Precision Measurement of the Higgs Boson Mass in Decays into Four Leptons with the ATLAS Detector

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$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

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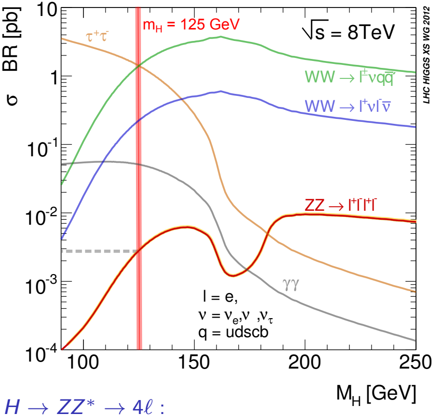
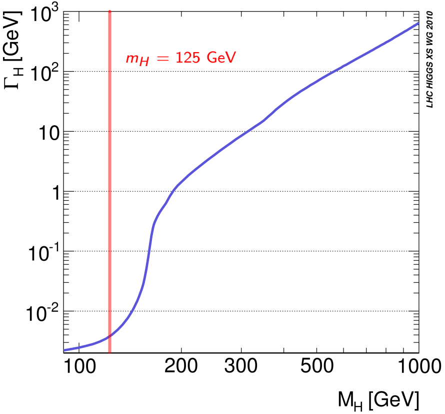
Why Measure the Higgs Boson Mass Precisely?

- m_H is a free parameter and not predicted by the Standard Model.
- But m_H is needed to predict production and decay rates of the Higgs boson.
- Precise measurement of m_H is important to check self-consistency of the SM (stability of the electroweak vacuum).

Decay of the Standard Model Higgs Boson

Discovery of the Higgs boson with $m_H \approx 125$ GeV.



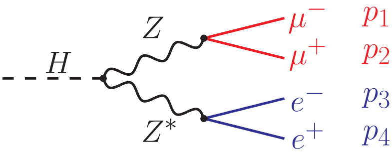


$H \to ZZ^* \to 4\ell$:

- Rare decay channel: $\sigma \times BR \approx 2$ fb.
- Benefits from a good signal to background ratio.
- Contributed to the discovery of the Higgs boson!

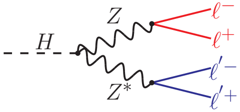
- $\Gamma_H(m_H = 125 \text{ GeV}) \approx 4$ MeV.
- Measured decay width is completely determined by the detector resolution ($\sigma = 2$ GeV).

The $H \to ZZ^* \to 4\ell$ Decay Channel



- $m_H < 2m_Z$: one on-shell and one off-shell Z boson.
- Background contribution depends on the flavour of the leptons in the final state.
- Four different final states: 4μ, $4e$, $2e2\mu$ and $2\mu 2e$.

- **2 same-flavor and oppositely charged muon or electron pairs from a common vertex.**



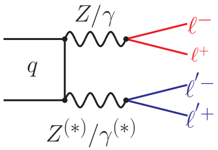
muons: $p_T > 6$ GeV | **electrons:** $E_T > 7$ GeV

muons: $|\eta| < 2.7$ | **electrons:** $|\eta| < 2.47$

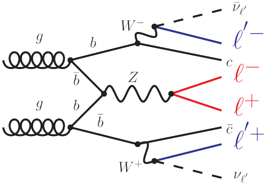
- Require **isolated leptons** (not inside jets).
- Leading lepton pair from an on-shell Z boson: $50\ \text{GeV} < m_{12} < 106\ \text{GeV}$.

Background Processes

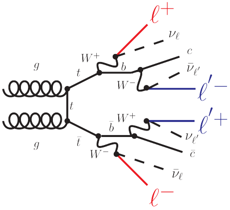
irreducible:
SM ZZ^* continuum
Estimated from MC



reducible:
$Z + b\bar{b}$ / Z+jets
Estimated from data



reducible:
$t\bar{t}$ production
Estimated from data

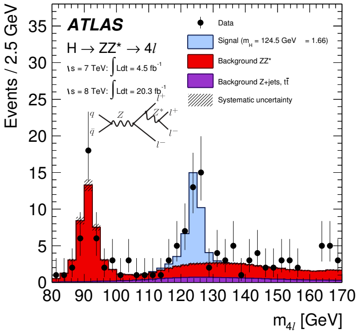


Results of the Selection

Analysis based on 2011 and 2012 LHC *pp* collision data corresponding to 4.5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV.

