Higgs mass measurement at ATLAS

Sarah Heim, University of Pennsylvania
on behalf of the ATLAS collaboration

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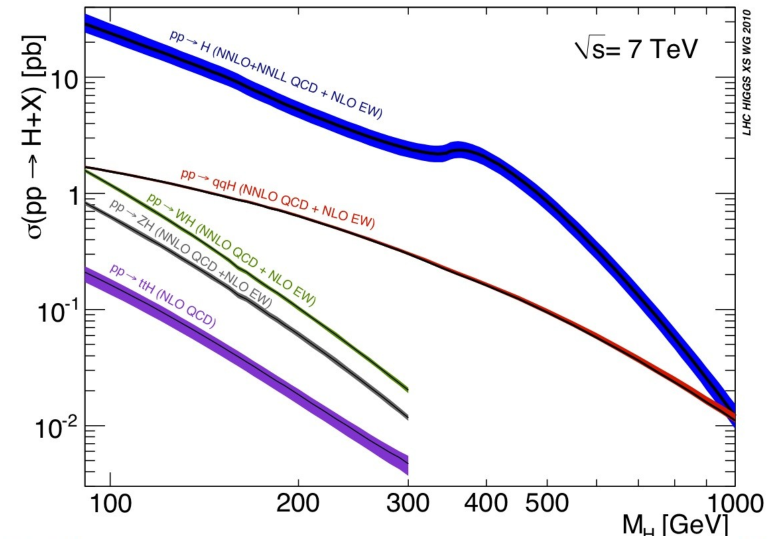
Introduction and overview

The Higgs mass is not predicted by the Standard Model

→ important Higgs property to measure

→ important for comparisons of theoretical predictions to measurements

(“crucial input parameter for Higgs physics” - G. Weiglein)



ATLAS Higgs mass measurement

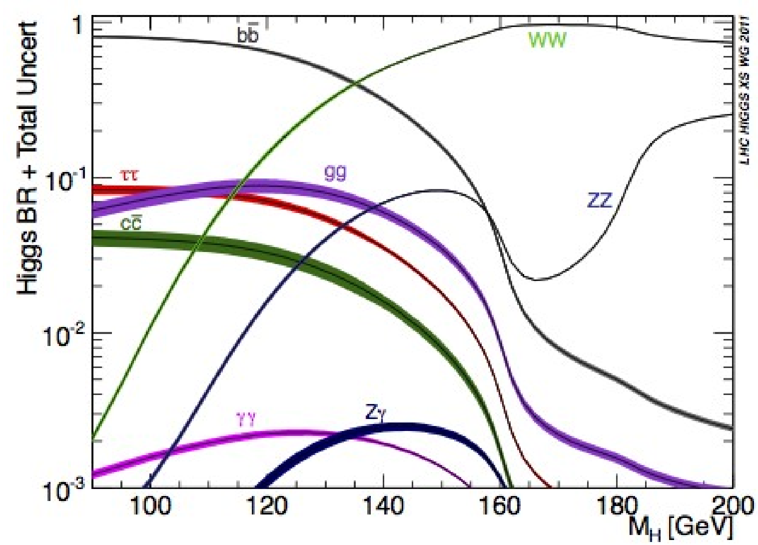
- H → $\gamma\gamma$ and H → 4l channels

- 25 fb^{-1}, 7 and 8 TeV data

- 2014 analysis documented in paper:

arXiv:1406.3827,

submitted to Physical Review D



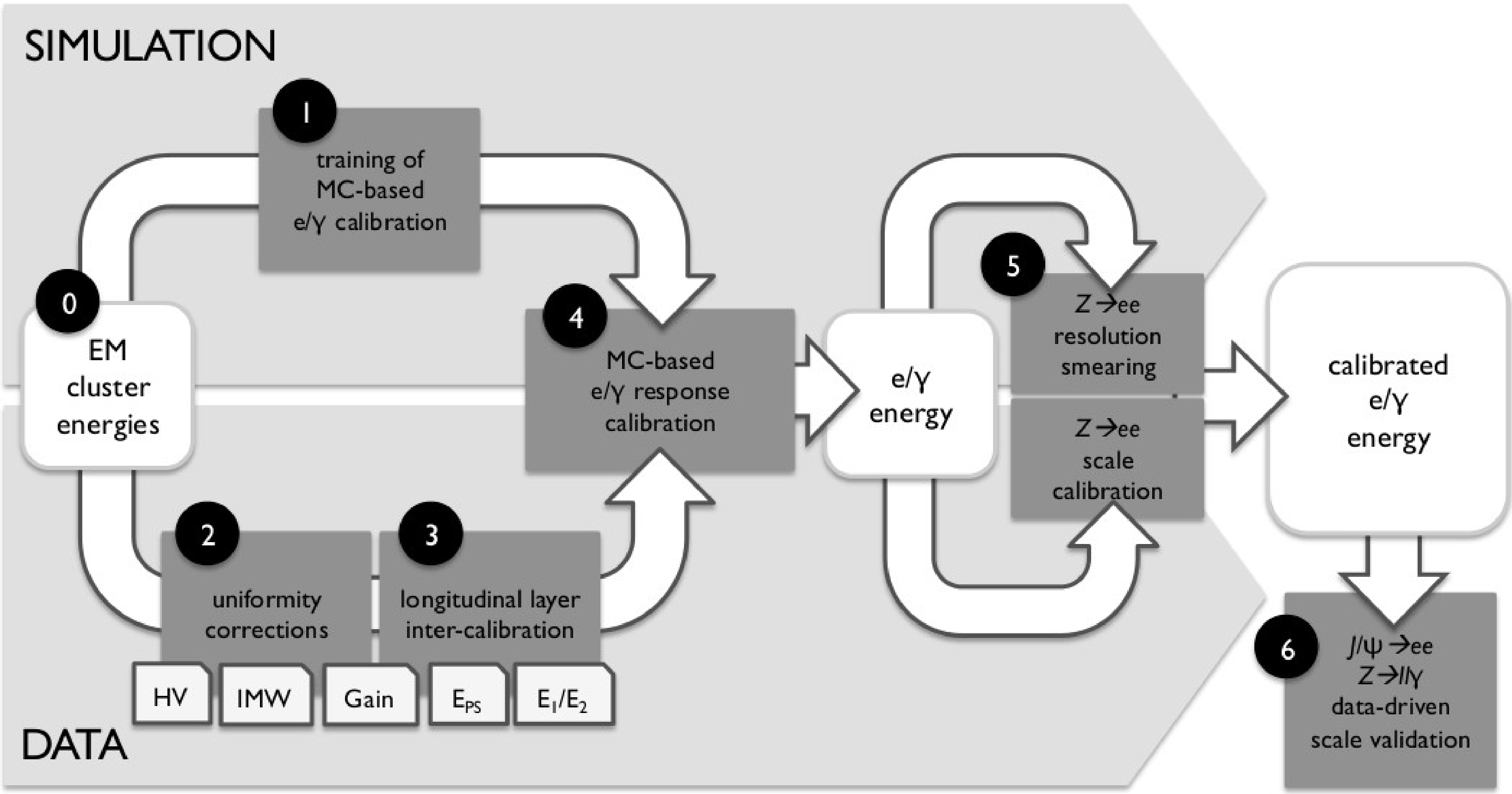
- improvements with respect to 2013 results:

