Measurements of the Higgs boson mass and natural width with the ATLAS detector

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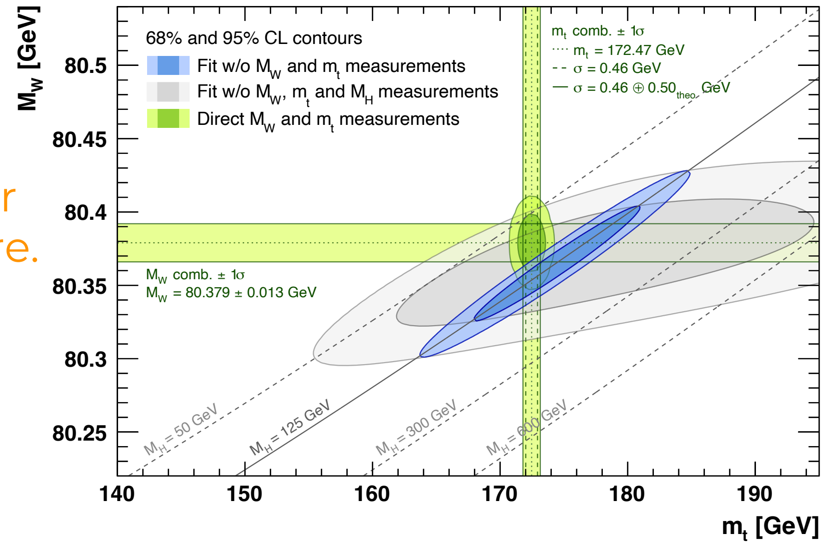
Motivations

- The Higgs boson mass (m_H) is a fundamental parameter of the SM that can only be measured experimentally.
  - Its value determines the Higgs boson production rates and decay BR: mandatory for a coherent test of the Higgs coupling structure.
  - Verify the internal consistency of the SM, (interplay between the m_{top}, m_W and m_H)
  - The stability of the EW vacuum depends on the value of the Higgs boson mass

Eur. Phys. J. C78, 675 (2018)



- Higgs boson width is predicted in the SM as a function of m_H (~ 4.1 MeV for m_H=125 GeV). Important measurement :
  - Verify the SM predictions
  - Solve the degeneracy between couplings and width: Higgs production cross-sections as measured in different production and decay gives access to this ratio:

$$\sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

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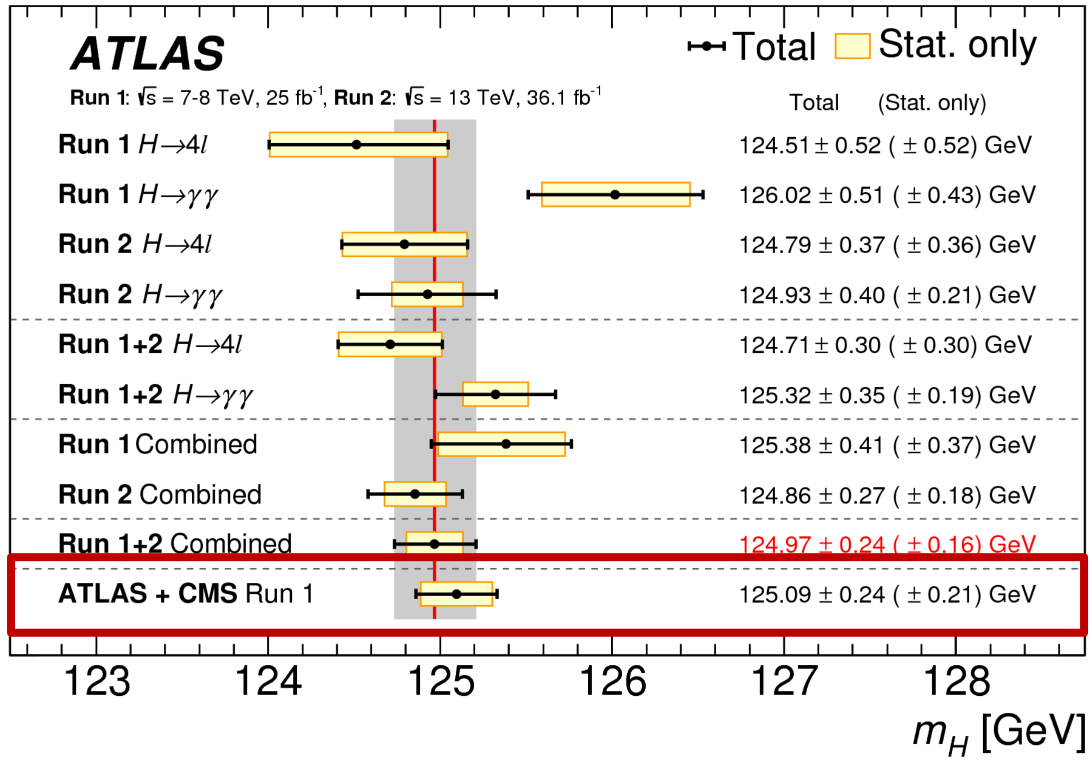
The starting point

At the LHC m_H was measured in H→γγ and H→ZZ*→4ℓ decay channels due to their excellent mass resolution (1-2%), which produces a clear peak above a continuum background in the $m_{\gamma\gamma}$ or m_{4l} distributions

- In RUN1 (25 fb^{-1} at √s=7/8 TeV) ATLAS+CMS measured m_H with a precision of 0.2%

- ATLAS provided intermediate RUN2 results (36 fb^{-1} at √s=13 TeV)
  - m_H (4l) = 124.79 ± 0.36 (stat.) ± 0.05 (syst.) GeV (limited by stat)
  - m_H (γγ) = 124.93 ± 0.21 (stat.) ± 0.34 (syst.) GeV (limited by syst)

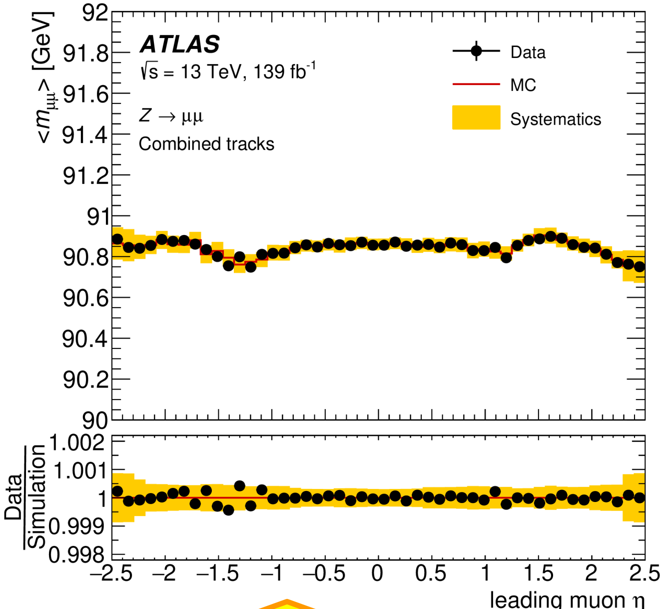


- This presentation: legacy RUN2 measurements on 140 fb^{-1} at √s = 13 TeV and their combination

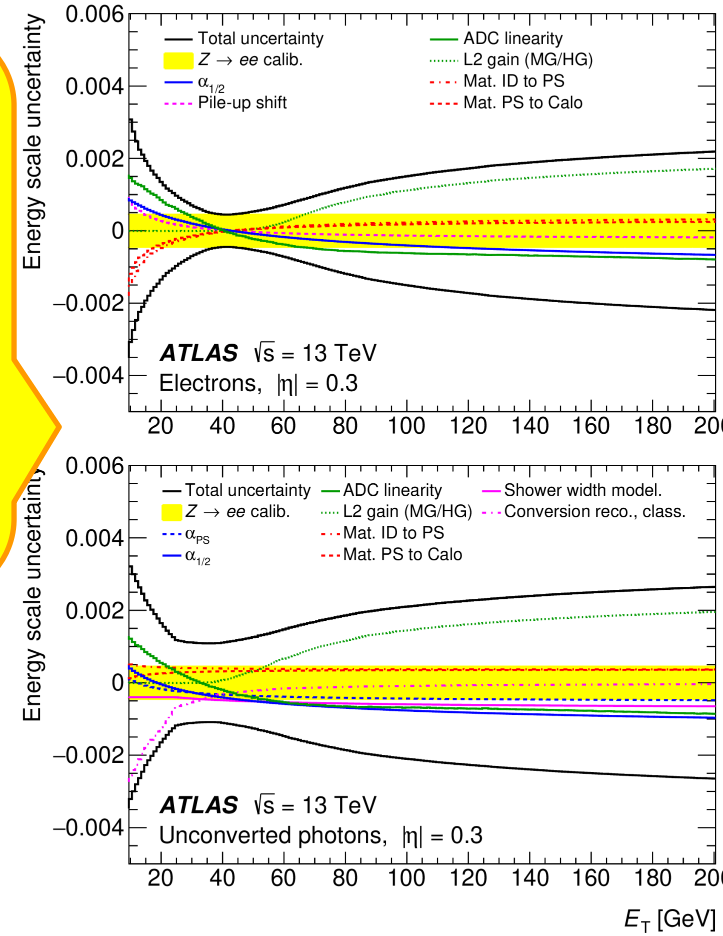
What happened in the meantime

JINST 19 (2024) P02009
Eur. Phys. J. C 83 (2023) 686

In-depth understanding of the detector performance using the full RUN2 dataset (5-6 years after the end of the data taking)



- Larger datasets (Zee, Zlly), improved methods,
- Measurement of the linearity (Z-> ee) constraints p_T dependent syst
- Overall calibration uncertainty reduced by a factor of 2–3, depending on particle type, η and P_T



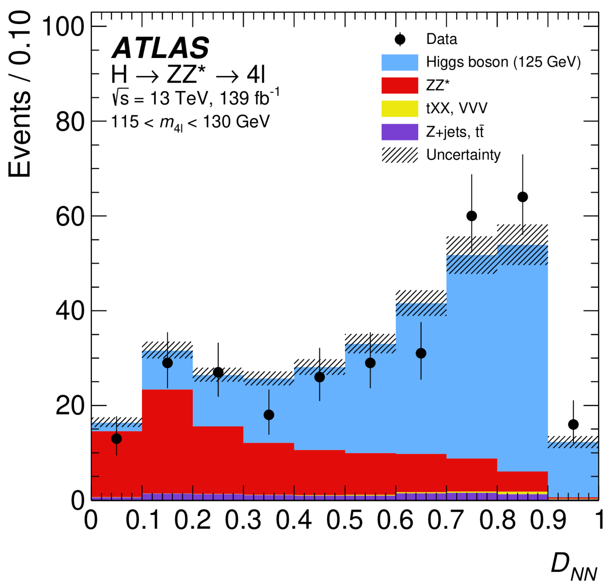
- Correction of charge-dependent bias,
- new J/ψ → $\mu\mu$ data (improved trigger strategies)
- New fitting techniques with better convergence
- Sgnificantly larger data sample
- Momentum scale uncertainty reduced by up to a factor of 2 : for Z → μμ decays, the uncertainty from 0.05% to 0.15%

