Measurement of the Higgs boson mass with the ATLAS detector

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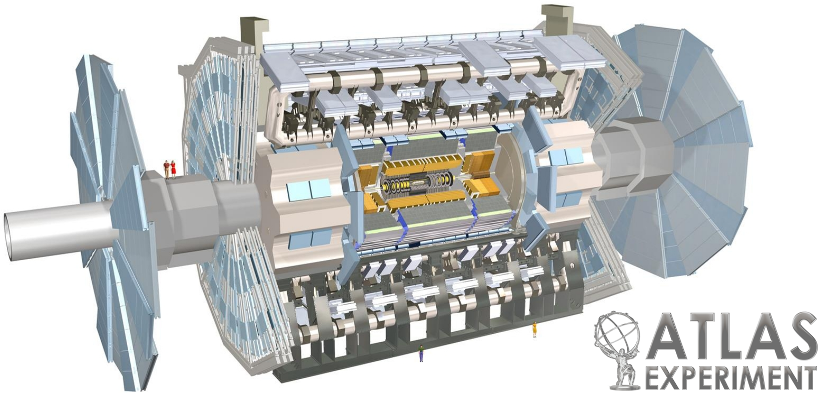
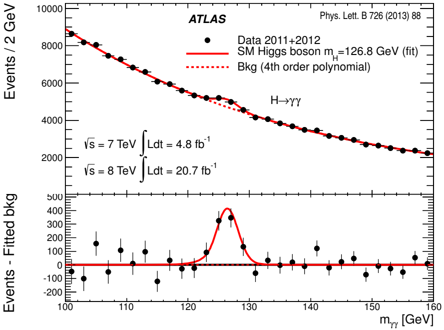
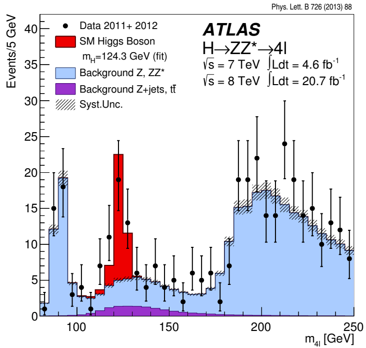


Measurement of the mass of the Higgs boson

- Measurement 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.
- Mass obtained from a simultaneous fit to the $m_{\gamma\gamma}$ and $m_{4\ell}$ $(\ell = e, \mu)$ spectra.



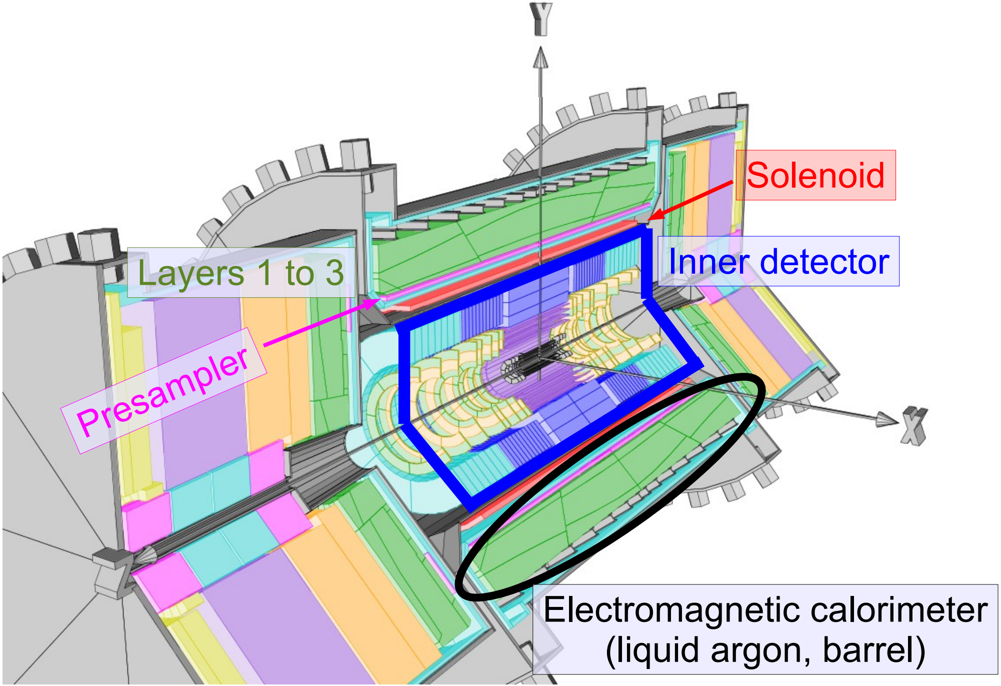


- Original mass measurement (Phys. Lett. B 726 (2013) 88)

