Precision measurements of the Higgs boson mass and width using four-lepton and di-photon final states

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On behalf of the ATLAS Collaboration

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- Importance of m_H and Γ_H in several aspects of our understanding of fundamental physics.

Power law expansion of the potential

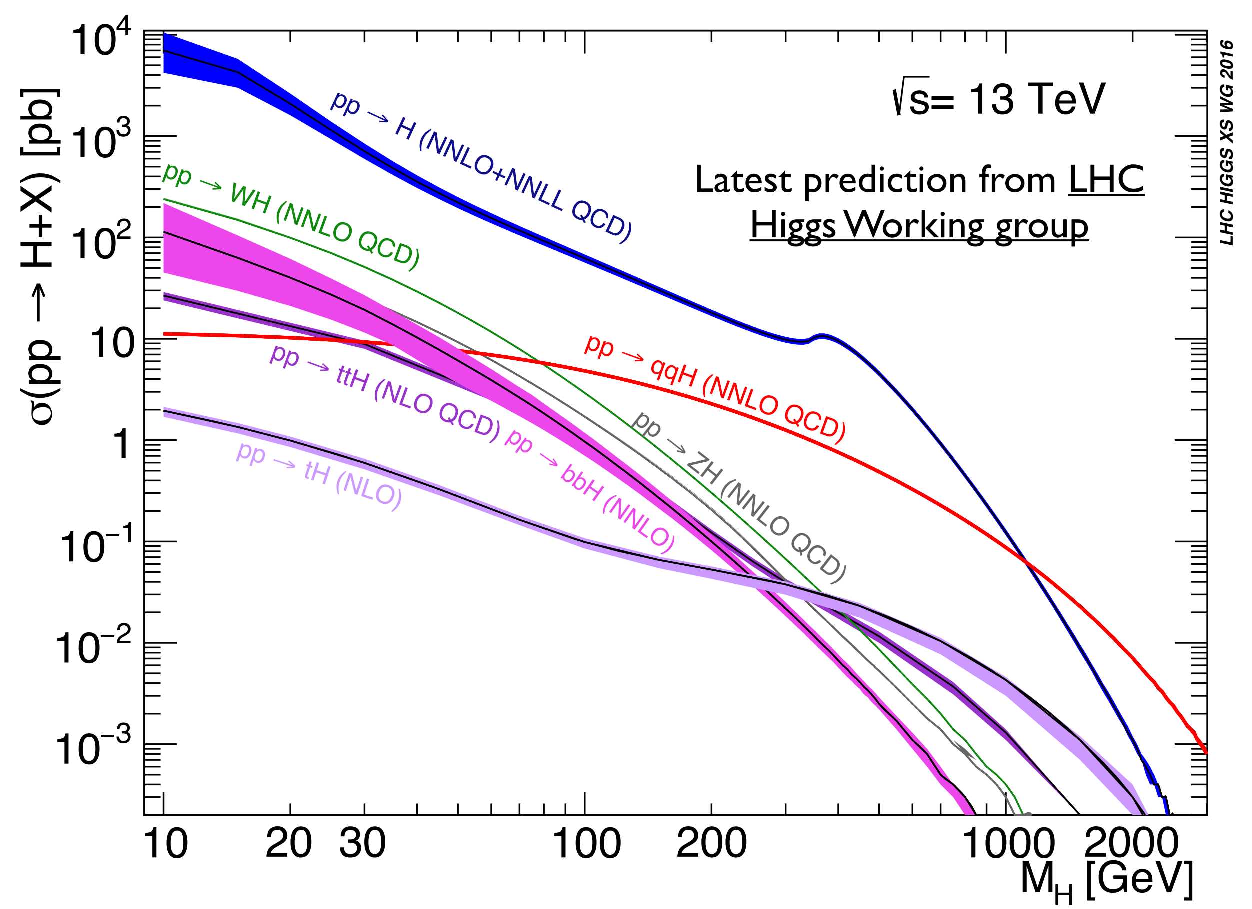
$$V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

- Understanding the perturbative expansion of its potential ($\lambda v^2 h^2$).
- Higgs couplings defined by the value of m_H.
- Input to precision global fit of the Standard Model.

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\Psi}\not{D}\psi \\ &+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ &+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.\end{aligned}$$

- ATLAS run I precision on m_H of 0.33%
  - combined measurement from $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$.

Channel	Mass measurement [GeV]
$H\to\gamma\gamma$	$125.98 \pm 0.42\,(\text{stat}) \pm 0.28\,(\text{syst}) = 125.98 \pm 0.50$
$H\to ZZ^*\to 4\ell$	$124.51 \pm 0.52\,(\text{stat}) \pm 0.06\,(\text{syst}) = 124.51 \pm 0.52$
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

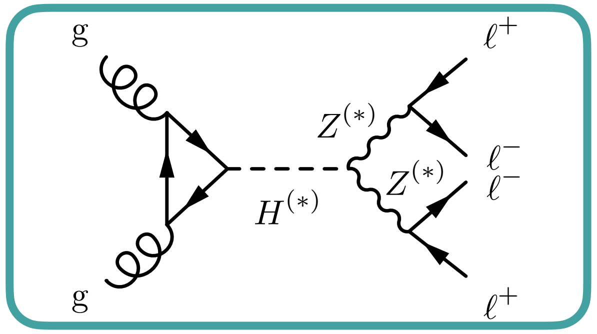


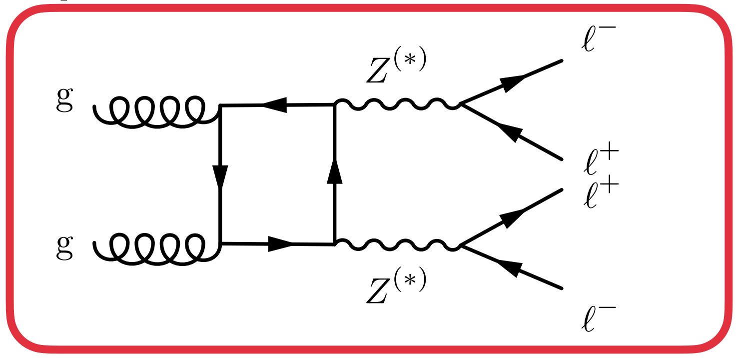
Prediction and uncertainties of Higgs production processes as a function of the m_H

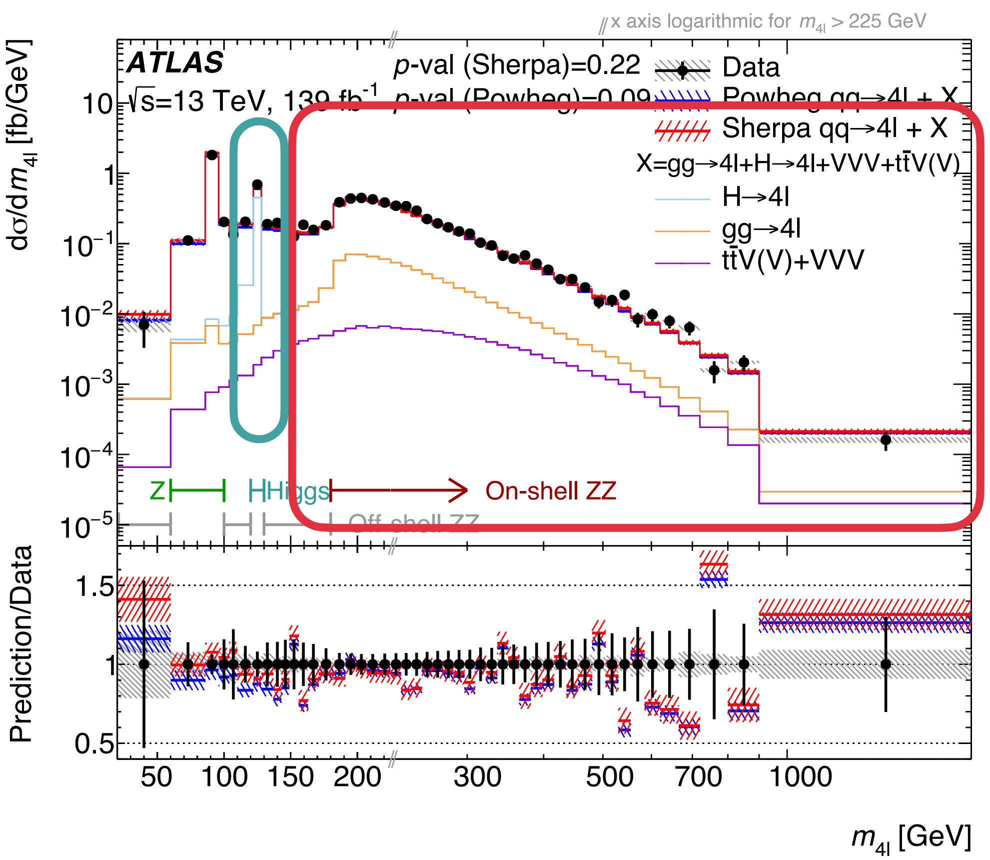
Higgs width

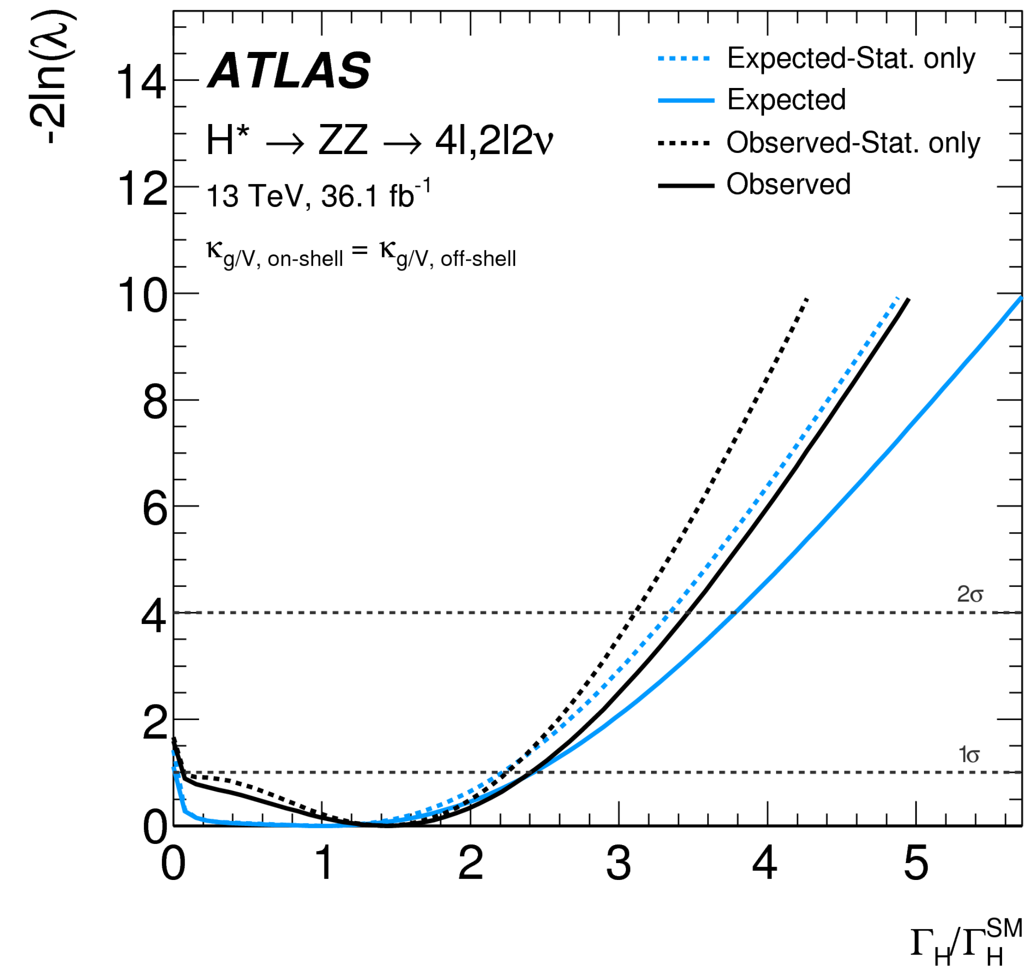
- Study of the the $m_{4\ell}$ spectrum and Off-shell H production.

[JHEP 04 (2019) 048](), [Phys. Lett. B 786 (2018) 223]()









- Off-shell Higgs production, enhanced at 350 GeV because of top-quark loops in ggF, above ~ $2m_Z$ enhancements of $qq\rightarrow ZZ$ and $gg\rightarrow ZZ$.

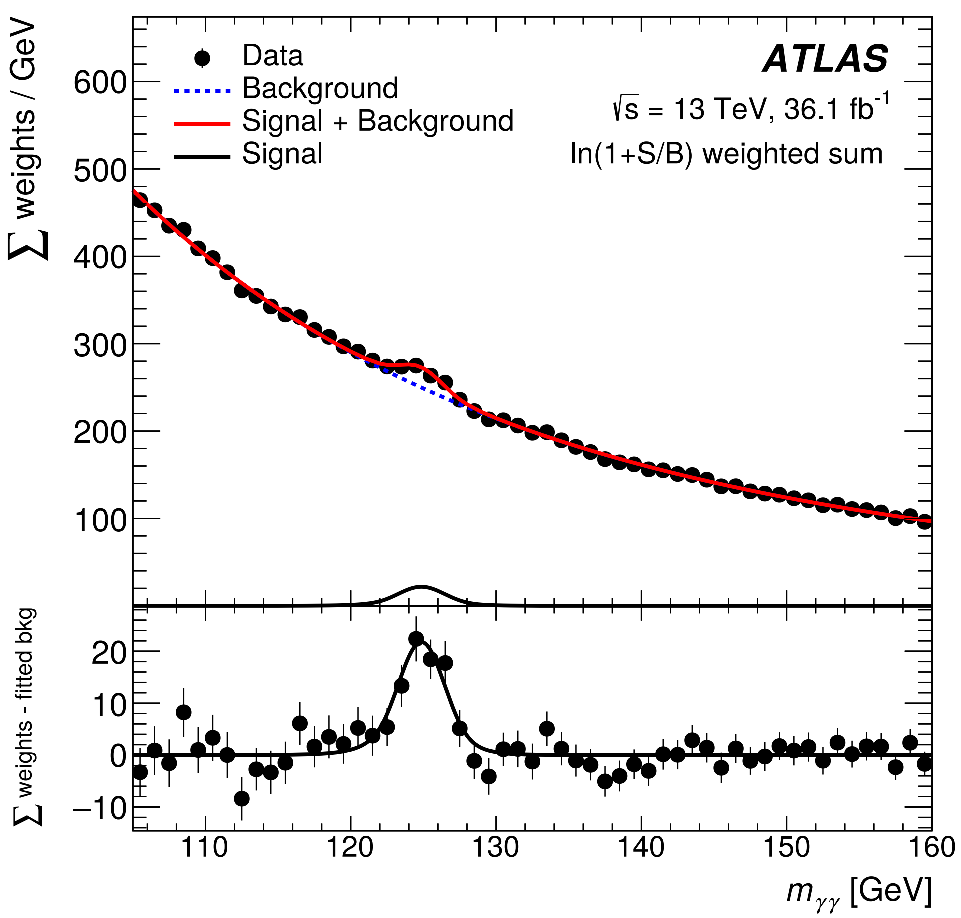
- Limit Γ_H possibile from the off-shell to on-shell event yield ratio
  - on-shell event yields ~ $k^2_{\text{g,on-shell}} / \Gamma_H$, while off-shell ~ $k^2_{\text{g,off-shell}}$

- Observed (expected) upper limit on Γ_H 14.4 (15.2) MeV

$H \rightarrow \gamma\gamma$ Mass measurement

- $H \rightarrow \gamma\gamma$ updated result at Run II with 36.1 fb^{-1}. Phys. Lett. B 784 (2018) 345
  - Analytical $m_{\gamma\gamma}$ background functions in kinematic and detector related categories.
  - Reduction of uncertainty through categorisation of events as a function of:
    - resolution and signal significance.
    - Systematic uncertainties.
- Expected statistical uncertainty of 0.21 GeV and 0.34 GeV systematic uncertainty

