Higgs Properties in $H \to ZZ$, $H \to \gamma\gamma$ channels at CMS

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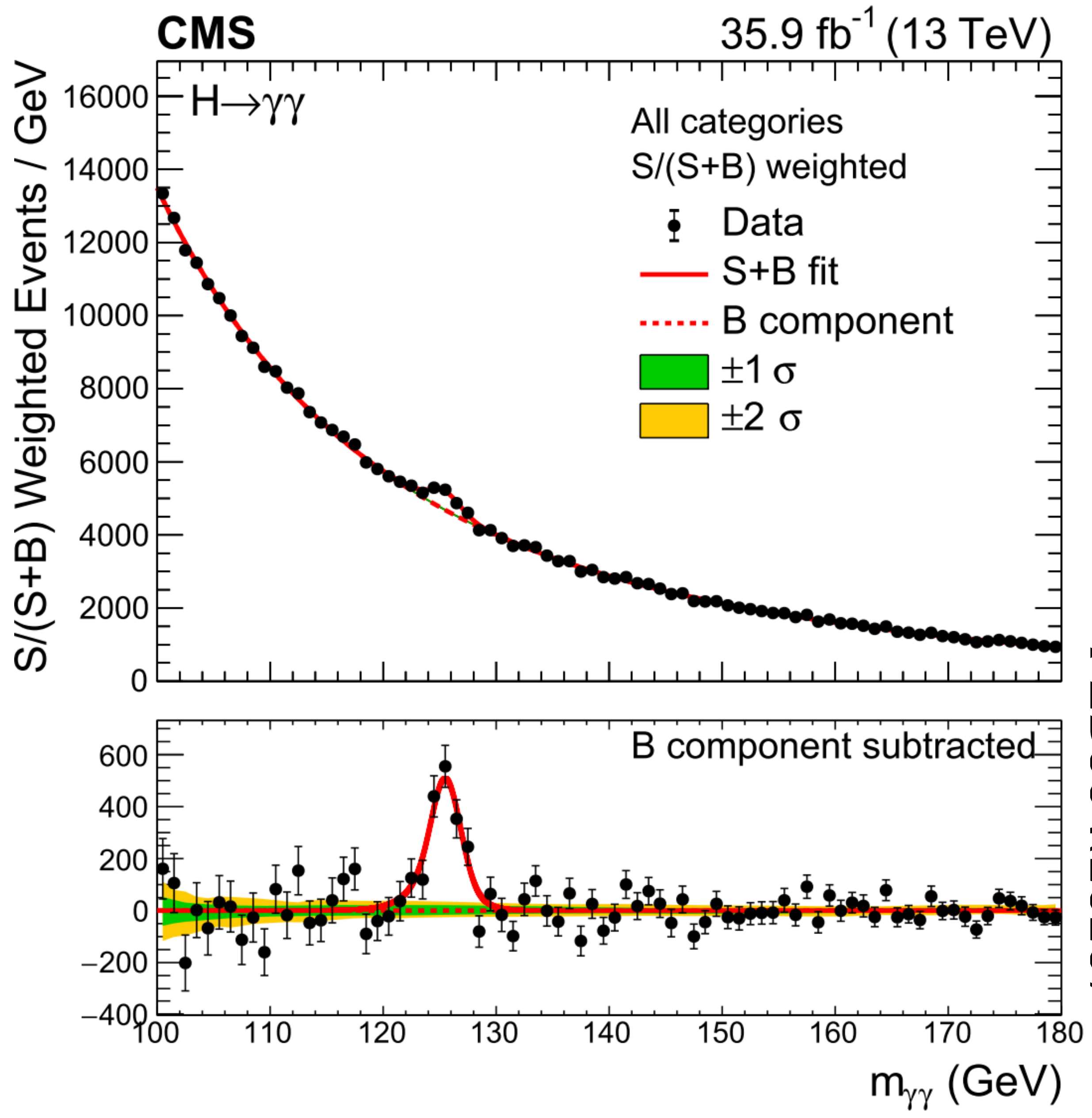
Introduction to $H \to ZZ, H \to \gamma\gamma$

- The Higgs boson discovery has marked the LHC Run1
- LHC Run2 and Run3 are the eras of precision measurements of the Higgs boson
- $H \to ZZ, H \to \gamma\gamma$, two golden channels serve Higgs measurements with clear signals
    - This talk focus on m_H and Γ_H
    - See other talks
        - Cross section
        - Production, decay and coupling



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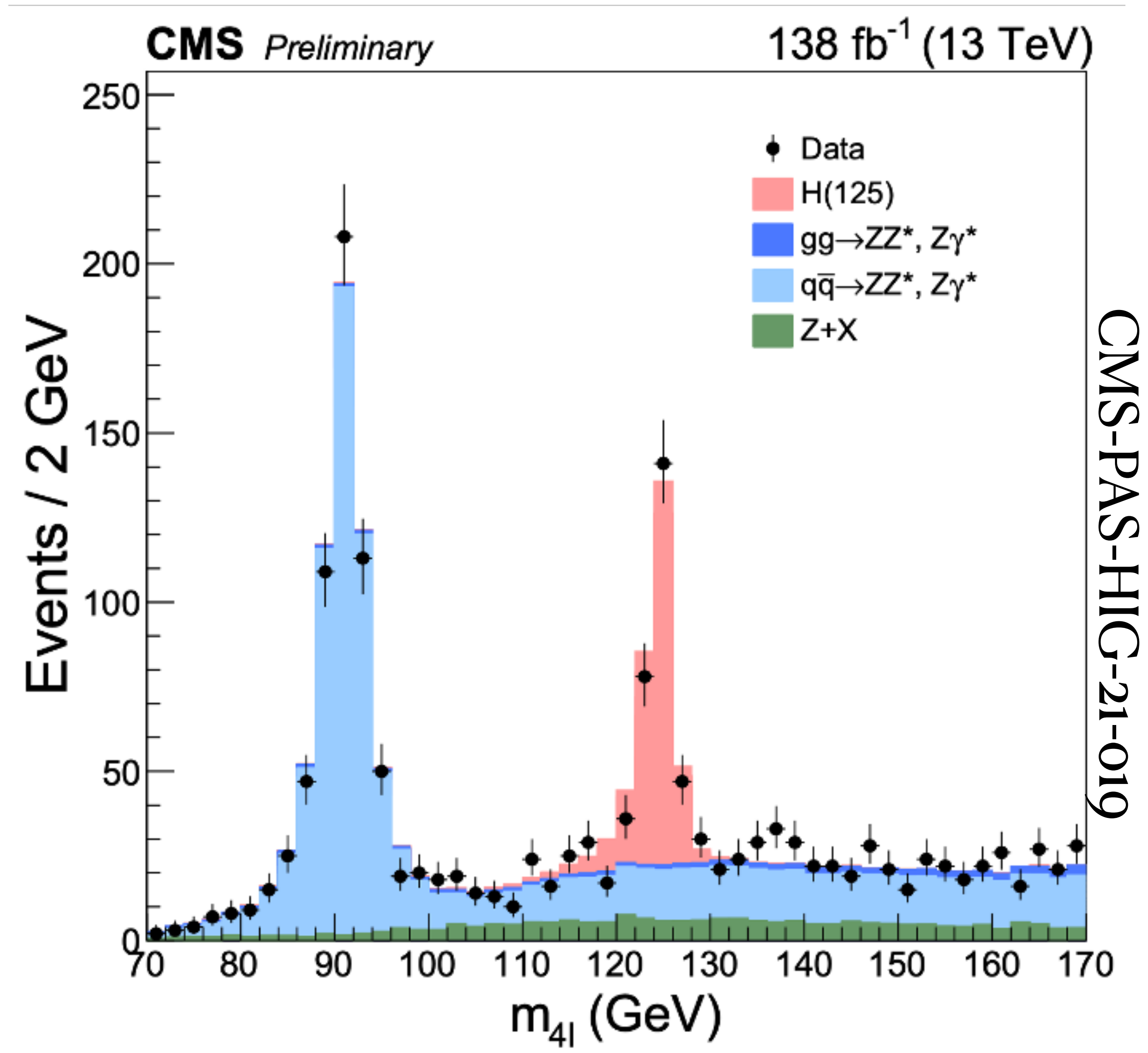