	Expected signal	ZZ^*	Z + jets, $t\bar{t}$	Observed
Total	16.2 ± 1.6	7.41 ± 0.40	2.95 ± 0.33	37

for 120 GeV $< m_H <$ 130 GeV



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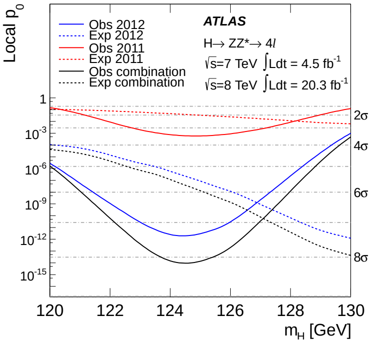

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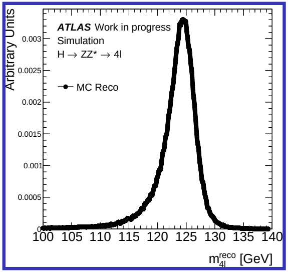
- p_0 value: probability that signal is caused by background fluctuations.
- Observation of an excess of 8.2 σ at $m_H = 124.5$ GeV.

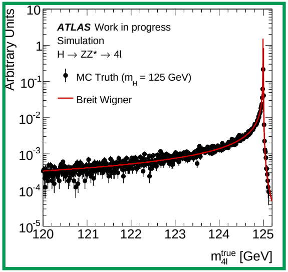
Measurement of the Higgs Boson Mass

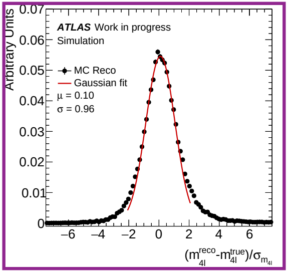
The Higgs boson mass can be measured with high precision from the four-lepton invariant mass spectrum.

Measured $m_{4\ell}$ spectrum = Mass distribution at generator level * mass resolution function

$$\mathcal{F}(m_{4\ell}^{\text{rec}}) = \int_0^\infty \mathcal{G}(m_{4\ell}^{\text{true}}, m_H)\,\mathcal{R}(m_{4\ell}^{\text{reco}}, m_{4\ell}^{\text{true}}, \sigma_{m_{4\ell}})\,\mathrm{d}m_{4\ell}^{\text{true}}.$$







- $\mathcal{G}(m_{4\ell}^{\text{true}}, m_H)$ is determined from MC simulation at generator level.

→ Large tails due to final state radiation.

- $\mathcal{R}(m_{4\ell}^{\text{reco}}, m_{4\ell}^{\text{true}}, \sigma_{m_{4\ell}})$ is approximated by a Gaussian: $\frac{1}{\sigma_{m_{4\ell}}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{m_{4\ell}^{\text{reco}} - m_{4\ell}^{\text{true}}}{\sigma_{m_{4\ell}}}\right)^2}$.
- m_H is the only free parameter!
- $\sigma_{m_{4\ell}}$ needs to be determined in the following.

The achievable precision of the m_H measurement is limited by $\sigma_{m_{4\ell}}$.
The four-lepton invariant mass is given by

$$m_{4\ell} = \sqrt{\sum_{i=1}^{3} \sum_{j>i}^{4} 2E_i E_j (1 - \cos\vartheta_{ij})}.$$

- $\sigma_{m_{4\ell}}$ can in principle be calculated:

$$\sigma_{m_{4\ell}} = \frac{1}{2m_{4\ell}} \cdot \sqrt{\sum_{i=1}^{4} \left(\sum_{j=1, j\neq i}^{4} 2E_j (1 - \cos\vartheta_{ij}) \right)^2 \cdot \sigma_{E_i}^2}.$$

- ϑ_{ij} is the angle between $\vec{p}_i$ and $\vec{p}_j$.
- Angles are measured with very high precision.

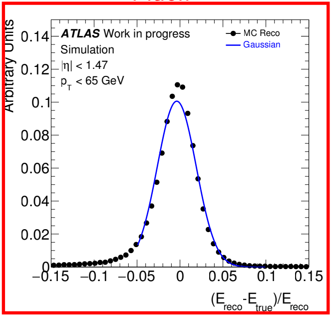
$\Rightarrow$ $\sigma_{m_{4\ell}}$ is dominated by the error of E_i.

- Energy resolution depends on the detector region (η, ϕ) and of the p_T of the lepton.

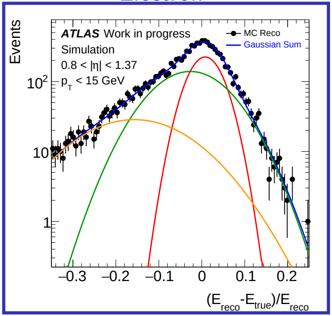
Lepton Energy Resolution Functions

- Lepton energy resolution functions are determined from MC simulation, as a function of η, ϕ and p_T.

Muon



Electron



Distribution can be described by a simple Gaussian.

Large tails caused by radiative energy loss. Distribution can be described by a sum of 3 Gaussians.