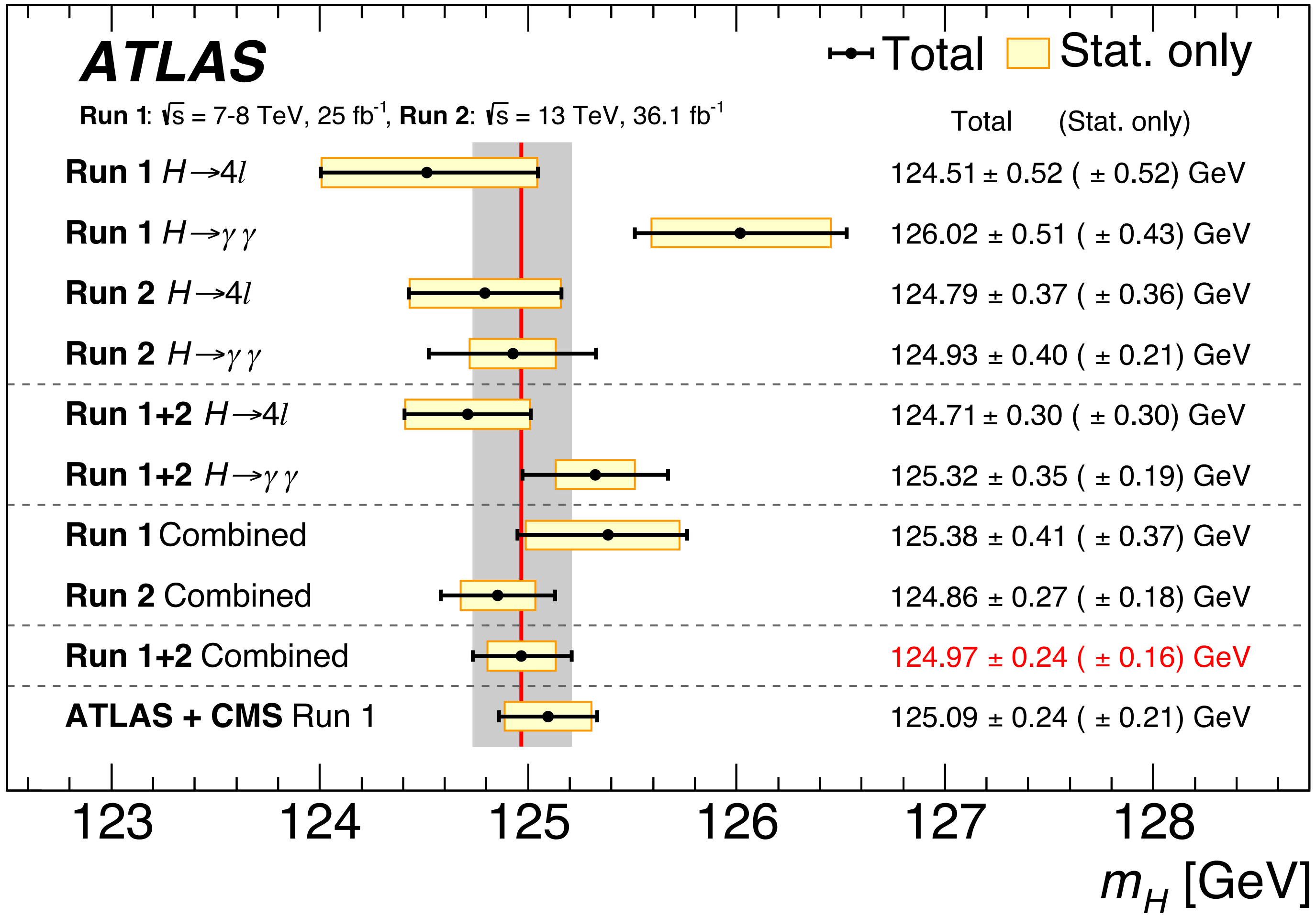
$$\boxed{m_H^{\gamma\gamma} = 124.93 \pm 0.40 \ (\pm 0.21 \text{ stat only}) \text{ GeV}}$$



Source	Systematic uncertainty on $m_H^{\gamma\gamma}$ [MeV]
EM calorimeter cell non-linearity	± 180
EM calorimeter layer calibration	± 170
Non-ID material	± 120
ID material	± 110
Lateral shower shape	± 110
$Z \rightarrow ee$ calibration	± 80
Conversion reconstruction	± 50
Background model	± 50
Selection of the diphoton production vertex	± 40
Resolution	± 20
Signal model	± 20

- 4ℓ and $\gamma\gamma$ measurements are combined with ATLAS Run 1 result

Phys. Lett. B 784 (2018) 345



- Run 2 precision improved w.r.t Run 1.

$$m_H = 124.86 \ \pm \ 0.27(\pm 0.18 \text{ stat only}) \text{ GeV}$$

- ATLAS Run 1 + 2 comparable precision to LHC Run 1 combination.

$$m_H = 124.97 \ \pm \ 0.24(\pm 0.16 \text{ stat only}) \text{ GeV}$$

Ingredients for precision

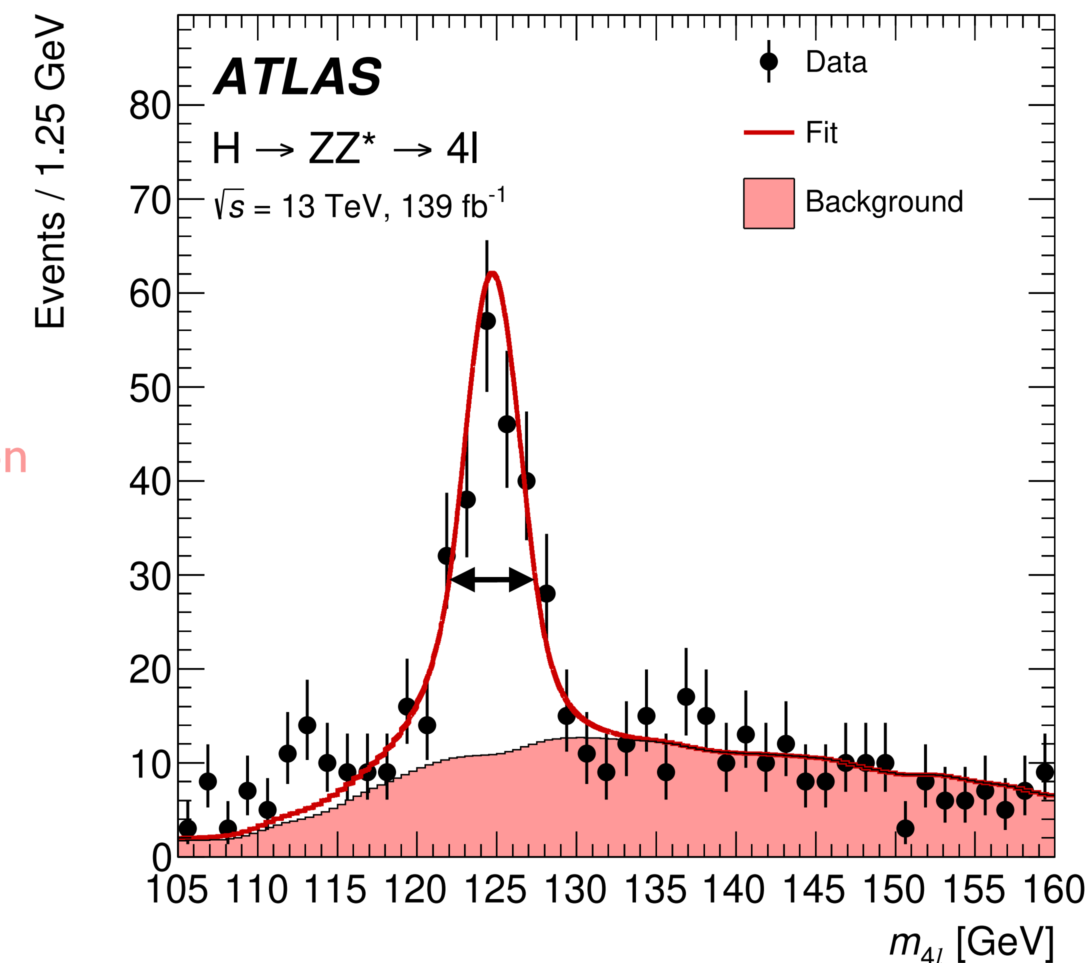
- In the $H \to ZZ \to 4\ell$ the signal is a narrow resonant peak above a background continuum.

ℓ = electron or muon

- 4ℓ final state forms 4μ, $4e$, $2\mu 2e$, and $2e2\mu$ channels.

Higgs signal, resonant at the value of m_H

Non resonant background from non H production



Invariant mass distribution

$$\delta m_H \simeq \frac{\sigma(m_{4\ell,\gamma\gamma})}{\sqrt{N - N_b}}$$

Statistical uncertainty on m_H approximated by the uncertainty on the mean of the mass distribution

(I) Statistical precision precision depends upon:

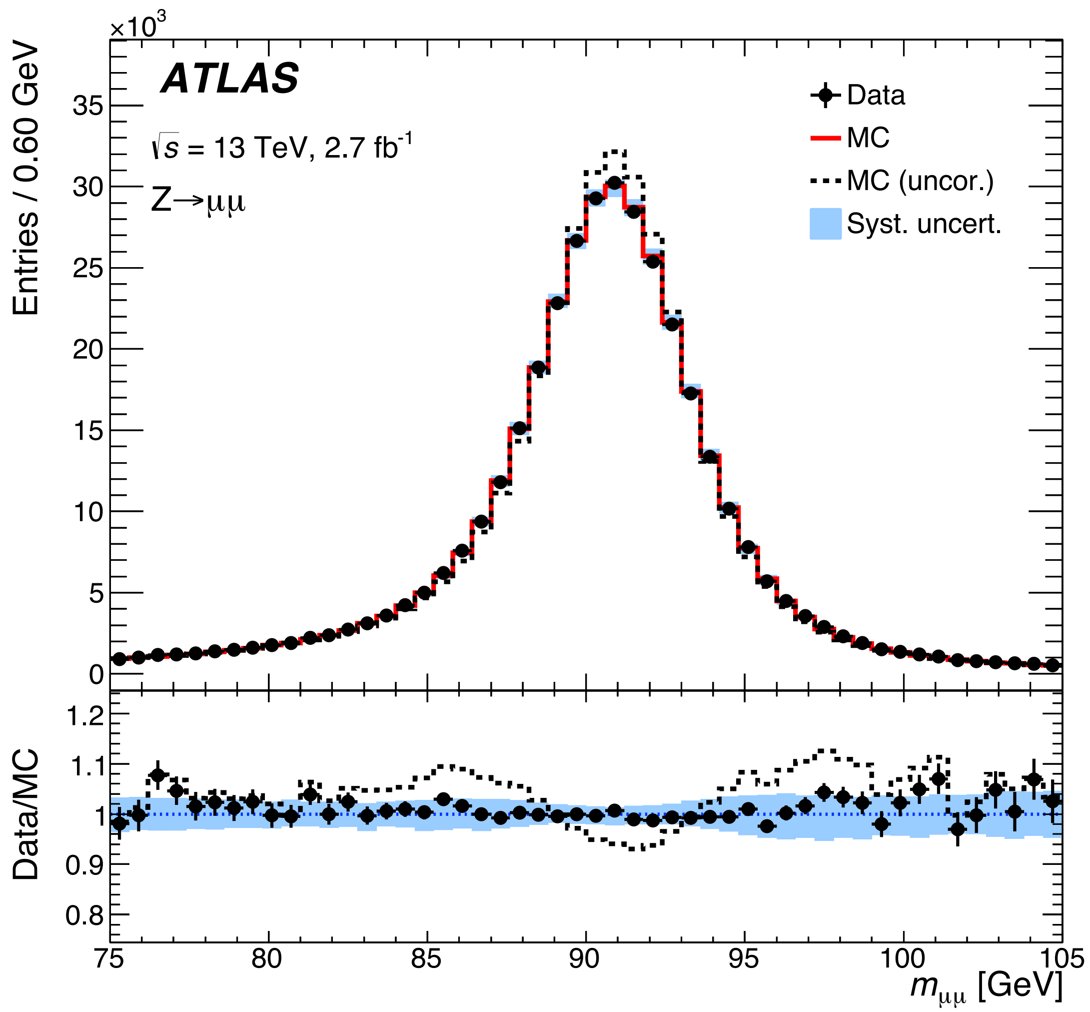
- resolution of the reconstructed final state and number of signal events.

(II) Systematic uncertainty from understanding of detector performance.

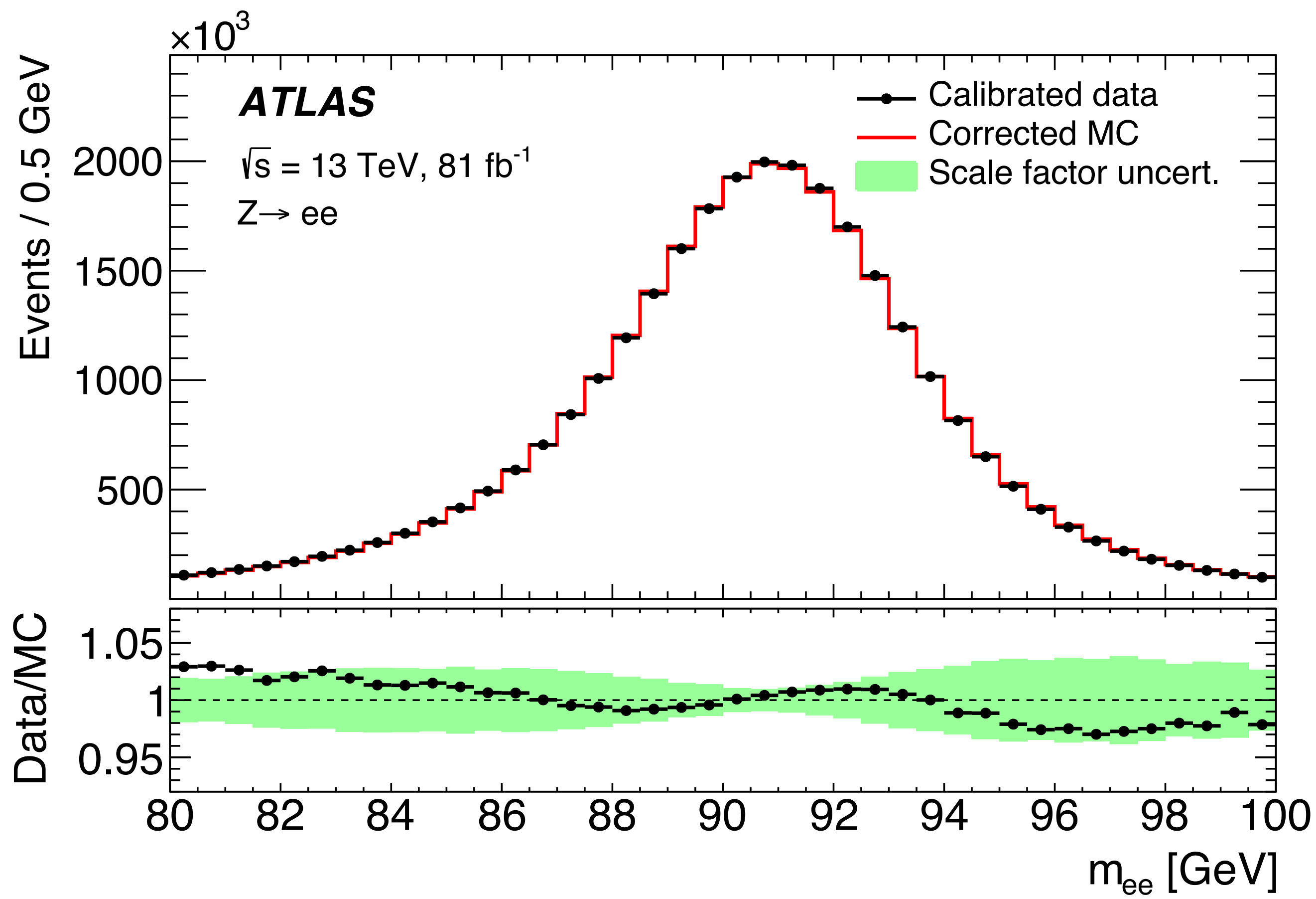
Energy and p_T calibration

- Resolution in electron and muon reconstruction crucial for m_H uncertainty. See F. He talk.

