Istituto Nazionale di Fisica Nucleare
Sezione di Roma

Measurements of the Higgs boson mass and width at CMS

F. Errico,
INFN Roma
on behalf of the CMS Collaboration

ICNFP 2024
26 Aug - 04 Sept 2024, OAC, Kolymbari (Crete)

Overview

Higgs boson discovery was announced on the 4th of July 2012.

Since then, much effort has been put into determining its properties

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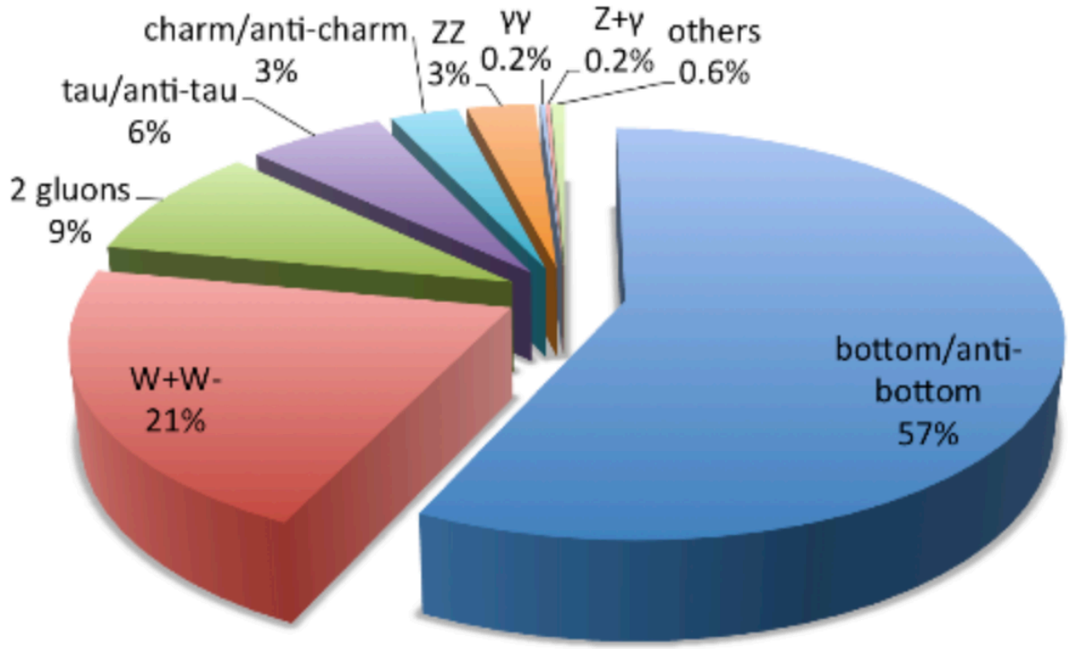
$\sqrt{s}$ (TeV)	Production cross section (in pb) for $m_H = 125\,\text{GeV}$					
	ggF	VBF	WH	ZH	$t\bar{t}H$	total
7	$16.9^{+5.5\%}_{-7.6\%}$	$1.24^{+2.2\%}_{-2.2\%}$	$0.58^{+2.2\%}_{-2.3\%}$	$0.34^{+3.1\%}_{-3.0\%}$	$0.09^{+5.6\%}_{-10.2\%}$	19.1
8	$21.4^{+5.4\%}_{-7.6\%}$	$1.60^{+2.1\%}_{-2.1\%}$	$0.70^{+2.1\%}_{-2.2\%}$	$0.42^{+3.4\%}_{-2.9\%}$	$0.13^{+5.9\%}_{-10.1\%}$	24.2
13	$48.6^{+5.6\%}_{-7.4\%}$	$3.78^{+2.1\%}_{-2.1\%}$	$1.37^{+2.0\%}_{-2.0\%}$	$0.88^{+4.1\%}_{-3.5\%}$	$0.50^{+6.8\%}_{-9.9\%}$	55.1
14	$54.7^{+5.6\%}_{-7.4\%}$	$4.28^{+2.1\%}_{-2.1\%}$	$1.51^{+1.8\%}_{-1.9\%}$	$0.99^{+4.1\%}_{-3.7\%}$	$0.61^{+6.9\%}_{-9.8\%}$	62.1

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



All theoretical information (such as XS and BR) has been extracted for a Higgs boson mass of 125 GeV

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Overview

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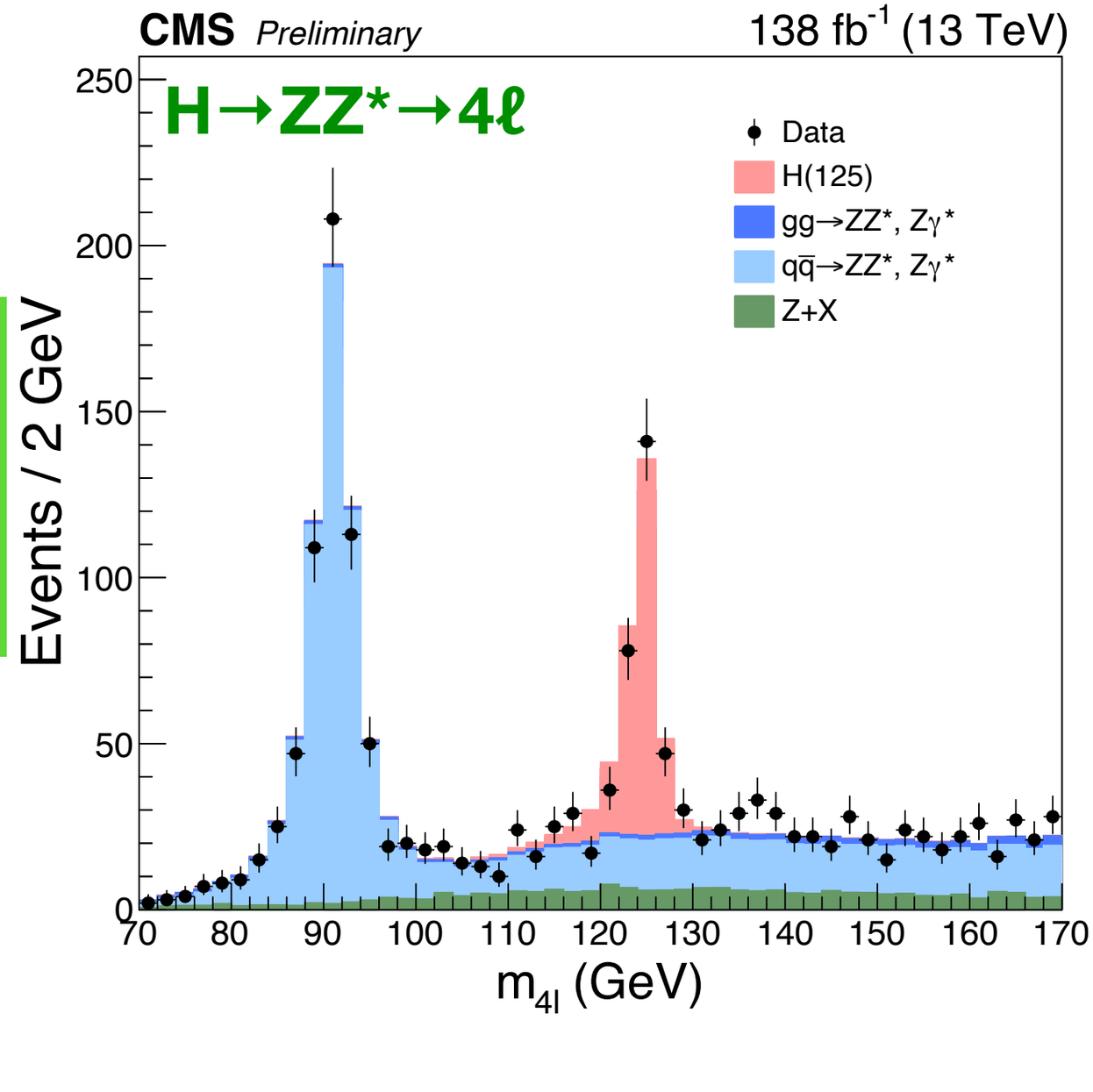
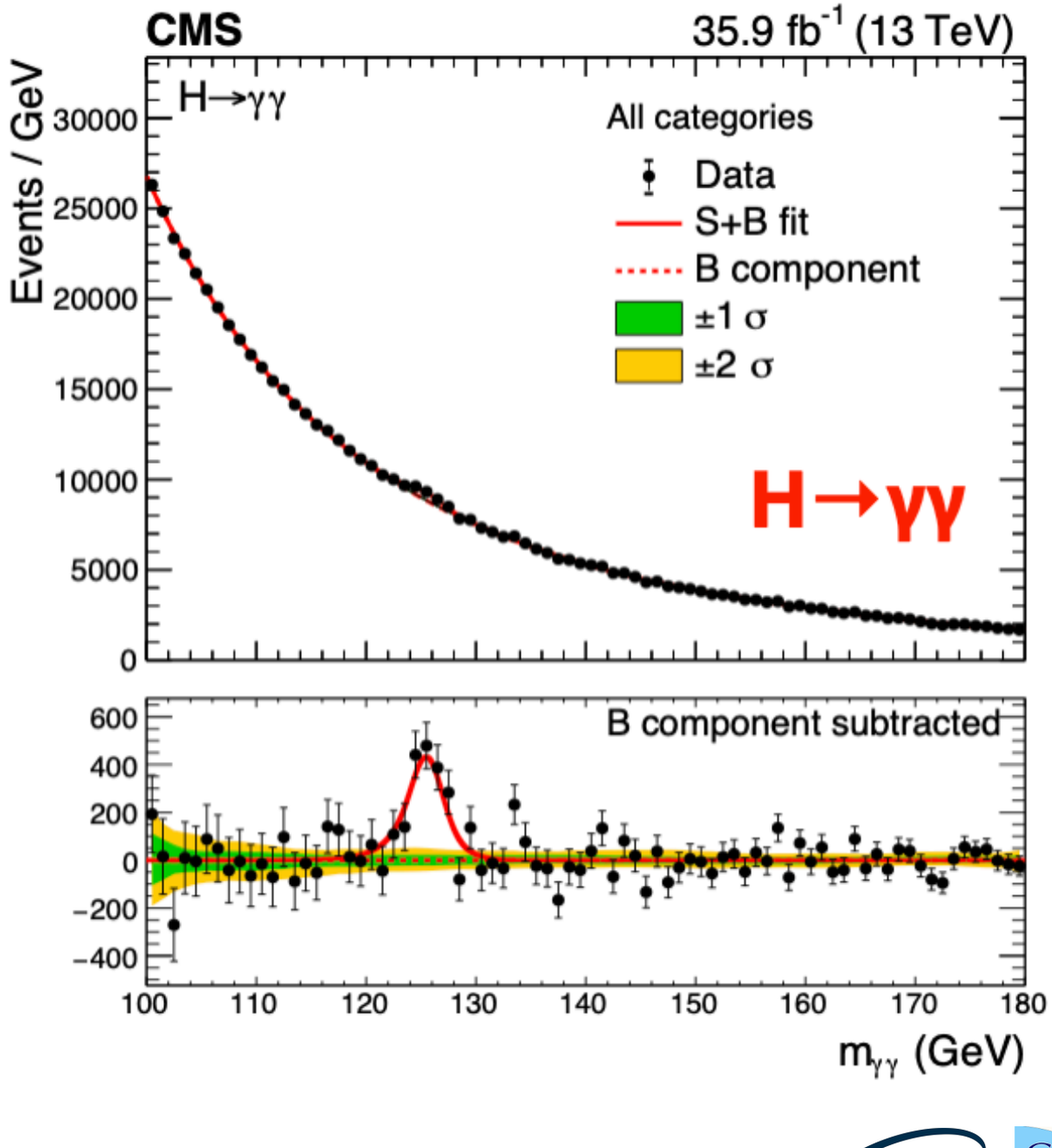
The Higgs boson mass is one of the most important free parameters of the Standard Model.

It is crucial to properly determine its value since it determines all the other Higgs boson properties

Higgs boson mass

Higgs boson mass measurement is performed using **H→ZZ*→4ℓ** and **H→γγ**, thanks to their mass resolution (1-2%) and complete reconstruction of the final state.