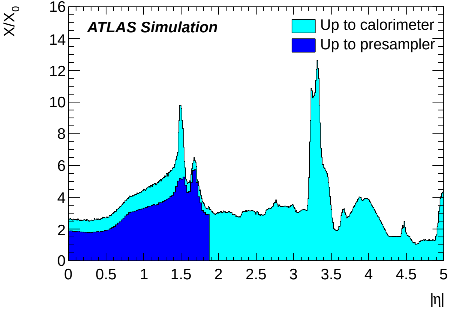
$$m_H = \left[125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\right] \text{ GeV}$$

dominated by the systematic uncertainties on the γ, e, μ energy scales.
- Topic of this talk: m_H measurement with highly reduced energy scale uncertainties due to improved calibration procedures.

Inner detector and e.m. calorimeter for e/γ detection



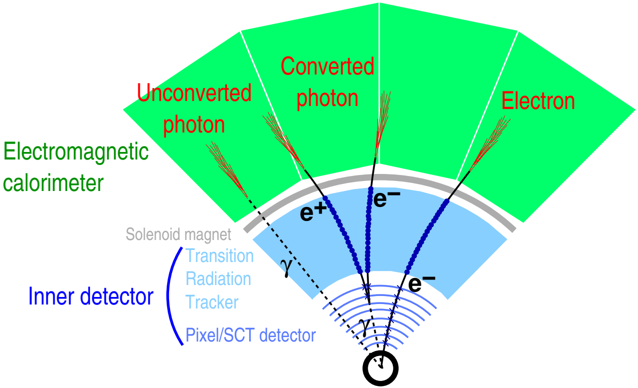
Electron and photon reconstruction



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

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

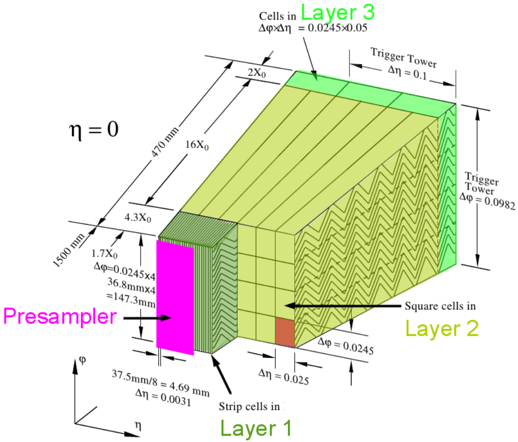
$\Rightarrow$ 3 topologies have to be considered:



Initial calibration of the e/γ 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 $Z \to e^+e^-$ decays.
- A more advanced calibration strategy has been adopted for the updated Higgs mass measurement (see next slide).

Refined calibration of the e/γ energy scale

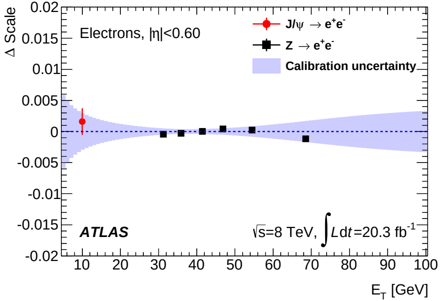


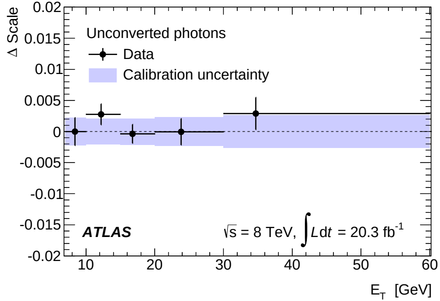
1. Cell energy calibration with test pulses
2. Intercalibration of the different calorimeter layers
   - No muon energy loss before the ECAL.
   - $\Rightarrow$ Intercalibration of layers 1 to 3 with muons from Z decays.
   - Relative calibration of the presampler with electrons as a function of the 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

