Measurements of the Higgs boson mass and width at CMS

Higgs Hunting
15 July 2025

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On behalf of the CMS collaboration

$H \rightarrow ZZ \rightarrow 4l$

Phys. Rev. D 111, 092014
https://doi.org/10.1103/PhysRevD.111.092014

Motivation

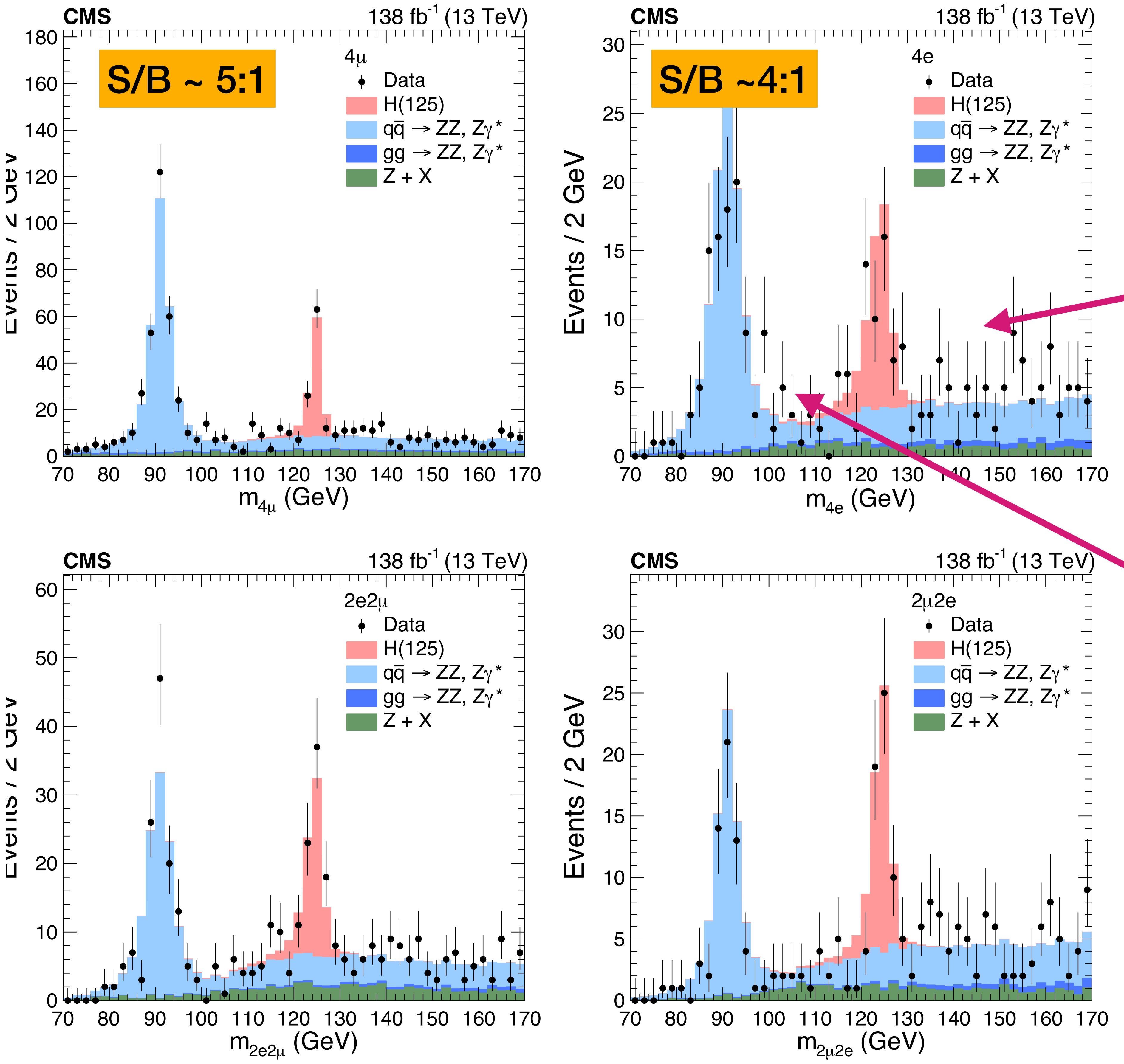
- The Higgs boson mass is a free parameter of the Standard Model (SM)
- m_H can be measured precisely in the two decay modes : $H \to \gamma\gamma$ and $H \to ZZ \to 4l$
  - Both have well reconstructed final states with excellent mass resolution (1-2%)
  - $H \to ZZ \to 4l$ has small branching fraction (BR ~ 0.01%) compared to $H \to \gamma\gamma$ (BR ~ 0.2%), but:
    - high signal-to-background ratio (S/B) ~4:1

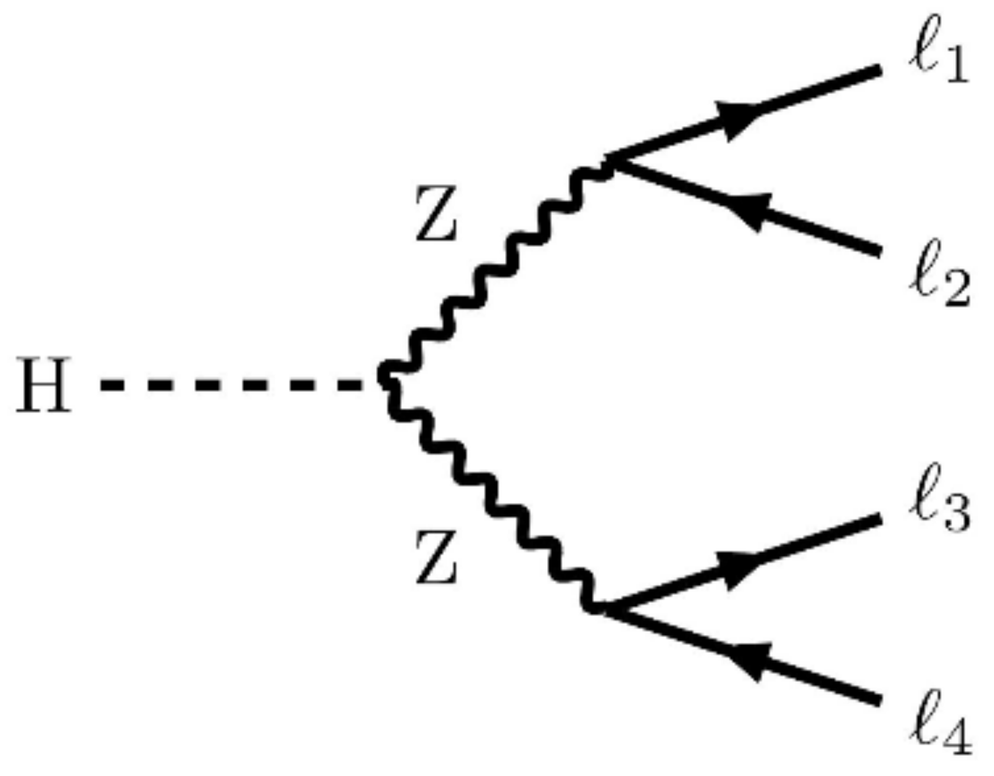
- Higgs decay width (Γ_{H}) predicted precisely in the SM (~4 MeV for m_{H} = 125 GeV)

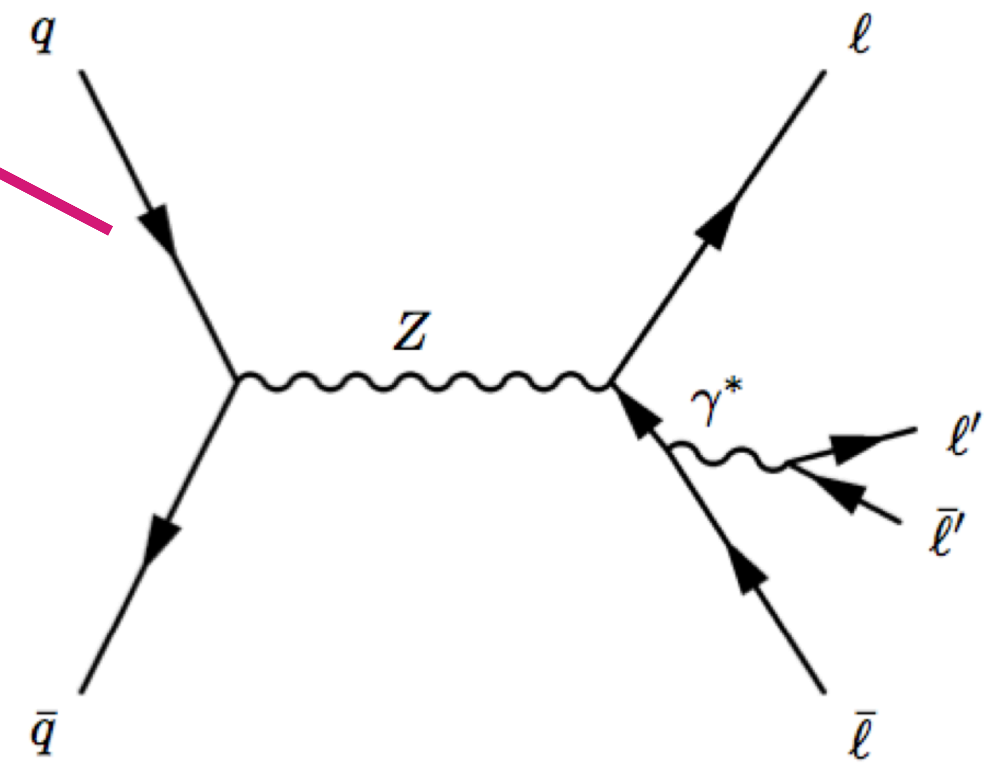
  $\to$ any deviation hints at new physics
- Width can be constrained both
  - Directly from line-shape in on-shell region
  - Indirectly from off-shell Higgs production
- This talk focuses on mass and width measurement in $H \to ZZ \to 4l$ at CMS
- The measurement in $H \to \gamma\gamma$ will be presented in the talk on Higgs Properties at CMS (Amrutha's talk)