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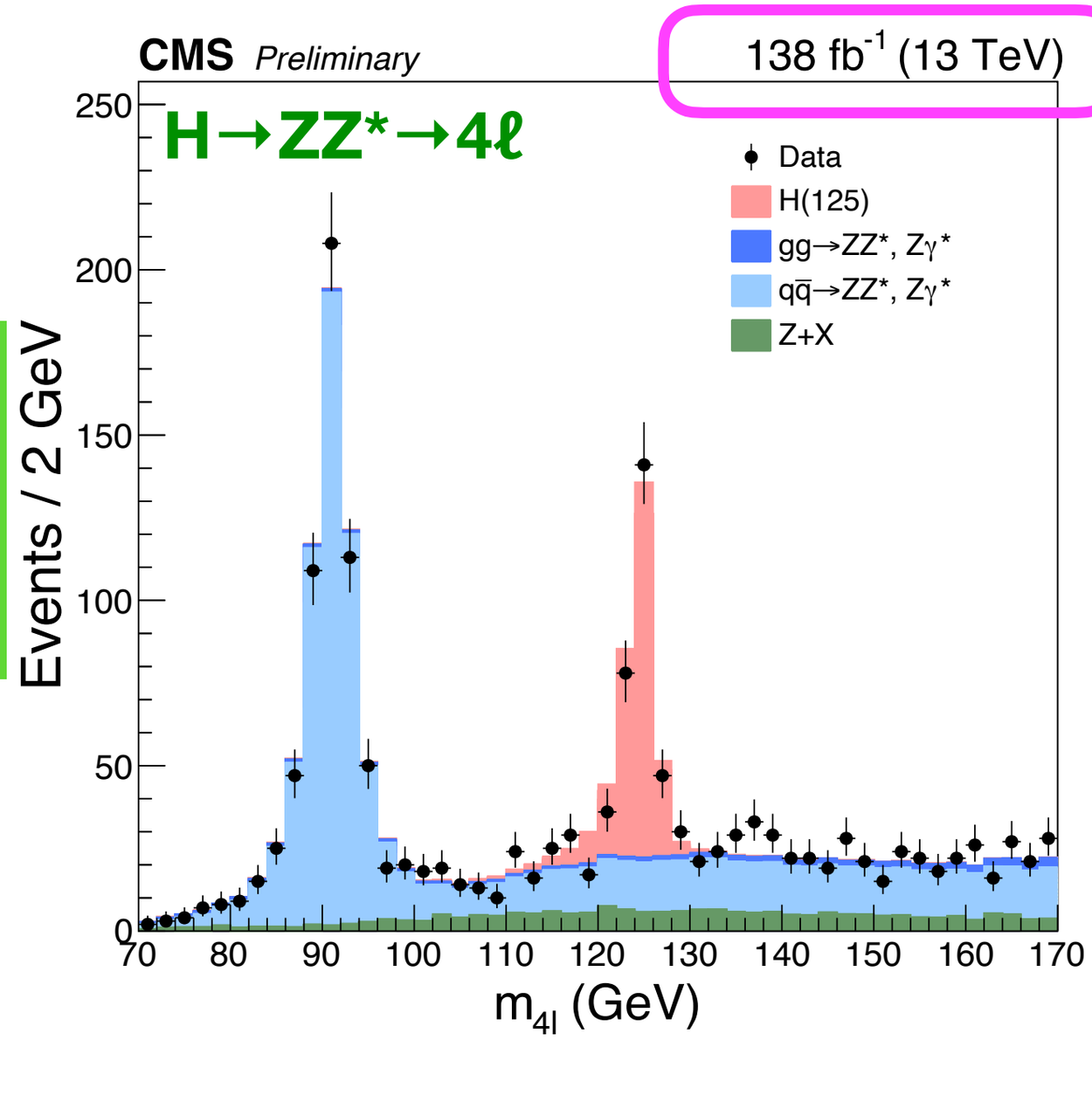

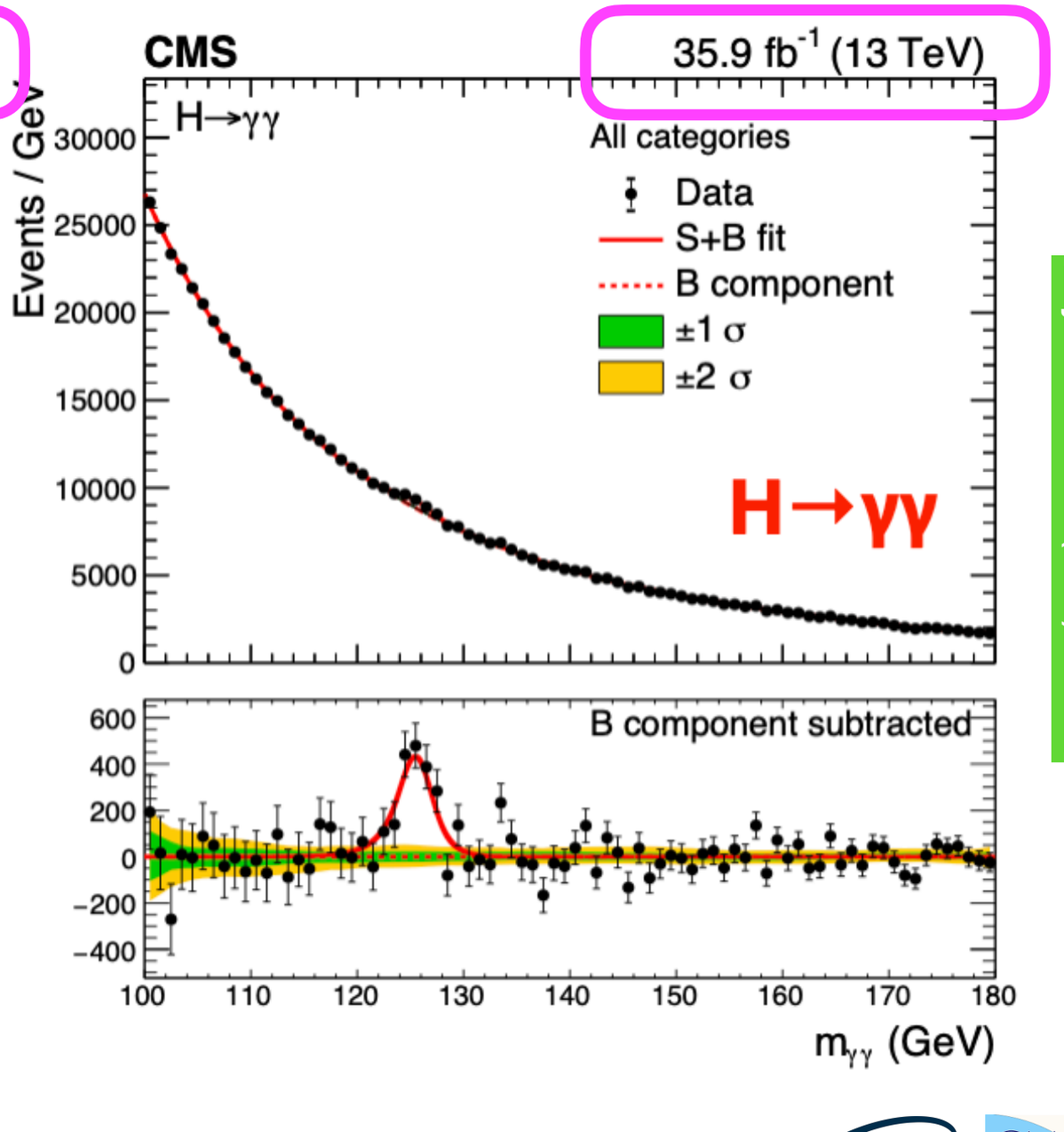

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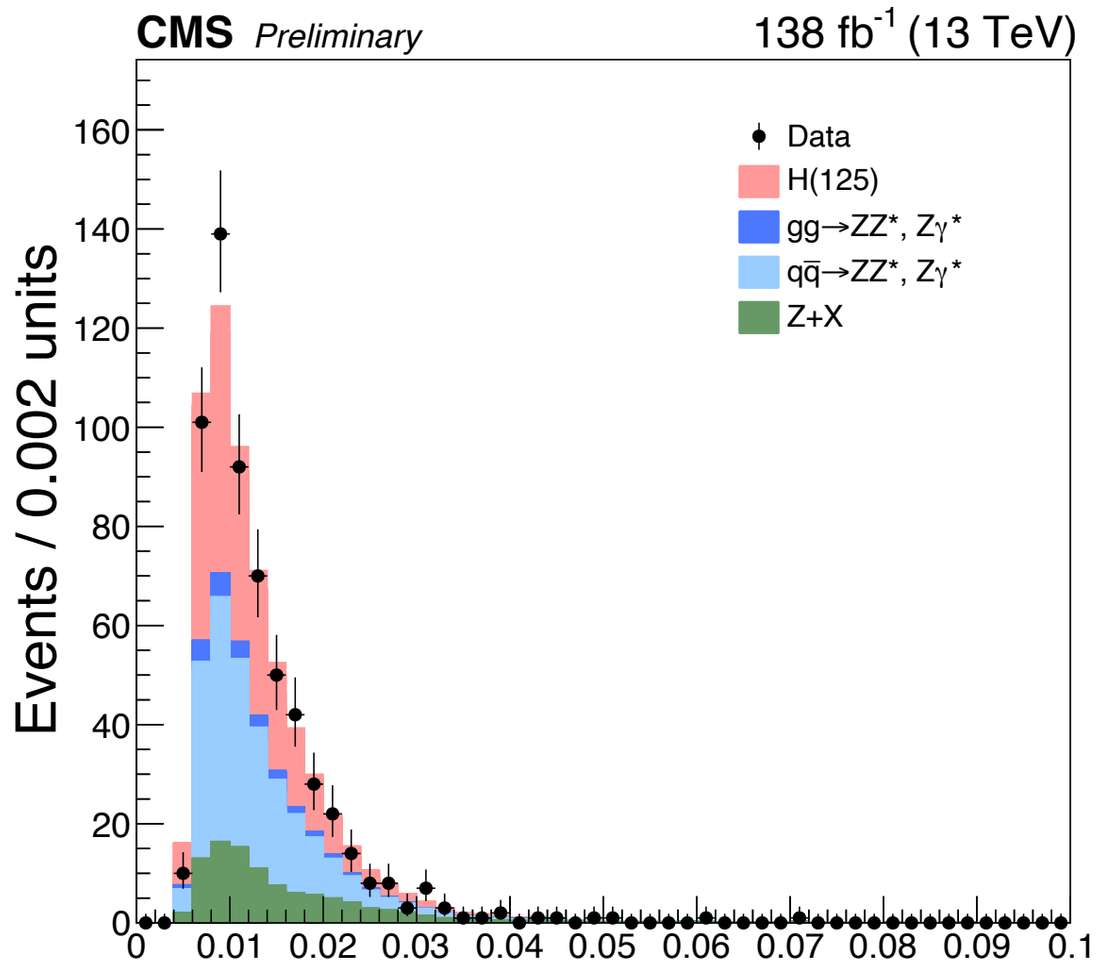
Higgs boson mass: H→ZZ*→4ℓ

Latest result uses **Full Run 2 data**, (138/fb)

Final results have been extracted adopting a **Nx2D likelihood**:

- N = number of categories based on the relative mass uncertainty



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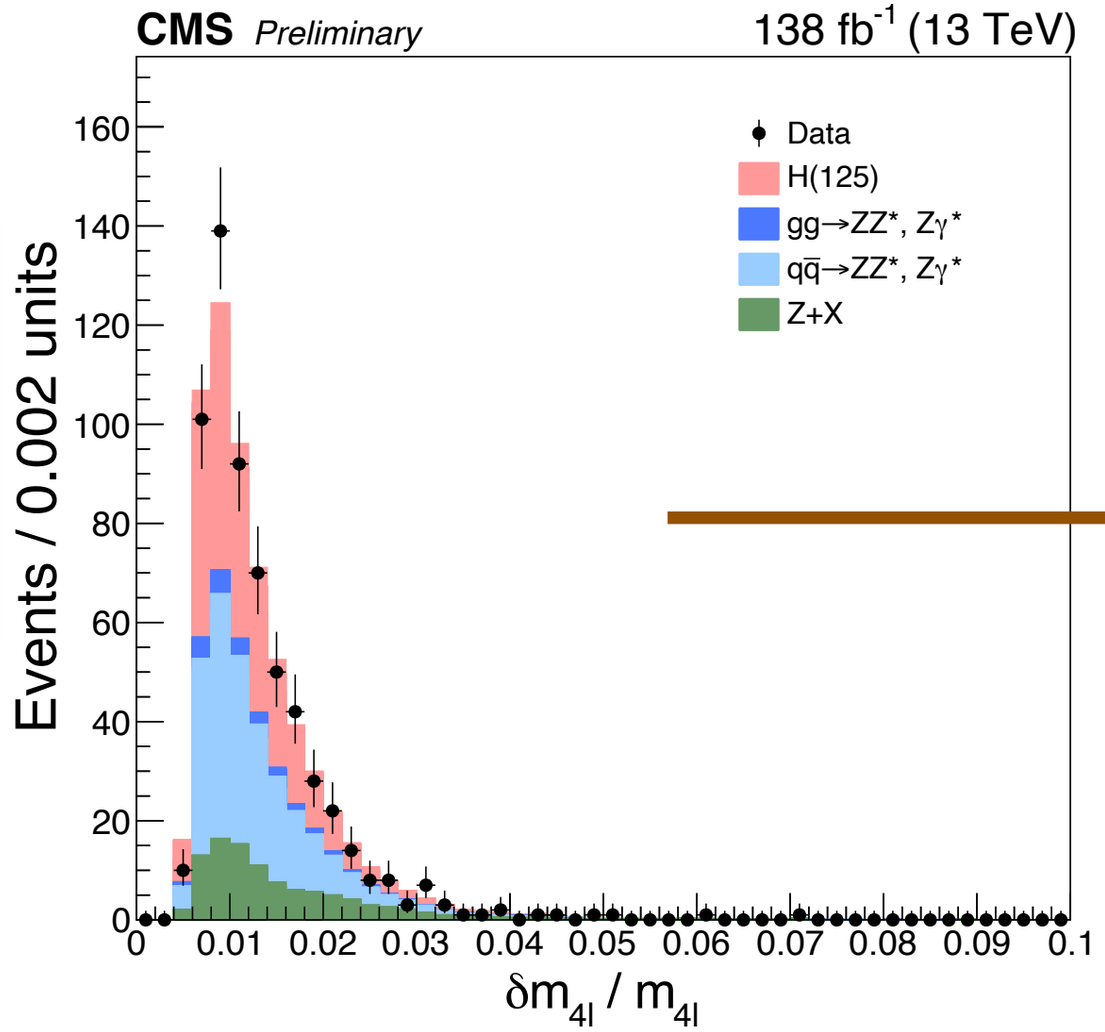
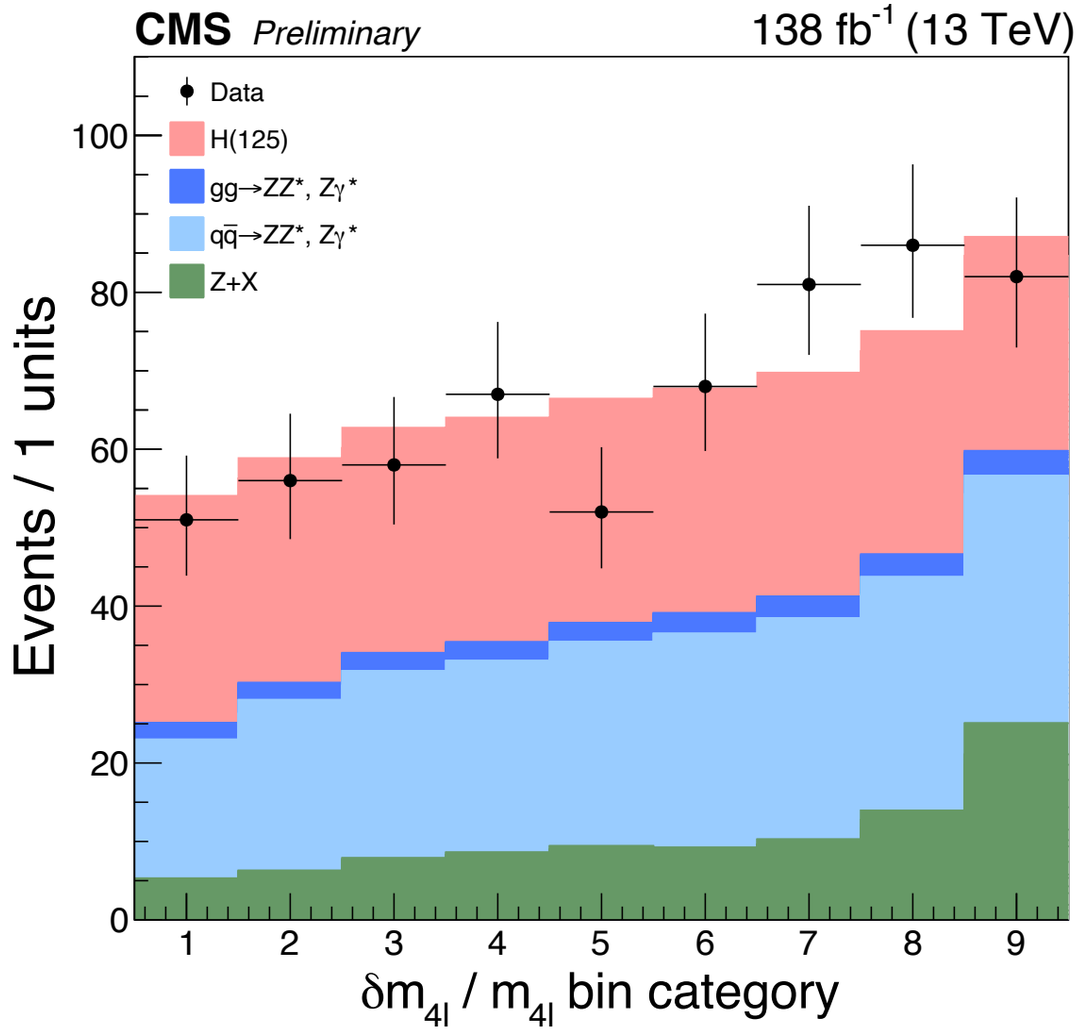