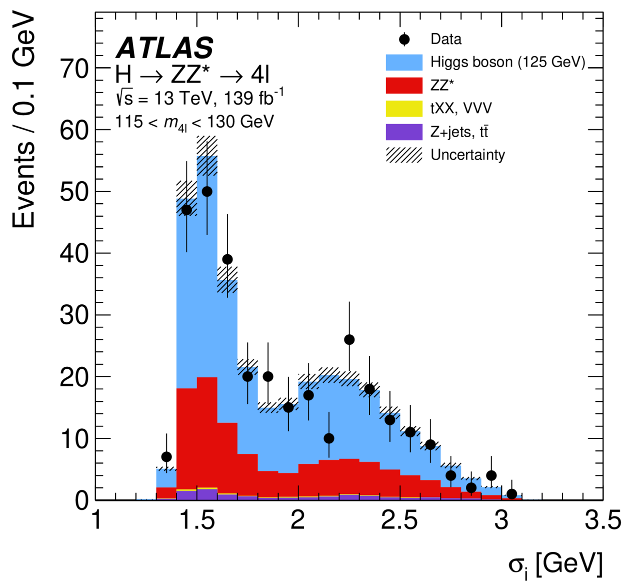
Phys. Lett. B 843 (2023) 137880

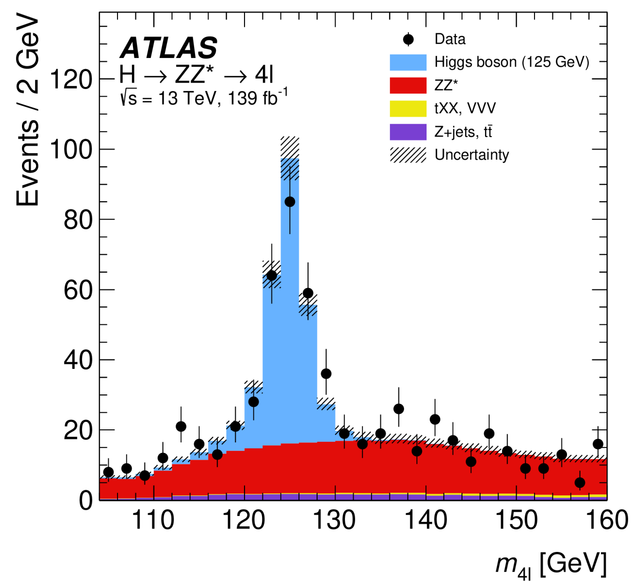
Higgs boson mass measurement in the 4l channel

Narrow peak above a background continuum (mostly non-resonant ZZ*) :

- The analysis considers four channels: 4μ, 4e, 2μ2e, 2e2μ
- Constraint to m_Z with kinematic fit (17% improvement in resolution)
- Neural Network based discriminant selecting signal and background (D_{NN})
- Modelling of per-event resolution (σ_i)
  - The resolution ranges from 1.5 GeV (4μ and 2e2μ) to about 2.1 GeV (2e2μ and 4e)
- Signal PDF modelled as a function of, D_{NN} , σ_i and m_{4l}







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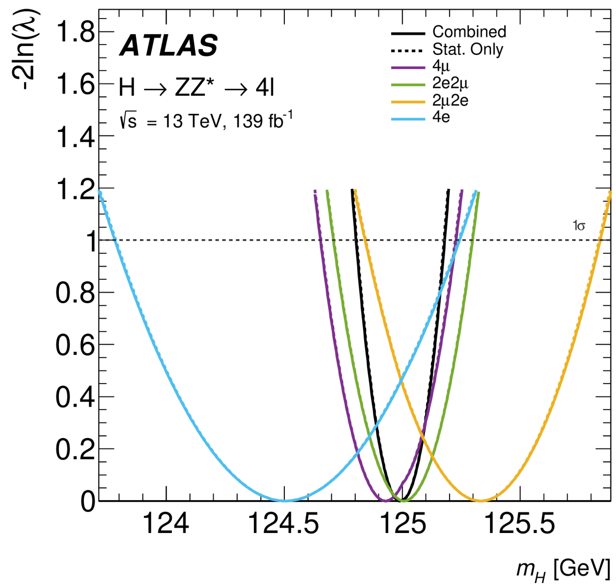
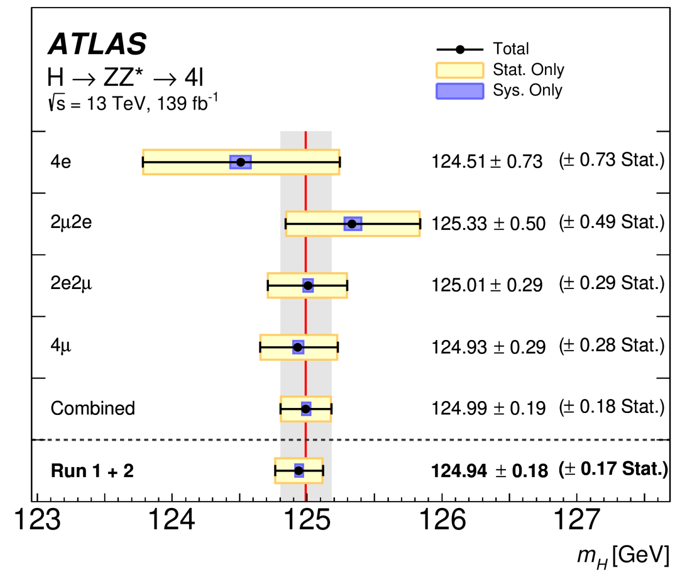
Higgs boson mass measurement in the 4l channel

The value of m_H from a simultaneous ML fit on all categories (4μ, 4e, 2μ2e, 2e2μ)





RUN2 : m_H = 124.99 ± 0.18 (stat.) ± 0.04 (syst.) = 124.99 ± 0.19 GeV

- Dominant syst unceratinties from muon and electron scale

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

RUN1+RUN2 : m_H = 124.94 ± 0.17 (stat.) ± 0.03 (syst.) = 124.94 ± 0.18 GeV

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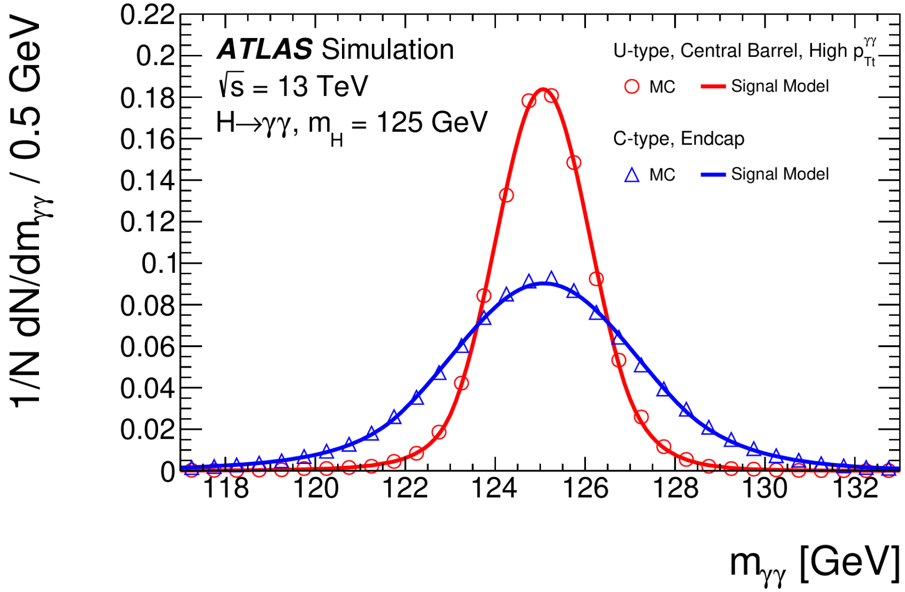
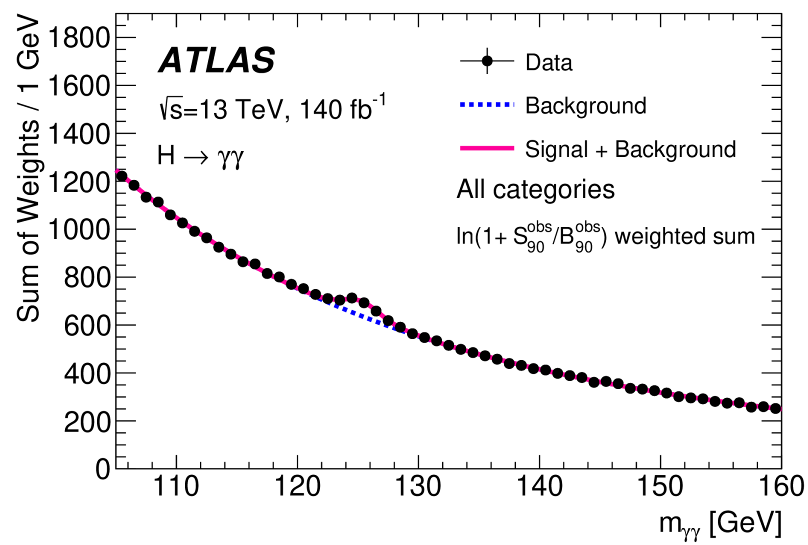
Higgs boson mass measurement in the $\gamma\gamma$ channel

- Require two good-quality and isolated photons with $p_T/m_{\gamma\gamma}$ > 0.35 (0.25)
- Separate events in mutually exclusive categories to minimise the total expected uncertainty on m_H
- Model the signal and smoothly falling background with analytical functions
- Systematic uncertainties included in the model as nuisance parameters
- m_H from a maximum likelihood fit on the $m_{\gamma\gamma}$ distributions simultaneously in all categories





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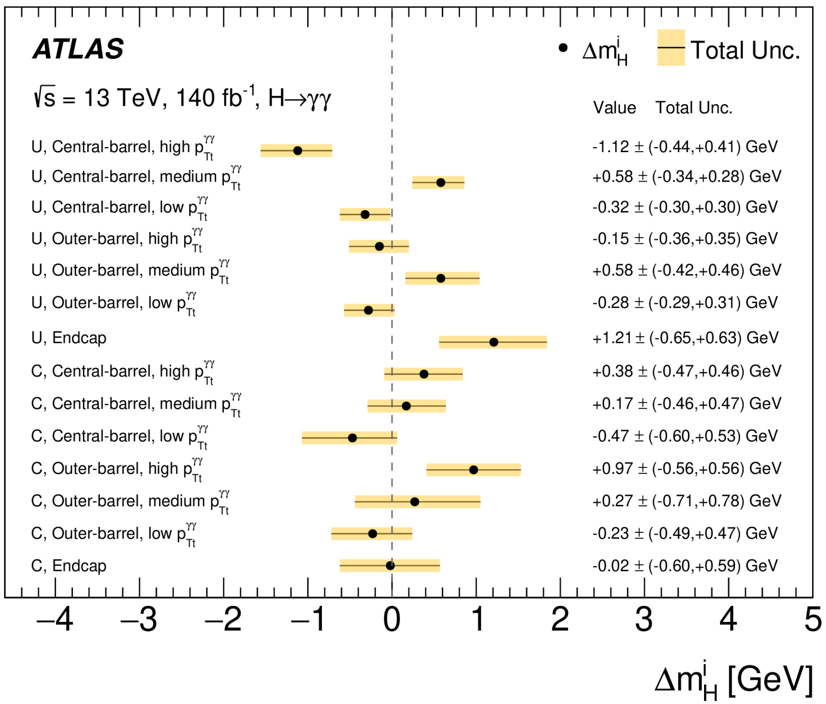
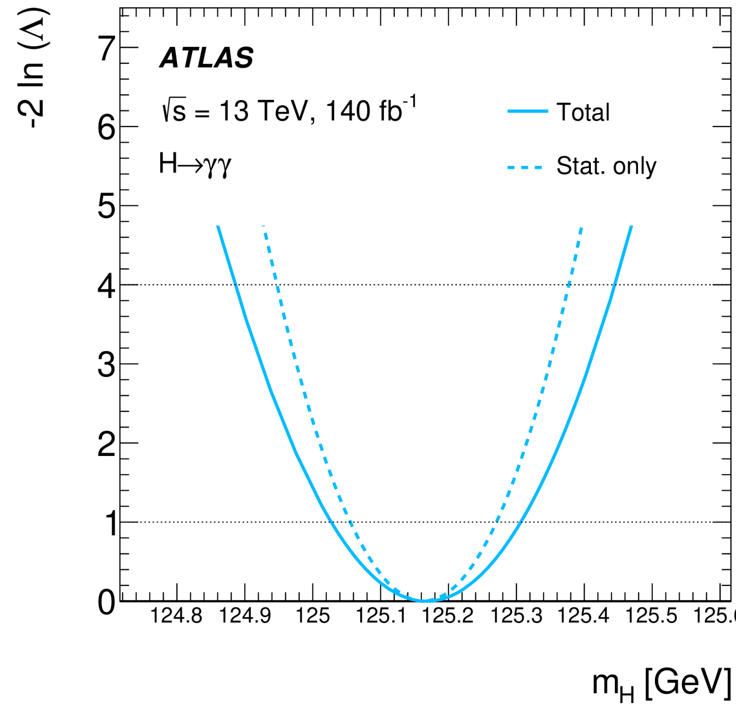
Higgs boson mass measurement in the $\gamma\gamma$ channel

m_H from a simultaneous maximum likelihood fit on the 14 categories





$$m_H = 125.17 \pm 0.11\ (\text{stat.}) \pm 0.09\ (\text{syst.}) = 125.17 \pm 0.14\ \text{GeV}$$

