Science & Technology Facilities Council
Rutherford Appleton Laboratory

LHC Higgs boson mass combination

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on behalf of the ATLAS and CMS collaborations

SM@LHC

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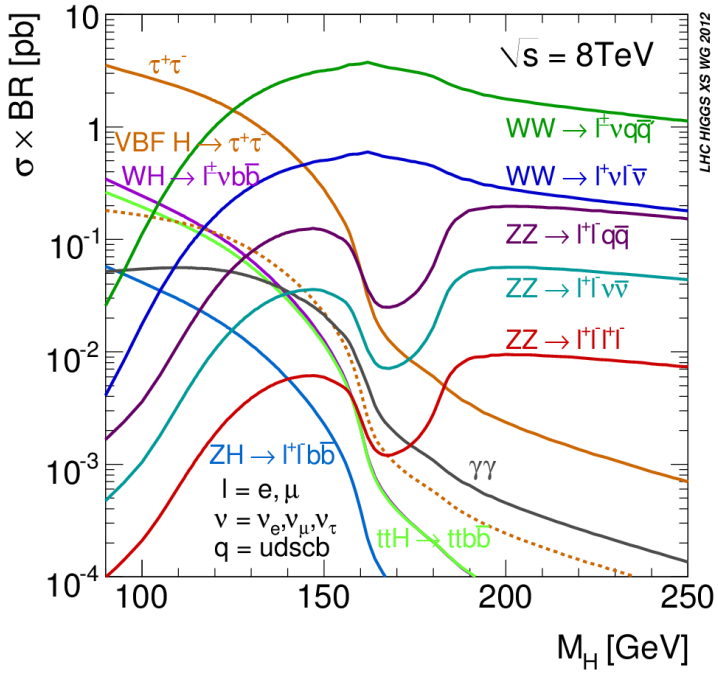
Higgs mass measurement

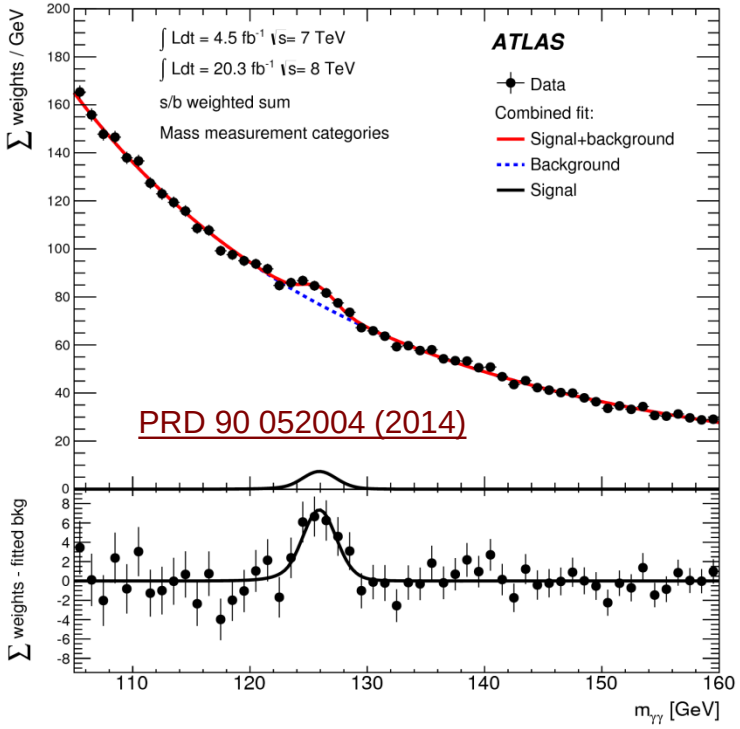
- The mass of the Higgs boson is not predicted
  - It is a free parameter of the Standard Model
  - Once we know the mass, all Higgs couplings (production and decay) within the SM are known

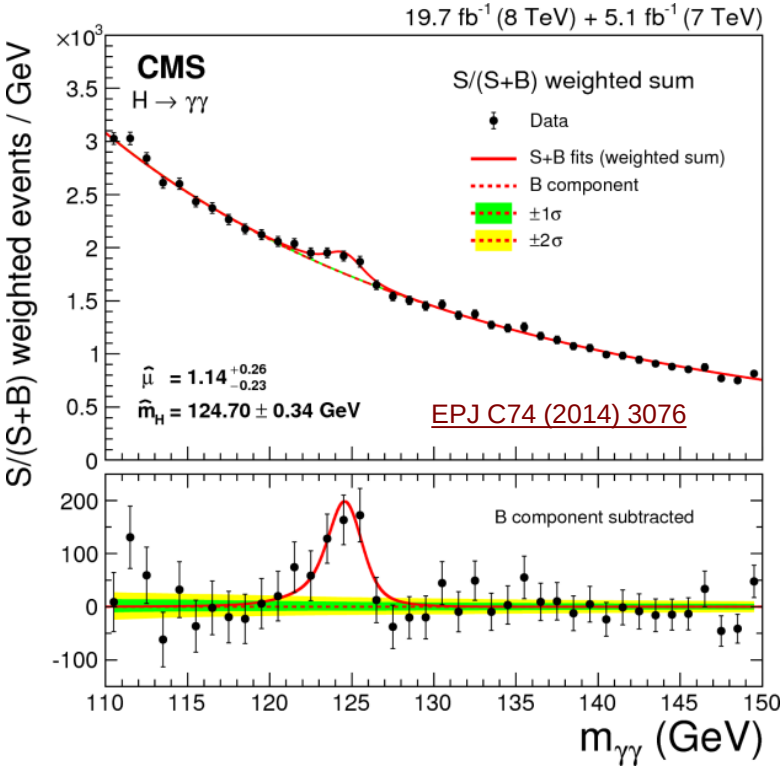


- Previously, ATLAS and CMS have presented separate measurements for m_H using $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$ decay modes
  - Only these decay modes (of those so-far observed) allow us to fully reconstruct the final state and measure the mass with any precision
- Now we can present a combined measurement

H→γγ channel

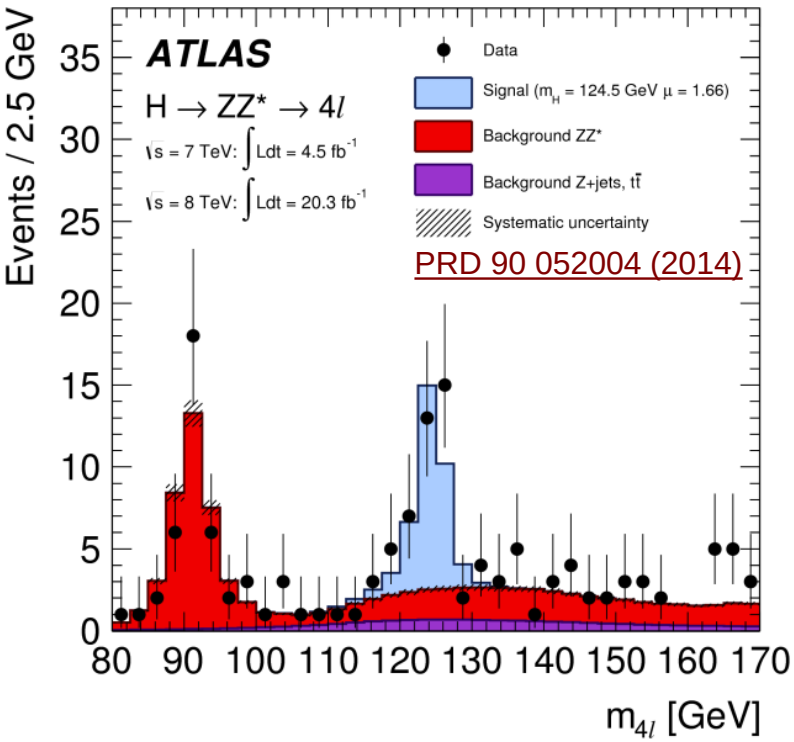
- ATLAS and CMS categorise events with two high p_T photons, used to reconstruct $m_{\gamma\gamma}$
  - categories chosen (blind, in advance) according to the expected S/B
- ATLAS: 10 discrete categories based on photon conversions, detector region (η), diphoton momentum (p_{Tt})
- CMS: 5 categories according to multivariate discriminant (BDT) based on kinematics, photon ID/shower shape, and resolution
  - additional 9 categories in CMS select (rarer) VBF, VH, and ttH production modes – in common with couplings analysis

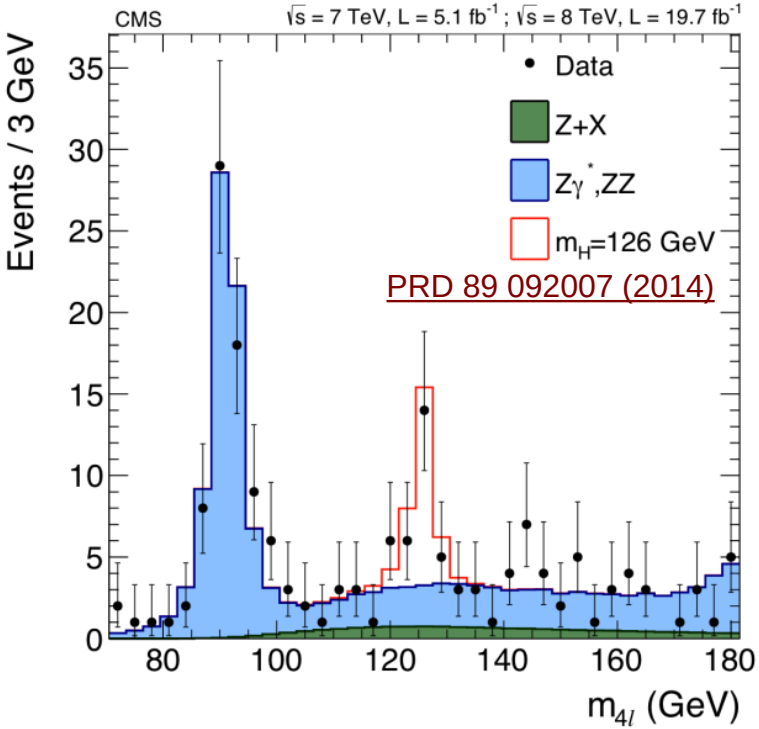




H→ZZ*→4*l* channel

- Select two pairs of opposite-charged same-flavour leptons:
  $e^+e^-e^+e^-$, $\mu^+\mu^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$
  - ATLAS: 2D fit of m_{4l} and kinematic discriminant (BDT), used to reject ZZ* continuum background
  - CMS: 3D fit, similar to ATLAS, but also including per-event uncertainty on m_{4l}