Improvement of the Mass Resolution: Z Mass Constraint

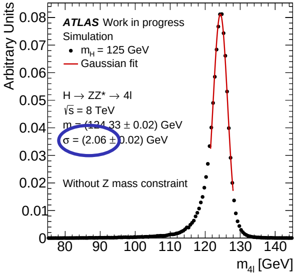
The Z mass constraint is implemented by a kinematic fit to the Z resonance (m_Z, Γ_Z):

$$L(\epsilon_k; E_k^{\text{reco}}) = \frac{N}{(\mu_{12}^2 - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \times \prod_{k=1}^{2} \mathcal{R}_k(E_k^{\text{reco}}, \epsilon_k)$$

Breit-Wigner function × Lepton energy resolution functions

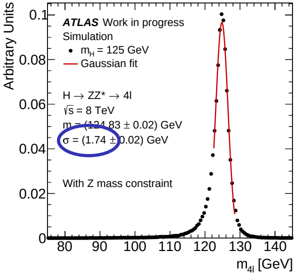
- Two free parameters: $\epsilon_{1,2}$ determined for each event.
- $\mu_{12} = \sqrt{2\epsilon_1\epsilon_2(1 - \cos\vartheta_{12})}$ constrained mass of the leading lepton pair.

Without Z mass constraint



Gain of about 15% in resolution.

With Z mass constraint



$\Longrightarrow$ $\sigma_{m_{4\ell}}$ can be improved by using the Z mass constraint.

Determination of $\sigma_{m_{4\ell}}$ Event-by-Event

$$L(\epsilon_k; E_k^{\text{reco}}) = \frac{N}{\left(\mu_{12}^2 - m_Z^2\right)^2 + m_Z^2 \Gamma_Z^2} \times \prod_{k=1}^{2} \mathcal{R}_k(E_k^{\text{reco}}, \epsilon_k)$$

- Use energy - momentum relation to eliminate ϵ_2.

$\Longrightarrow$ Two free parameters: ϵ_1 and $\mu_{4\ell}$.

Resulting in

- an estimate of $\mu_{4\ell}$ for each event i with an improved resolution: $\mu_{4\ell,i}$.
- an event-by-event mass error $\sigma_{m_{4\ell},i}$.
- an improved precision in the m_H measurement by using per-event mass errors.

Measurement of the Higgs Boson Mass: ATLAS Data

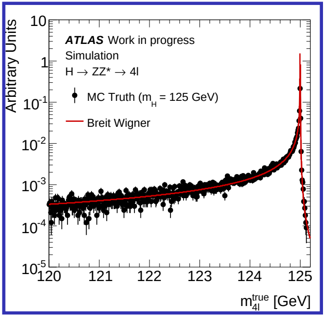
Maximum likelihood fit to the measured $m_{4\ell}$-spectrum:

$$L(m_H, n_{\text{sig}}, n_{\text{bkg}}) = \prod_i^{\#\text{events}} \int_0^{\infty} \mathcal{G}(m_{4\ell}^{\text{true}}, m_H)\mathcal{R}(\mu_{4\ell,i}, m_{4\ell}^{\text{true}}, \sigma_{m_{4\ell},i})\text{d}m_{4\ell}^{\text{true}}.$$

- $\mathcal{R}(\mu_{4\ell,i}, m_{4\ell}^{\text{true}}, \sigma_{m_{4\ell},i})$ mass resolution function is approximated by a Gaussian.
- $\mathcal{G}(m_{4\ell}^{\text{true}}, m_H)$ is the linear combination of the signal and the background mass distributions:

$$\mathcal{G}(m_{4\ell}^{\text{true}}, m_H) = [n_{\text{sig}} \cdot \mathcal{G}_{\text{sig}}(m_{4\ell}^{\text{true}}, m_H) + n_{\text{bkg}} \cdot \mathcal{G}_{\text{bkg}}(m_{4\ell}^{\text{true}})]$$

- n_{sig} (n_{bkg}) number of signal (background) events.



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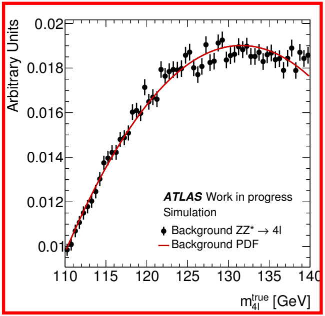
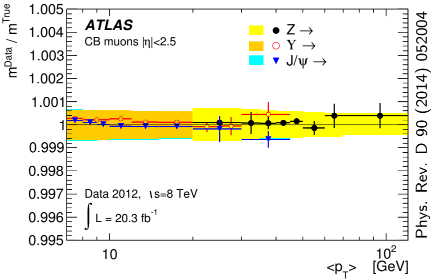
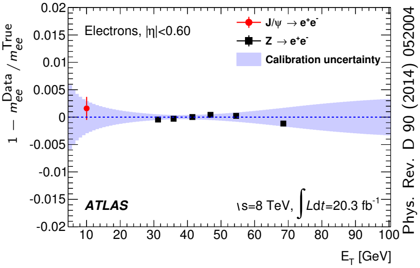


- Systematic uncertainties: dominated by the lepton energy scale uncertainties.
- Minimized uncertainties due to huge effort of the MPP group!
- Energy scale is calibrated and validated using known resonances $Z, J/\Psi$ and Υ.