- ❑ Reaching a precision of 0.11% : syst uncertainties below stat !
- ❑ Global compatibility of the m_H for the individual categories with a p-value of 8%

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Higgs boson mass measurement in the $\gamma\gamma$ channel

Systematic uncertainty on m_H dominated by photon energy scale (PES):

- huge effort to refine the PES and PES uncertainties: PES uncertainty impact is reduced from 330 to 83 MeV

New clustering: better energy collection (especially for converted photons)

E_T dependent systematics are constrained by the measurement scale factors in E_T bins (*linearity fit*)

dedicated correction for photon out-of-cluster energy leakage mis-modeling by simulation

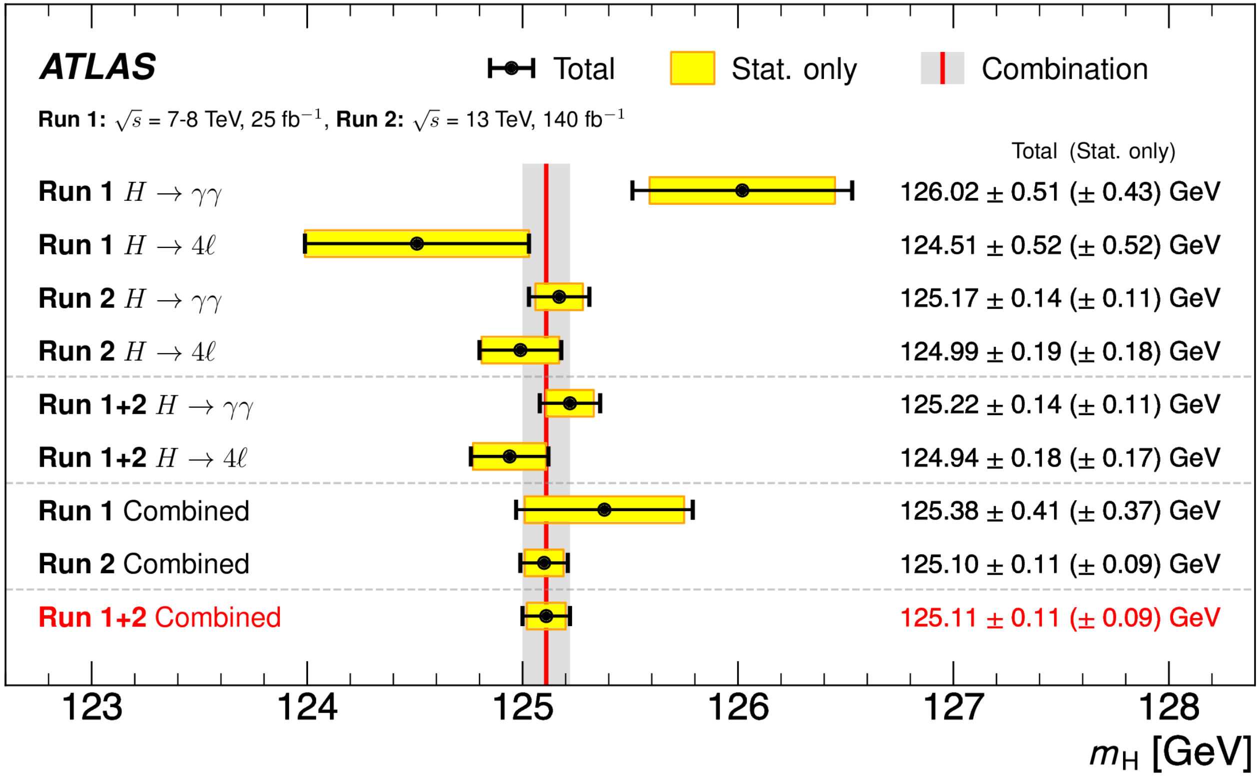
Source	Impact [MeV]
Photon energy scale	83
$Z \to e^+e^-$ calibration	59
E_T-dependent electron energy scale	44
$e^\pm \to \gamma$ extrapolation	30
Conversion modelling	24
Signal–background interference	26
Resolution	15
Background model	14
Selection of the diphoton production vertex	5
Signal model	1
Total	90

interference between the signal and the gg/qg→γγ background included as a systematic uncertainty (no central value correction)

Minor impact from signal and background modelling

Phys. Rev. Lett. 131 (2023) 251802

Combined ATLAS Higgs boson mass measurement



m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) = 125.11 ± 0.11 GeV

- Current most precise measurement of m_H reaching a precision < 1 per mill (0.09%)
- Systematic uncertainties dominated by $H\rightarrow\gamma\gamma$ channel uncertainties

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Measurement of the Higgs boson width

SM predicts the Higgs boson width of Γ_H = 4.1 MeV : too small for direct on-shell measurement !

- Indirect measurement from the ratio of on-shell/off-shell Higgs boson production in the H→ZZ decay channel
- In fact, for gg → H → ZZ final state and write the production cross-section as a function of the invariant mass of four leptons M_{4l}

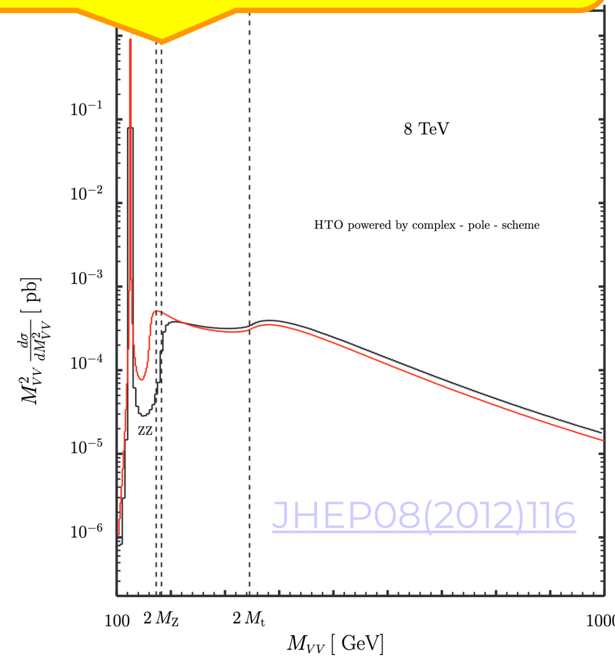
$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

→ $\frac{g_{Hgg}^2 g_{HZZ}^2}{m_H^2\Gamma_H^2}$ for $M_{4l} \sim m_H$

→ $\frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2)^2}$ for $|M_{4l}| >> m_H$

- Assuming that the on-shell and off-shell Higgs production follow SM prediction (no new physics), Γ_H can be determined

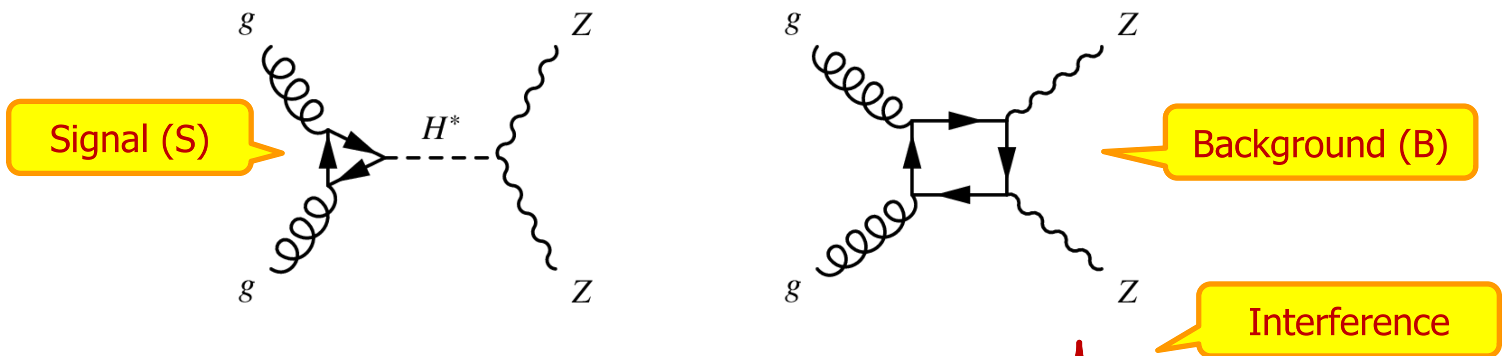
Enhancement of the off-shell production above the VV threshold (~ 8% in ZZ case)



JHEP08(2012)116

Measurement of the Higgs boson width

- Measuring the off- shell contribution not straightforward : interference with continuum background. Gluon-gluon case :



$$N_{gg\to(H*)\to ZZ} = \mu_{\mathrm{off-shell}} N_S + \sqrt{\mu_{\mathrm{off-shell}}}\left(N_{S+B} - N_S - N_B\right) + N_B$$

- In SM, negative ⇒ off-shell Higgs manifestation = deficit of events w.r.t. background only expectation
- Can also consider EW (VBF+VH) production and different modifiers $\mu_{\mathrm{off-shell}}$ (ggF) and $\mu_{\mathrm{off-shell}}$(EW)
- Need a very good MC modelling of signal and interfering background

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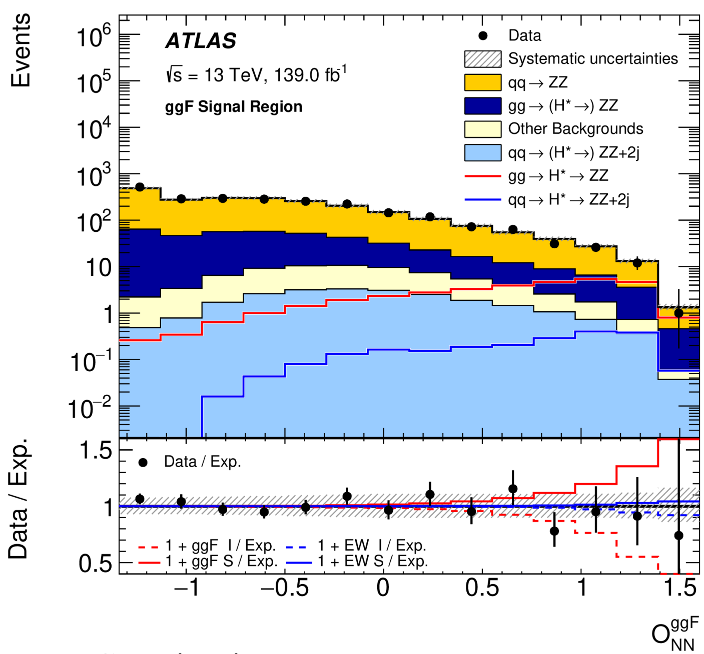
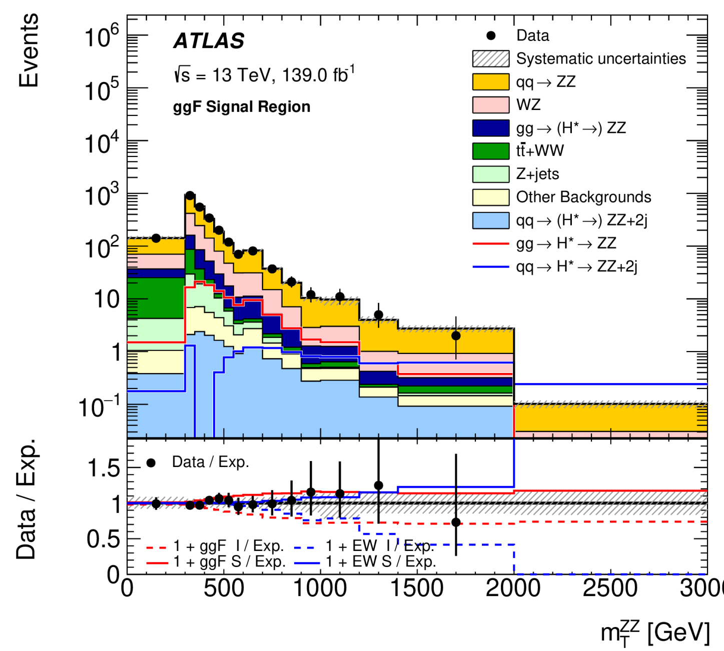
Measurement of the Higgs boson width