Energy scale uncertainties

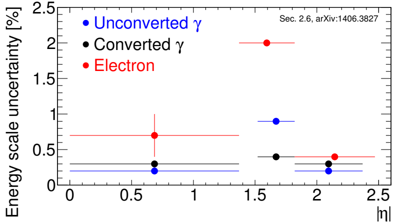
Checks of the e/γ energy scale

- $J/\psi \to e^+e^-$ probes the electron energy scale at low $E_\mathrm{T} \sim 7 \ldots 35$ GeV.
- $Z \to \ell^+\ell^-\gamma$ probes the photon energy scale for $E_\mathrm{T} \sim 30$ GeV.





Total energy scale uncertainties

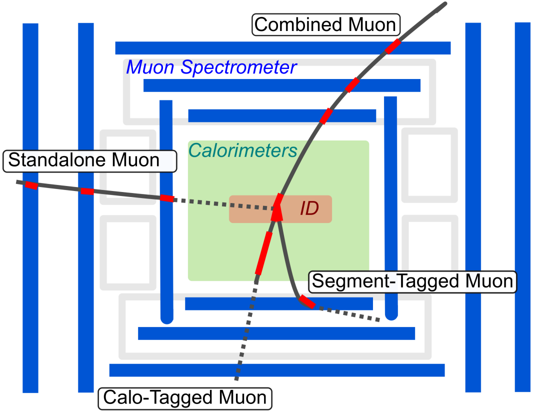


Main source of the scale uncertainties

- 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: $0.1 \ldots 0.3\%$.

Muon reconstruction

Muon types



Energy/momentum measurements

- Calo- and segment tagged muons:

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

- Stand-alone muons:

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

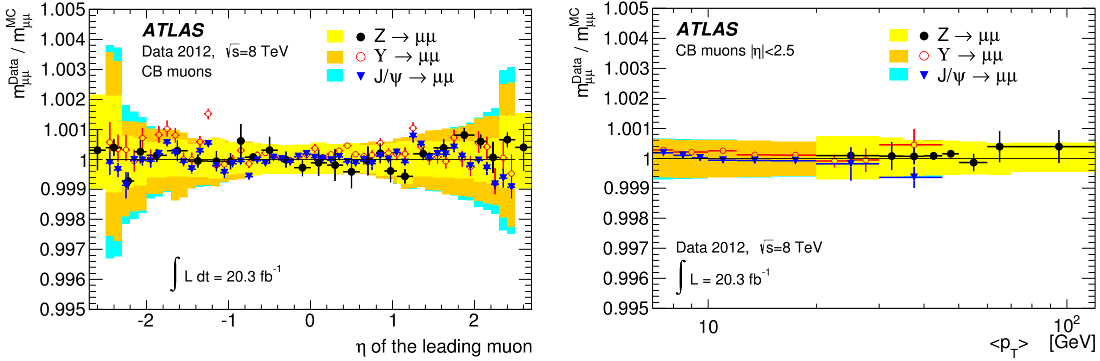
- Combined mouns:

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

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

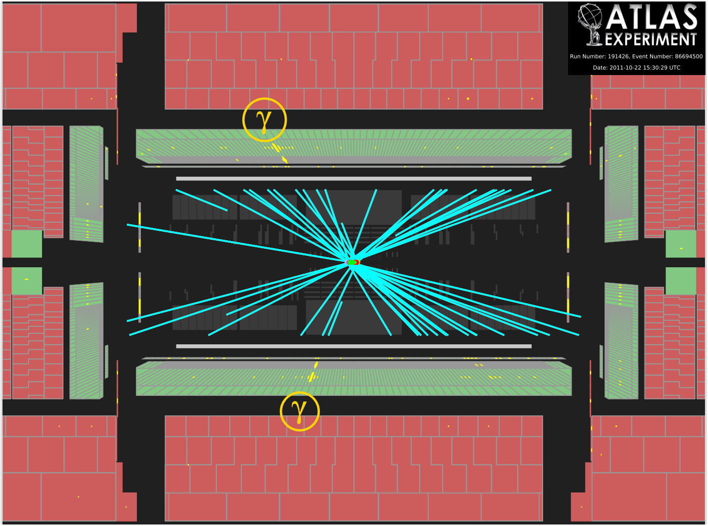
$\Rightarrow$ New calibration uses $Z \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decays.