Mass measurement in $H \rightarrow ZZ \rightarrow 4l$ using full Run2 data (138 fb-1)

- For the mass measurement, events are categorised into four final states : $4\mu,\ 4e,\ 2\mu 2e,\ 2e2\mu$
- In $2\mu 2e$, the pair $\mu\mu$ forms Z_1 (closest to nominal Z boson), and in $2e2\mu$, the ee pair forms Z_1
- These final states have different mass resolutions, due to detector performance differences between muons and electrons
- They also exhibit different signal-to-background ratios (S/B), depending on whether Z_1 is formed from $\mu\mu$ or ee



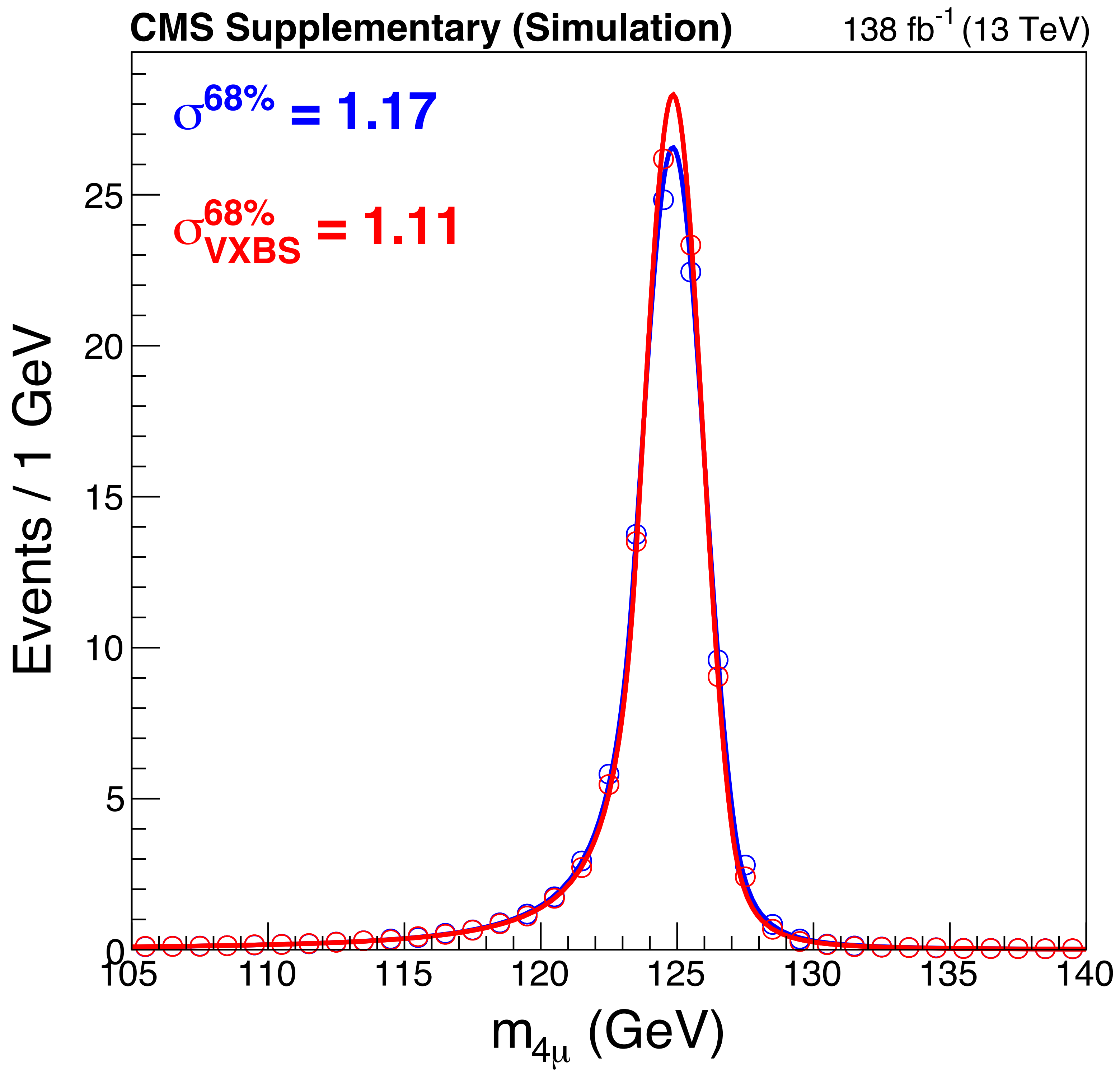




Beam Spot constraint NEW

- The beam spot represents a 3-D profile of the luminous region over which beams collide
- Beam spot (BS) position and transverse spread measured precisely
- Constrain muon tracks to come from the beam spot (BS)
- This improves muon momentum (p_T) resolution by 5-10%
- Electron momentum precision is dominated by the energy measured in ECAL system, and hence electrons kinematic parameters are not modified

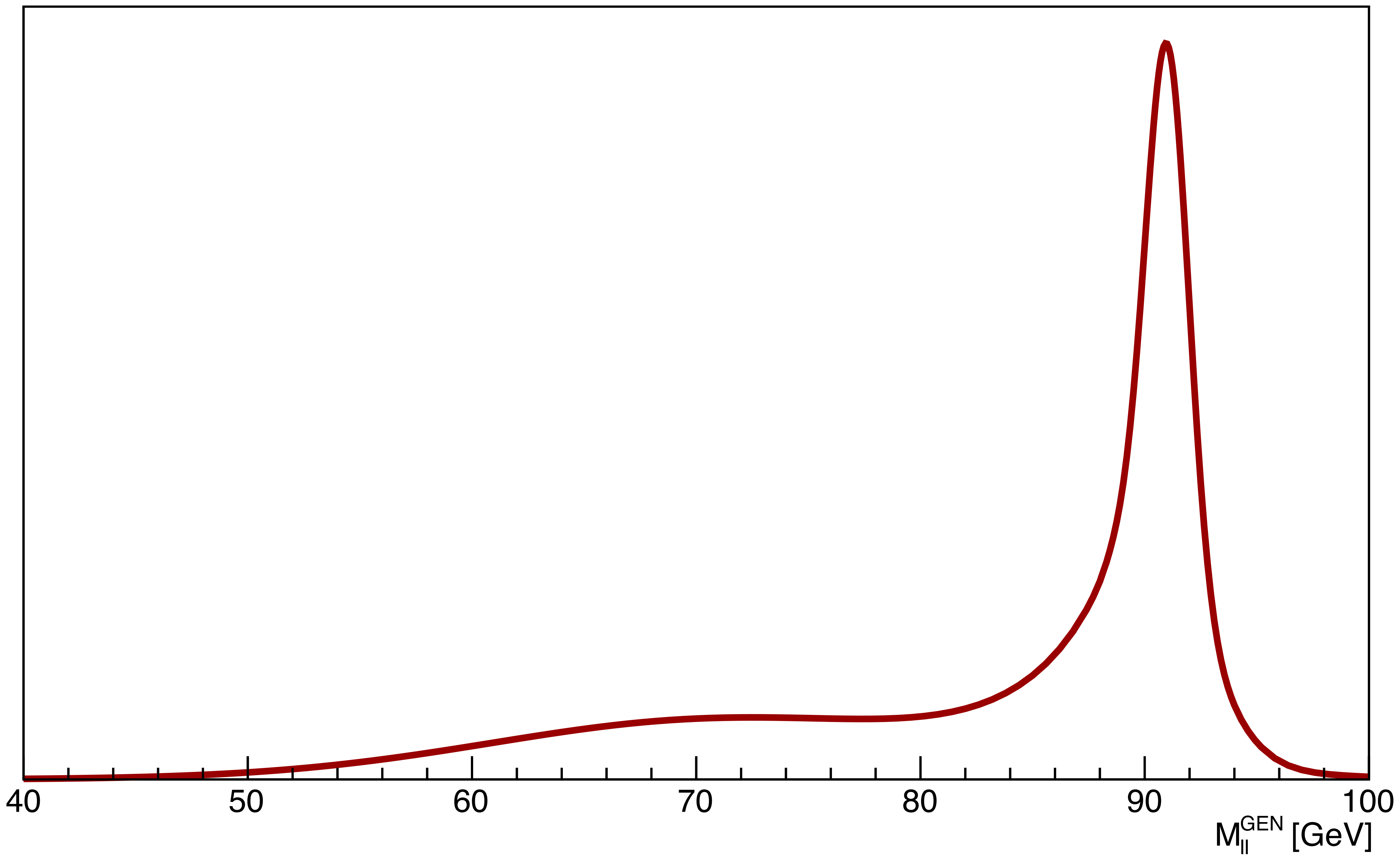
- **Overall improvement in m_H uncertainty ~ 5%**



Z_1 line shape constraint

- $H \to Z_1 Z_2 \to 4l$, Z_1 is mostly on-shell with $m(Z_1) \sim m(Z)$
- To improve the mass resolution, a kinematic fit is performed using a mass constraint on the intermediate on-shell Z resonance
- Re-evaluate p_T of two leptons forming Z_1, constraining reconstructed Z_1 mass to follow the Z boson true line shape