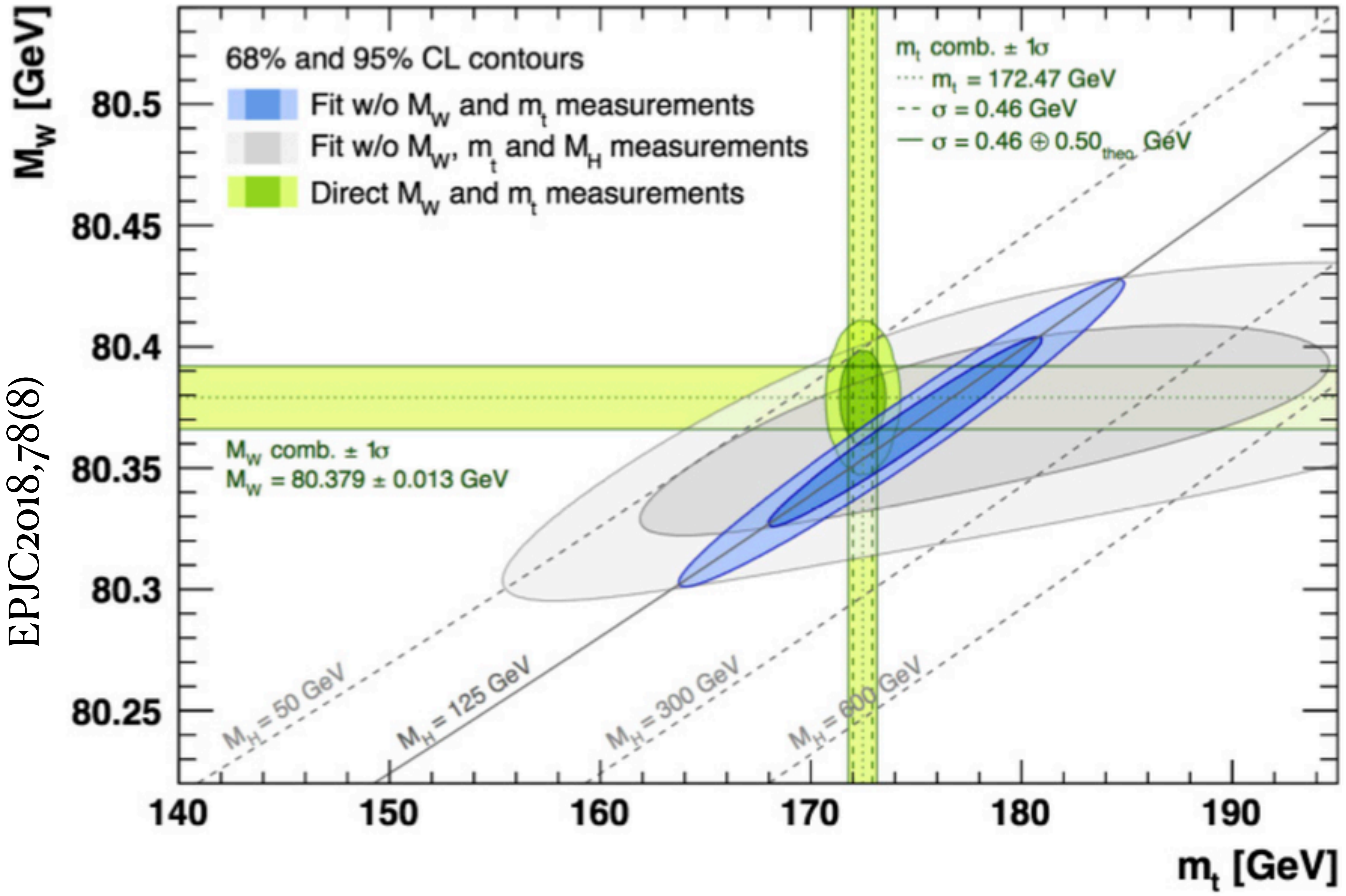
CMS-PAS-HIG-21-019

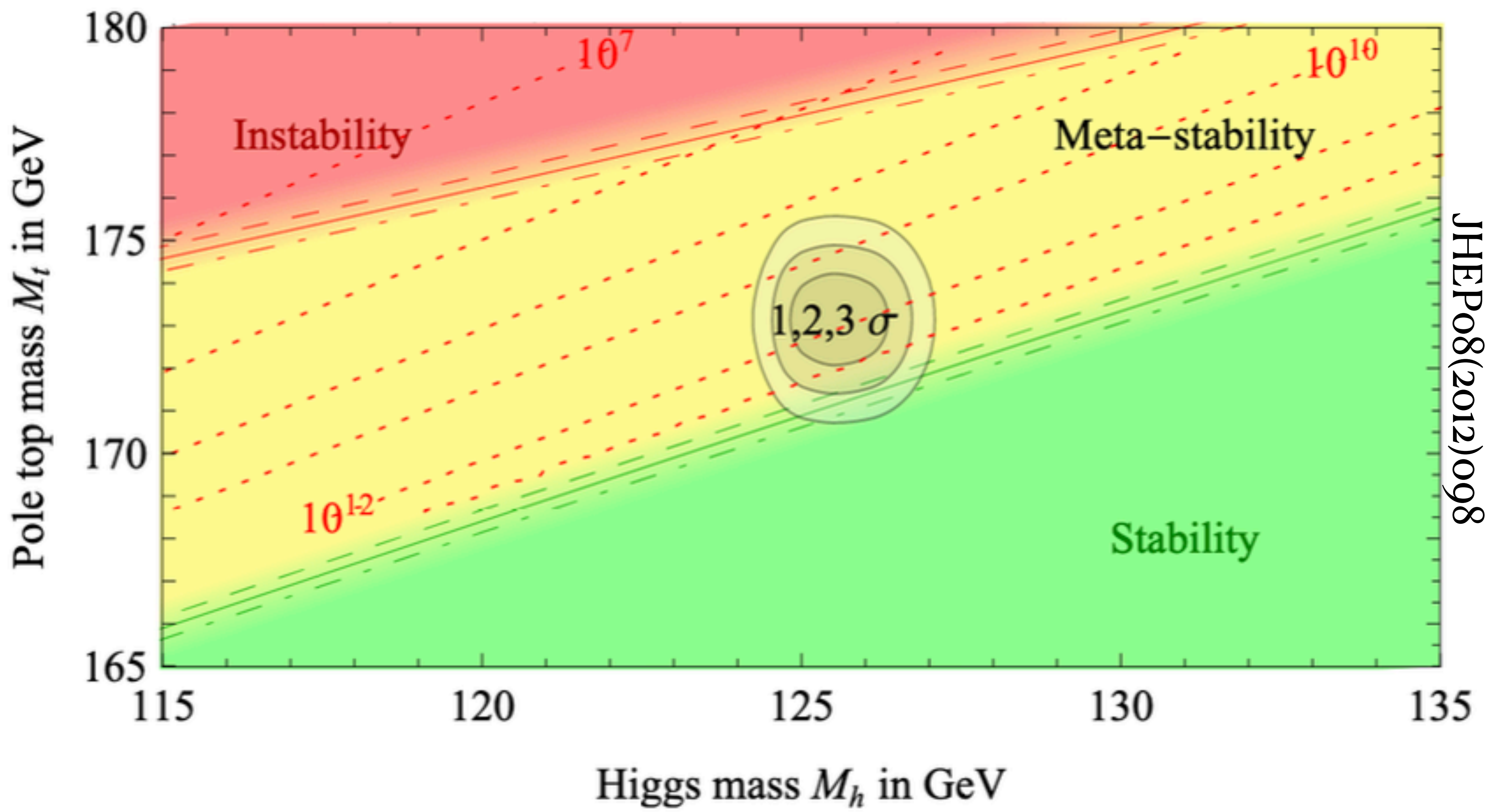
Introduction to m_H

- m_H is the only one free parameter in the SM Higgs sector and determines all other properties of Higgs boson (couplings, BR…)

- SM self-consistency
- m_H and m_t determine EW vacuum

EPJC2018,78(8)





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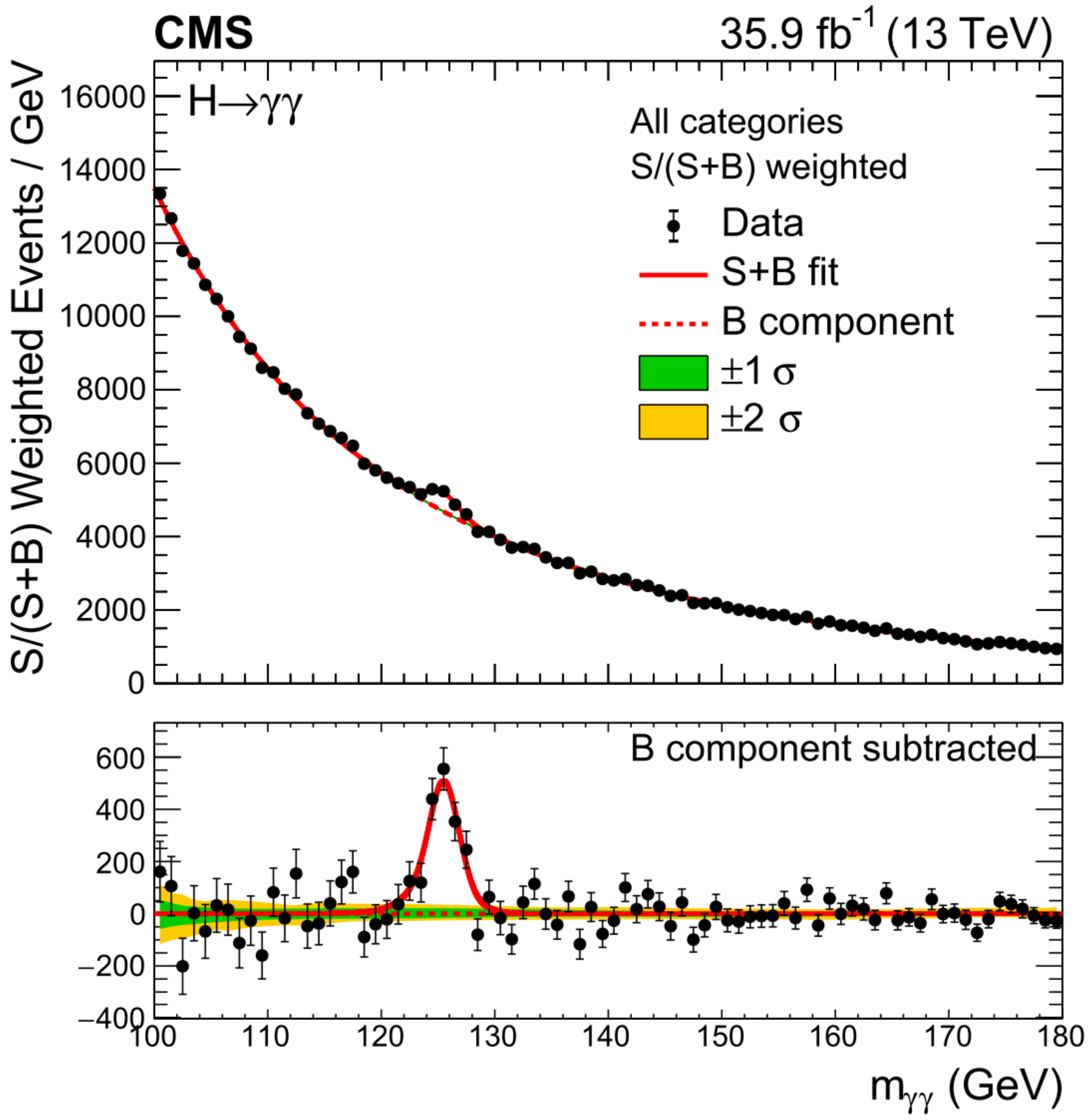
m_H measurement in $H \to \gamma\gamma$