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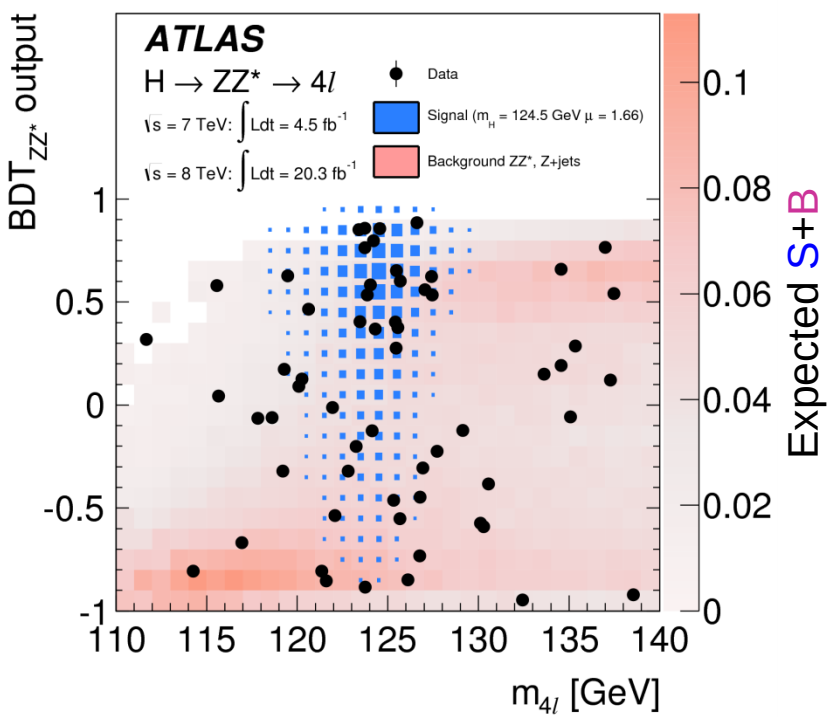
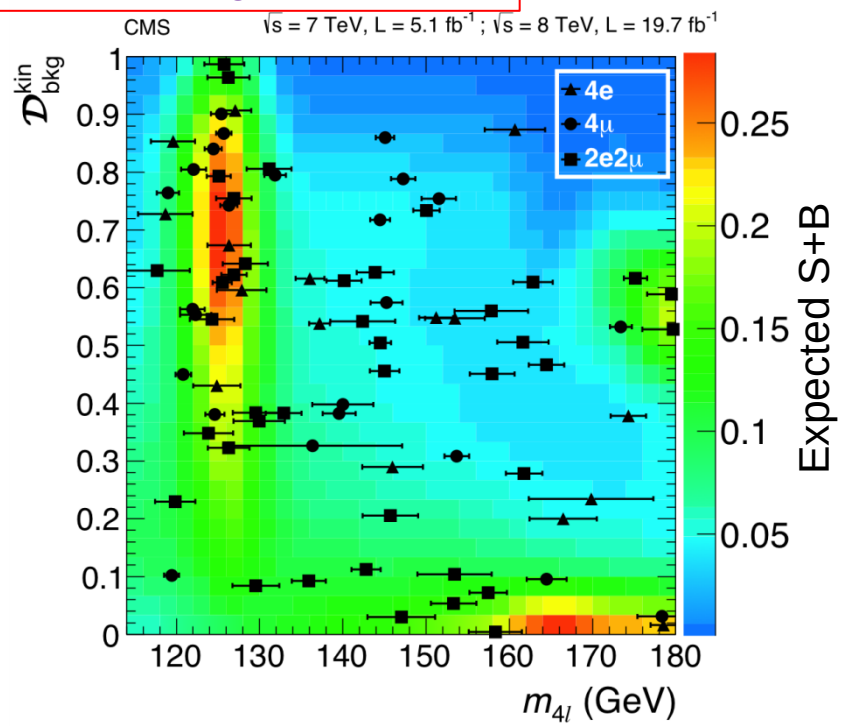
  - ATLAS: 2D fit of m_{4l} and kinematic discriminant (BDT), used to reject ZZ* continuum background
  - CMS: 3D fit, similar to ATLAS, but also including per-event uncertainty on m_{4l}

kinematic discriminant (BDT_{ZZ^*} or $\mathcal{D}^{kin}_{bkg}$) vs m_{4l}

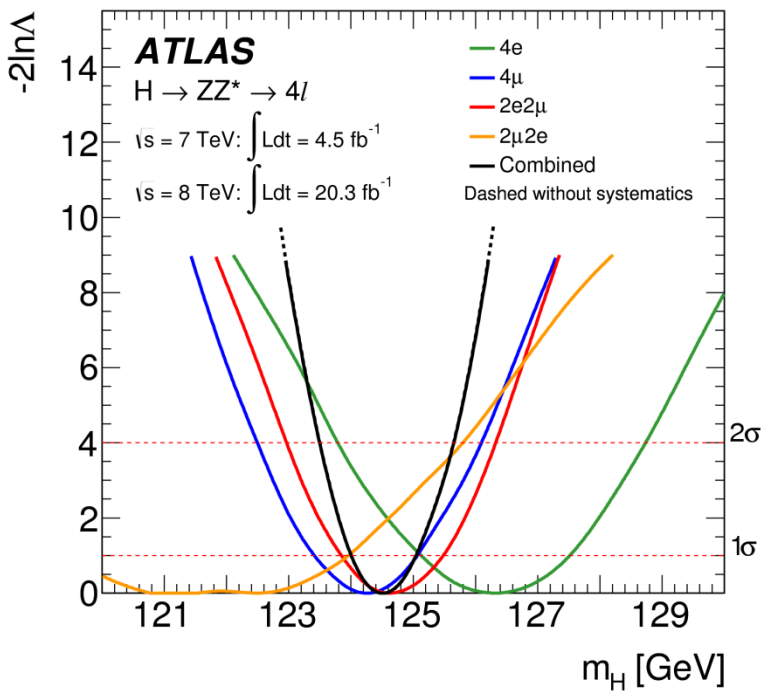


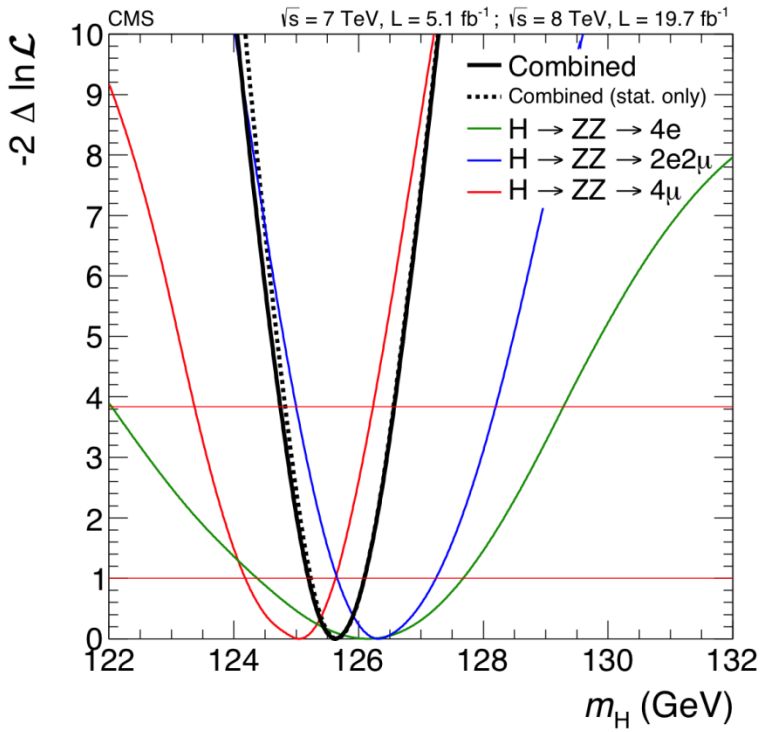


H→ZZ*→4*l* channel

- Select two pairs of opposite-charged same-flavour leptons:
  $e^+e^-e^+e^-$, $\mu^+\mu^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$
  - ATLAS: 2D fit of m_{4l} and kinematic discriminant (BDT), used to reject ZZ* continuum background
  - CMS: 3D fit, similar to ATLAS, but also including per-event uncertainty on m_{4l}

ATLAS have separate categories depending on whether muon or electron pair is leading

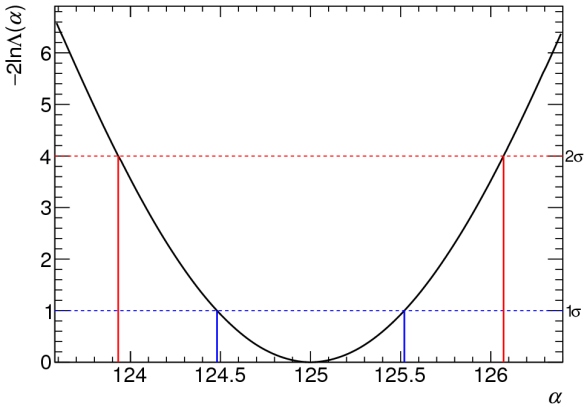




Likelihood fits and their combination

- Confidence intervals (eg. value±error), limits, and significances (eg. compatibility) based on the profile likelihood ratio:

$$\Lambda(\boldsymbol{\alpha}) = \frac{L(\boldsymbol{\alpha}, \hat{\hat{\boldsymbol{\theta}}}(\boldsymbol{\alpha}))}{L(\hat{\boldsymbol{\alpha}}, \hat{\boldsymbol{\theta}})} = \frac{\text{maximum likelihood for a given } \boldsymbol{\alpha}}{\text{global maximum likelihood}}$$



- Depends on one or more parameters of interest (POIs), $\boldsymbol{\alpha}$
  - eg. m_H
- Systematic uncertainties modelled using nuisance parameters (NPs), $\boldsymbol{\theta}$, with constraints (eg. log-normal)
  - $\hat{\theta}$ is the best-fit θ
  - $\hat{\hat{\theta}}(\boldsymbol{\alpha})$ is the conditional best-fit θ for a particular $\boldsymbol{\alpha}$
- Likelihood functions built using products of signal and background PDFs
  - functions of discriminating variables (eg. $m_{\gamma\gamma}$),
  - evaluated for each event (or histogram bin)

- To combine, simply multiply the likelihood terms for each channel
  - careful choice of parameters (POIs and NPs) to correlate (set equal) or uncorrelate (keep separate) between channels
    - may also need to reparameterise, to express more useful POIs (eg. $\Delta m_H = m_{\gamma\gamma} - m_{4l}$) or partial correlation of NPs

Combination of Higgs mass measurements

- Combine model and datasets from four input channels
  - $H\to\gamma\gamma$ and $H\to ZZ\to 4l$, each in ATLAS and CMS
- Profile likelihood ratio of the combined model:

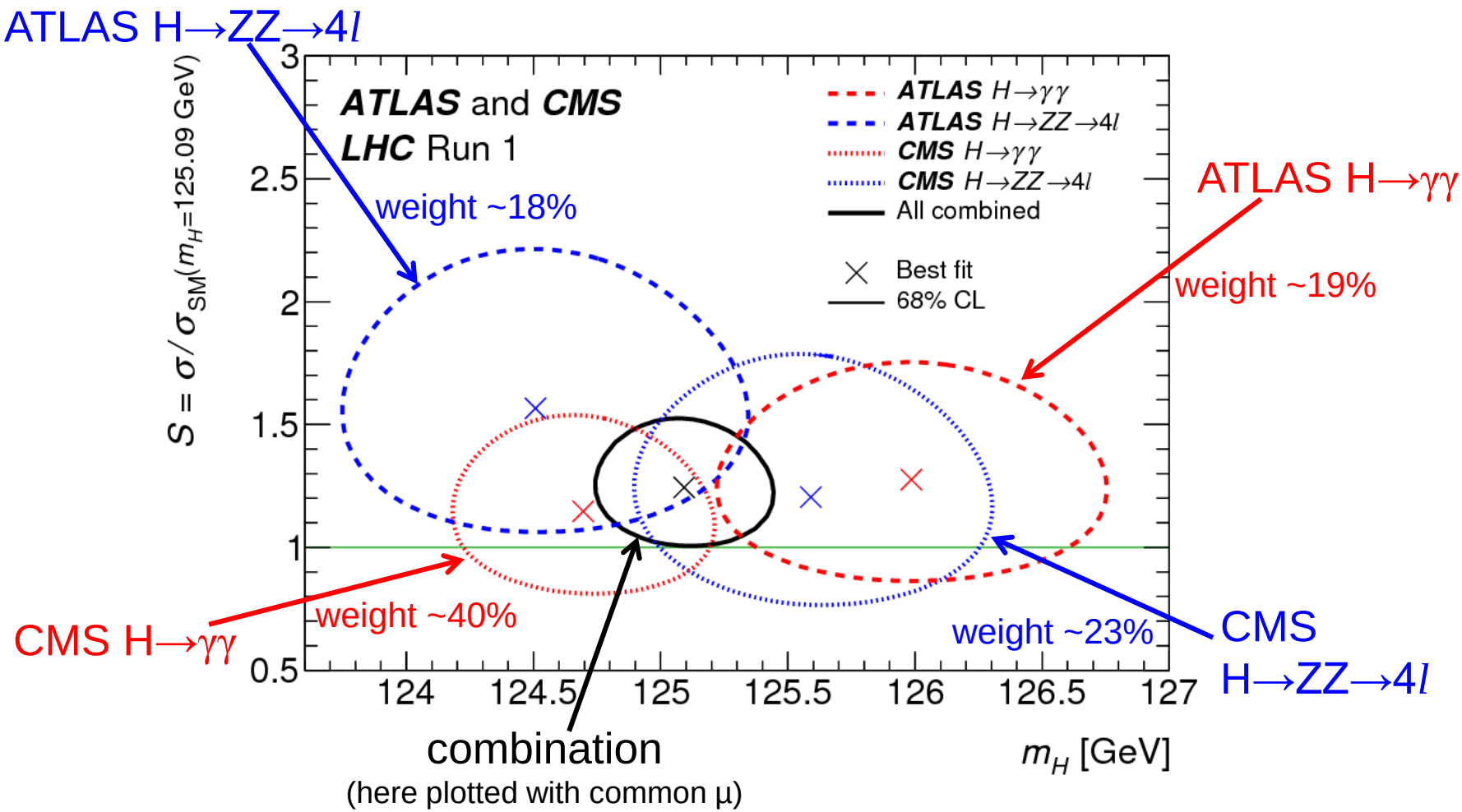
$$\Lambda(m_H) = \frac{L\left(m_H, \hat{\hat{\mu}}^{\gamma\gamma}_{gg\mathrm{F}+t\bar{t}H}(m_H), \hat{\hat{\mu}}^{\gamma\gamma}_{\mathrm{VBF}+VH}(m_H), \hat{\hat{\mu}}^{4\ell}(m_H), \hat{\hat{\boldsymbol{\theta}}}(m_H)\right)}{L\left(\hat{m}_H, \hat{\mu}^{\gamma\gamma}_{gg\mathrm{F}+t\bar{t}H}, \hat{\mu}^{\gamma\gamma}_{\mathrm{VBF}+VH}, \hat{\mu}^{4\ell}, \hat{\boldsymbol{\theta}}\right)}$$

