical uncertainty:
  - mass resolution improvements, event categorisation.
  - compatible with expectation: 0.35 (0.45) GeV for μ = 1.3 (1).
  - Increase due to statistical fluctuations (16% probability).
- Systematic uncertainty: dominated by γ energy scale uncertainty (reduced by a factor of 2.5)
- Cross checks were done by dividing data into subsamples.

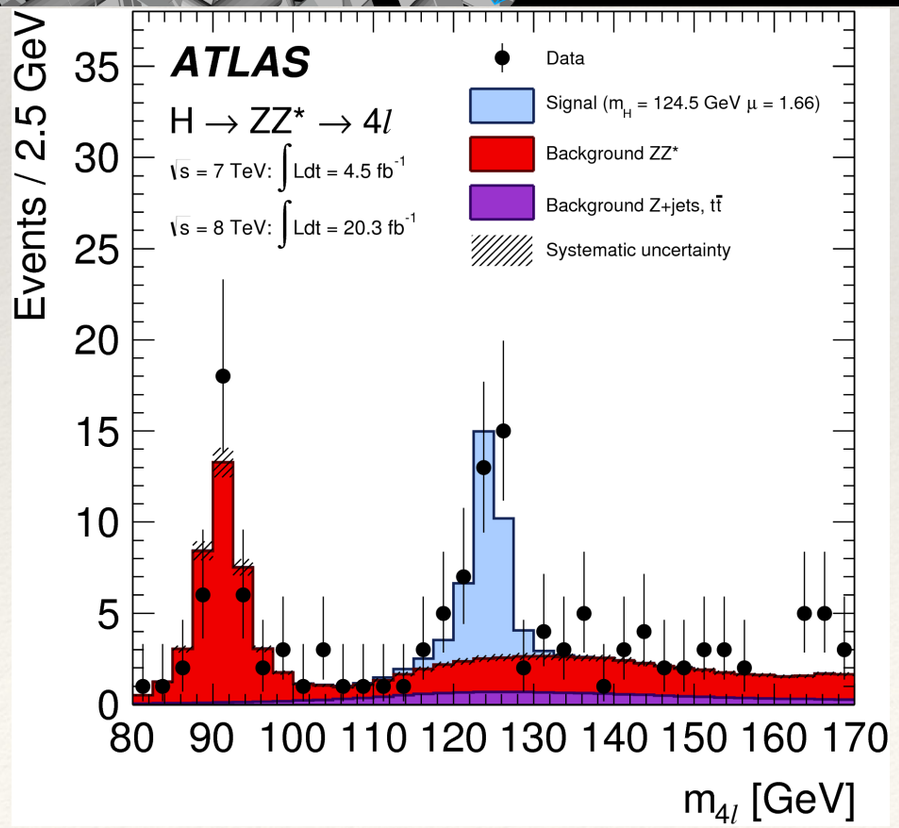
No global inconsistency larger than 1.5σ was found.

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

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

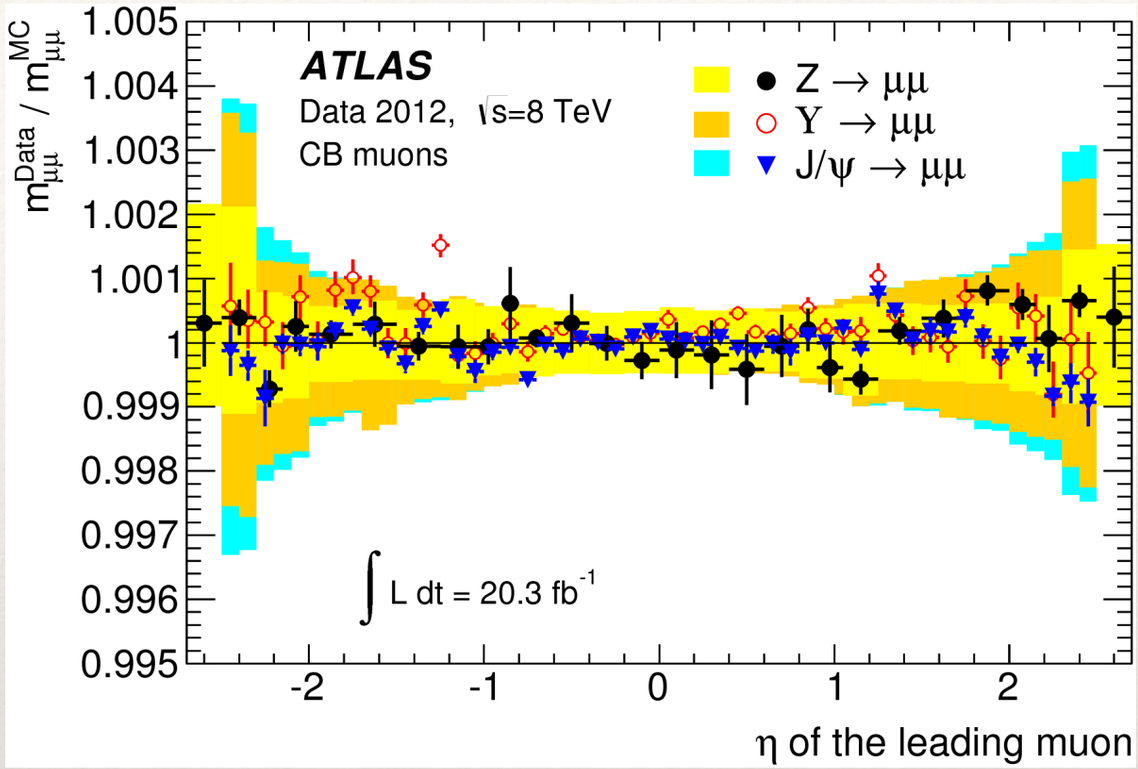
- Good sensitivity: S/B ~ 2 (120 GeV < m_{4l} <130 GeV).
- The final states are divided into four categories: μμμμ (4μ), eeee (4e), μμee (2μ2e) and eeμμ (2e2μ).
- Excellent mass resolution in the four final states: 1.6 GeV to 2.2 GeV.
- Backgrounds:
  - Irreducible ZZ (QCD ZZ production)
  - Z+jets and $t\bar{t}$.
- **Event selection:**
  - Two opposite sign and same flavour dilepton pair in an event.
  - Z mass constraint was applied.
- The m_{4l} distribution was modelled from:
  - MC for signal and the irreducible background.
  - Data driven estimations for Z+jets and $t\bar{t}$.