- detector material description

- e, γ, muon calibration

- analysis methods

Improvements in electron and photon calibration



for (1) and (5) improved material description of detector very important

(2), (3) data-driven

(5) extraction of final energy scale

(6) important checks of systematic uncertainties

(1) alone: 10% improvement in expected mass resolution for H → $\gamma\gamma$

Improvements in electron and photon calibration

arXiv:1407.5063, submitted to Eur. Phys. J. C

Resulting uncertainties on energy scale

- photons from Higgs decay:

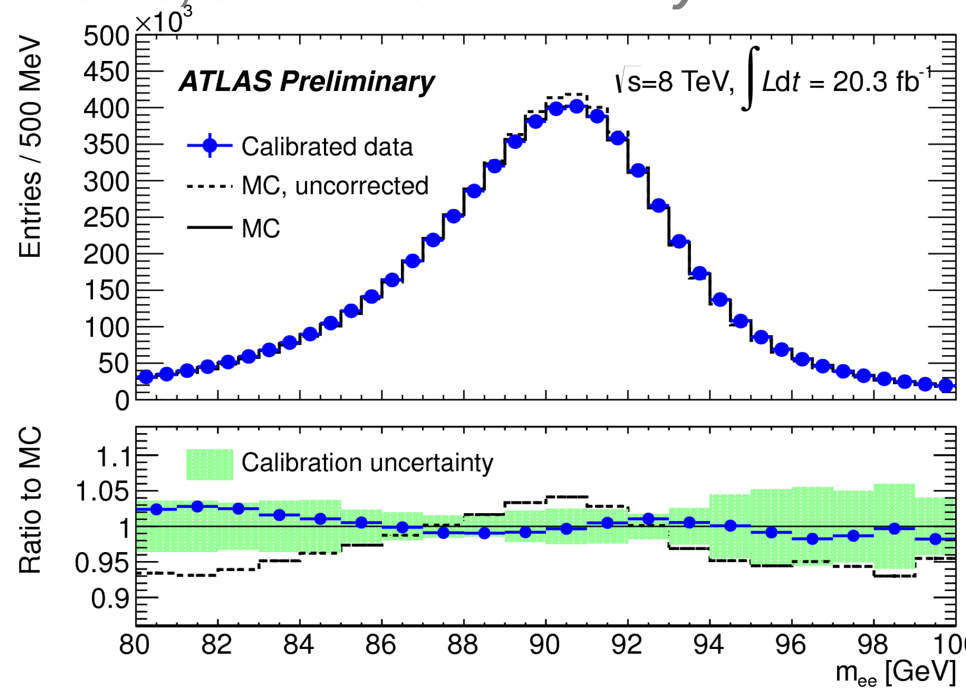
~0.3% for most of acceptance

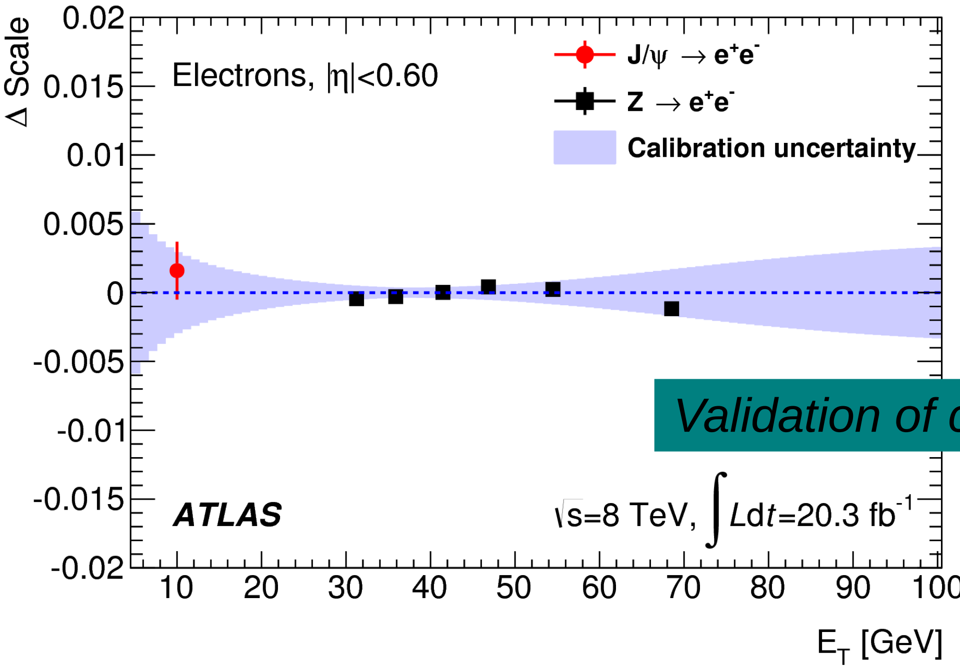
- electrons 10 (45) GeV:

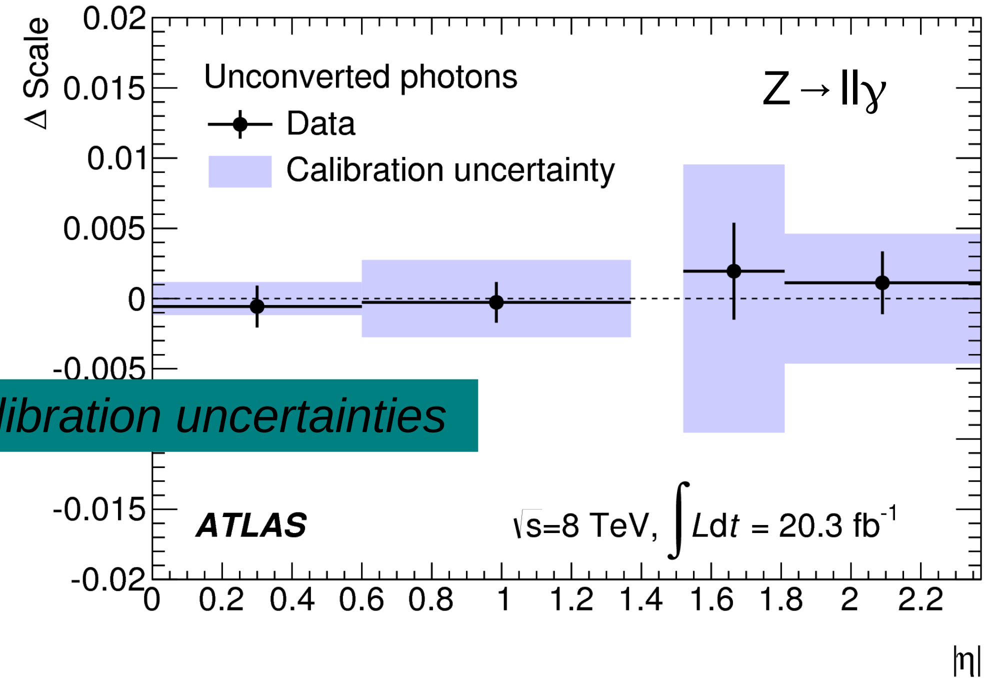
0.4 - 1 (~0.04)% for most of acceptance

→ reduces systematic uncertainty

on H → γγ mass measurement by 60%







Validation of calibration uncertainties

Muon calibration

arXiv:1407.3935, submitted to Eur. Phys. J. C

- simulation is corrected to match resolution and momentum scale in data
- corrections determined from fits to invariant mass distributions for