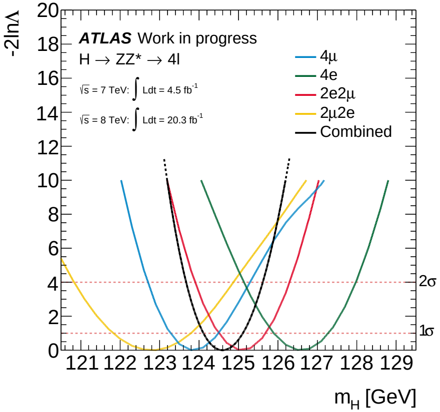


Very small systematic uncertainties on m_H: $\pm 0.03\% \,\widehat{=}\, \pm 60$ MeV.

Results of the Mass Measurement

Method is applied to the recorded 2011 and 2012 ATLAS datasets.
Independent measurement of m_H for all four final states.

	$m_H \pm \Delta_{m_H}^{\text{stat.}}$ [GeV]
4μ	$123.90^{+0.65}_{-0.57}$
$4e$	$126.60^{+0.71}_{-0.69}$
$2e2\mu$	$125.01^{+0.59}_{-0.59}$
$2\mu 2e$	$122.80^{+0.99}_{-0.98}$
Combined	$124.58^{+0.53}_{-0.47}$



- Best resolution for 4μ and $2e2\mu$.
- Poorer resolution for $2\mu 2e$: low energy electrons.

- Very precise measurement of the Higgs boson mass:

$$m_H = 124.58^{+0.53}_{-0.47}(\text{stat.}) \pm 0.06(\text{syst.})\ \text{GeV}.$$

$\Longrightarrow$ Precision of the measurement is 0.4%!

Model Independent Constraint on the Higgs Width

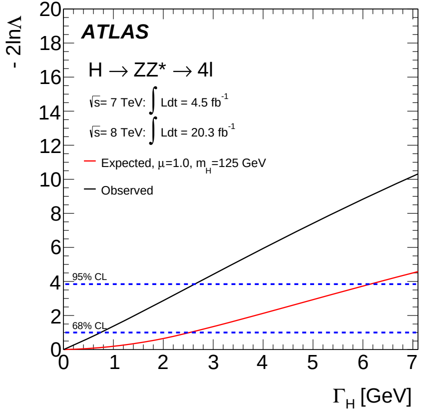
$$\mathcal{G}(m_{4\ell}^{\text{true}}, m_H, \Gamma_H) = [n_{\text{sig}} \cdot \mathcal{G}_{\text{sig}}(m_{4\ell}^{\text{true}}, m_H, \Gamma_H) + n_{\text{bkg}} \cdot \mathcal{G}_{\text{bkg}}(m_{4\ell}^{\text{true}})]$$

- The method can be used to set an upper limit on the Higgs decay width.
- Γ_H was added as a free parameter to the fit, while fixing m_H to the measured value.

$\Gamma_H < 2.6$ GeV at 95%CL

Expected limits:

- $\Gamma_H < 6.2$ GeV for $\mu = 1.0$
- Upper limit on Γ_H is stronger than the expected due to slight excess in number of signal events compared to SM prediction.



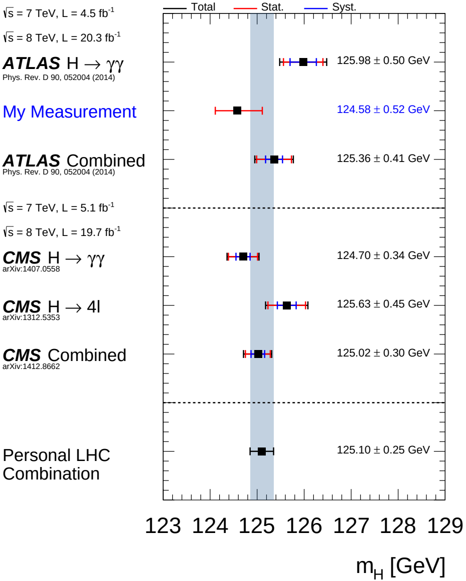
Measured Γ_H already allows to exclude several theories beyond the SM!

Summary

- High precision measurement of m_H with ATLAS run 1 data.
- Per-event mass errors and the Z mass constraint increase the precision.
- Very small systematic uncertainties on m_H, due to extensive callibration effort in contrary to CMS.
- Attainable precision in $H \to 4\ell$ is mainly limited by statistics.

  But the precision is already on the 0.4% level!

  Combined m_H measurement: precision is 0.2%!
- Due to statistical limitation: further data taking will improve the results.