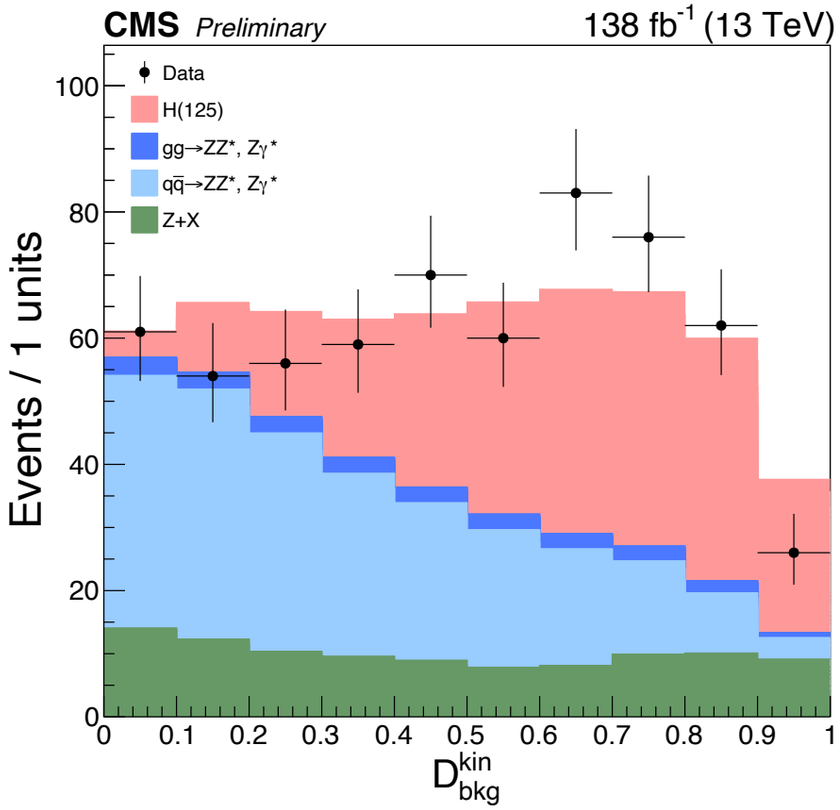
CMS-PAS-HIG-21-019

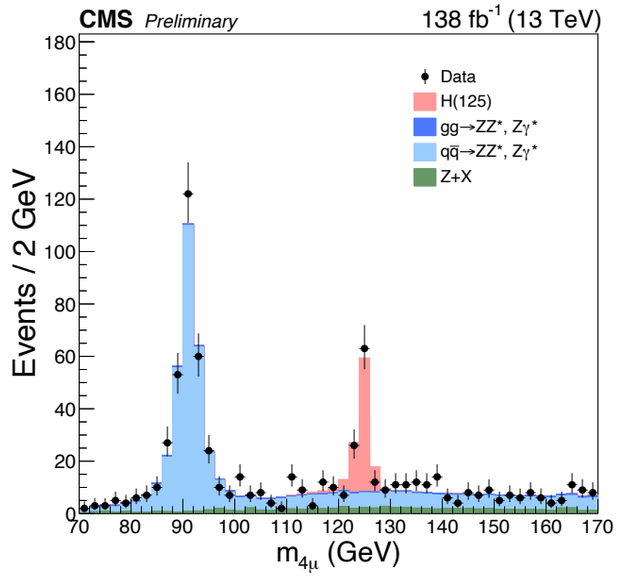
Higgs boson mass: H→ZZ*→4ℓ

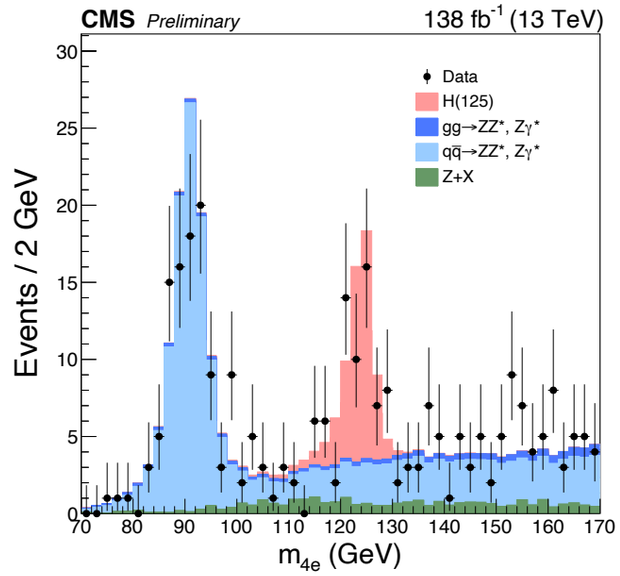
Latest result uses **Full Run 2 data**, (138/fb)

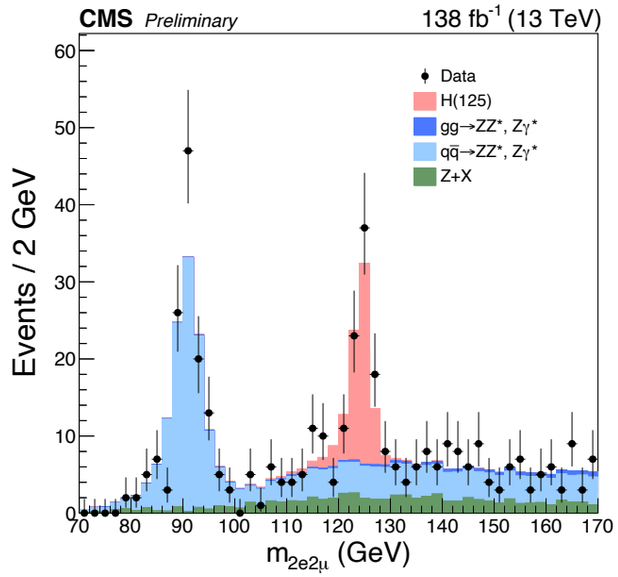
Final results have been extracted adopting a **Nx2D likelihood**:

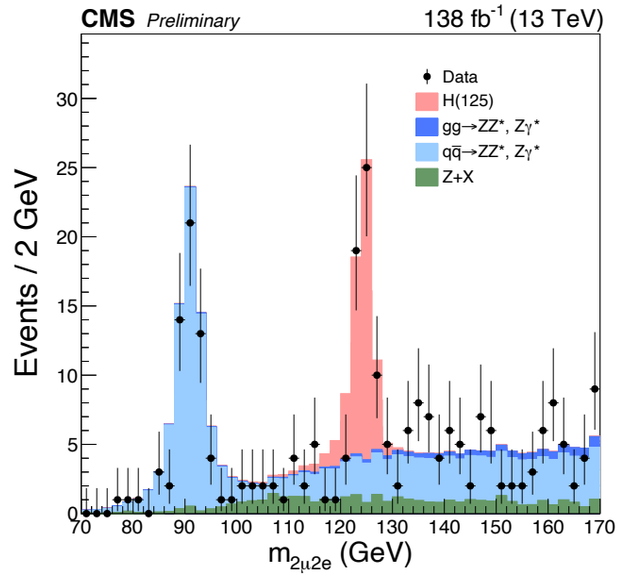
- N = number of categories based on the relative mass uncertainty
- 1D = four lepton mass
- 2D = kinematic discriminant











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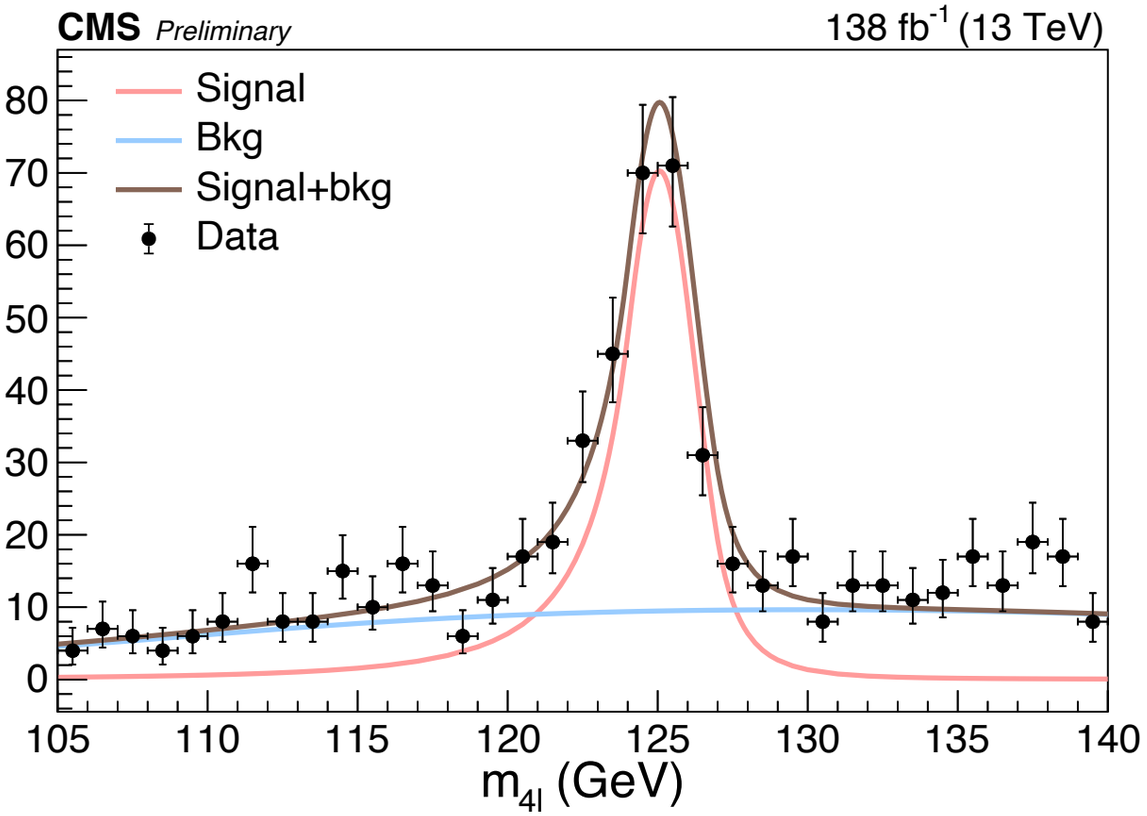