- Previous analysis with 2016 Run2 dataset (35.9fb^{-1},13TeV)
- Expected event yield ~ 1900 events with S/B ~ 1:10 at peak range
- Larger event yield and worse reconstruction precision (w.r.t $H \to ZZ$)
  - Final precision is driven by systematic uncertainties
  - Put a lot of effort on calibrations for detector effects, energy leak, material effect, non-linearity responses and etc.



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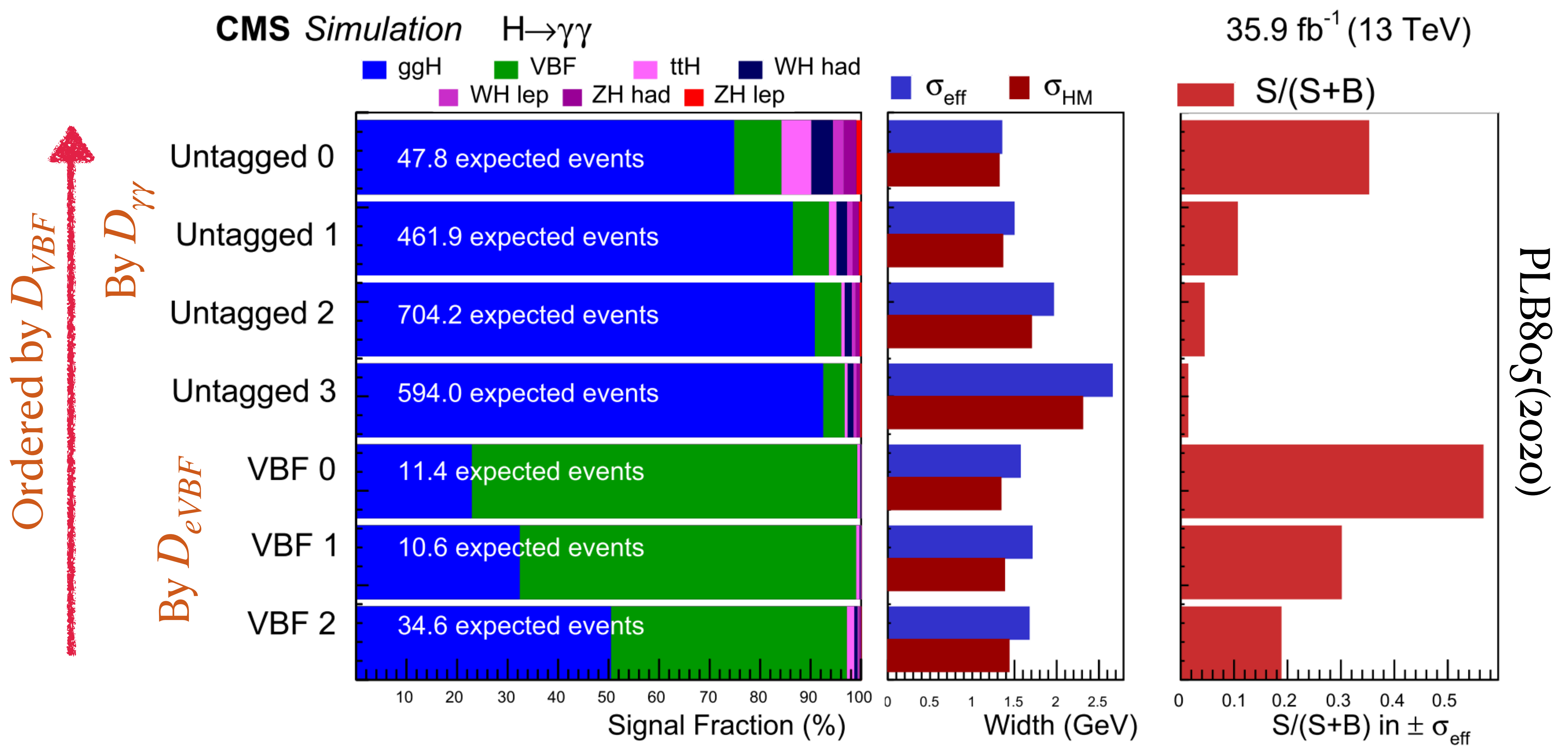
m_H measurement in $H \rightarrow \gamma\gamma$

- Event categorisation
  - Di-photon MVA discriminant $D_{\gamma\gamma}$ (higher score for better mass resolution and higher photon purity)
  - VBF MVA discriminat D_{VBF} (trained vs $gg \rightarrow H$ and bkg.)
  - Enhanced VBF MVA discriminant D_{eVBF}
- Systematic uncertainties
  - $Z \rightarrow ee$ for energy calibration
  - e/γ extrapolation