Backup

The symmetry is spontaneously broken by choosing one particular ground state

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix},$$

with the $v = \sqrt{\frac{-\mu^2}{2\lambda}} \approx 246$ GeV the vacuum expectation value. Field excitations from the ground state can be parametrized in the unitary gauge as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix},$$

with the Higgs field H. The masses of the weak gauge bosons and of the Higgs boson are given by

$$m_W = \frac{g \cdot v}{2},\ m_Z = \frac{m_W}{\cos\theta_W} \text{ and } m_H = \sqrt{2\lambda v^2} = \sqrt{-2\mu^2}.$$

The fermion masses are generated via Yukawa couplings:

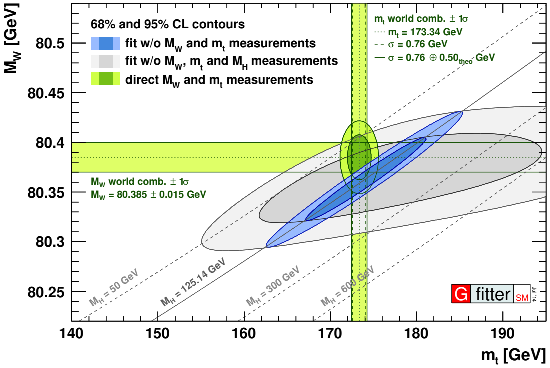
$$m_f = \frac{\lambda_f v}{\sqrt{2}},$$

with λ_f the fermion coupling constants.

Importance of the Higgs Boson Mass

Precise measurement of m_H

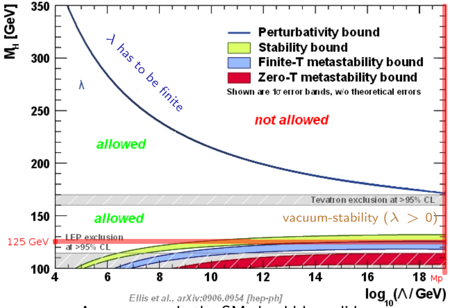
- is needed as the SM does not predict the mass of the Higgs boson.
- in order to predict production and decay properties of the Higgs boson.
- is essential to check self-consistency of the SM.
  - $\Rightarrow$ Indirect determination of m_W and m_t.

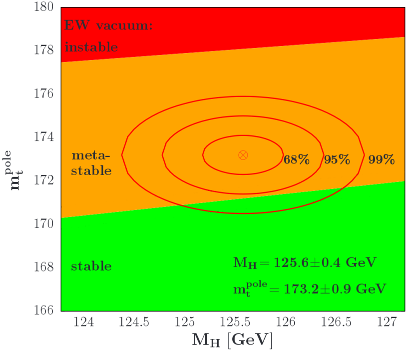


- Knowledge of m_H improves the SM predictions of several EW parameters.

Role of the Higgs Boson Mass

Theoretical bounds for m_H from self-consistency arguments of the SM



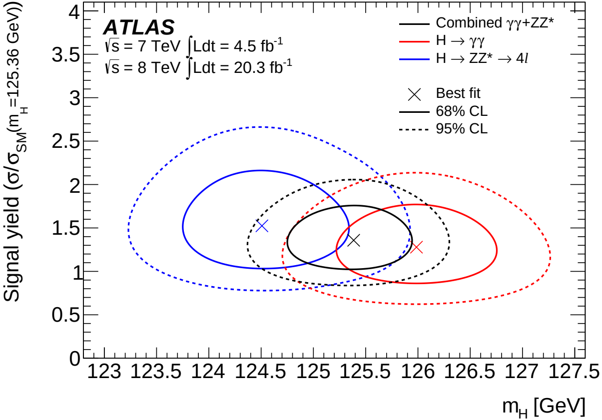


Λ: energy-scale the SM should be valid.

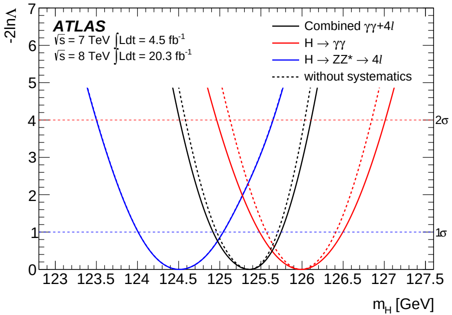
- SM is valid up to $\Lambda = \mathcal{O}(1\ \text{TeV})$ then $m_H \approx 50 - 730$ GeV.
- SM is valid up to $\Lambda = \mathcal{O}(\text{M}_{\text{Planck}})$ then $m_H \approx 130 - 175$ GeV.

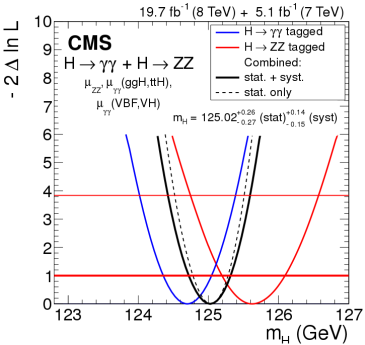
Meta-stable universe? New physics above $\Lambda > 1$ TeV?