- We used well known processes to calibrate the detector response.
  - Resonant process of J/ψ, (Υ) and Z,
  - for modelling of calorimeters deposits, alignment precision, etc.



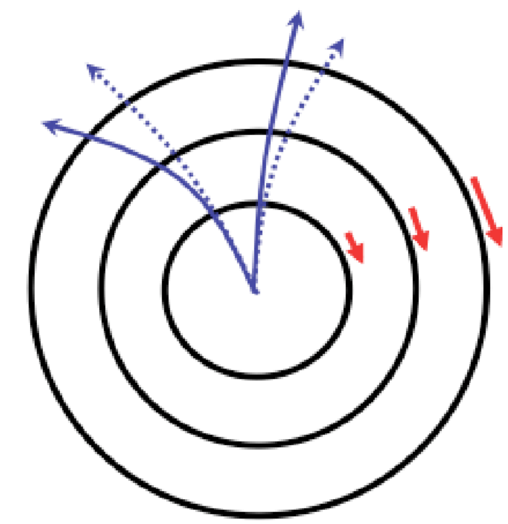
$Z\rightarrow\mu\mu$ resonant line shape for data and detector simulation



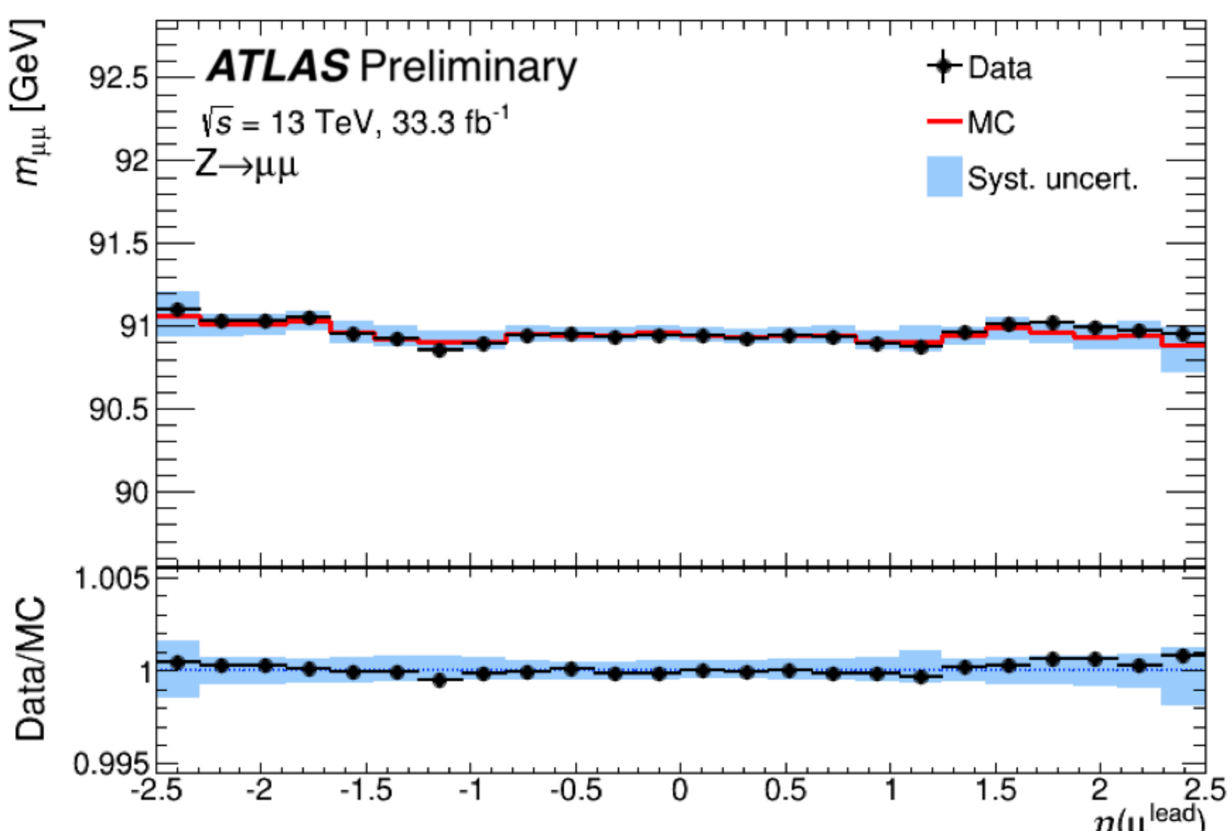
$Z\rightarrow ee$ resonant line shape for data and detector simulation

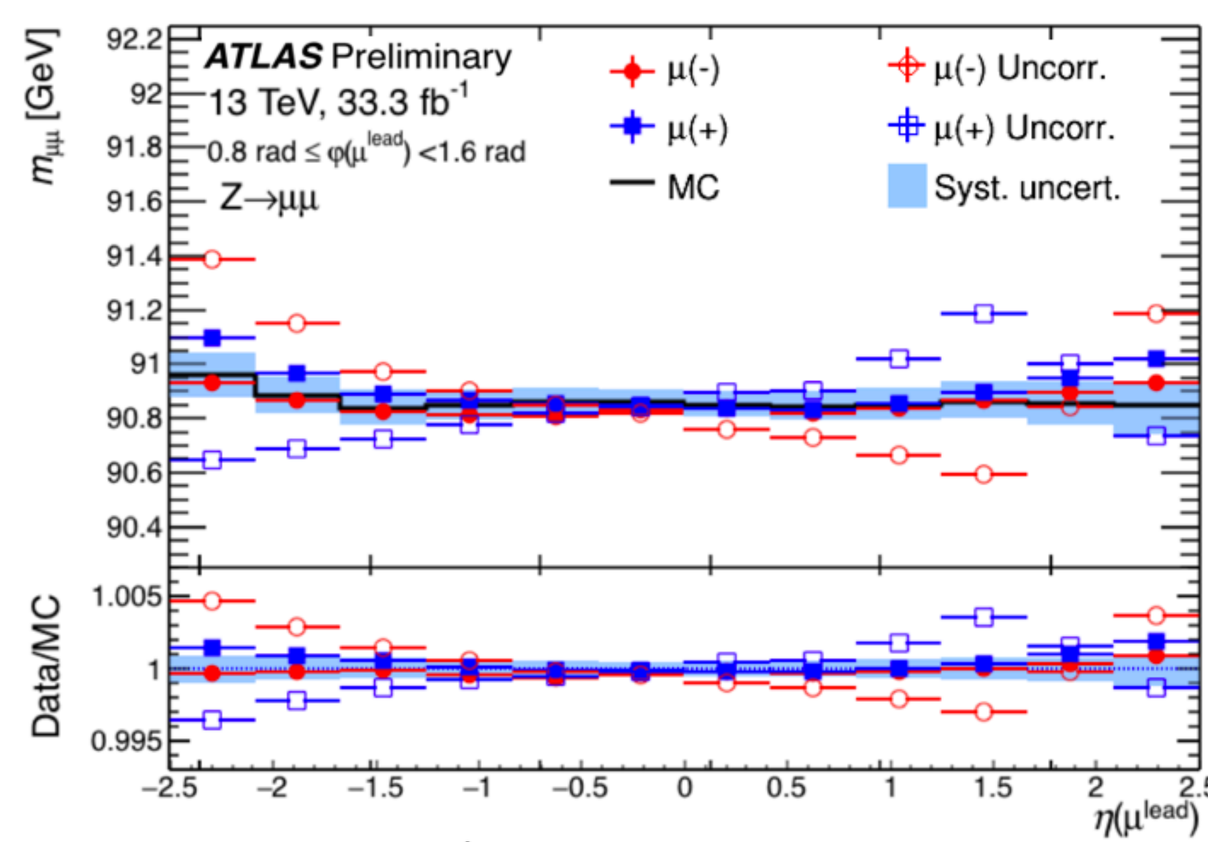
Muon p_T resolution

- Local misalignments and second order effects:
  - Charge dependent sagitta bias, with net effect of worsening resolution
  - *In-situ* correction based on $Z\to\mu\mu$ data, recovers up to 5% in resolution.
- Momentum scale understood down to the per mille level
  - Precision down to 0.5 per mille for |η|<1.0



Detector layer movements biasing the measurement of the bending of the particle





See F. He talk.

Biased positive and negative tracks
Corrected positive and negative tracks

Higher level improvements

- Three-prong approach to reduce uncertainty at analysis level:

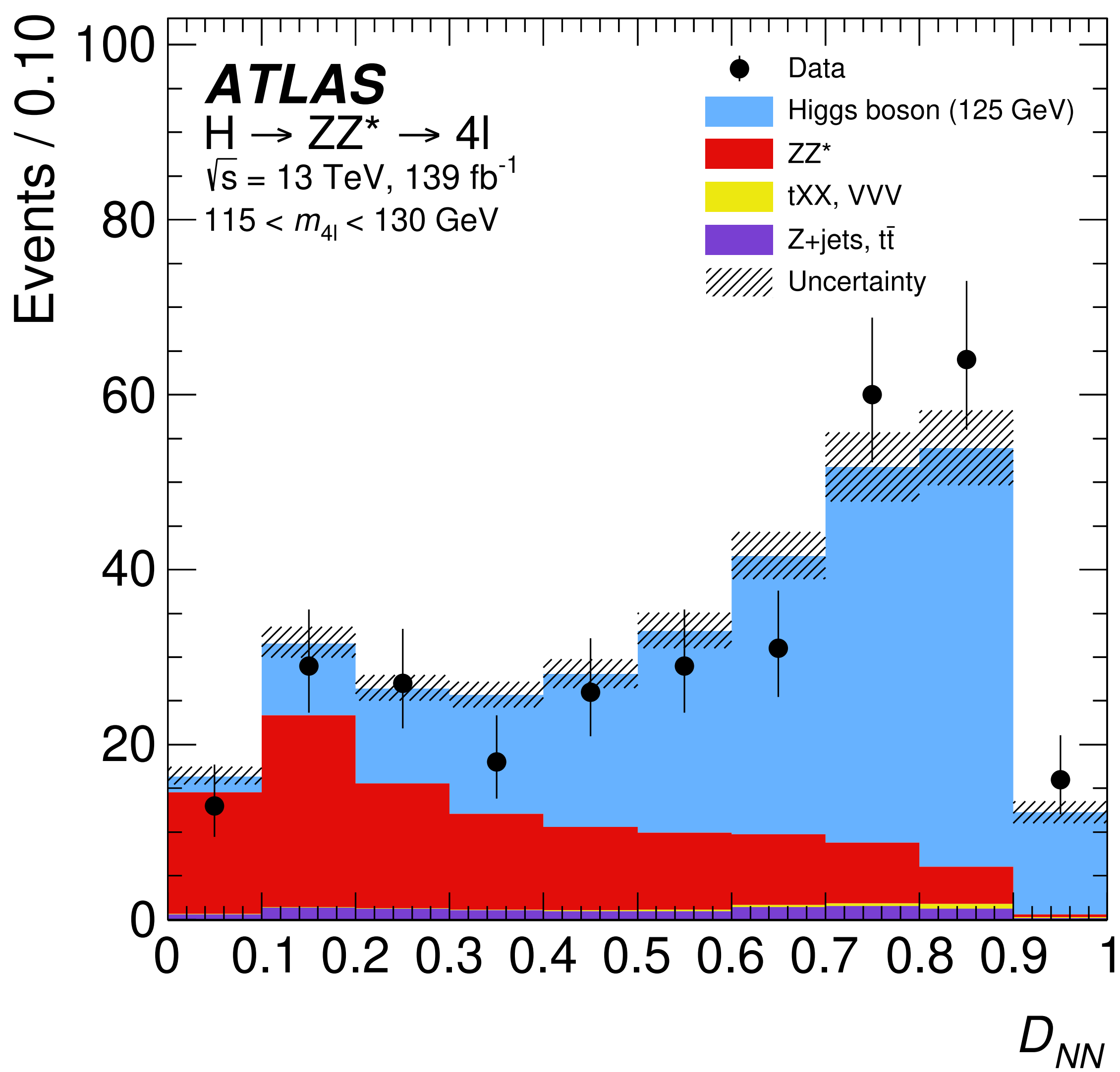
New: arXiv:2207.00320

(i) constraint to m_Z with kinematic fit and second order detector effects.

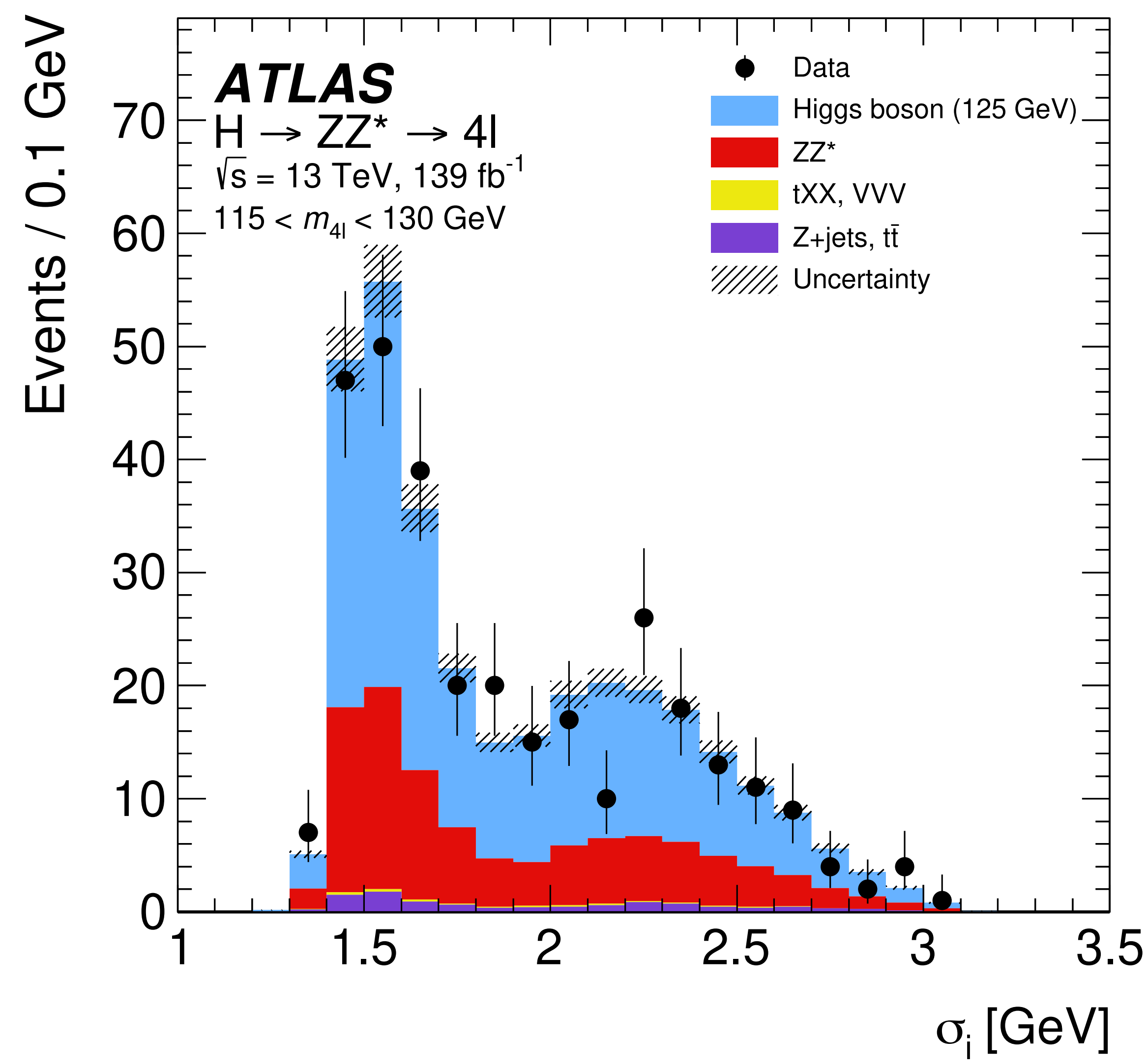
(ii) machine-learning discriminant selecting signal and background events

(iii) Per-event resolution likelihood.