Muon momentum scale uncertainty



- Use of $Z \to \mu^+\mu^-$ and $J/\psi \to \mu^+\mu^-$ decays in the calibration procedure reduces the muon momentum scale uncertainty from $\sim 0.1\%$ to $\sim 0.01\%$.

$H \to \gamma\gamma$ selection and event categories



Requirements

- 2 isolated high p_{T} photons:

$$|\eta| < 2.37, |\eta| \notin [1.37, 1.56]$$

$$E_{\mathrm{T}}^{(1)} > 0.35 m_{\gamma\gamma}$$

$$E_{\mathrm{T}}^{(2)} > 0.25 m_{\gamma\gamma}$$

- Main background: $\gamma\gamma$ continuum production. Significantly smaller contributions from γj and jj.

To improve the m_H measurement accuracy 10 event categories are used.

Both photons uncoverted					≥1 photon converted				
"central" ($\lvert\eta_{1,2}\rvert<0.75$)		"transition" ($1.3<\lvert\eta_{1 \text{ or } 2}\rvert<1.75$)	"rest"		"central" ($\lvert\eta_{1,2}\rvert<0.75$)		"transition" ($1.3<\lvert\eta_{1 \text{ or } 2}\rvert<1.75$)	"rest"	
$P_T(\gamma\gamma)<70$ GeV	$P_T(\gamma\gamma)>70$ GeV		$P_T(\gamma\gamma)<70$ GeV	$P_T(\gamma\gamma)>70$ GeV	$P_T(\gamma\gamma)<70$ GeV	$P_T(\gamma\gamma)>70$ GeV		$P_T(\gamma\gamma)<70$ GeV	$P_T(\gamma\gamma)>70$ GeV

The categories differ from each other in $\frac{S}{B}$, $\sigma\left(m_{\gamma\gamma}\right)$, systematic uncertainties.

Mass measurement procedure in the $H \to \gamma\gamma$ channel

Invariant mass resolution

$$m_{\gamma\gamma} = 2E_{\gamma_1}E_{\gamma_2}\left[1 - \cos(\theta(\gamma_1, \gamma_2)\right]$$

Thanks to the longitudinal segmentation of the electromagnetic calorimeter $z_{\gamma_{1,2}}$ is known with 15 mm precision.

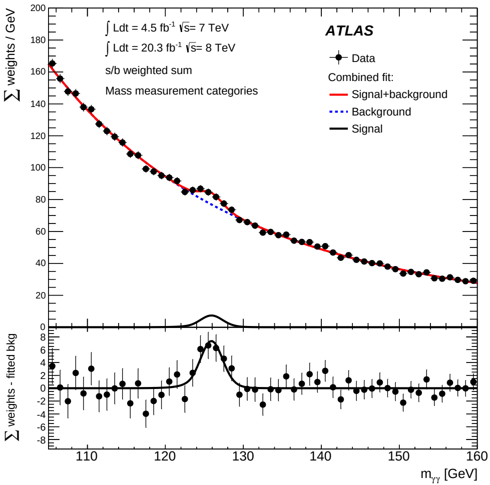
$\Rightarrow$ $\sigma\left(m_{\gamma\gamma}\right)$ is dominated by the γ energy resolution!

$\Rightarrow$ $\sigma\left(m_{\gamma\gamma}\right) \sim 1.7$ GeV at $m_{\gamma\gamma} \sim 125$ GeV.