Comparison of the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ Results



The results agree within 1.92σ.





ATLAS:

$$m_H = 124.58^{+0.53}_{-0.47}(\text{stat.}) \pm 0.06(\text{syst.})\ \text{GeV}.$$

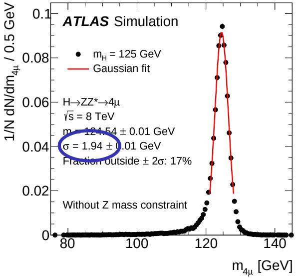
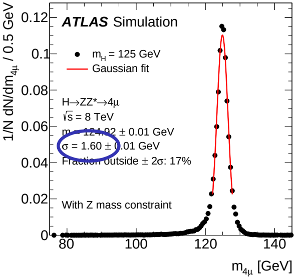
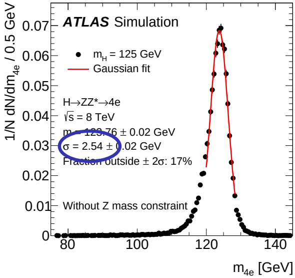
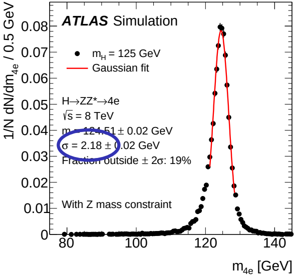
CMS:

$$m_H = 125.6 \pm 0.4(\text{stat.}) \pm 0.2(\text{sys.})\ \text{GeV}.$$

- Statistical uncertainties nearly the same.
- Systematic uncertainties on the Higgs boson mass greatly reduced in the latest ATLAS results.

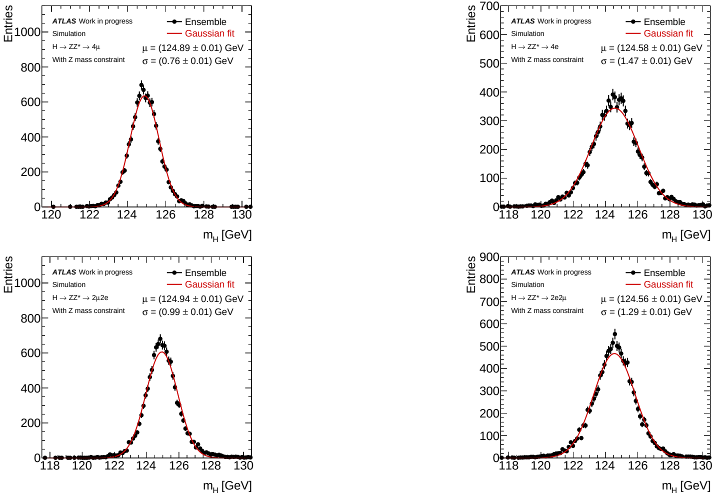
⇒ Leading contribution of the MPP.

Effect of the Z Mass Constraint

	Without Z mass constraint		With Z mass constraint
4μ		Gain of about 15% in resolution	
$4e$		Gain of about 18% in resolution	

Validation of the Event-by-event Method: Ensemble Test

MC events are grouped in ensembles, size correspond to the number of events in data. The Higgs boson mass is measured for several ensembles and for each sub-channel.

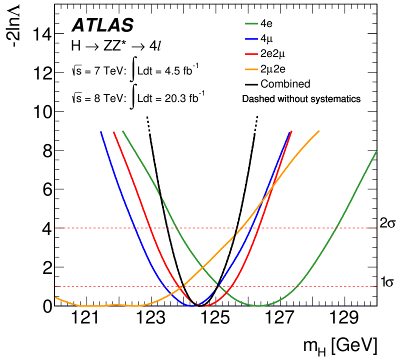


- Small bias in the used method: $\mu_{4\ell}$ is corrected for the mass measurement for ATLAS data.

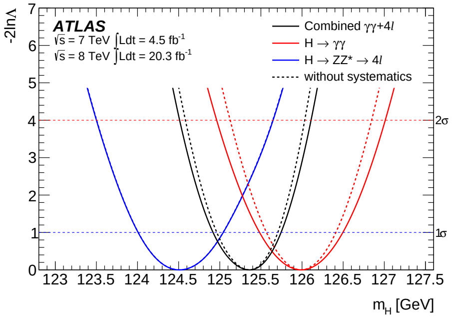
MC template method

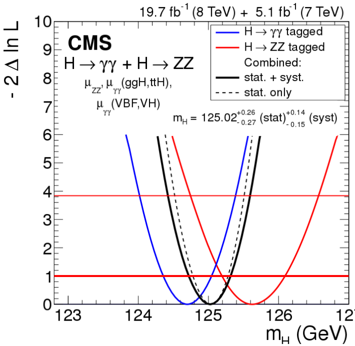
- MC template-based PDFs of $m_{4\ell}^{rec}$ at different m_H are used to obtain the best fit value of m_H.
- 1D method uses a single observable: $m_{4\ell}^{rec}$ (for validation).
- 2D method uses two observables: $m_{4\ell}^{rec}$ and BDT (baseline method).
- Uncertainties are dominated by statistics.
- Systematic uncertainties are due to $\sigma(E_{i,j})$ and the scale energy/momentum scale uncertainties.