✦ Machine Learning to target each event's unique characteristics

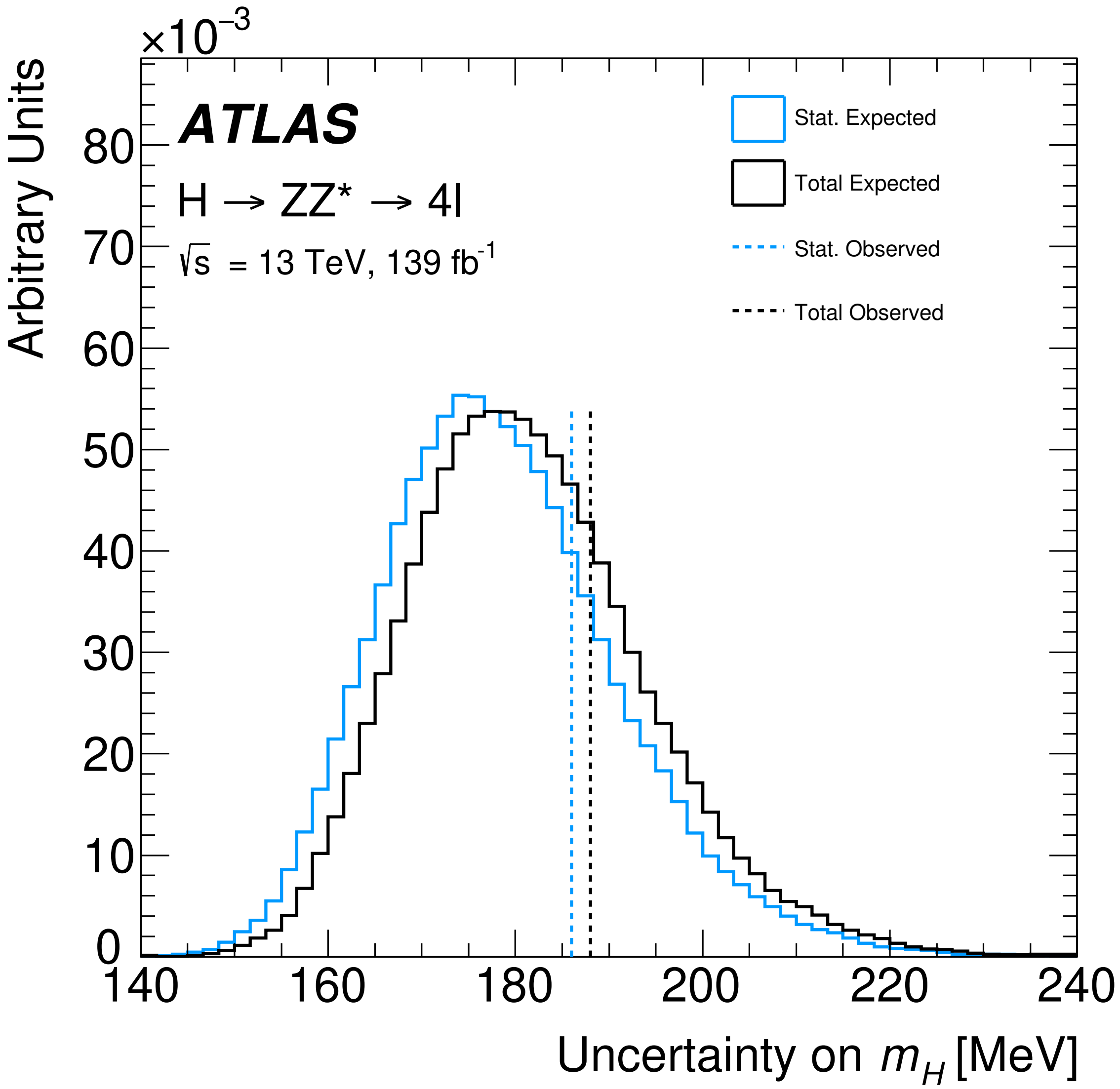


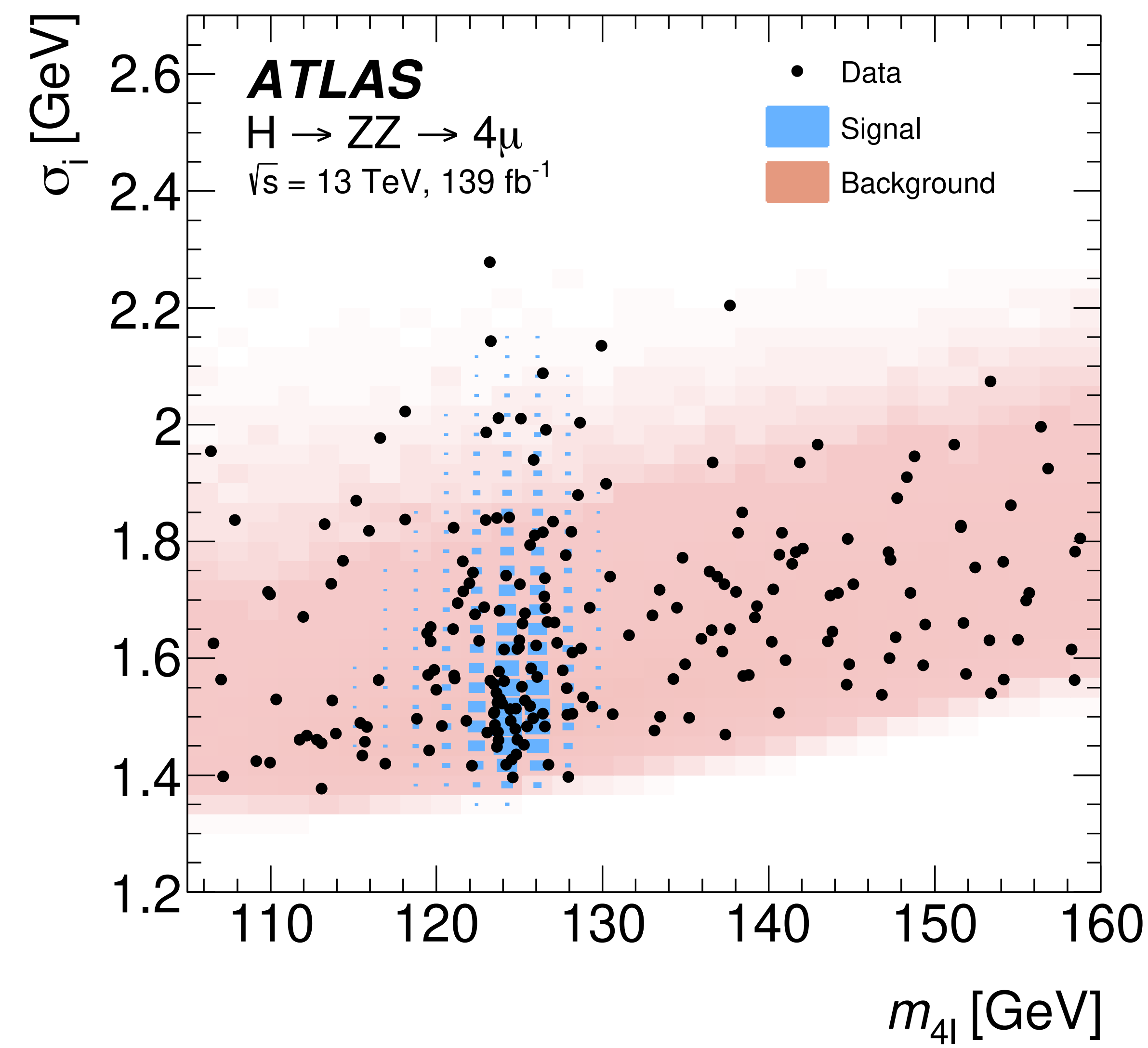
Neural network output of the event's resolution



ML output for signal and background

- Output used in multidimensional fit, improving with respect to average detector response.
  - Fit dimensions: $m_{4\ell}$ x D_{NN} x σ_i
  - Tailored resolution to each event's characteristics.
  - One-sided p-value for compatibility between the observed and expected total uncertainties is 0.28.





MC-based per-event pseudo experiments.

New: arXiv:2207.00320

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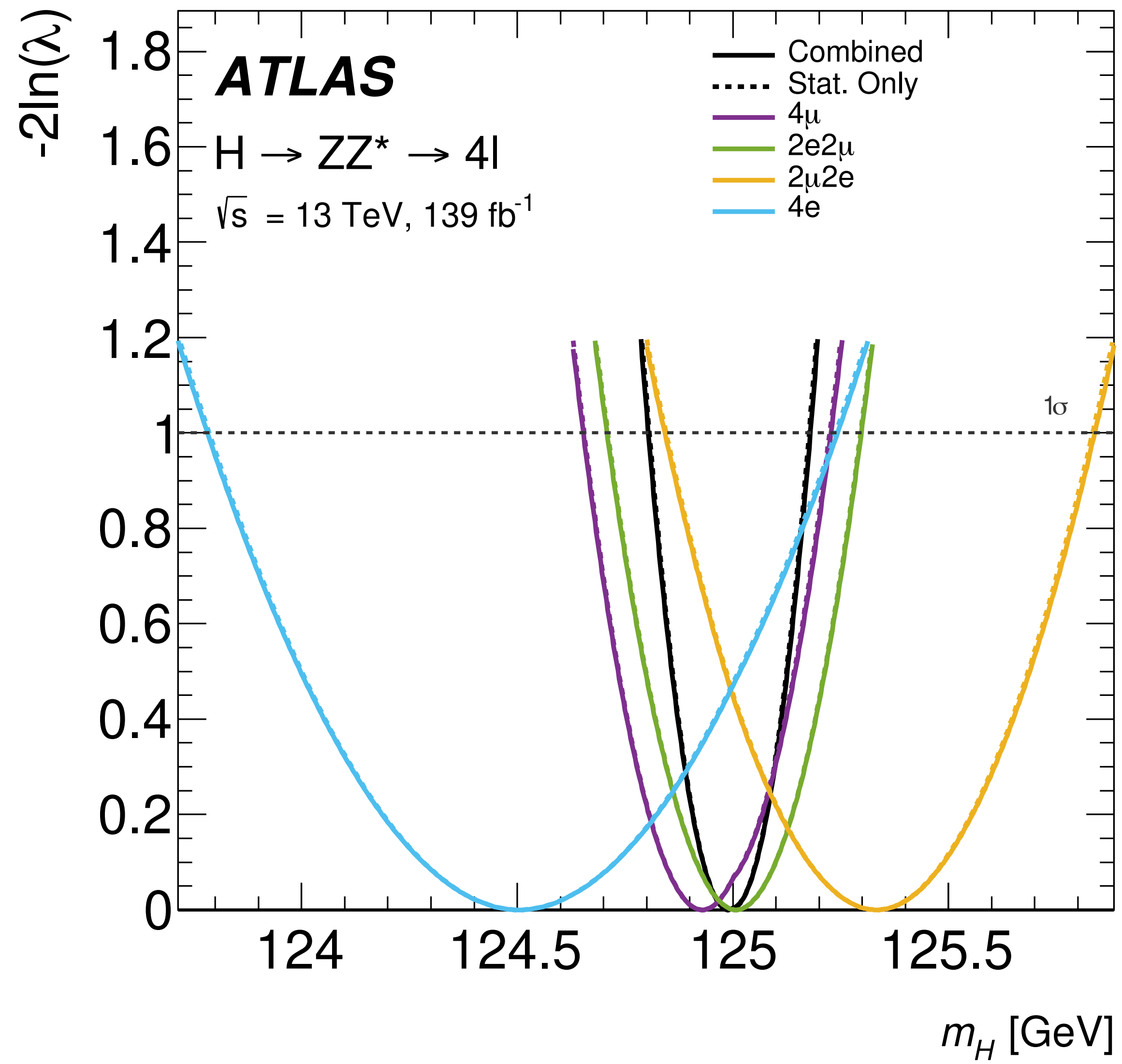
- Simultaneous fit for all channels over the multidimensional model
  - Channel compatibility within a p-value of 0.8
- Systematic uncertainty of 40 MeV
- Result:

Systematic Uncertainty	Contribution [MeV]
Muon momentum scale	± 28
Electron energy scale	± 19
Signal-process theory	± 14



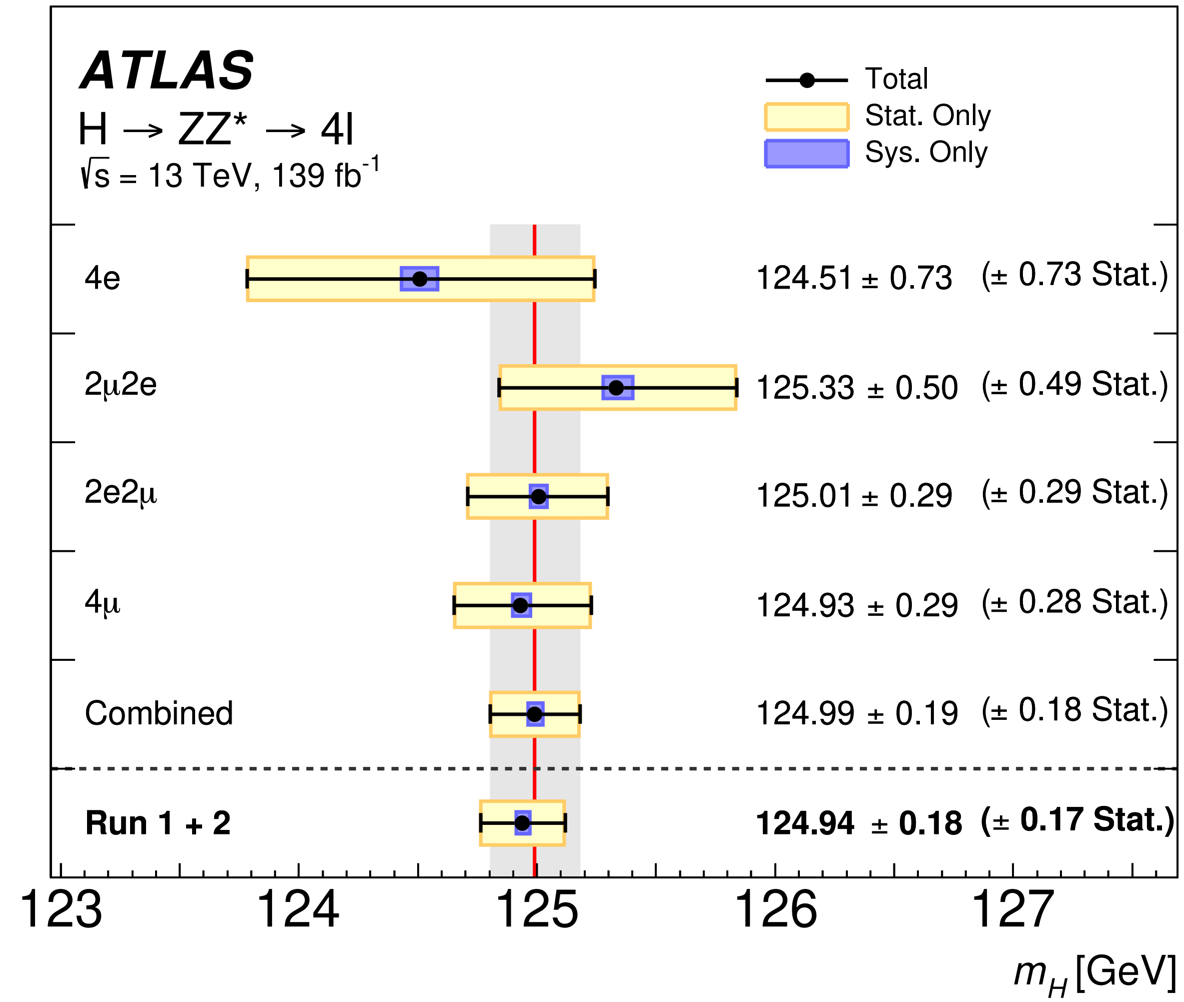
- 26% improved (total) precision with respect to Run I Combination.

$$m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})\ \text{GeV}$$

New: arXiv:2207.00320

- Combination with $H \to ZZ \to 4\ell$ Run-1 measurement.
  - New p_T calibration techniques → uncorrelated $p_T(\mu)$ systematics between Run1 and Run2

- Total uncertainty of 0.14%
- Systematic uncertainty of 0.02%
  - 88% improvement w.r.t $m_H^{H \to ZZ, \text{Run1}}$
  - Momentum scale uncertainties reduced by a factor 2.
  - 33% improved precision w.r.t previous $m_H^{\text{ATLAS,Run1+2}}$
  - Most precise measurement by ATLAS, so far.