Fit function for the simultaneous fit of the $m_{\gamma\gamma}$ spectra of the 10 categories

- Linear combination of signal and background functions.
- **Signal**: Crystal Ball with category dependent resolutions.
- **Background**: Category dependent analytic functions.
- **Free parameters**:
    - Signal strength $\mu_{\gamma\gamma}$;
    - Higgs boson mass m_H;
    - Background function parameters;
    - Nuisance parameters for systematic uncertainties.

Measured Higgs boson mass in the $H \to \gamma\gamma$ channel



New result

$$m_H = [125.98 \pm 0.42(\text{stat}) \pm 0.28(\text{syst})] \text{ GeV}$$

with $\mu_{\gamma\gamma} = 1.29 \pm 0.30$.

Old result

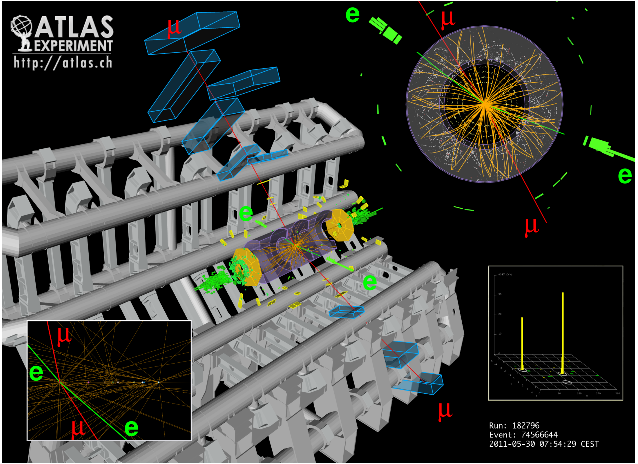
$$m_H = [126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})] \text{ GeV}$$

with $\mu_{\gamma\gamma} = 1.55$.

Comments

- Shift of m_H to lower value than before due to new calibration.
- Increased statistical error on m_H compared to before due to reduced signal strength.
- Reduced systematic uncertainty on m_H compared to before thanks to reduced photon energy scale uncertainty.

$H \to ZZ^* \to 4\ell$ selection and event categories



Requirements

- 2 pairs of isolated same-flavour, opposite-sign leptons (e or μ) from a common vertex.
- Invariant mass requirement:

$$50 \text{ GeV} < m_{12} < 106 \text{ GeV}$$

- To improve the $m_{4\ell}$ resolution: FSR recovery and Z mass constraint.
- Main background: ZZ^* continuum production. Small contributions from $Z + j$ and $t\bar{t}$.

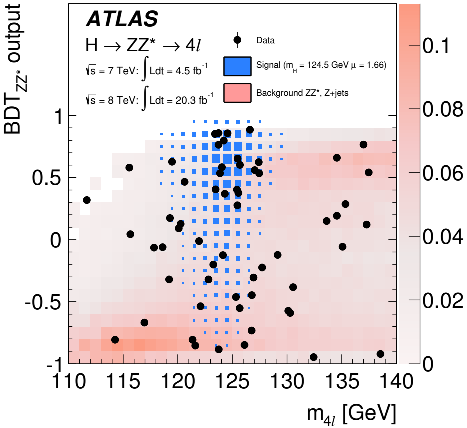
To improve the m_H measurement accuracy 4 event categories are used:

$$4\mu,\ 4e,\ 2\mu 2e,\ 2e2\mu.$$

The categories differ from each other in $\frac{S}{B}$, $\sigma\left(m_{4\ell}\right)$, systematic uncertainties.

Mass measurement procedure in the $H \to ZZ^* \to 4\ell$ channel

Multivariate discriminant to distinguish ZZ^* background from $H \to ZZ^*$ signal: "BDT$_{ZZ}$ output".