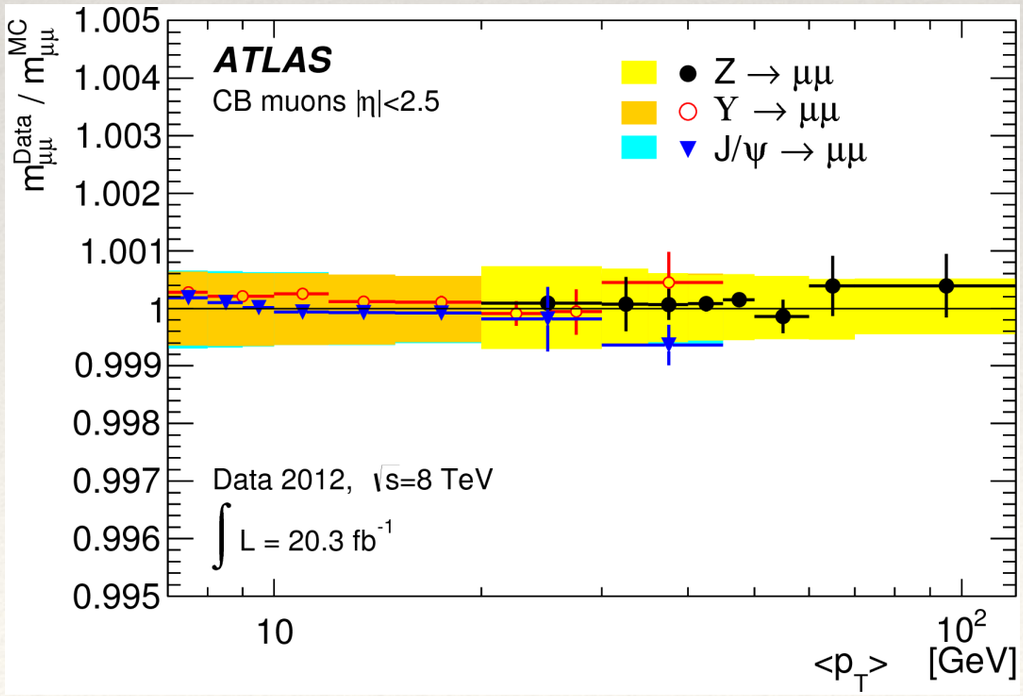




Improvements since July 2013

- Electron identification (8 TeV): cut-based → likelihood method.
- Energy calibration for electron and FSR photons.
- New combined fit of the track momentum (ID) and cluster energy (EM). 4% improvement in resolution for 4e, 2μ2e.
- Muon p_T corrections in simulation: $J/\psi \to \mu^+\mu^-$ and $Z \to \mu^+\mu^-$ events were used and checked with $\Upsilon \to \mu^+\mu^-$.
- Momentum scale uncertainties varies from 0.04% to 0.2% depending on η .
- Multivariate discriminant (BDT_{ZZ}) to separate signal and ZZ^* background.
  - BDT input: p_T, η and matrix-element kinematic discriminant.