  Z → μμ

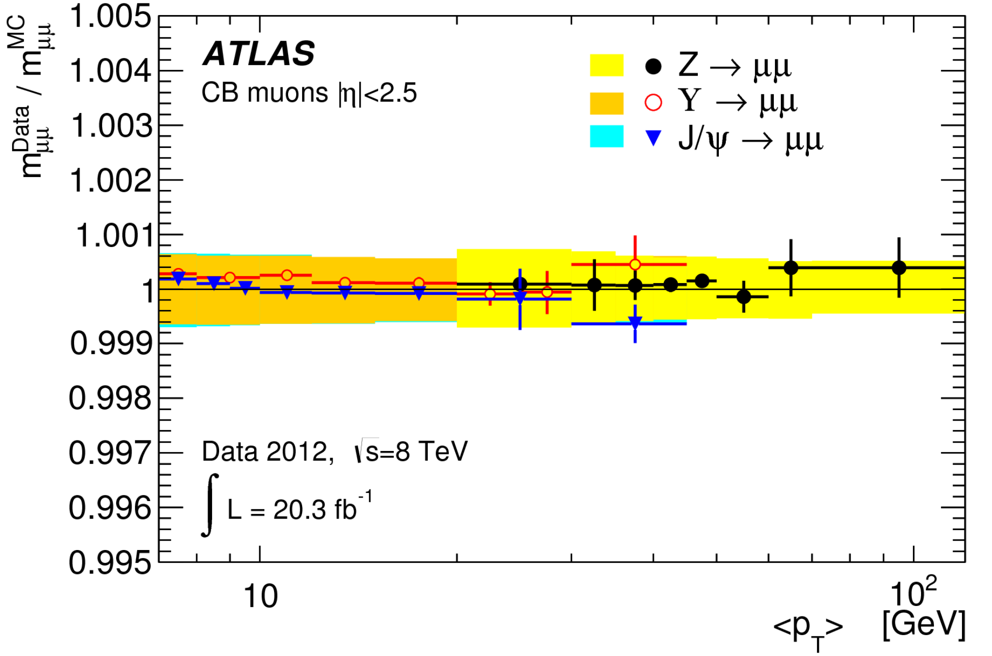
  J/Ψ → μμ (previously used as cross-check)

NEW

- cross-checked with

  Υ → μμ

Momentum scale corrections are of the same order as their uncertainties: 0.04 – 0.2%, depending on η (for muons whose momentum is reconstructed from ID and MS)



Mass fits

Profile likelihood ratio build from sums of signal and background PDFs of the discriminating variables:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}, \hat{\hat{\theta}})}{L(\hat{m}_H, \hat{\mu}, \hat{\theta})}$$

^ unconditional maximum likelihood estimate
^^ conditional maximum likelihood estimate, for fixed m_H

m_H: fit parameter of interest

signal strength μ: nuisance parameter, profiled/fit

→ measured in dedicated couplings analyses

uncertainties θ: nuisance parameters, profiled/fit

For combination:

- signal strengths $\mu(m_H,\gamma\gamma)$ and $\mu(m_H,4l)$ are treated as independent nuisance parameters

→ (almost) no assumption about Higgs coupling is made

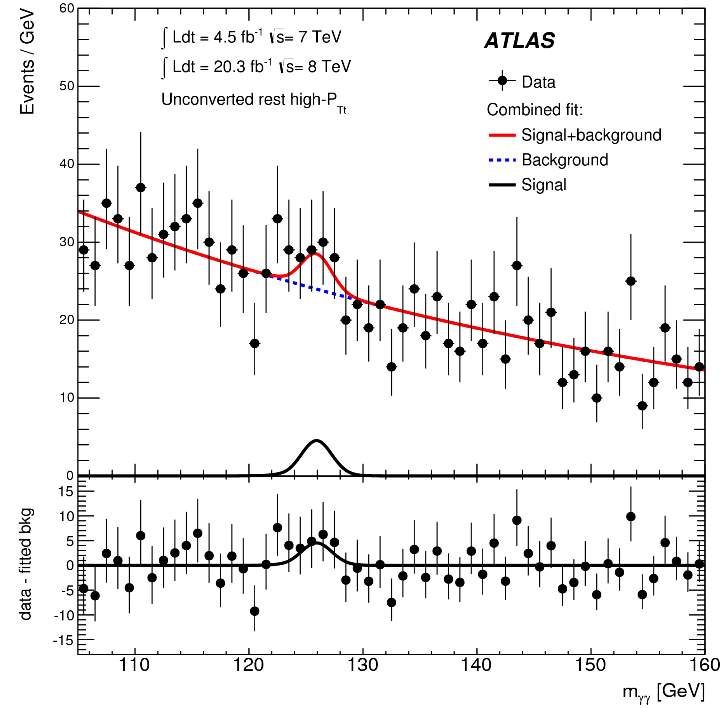
$$\Lambda(m_H) = \frac{L(m_H\,,\, \hat{\hat{\mu}}_{\gamma\gamma}(m_H)\,,\, \hat{\hat{\mu}}_{4\ell}(m_H)\,,\, \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