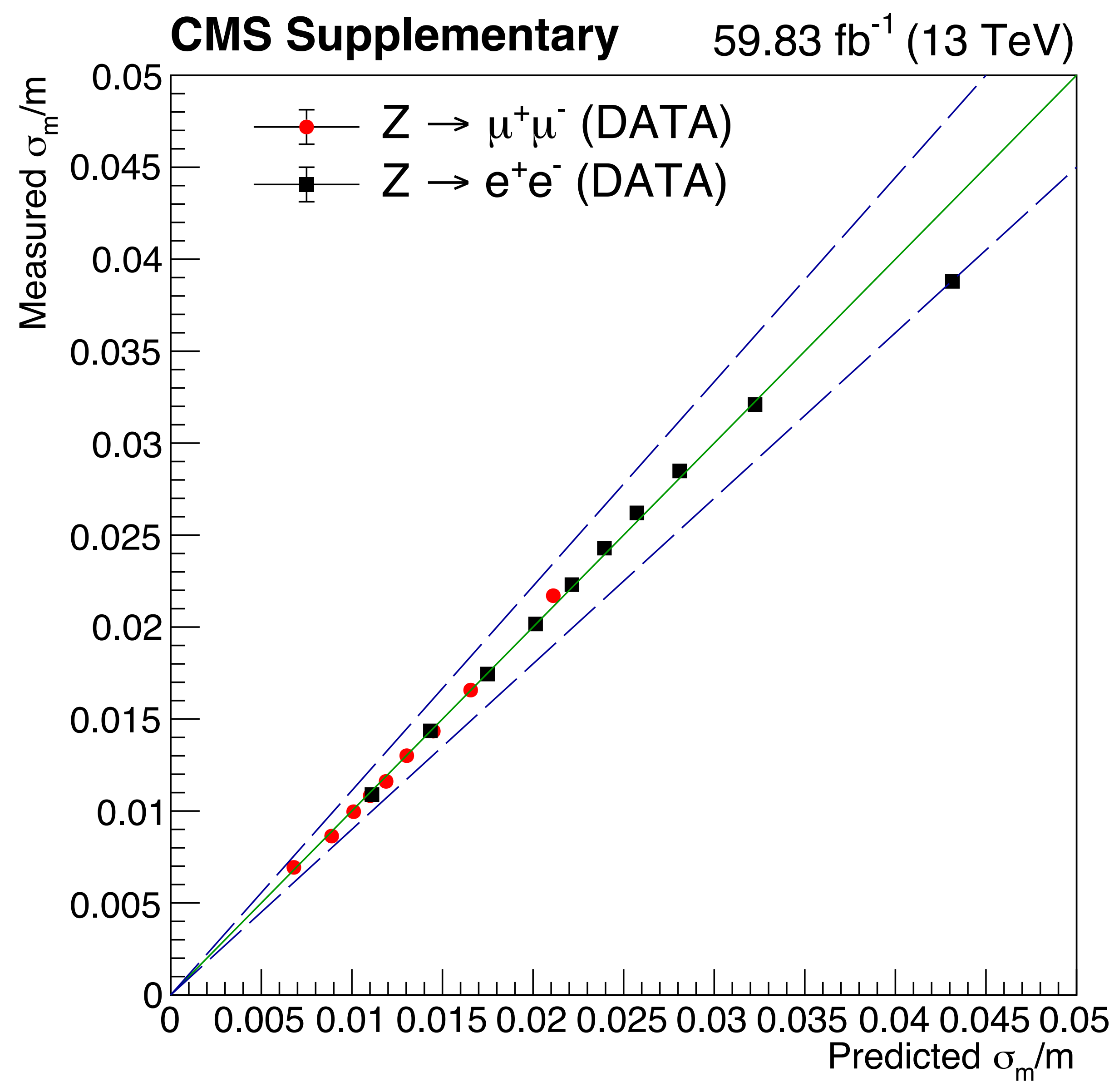
- **Overall improvement in m_H uncertainty ~ 8%**