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Signal model shape: DSCB

Background model shape: polynomial functions (from either MC and DATA)

Higgs boson mass: H→ZZ*→4ℓ

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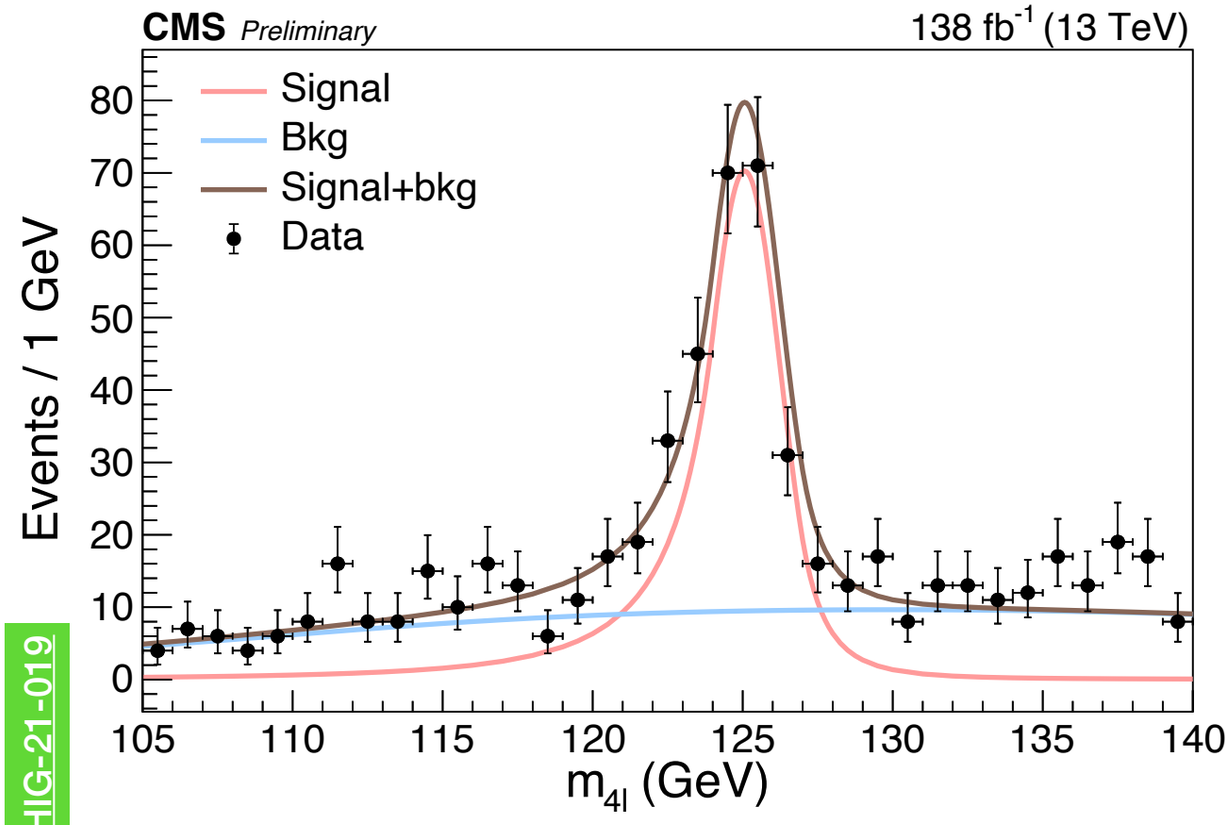

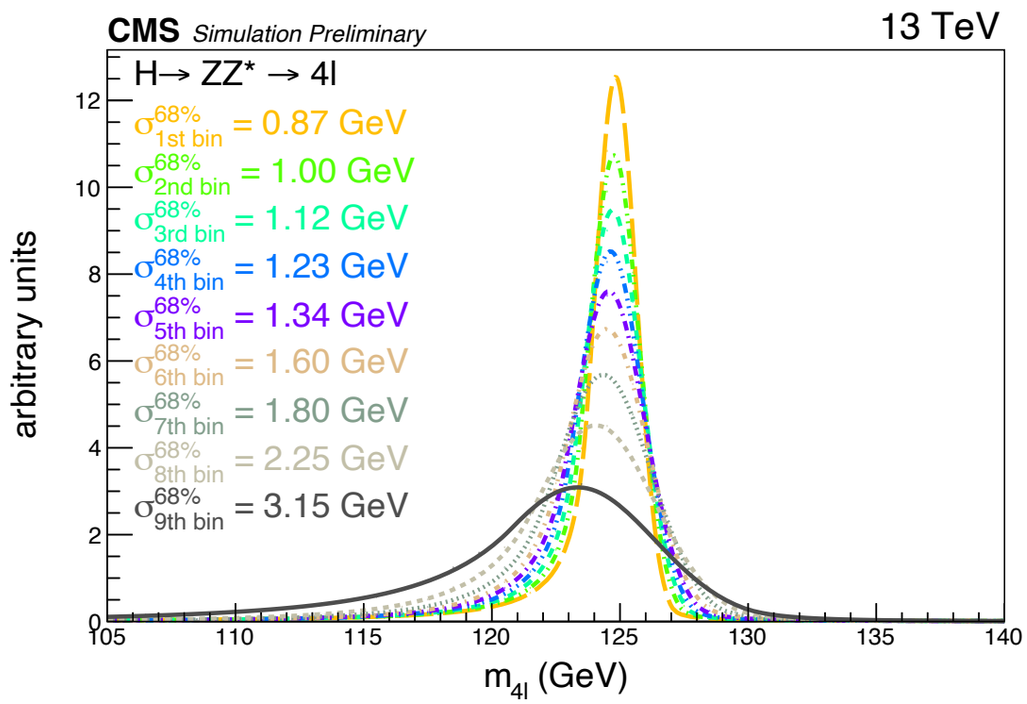

Resolution vs categories

Signal model shape: DSCB

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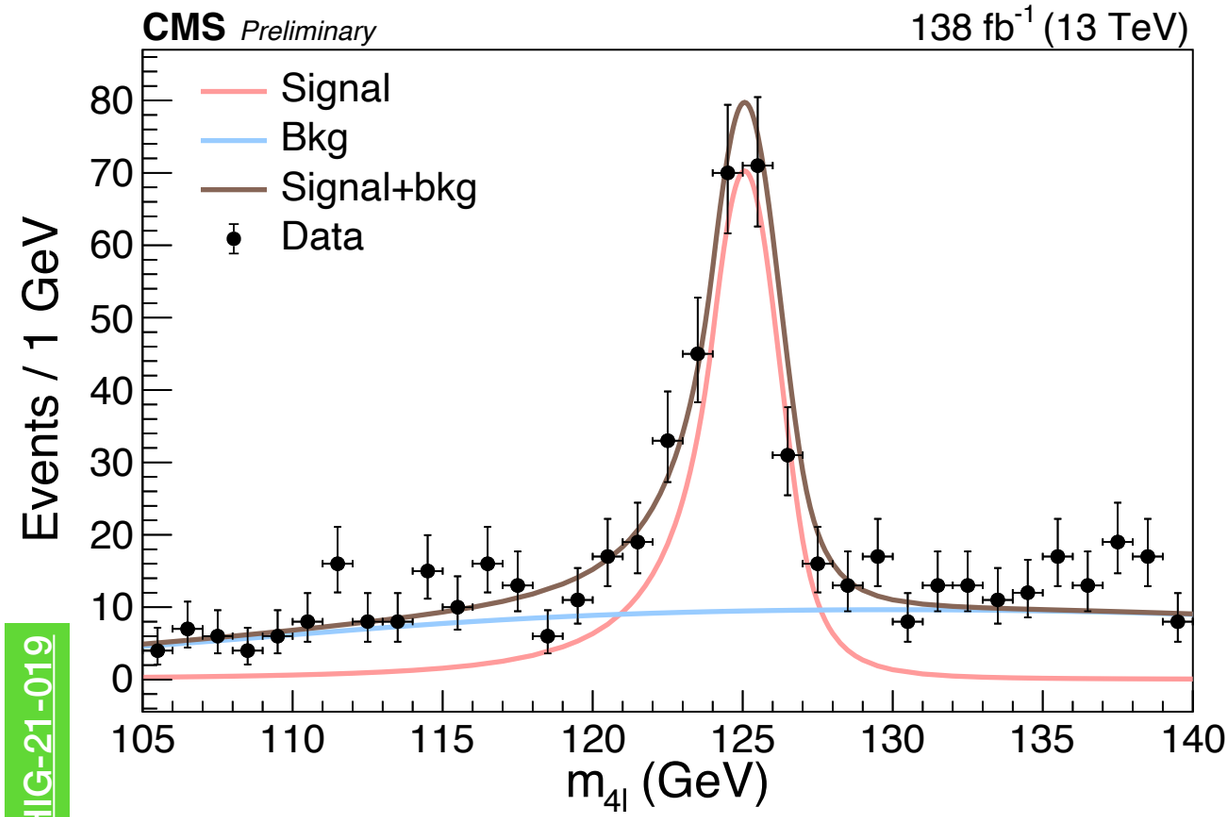

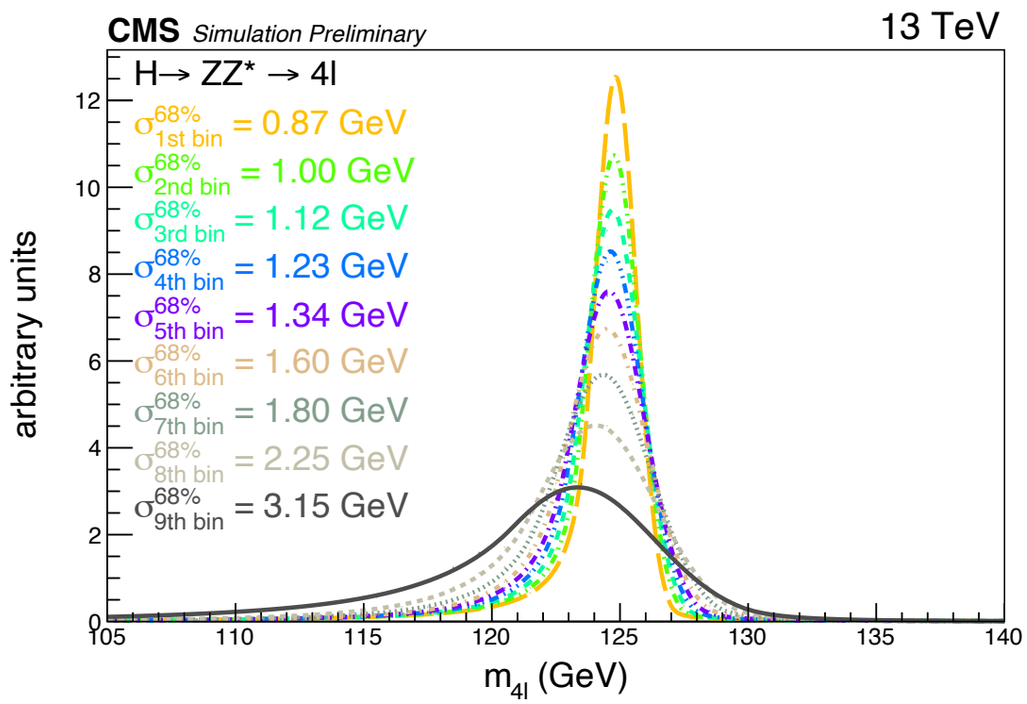

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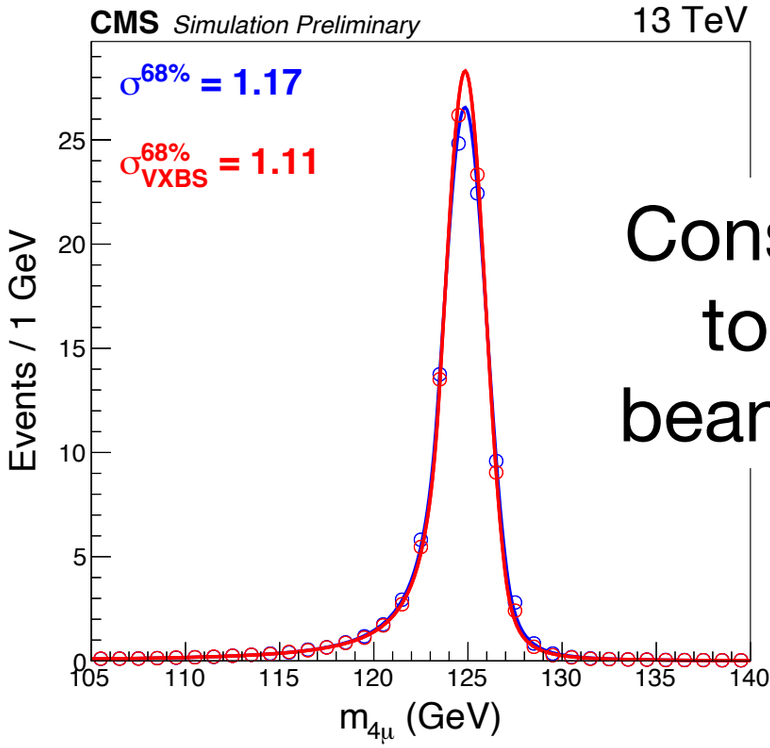