- Parameter of interest: m_H
- Fit additional parameters to data ("profiled"):
  - Signal strength parameters ($\mu_X=\sigma_X/\sigma_{SM}$) for 3 processes – don't assume SM Higgs
    - $\mu^{\gamma\gamma}_{ggF+ttH}$ ggF (+ttH) production, $H\to\gamma\gamma$ decay
    - $\mu^{\gamma\gamma}_{VBF+VH}$ VBF (+VH) production, $H\to\gamma\gamma$ decay
    - μ^{4l} $ZZ\to 4l$ decay
  - Remaining nuisance parameters, $\boldsymbol{\theta}$:
    - ~200 theory and experimental systematic uncertainties (constrained parameters)
    - ~100 $H\to\gamma\gamma$ background shape and normalisation parameters (fitted to data)

Individual results and their combination

Show 1σ contours in ***S*** vs m_H plane

- signal yield, $\boldsymbol{S} \equiv \sigma/\sigma_{SM}(m_H=125.09\text{ GeV})$, similar to $\mu \equiv \sigma/\sigma_{SM}$, but expected SM yields use fixed-m_H in σ_{SM} (removes m_H-dependence from theory expectation of XS, BR, etc)



Combined result

- The combined ATLAS+CMS $\gamma\gamma$+4l mass is:

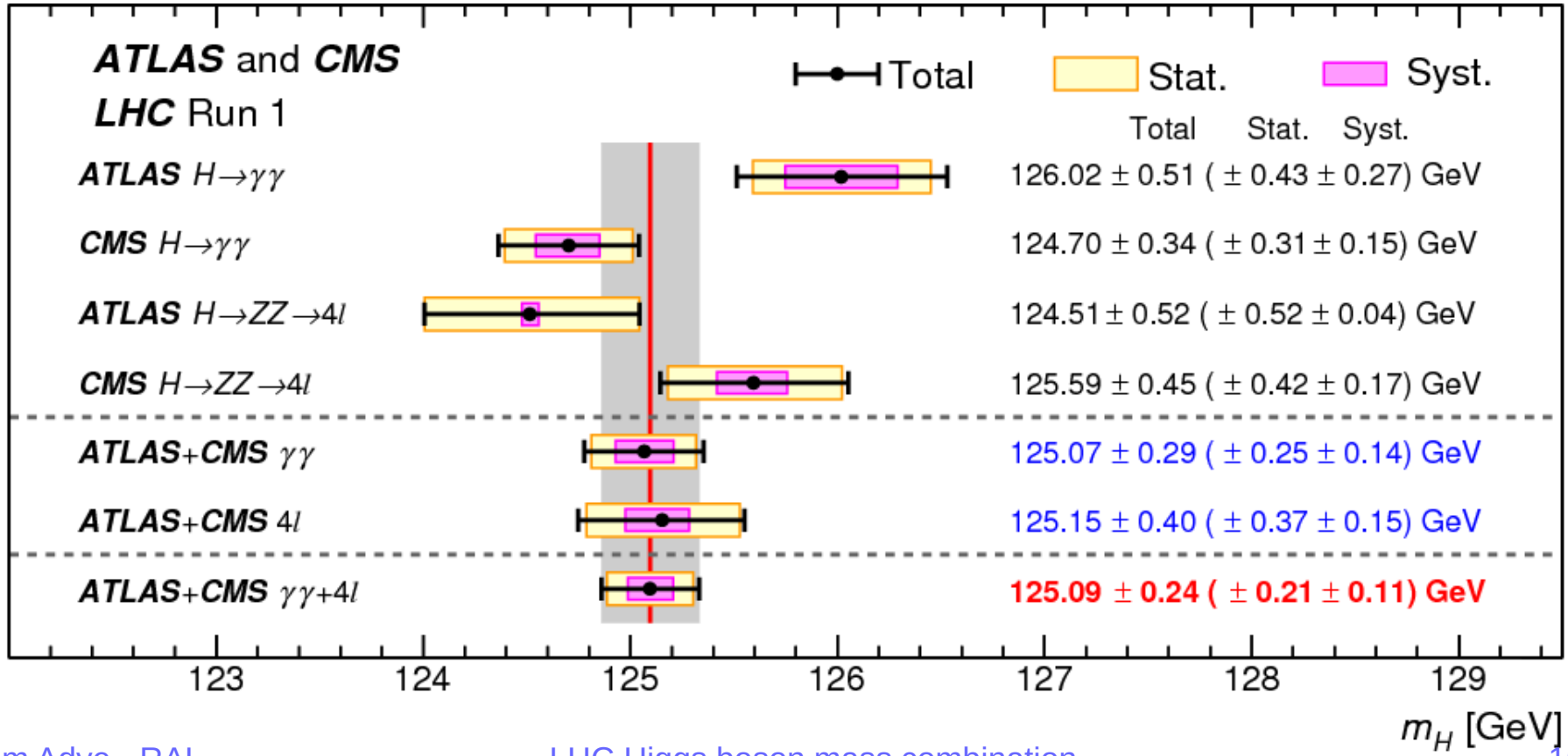
$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

← **0.2% precision!**

$$= 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.}) \text{ GeV}$$

allowing signal strengths to float

- increases by 70 MeV if fixed to SM (μ=1) – mainly due to m_H dependence of BR_{ZZ}



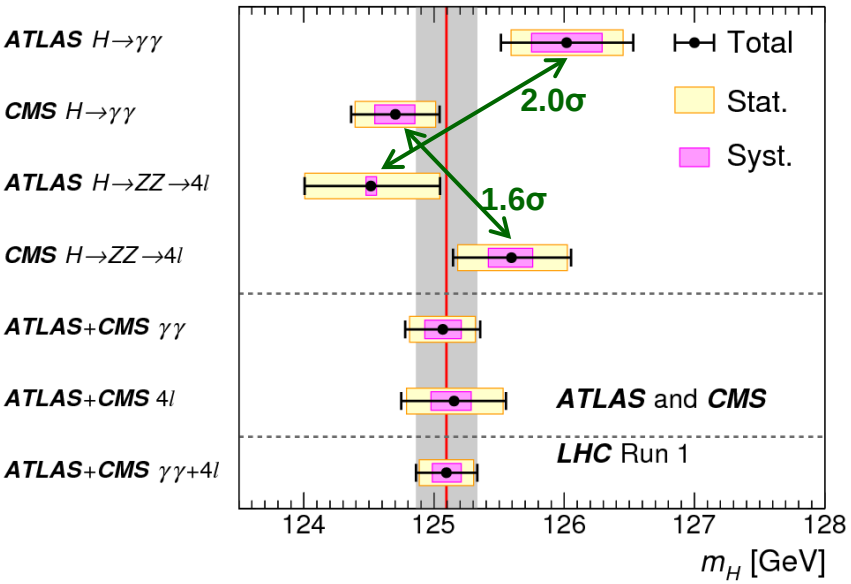
Compatibility between channels

- Some tension between channels within each experiment

  $m^{\gamma\gamma} - m^{4l}$ = 1.47±0.72 GeV (2.0σ) ATLAS
  = −0.89±0.57 GeV (1.6σ) CMS

  but opposite signs, so combined results show no tension

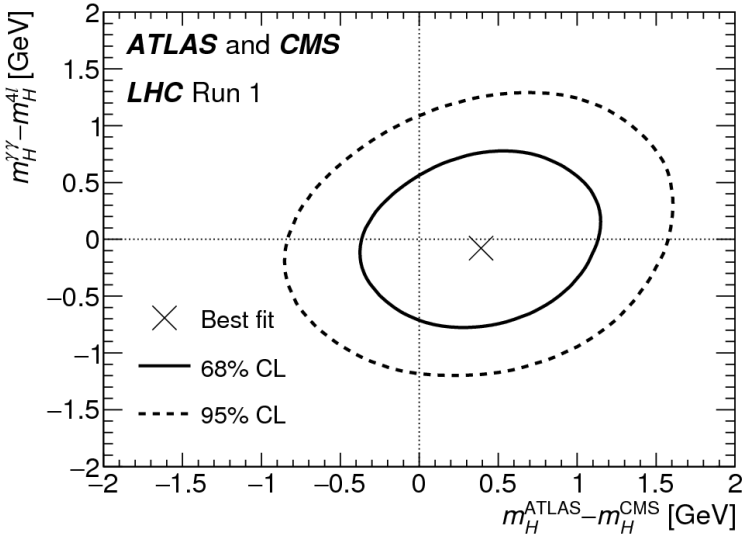
  - tensions between experiments in each channel: 2.1σ (γγ) or 1.3σ (4*l*)



- Overall compatibility of m_H results in the four channels:
  - 10% or
  - 7% – allowing different signal strengths in ATLAS and CMS (different particles)