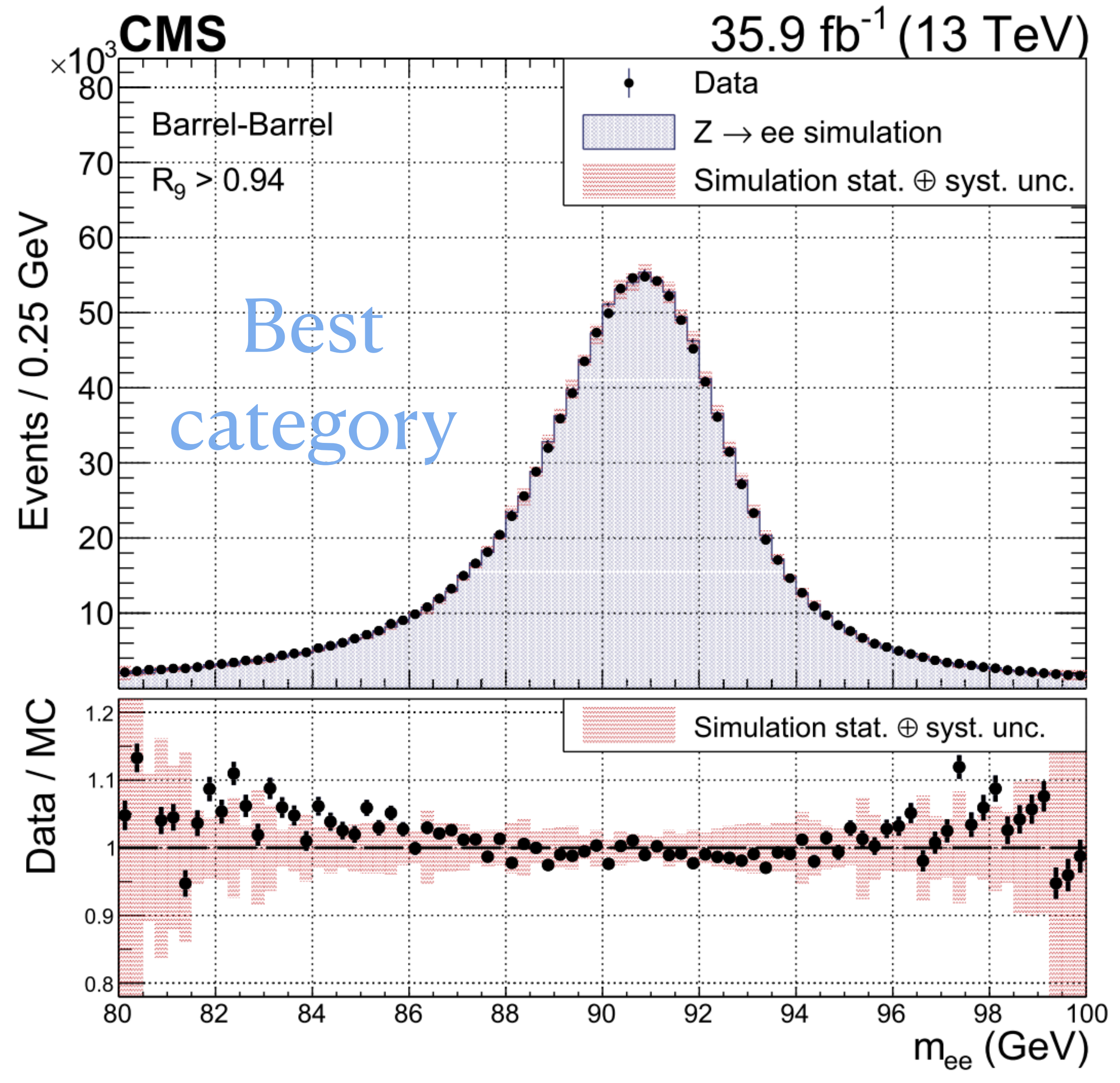
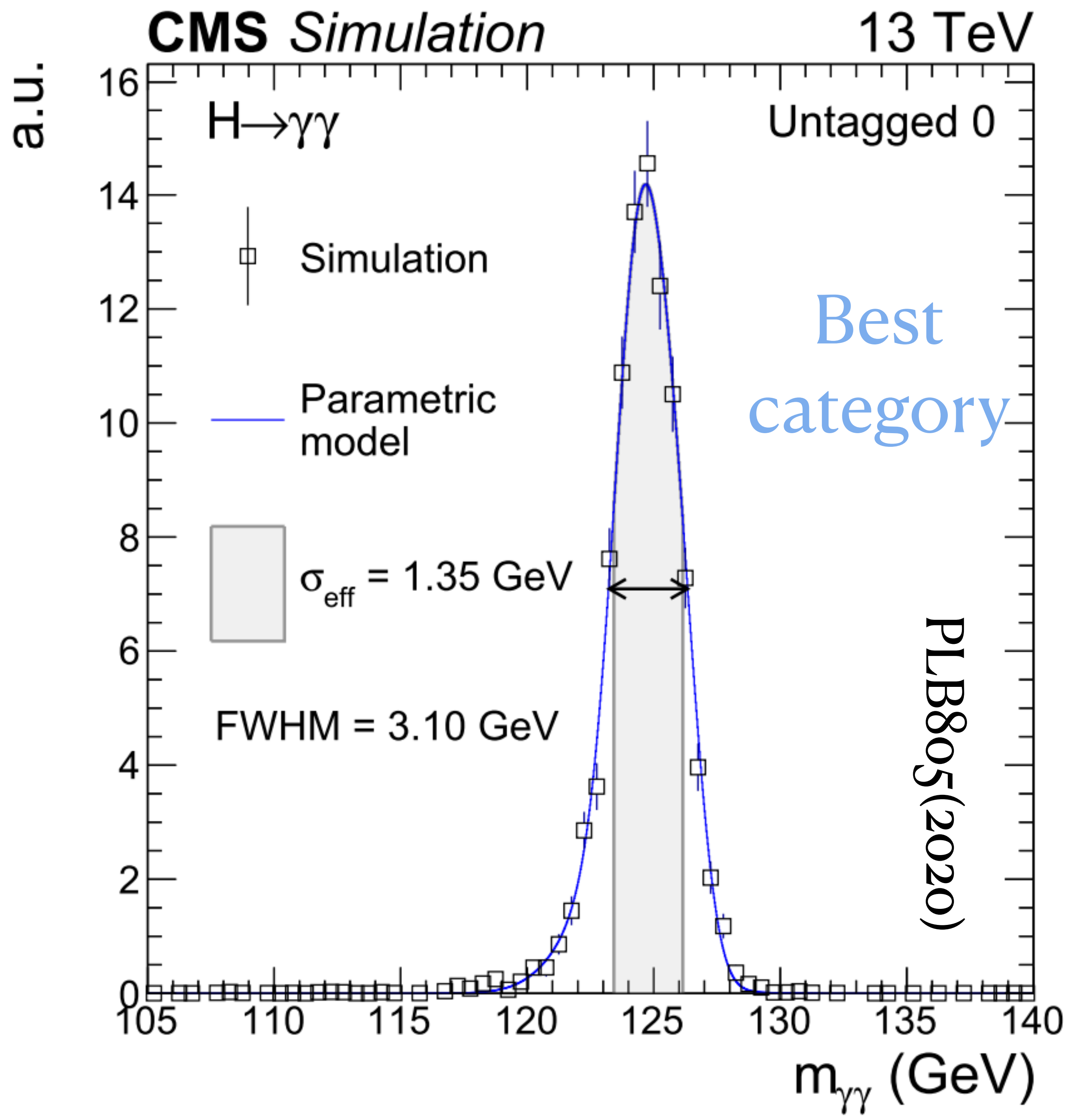


Table 1
The observed impact of the different uncertainties on the measurement of m_H.

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

m_H measurement in $H \to \gamma\gamma$

- Modelling
  - Multiple gaussian for sig. pdf , data sideband for bkg.
  - Maximum likelihood, $N \times PDF(m_{\gamma\gamma} | m_H) + BKG$
  - Simultaneous fit on 7 categories



Best category

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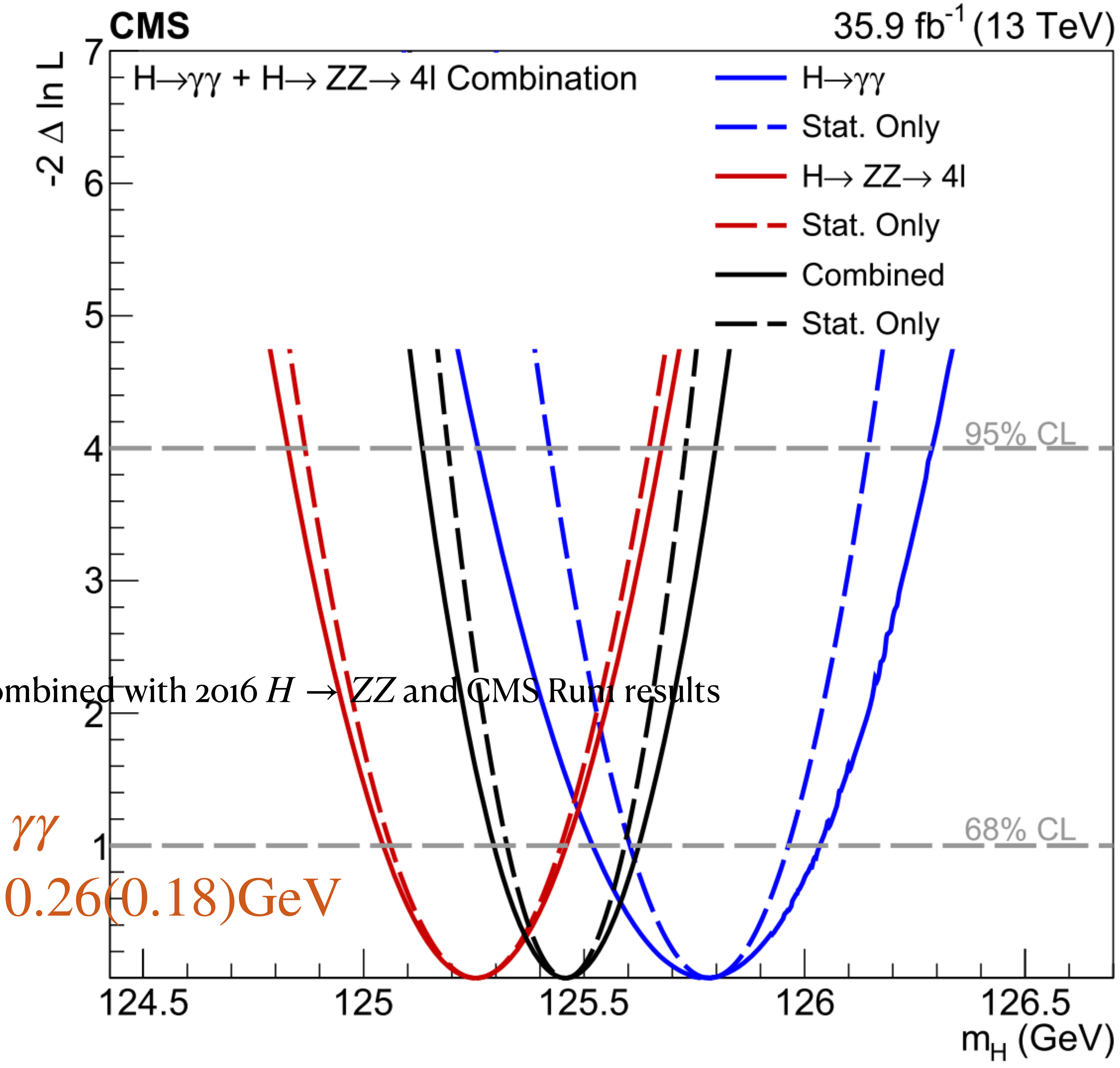