Constraint to the beam spot

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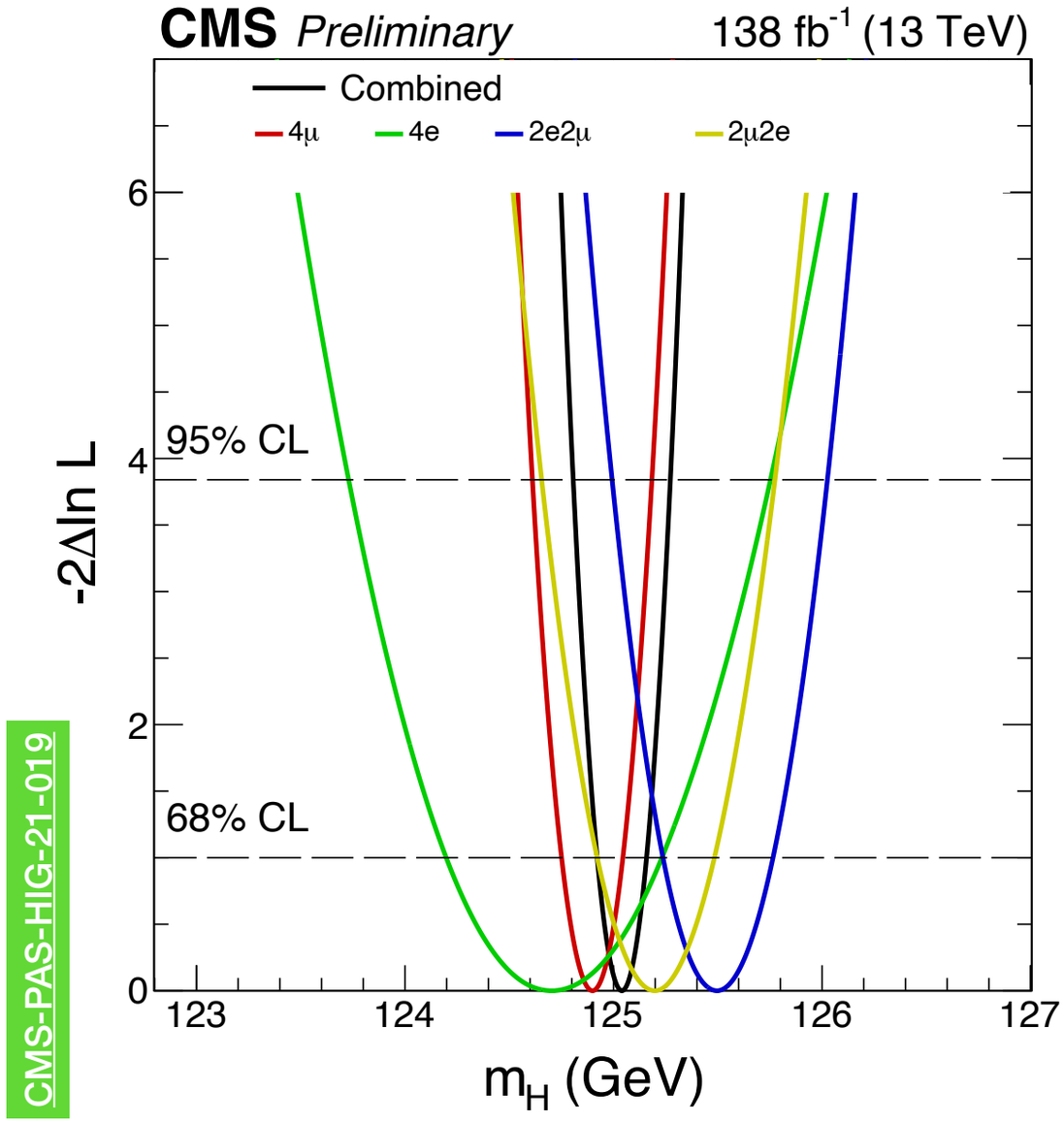
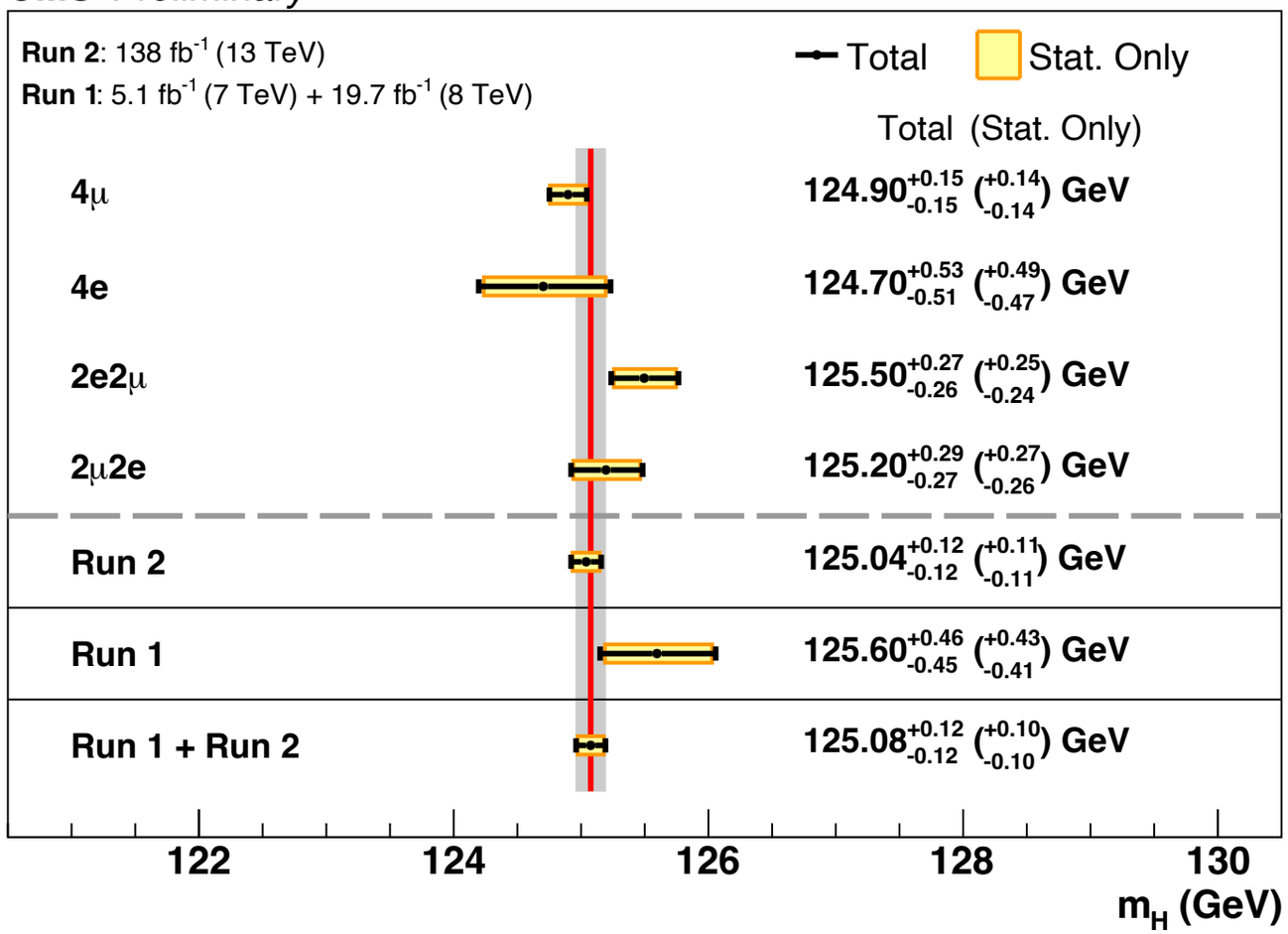
Higgs boson mass: H→ZZ*→4ℓ





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$$m_H = 125.08 \pm 0.12\ [0.10(stat) \pm 0.05(syst)]\ GeV$$

Best measurement up to date in a single channel

Higgs boson mass: H→γγ

Latest result uses **2016 data + Run1**

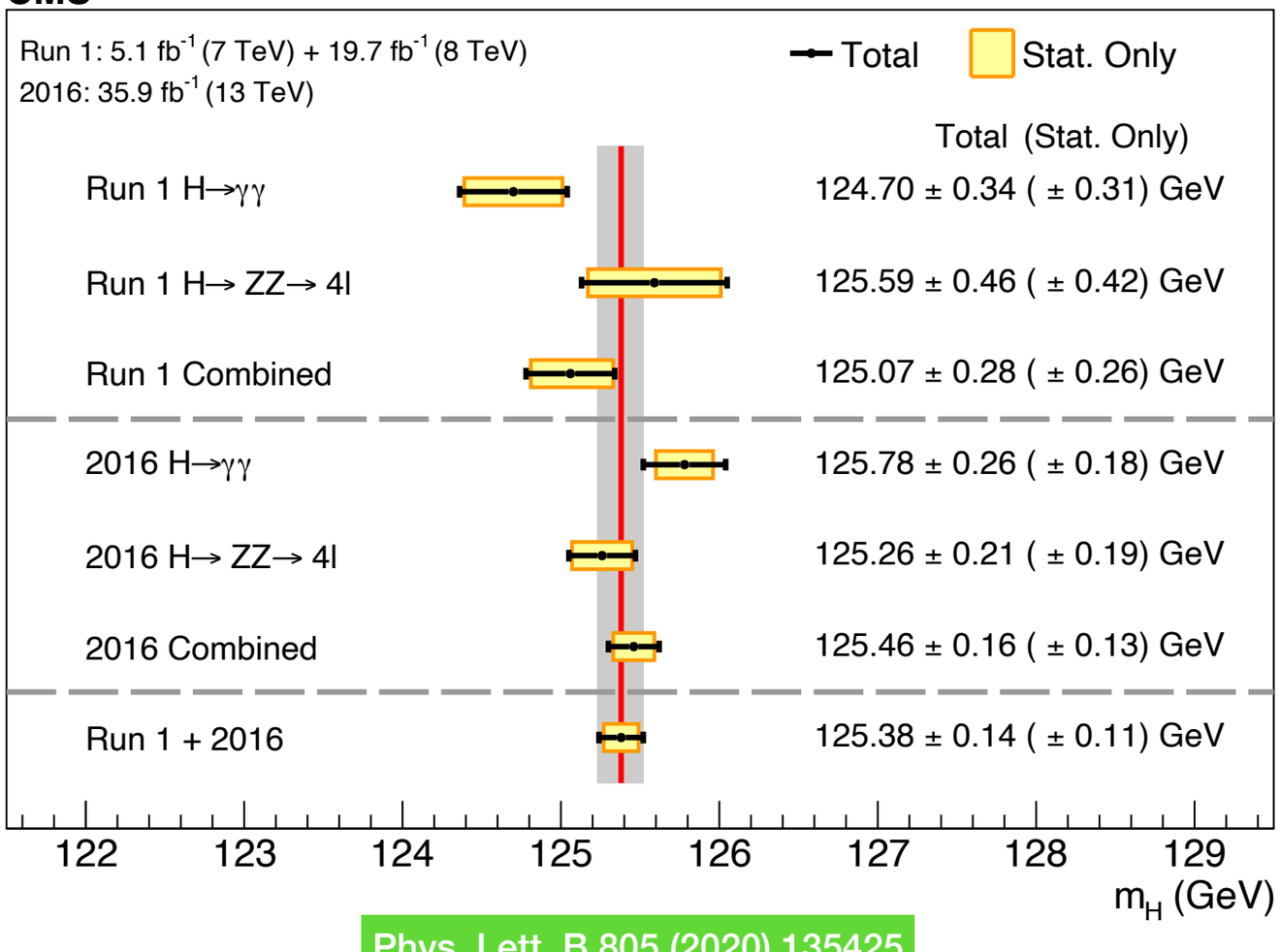
- **Critical component** → energy calibration of the response of the detector to photons. Correction are derived using a multivariate regression technique

- **Dedicated method developed** → deals with residual differences between data and MC, after applying corrections

  ✦ Multistep scale corrections with Z→ee events (time stability => η, shower category and E_T)

- **Events classification** → according to their production mode, mass resolution and their predicted signal-to-background ratio; S/(S+B) value is obtained using a multivariate discriminant (BDT).