    - Compatibility based on likelihood ratio

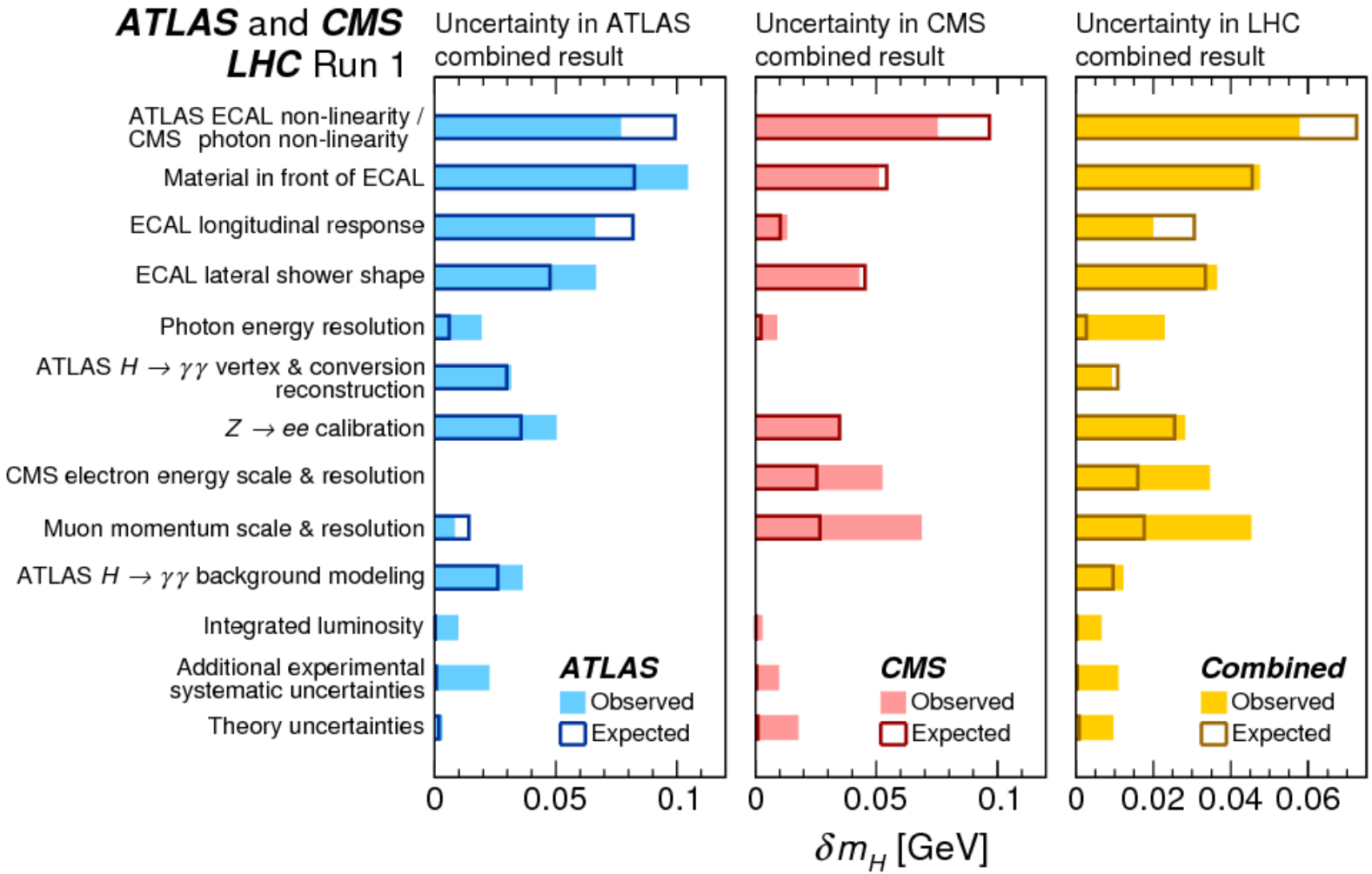
$$\frac{L\,(\hat{m}^{\gamma\gamma}_{ATLAS}, \hat{m}^{\gamma\gamma}_{CMS}, \hat{m}^{4l}_{ATLAS}, \hat{m}^{4l}_{CMS}, \ldots)}{L\,(\text{common } \hat{m}_H, \ldots)}$$



Systematic uncertainties

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV}$$

Show impact from groups of systematic uncertainties on ATLAS, CMS, and ATLAS+CMS combined results (~200 individual systematics!)

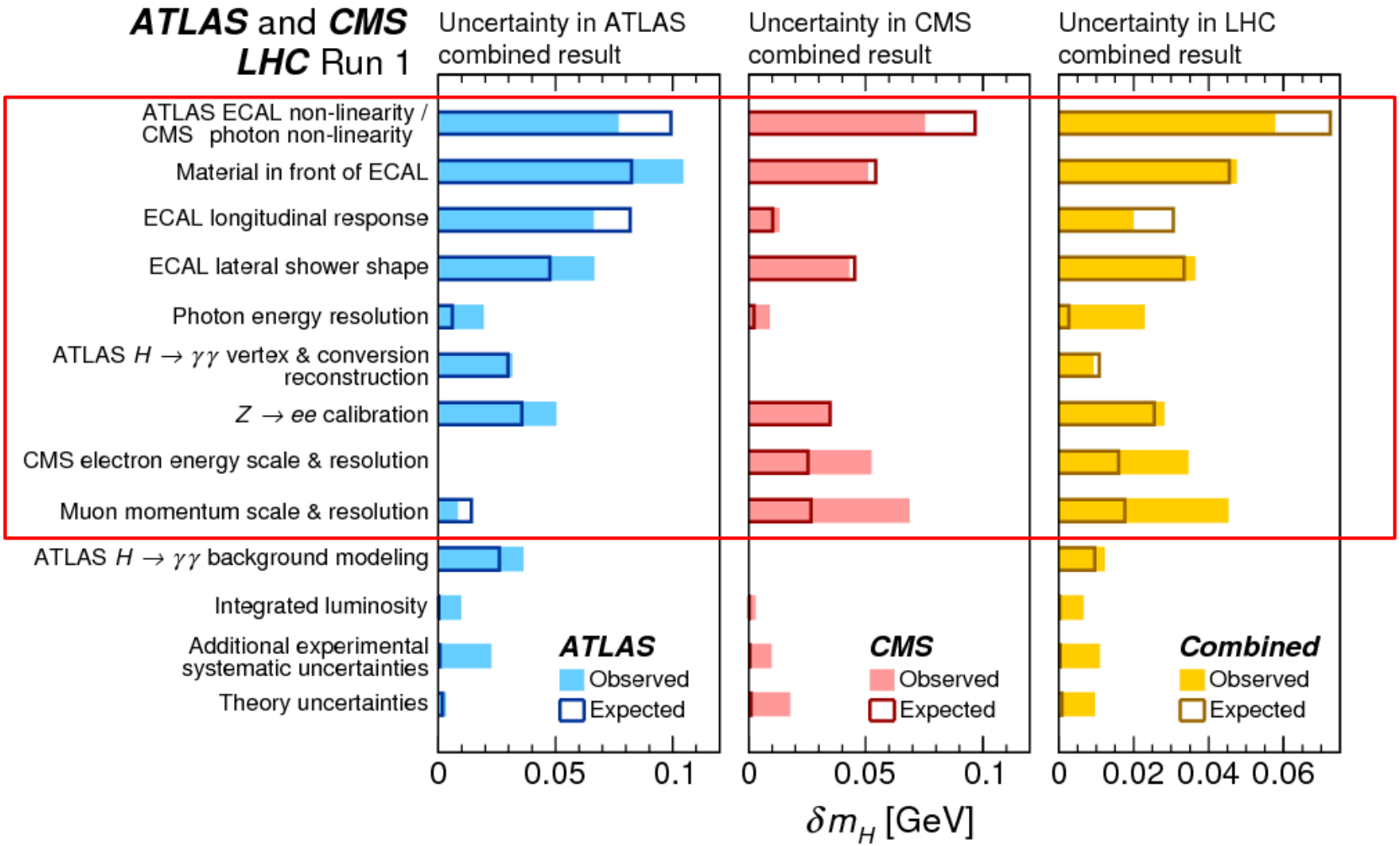


Systematic uncertainties – scale

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \boxed{\pm 0.11\,(\text{scale})} \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV}$$

Energy/momentum scale/resolution on γ, e, μ dominate

- uncorrelated between ATLAS and CMS – independent calibration procedures

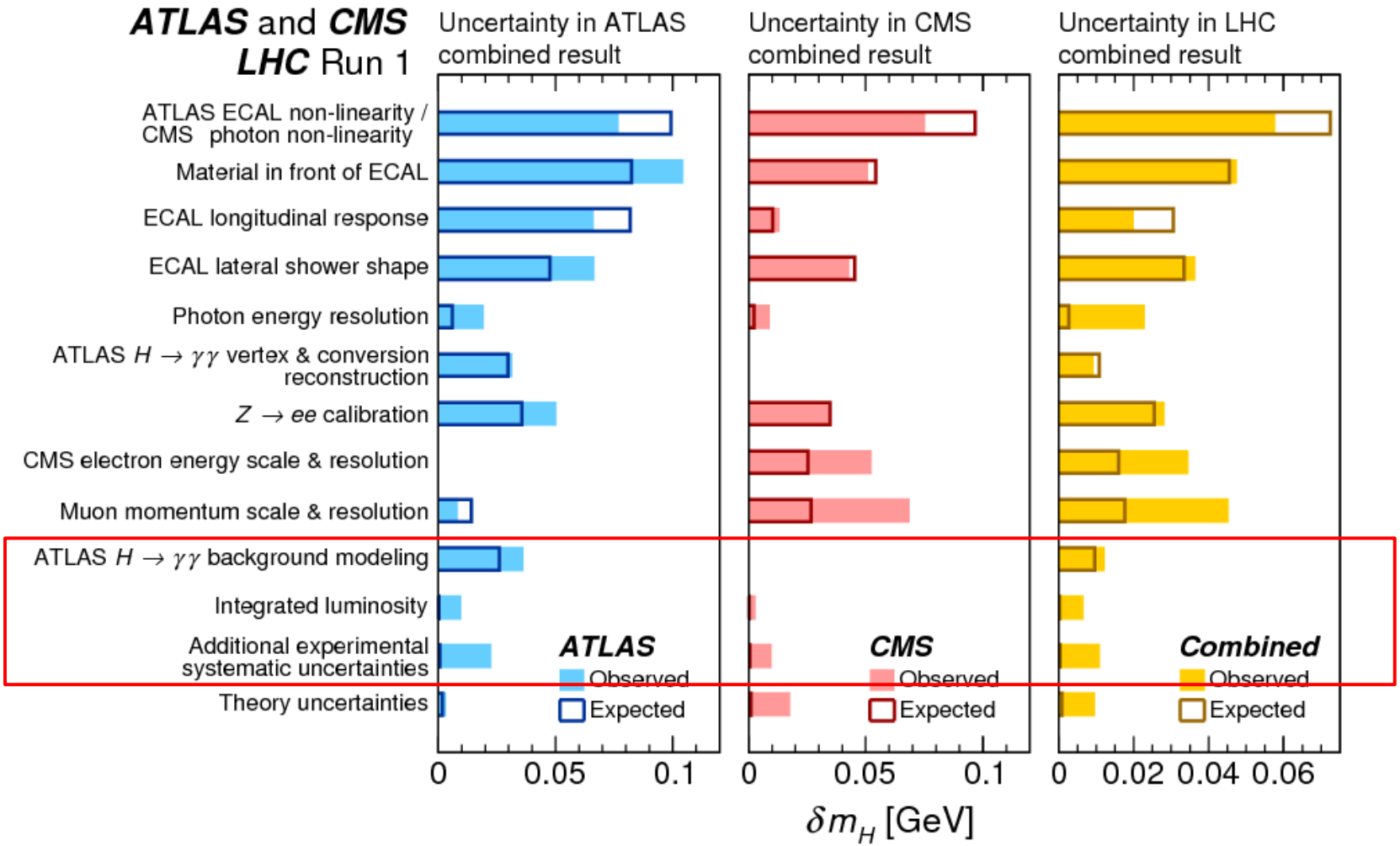


Systematic uncertainties – other experimental

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \boxed{\pm 0.02\,(\text{other})} \pm 0.01\,(\text{theory})\ \text{GeV}$$

Other experimental uncertainties, eg. H→γγ background modelling, efficiencies, etc