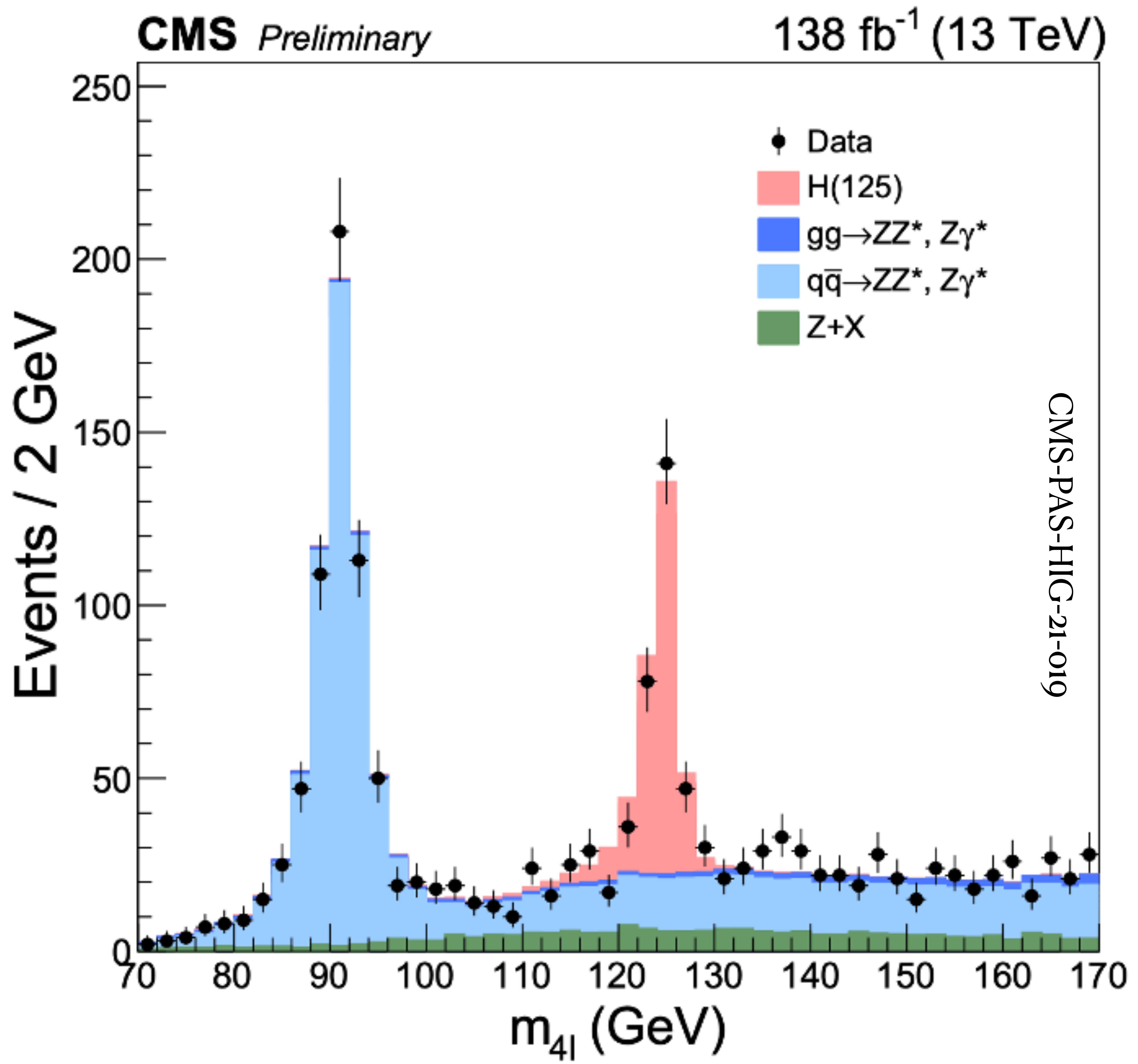
Final m_H in $H \to \gamma\gamma$ combined with 2016 $H \to ZZ$ and CMS Run1 results

Only 2016 $H \to \gamma\gamma$

$m_H = 125.78 \pm 0.26(0.18)\text{GeV}$

m_H measurement in $H \to ZZ$

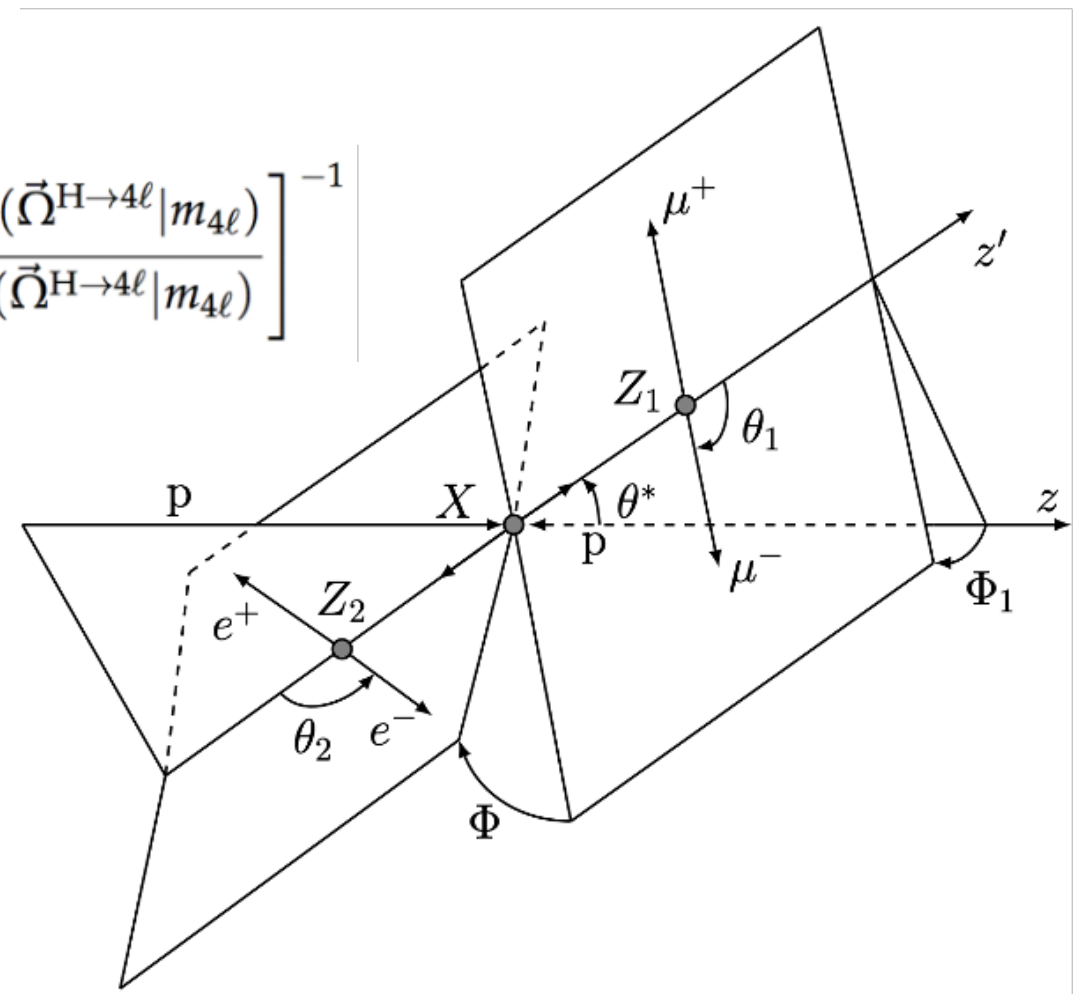
- Newest result with full Run2 dataset ($138\mathrm{fb}^{-1}$, $13\mathrm{TeV}$)
- Expected event yield ~ 600 events with S/B ~ 1:1
- Lower statistics with better momentum measurement (w.r.t $H \to \gamma\gamma$)
    - Final m_H precision is determined by statistical uncertainty
    - More effort on reducing statistical part, detector resolution optimisation, sig-bkg separation, etc.