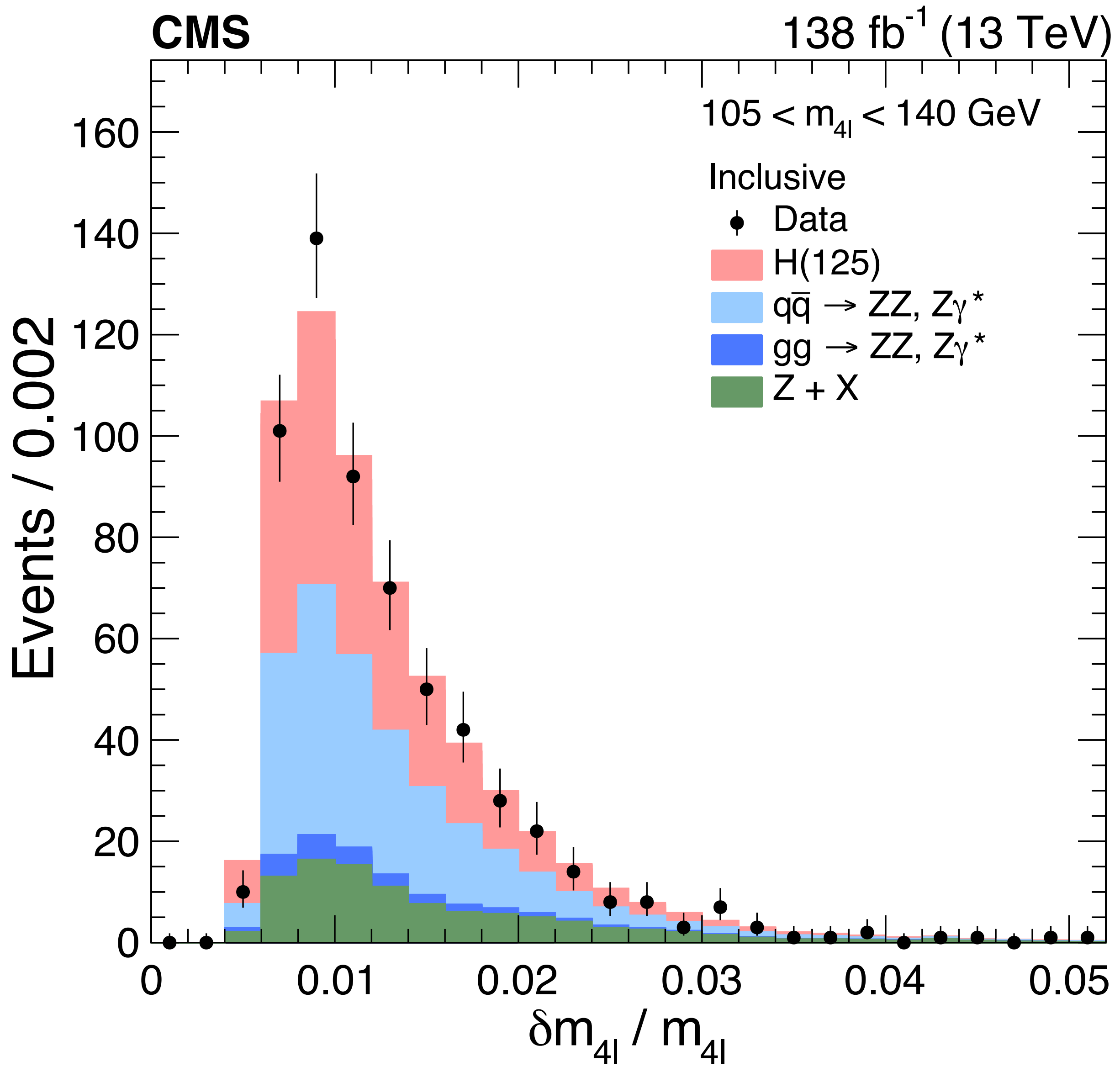


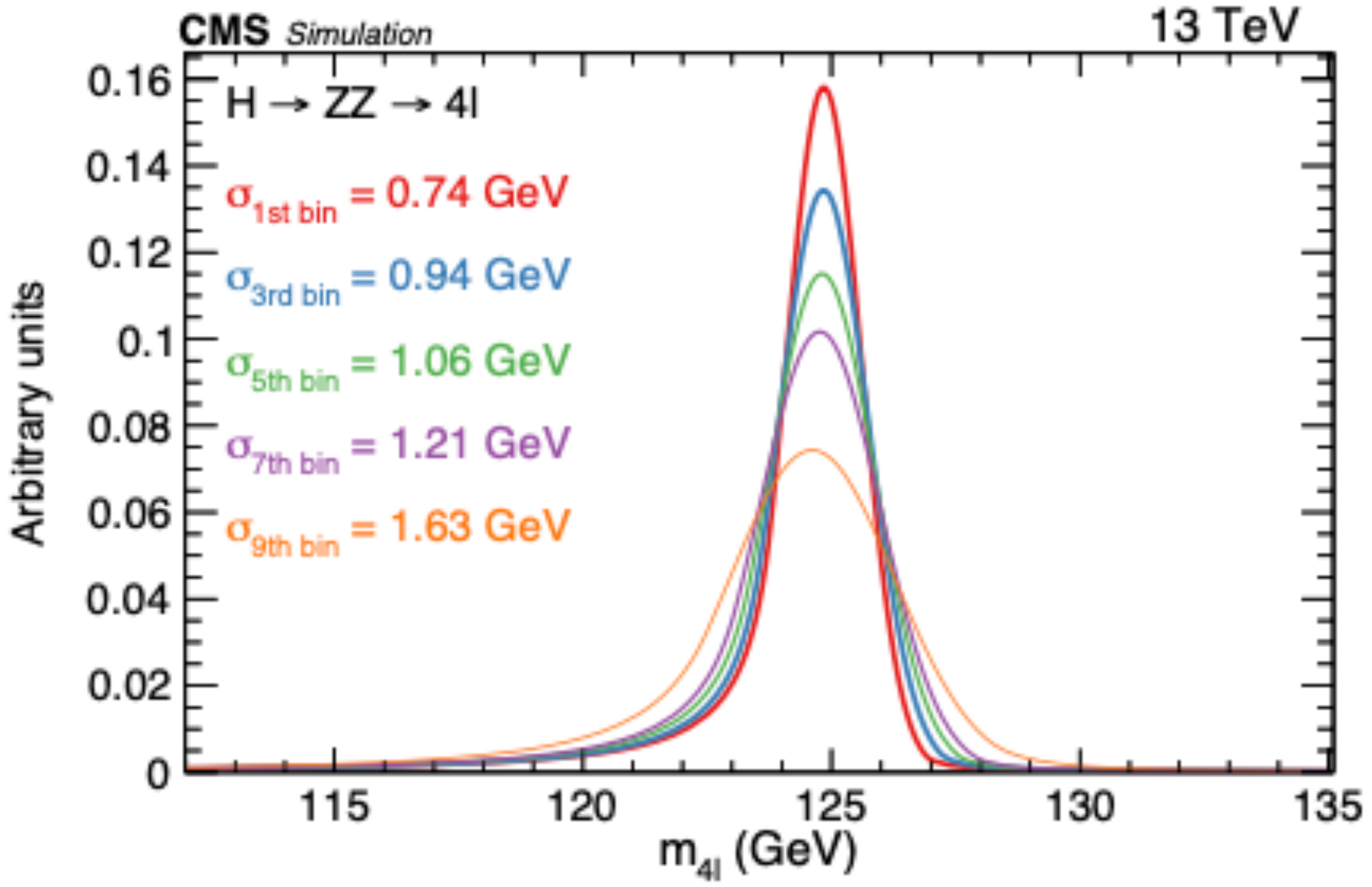
Categorisation : per-event mass uncertainty

- Per-event mass uncertainty on the Higgs boson (δm_{4l}) is estimated from the reconstructed lepton momentum uncertainties (δp_T)
- Per-event lepton momentum uncertainties further corrected using $Z \rightarrow 2l$ events for calibration
- Based on relative mass resolution ($\delta m_{4l}/m_{4l}$), 9 sub-categories defined to isolate events with better mass resolution

- **Overall improvement in m_H uncertainty ~ 8%**







Distribution of m_{4l} in five of the $\delta_{m_{4l}}/m_{4l}$ categories

Matrix element (ME) based kinematic discriminant

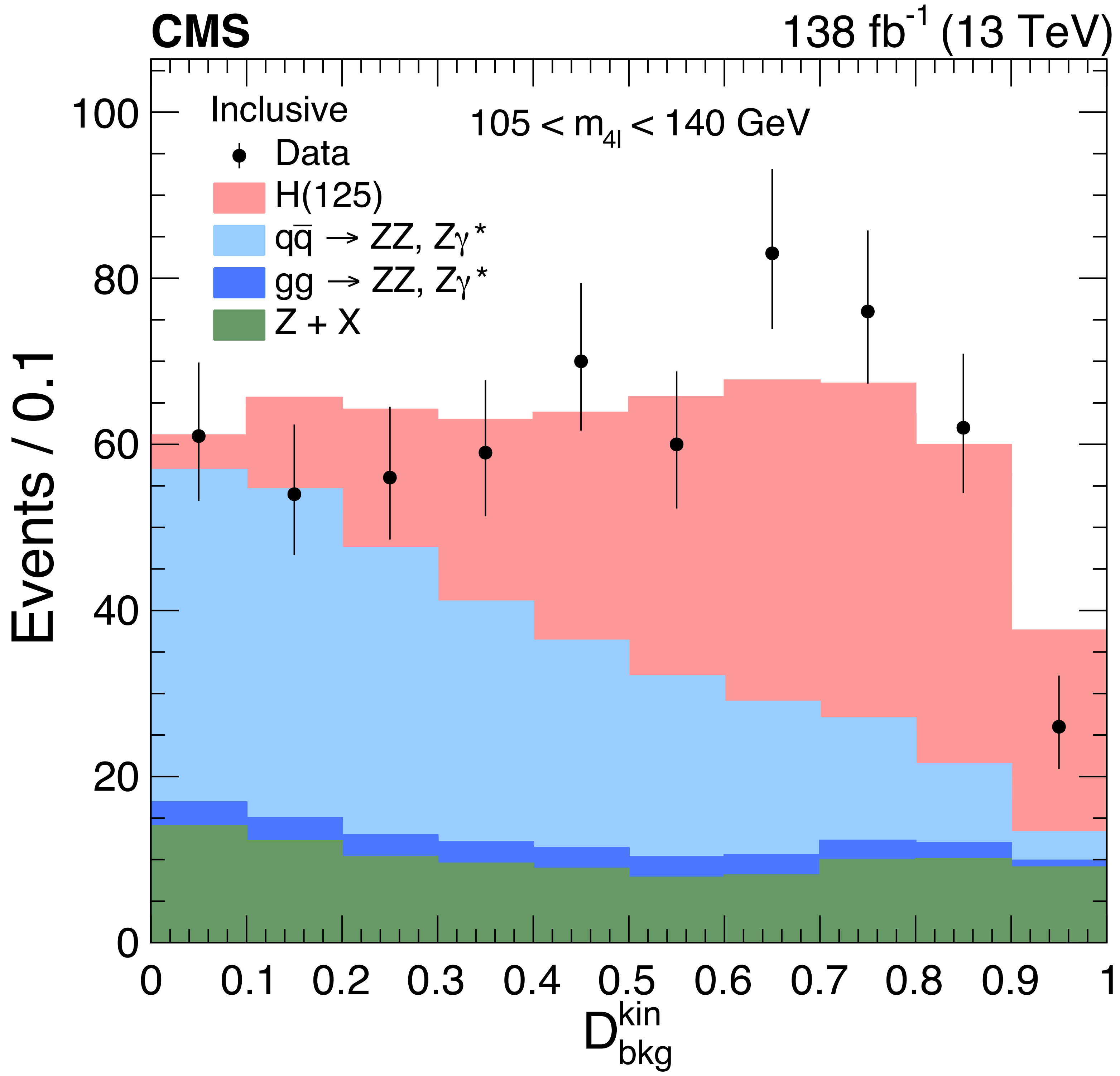
$$R = \left| \frac{\mathrm{ME}(\mathrm{event}\,|\,\tilde{H})}{\mathrm{ME}(\mathrm{event}\,|\,ZZ)} \right|^2$$

- Matrix element calculations performed using optimal set of observables that capture the full decay kinematics of signal(H $\rightarrow 4l$) and background(ZZ $\rightarrow 4l$)
- R is transformed to $D^{\mathrm{kin}}_{\mathrm{bkg}}[0,1]$,

$$D^{\mathrm{kin}}_{\mathrm{bkg}} = \frac{R}{R+1}$$

- Helps in separating signal like events ($D^{\mathrm{kin}}_{\mathrm{bkg}}$ close to 1) from background
- Second observable in the mass fit
- **Overall improvement in m_H uncertainty ~ 4%**