Interference effects between signal and background neglected

H → γγ

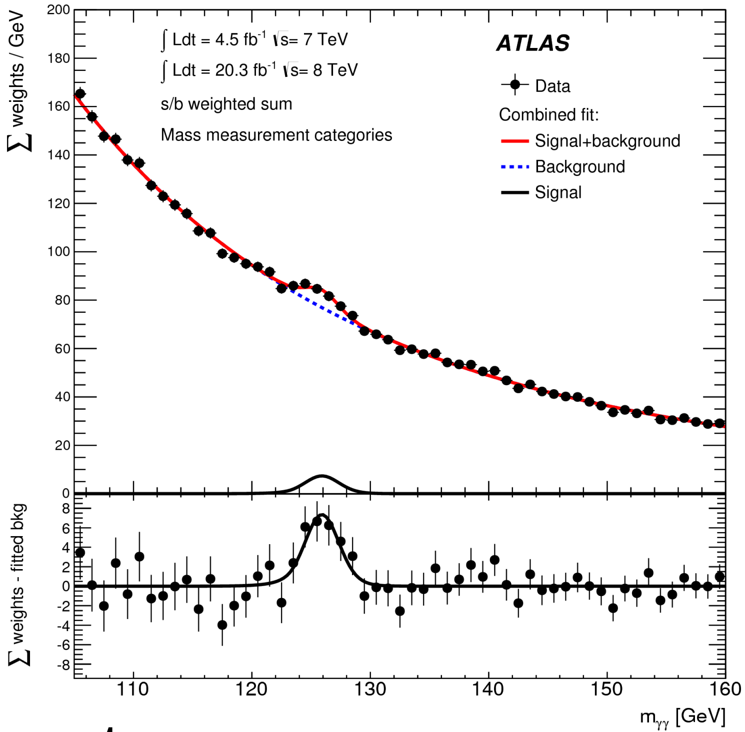
- select 2 reconstructed isolated photons
  - $E_T(1) > 0.35*m_{\gamma\gamma}$, $E_T(2) > 0.25*m_{\gamma\gamma}$
- reconstruct γγ invariant mass from
  - measured photon energies
  - opening angle determined from photon directions measured in calorimeter/using conversions plus primary vertex

  → opening angle resolution contribution to the mass resolution is negligible



- split sample into 10 detector based event categories with different
  - signal-to-background ratios (inclusive S/B: 3%, categories: 2 – 30%)
  - γγ invariant mass resolutions (inclusive: σ(68%) = 1.7 GeV, categories: 1.1 – 2.4 GeV)
  - systematic uncertainties
- backgrounds:
  - dominant: continuum γγ
  - further: γ+jet, dijet

H → γγ



Mass measurement

- simultaneous unbinned maximum likelihood fit to $m_{\gamma\gamma}$ distributions for 10 categories and 7 and 8 TeV data

- signal model:

- sum of Crystal-Ball and wide Gaussian

- parameters (parametrized in m_H) are fixed by fits to simulated samples

- background model

- choose functions with smallest number of parameters that have small signal bias in signal+background fits on background-only MC samples

- depend on category (low stats: exp, high stats: exp(pol2))

- background fit parameters profiled in fit

Same functions found for 2011, 2012

Direct limit on Higgs width

- convolute the signal model with Breit-Wigner distribution

H → γγ results

m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

at a signal strength μ(γγ) = 1.29 ± 0.30

observed width limit (95% C.L.): 5 GeV

(expected width limit at μ = 1: 6.2 GeV)

Systematic uncertainties depend on categories

γ energy scale	**0.2 – 0.7 GeV**
background	**0.06 – 0.25 GeV**
primary vertex	**0.04 GeV**

Comparison to previous result:

m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV (μ(γγ) = 1.55)

diff (old-new): 0.82 (central)/-0.22 (stat)/0.42 (syst)

<u>change in central value and systematic uncertainty</u>

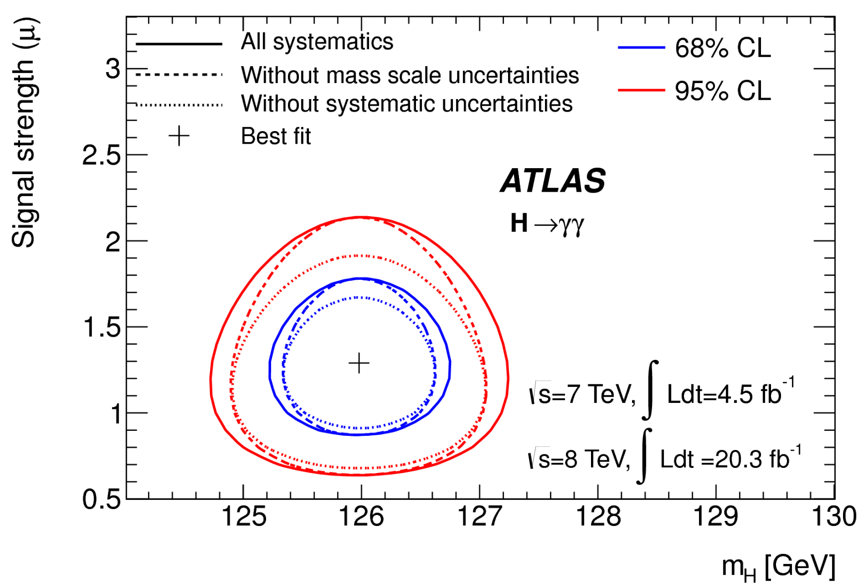
- improved calibration procedure

<u>change in stat uncertainty</u>

- dominant: smaller fitted signal strength

- changes in mass resolution

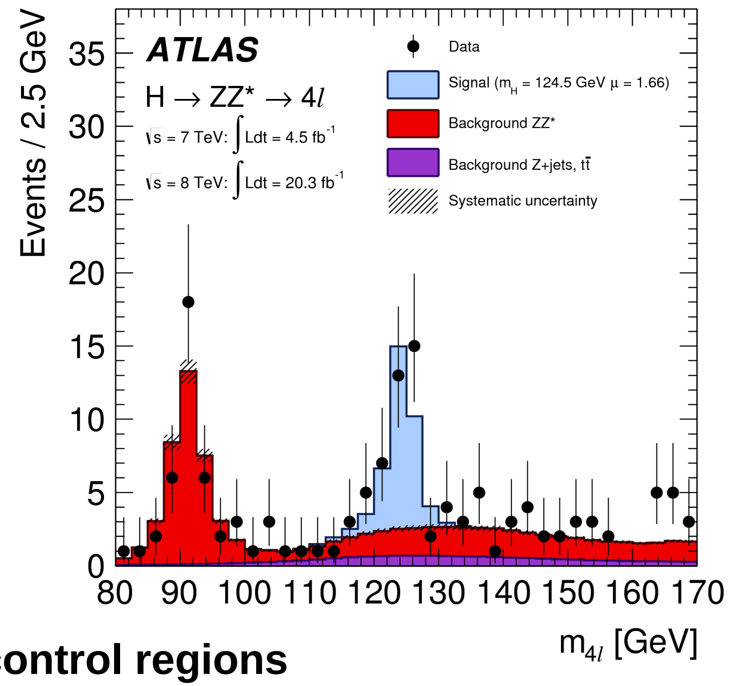
- changes in categorization



H → ZZ → 4l

- select events with 4μ, 2μ2e/2e2μ or 4e
  - μ: 20, 15, 10, 6 GeV
  - e: 20, 15, 10, 7 GeV
- mass resolution (Gauss σ)

  4μ: 1.6 GeV, 4e: 2.2 GeV
- signal/background ~ 2 (8 TeV analysis)



- background estimate
  - ZZ: simulated samples
  - tt̄/Z+jets: data-driven, extrapolate from control regions

NEW

- improvements to analysis strategy
  - multivariant discriminant (BDT) to separate ZZ and signal, variables:
    - transverse momentum, rapidity of 4l system
    - matrix element based kinematic discriminant (LO calculation)
  - multivariate electron identification (8 TeV data)
  - combined track momentum + cluster energy fit for electrons
  - improved electron resolution model for Z Mass constraint