Higgs boson mass: H→γγ



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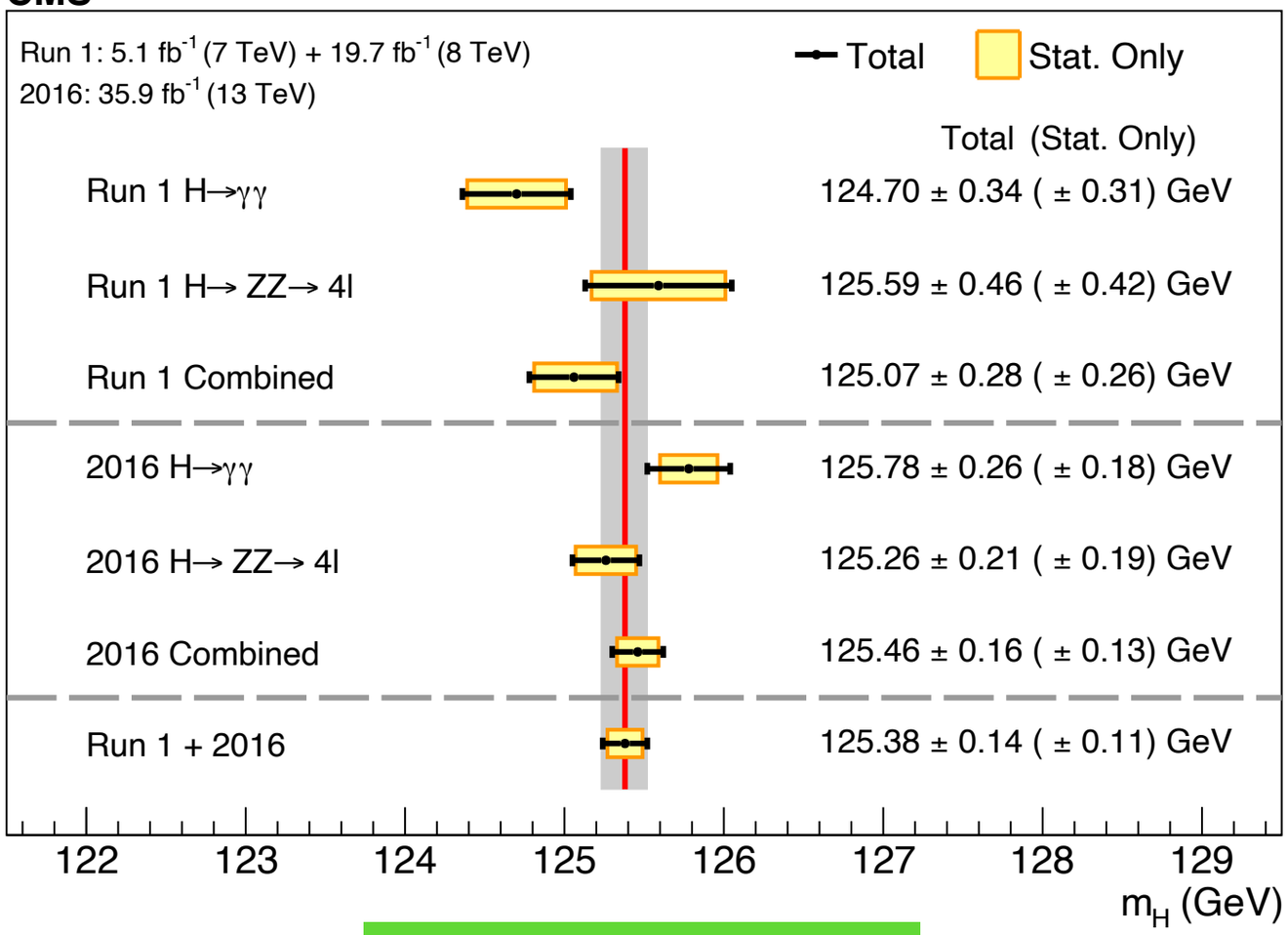

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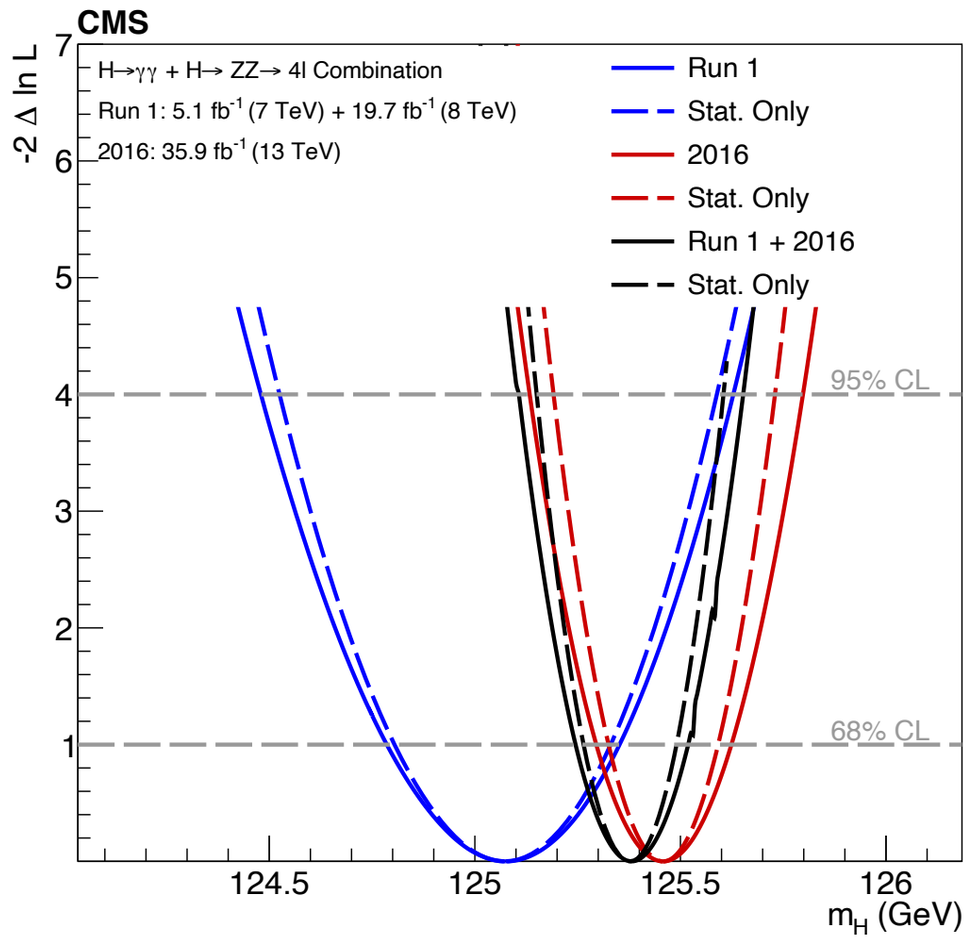

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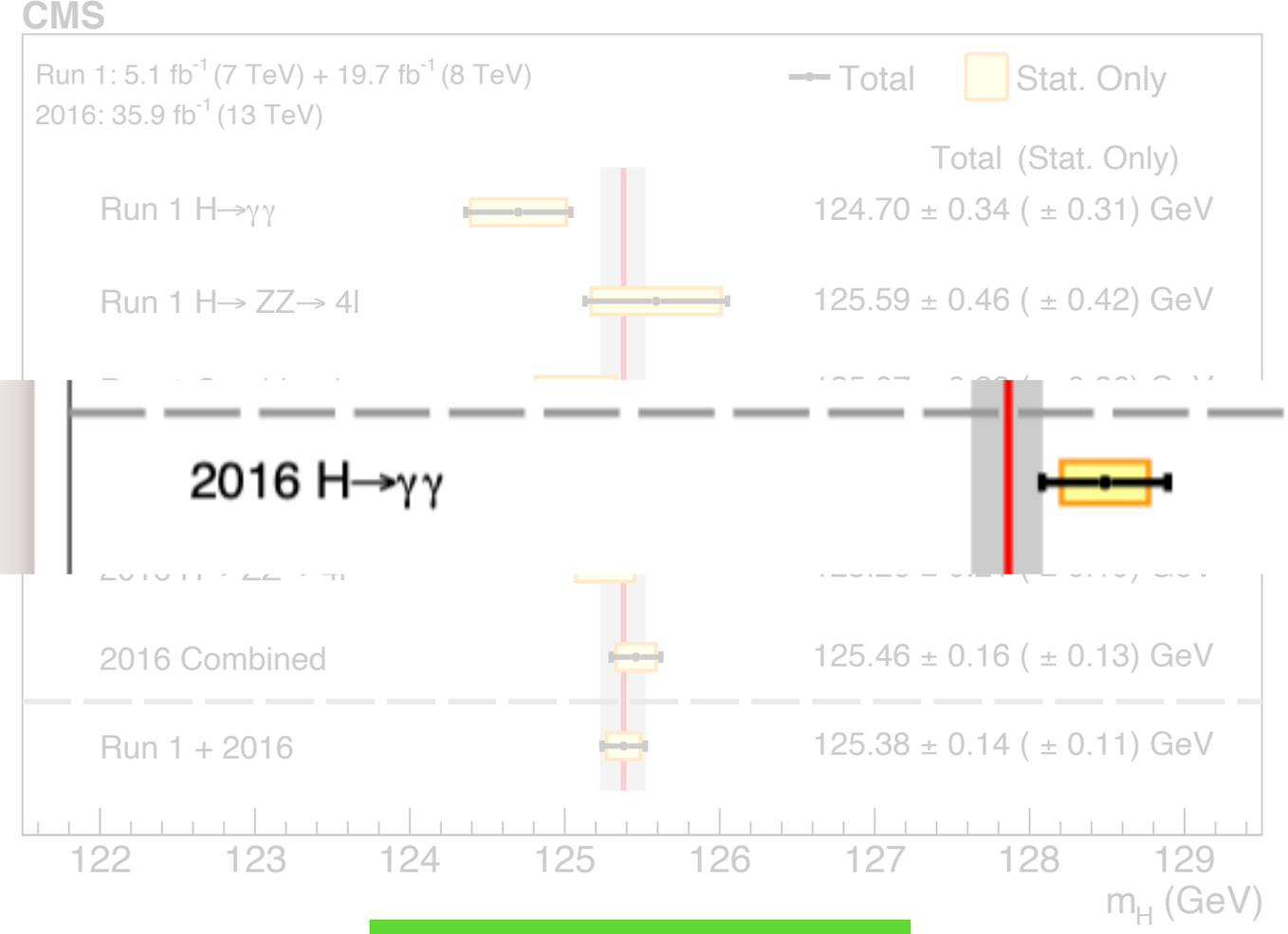
$$m_H = 125.38 \pm 0.14\ [\pm 0.11(stat) \pm 0.08(syst)]\ GeV$$

Higgs boson mass: H→γγ



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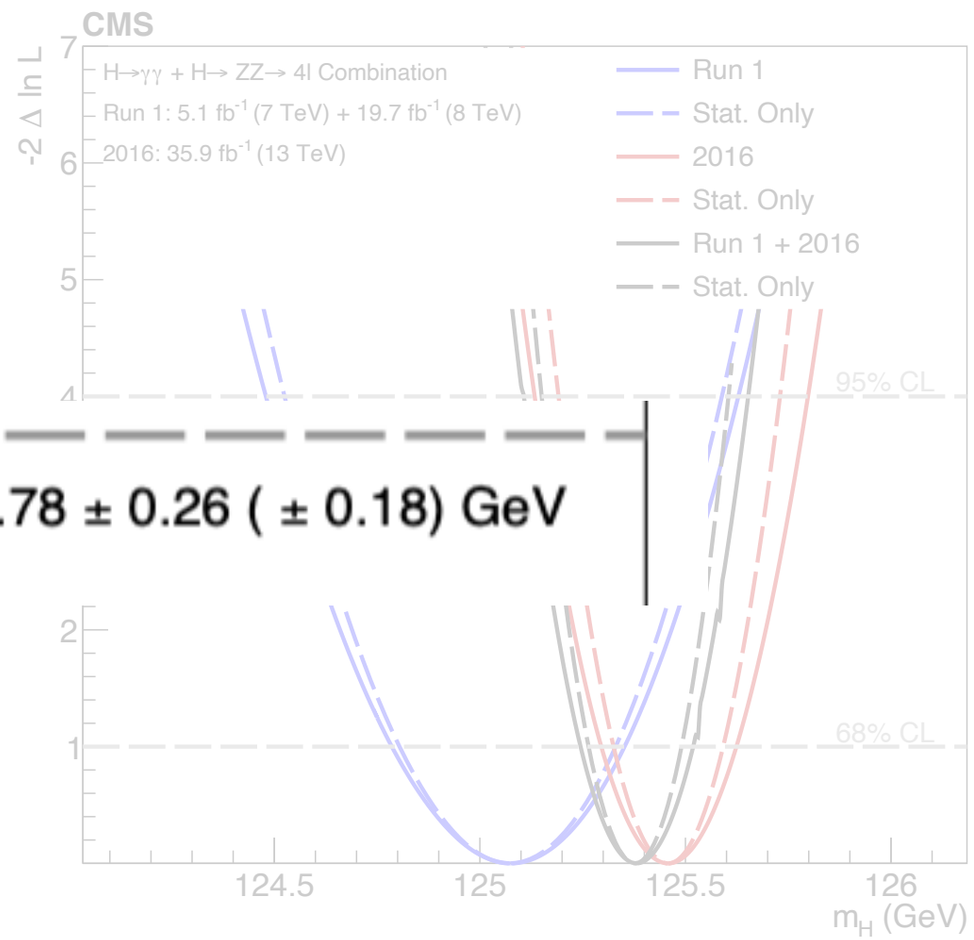