The scan of the profile likelihood, $-2\ln\Lambda(m_H)$, as a function of m_H.



$$m_H = 124.51 \pm 0.52(\text{stat.}) \pm 0.06(\text{sys.})\ \text{GeV}$$



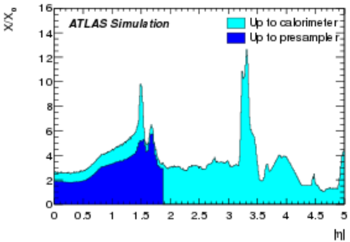


ATLAS Combination:

$$m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.06(\text{sys.})\ \text{GeV}.$$

CMS Combination:

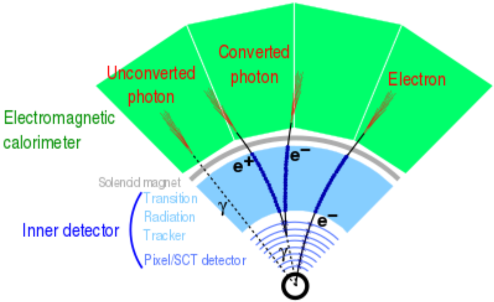
$$m_H = 125.02^{+0.26}_{-0.27}(\text{stat.}) \pm 0.14(\text{sys.})\ \text{GeV}.$$



- Large amount of material in front of the electromagnetic calorimeter ($\sim 2X_0$).

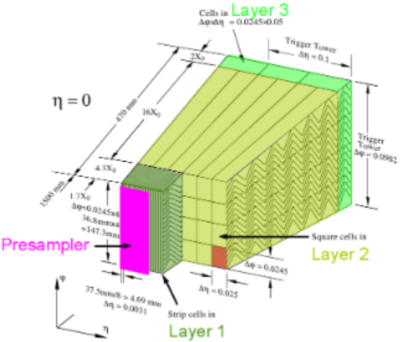
⇒ Non-neglible probability of $\gamma \rightarrow e^+e^-$ conversions before the calorimeter.

⇒ 3 topologies have to be considered:



Initial Calibration of the $e\gamma$ Energy Scale

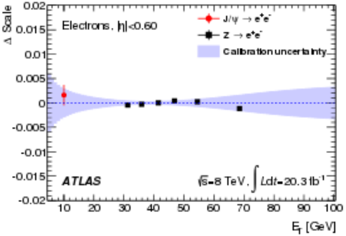
- $E_{e/\gamma}$= sum of the energies of the calorimeter cells associated to the e/γ corrected for energy loss due to absorption in the passive material and leakage outside the cluster.
- Previous calibration of the energy measurement:
  1. Gain of the individual amplifiers determined periodically with test pulses.
  2. Simulation and test-beam based corrections.
  3. Energy scale correction derived from $Z \rightarrow e^+e^-$ decays.
- A more advanced calibration strategy has been adopted for the updated Higgs mass measurement (see next slide).

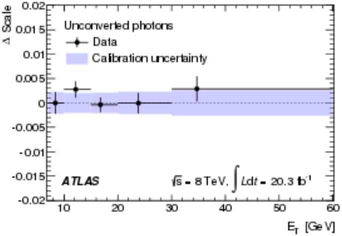


1. Cell energy calibration with test pulses
2. Intercalibration of the different calorimeter layers
   - No muon energy loss before the ECAL.
   - ⇒ Intercalibration of layers 1 to 3 with muons from Z decays.
   - Relative calibration of the presampler with electrons as a function of the longitudinal shower development in the ECAL.
3. Determination of the material in front of the EM calorimeter
   - Measurement of the material between the presampler and the first layer with unconverted photons as a function of the longitudinal shower development.
   - Integral material in front of the presampler is extracted from the difference of electron and unconverted photon longitudinal shower profiles.
4. Global calorimeter energy scale adjustment with $Z \to e^+e^-$ events

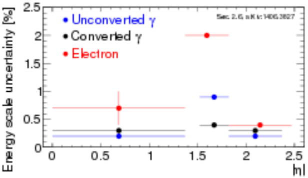
Checks of the e/γ energy scale

- $J/\psi \to e^+e^-$ probes the electron energy scale at low $E_T \sim 7\dots35$ GeV.
- $Z \to \ell^+\ell^-\gamma$ probes the photon energy scale for $E_T \sim 30$ GeV.