- The measurement is performed considering two final states
  - ZZ → 4ℓ: clean and fully reconstructible final state
  - ZZ→2ℓ2ν: six times higher branching ratio
- Targeting off shell contribution from both ggF and EW (VBF+VH) modes
  - Events are separated in ggF-like, electroweak-like and mixed categories
  - Normalization of non-interfering background from qq→ZZ fitted on data CR
- Signal vs bkg discriminated using NN (4l) or transverse mass (2l2v)





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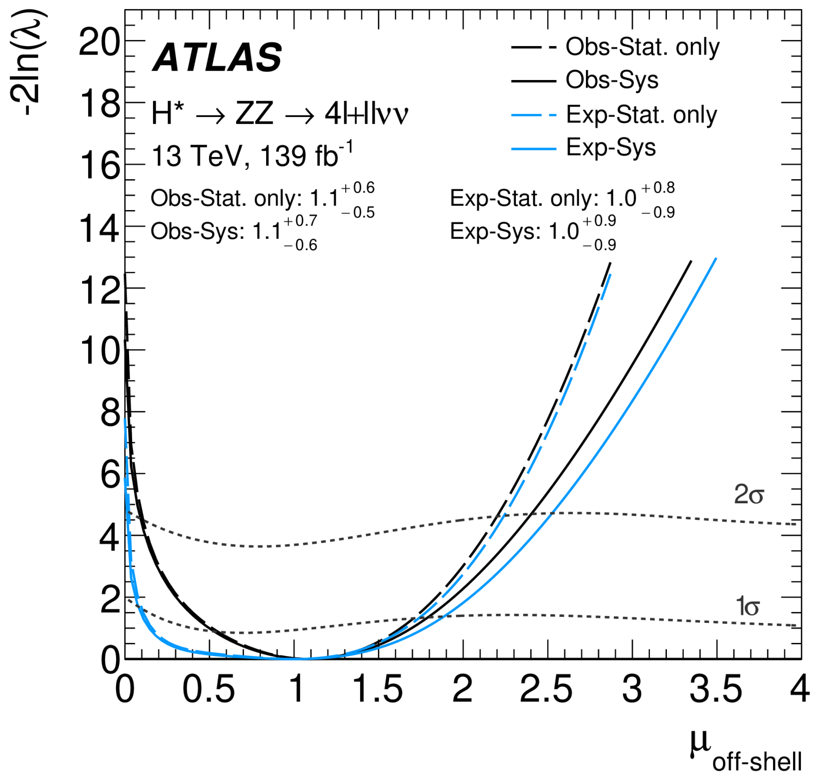
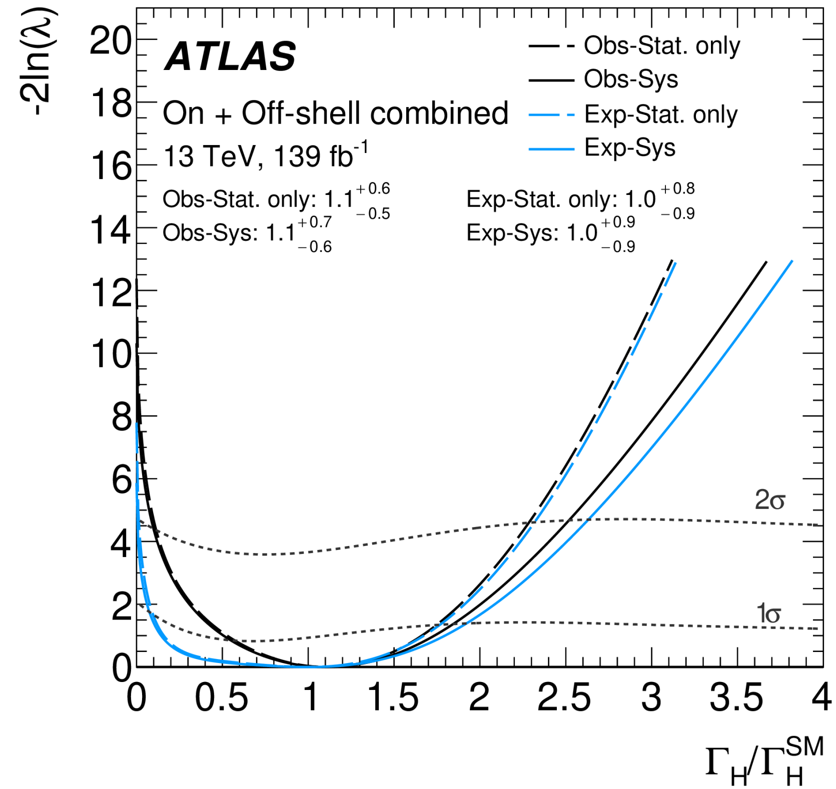
Measurement of the Higgs boson width





- $\mu_{\text{off-shell}} = 1.1^{+0.7}_{-0.6}$ with a significance of off-shell production 3.3 (2.2) σ
- After combining the off-shell measurement with the on-shell H→ZZ*→4ℓ

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV and 0.5 (0.1) < Γ_H < 10.5 (10.9) MeV at 95% CL

Conclusions

- ATLAS made huge efforts in improving the understanding of the detector's performance during RUN2 allowing sizeable improvements in m_H uncertainty

- The new ATLAS measurements of the Higgs boson mass by combining $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ final states and using $\sqrt{s}$=7,8 and 13 TeV data, resulted in the current most precise m_H measurement with an uncertainty of 0.09%

m_H = 125.11 ± 0.09 (stat.) ± 0.06 (syst.) = 125.11 ± 0.11 GeV

- The determination of the Higgs boson width is very hard at a hadron colliders: exploiting the ratio of off-shell to on-shell Higgs boson production in the ZZ decay channel with reasonable assumptions, ATLAS measured the Higgs boson width Γ_H

  - **$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV and 0.5 (0.1) < Γ_H < 10.5 (10.9) MeV at 95% CL**