    (kinematic fit to the first dilepton pair)
  - recovery of non-collinear final state radiation

H → ZZ → 4l

Mass measurement

- 2D unbinned maximum likelihood fit to m4l and BDT discriminant against ZZ background

- signal model based on templates from simulation

- simultaneous fit to 4 final states and 7/8 TeV center of mass energy

→ expected improvement of 8% in statistical uncertainty wrt 1D fit

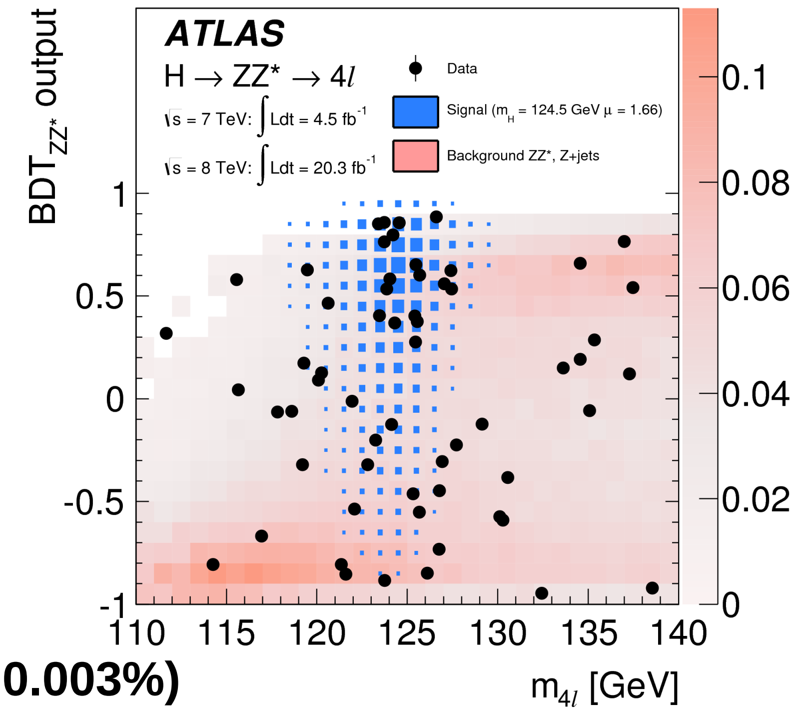
Cross-checks:

- 1D fit to m4l

- 2D fit with analytic description of the signal

- per-event mass resolution from expected detector response of the four individual leptons

- used for width limit



Systematic uncertainties dominated by

- μ momentum scale

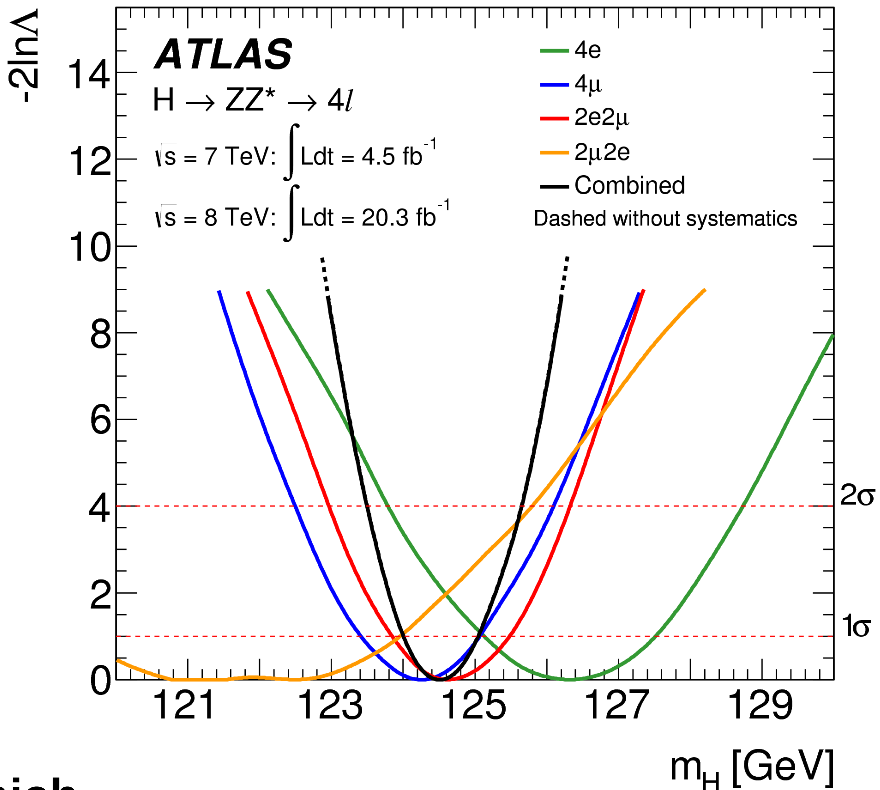
- electron energy scale (both about 0.03%, all other uncertainties < 0.003%)

H → ZZ → 4l results

m_H = 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV **$\mu(4l) = 1.66^{+0.45}_{-0.38}$**

→ completely dominated by statistical uncertainties

direct width limit (95% C.L.): 2.6 GeV (6.2 GeV expected)



Comparison to previous results:

m_H = 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

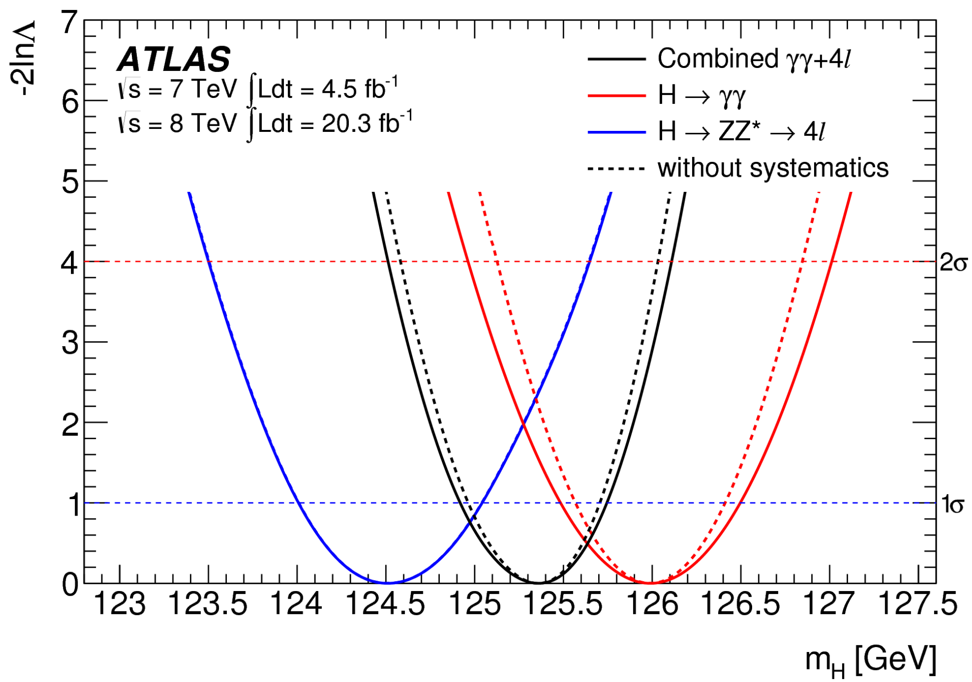
diff: -0.21 (central)/0.08,-0.02 (stat)/ 0.44,0.24 (syst)