- luminosity uncertainty partially correlated

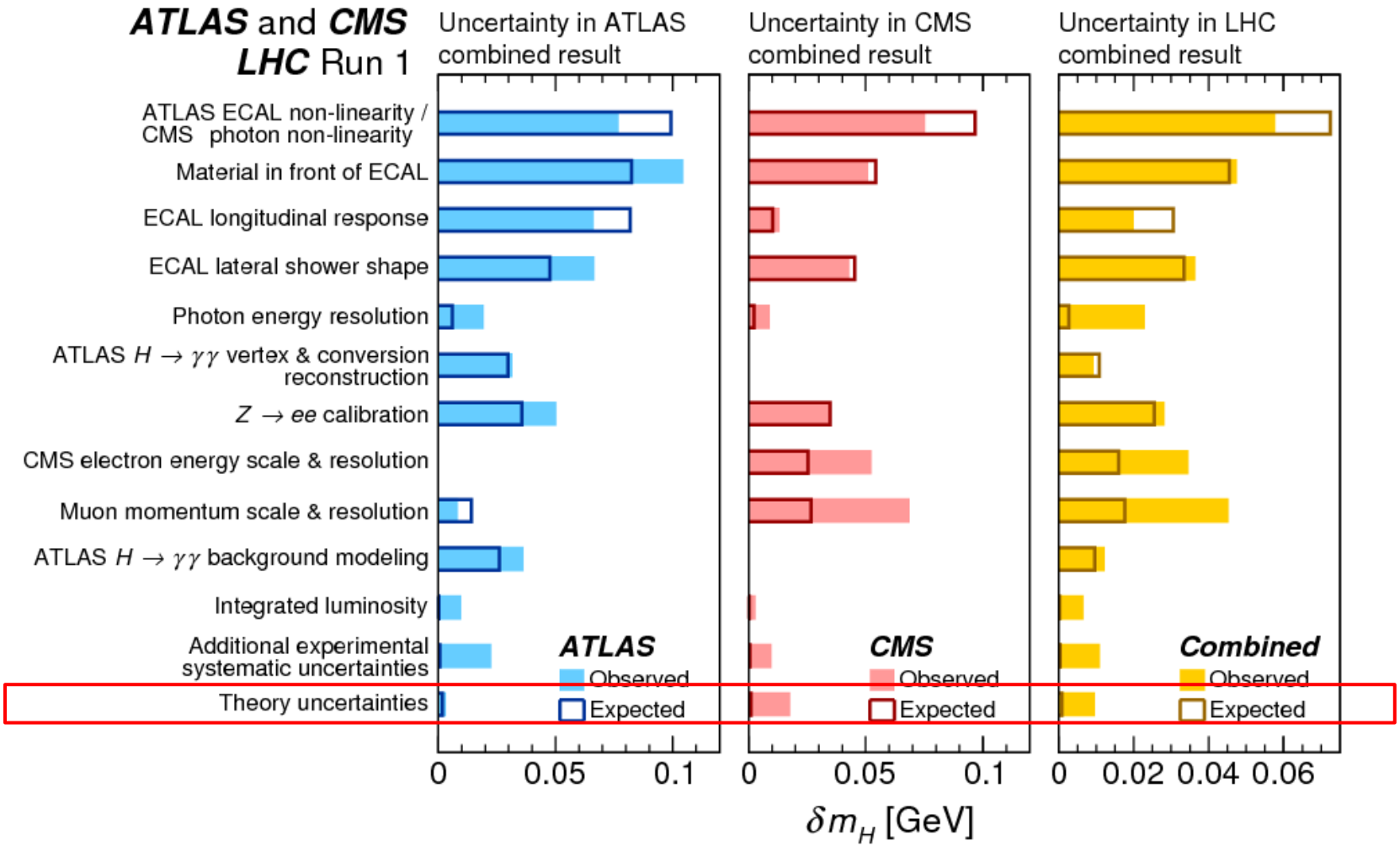


Systematic uncertainties – theory

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{scale}) \pm 0.02\,(\text{other}) \pm 0.01\,(\text{theory})\ \text{GeV}$$

Theory uncertainties, eg. QCD scale, PDF, SM branching ratio, etc

- 100% correlated between ATLAS and CMS
  - Expected small interference between Higgs signal and continuum background neglected



Conclusion

- ATLAS and CMS measure m_H = 125.09 ± 0.24 GeV
  = 125.09 ± 0.21 (stat.) ± 0.11 (syst.) GeV
  - Final and most precise Higgs mass measurement from LHC Run 1 data
  - Result is statistically dominated, so hope to improve with luminosity (Run 2)
  - Systematic uncertainty is dominated by energy scale in $H\rightarrow\gamma\gamma$
    - this should also improve with more data (eg. calibration samples)
  - $H\rightarrow ZZ\rightarrow 4l$ is almost entirely statistics-dominated

- First joint ATLAS+CMS paper accepted by PRL: arXiv:1503.07589 (>5000 authors!)
  - Invaluable experience combining Higgs measurements between ATLAS and CMS
    - process continues into LHC coupling combination (now ongoing)
  - Further understanding (within the collaborations) of differences between experiments and techniques
    - detailed studies of analysis strategies, statistical and systematic uncertainties

- Higgs mass is a vital input for testing the Higgs couplings against the SM
  - eg. $H\rightarrow ZZ^*$ branching ratio strongly dependent on m_H

References

- ATLAS+CMS combined Higgs mass
  - *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS Experiments*, accepted by PRL, arXiv:1503.07589

- ATLAS combined Higgs mass
  - *Measurement of the Higgs boson mass from the $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$ channels with the ATLAS detector using 25 fb^{-1} of pp collision data,* PRD 90 052004 (2014), arXiv:1406.3827

- CMS combined Higgs mass (and couplings)
  - *Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV,* accepted by EPJC, arXiv:1412.8662

Backup

γγ and ZZ combined results

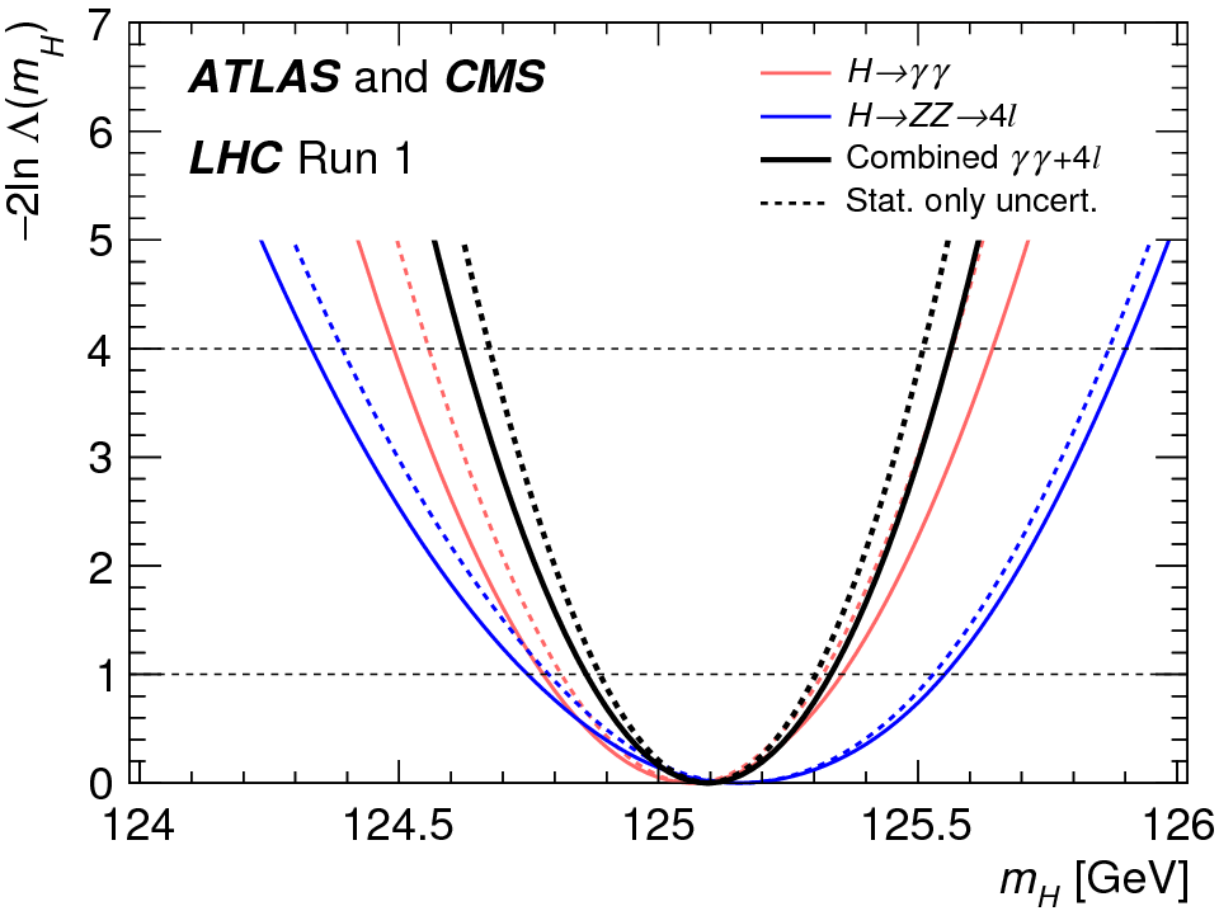


Figure 1: Scans of twice the negative log-likelihood ratio $-2\ln\Lambda(m_H)$ as functions of the Higgs boson mass m_H for the ATLAS and CMS combination of the **H→γγ**, **H→ZZ→4*l***, and **combined** channels. The dashed curves show the results accounting for statistical uncertainties only, with all nuisance parameters associated with systematic uncertainties fixed to their best-fit values. The 1 and 2 standard deviation limits are indicated by the intersections of the horizontal lines at 1 and 4, respectively, with the log-likelihood scan curves.