- $\tilde{H}$ - Higgs with mass $m_{\tilde{H}} = m_{4l}$
- ZZ - background



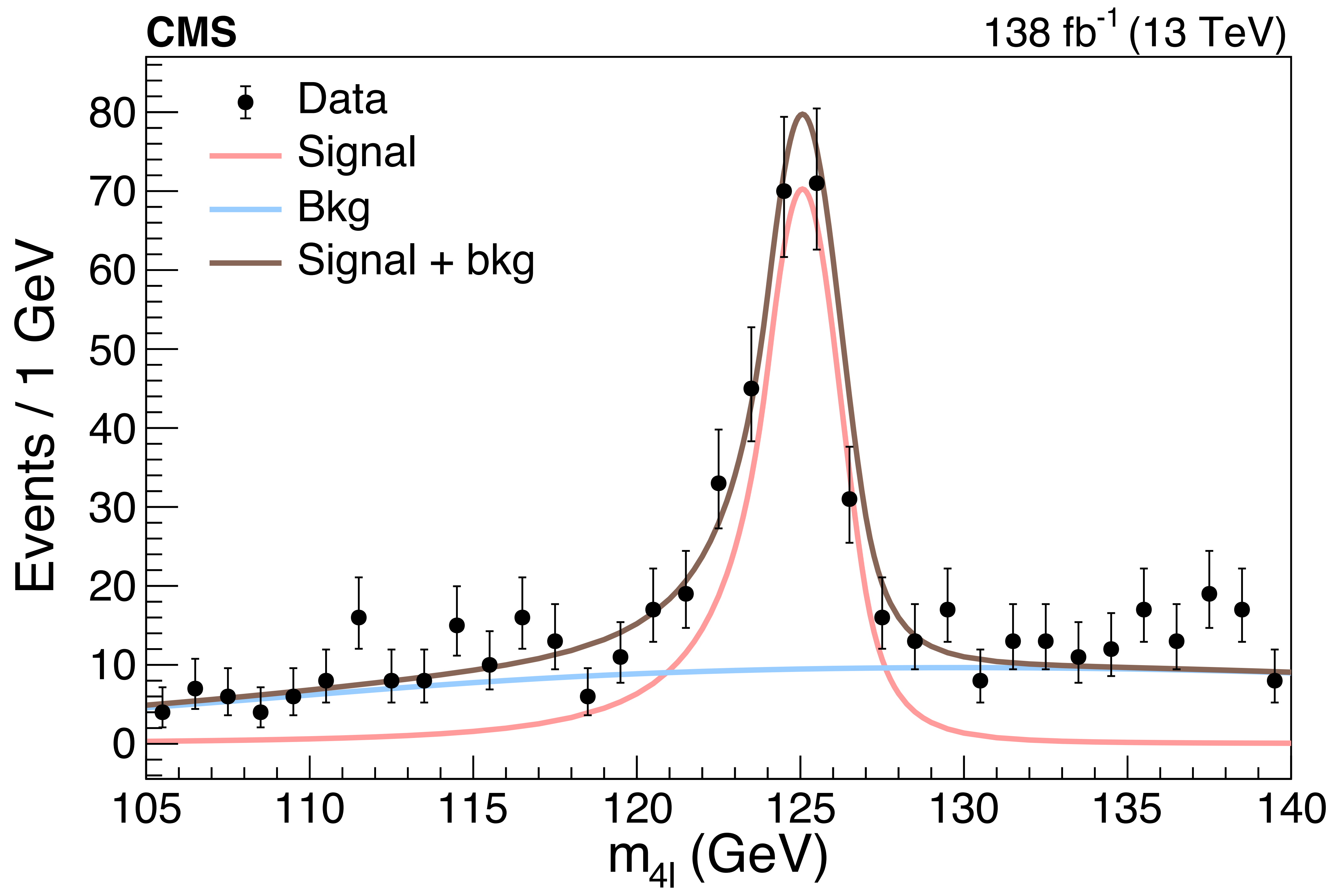
Mass measurement in $H \to ZZ \to 4l$: final fit

Signal modelling :

- Double-Sided Crystal Ball function (DSCB) used for mass measurement

Backgrounds :

- **Irreducible (qq->ZZ, gg->ZZ)** - estimated from MC
- **Reducible (Z+X),** with at least one non-prompt/ misidentified lepton - derived from data



A final 2D likelihood fit using the observables (m_H, D_{bkg}^{kin}) across 9 mass resolution categories and four lepton final states, to extract Higgs mass (m_H)

In the m_H fit, signal strength (μ) is floating, while Γ_H fixed to 0 (since the SM value ~4 MeV is negligible compared to detector resolution)

Mass measurement in $H \to ZZ \to 4l$: Results

Observed results :

Most precise single channel measurement of Higgs boson mass

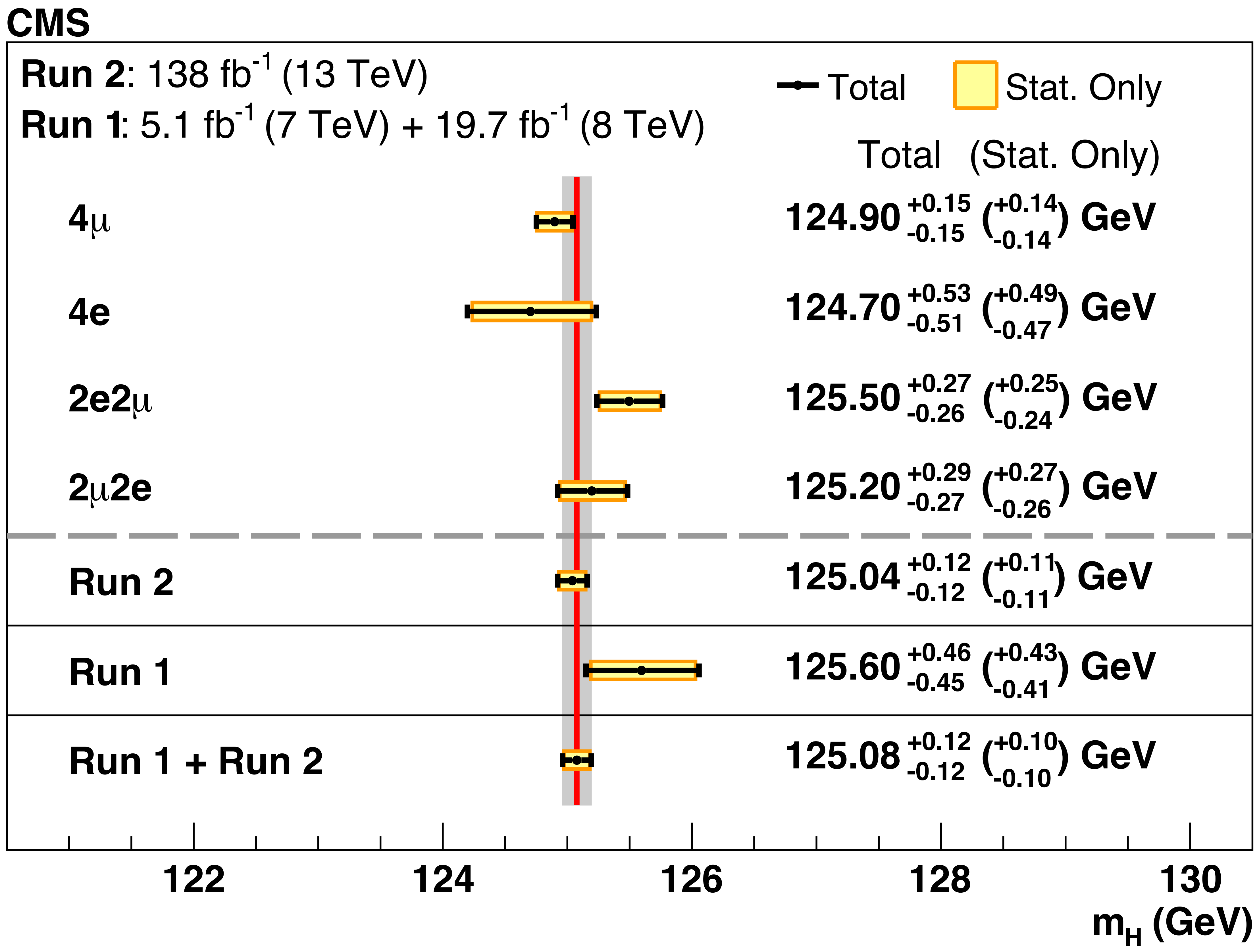
$m_H = 125.04 \pm 0.12$ GeV(± 0.11 (stat) ± 0.05 (sys) GeV)

CMS Observed results (Run1+Run2) $H \to ZZ \to 4l$:

$m_H = 125.08 \pm 0.12$ GeV(± 0.10 (stat) ± 0.05 (sys) GeV)

ATLAS Observed results (Run1+Run2) $H \to ZZ \to 4l$:

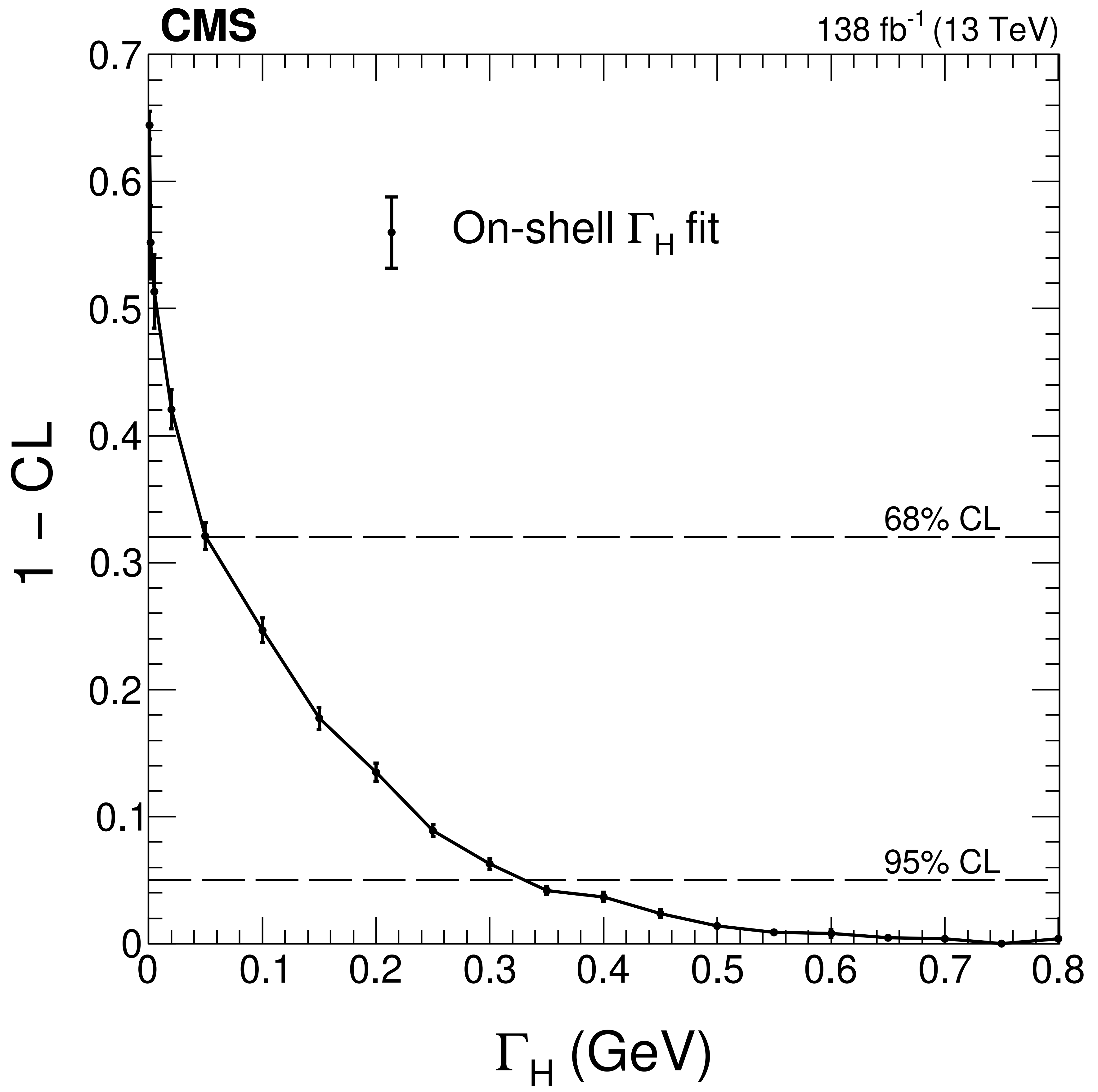
$m_H = 124.94 \pm 0.18$ GeV (± 0.17 (stat) ± 0.03 (sys) GeV)