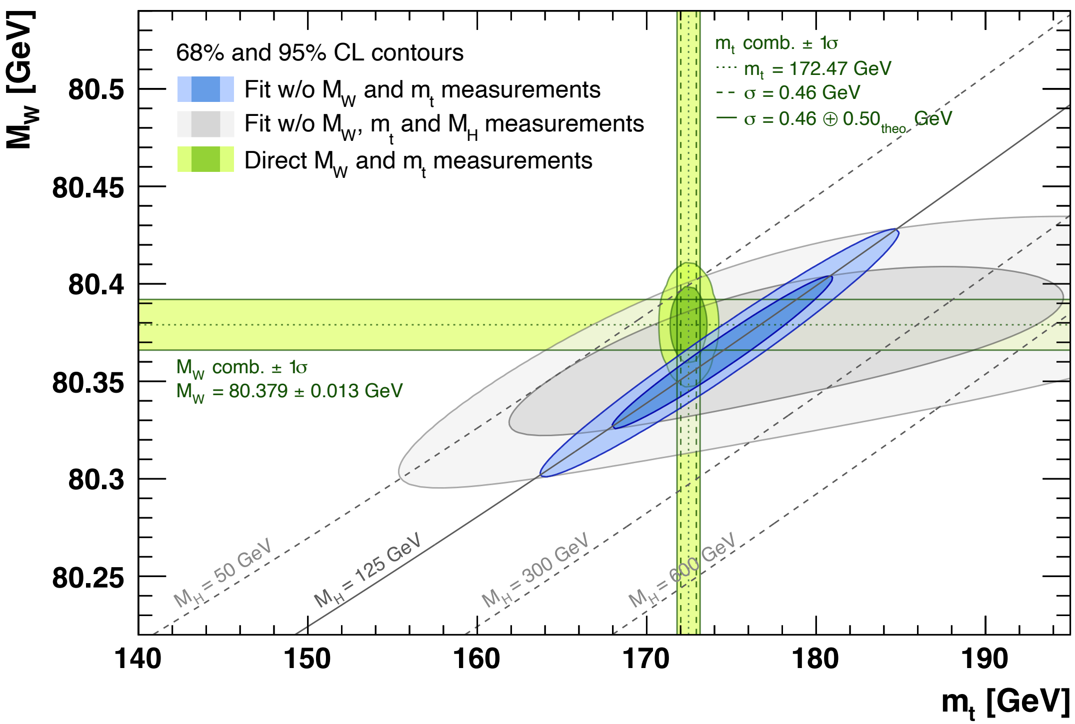
THANKS

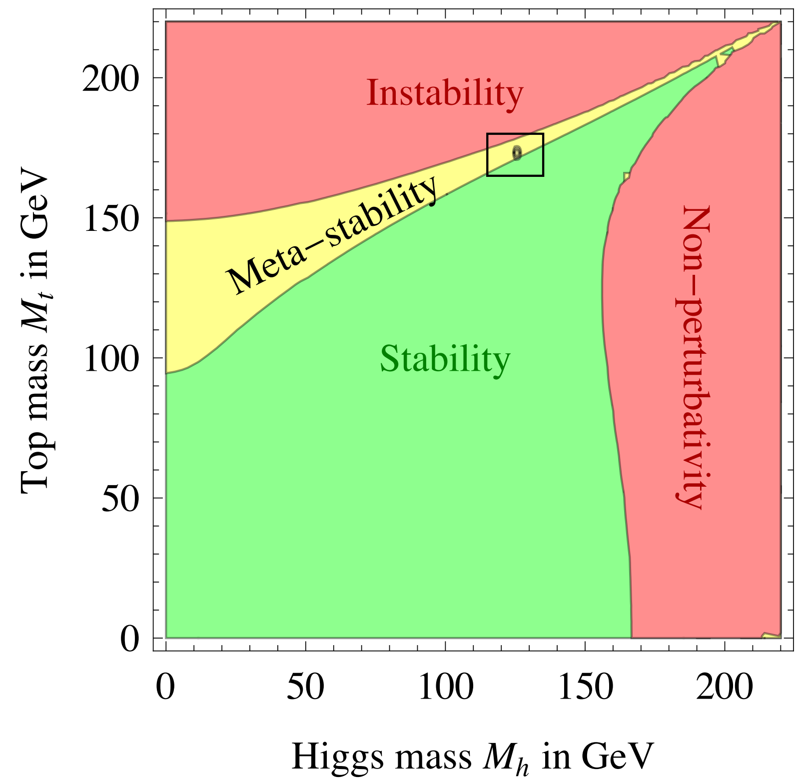
Backup

Motivations

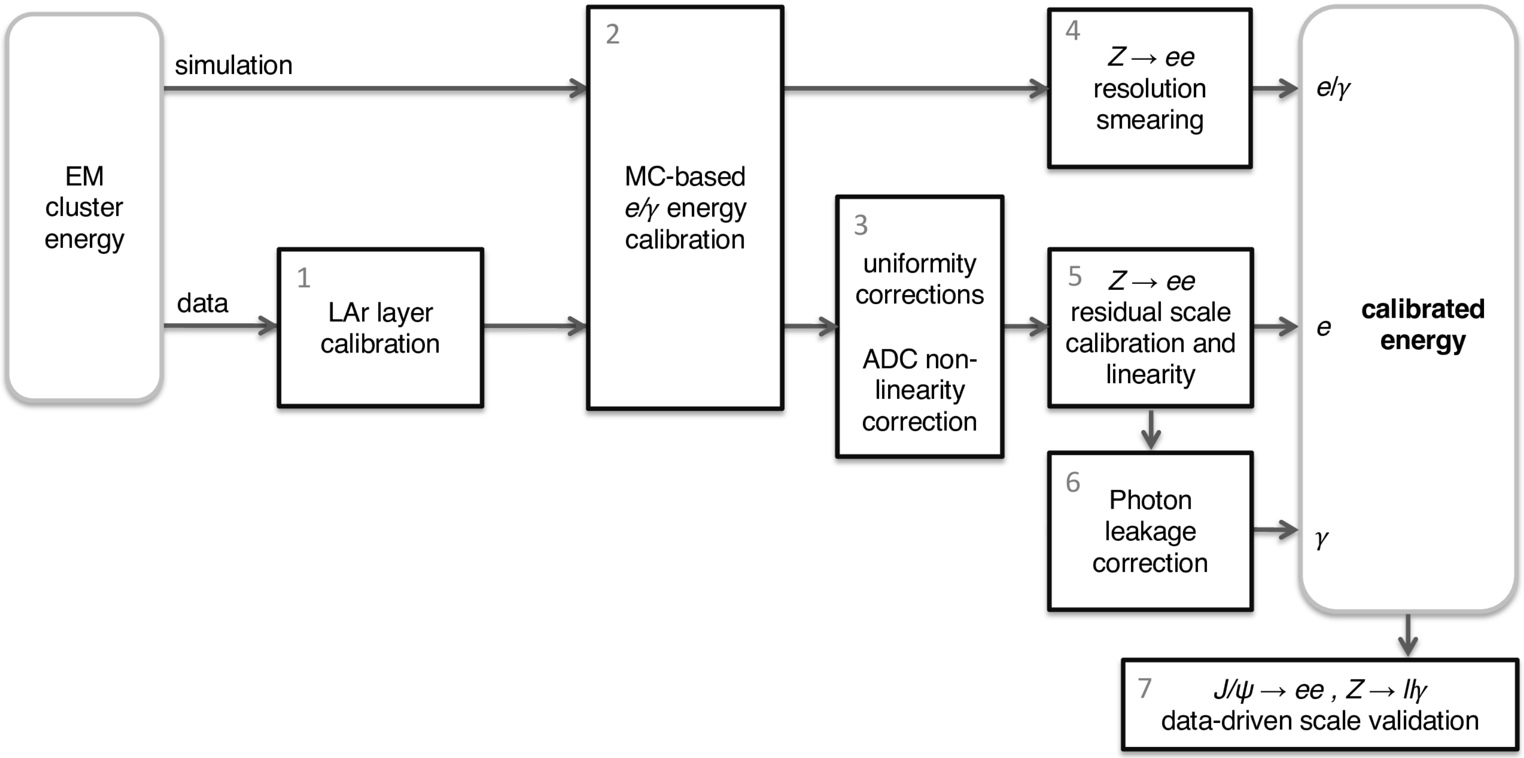
Eur. Phys. J. C78, 675 (2018)

arXiv:1205.6497





Electron/photon calibration



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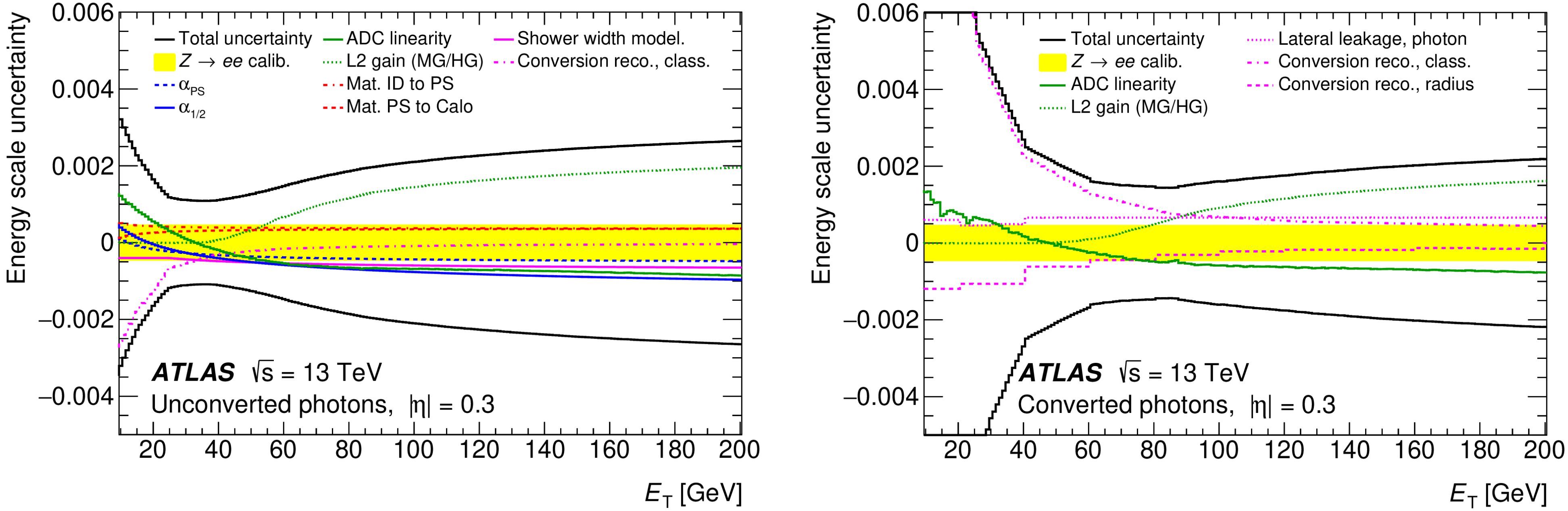

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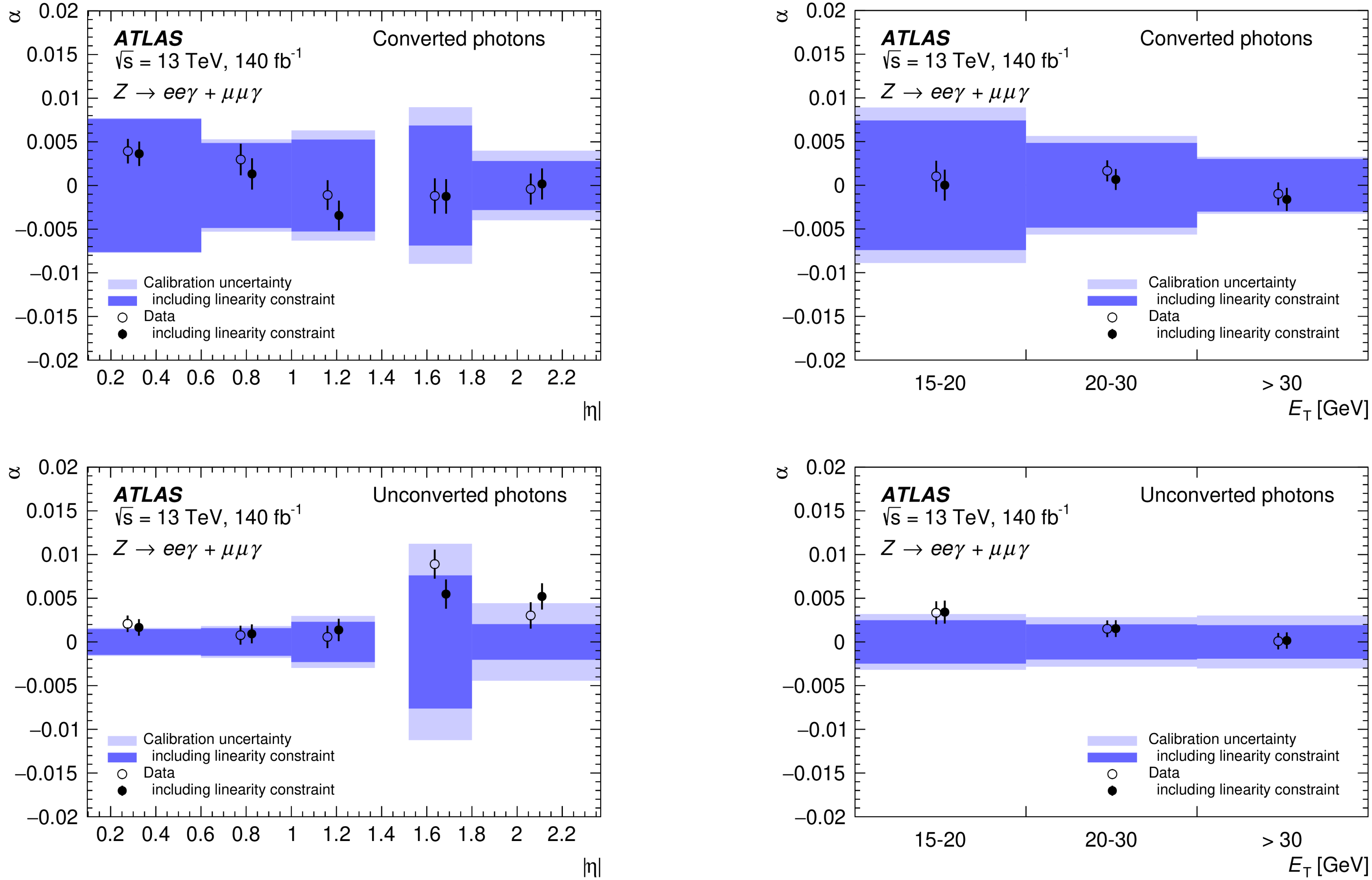