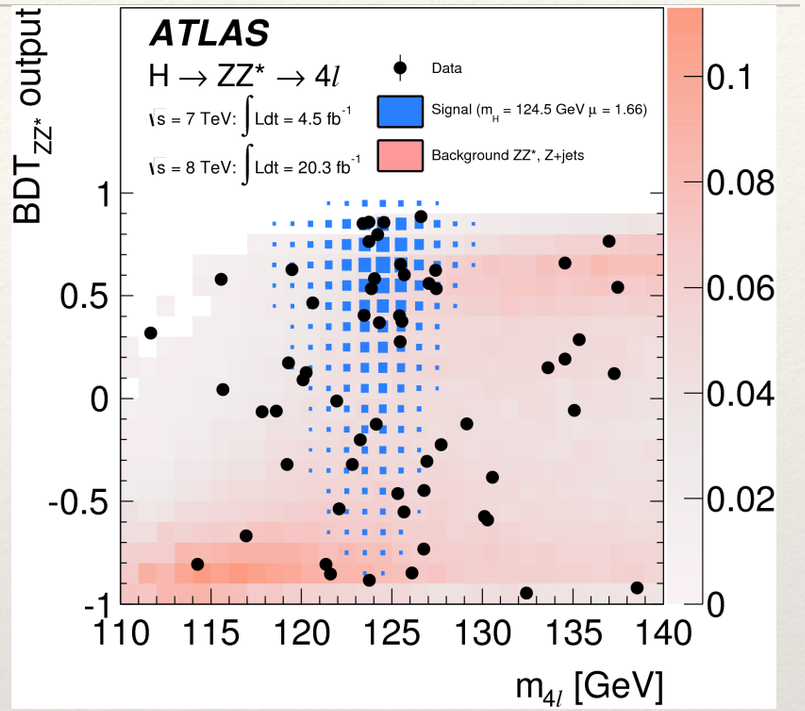


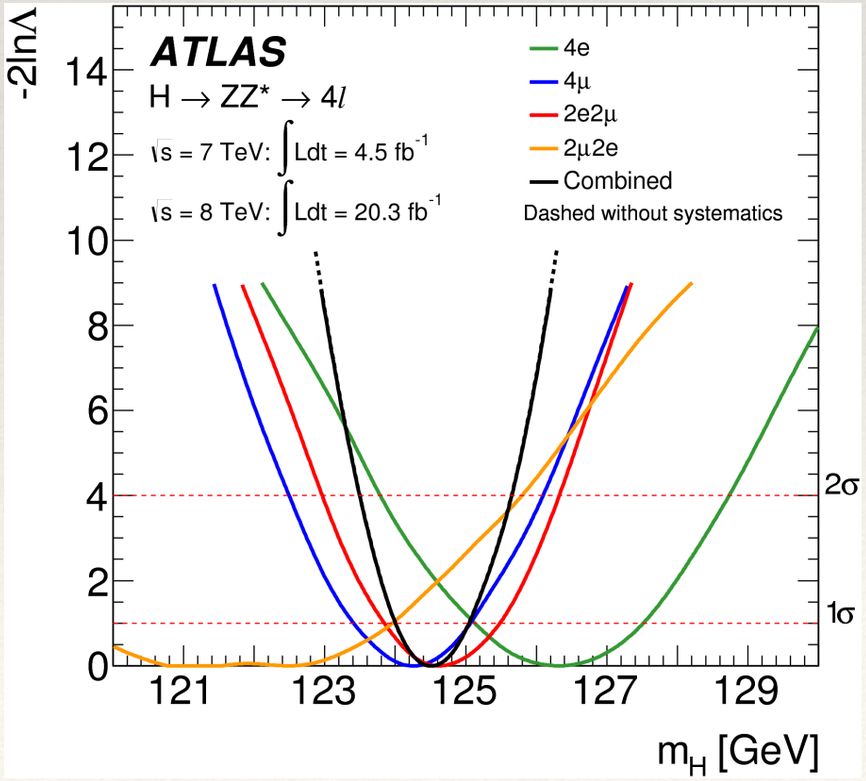
Result for $H \rightarrow ZZ^* \rightarrow 4l$

- 2D likelihood fit method (m_{4l}, BDT_{ZZ})
  reduced expected statistical uncertainty by 8% w.r.t 1D.

$$m_H = 124.51 \pm 0.52\ (stat) \pm 0.06\ (syst)\ GeV$$
$$= 124.51 \pm 0.52\ GeV$$
$$\mu = 1.66 + 0.45(-0.38)$$

Previous result:
m_H= 124.3 +0.6(-0.5) (stat) +0.5(-0.3)(syst) GeV
μ = 1.43 +0.40(-0.38)
arXiv:1307.1427v1





- Systematic uncertainty: almost negligible due to improvement on the electron and photon energy uncertainty. Reduced by a factor of ~ 8.
- Cross checks with 1D likelihood and a method utilising per-event lepton resolution without the Z-mass constraint. All consistent with 2D method.