Constraint on Higgs Width (Γ_H) : $H \to ZZ \to 4l$

Higgs boson decay width (Γ_H) is constrained by modelling signal with a DSCB convoluted with a Breit–Wigner (with m_H floating)

$\Gamma_H < 50\ (330)$ MeV @ $68\ (95)\ \%$ CL

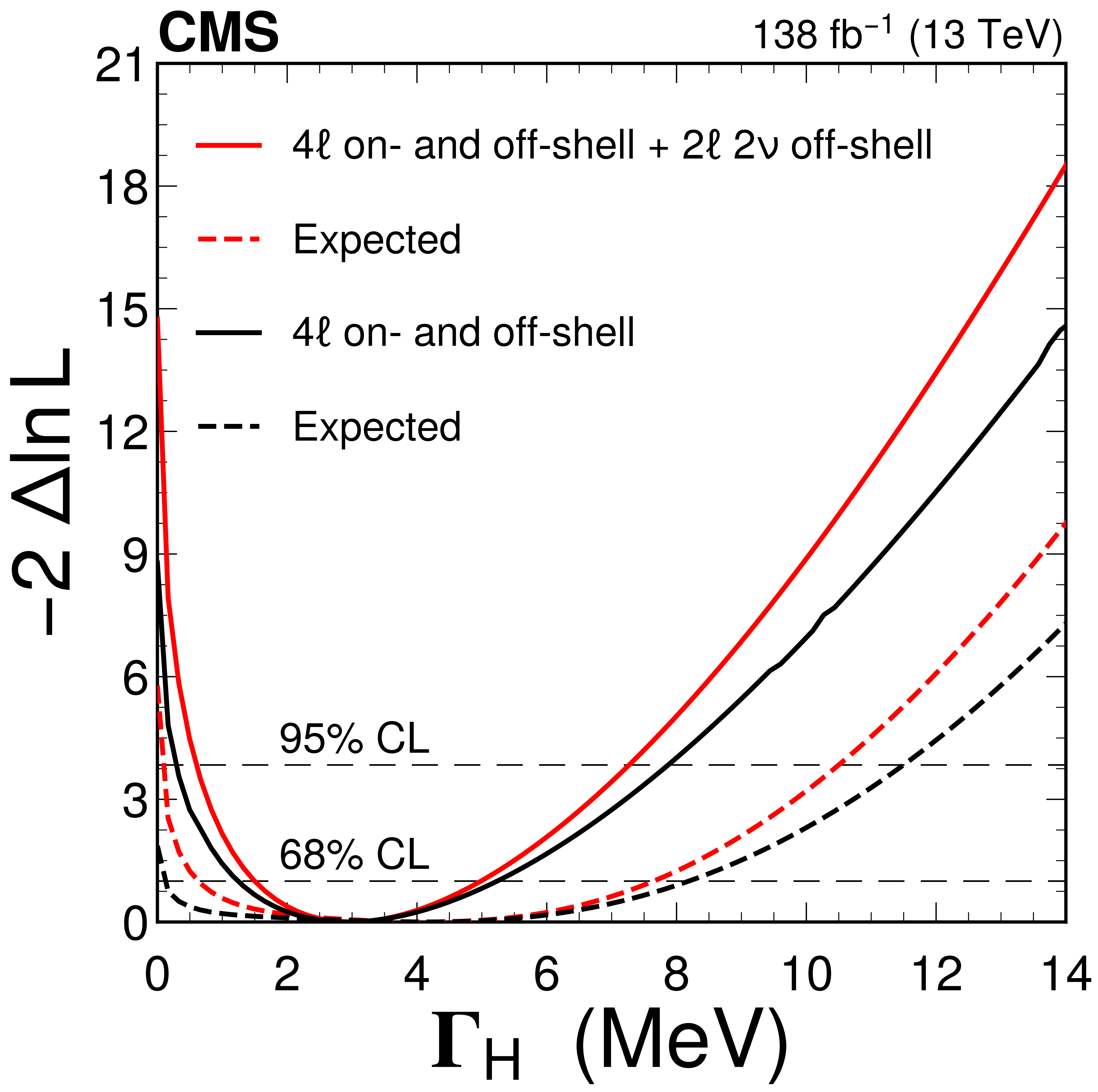


Constraint on Γ_H from ratio of off-shell and on-shell production

Combination with 2l2υ analysis + on-shell

$\Gamma_H < 3.0^{+2.0}_{-1.5}$ MeV

$$\frac{\sigma^{\text{off-shell}}_{H\to 4l}}{\sigma^{\text{on-shell}}_{H\to 4l}} \propto \Gamma_H$$



Summary

- Most precise single channel mass measurement (m_{H}) performed in $H \to ZZ \to 4l$, with measurement uncertainty $\mathcal{O}(0.1\%)$

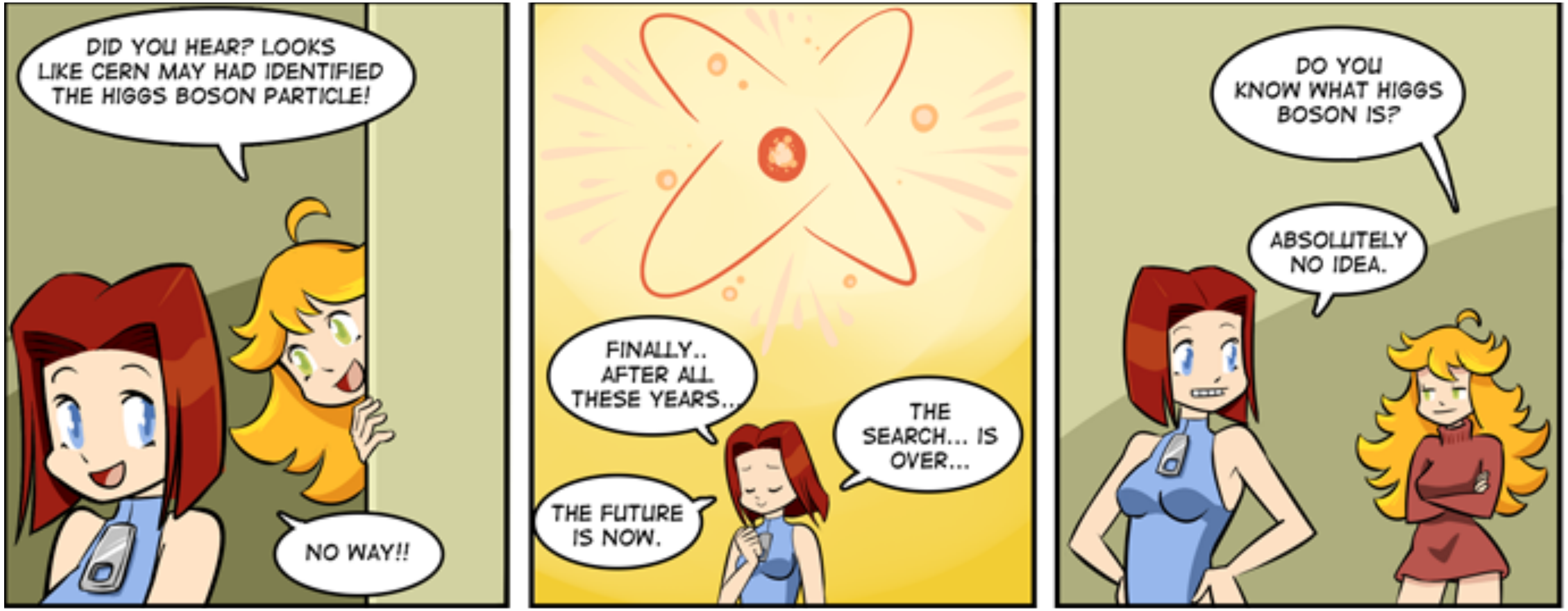
$$m_H = 125.04 \pm 0.120 \text{ GeV} (\pm 0.11 \text{ (stat)} \pm 0.05 \text{ (sys) GeV})$$

- The Higgs boson width (Γ_H) effectively constrained using on-shell/off-shell Higgs production :

on-shell : $\Gamma_H < 50\ (330)$ MeV @ $68\ (95)\ \%$ CL ;

off-shell : $\Gamma_{\text{H}} < 3.0^{+2.0}_{-1.5}$ MeV

Backup


DID YOU HEAR? LOOKS LIKE CERN MAY HAD IDENTIFIED THE HIGGS BOSON PARTICLE!
NO WAY!!
FINALLY.. AFTER ALL THESE YEARS...
THE SEARCH... IS OVER...
THE FUTURE IS NOW.
DO YOU KNOW WHAT HIGGS BOSON IS?
ABSOLUTELY NO IDEA.