Change in systematic uncertainty

- dominant: new material/calibration

- improvements to Z mass constraint which reduce the impact of the energy scale variations

Combined mass results



Dominating systematic uncertainties:

electron/photon calibration ~150 MeV

H → γγ background model ~ 40 MeV

primary vertex (γγ) ~ 20 MeV

muon momentum scale ~ 10 MeV

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

Supersedes results from 2013 publication (Phys. Lett. B 726):

$m_H = 125.49 \pm 0.34\ (\text{stat})\ ^{+0.50}_{-0.58}\ (\text{syst})$ GeV

diff (old-new): 0.13 (central)/-0.03 (stat)/0.32,0.4 (syst)

Compatibility check

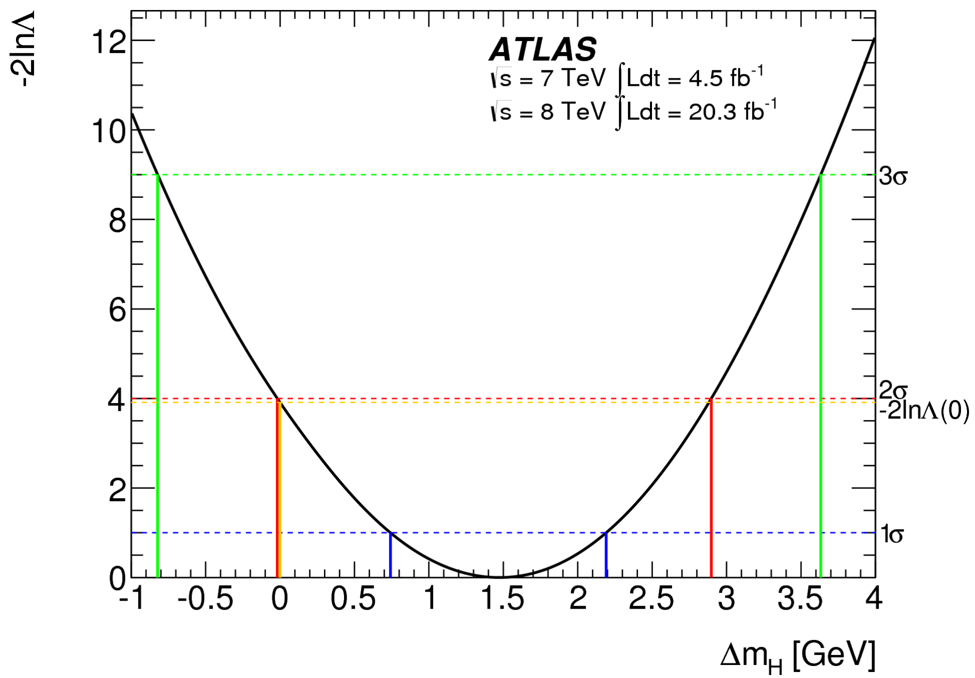
- parametrize likelihood it terms of

  $\Delta m_H = m_H(\gamma\gamma) - m_H(4l)$

- m_H and signal strengths are treated as nuisance parameters and profiled

→ correlations between measurements taken into account

→ the two measurements are compatible if Δm_H is compatible with 0



Compatibility between H → γγ and H → 4l results: ~5%, 2.0 σ

(2.5 σ in Phys. Lett. B 726)

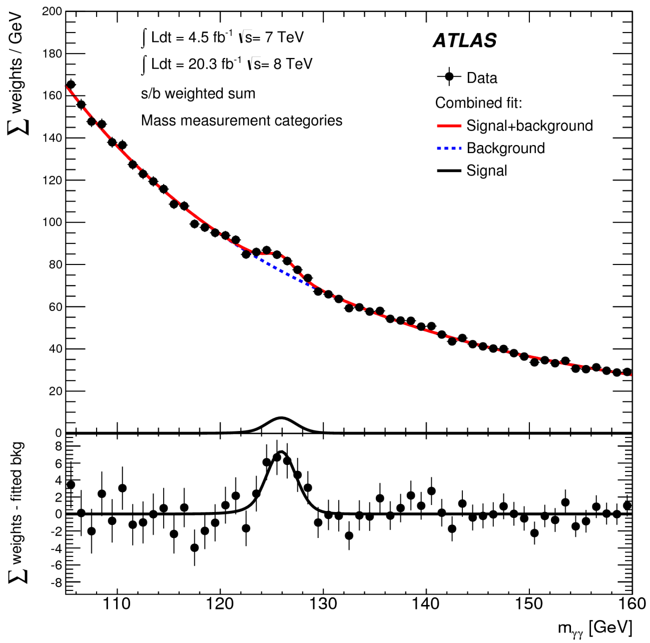
Conclusion

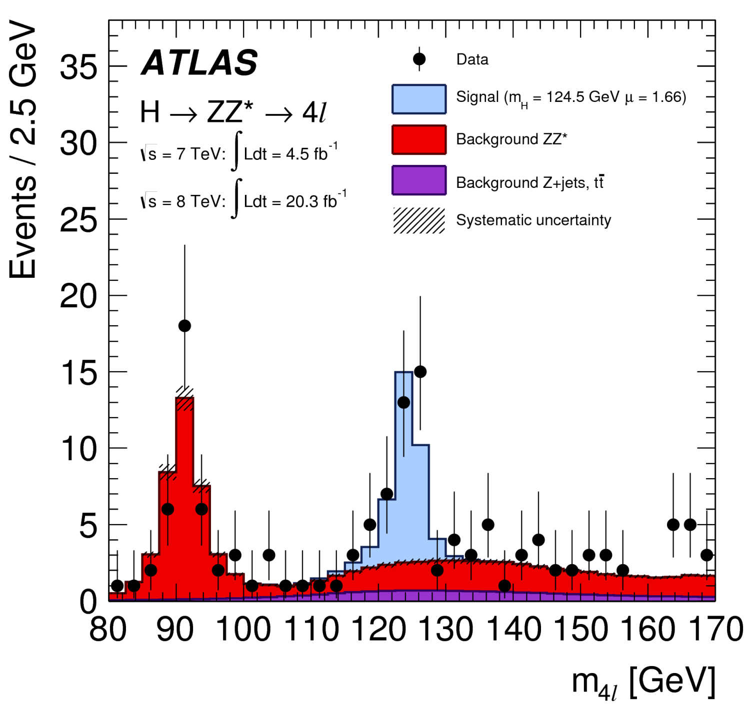
Updated measurement of the Higgs boson mass in the