Combined results of $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ channels

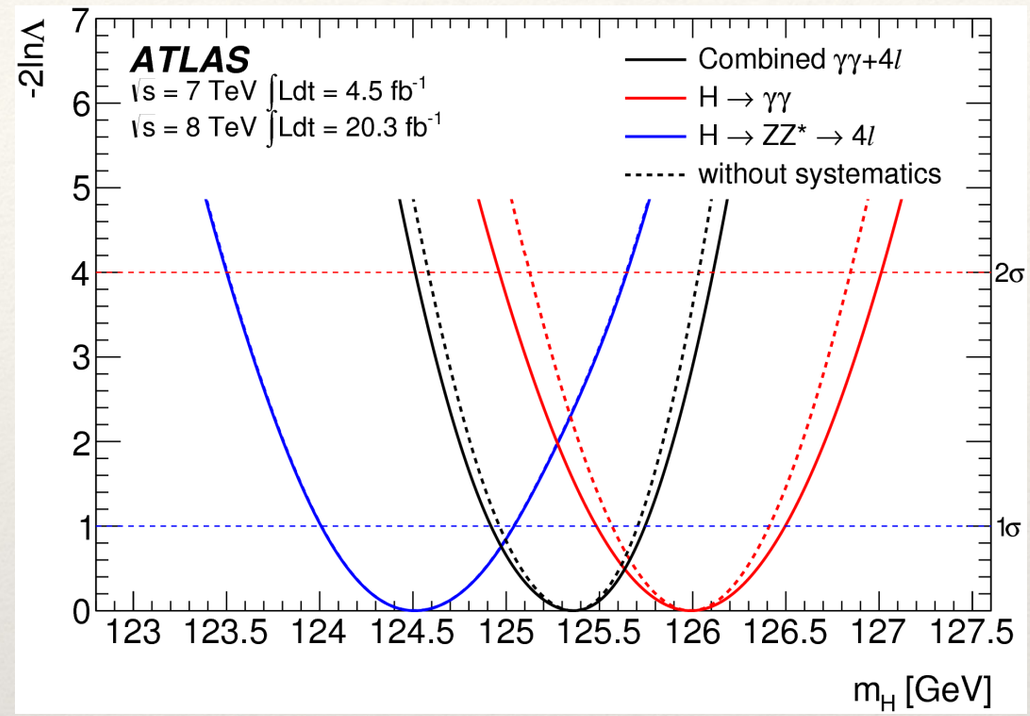
Combination

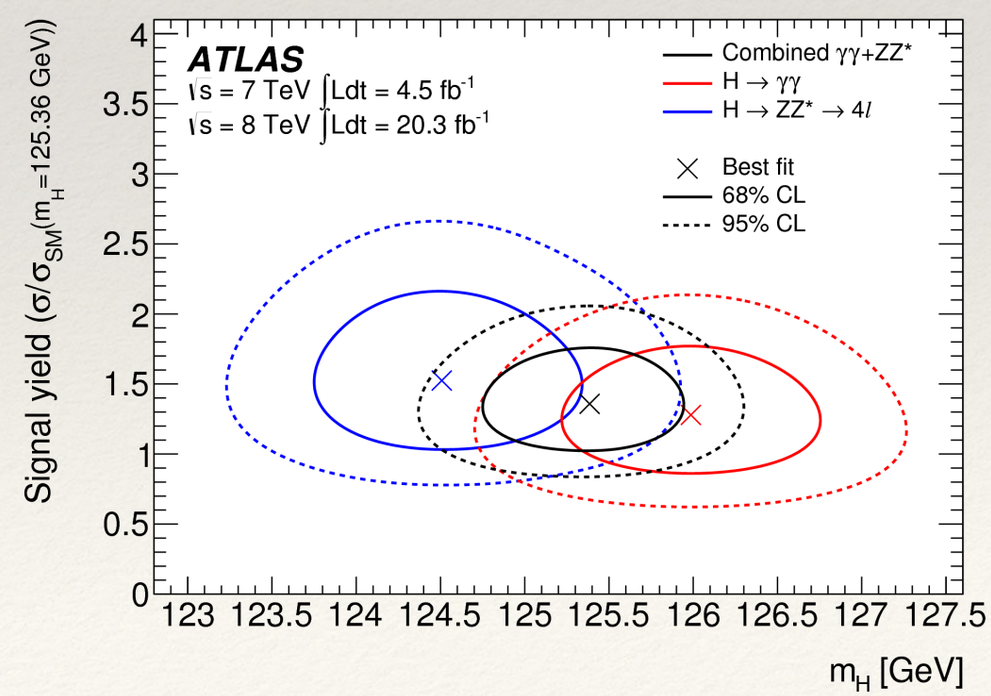
m_H= 125.36 ± 0.37 (stat) ± 0.18 (syst) GeV
= 125.36 ± 0.41 GeV