μ vs m_H for input channels and combination

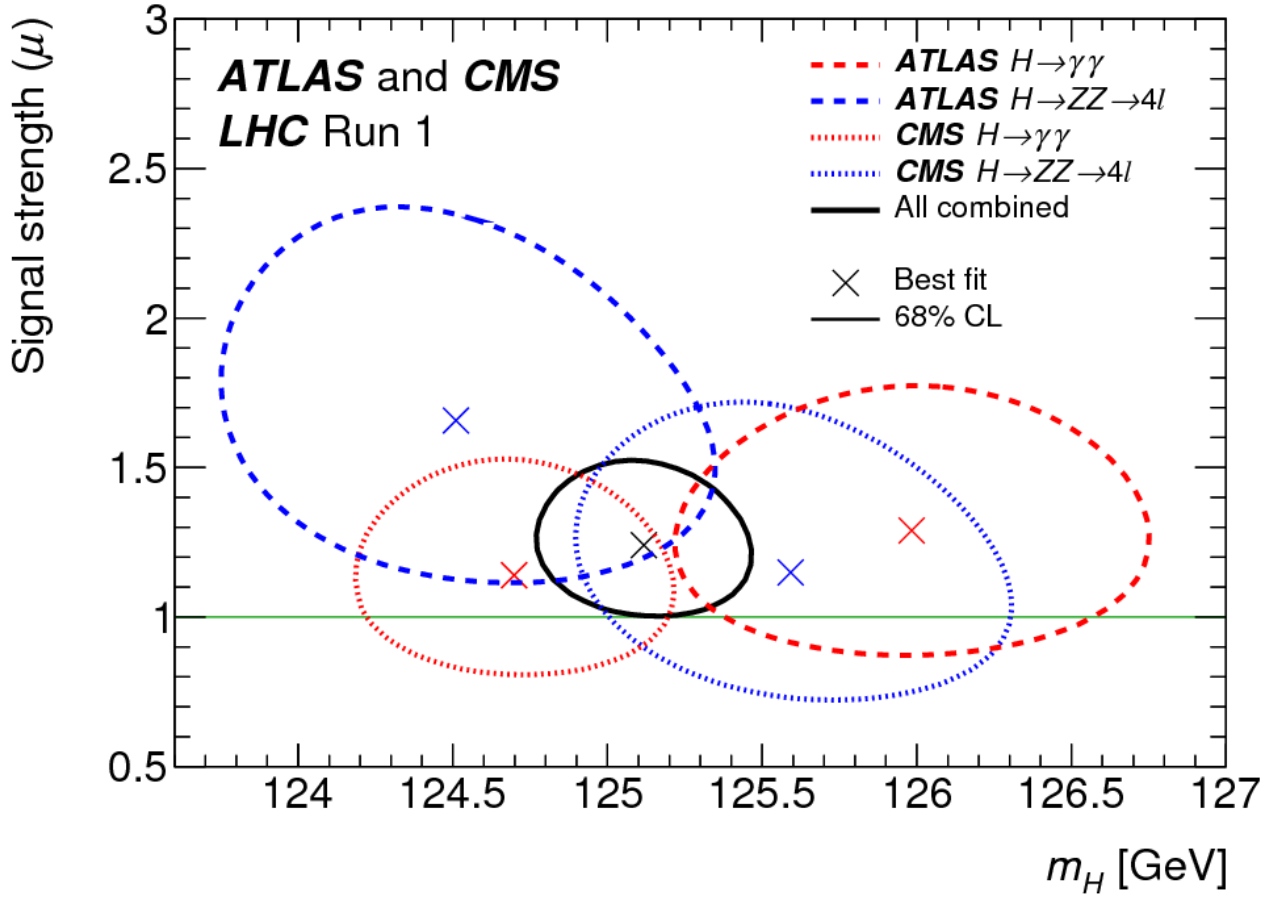
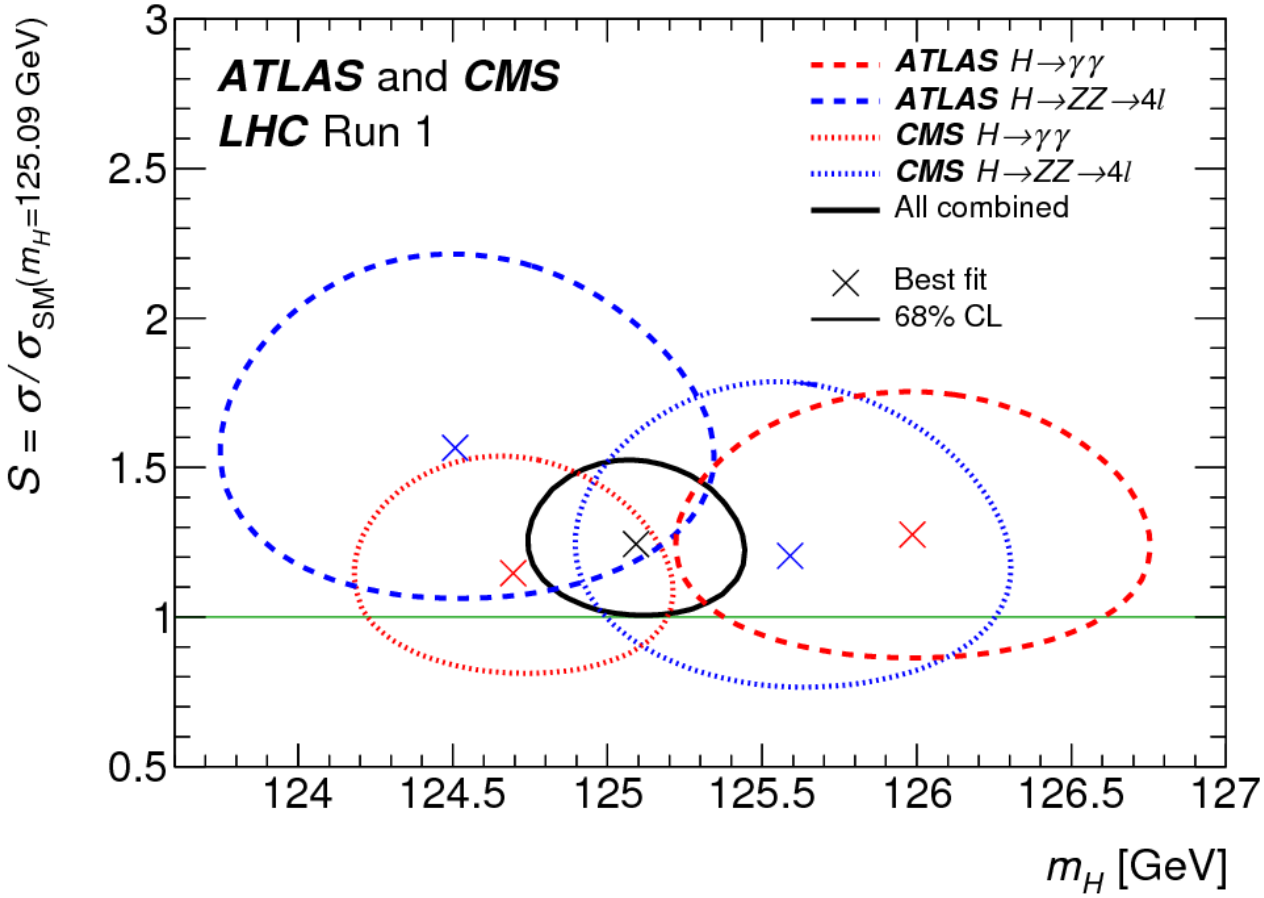


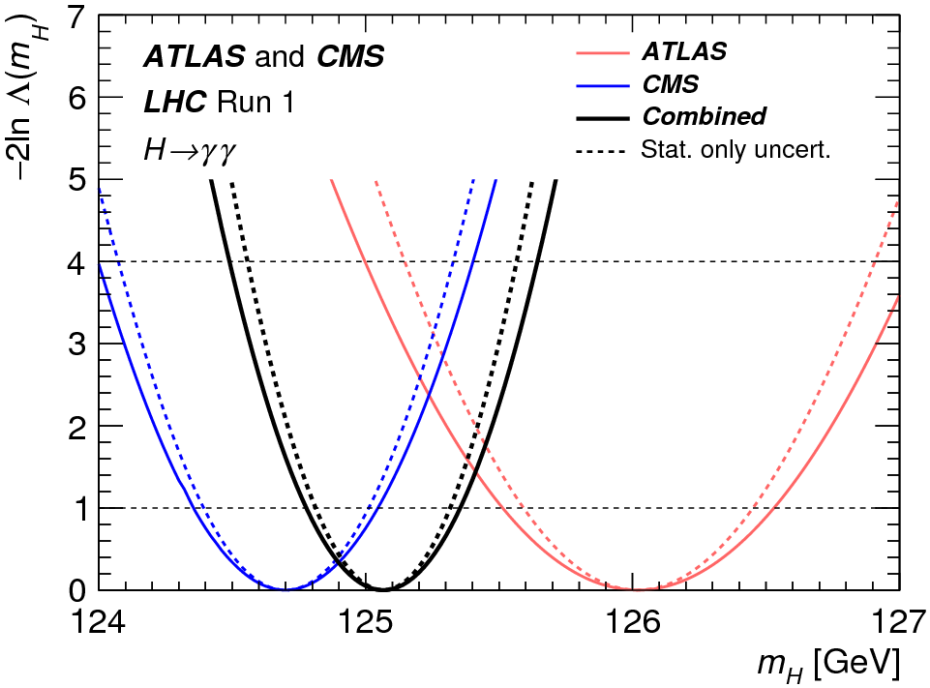
Figure 4: Summary of likelihood scans in the 2D plane of signal strength μ versus Higgs boson mass m_H for the ATLAS and CMS experiments. The 68% CL confidence regions of the individual measurements are shown by the dashed curves and of the overall combination by the solid curve. The markers indicate the respective best-fit values. The SM signal strength is indicated by the horizontal line at μ=1.

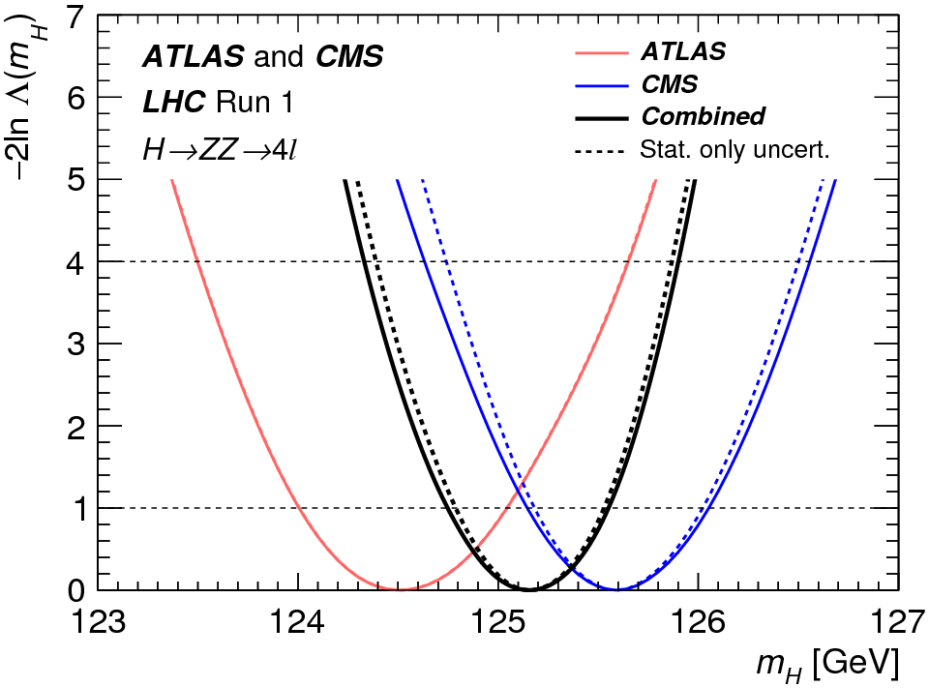
normalised signal yield vs m_H



Summary of likelihood scans in the 2D plane of the normalized signal yield $S \equiv \sigma/\sigma_{SM}(m_H=125.09\ \text{GeV})$ versus Higgs boson mass m_H for the ATLAS and CMS experiments. S is similar to the signal strength $\mu \equiv \sigma/\sigma_{SM}(m_H)$, except the m_H-dependence of the expected SM event yield that enters into the denominator, principally for the $H\rightarrow ZZ\rightarrow 4\boldsymbol{l}$ channel, is removed by fixing m_H to the combined best-fit mass. The 68% CL confidence regions of the individual measurements are shown by the dashed curves and of the overall combination by the solid curve. The markers indicate the respective best-fit values. The fitted signal yield is observed to be independent of the measured mass. The SM signal strength is indicated by the horizontal line at $\mu=1$.

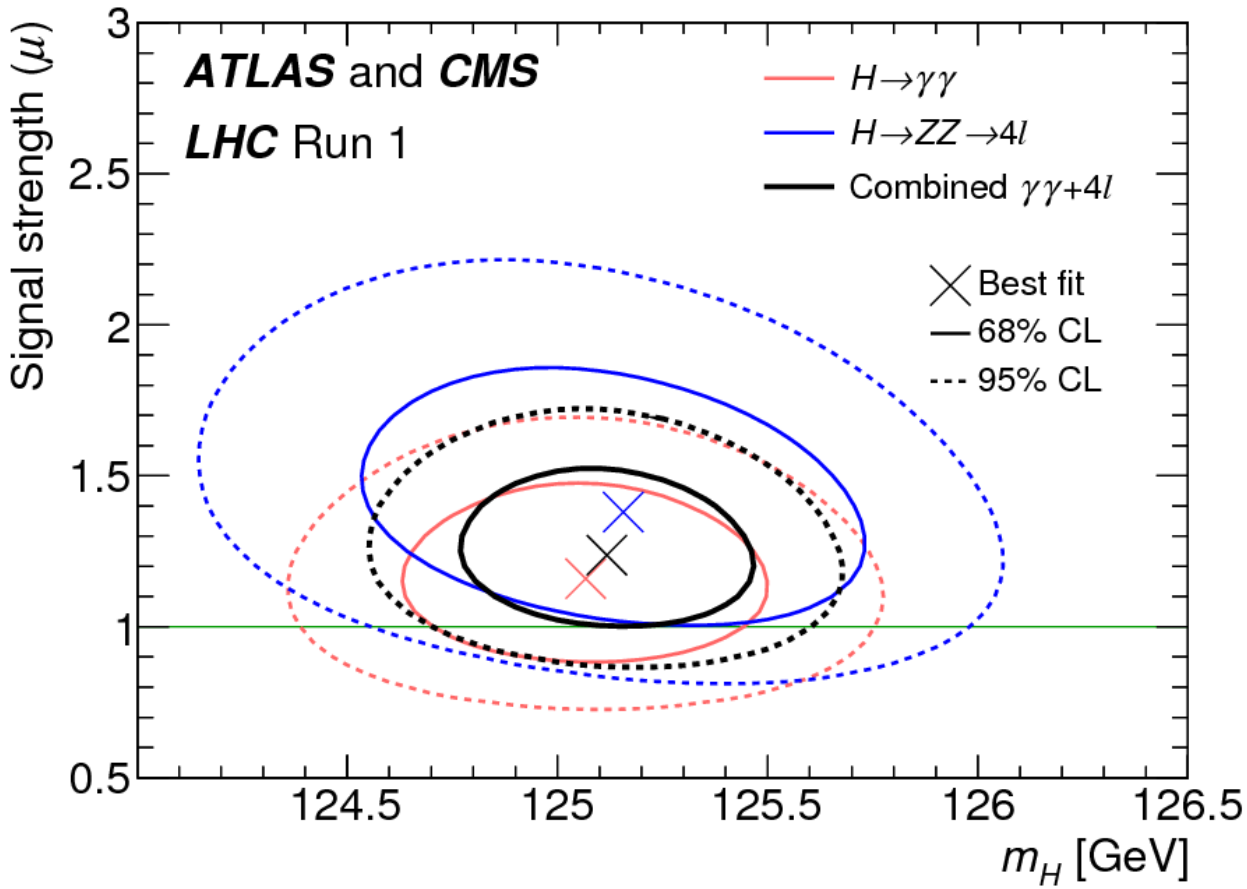
Individual and combined results in γγ and ZZ