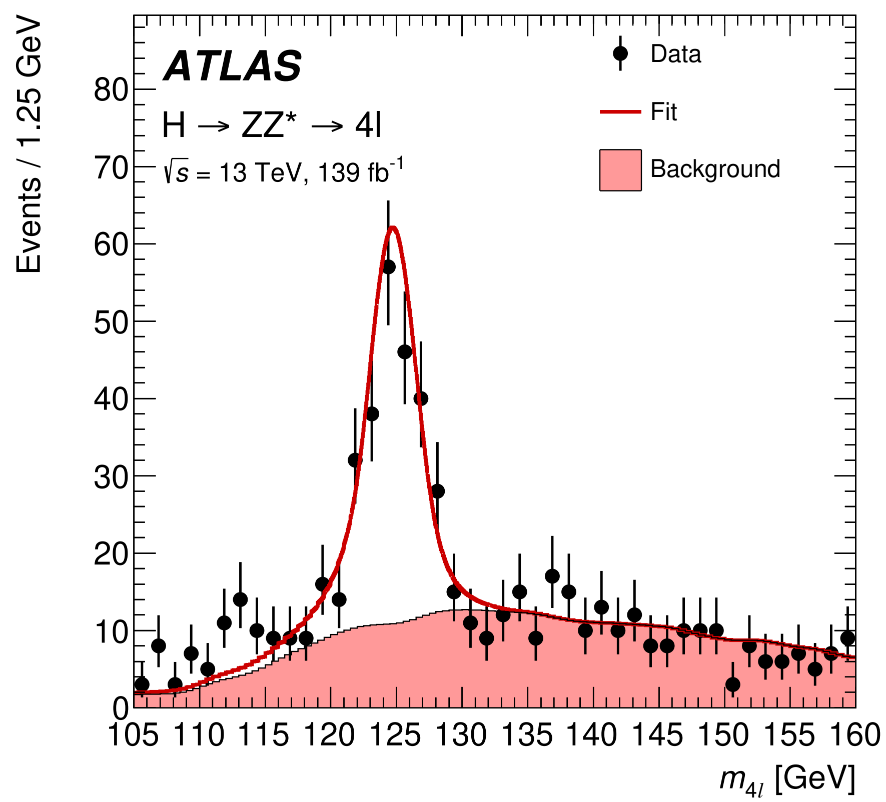
Measured m_H for all channels and combined.

$$m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})\ \text{GeV}$$

Conclusion

- After a decade of cracking the mass problem:
  1. Measurement of m_H at 1.4 per mille precision level.
  2. Measurement of the Higgs width.

- Higgs physics provide an excellent picture for
  - Searches for new phenomena resonant at higher scales, searches for deviations to theory within the scales of the experiment.
  - m_H one of the most precise measurements in the LHC scientific program.



- Full set of ATLAS results:

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

Additional material

- Importance of m_H and Γ_H in several aspects of our understanding of fundamental physics.

Power law expansion of the potential

$$V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

$$\begin{aligned} \mathcal{L} = &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ &+ i\bar{\Psi}\not{D}\psi \\ &+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) \\ &+ \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c. \end{aligned}$$

- Understanding the perturbative expansion of its potential ($\lambda v^2 h^2$).
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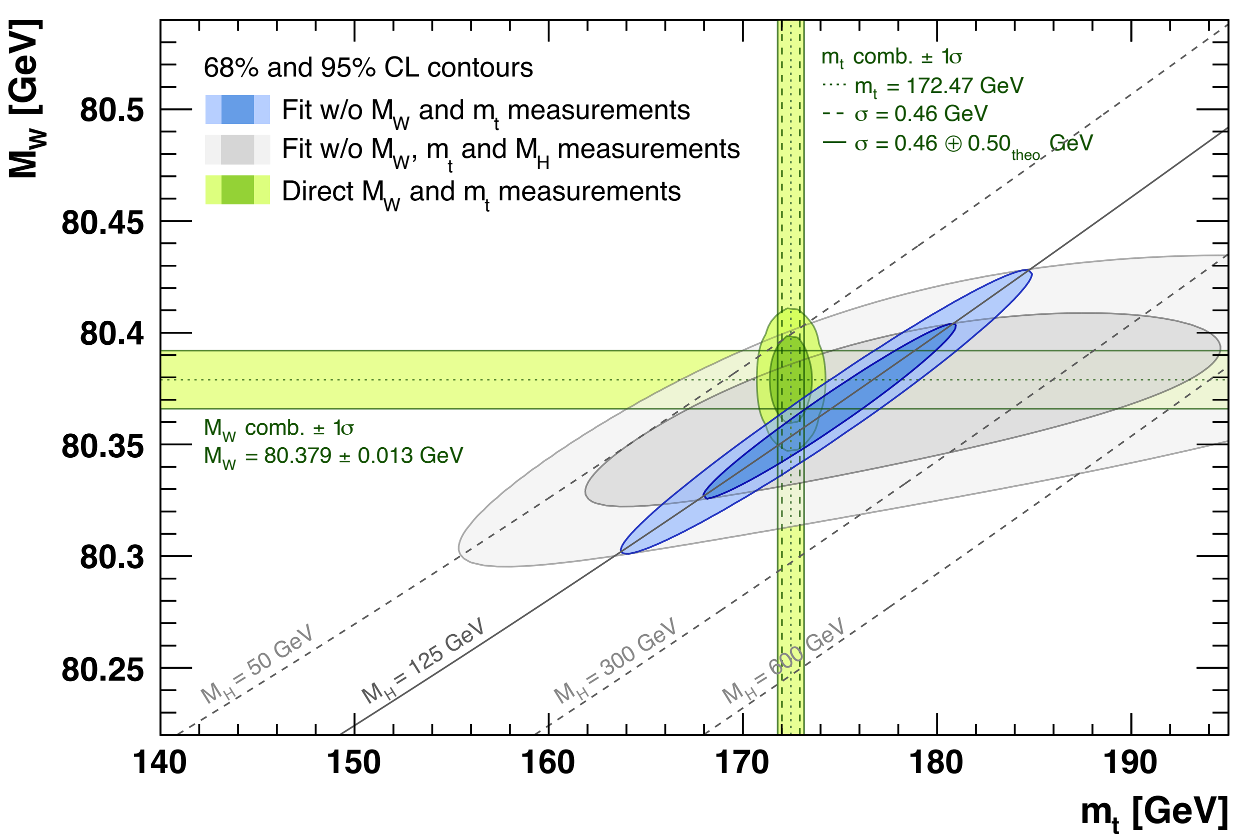
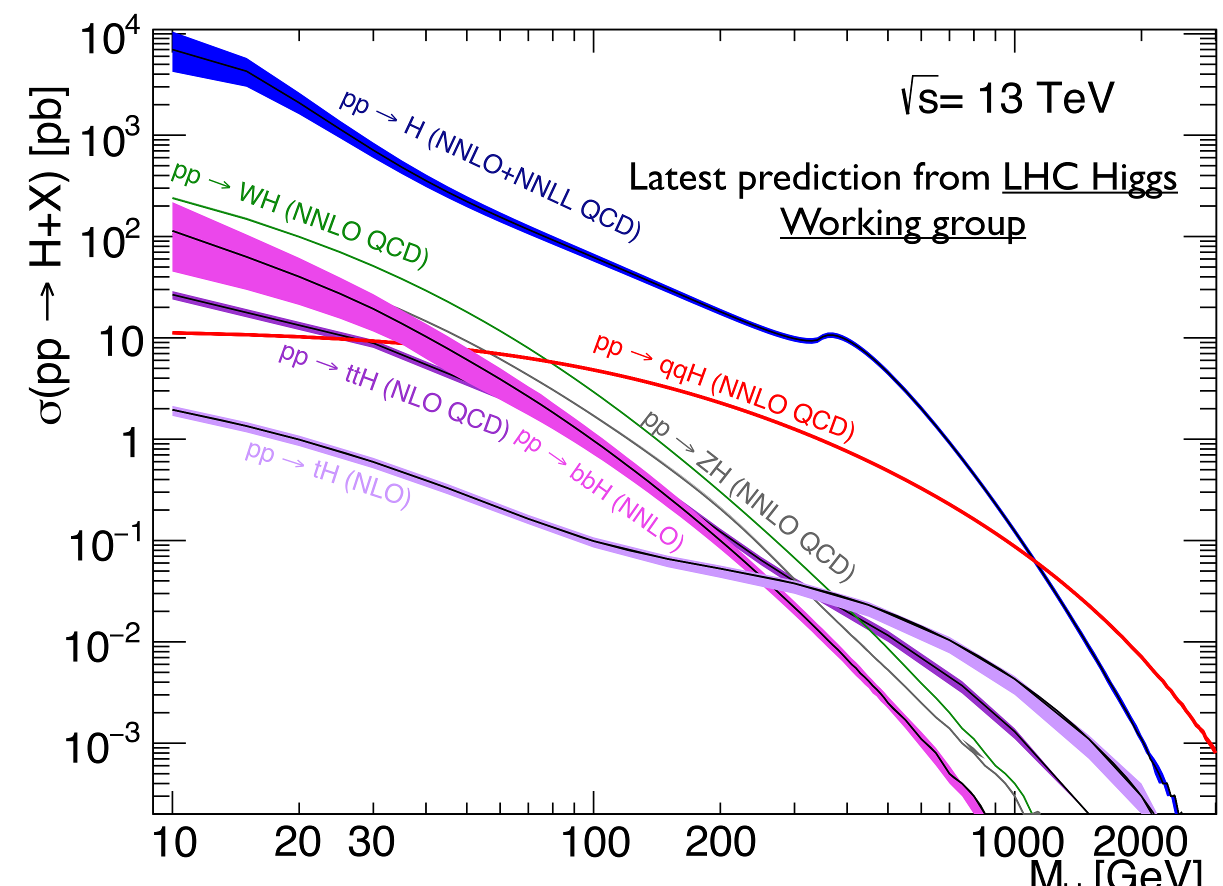


Global Electroweak fits from the Gfitter Collaboration



Prediction and uncertainties of Higgs production processes as a function of the m_H

Run I status

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  - combined measurement from $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4\ell$.

Channel	Mass measurement [GeV]
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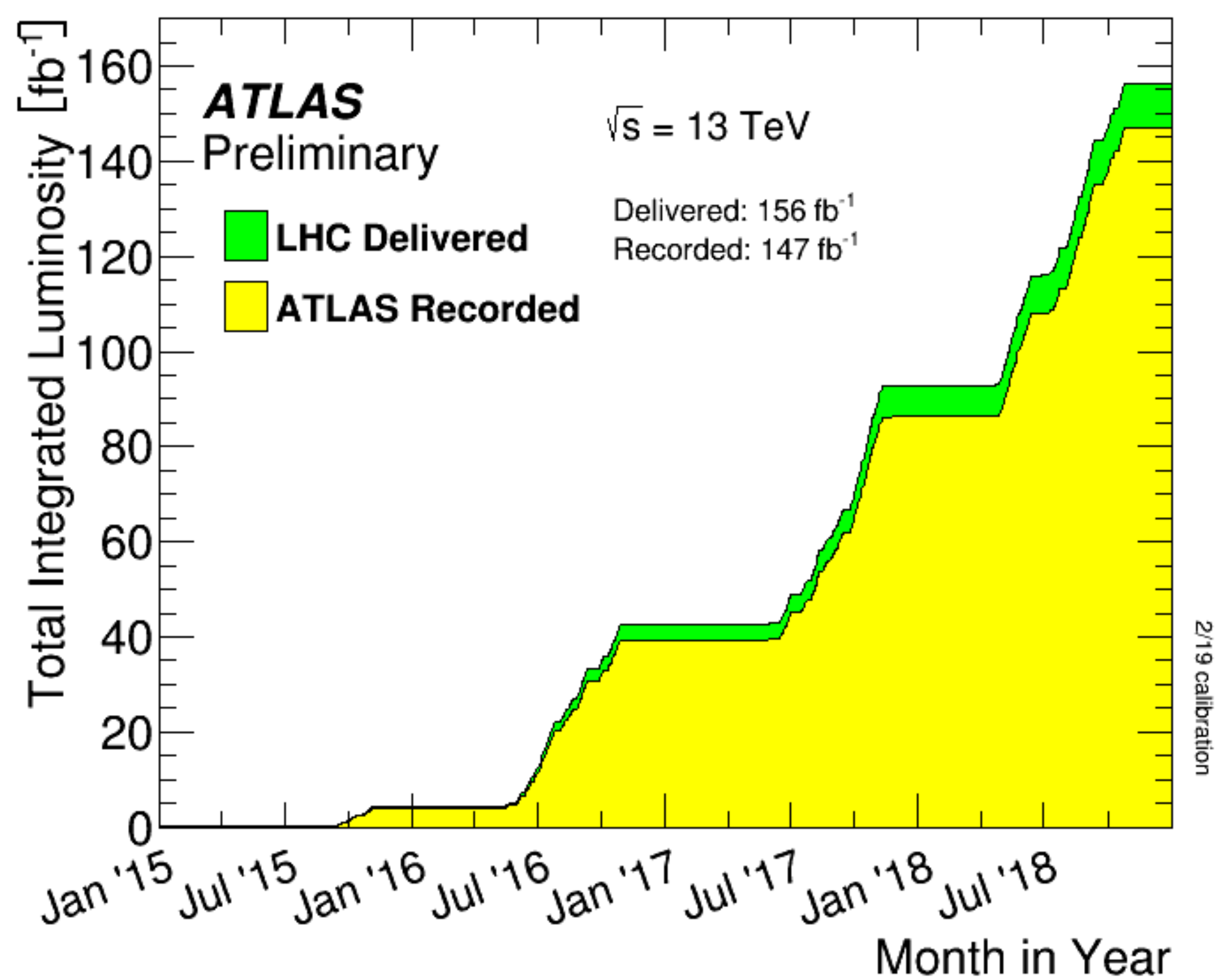
Combined	$125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst}) = 125.36 \pm 0.41$

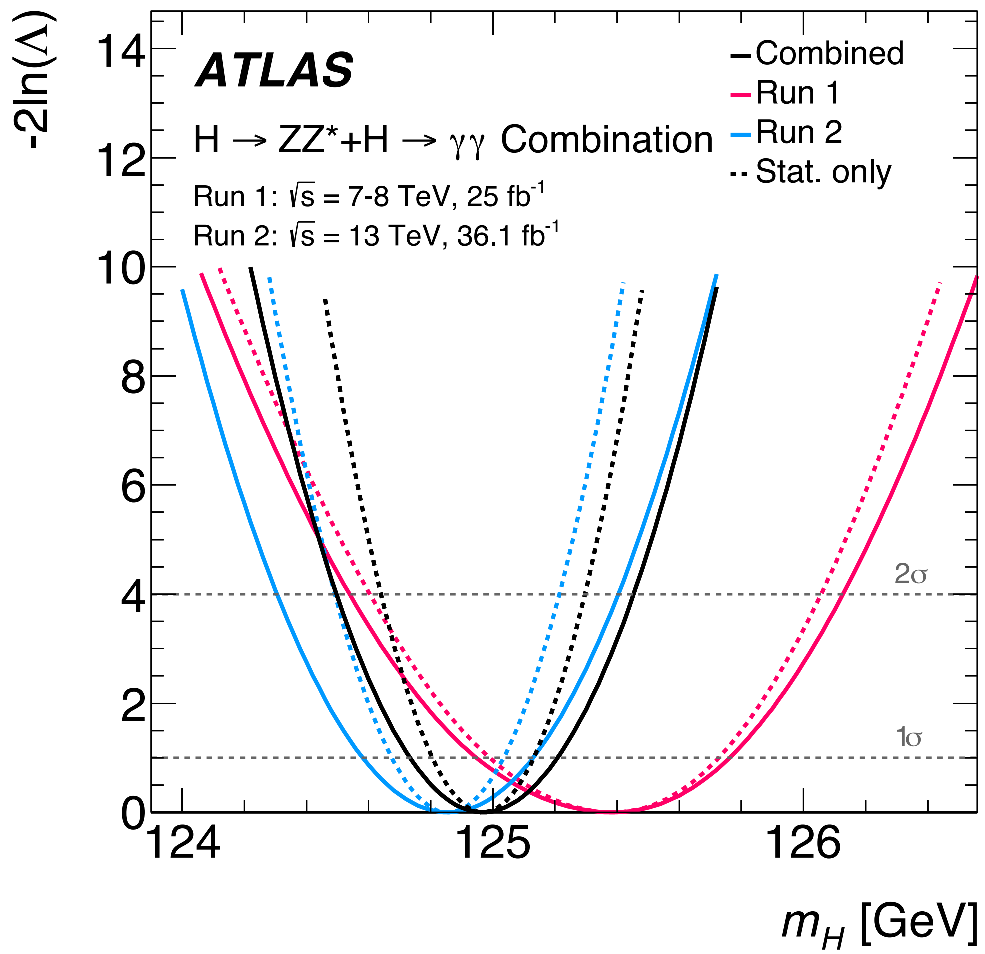
  - Both channels dominated by statistical uncertainty

- At Run2 aim in improving significantly the precision:
  - Expect 7 times more candidates, with 139 fb^{-1} at $\sqrt{s}$=13 TeV
  - Improve on the detector calibration.