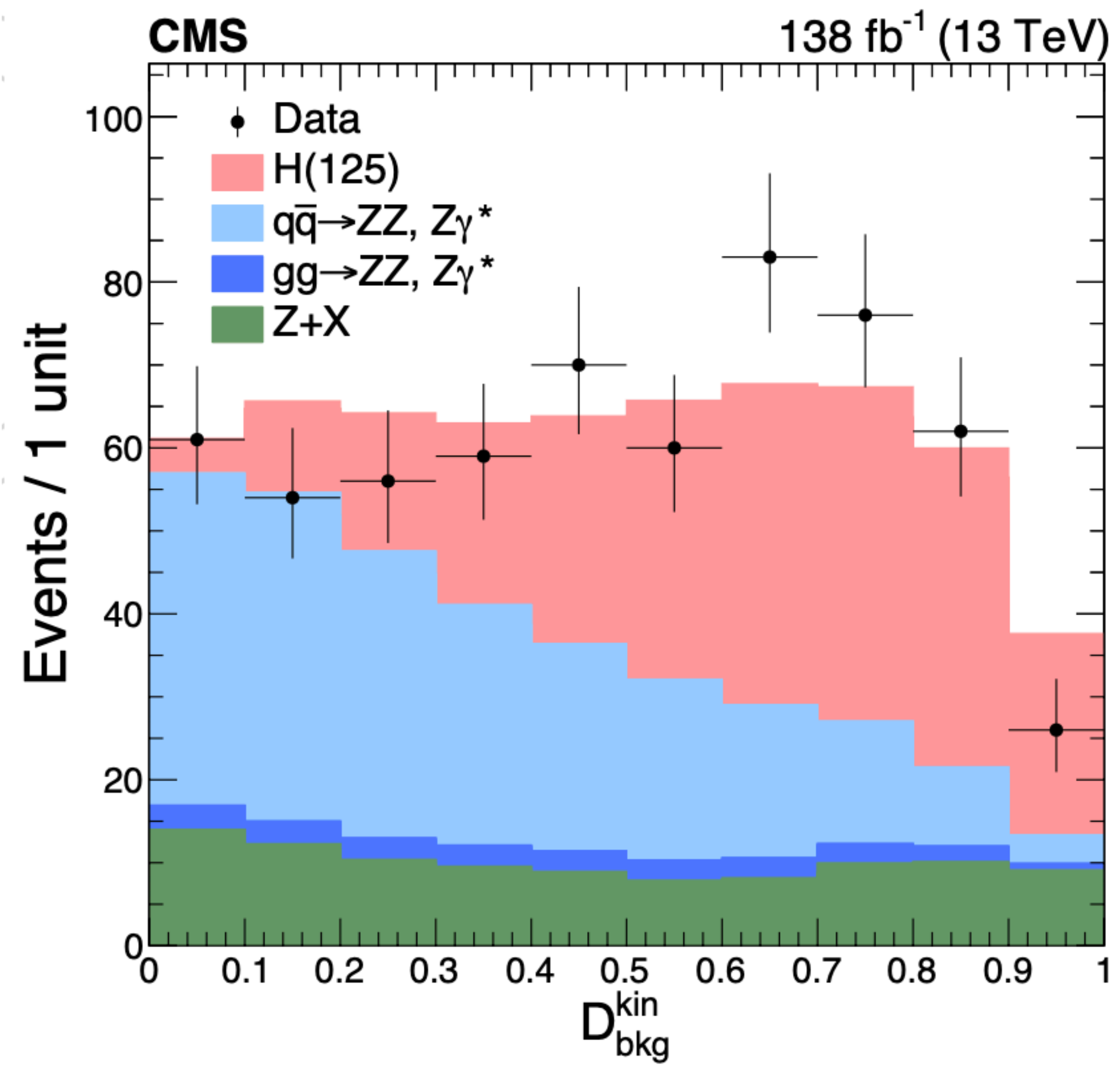


m_H measurement in $H \to ZZ$

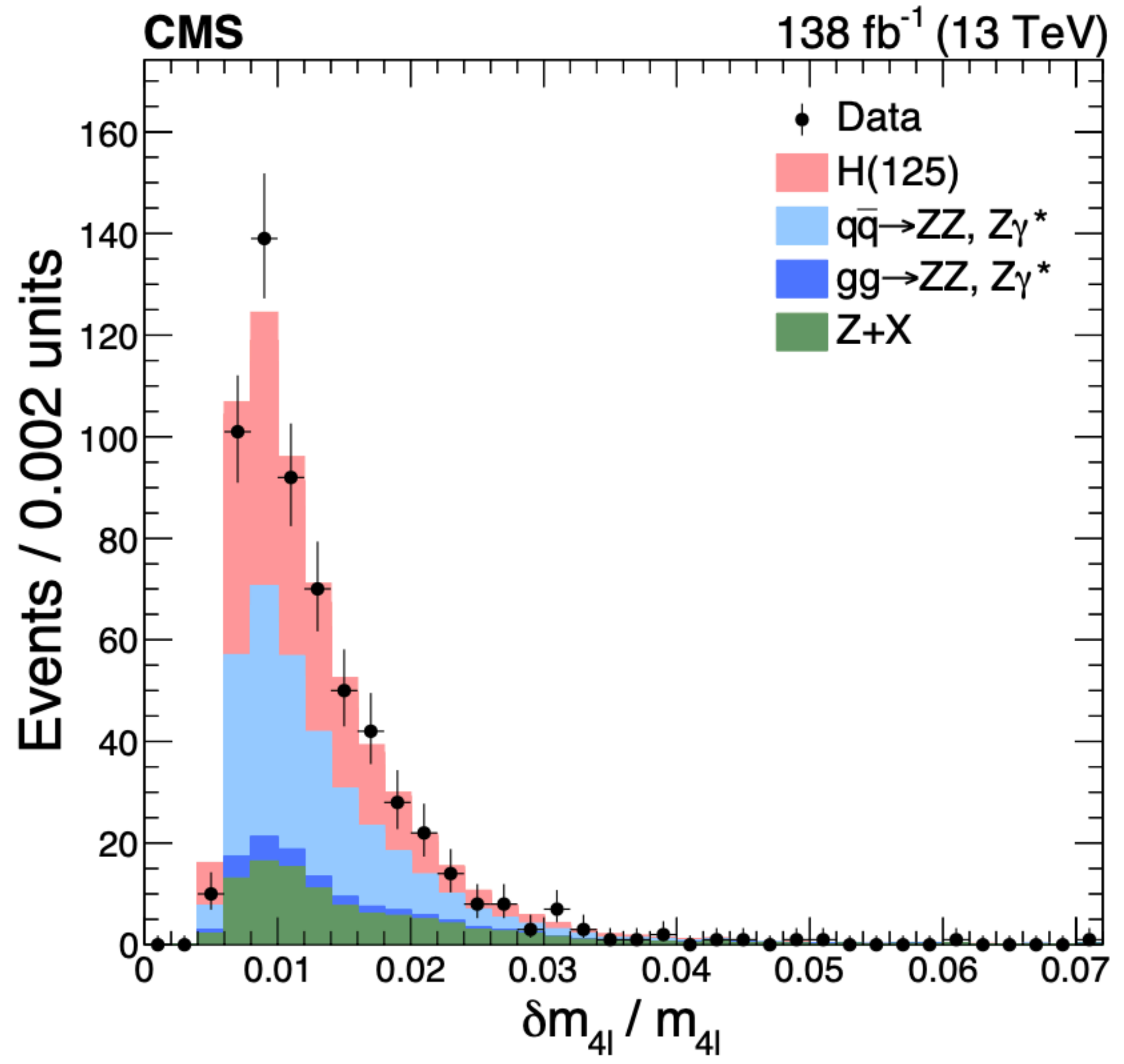
- Observables
  - Four-lepton invariant mass ($m_{4\ell}$)
  - ME-based discriminant (D)
  - Event by event mass error (ebe)

$$\mathcal{D}_{\text{bkg}}^{\text{kin}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}^{q\bar{q}}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}{\mathcal{P}_{\text{sig}}^{gg}(\vec{\Omega}^{H\to 4\ell}|m_{4\ell})}\right]^{-1}$$





- Improvements on momentum resolution
  - Z_1 mass constraint
    - A kinematic fit using the intermediate on-shell Z line-shape to calibrate leading lepton pair momentum
  - Beam-spot constraint
    - Muon tracks are constrained to beam-spot by KM algorithm, inject more information provided by BS position to track reconstruction
    - Improve Higgs mass resolution by 5~8% in 4μ final state, smaller impacts for $2e2\mu$ and $2\mu2e$