Previous result:
m_H= 125.49 ±0.24 (stat) +0.50(-0.58)(syst) GeV

- Statistical uncertainty: Increased due to H→γγ.
- Systematic uncertainty improved by a factor of ~ 3 w.r.t previous results:
  - The calibration in photons and electrons.
  - Reduction on the momentum uncertainty.
- Compatibility check was performed in between both channels.

From 2.5σ to 2.0σ w.r.t previous analysis.





Conclusion

- Improved calibration for photons, electrons and muons.
  - Better systematic uncertainty for both channels.
- Improved analysis techniques.
- Improved mass measurement (based on 7 and 8 TeV data) from the combination of $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ has been achieved.
- The final result: $m_H = 125.36 \pm 0.37$ (stat) ± 0.18 (syst) GeV.
- Compatibility of both channels is at the level of 2σ.
- A 40% reduction on the total uncertainty since previous measurement.

Thank you!

Back up slides

e/γ 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.

Event selection $H \rightarrow \gamma\gamma$

- Diphoton trigger (loose photon ID applied at trigger level):
  - 7 TeV data: $E_T > 20$ GeV for both photons.
  - 8 TeV data: $E_T > 35$ and 25 GeV.
- Two isolated high energy photons.
- Only photon candidates with $|\eta|<2.37$ are considered (without transition region $1.37<|\eta|<1.56$).
- Tight identification criteria based on shower shapes in EM.
  - 7 TeV data: neural network discriminant to reduce background.
  - 8 TeV: set of cuts for the pile up conditions.
- For further background rejection (jets misidentified as photons):
  - Calorimeter isolation: energy in area of size $\Delta\eta\times\Delta\phi = 0.125\times0.175$ 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.
- Reconstructed primary vertex candidate: Neural network discriminant with diphoton primary vertex z position plus track information (±15mm).
- Diphoton invariant mass $m_{\gamma\gamma}$: measured photon energies and opening angles from the selected primary vertex and the photon impact points in the calorimeter.
  - $E_T > 0.35(0.25) \times m_{\gamma\gamma}$ for photon with highest (lowest) E_T.
- Signal reconstruction and selection efficiency at 125 GeV: 40%

$H \rightarrow \gamma\gamma$ categories

- 10 categories optimised to minimize expected mass measurement uncertainty:
  - Different signal to background ratios.
  - Different diphoton mass resolution.
  - Different systematic uncertainties.
- First two groups: both photons are unconverted. One photon is converted (energy resolution better for unconverted photons, energy scale systematic uncertainties different).
- Then, according to η,
  - *Central region:* $|\eta| < 0.75$. Has best mass resolution and S-B ratio, smallest energy scale uncertainty.
  - *Transition region:* At least 1 photon in $1.3 < |\eta| < 1.75$. Has worse energy resolution due to material in front of calorimeter, larger E-scale uncertainties.
  - the *rest*
- Finallly, (central and rest) low and high $\mathbf{p_{Tt}}$: component of diphoton transverse momentum orthogonal to diphoton thrust axis in the transverse plane:
  - low $\mathbf{p_{Tt}}$: <70 GeV.
  - high $\mathbf{p_{Tt}}$: > 70 GeV. Better S-B ratio and mass resolution, but small yield.

H→γγ categories

Table 1: Summary of the expected number of signal events in the 105–160 GeV mass range n_{sig}, the FWHM of mass resolution, σ_{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 (σ_{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_{sig}	FWHM [GeV]	σ_{eff} [GeV]	b in $\pm\sigma_{eff90}$	s/b [%]	$s/\sqrt{b}$
			$\sqrt{s}$=8 TeV			
Inclusive	402.	3.69	1.67	10670	3.39	3.50
Unconv. central low p_{Tt}	59.3	3.13	1.35	801	6.66	1.88
Unconv. central high p_{Tt}	7.1	2.81	1.21	26.0	24.6	1.26
Unconv. rest low p_{Tt}	96.2	3.49	1.53	2624	3.30	1.69
Unconv. rest high p_{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_{Tt}	37.2	3.47	1.52	589	5.69	1.38
Conv. central high p_{Tt}	4.5	3.07	1.35	20.9	19.4	0.88
Conv. rest low p_{Tt}	107.2	4.23	1.88	3834	2.52	1.56
Conv. rest high p_{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_{Tt}	10.8	2.89	1.24	128	7.55	0.85
Unconv. central high p_{Tt}	1.2	2.59	1.11	3.7	30.0	0.58
Unconv. rest low p_{Tt}	16.5	3.09	1.35	363	4.08	0.78
Unconv. rest high p_{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_{Tt}	7.1	3.28	1.44	105	6.06	0.62
Conv. central high p_{Tt}	0.8	2.87	1.25	3.5	21.6	0.40
Conv. rest low p_{Tt}	21.0	3.93	1.75	695	2.72	0.72
Conv. rest high p_{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