- 4ℓ and $\gamma\gamma$ measurements are combined with ATLAS Run 1 result

arXiv:1806.00242



Source	Systematic uncertainty in m_H [MeV]
EM calorimeter response linearity	60
Non-ID material	55
EM calorimeter layer intercalibration	55
$Z \to ee$ calibration	45
ID material	45
Lateral shower shape	40
Muon momentum scale	20
Conversion reconstruction	20
$H \to \gamma\gamma$ background modelling	20
$H \to \gamma\gamma$ vertex reconstruction	15
e/γ energy resolution	15
All other systematic uncertainties	10

- Run 2 precision improved w.r.t Run 1.

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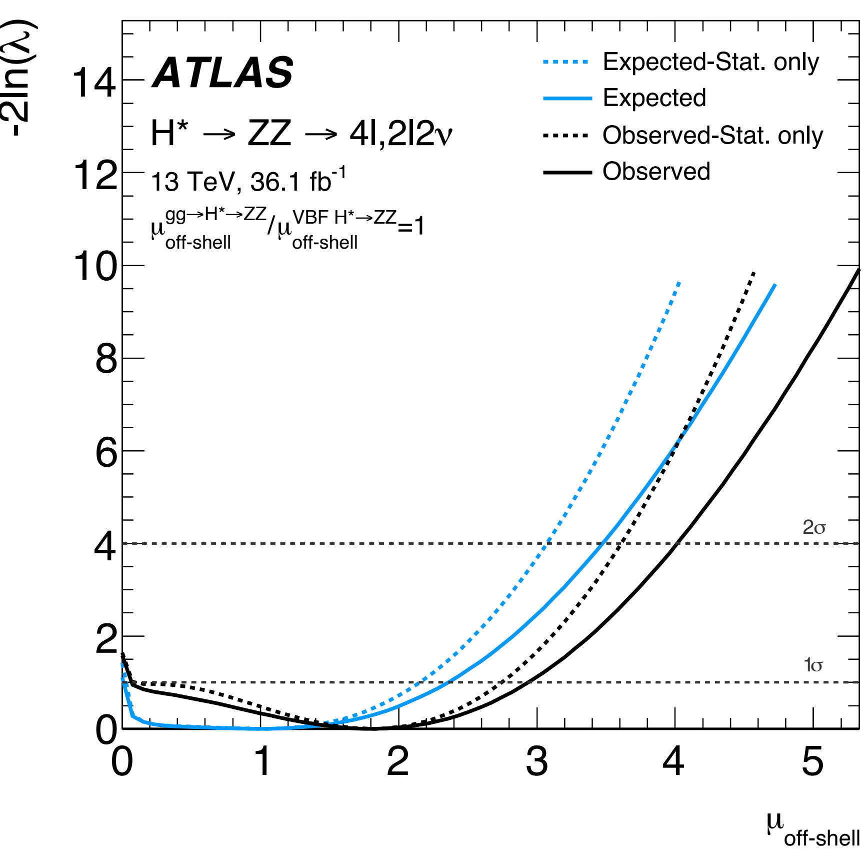
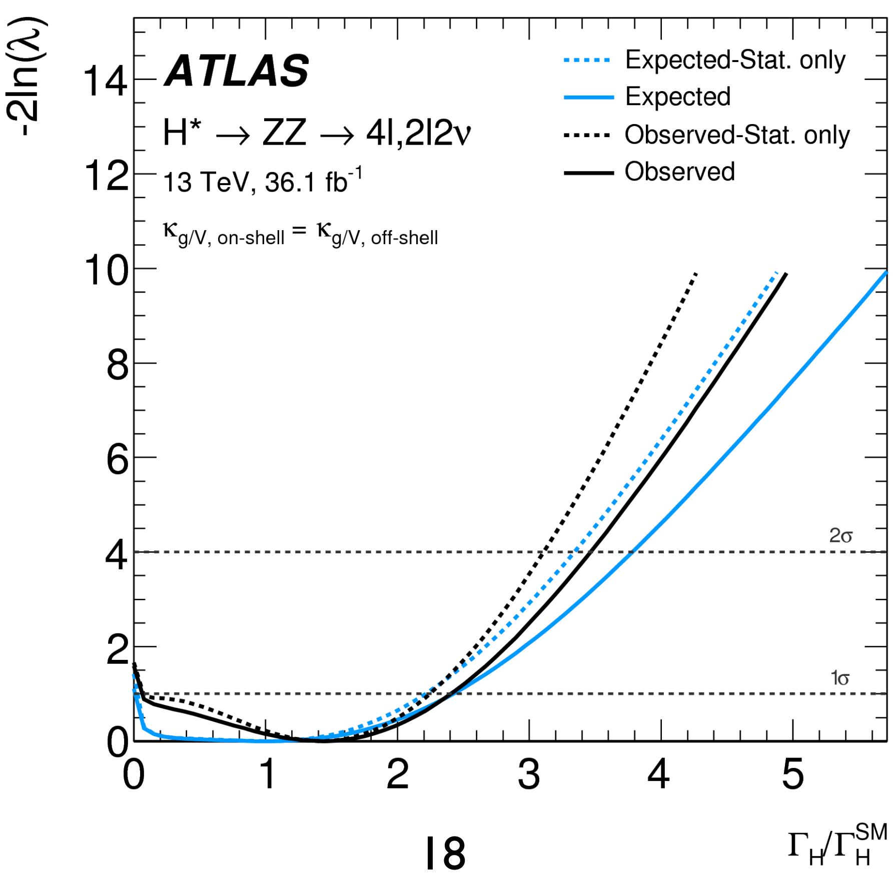
Higgs width

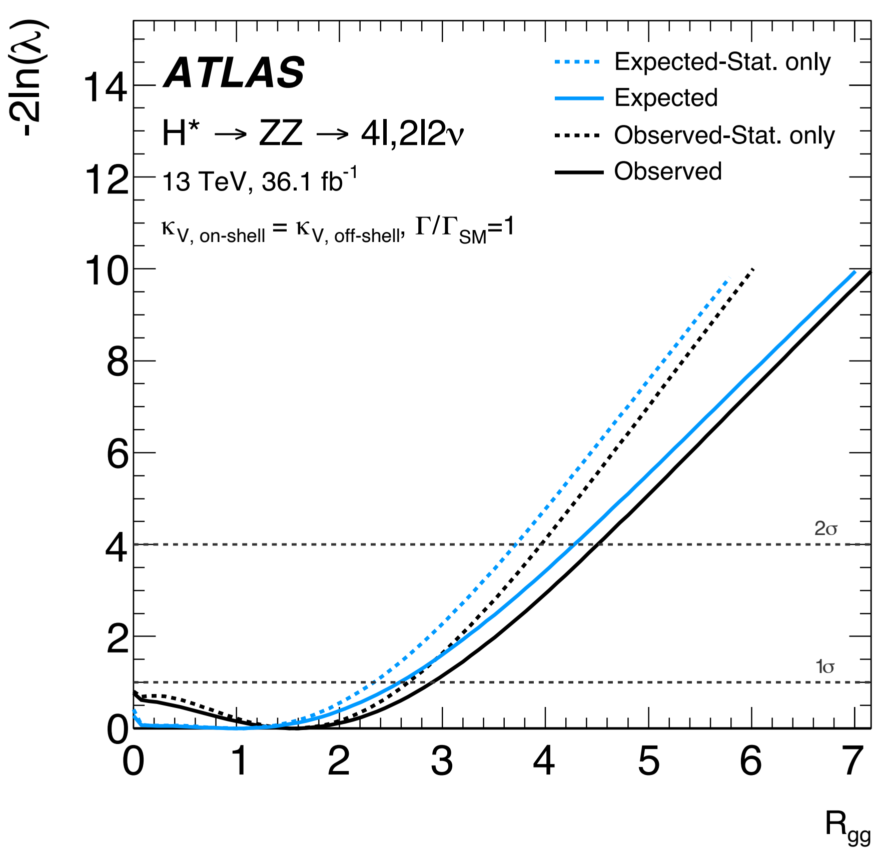
- Study of the the $m_{4\ell}$ spectrum and off-shell H production

JHEP 04 (2019) 048, Phys. Lett. B 786 (2018) 223

  - Measured upper limit on width combining 4ℓ and $\ell\bar{\ell}\nu\bar{\nu}$
  - Limit Γ_H possibile from the off-shell to on-shell event yield ratio R_{gg}
    - on-shell event yields ~ $k^2{}_{\mathrm{g,on\text{-}shell}} / \Gamma_H$, while off-shell ~ $k^2{}_{\mathrm{g,off\text{-}shell}}$
  - Observed (expected) upper limit on Γ_H 14.4 (15.2) MeV







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  - Analytical $m_{\gamma\gamma}$ background functions in kinematic and detector related categories.
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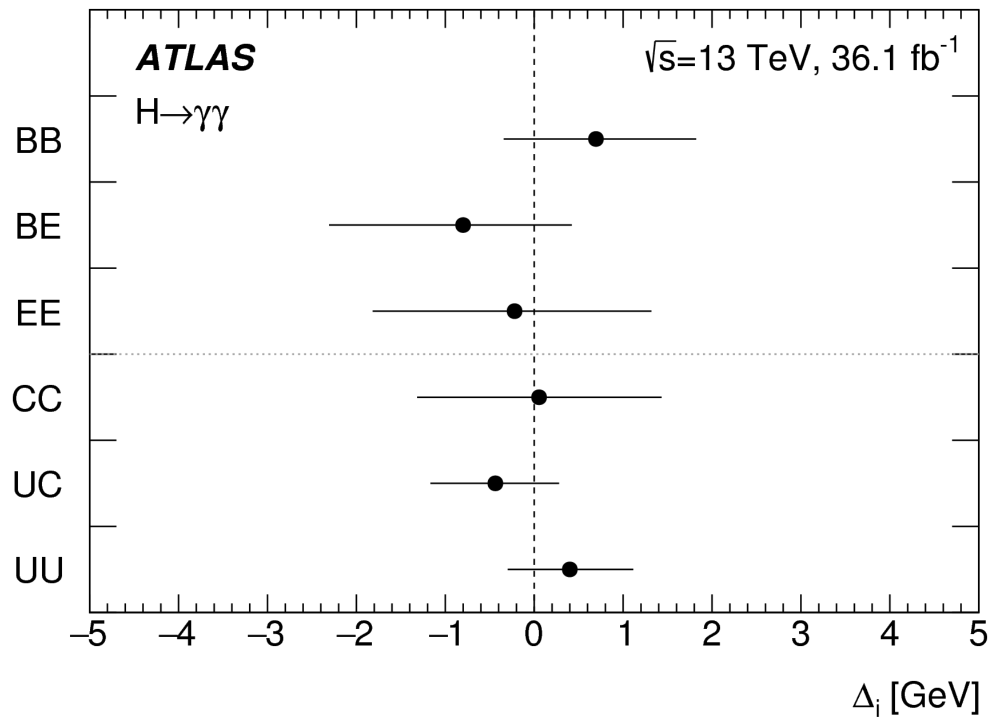

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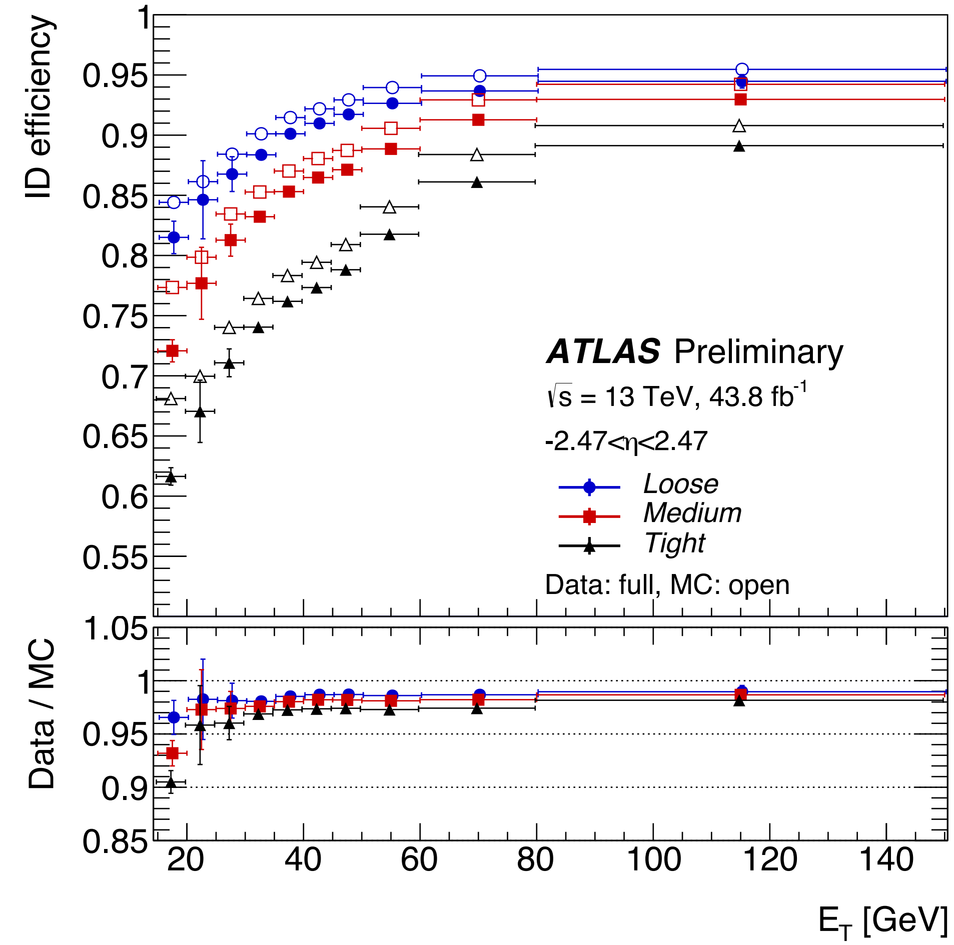
Resolution	±20
Signal model	±20