H → γγ and H → ZZ → 4l channels with the ATLAS detector

- **improved detector material description**
- **improved electron/photon and muon calibration**
- **improved analysis methodologies**

---> reduction of systematic uncertainty on the mass by 60%





BACKUP

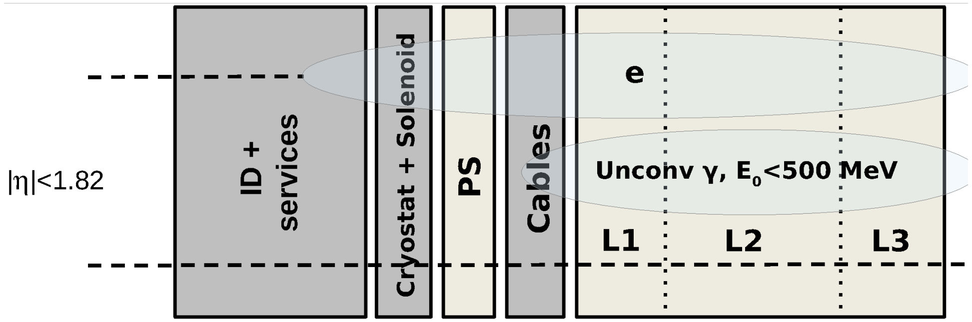
Backup: Improved material description

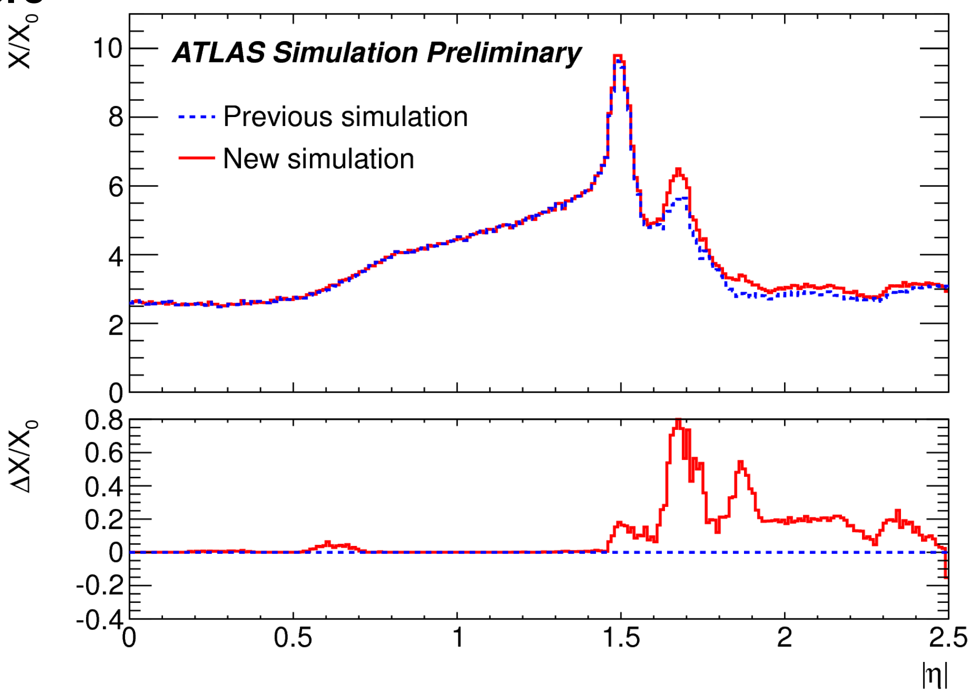
Problem: Need to estimate energy loss due to material in front of electromagnetic calorimeter

Step 1: Layer calibration using muons (not sensitive to detector material)

Step 2: Use showers from electrons and unconverted photons

- unconverted photons insensitive to ID material
- compare E1/E2 in data and simulation (vary detector material in simulation)
- most areas in which discrepancies were found are known to have approximate descriptions





Backup: E-p combination for electrons

Combine track momentum measurement with calorimeter energy to improve electron energy measurement

- ET < 30 GeV, |η| < 1.52

- if track and cluster measurements are consistent

- maximum likelihood fit of ET(track) and ET(cluster) with PDFs obtained as ET(track)/ET(truth) and ET(cluster)/ET(truth)

- electrons are categorized according to ET, η and Bremsstrahlung loss

→ 4% resolution improvement in H → 4e channel, reduction of tails

Backup: 4l expected/observed events

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
$2\mu2e$	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
$2\mu2e$	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
$2\mu2e$	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

Backup: H → ZZ → 4l, Z mass resolution

Z mass resolution

- cluster energy – track momentum measurement combination for electrons

  - improves 4l resolution in electron channels by about 4%

- final state photon radiation is well modelled

  - final state recovery (add at most one photon to event)

    - for collinear to leading dimuon pairs

    - for un-collinear to leading dimuon and dielectron pairs

- kinematic fit to the leading dilepton pair

  - constrains to Z pole mass, within experimental resolution

  →improves four-lepton mass resolution by ~15%

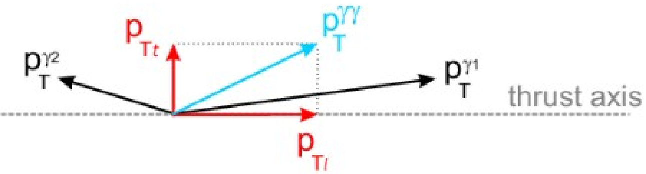
Backup: H → γγ categories

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 $H \rightarrow \gamma\gamma$ 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

Central: Both photons are within $|\eta| < 0.75$
Transition: At least one photon in $1.3 < |\eta| < 1.75$

p_{Tt} : Component of diphoton transverse momentum orthogonal to the diphoton thrust axis in the transverse plane