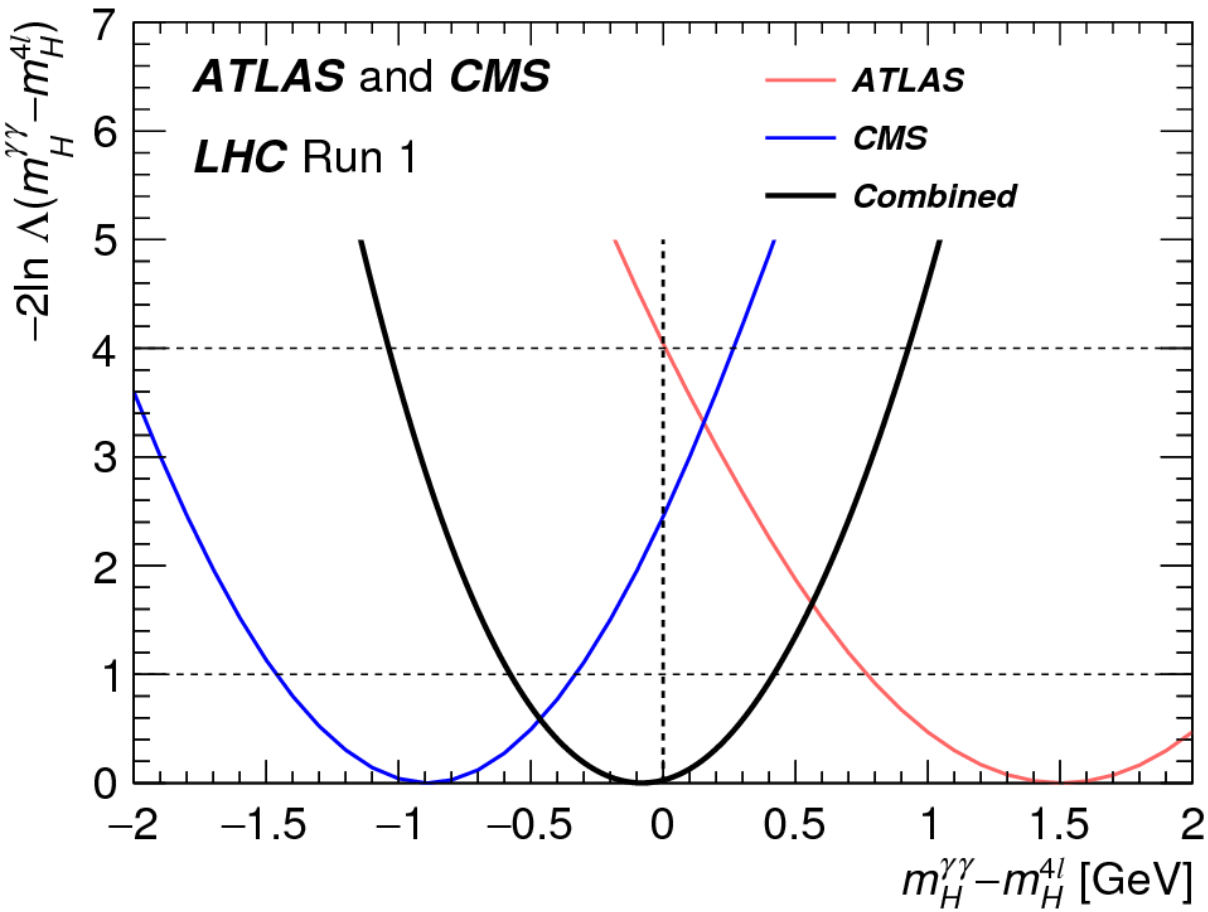
Likelihood curves for the Higgs boson mass m_H measured in the H→γγ (left) and H→ZZ→4*l* (right) channels by the **ATLAS** and **CMS** experiments, and their **combination**. The dashed curves reflect the statistical components of the uncertainties.

μ vs m_H for γγ and ZZ combined results



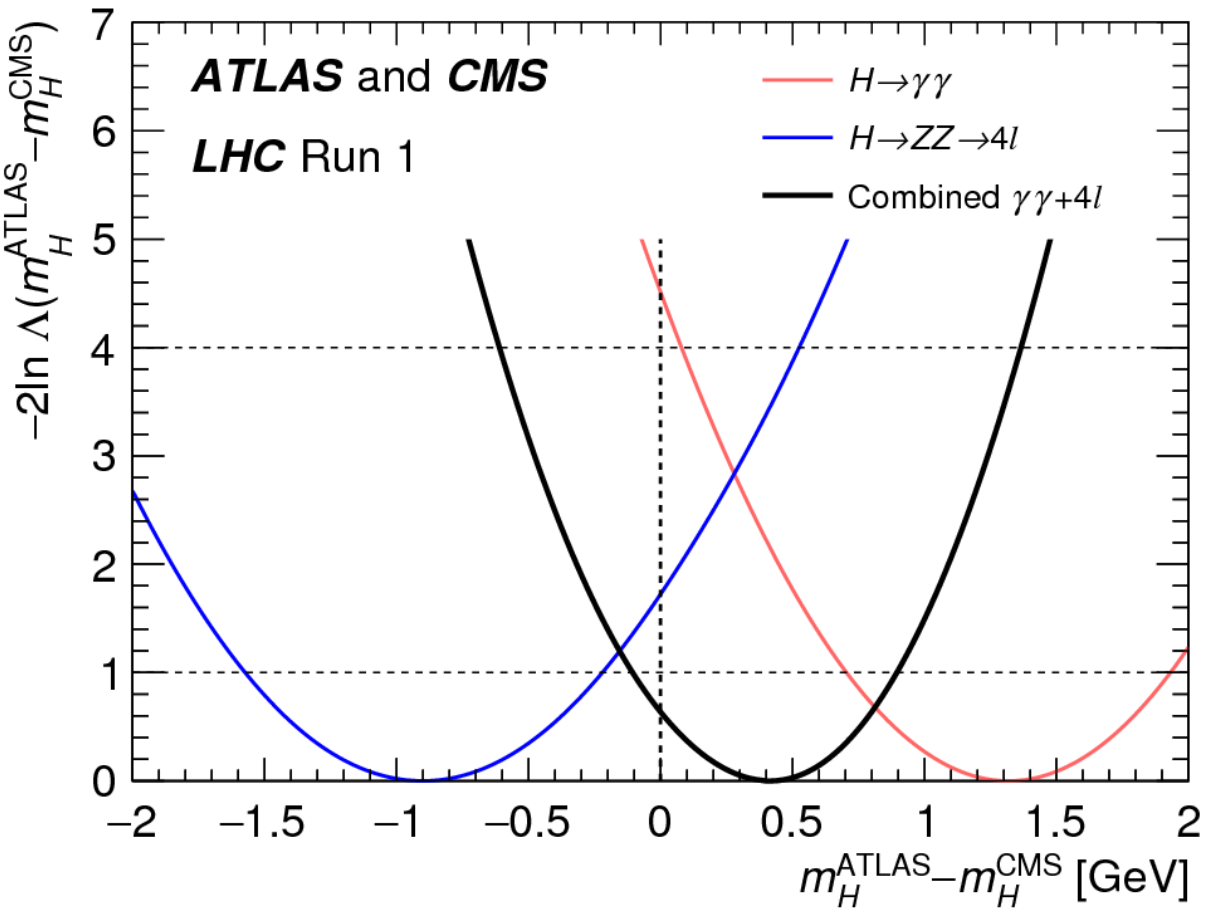
Summary of likelihood scans in the 2D plane of signal strength μ versus Higgs boson mass m_H for the **H→γγ** and **H→ZZ→4*l*** channels, and their **combination**. The 68% and 95% CL confidence regions of the individual measurements are shown by the solid and dashed curves, respectively. The markers indicate the respective best-fit values.

$\gamma\gamma$–4l compatibility



Likelihood curves for the mass difference, $\Delta m_{\gamma Z} \equiv m_H^{\gamma\gamma} - m_H^{4l}$, for the **ATLAS** and **CMS** experiments, and their **combination**. The common signal strength parameters $\mu_{ggF+ttH}^{\gamma\gamma}$, $\mu_{VBF+VH}^{\gamma\gamma}$, and μ^{4l} are allowed to vary independently. The tension between two channels is evaluated to be 2.0σ in ATLAS experiment, 1.6σ in CMS experiment, and within 1σ (0.2σ) in the full combination.

ATLAS–CMS compatibility



Likelihood curves for the mass difference, $\Delta m^{exp} \equiv m_H^{ATLAS} - m_H^{CMS}$, for the **H → γγ** and **H → ZZ → 4*l*** channels, and their **combination**. The signal strength parameters $\mu_{ggF+ttH}^{\gamma\gamma}$, $\mu_{VBF+VH}^{\gamma\gamma}$, and μ^{4l} are allowed to vary independently. The tension between two experiments is evaluated to be 2.1σ in H→γγ channel, 1.3σ in H→ZZ→4*l* channel, and within 1σ (0.8σ) in the full combination.