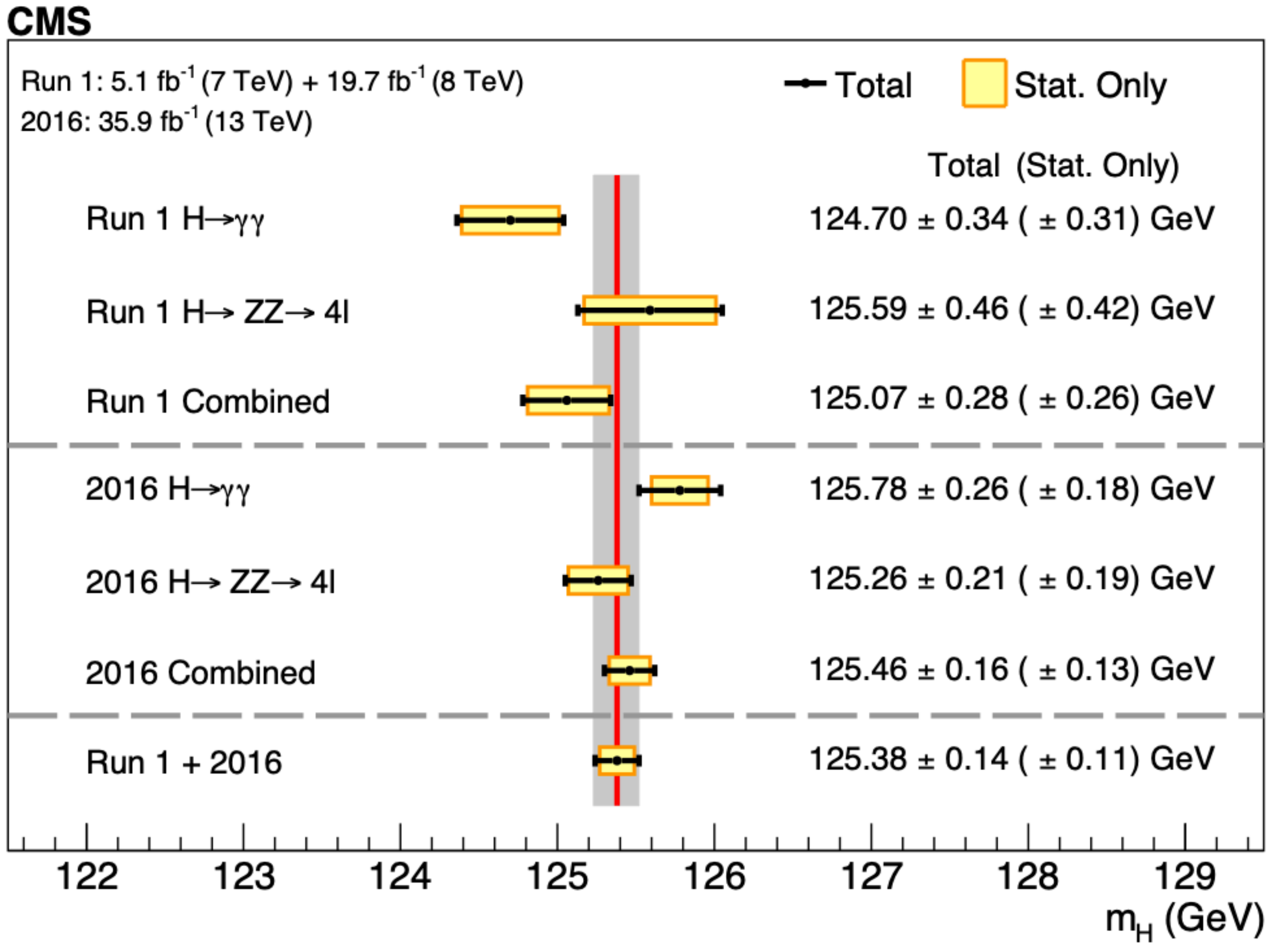
Mass measurement results : ATLAS and CMS

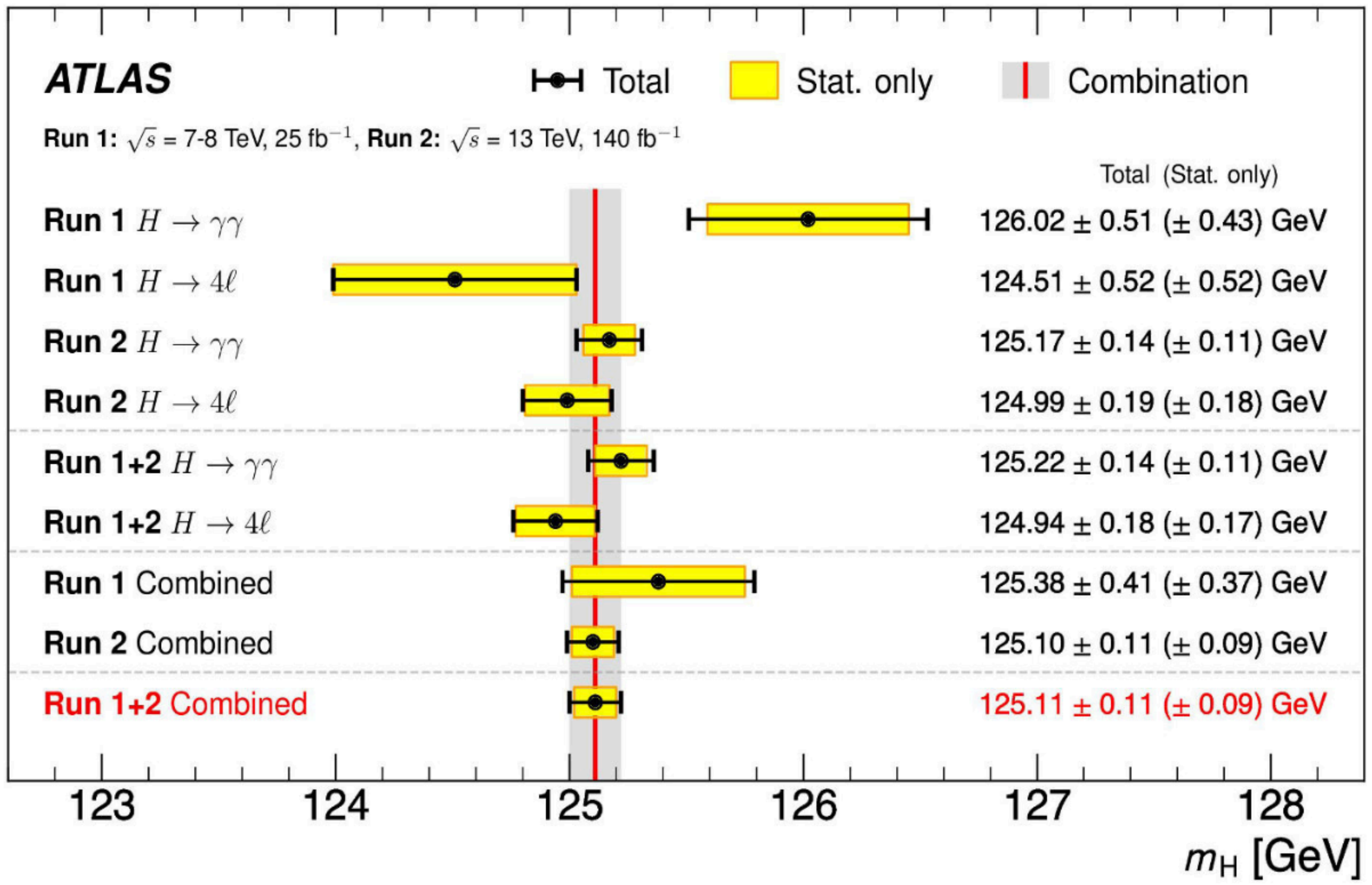
CMS Observed results (2016) $H \to \gamma\gamma$ [*]

$m_H = 125.78 \pm 0.26$ GeV (± 0.18 (stat) ± 0.18 (sys) GeV)