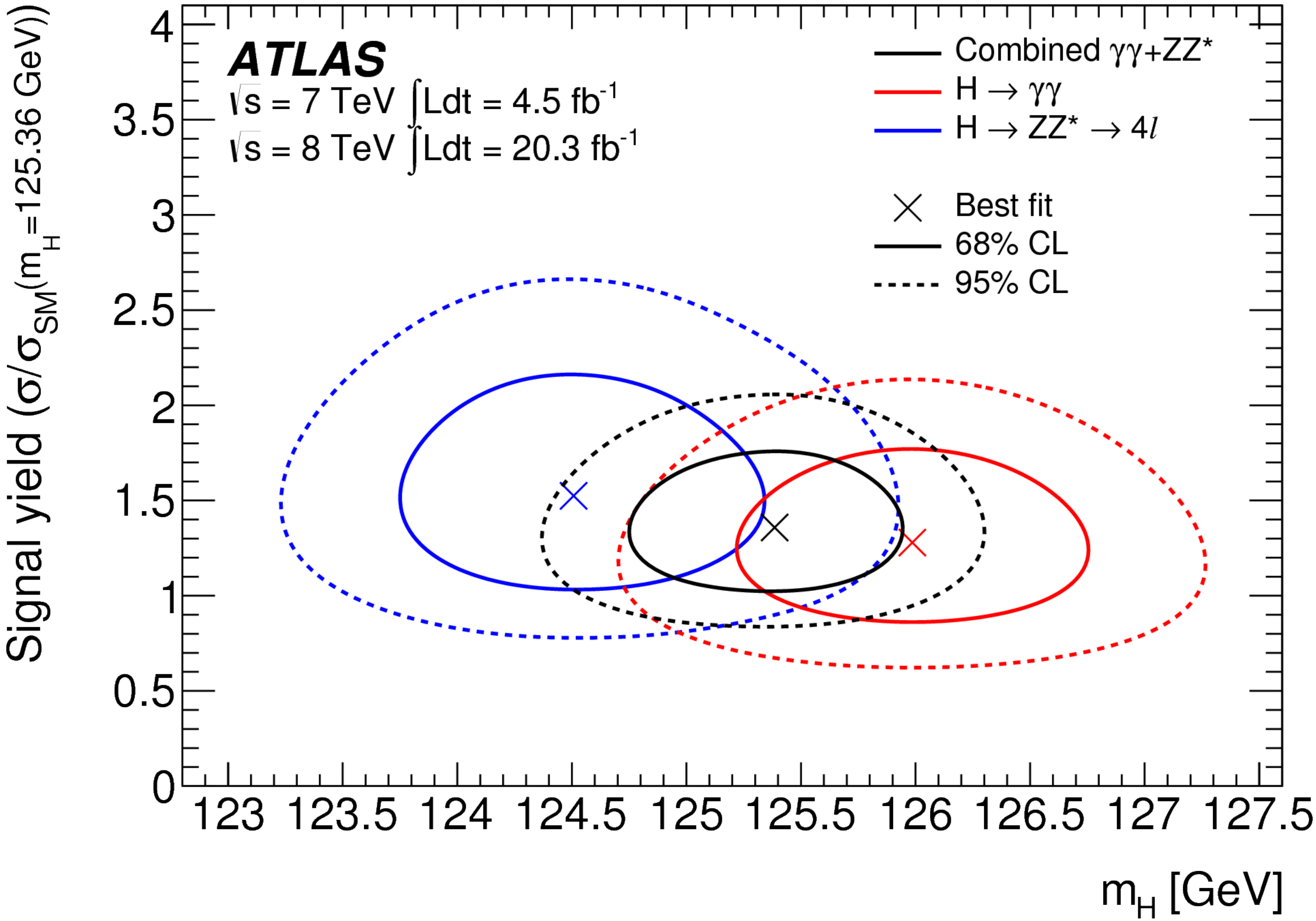


Backup: H → γγ uncertainties

Table 2: Summary of the relative systematic uncertainties (in %) on the $H \to \gamma\gamma$ mass measurement for the different categories described in the text. The first seven rows give the impact of the photon energy scale systematic uncertainties, grouped into seven classes.

	Unconverted					Converted				
	Central		Rest		Trans.	Central		Rest		Trans.
Class	low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}		low p_{Tt}	high p_{Tt}	low p_{Tt}	high p_{Tt}	
$Z \to e^+e^-$ calibration	0.02	0.03	0.04	0.04	0.11	0.02	0.02	0.05	0.05	0.11
LAr cell non-linearity	0.12	0.19	0.09	0.16	0.39	0.09	0.19	0.06	0.14	0.29
Layer calibration	0.13	0.16	0.11	0.13	0.13	0.07	0.10	0.05	0.07	0.07
ID material	0.06	0.06	0.08	0.08	0.10	0.05	0.05	0.06	0.06	0.06
Other material	0.07	0.08	0.14	0.15	0.35	0.04	0.04	0.07	0.08	0.20
Conversion reconstruction	0.02	0.02	0.03	0.03	0.05	0.03	0.02	0.05	0.04	0.06
Lateral shower shape	0.04	0.04	0.07	0.07	0.06	0.09	0.09	0.18	0.19	0.16
Background modeling	0.10	0.06	0.05	0.11	0.16	0.13	0.06	0.14	0.18	0.20
Vertex measurement	0.03									
Total	0.23	0.28	0.24	0.30	0.59	0.21	0.25	0.27	0.33	0.47

Backup: Likelihood contour



Backup: Comparison Atlas CMS

ATLAS : 125.98 ± 0.42 ± 0.28 GeV

CMS : 124.70 ± 0.31 ± 0.15 GeV

Difference ~ 2.1 σ

Differences in systematic uncertainties

- CMS has different EM calo system:

- no cryostat in front

- better Er resolution

- crystals that are sensitive to aging and need time-dependent calibrations

- no longitudinal segmentation (worse for pointing but easier to calibrate crystals)

- CMS less conservative in yy channel?

Would like to see scale validation plots

Backup: H → γγ primary vertex selection

- primary vertex selection using multivariate technique
    - diphoton vertex position from photon pointing
    - information on additional tracks in event
        - tracks from photon conversions
        - sum p_T of tracks
        - sum p_T^2 of tracks
        - azimuthal angle between combined photon system and the combined track system in transverse plane
- 93% within 15 mm of true vertex

→ opening angle resolution significantly smaller than energy resolution in mass calculation

Backup: Updates to analyses and expected changes

m_H = 125.98 ± 0.42 (stat) ± 0.28 (syst) GeV

m_H =126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

diff (old-new): 0.82 (central)/-0.22 (stat)/0.42 (syst)

1) H → yy

Updates

- new photon calibration

- new categorization

Changes in central value

- expected from calibration: -0.45 +/- 0.35

Changes in statistical uncertainty

- smaller fitted signal yield

- (smaller extend: categorization, resolution)

- expected stats uncertainty for μ = 1: 0.45 GeV

Changes in systematic uncertainties

- improved photon calibration

Backup: Updates to analyses and expected changes

2) H → ZZ → 4l

m_H = 124.51 ± 0.52 (stat) ± 0.06 (syst) GeV

$m_H = 124.3\,^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

diff: -0.21 (central)/0.08,-0.02 (stat)/0.44,0.24 (syst)

Updates

- **multivariant discriminant (BDT) to separate ZZ and signal, variables:**
  - **transverse momentum, rapidity of 4l system**
  - **matrix element based kinematic discriminant (LO calculation)**

→ 2D fit for mass extraction

- **multivariate electron identification**
- **combined track momentum + cluster energy fit for electrons**
- **improved electron resolution model for Z Mass constraint (kinematic fit to the first dilepton pair)**
- **recovery of non-collinear final state radiation**

<u>Changes in central value</u>

- **expected from 1D → 2D: 250 MeV (pseudo-experiments)**

<u>Changes in statistical uncertainty</u>

- **expected 8% improvement through 2D fit**

<u>Changes in systematic uncertainties</u>

- **updated calibration, better resolution model in Z mass constraint**