Estatistical error difference in $H \rightarrow \gamma\gamma$

3 reasons:

- μ decreases from current to previous result.

  uncertainty increases by a factor 1.2.
- Change in categorisation (minor).

  Statistical error 4% larger than previous.
- Accidental fluctuations.

  Observed error deviate 1σ (current) and -0.9σ (previous) from expected value.

	μ	σ(exp)	σ(obs)
Previous	1.55	0.33 GeV	0.24 GeV
Current	1.29	0.35 GeV	0.42 GeV

m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV
= 125.98 ± 0.50 GeV
μ = 1.29 ± 0.30

Previous result:
m_H= 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV
μ = 1.55 +0.33(-0.28)
arXiv:1307.1427v1

Event Selection $H \rightarrow ZZ^* \rightarrow 4l$

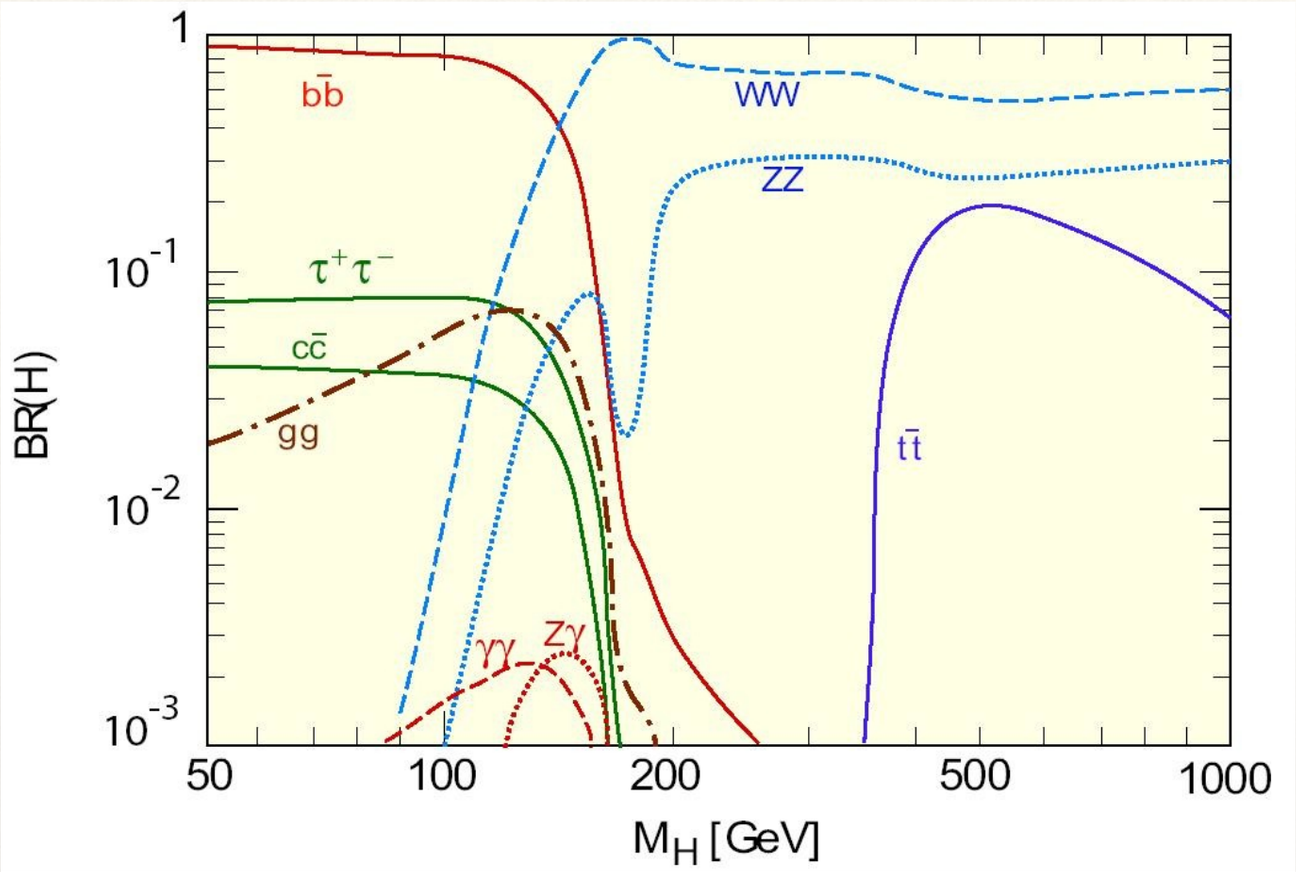
- Single-lepton and dilepton triggers:
  - Single-muon (single-electron) triggers from 18-24 (20-25) GeV between 7 and 8 TeV datasets.
  - Dilepton triggers start at 6 (10) GeV for muons (electrons) for 7 TeV, 13 (12) GeV for muons (electrons) for 8 TeV (with an asymmetric threshold of (8,18) GeV).
- 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.
- Two opposite sign and same flavour dilepton pair in an event.
  - Each lepton required to have longitudinal IP < 10 mm w.r.t primary vertex.
  - 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.
  - Separated from each other: $\Delta R > 0.1$ (0.2) for same (different) flavour leptons.
- Multiple quadruplets allowed (separately from each channel), only keep 1 per channel:
  - Lepton pair with m_{12} 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 $|d_0| / \sigma_{d0} < 3.5$ (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.