Total energy scale uncertainties

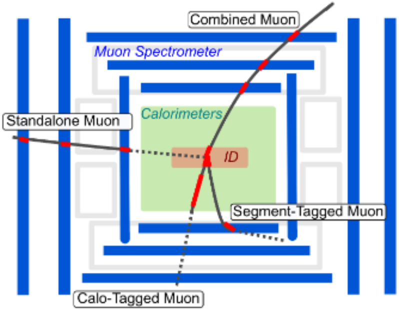


Main source of the scale uncertainties

- Non-linearity of the E measurement at cell level: $\sim 0.1\%$.
- Relative calibration of the different calorimeter layers: $\sim 0.1\%$.
- Material in front of the calorimeter: $0.1\dots0.3\%$.

Muon Reconstruction

Muon types



Energy/momentum measurements

- Calo- and segment tagged muons:

$$p_{muon} = p_{ID}.$$

- Stand-alone muons:

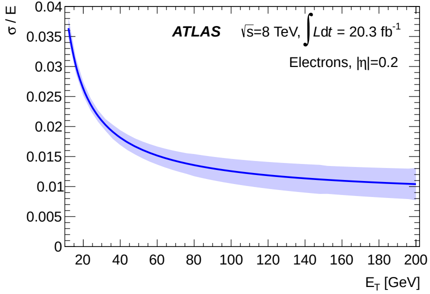
$$p_{muon} = p_{MS} + E_{loss}.$$

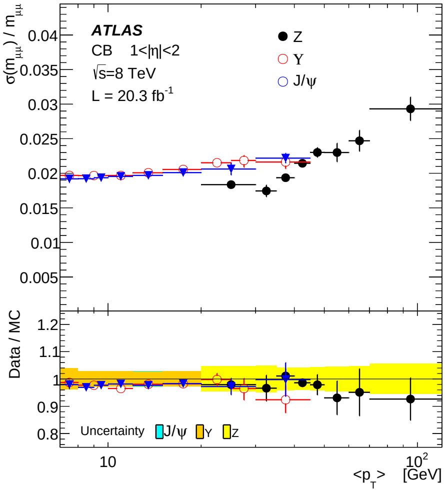
- Combined mouns:

$$p_{muon} = \text{Combination}(p_{ID}, p_{stand-alone}).$$

⇒ Calibrating the momentum scale only with $Z \to \mu^+\mu^-$ data does not reduce the uncertainty of the energy loss correction.

⇒ New calibration uses $Z \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decays.


ATLAS
√s=8 TeV, ∫Ldt = 20.3 fb-1
Electrons, |η|=0.2
σ / E
E_T [GeV]
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
20
40
60
80
100
120
140
160
180
200


ATLAS
CB 1<|η|<2
√s=8 TeV
L = 20.3 fb-1
Z
Υ
J/ψ
σ(m_μμ) / m_μμ
Data / MC
Uncertainty
J/ψ
Υ
Z
<p_T> [GeV]
10
10^2
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
1.2
1.1
1
0.9
0.8

Systematic Uncertainties on the Combined Mass

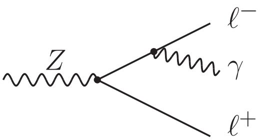
Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell nonlinearity (layer 2)	60
LAr cell nonlinearity (layer 1)	30
LAr layer calibration (barrel)	50
Presampler energy scale (barrel)	20
ID material model ($\|\eta\|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

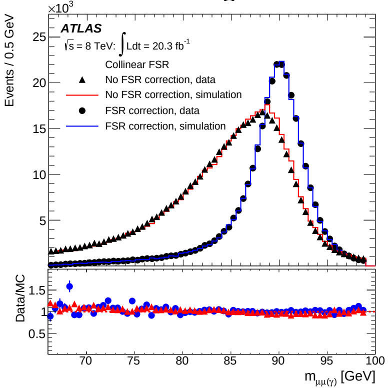
Final State Radiation

- Final state radiation (FSR) reduces the lepton energy.
- FSR photons are predominantly produced collinearly with the emitting lepton direction.
- Measured electron energy contains the energy of the photon.
- Measured muon energy does not contain the energy of the FSR photon.

$\Longrightarrow$ Recover the E_T from photons emitted by leptons.

- Invariant mass of events with a FSR photon is shifted to higher values.





Asymmetric Breit Wigner

$$\mathcal{F}_{\mathrm{BW}} = N \cdot \begin{cases} \frac{1}{2\pi} \frac{\Gamma}{(x-\mu)^2 + \frac{\Gamma^2}{4}}, & \text{for } \frac{x-\mu}{\Gamma} > -\alpha \\ A \cdot (B - \frac{x-\mu}{\Gamma})^{-n}, & \text{for } \frac{x-\mu}{\Gamma} \leq -\alpha \end{cases}.$$

Breit Wigner function has to be a continuous and differentiable function:

$A = \frac{2^{1-3n}}{\pi\Gamma} \frac{(\frac{n}{\alpha} + 4\alpha n)^n}{1+4\alpha^2}$ and $B = \frac{n}{2\alpha}(\alpha^2 + 1/4) - \alpha$.

α and n are fitted.