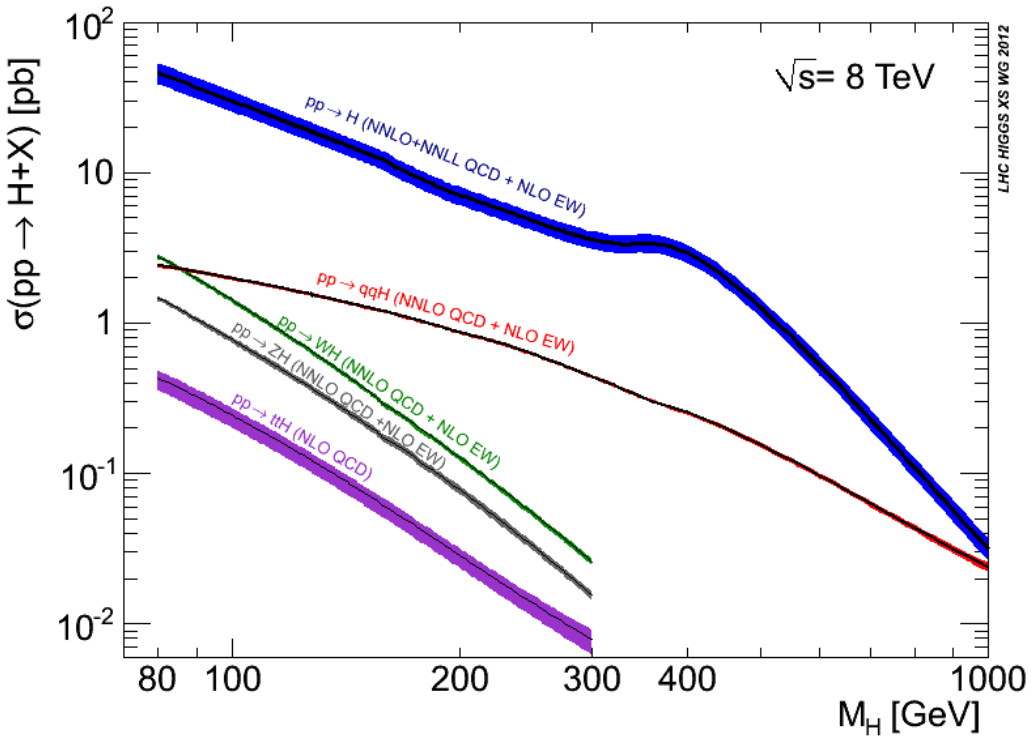
Systematics in input channels and ATLAS/CMS combinations

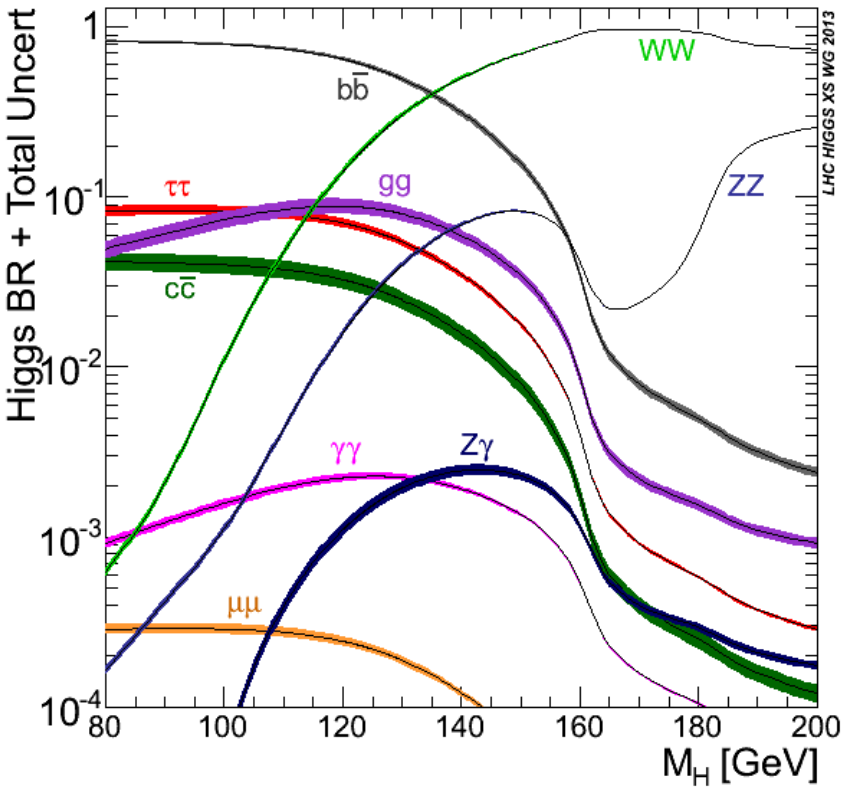
	Uncertainty in ATLAS results [GeV]: observed (expected)		Uncertainty in CMS results [GeV]: observed (expected)		Uncertainty in combined result [GeV]: observed (expected)	
	$H \to \gamma\gamma$	$H \to ZZ$llll	$H \to \gamma\gamma$	$H \to ZZ$llll	ATLAS	CMS
Scale uncertainties:						
ATLAS ECAL non-linearity / CMS photon non-linearity	0.14 (0.16)	–	0.10 (0.13)	–	0.02 (0.04)	0.05 (0.06)
Material in front of ECAL	0.15 (0.13)	–	0.07 (0.07)	–	0.03 (0.03)	0.04 (0.03)
ECAL longitudinal response	0.12 (0.13)	–	0.02 (0.01)	–	0.02 (0.03)	0.01 (0.01)
ECAL lateral shower shape	0.09 (0.08)	–	0.06 (0.06)	–	0.02 (0.02)	0.03 (0.03)
Photon energy resolution	0.03 (0.01)	–	0.01 (<0.01)	–	0.02 (<0.01)	<0.01 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.05 (0.05)	–	–	–	0.01 (0.01)	–
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.02)	0.05 (0.05)	–	0.02 (0.01)	0.02 (0.02)
CMS electron energy scale & resolution	–	–	–	0.12 (0.09)	–	0.03 (0.02)
Muon momentum scale & resolution	–	0.03 (0.04)	–	0.11 (0.10)	<0.01 (0.01)	0.05 (0.02)
Other uncertainties:						
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	–	–	0.01 (0.01)	–
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Additional experimental systematic uncertainties	0.03 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	<0.01 (<0.01)	0.02 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)	
Systematic uncertainty (sum in quadrature)	0.27 (0.27)	0.04 (0.04)	0.15 (0.17)	0.16 (0.13)	0.11 (0.10)	
Systematic uncertainty (nominal)	0.27 (0.27)	0.04 (0.05)	0.15 (0.17)	0.17 (0.14)	0.11 (0.10)	
Statistical uncertainty	0.43 (0.45)	0.52 (0.66)	0.31 (0.32)	0.42 (0.57)	0.21 (0.22)	
Total uncertainty	0.51 (0.52)	0.52 (0.66)	0.34 (0.36)	0.45 (0.59)	0.24 (0.24)	
Analysis weights	19% (22%)	18% (14%)	40% (46%)	23% (17%)	–	

Systematics in ATLAS, CMS, and LHC combination

	Uncertainty in ATLAS combined result [GeV]: observed (expected)	Uncertainty in CMS combined result [GeV]: observed (expected)	Uncertainty in LHC combined result [GeV]: observed (expected)
Scale uncertainties:			
ATLAS ECAL non-linearity / CMS photon non-linearity	0.08 (0.10)	0.08 (0.10)	0.06 (0.07)
Material in front of ECAL	0.10 (0.08)	0.05 (0.05)	0.05 (0.05)
ECAL longitudinal response	0.07 (0.08)	0.01 (0.01)	0.02 (0.03)
ECAL lateral shower shape	0.07 (0.05)	0.04 (0.05)	0.04 (0.03)
Photon energy resolution	0.02 (0.01)	0.01 (<0.01)	0.02 (<0.01)
ATLAS $H \to \gamma\gamma$ vertex & conversion reconstruction	0.03 (0.03)	–	0.01 (0.01)
$Z \to ee$ calibration	0.05 (0.04)	0.03 (0.03)	0.03 (0.03)
CMS electron energy scale & resolution	–	0.05 (0.03)	0.03 (0.02)
Muon momentum scale & resolution	0.01 (0.01)	0.07 (0.03)	0.05 (0.02)
Other uncertainties:			
ATLAS $H \to \gamma\gamma$ background modeling	0.04 (0.03)	–	0.01 (0.01)
Integrated luminosity	0.01 (<0.01)	<0.01 (<0.01)	0.01 (<0.01)
Additional experimental systematic uncertainties	0.02 (<0.01)	0.01 (<0.01)	0.01 (<0.01)
Theory uncertainties	<0.01 (<0.01)	0.02 (<0.01)	0.01 (<0.01)
Systematic uncertainty (sum in quadrature)	0.18 (0.17)	0.14 (0.13)	0.11 (0.10)
Systematic uncertainty (nominal)	0.18 (0.18)	0.14 (0.13)	0.11 (0.10)
Statistical uncertainty	0.37 (0.37)	0.27 (0.28)	0.21 (0.22)
Total uncertainty	0.41 (0.41)	0.30 (0.31)	0.24 (0.24)
Analysis weights	35% (36%)	65% (64%)	–

XS and BR vs m_H

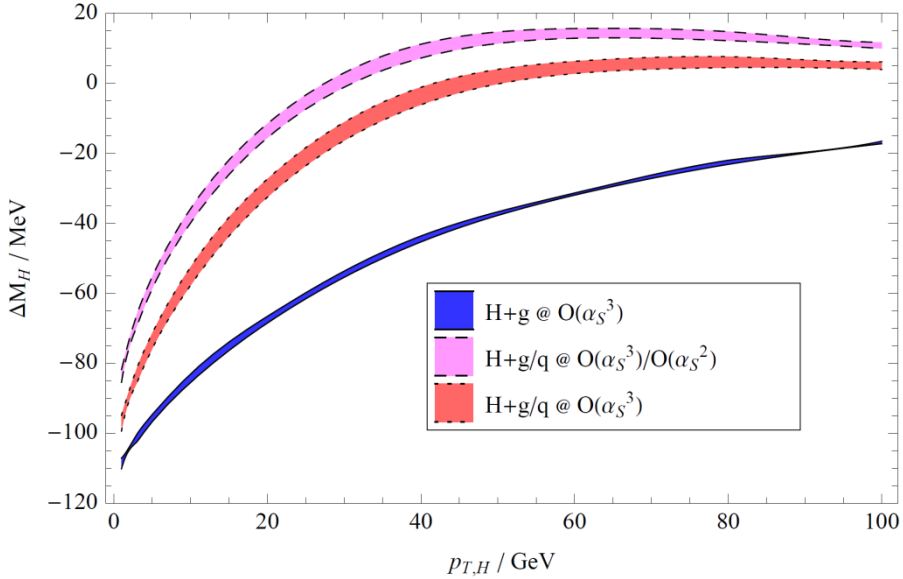




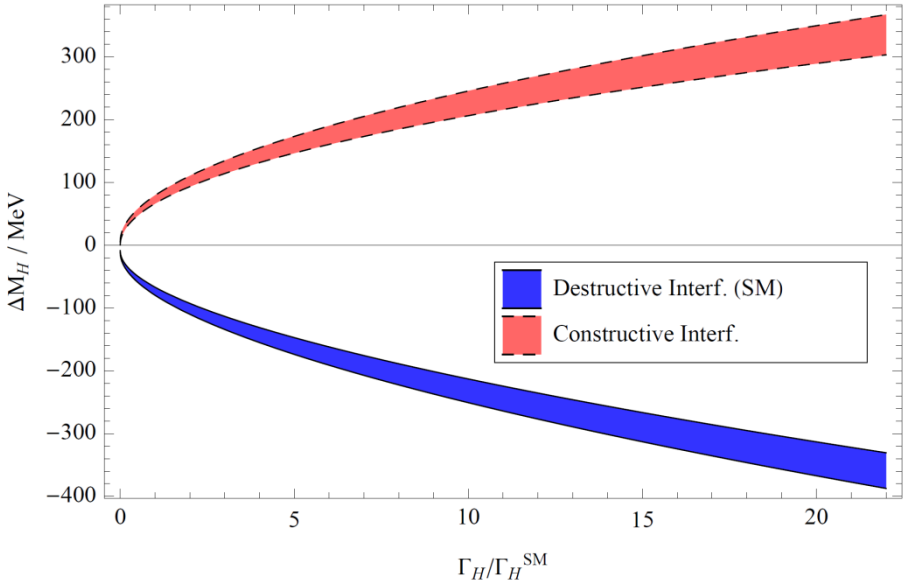
Interference of H→γγ with continuum background

- Estimated 20–50 MeV effect of interference on H→γγ mass measurements
  - after selections and relative weights in each category
- This effect is neglected in the present analysis

mass shift as a function of lower p_T cut



mass shift as a function of Higgs width



L. J. Dixon and Y. Li, *Bounding the Higgs Boson width through interferometry*, PRL 111 (2013) 111802, arXiv:1305.3854