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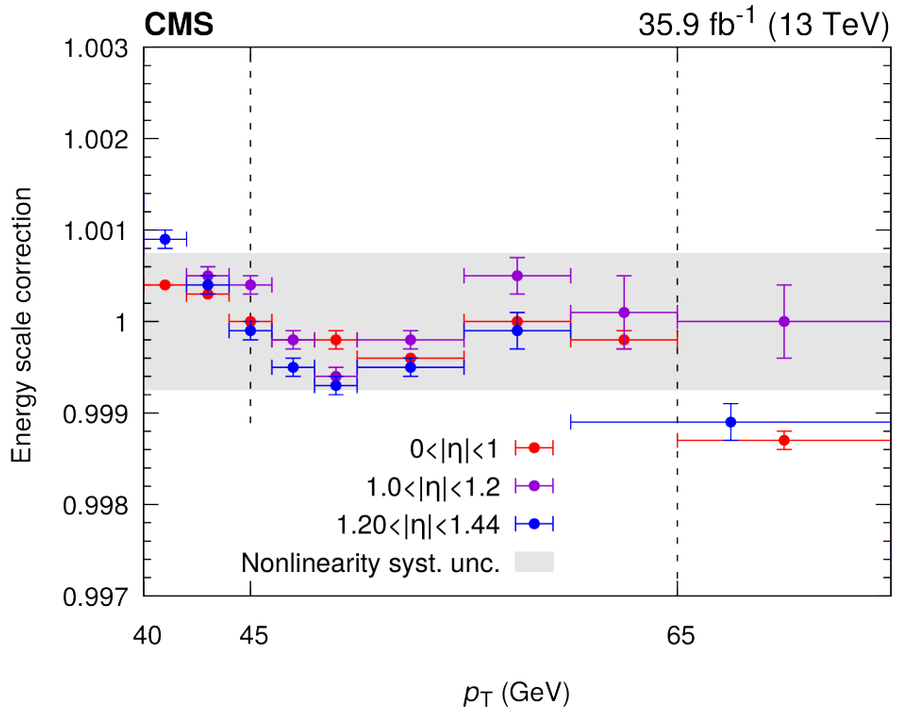
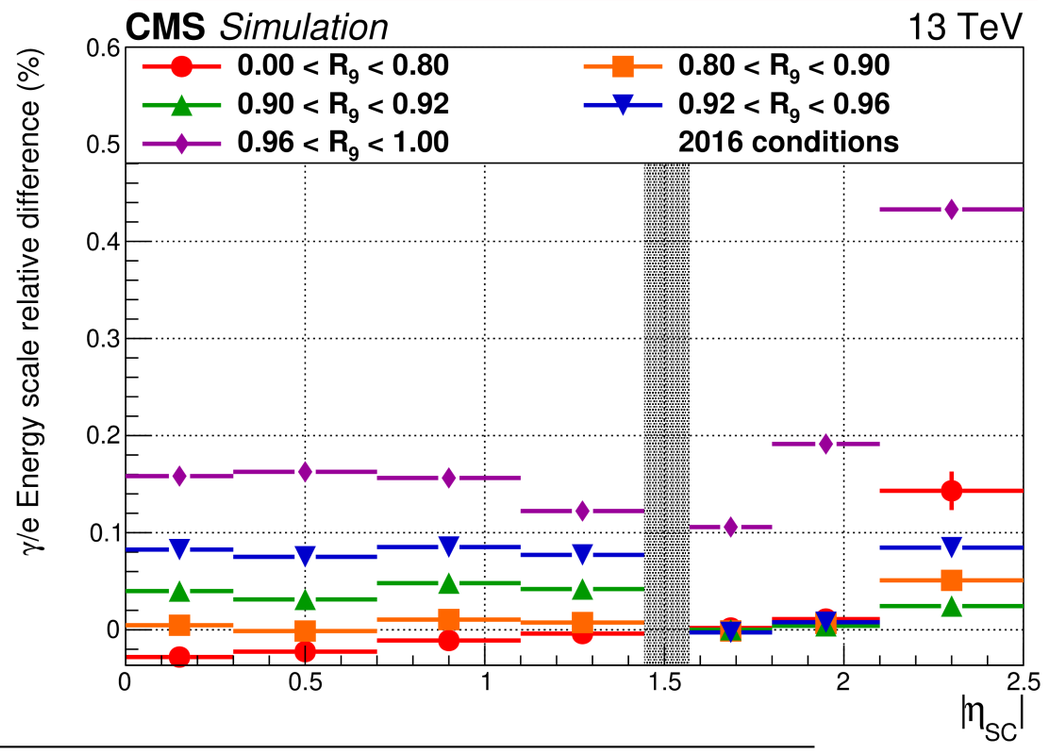


Electron to γ transport systematic evaluated with simulation + transparency loss measurements



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

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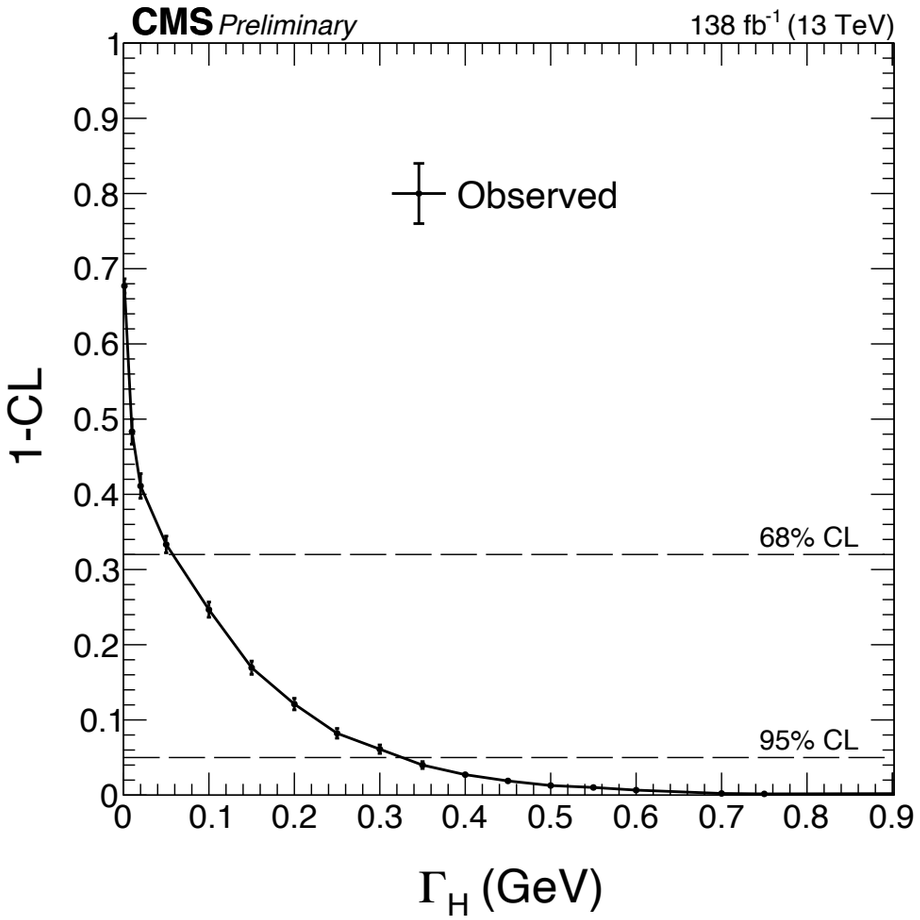
Higgs boson width

- Test of Higgs on-shell vs off-shell production
- Test for H→invisible particles

Measured in the **H→ZZ** channel, full Run 2 data from the on-shell distribution



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Fit four-lepton mass distribution

POI included in the signal model using a Breit-Wigner

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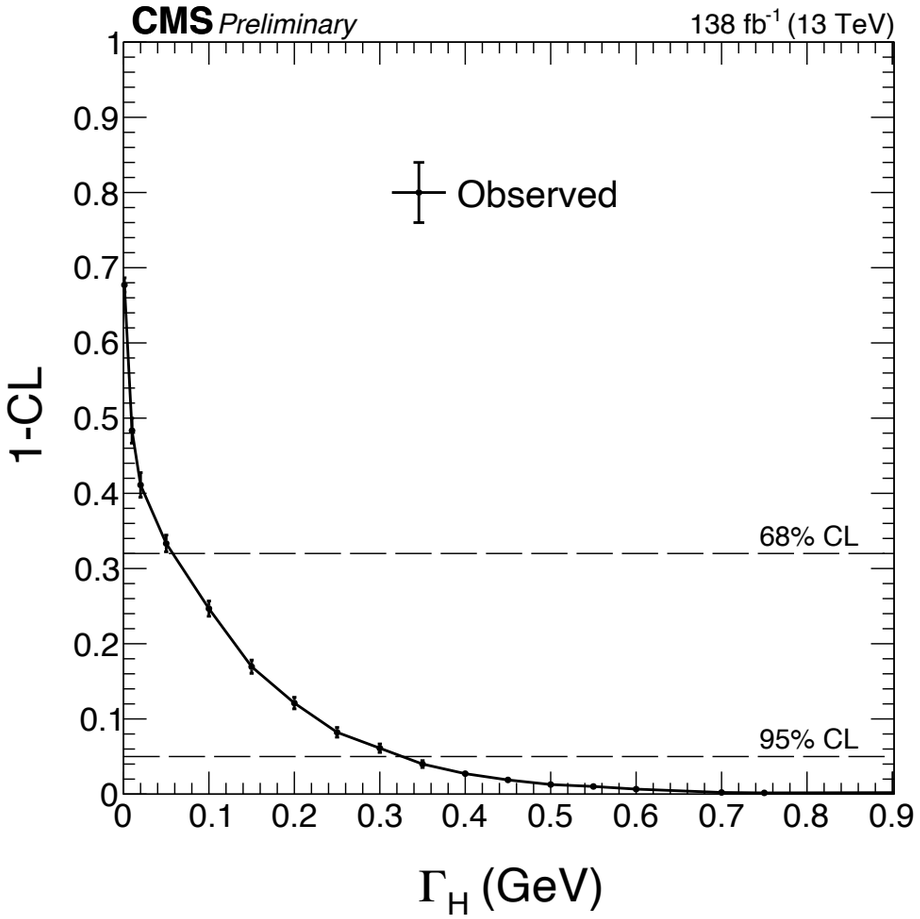

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$$\Gamma_H < 330\ MeV\ @\ 95\,\%\,C.L.$$

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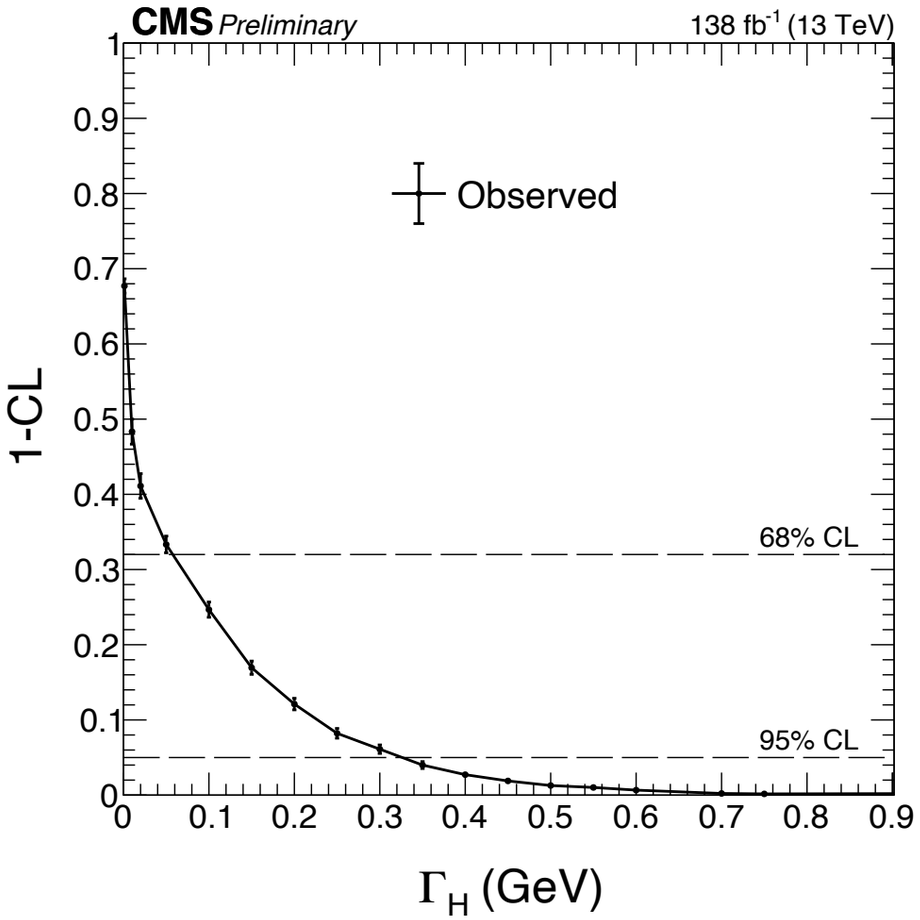

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—> measurement **limited by detector resolution**

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Higgs boson width

Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

*R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

Higgs boson width

Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.
Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production

- 3 exclusive categories
- Profit of several kinematic discriminant (sig vs bkg and also for interference)

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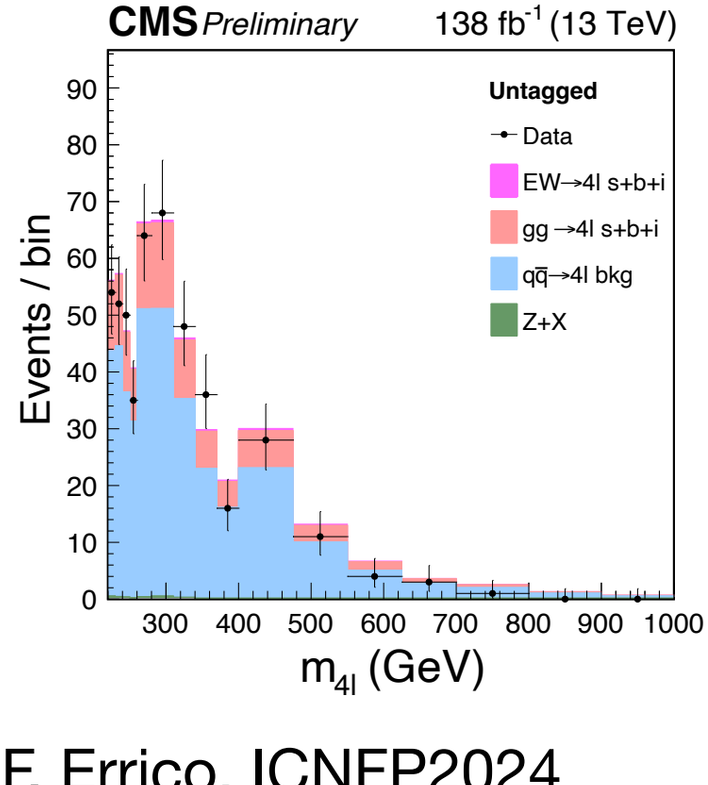