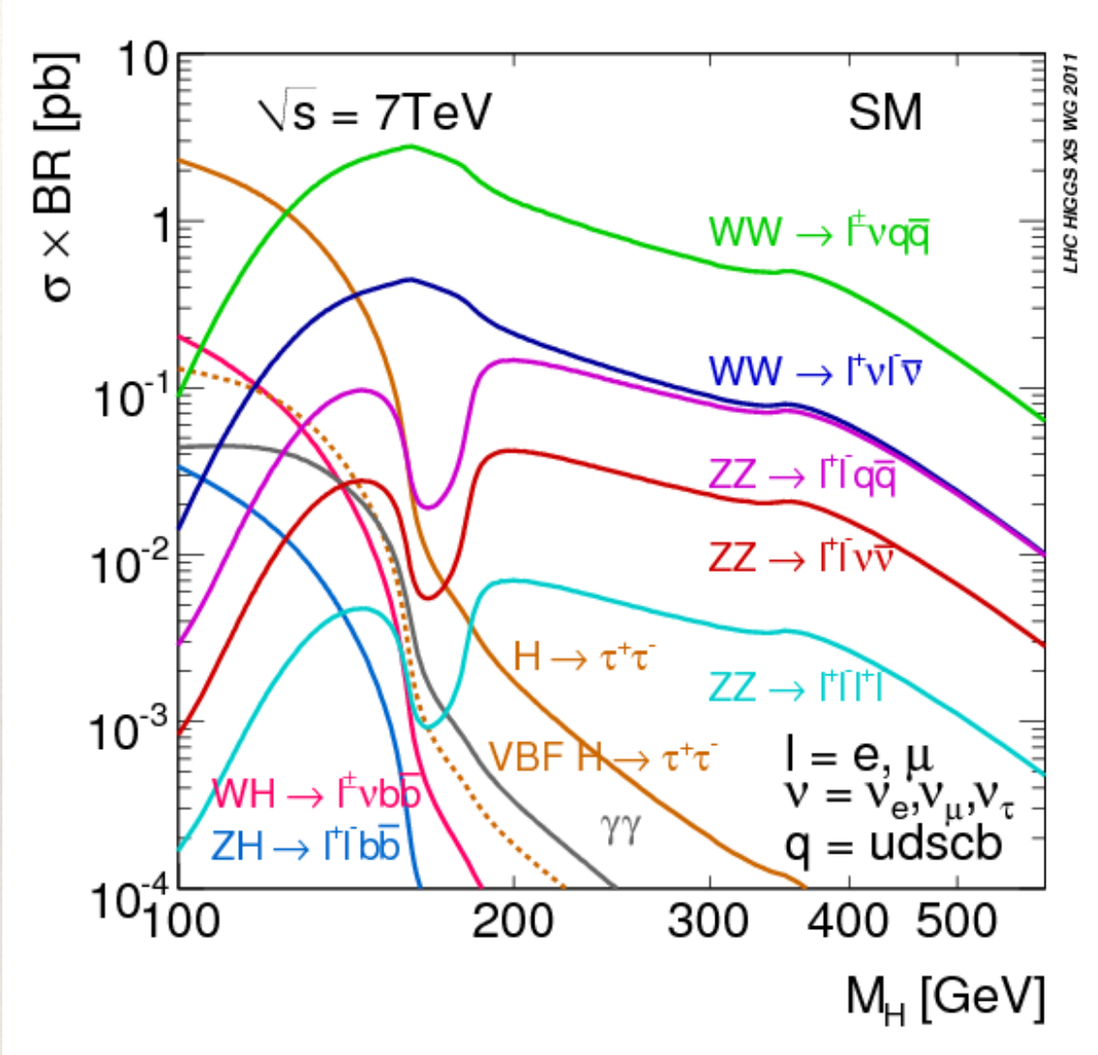
Events in $H \rightarrow ZZ^* \rightarrow 4l$