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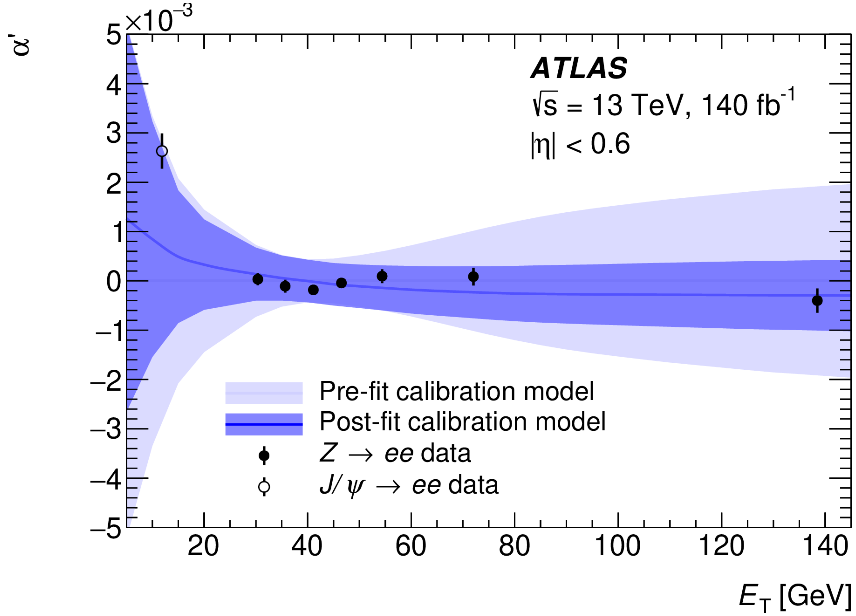
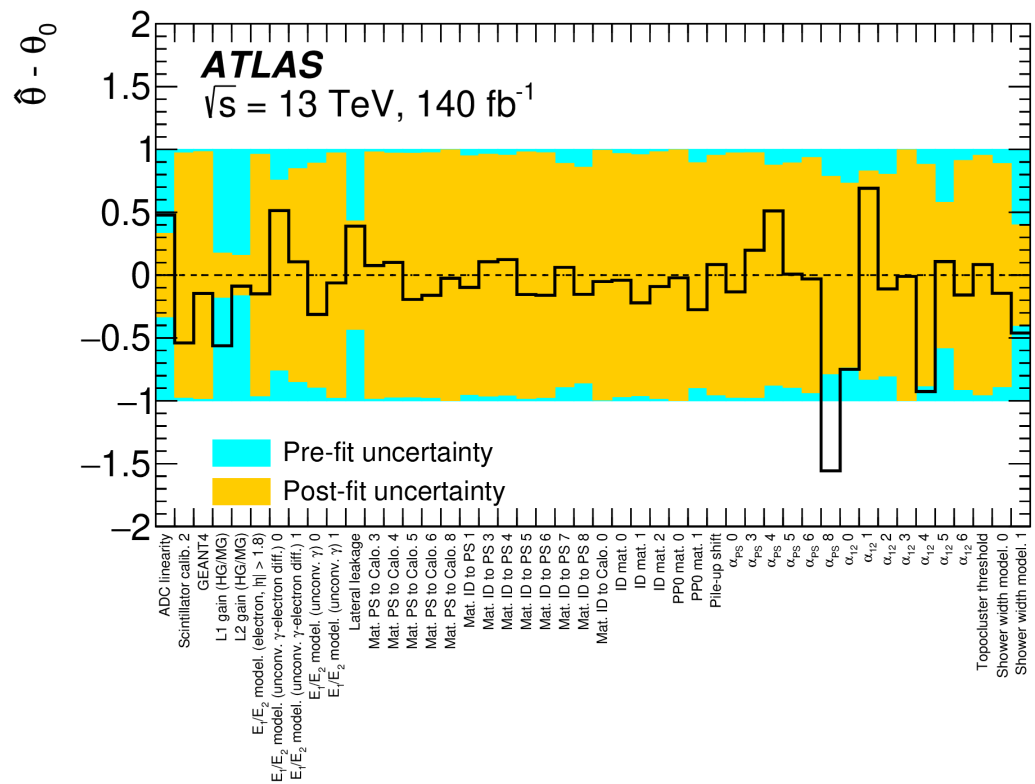
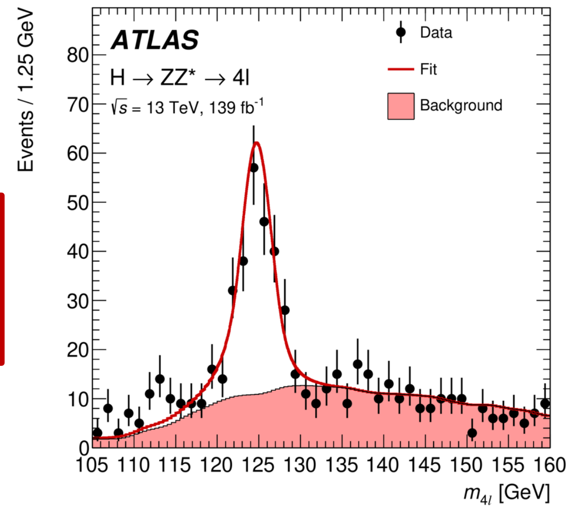
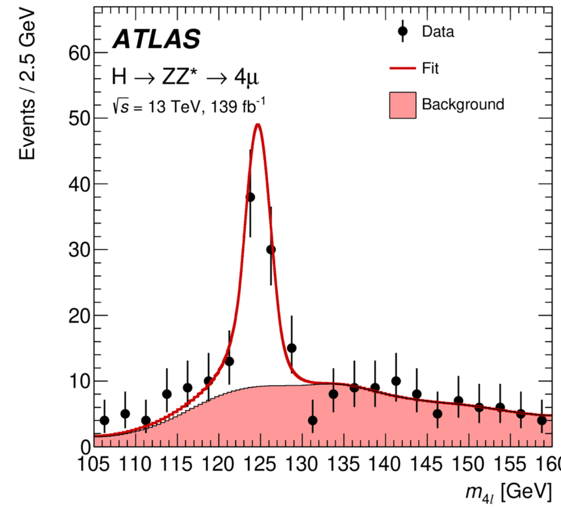


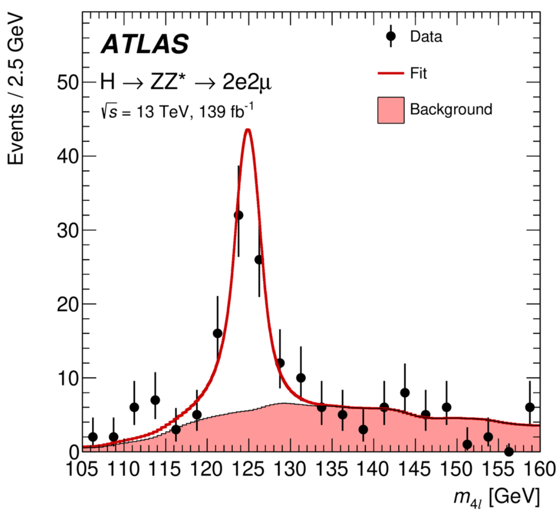


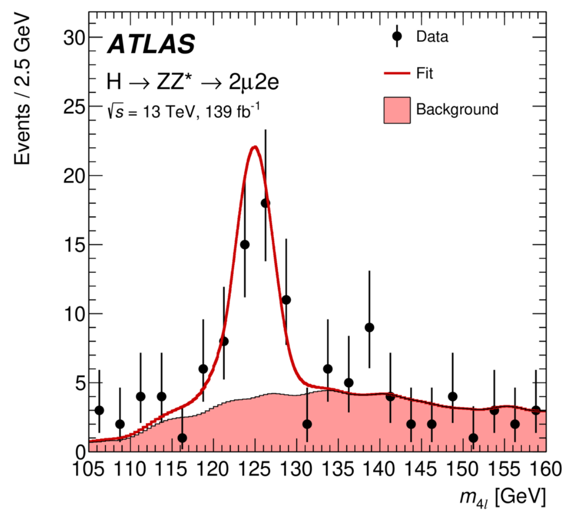
Higgs boson mass measurement in the 4l channel

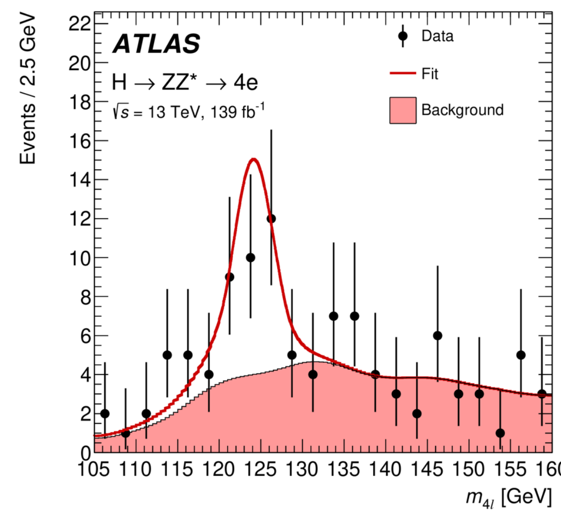
$$
\begin{aligned}
&\mathcal{P}(m_{4\ell}, D_{NN}, \sigma_i | m_H) \\
&\quad = \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | \sigma_i, m_H) \cdot \mathcal{P}(\sigma_i | m_H) \\
&\quad \simeq \mathcal{P}(m_{4\ell} | D_{NN}, \sigma_i, m_H) \cdot \mathcal{P}(D_{NN} | m_H),
\end{aligned}
$$











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Higgs boson mass measurement in the $\gamma\gamma$ channel

Best S/B for high p_{Tt} categories

Best resolution for U categories

Lower systematics for C categories

Category	$\sigma_{90}^{\gamma\gamma}$ [GeV]	S_{90}	B_{90}	f_{90} [%]	Z_{90}
U, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.88	42	65	39.1	4.7
U, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.34	102	559	15.4	4.2
U, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.63	837	13 226	6.0	7.2
U, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.16	31	83	27.4	3.3
U, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.63	108	981	9.9	3.4
U, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.00	869	22 919	3.7	5.7
U, Endcap	3.33	759	29 383	2.5	4.4
C, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.10	26	44	37.3	3.6
C, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.62	62	389	13.8	3.1
C, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.00	508	9 726	5.0	5.1
C, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.56	34	103	25.0	3.2
C, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.20	114	1 353	7.8	3.1
C, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	3.71	914	30 121	2.9	5.2
C, Endcap	4.04	1 249	52 160	2.3	5.5
Inclusive	3.32	5 653	128 774	4.2	15.6

This categorization reduces the total m_H uncertainty:

- By about 17% compared with an inclusive measurement
- by 6% compared to the event classification defined in partial RUN 2 measurement

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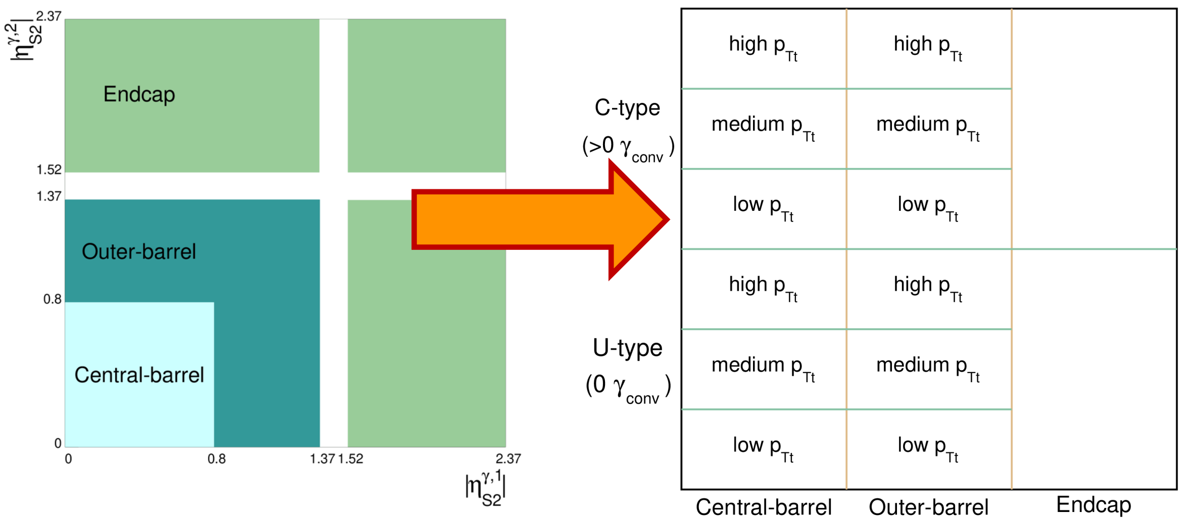
Higgs boson mass measurement in the $\gamma\gamma$ channel

- The diphoton events are divided in 14 mutually exclusive categories defined to optimize the total uncertainty on m_H
  - The optimal categorisation depends on S/B ratio, $m_{\gamma\gamma}$ resolution and photon energy scale uncertainties
- The category are defined based on:
  - The number of converted photons
  - The pseudorapidity of the two photons
  - The p_{Tt} of the diphoton system (0-70 GeV, 70-130 GeV, > 130 GeV)