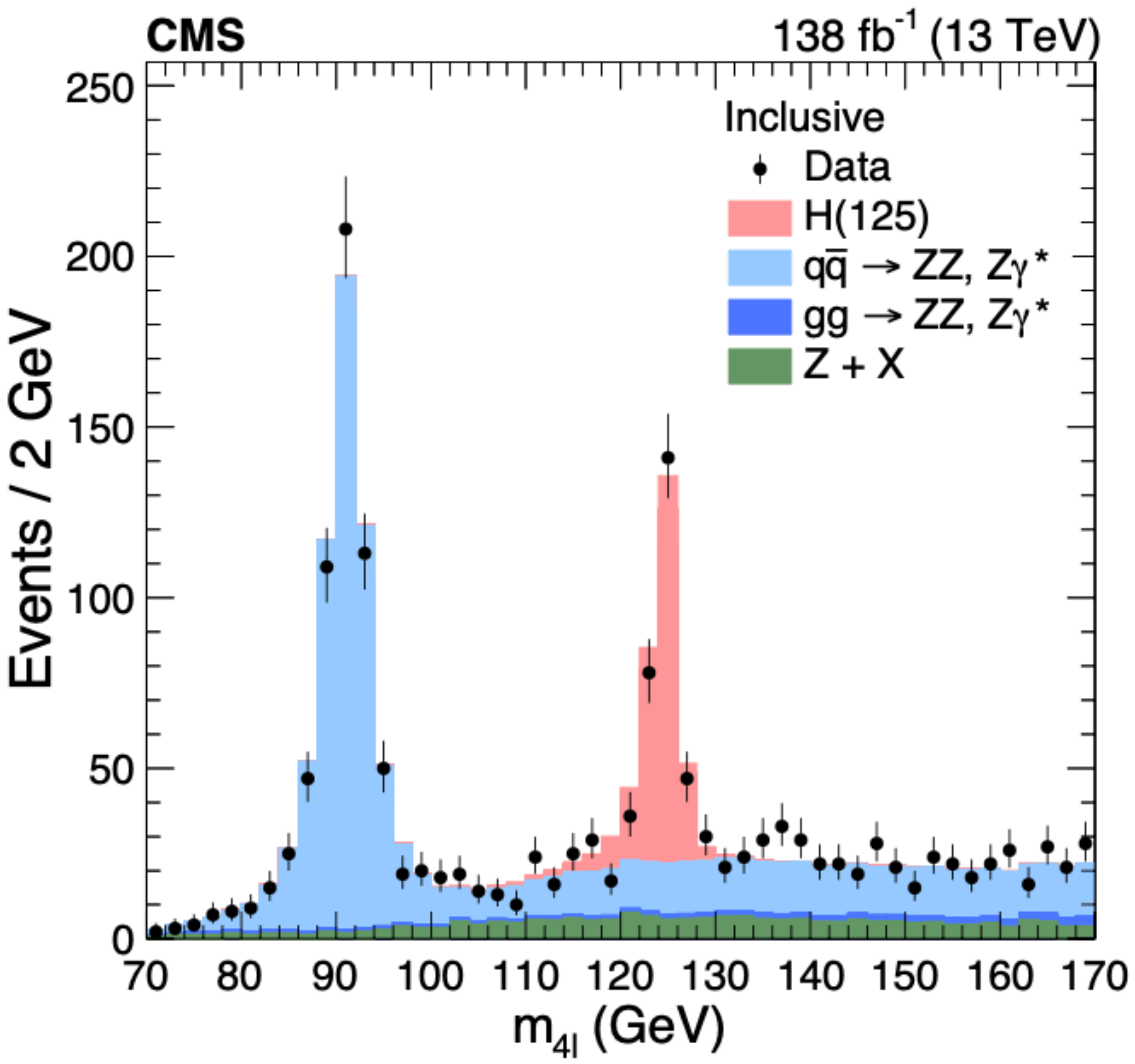
ATLAS Observed results (Run1+Run2) $H \to \gamma\gamma$:

$m_H = 125.22 \pm 0.14$ GeV (± 0.11 (stat) ± 0.09 (sys) GeV)





Expected mass distribution and yield : $H \to ZZ \to 4l$



Distribution of 4-lepton mass, combining all years

Yields in the signal region: [105-140]GeV, split in different final states

	4μ	4e	$2e2\mu$	$2\mu 2e$	Total
Total signal	90.9	48.7	65.5	53.3	258.4
$q\bar{q} \to 4\ell$ background	89.2	38.9	64.4	42.1	234.6
$gg \to 4\ell$ background	9.7	4.9	4.9	3.8	23.4
$Z + X$ background	32.4	12.2	28.2	18.6	91.3
Total expected	222.2	104.6	163.0	117.8	607.7
Observed	230	94	170	107	601

Mass measurement uncertainty in $H \to ZZ \to 4l$

4ℓ category	Observed ($\pm$stat$\pm$syst) (GeV)	Expected uncertainty ($\pm$stat$\pm$syst) (GeV)
Inclusive	$125.04 \pm 0.11 \pm 0.05$	$\pm 0.11 \pm 0.05$
4μ	$124.90 \pm 0.14 \pm 0.05$	$\pm 0.14 \pm 0.04$
$2e2\mu$	$125.50^{+0.25}_{-0.24} \pm 0.10$	$\pm 0.24 \pm 0.10$
$2\mu 2e$	$125.20^{+0.27+0.11}_{-0.26-0.07}$	$\pm 0.27 \pm 0.10$
4e	$124.70^{+0.49}_{-0.47} \pm 0.20$	$\pm 0.38 \pm 0.20$

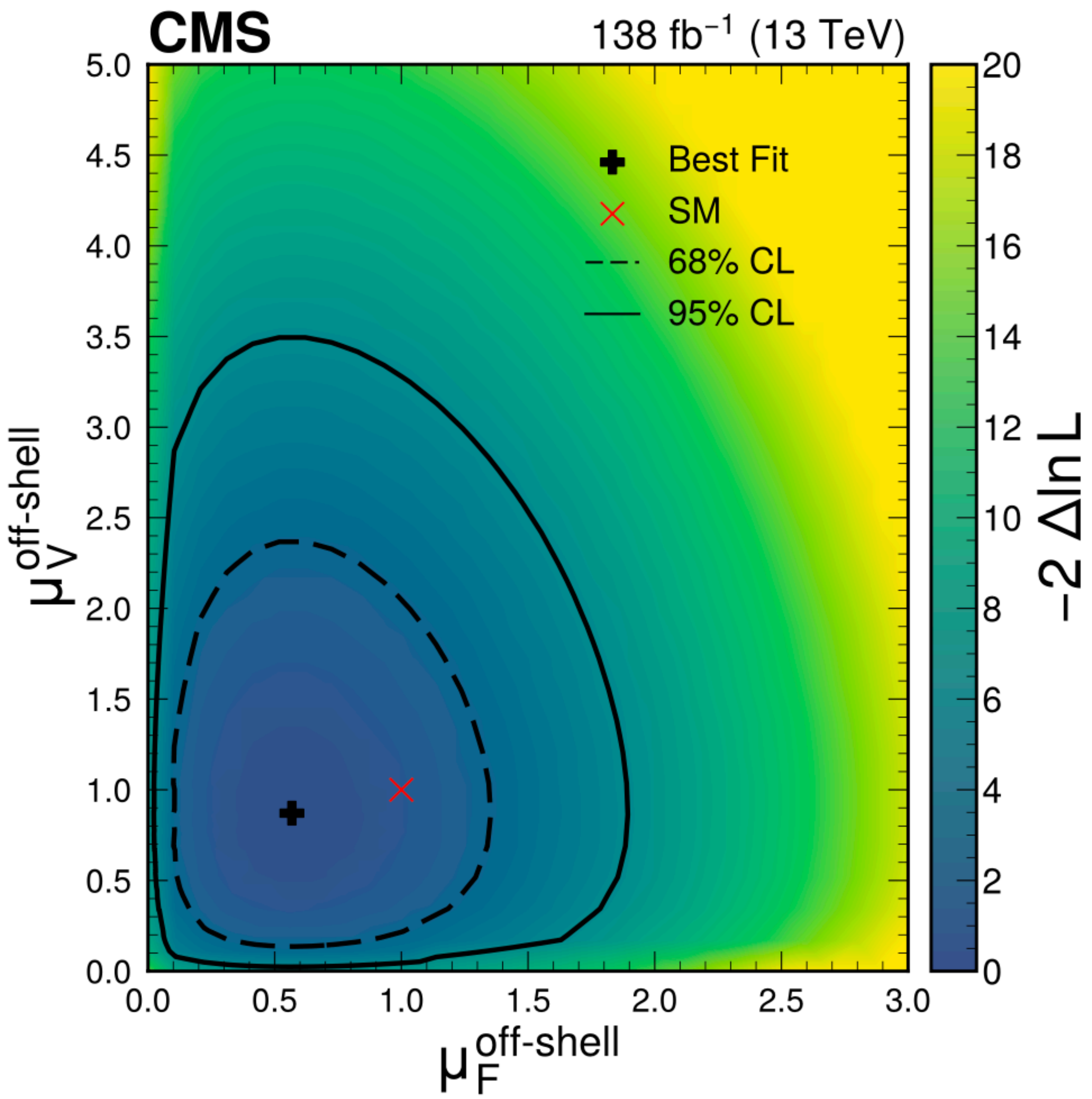
Constraint on Higgs Width (Γ_{H}) from off-shell : $H \to ZZ \to 4l$

- Assumptions :
  - identical production and decay couplings in off-shell and on-shell
  - No BSM effects modifying off-shell couplings
- Indirect constraint on Γ_{H} can be placed from the off-shell/on-shell even yield ratio

On-shell yield $\sigma_{H\to 4l}^{\text{on-shell}} \propto k^2_{g,\text{on-shell}}/\Gamma_{\mathrm{H}}$

Off-shell yeild $\sigma_{H\to 4l}^{\text{off-shell}} \propto k^2_{g,\text{off-shell}}$

$$\longrightarrow \quad \frac{\sigma_{H\to 4l}^{\text{off-shell}}}{\sigma_{H\to 4l}^{\text{on-shell}}} \propto \Gamma_{\mathrm{H}}$$



- Off-shell signal strengths ($\mu_{\mathrm{V}}^{\text{off-shell}}$ and $\mu_{\mathrm{F}}^{\text{off-shell}}$) are evaluated separately for the ggH (fermion-induced) and VBF/VH (vector boson-induced) production modes using dedicated event categories