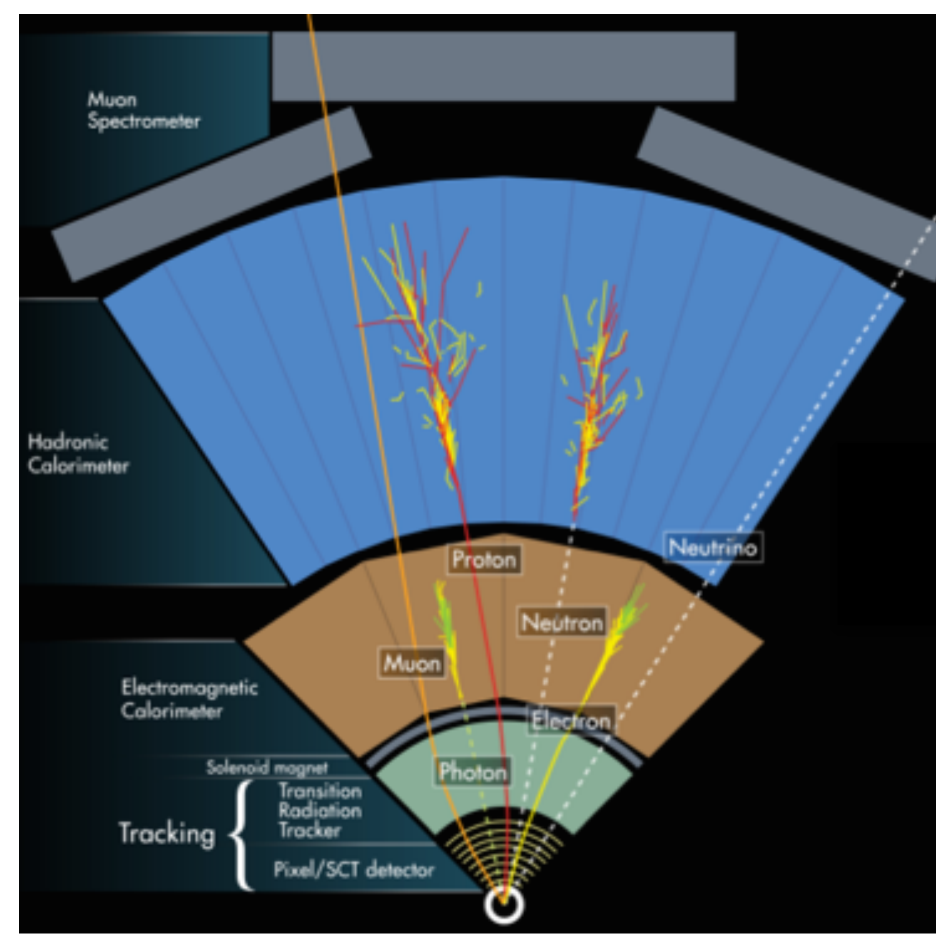
Object selection

- **Electrons** (e).
  - Isolated objects clustered from calorimeter energy deposits with associated ID track.
  - $E_T > 7$ GeV, $|\eta| < 2.47$ and $|z_0 \sin(\vartheta)| < 0.5$ mm

- **Muons** (μ).
  - Combined track fit of Inner Detector and Muon Spectrometer hits,
  - $p_T > 5$ GeV, $|\eta| < 2.7$ $|z_0 \sin(\vartheta)| < 0.5$ mm of "loose or medium quality"
  - Isolated objects

- **Missing transverse energy** (E_T^{miss}).
  - Inferred from transverse momentum imbalance





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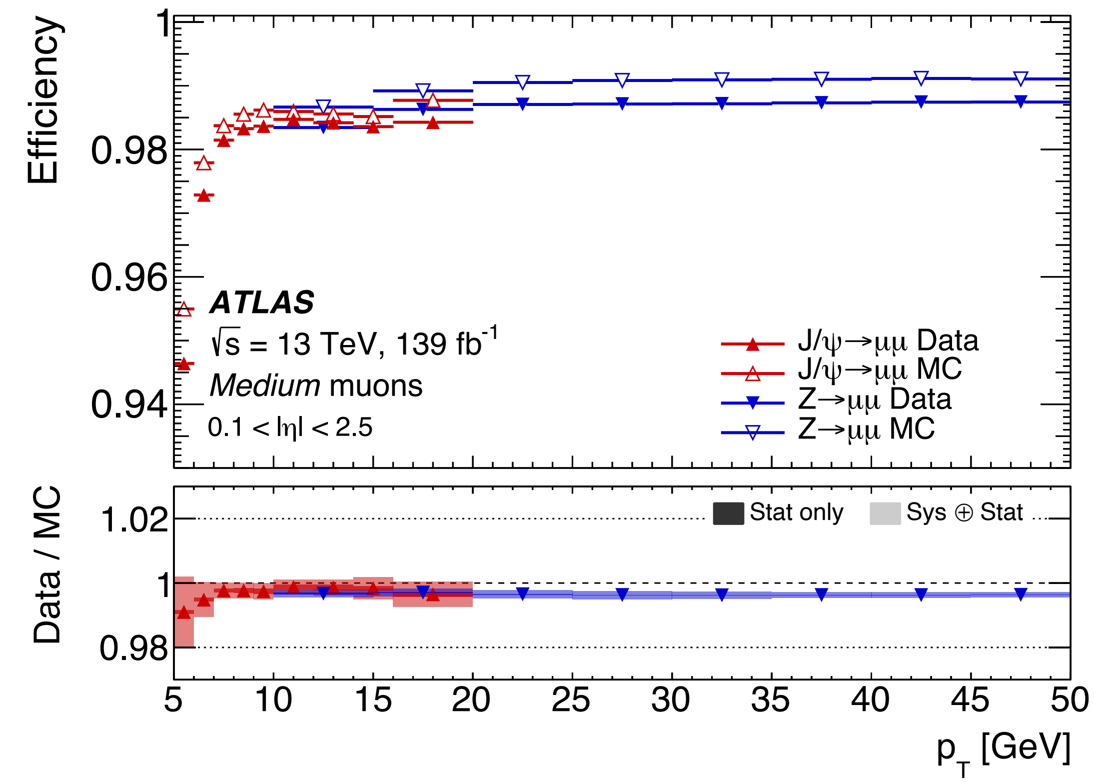

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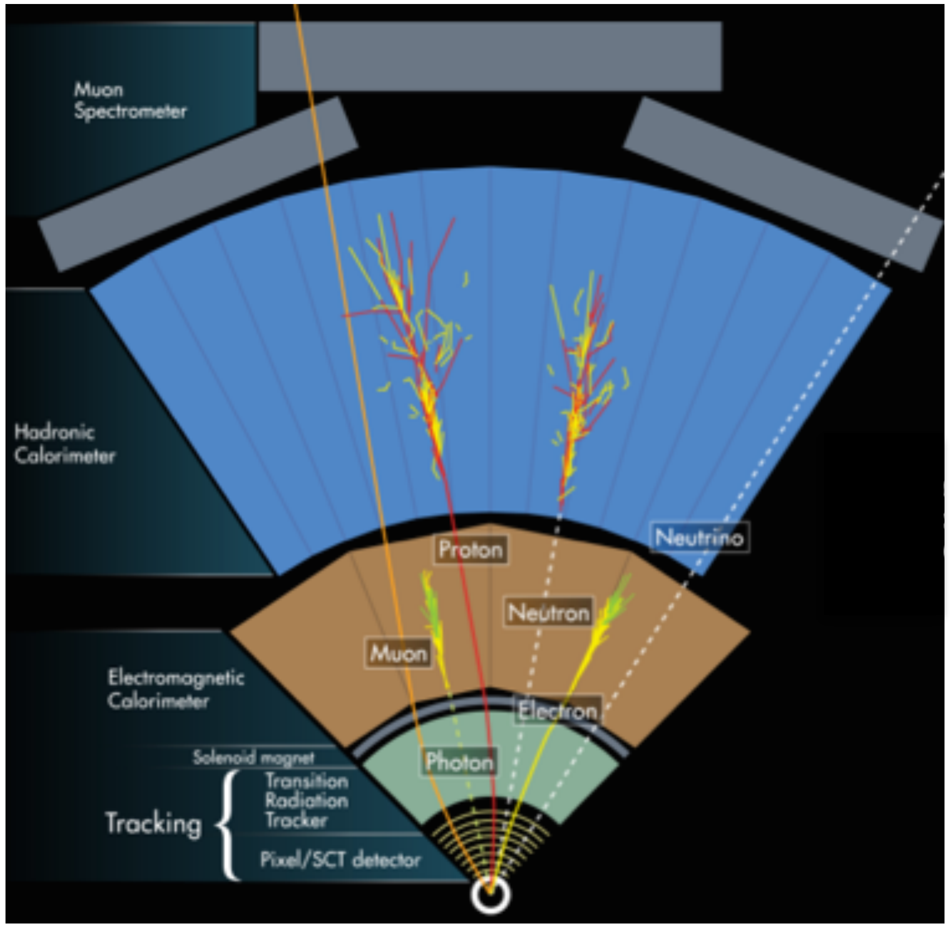
- Jets (j).
  - Energy deposit grouping with *infra*-red safe algorithm:
  - $p_T > 25$ GeV and $|\eta| < 4.5$
    - ✦ Clustering with anti-k_T, R=0.4



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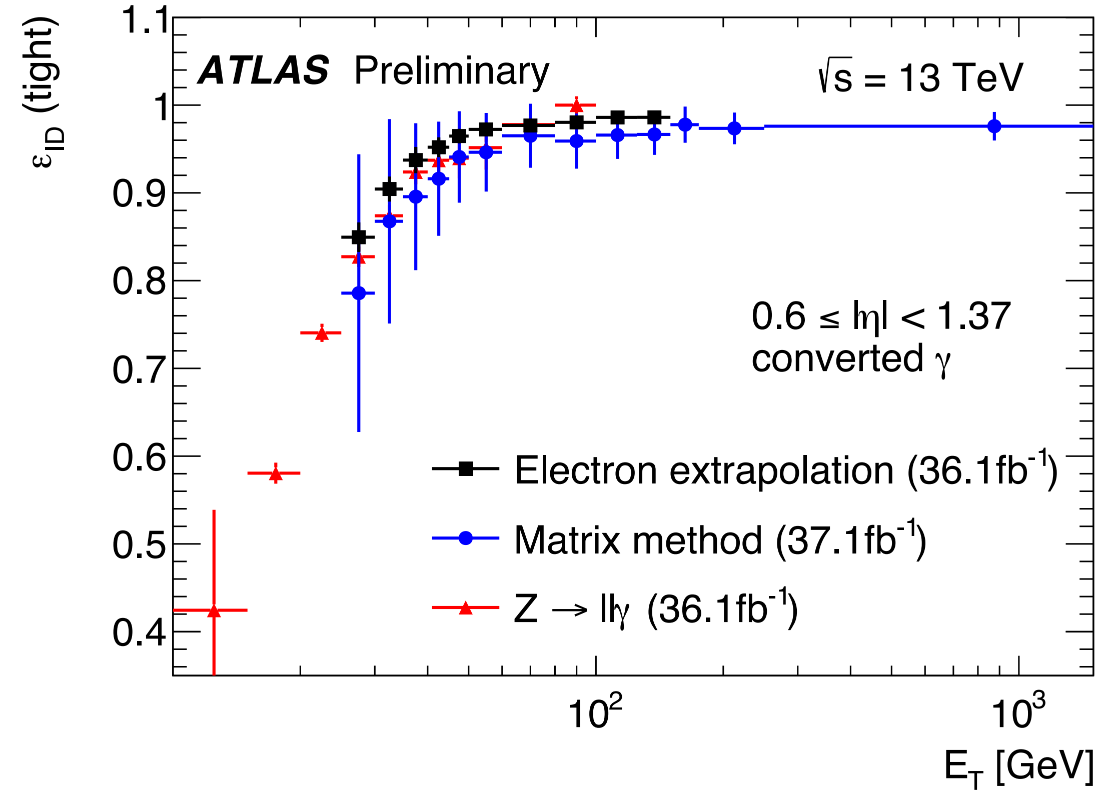

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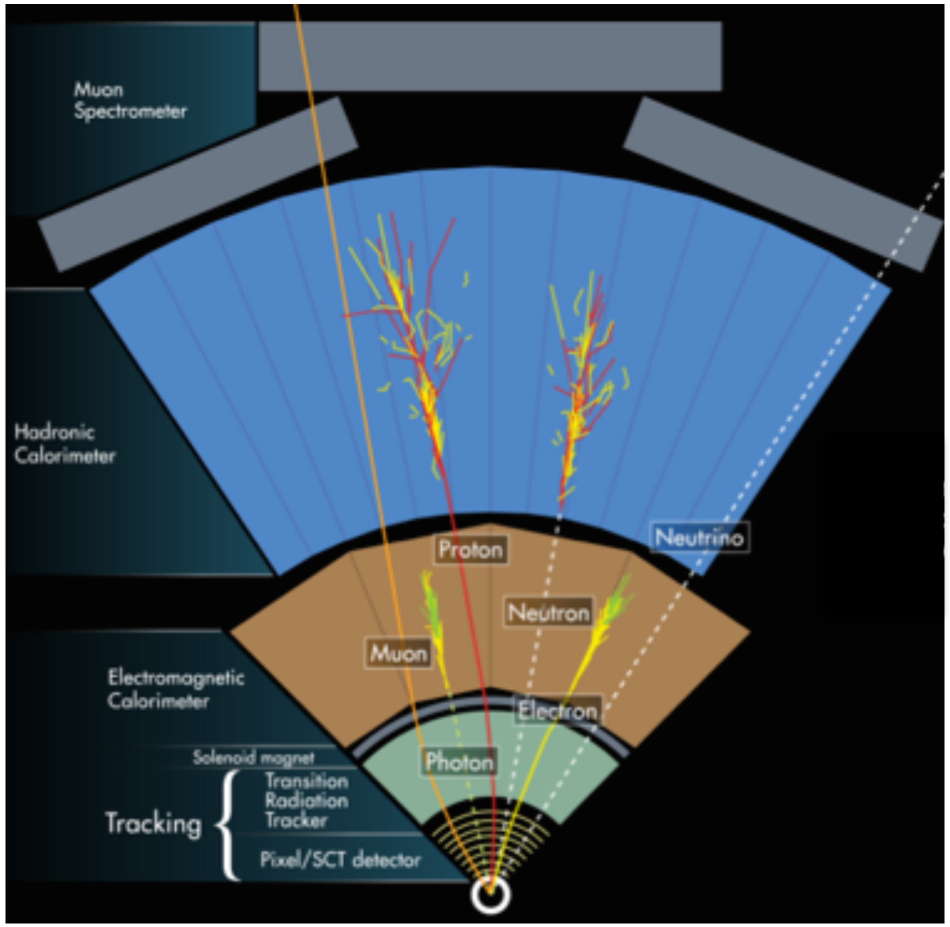
- Photons (γ).
  - Clustering of calorimeter energy deposits.
  - Identified with rectangular cuts on shower shapes.