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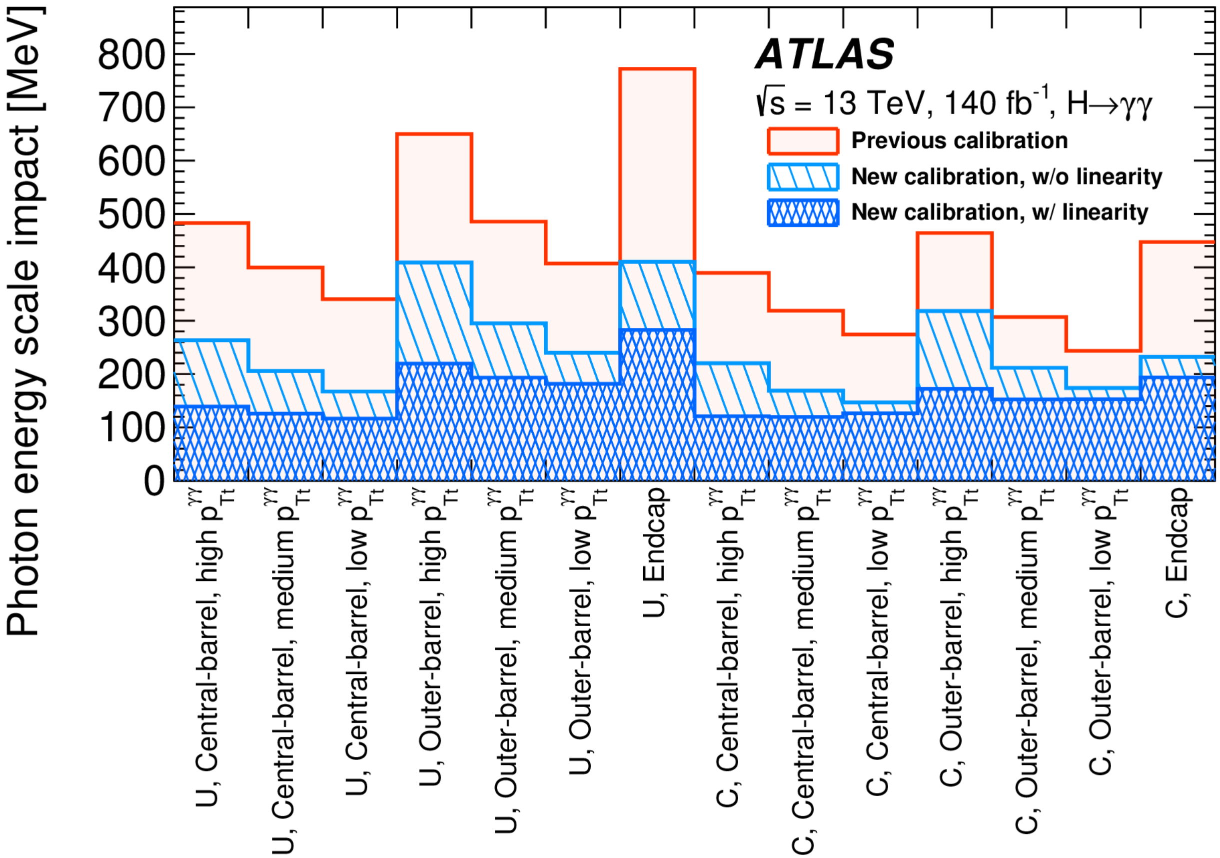
Higgs boson mass measurement in the $\gamma\gamma$ channel



Improved:

- ❑ material modelling (x3)
- ❑ ayer intercalibration and calorimeter readout
- ❑ non-linearity (x2)
- ❑ e→γ extrapolation (x3)

Et-dependent systematics increase for e/γ away from <E_T Z→ee > ~ 40 GeV

- ❑ They are constrained through a fit to E_T-differential measurements of energy scale from Z→ee

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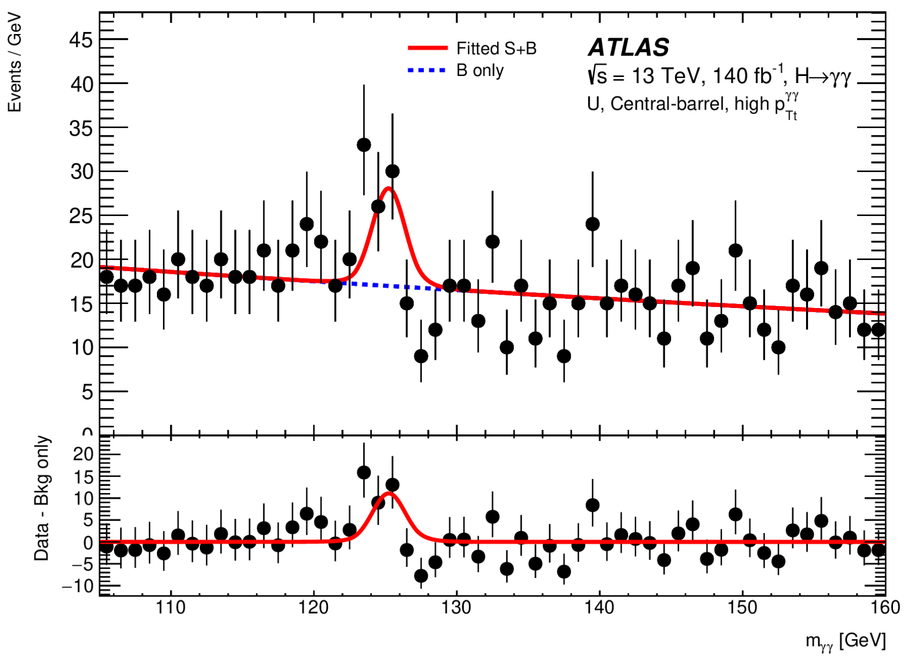
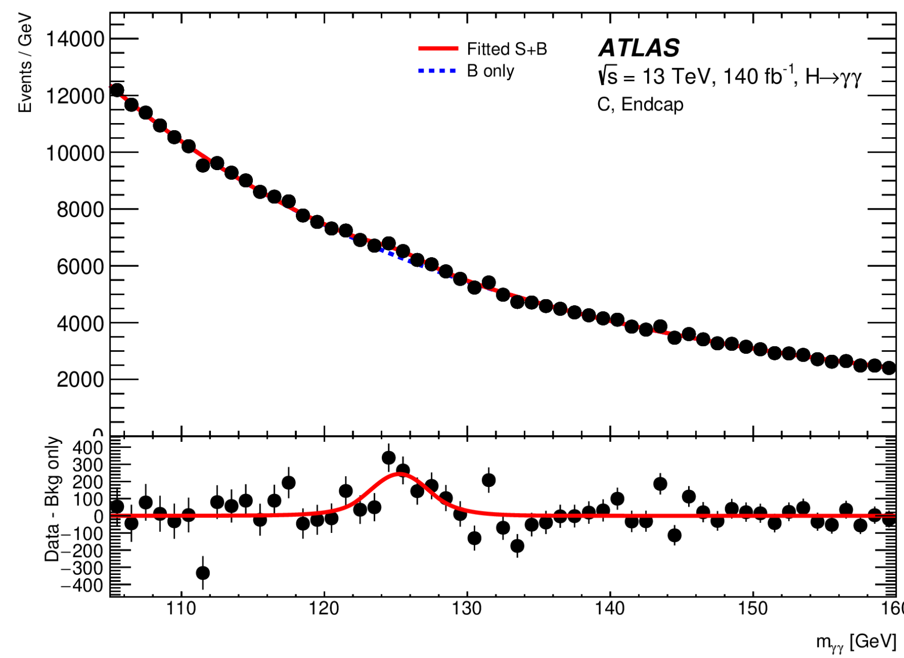
Higgs boson mass measurement in the $\gamma\gamma$ channel

Fit in the best resolution category (the fit is simultaneous in all categories)



Fit in the worse resolution category (the fit is simultaneous in all categories)



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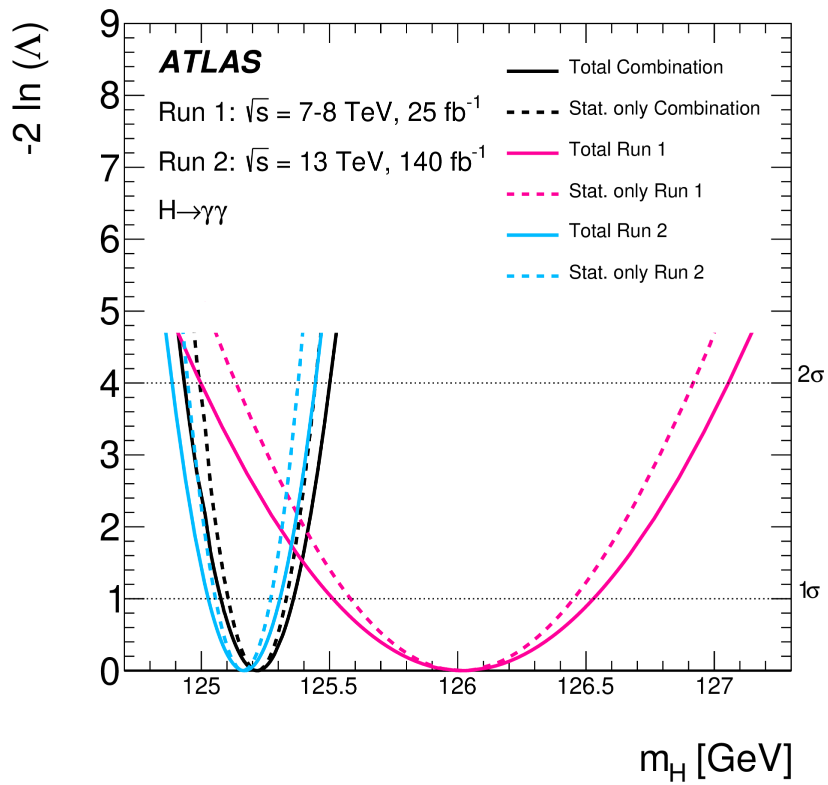
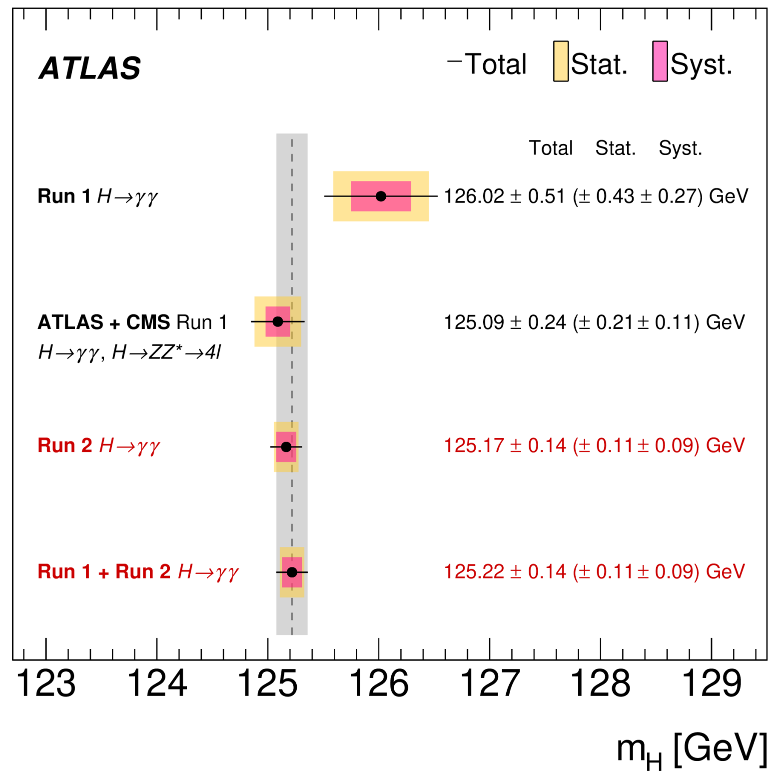
Higgs boson mass measurement in the $\gamma\gamma$ channel