m_H measurement in $H \to ZZ$

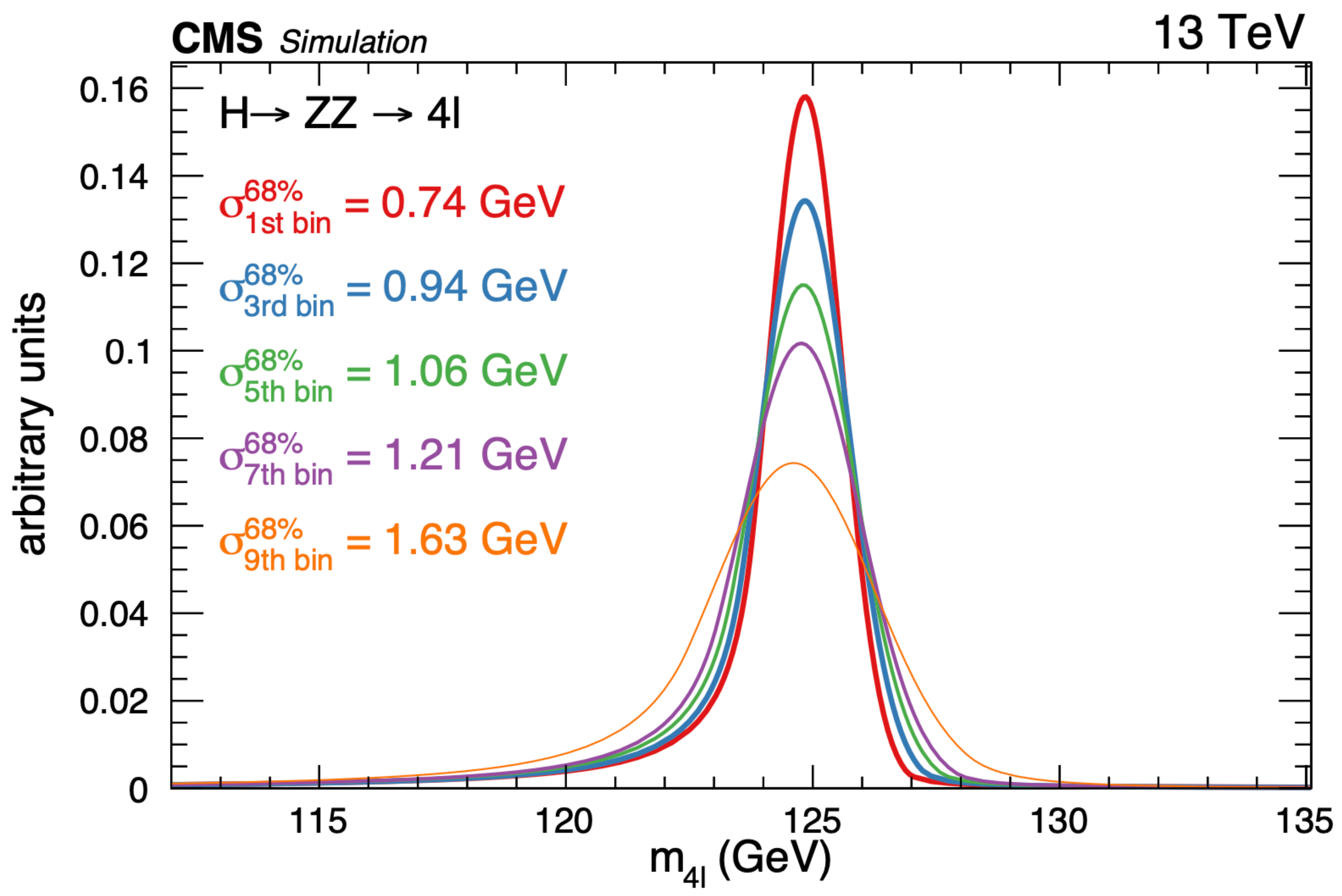
- Systematic uncertainties

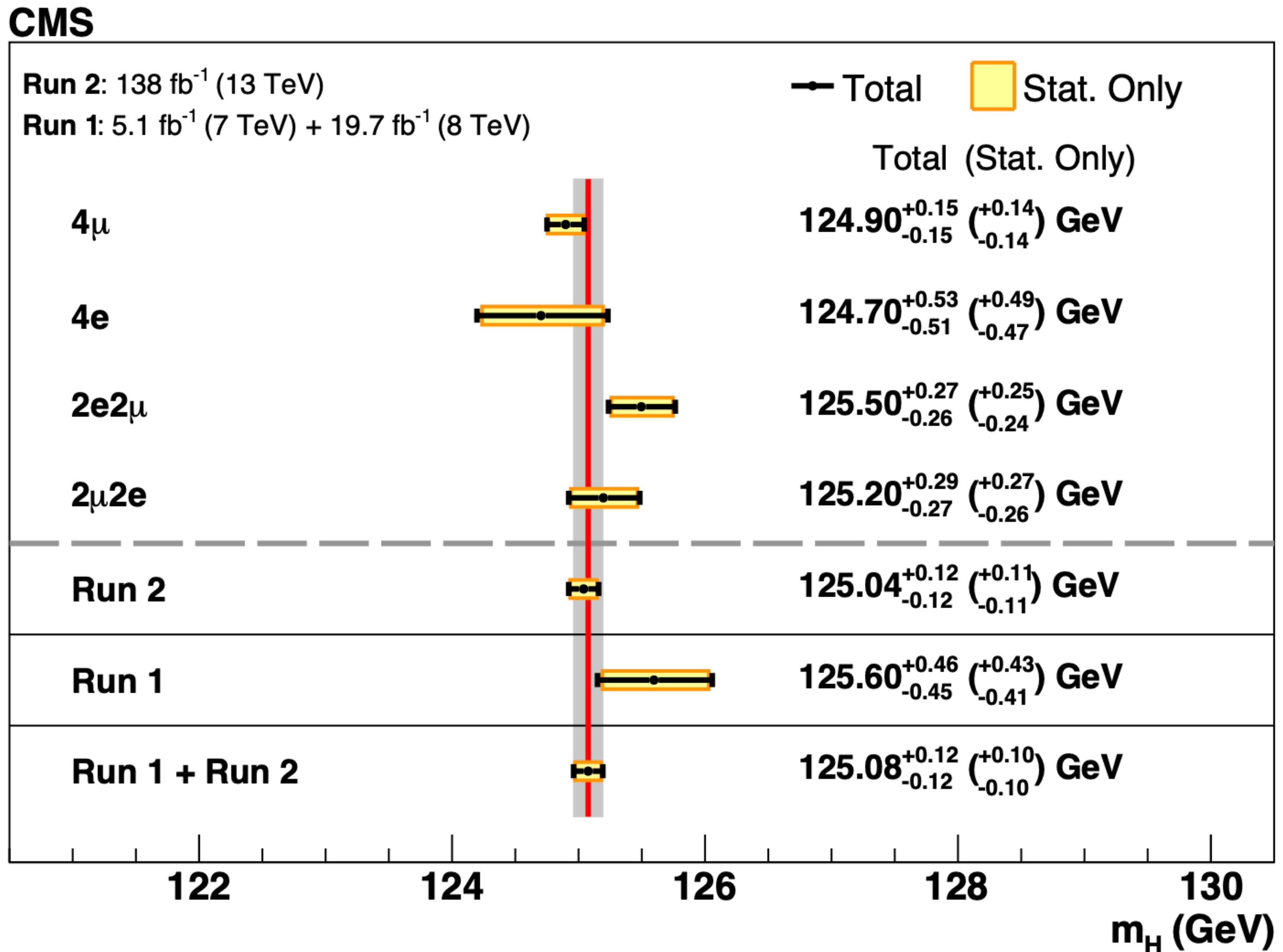
Difference(%)	4μ	4e	$2e2\mu$	$2\mu 2e$
Muon momentum scale	0.03%	-	0.03%	0.03%
Electron energy scale	-	0.15%	0.15%	0.15%
Muon momentum resoltuon	3%	-	3%	3%
Electron energy resolution	-	10%	10%	10%

- Modelling
  - 9 categories based on per-event mass error
  - $N_{ebe} \times PDF(m_{4\ell} | m_H) \times PDF(D | m_{4\ell}) + BKG$
  - Combination with CMS Run1 $H \to ZZ$