Table 3: The number of events expected and observed for a m_H=125 GeV hypothesis for the four lepton final states. The second column shows the number of expected signal events for the full mass range. The other columns show the number of expected signal events, the number of ZZ^* and reducible background events, the signal-to-background ratio (s/b), together with the numbers of observed events, in a window of $120 < m_{4\ell} < 130$ GeV for 4.5 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV as well as for the combined sample.

Final state	Signal full mass range	Signal	ZZ^*	Z + jets, $t\bar{t}$	s/b	Expected	Observed
			$\sqrt{s}$ = 7 TeV				
4μ	1.00 ± 0.10	0.91 ± 0.09	0.46 ± 0.02	0.10 ± 0.04	1.7	1.47 ± 0.10	2
$2e2\mu$	0.66 ± 0.06	0.58 ± 0.06	0.32 ± 0.02	0.09 ± 0.03	1.5	0.99 ± 0.07	2
$2\mu 2e$	0.50 ± 0.05	0.44 ± 0.04	0.21 ± 0.01	0.36 ± 0.08	0.8	1.01 ± 0.09	1
$4e$	0.46 ± 0.05	0.39 ± 0.04	0.19 ± 0.01	0.40 ± 0.09	0.7	0.98 ± 0.10	1
Total	2.62 ± 0.26	2.32 ± 0.23	1.17 ± 0.06	0.96 ± 0.18	1.1	4.45 ± 0.30	6
			$\sqrt{s}$ = 8 TeV				
4μ	5.80 ± 0.57	5.28 ± 0.52	2.36 ± 0.12	0.69 ± 0.13	1.7	8.33 ± 0.6	12
$2e2\mu$	3.92 ± 0.39	3.45 ± 0.34	1.67 ± 0.08	0.60 ± 0.10	1.5	5.72 ± 0.37	7
$2\mu 2e$	3.06 ± 0.31	2.71 ± 0.28	1.17 ± 0.07	0.36 ± 0.08	1.8	4.23 ± 0.30	5
$4e$	2.79 ± 0.29	2.38 ± 0.25	1.03 ± 0.07	0.35 ± 0.07	1.7	3.77 ± 0.27	7
Total	15.6 ± 1.6	13.8 ± 1.4	6.24 ± 0.34	2.00 ± 0.28	1.7	22.1 ± 1.5	31
			$\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV				
4μ	6.80 ± 0.67	6.20 ± 0.61	2.82 ± 0.14	0.79 ± 0.13	1.7	9.81 ± 0.64	14
$2e2\mu$	4.58 ± 0.45	4.04 ± 0.40	1.99 ± 0.10	0.69 ± 0.11	1.5	6.72 ± 0.42	9
$2\mu 2e$	3.56 ± 0.36	3.15 ± 0.32	1.38 ± 0.08	0.72 ± 0.12	1.5	5.24 ± 0.35	6
$4e$	3.25 ± 0.34	2.77 ± 0.29	1.22 ± 0.08	0.76 ± 0.11	1.4	4.75 ± 0.32	8
Total	18.2 ± 1.8	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	1.6	26.5 ± 1.7	37

Channels


BR(H)
1
10^{-1}
10^{-2}
10^{-3}
50
100
200
500
1000
M_H [GeV]
$b\bar{b}$
WW
ZZ
$\tau^+\tau^-$
$c\bar{c}$
gg
$t\bar{t}$
$\gamma\gamma$
$Z\gamma$


$\sigma \times$ BR [pb]
$\sqrt{s}$ = 7TeV
SM
LHC HIGGS XS WG 2011
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
200
300
400
500
M_H [GeV]
$WW \to l^+\nu q\bar{q}$
$WW \to l^+\nu l^-\bar{\nu}$
$ZZ \to l^+l^- q\bar{q}$
$ZZ \to l^+l^-\nu\bar{\nu}$
$H \to \tau^+\tau^-$
$ZZ \to l^+l^-l^+l^-$
VBF $H \to \tau^+\tau^-$
$WH \to l^+\nu b\bar{b}$
$ZH \to l^+l^- b\bar{b}$
$\gamma\gamma$
$l = e, \mu$
$\nu = \nu_e, \nu_\mu, \nu_\tau$
q = udscb