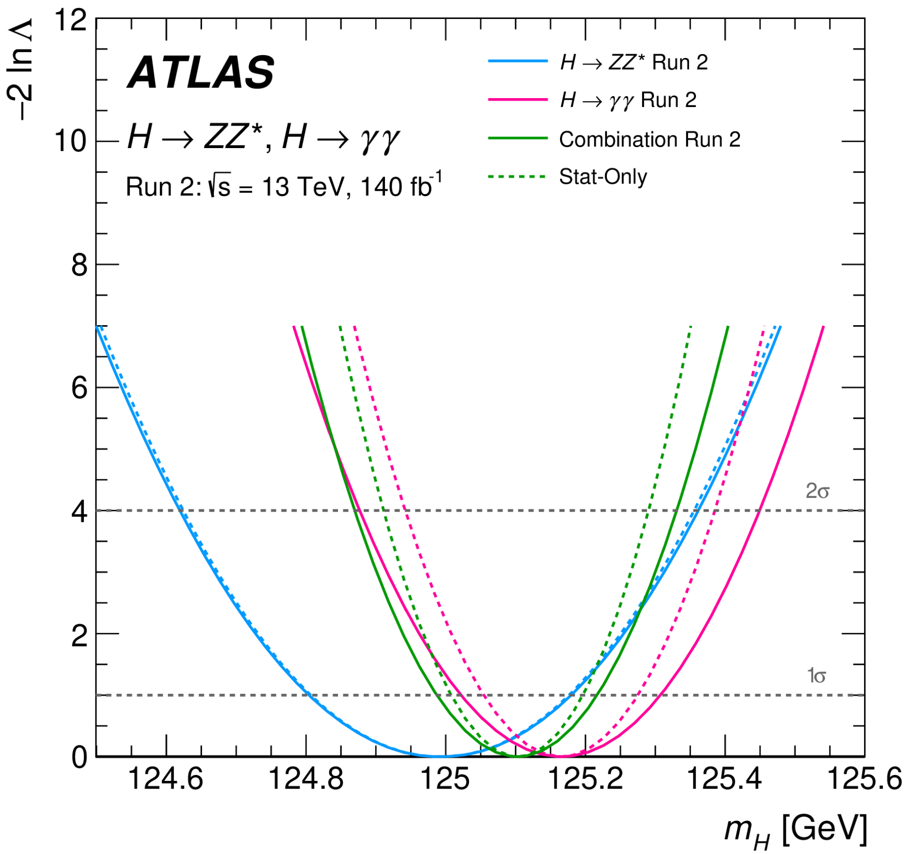


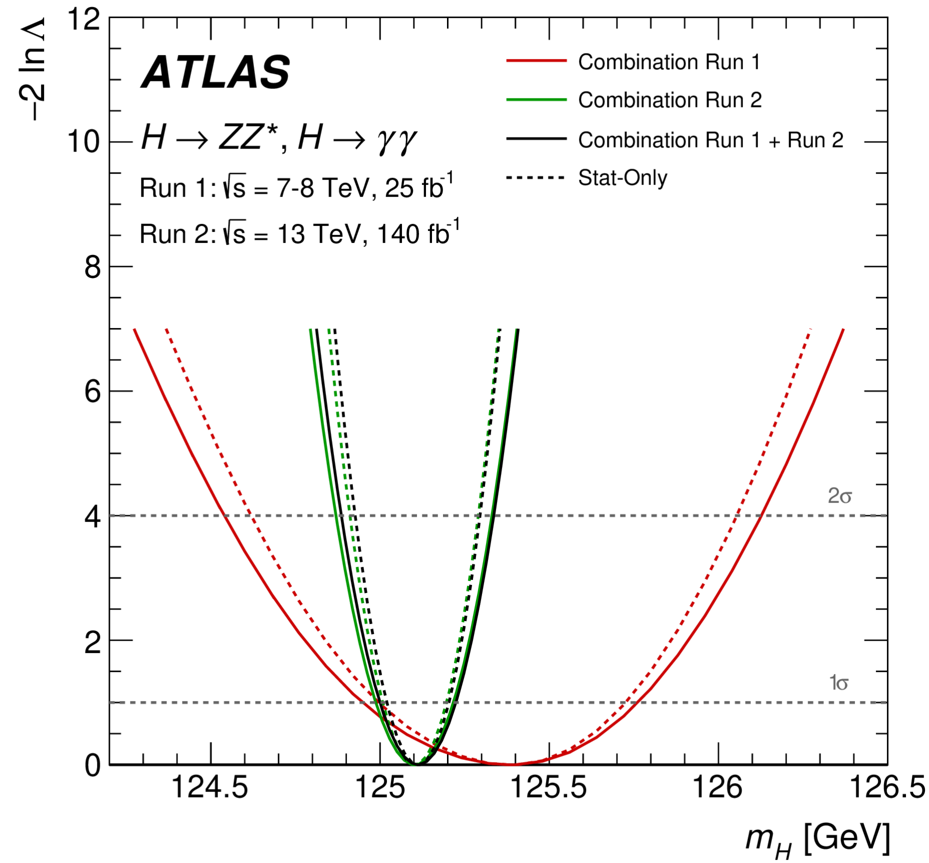


m_H = 125.22 ± 0.11 (stat.) ± 0.09 (syst.) = 125.22 ± 0.14 GeV

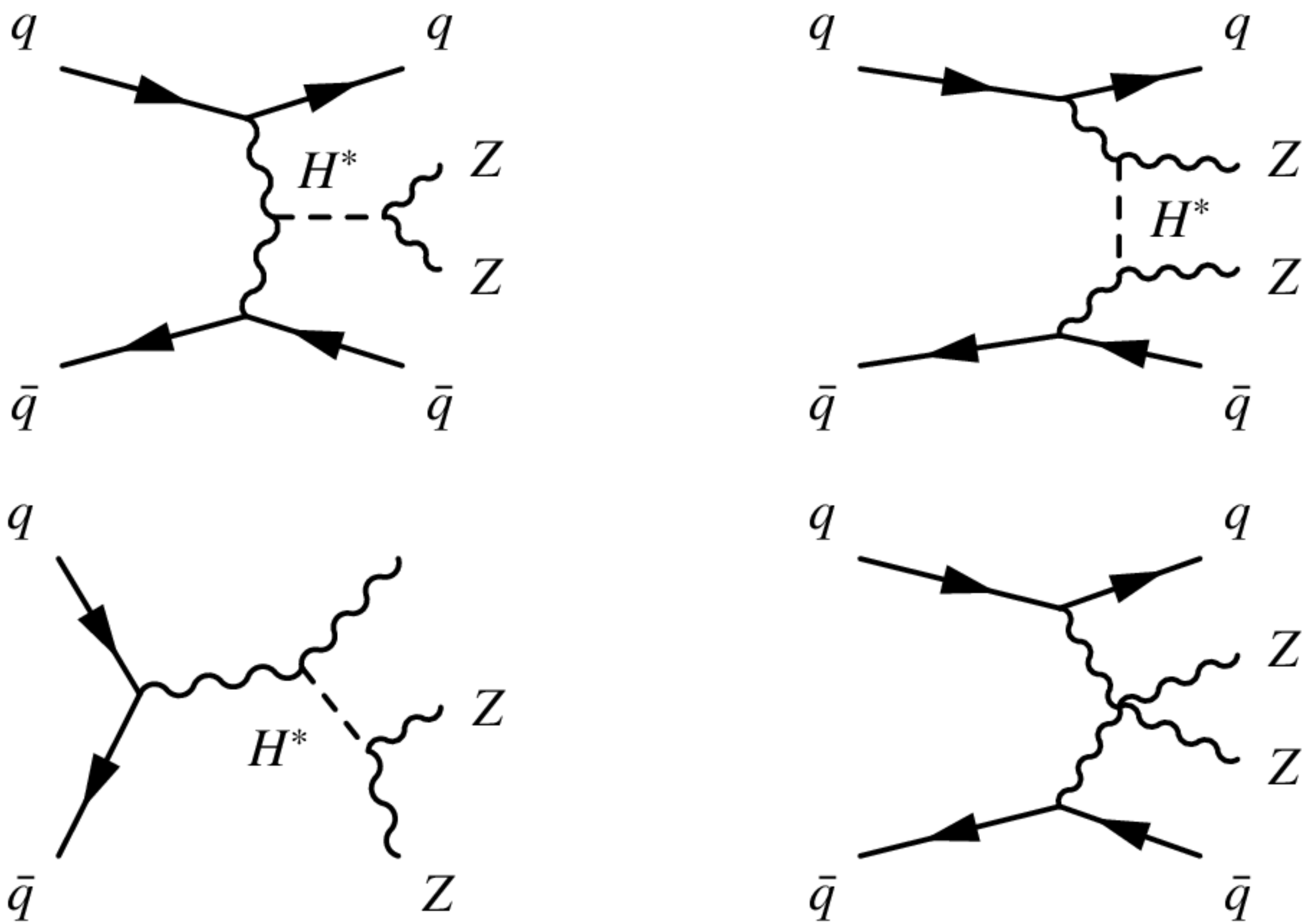
- Combination produces +50 MeV shift of the central value and a <10 MeV reduction of the statistical uncertainty

Combined Higgs boson mass measurement





Measurement of the Higgs boson width

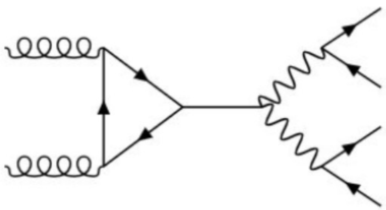


Measurement of the Higgs boson width

Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ value at which $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

Measurement of the Higgs boson width

ggF Signal region

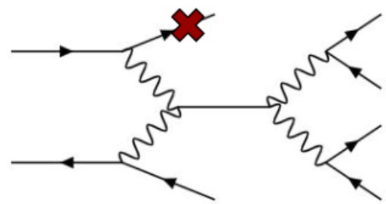


$n_{\text{jets}} = 0$

$n_{\text{jets}} = 1$ and $\eta_j < 2.2$

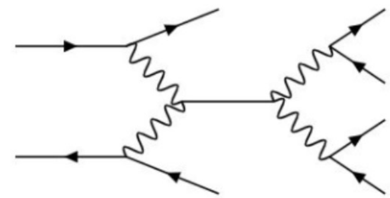
$n_{\text{jets}} \geq 2$ and $\Delta\eta_{jj} < 4.0$

1 jet mixed signal region



$n_{\text{jets}} = 1$ and $\eta_j \geq 2.2$

EW signal region



$n_{\text{jets}} \geq 2$ and $\Delta\eta_{jj} \geq 4.0$

Measurement of the Higgs boson width

Process	Uncertainty	Final State	Value (%)
	ggF Signal Region		
$qq \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	4–40
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	21–28
$qq \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	22–37
$qq \rightarrow ZZ + 2j$	Parton Shower	$2\ell 2\nu$	1–67
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	8–45
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	Parton Shower	$2\ell 2\nu$	6–43
$WZ + 0j$	QCD Scale	$2\ell 2\nu$	1–54
	1-jet Signal Region		
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow H^* \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	13–18
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$qq \rightarrow ZZ$ (EW)	QCD Scale	$2\ell 2\nu$	7–18
	2-jet Signal Region		
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	18–26
$qq \rightarrow ZZ + 2j$	QCD Scale	$2\ell 2\nu$	8–32
$gg \rightarrow H^* \rightarrow ZZ$	Parton Shower	4ℓ	27
$gg \rightarrow ZZ$	Parton Shower	4ℓ	38
$gg \rightarrow ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	20–22
	$qq \rightarrow ZZ$ Control Regions		
$qq \rightarrow ZZ + 2j$	QCD Scale	4ℓ	26
	Three-lepton Control Regions		
$WZ + 2j$	QCD Scale	$2\ell 2\nu$	28

The dominant uncertainties in the leading processes in the signal and background regions

Measurement of the Higgs boson width

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \to H^* \to ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \to (H^* \to)ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \to ZZ$	1878 ± 151	135 ± 23	22.0 ± 8.3
Other backgrounds	50.6 ± 2.5	1.79 ± 0.16	1.65 ± 0.16
Total expected (SM)	2293 ± 209	181 ± 29	45.3 ± 10.0
Observed	2327	178	50

4l channel

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	210 ± 53	19.7 ± 4.9	4.29 ± 1.10
$gg \to H^* \to ZZ$	111 ± 26	10.9 ± 2.5	3.26 ± 0.82
$gg \to ZZ$	251 ± 66	23.4 ± 6.2	5.31 ± 1.46
$qq \to (H^* \to)ZZ + 2j$	14.0 ± 3.0	1.63 ± 0.17	4.46 ± 0.50
$qq \to ZZ$	1422 ± 112	80.4 ± 11.9	7.74 ± 2.99
WZ	678 ± 54	51.9 ± 6.9	7.89 ± 2.50
Z+jets	62.3 ± 24.3	7.51 ± 6.94	0.62 ± 0.54
Non-resonant-$\ell\ell$	106 ± 39	9.17 ± 2.73	1.55 ± 0.42
Other backgrounds	22.6 ± 5.2	1.62 ± 0.25	1.40 ± 0.10
Total expected (SM)	2515 ± 165	172 ± 17	28.0 ± 4.1
Observed	2496	181	27

2l2v channel