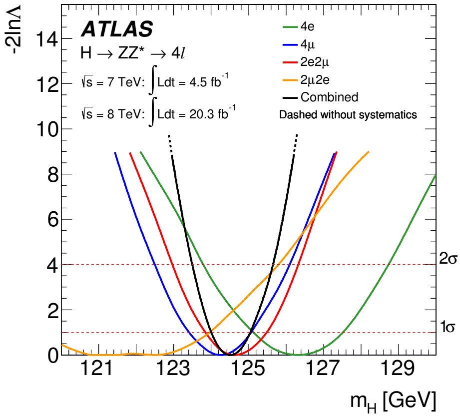
Fit function for the simultaneous fit of the BDT$_{ZZ}$ output versus $m_{4\ell}$ spectra of the 4 categories

- Linear combination of a 2D signal and a 2D background distribution.
- The 2D signal and ZZ distributions are taken from MC samples, the reducible background shape is data-driven.
- **Fit parameters:**
  - Signal strength $\mu_{4\ell}$;
  - Higgs boson mass m_H;
  - Nuisance parameters for systematic uncertainties.

Cross checks:

- Simultaneous fits of the 1D m_ℓ distributions like in the past.
- Simultaneous fits of the 2D distributions taken into account per-event $m_{4\ell}$ resolution values.

Measured Higgs boson mass in the $H \to ZZ^* \to 4\ell$ channel



- Individual mass measurements in the 4 categories lead to compatible results.
- New result

$$m_H = [124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{syst})] \text{ GeV}$$

with $\mu_{4\ell} = 1.66^{+0.45}_{-0.38}$.

- Old result

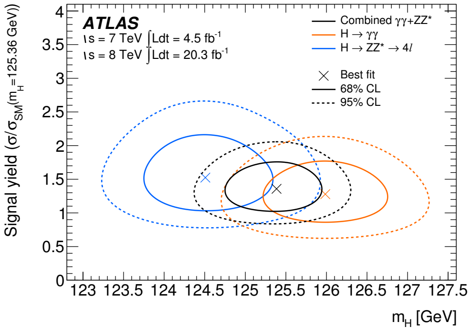
$$m_H = \left[124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\right] \text{ GeV}$$

with $\mu_{4\ell} = 1.43^{+0.40}_{-0.35}$.

Comments

- Shift of m_H to slightly higher value than before due to new electron energy calibration.
- Increased signal strength compared to before due to increased m_H value.
- Reduced systematic uncertainty on m_H compared to before thanks to reduced lepton energy/momentum scale uncertainty.

Combined Higgs boson mass measurement



New result

$$m_H = [125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})] \text{ GeV}$$

Old result

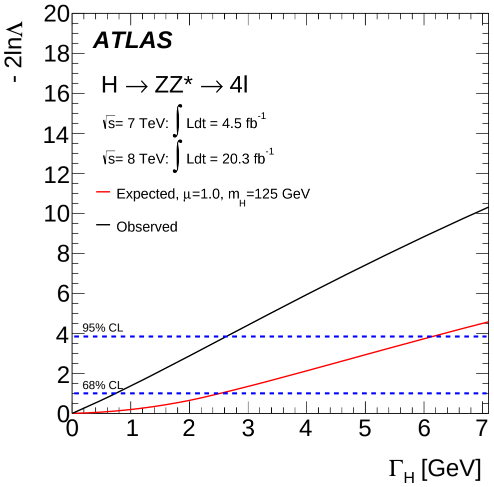
$$m_H = \left[125.49 \pm 0.24(\text{stat})^{+0.50}_{-0.58}(\text{syst})\right] \text{ GeV}$$

Comments

- Shift of m_H to slightly smaller value than before due to the lower m_H value in the $H \to \gamma\gamma$ channel.
- Increased statistical error on m_H compared to before due to increased statistical uncertainty of m_H in the $H \to \gamma\gamma$ channel.
- Compatibility between the m_H measurements in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels is 2.0σ compared to 2.5σ before.

Bonus slide

Measurement of the Higgs boson width with $H \to 4\ell$ data



- The $H \to 4\ell$ data were used to set an upper limit on the natural width Γ_H of the Higgs boson.
- Γ_H was added as a free parameter to the 3D fit while fixing m_H to the measured value.

$\boxed{\Gamma_H < 2.6 \text{ GeV at 95\% CL}}$

Expected limits:

- $\Gamma_H < 6.2$ GeV for $\mu_{4\ell} = 1$.
- $\Gamma_H < 3.5$ GeV for $\mu_{4\ell} = 1.66$.