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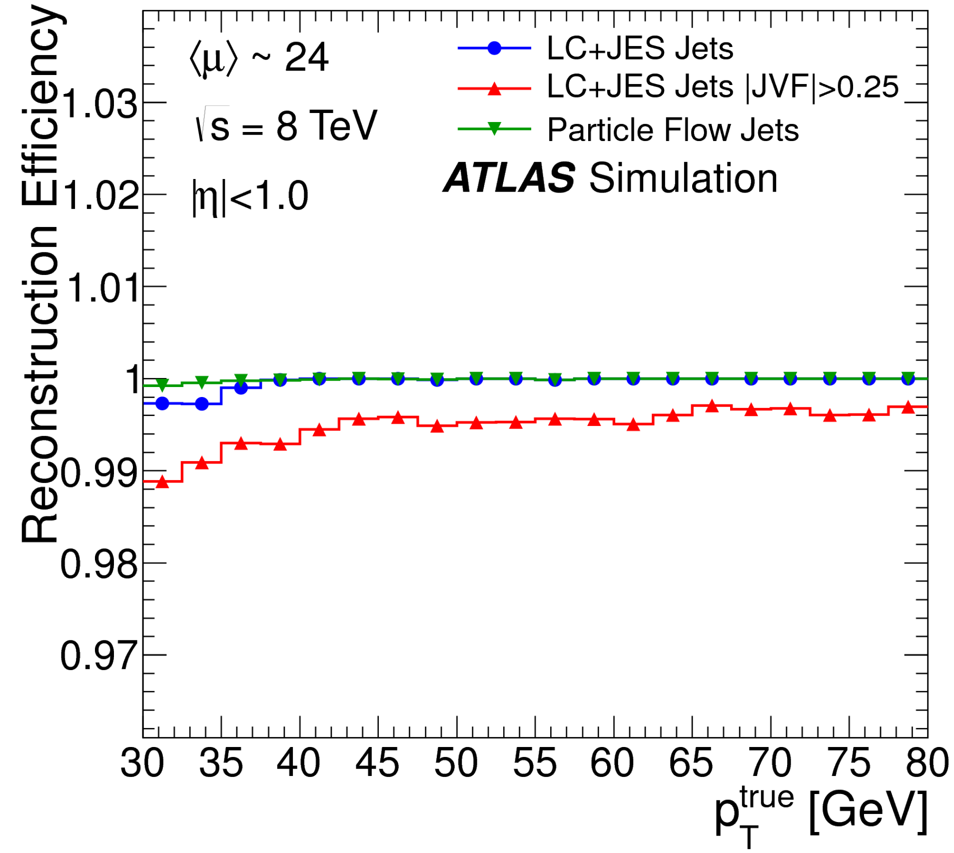

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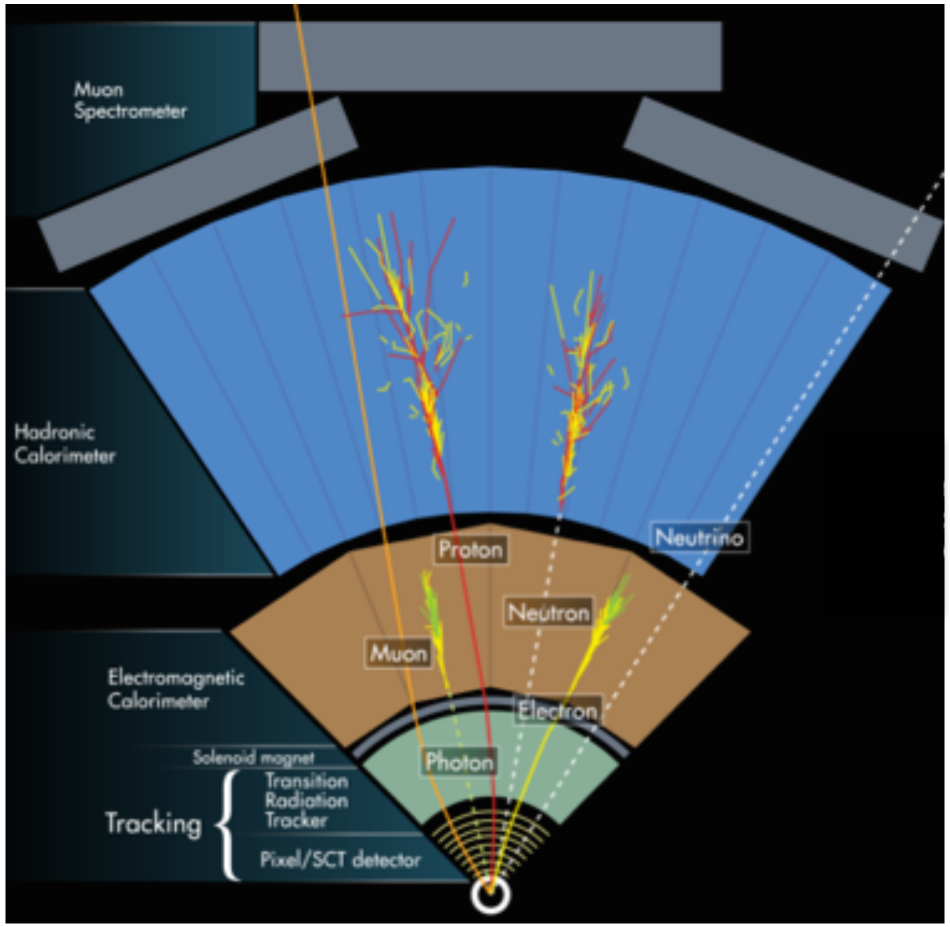

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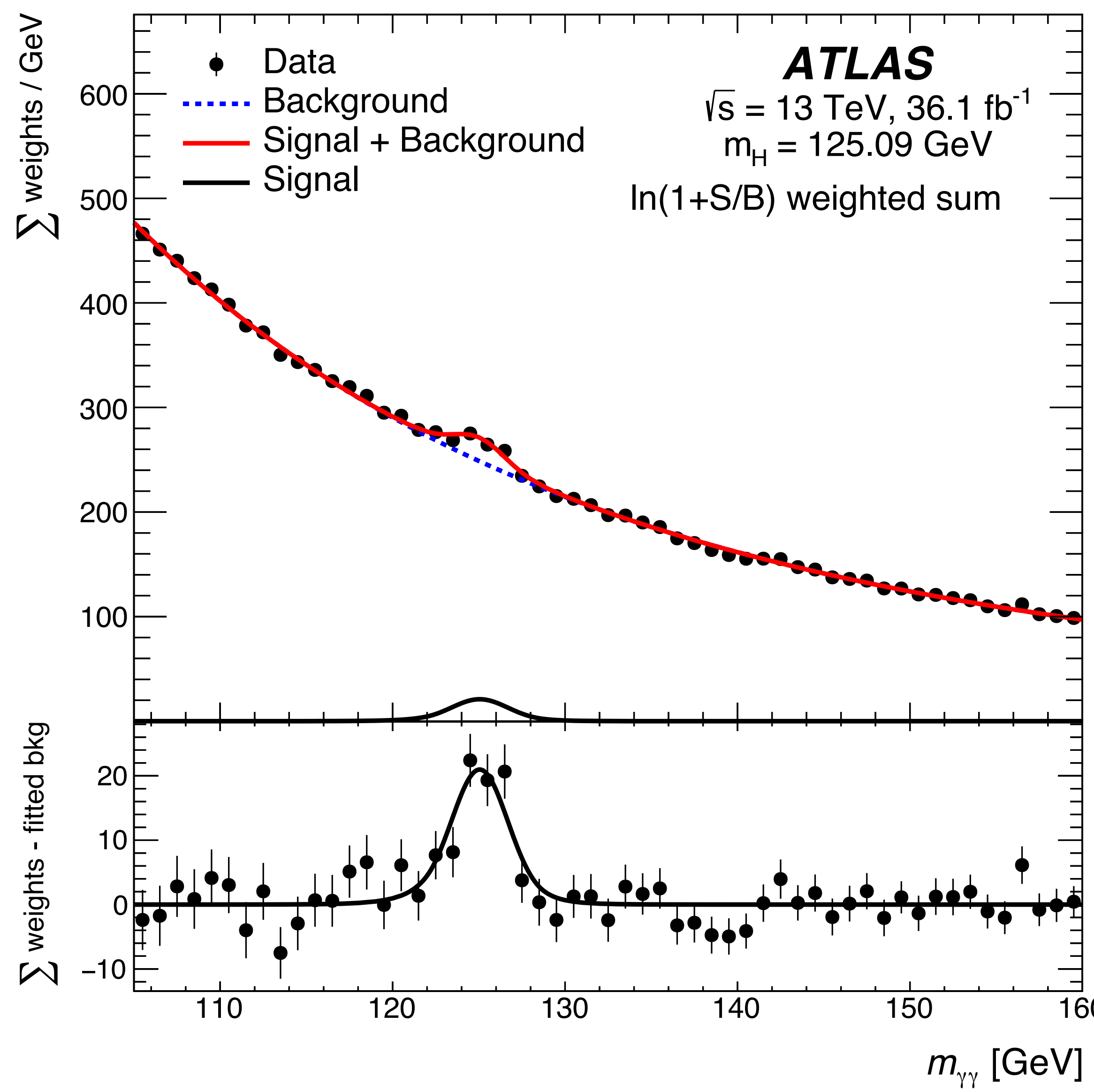
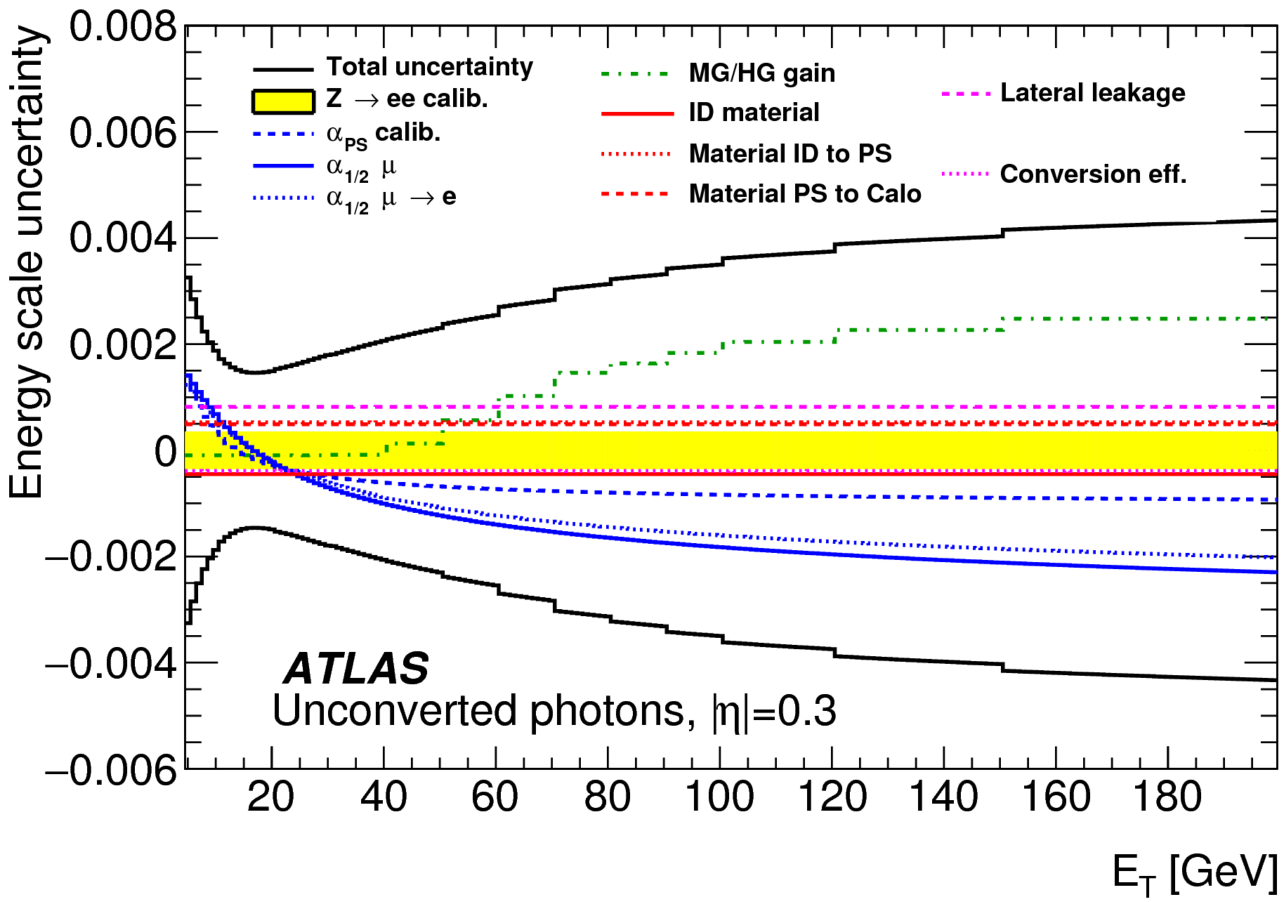
- Diphoton event selection
  - At least two photon with E_T> 25 GeV
  - Highest E_T pair forms candidate.
  - Vertex identification with Neural Network
    - Vertex within 0.3 mm for 79% of ggH events.

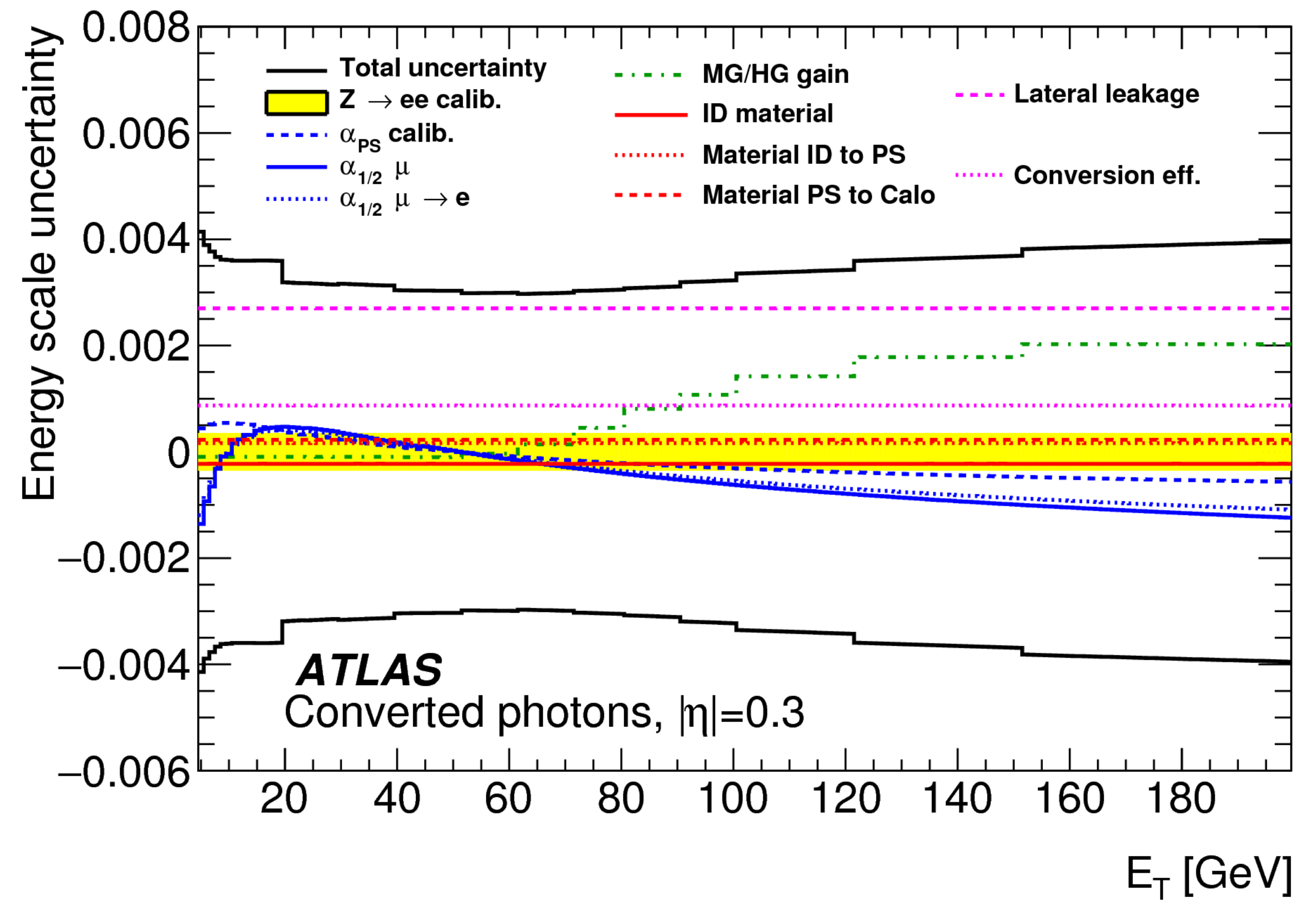


- Background estimation
  - Entirely estimated from data
  - Prompt photons: maximum likelihood fit to $m_{\gamma\gamma}$ spectrum
  - Jets misidentified as photons: from control sample

$E_T(e/\gamma)$ resolution

- Good energy calibration necessary for increased precision on m_H
  - Two step approach: i) material energy loss and ii) global calorimetric scale from $Z \rightarrow ee$ data
- Total scale uncertainty of at 40 GeV at the per-mille level.





Muon resolution

- Correction for local misalignments
  - Charge dependent bias, with net effect of worsening resolution
  - In-situ correction based on Z→μμ data, recovers up to 5% in resolution.