$$m_H = 125.08 \pm 0.12(\pm 0.10)\ GeV$$

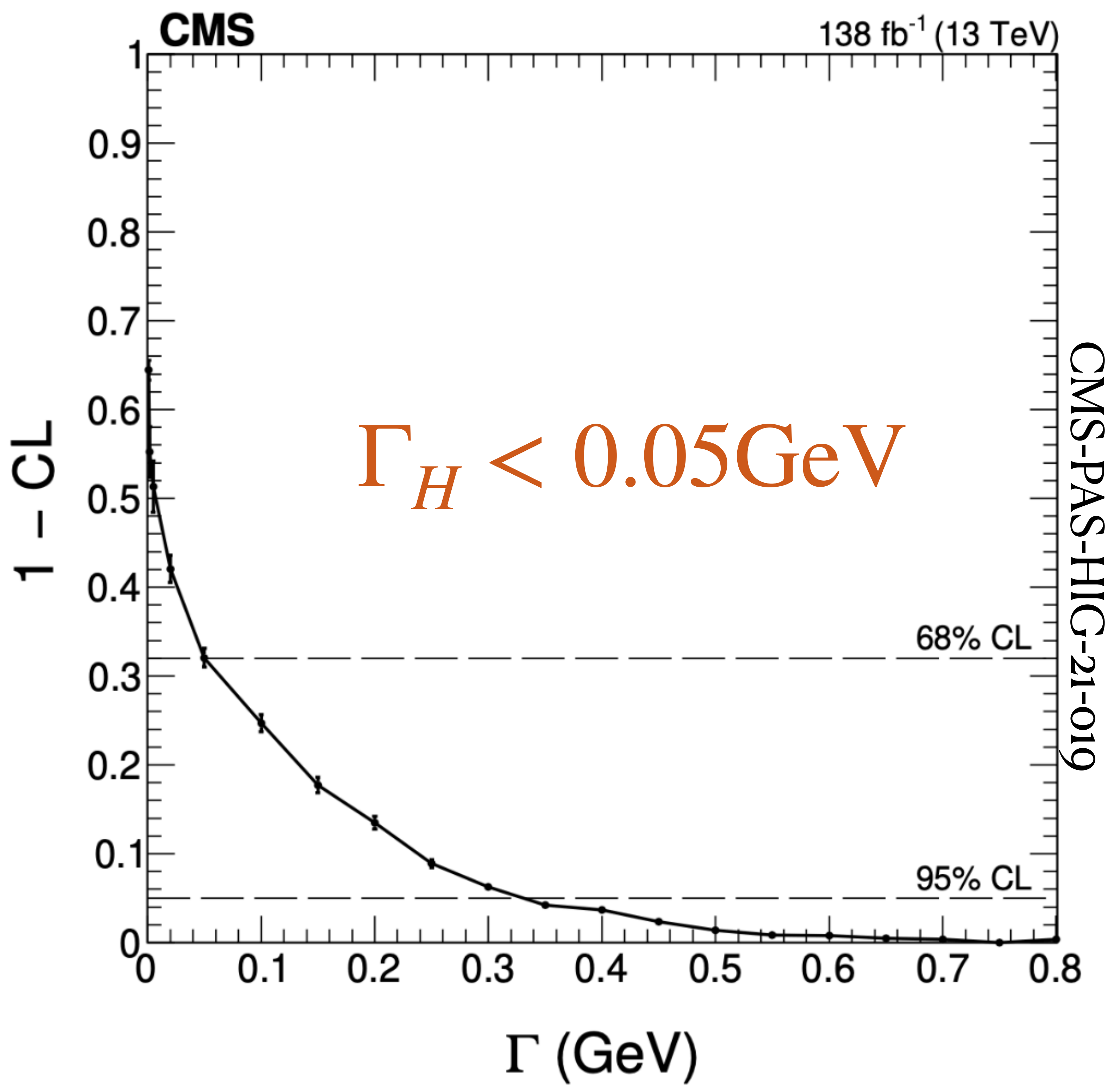
Expected: 0.12 GeV



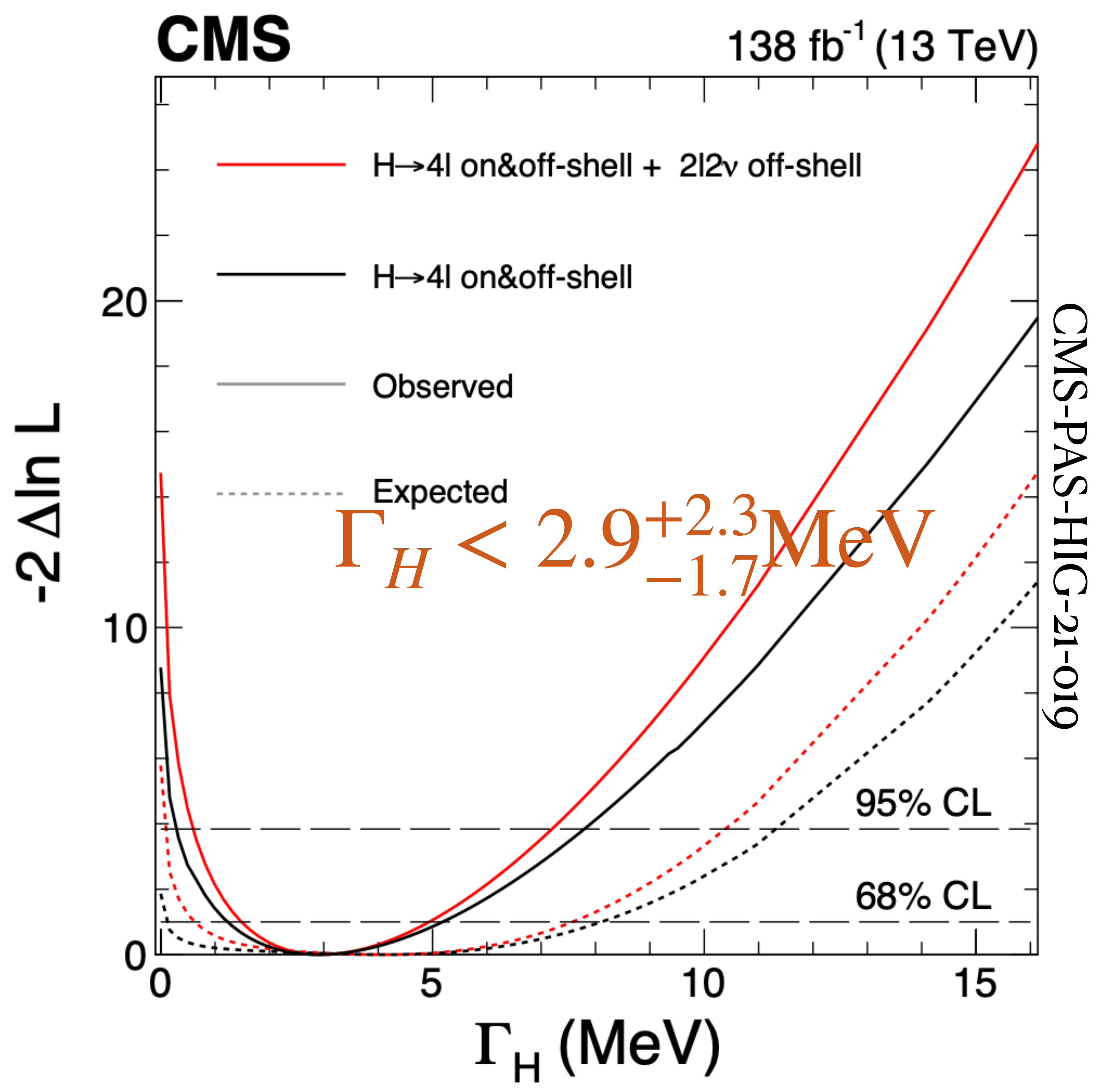


Γ_H measurement in $H \to ZZ$

- On-shell
  - The same procedure as m_H measurement, treat Γ_H as POI and signal strength and m_H as free parameters
  - Bounded parameter, Feldman-Cousins algorithm implemented



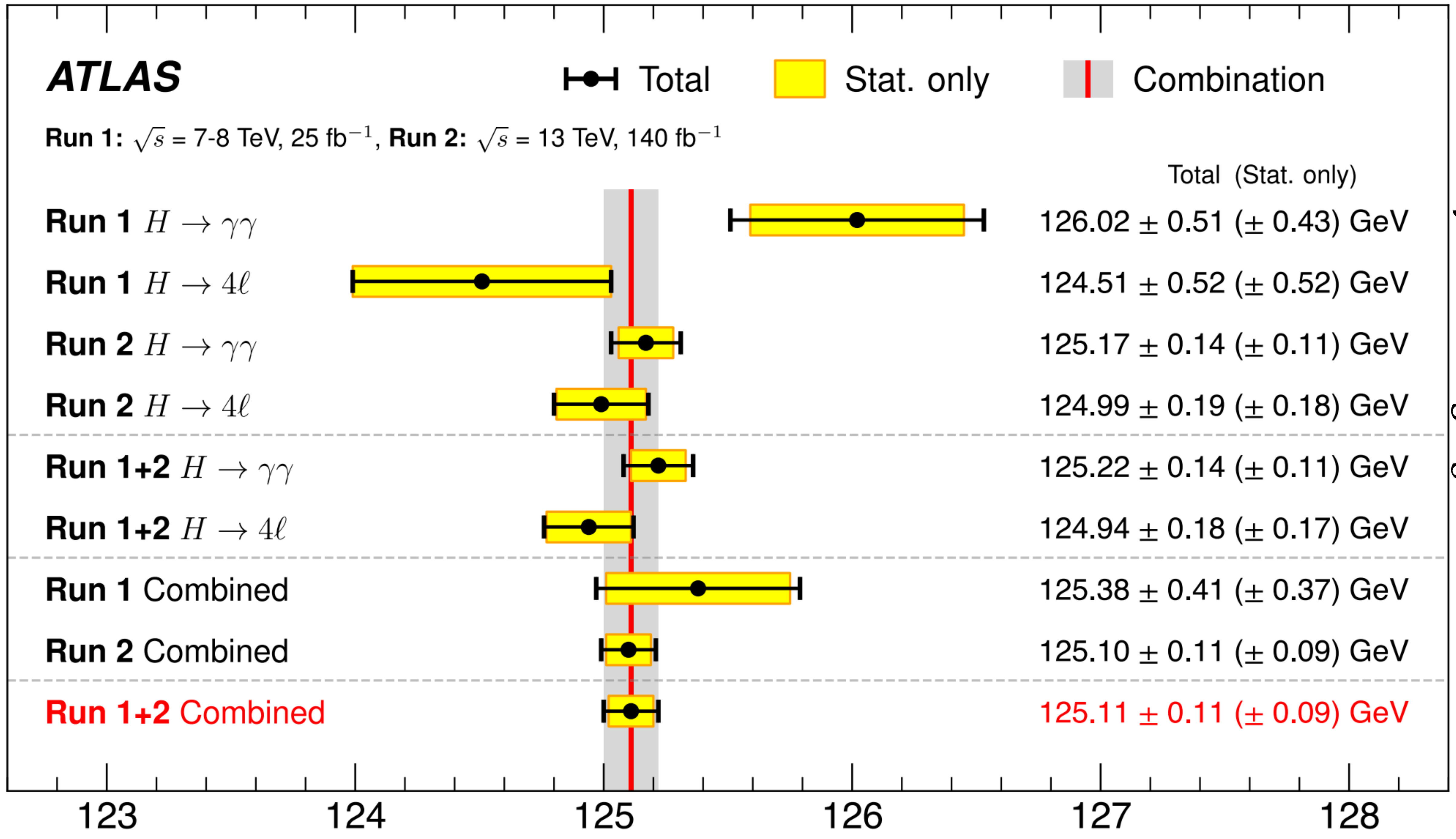
- Off-shell
  - Aim to measure width from the ratio of on-shell and off-shell yields
  - $$\frac{\sigma^{on-shell}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{off-shell}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$



Summary

- Higgs mass measurement has been introduced from aspects of achievable precision, methods, advantages/drawbacks of the two golden channels
  - Statistical uncertainty dominates $H \to ZZ$. How to improve mass resolution and efficiency
  - Systematic uncertainty dominates $H \to \gamma\gamma$. How to calibrate ECAL energy reconstruction
- Cross reference from ATLAS

LHC full Run2	ATLAS	CMS
$H \to ZZ$	124.99 ± 0.19GeV	125.04 ± 0.12GeV
$H \to \gamma\gamma$	125.17 ± 0.14GeV	-



PhysRevLett.131.251802

- Γ_H from $H \to ZZ$
  - Off-shell: $\Gamma_H < 2.9^{+2.3}_{-1.7}$ MeV
  - On-shell: $\Gamma_H < 0.05$ GeV