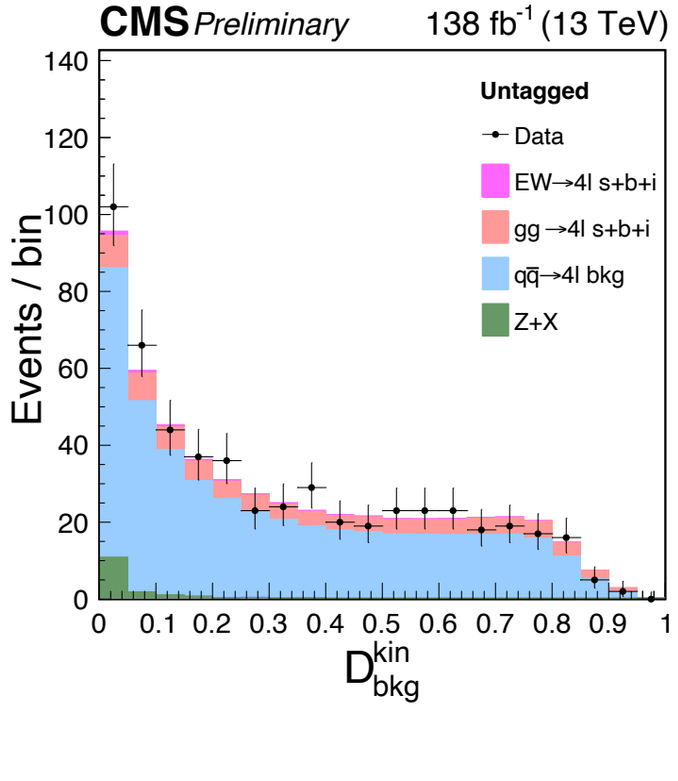

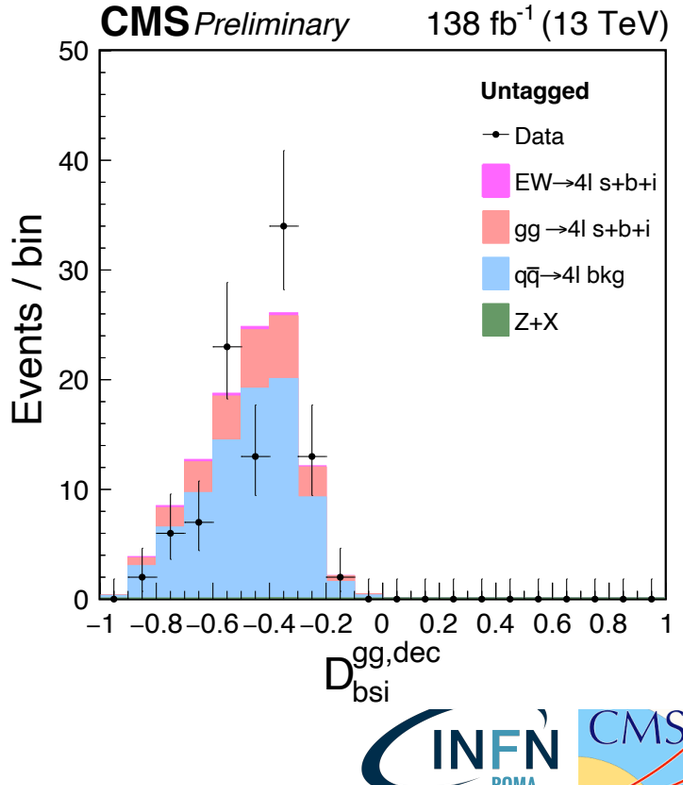

F. Errico, ICNFP2024

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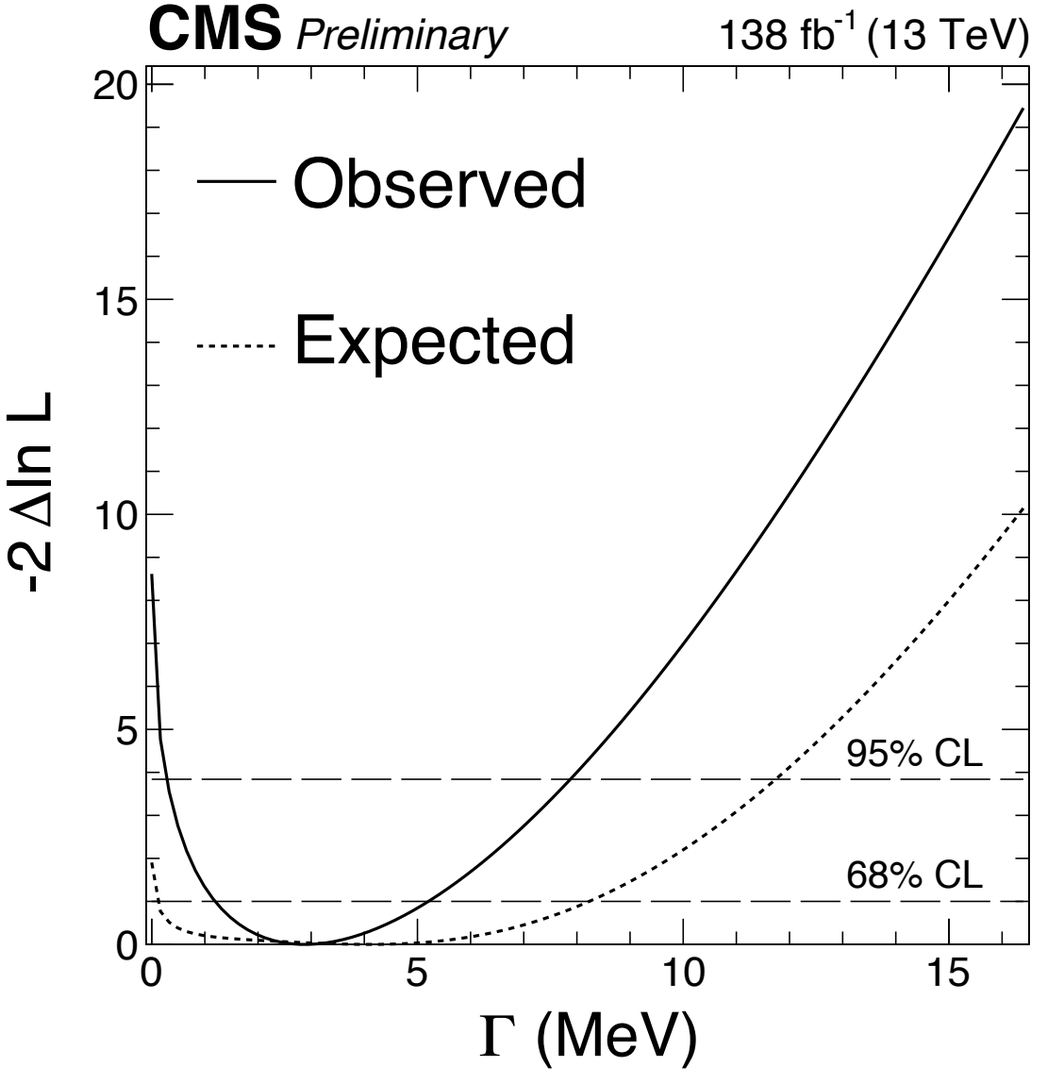

$$\Gamma_H = 2.9^{+2.3}_{-1.7}\ MeV\ @68\,\%\,C.L.$$

All signal strength constrained to 1

Higgs boson width

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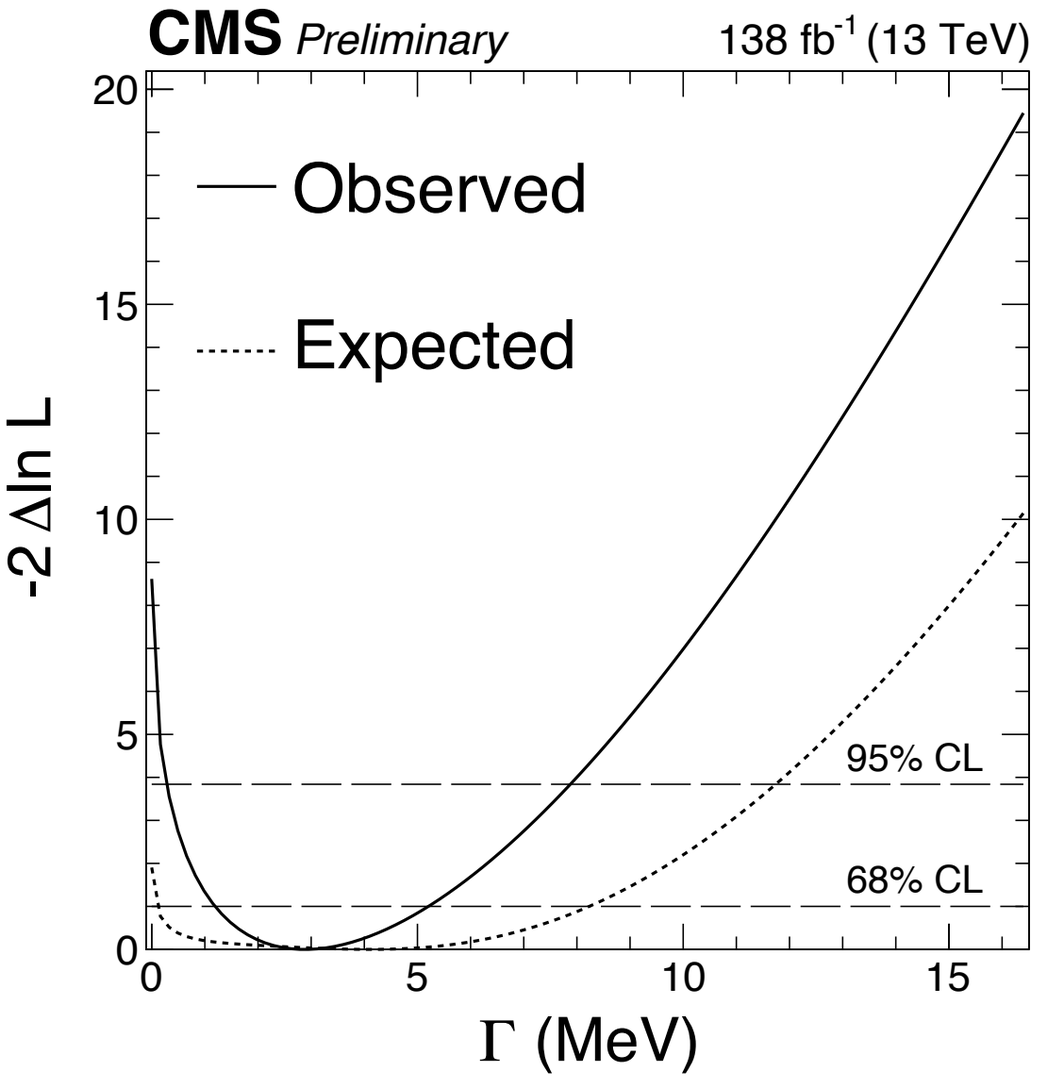

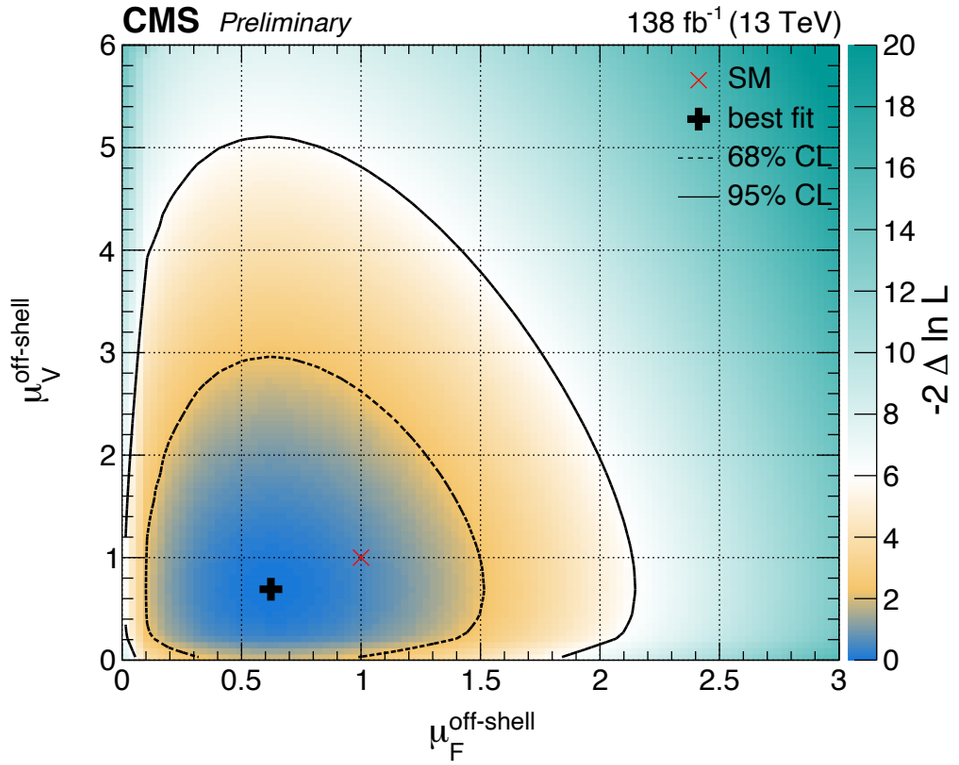

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Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.64^{+0.50}_{-0.37}$ [0.06, 1.69]	$1.00^{+0.99}_{-0.97}$ [0.00, 2.80]
$\mu_{\text{F}}^{\text{off-shell}}$	$0.62^{+0.57}_{-0.41}$ [0.03, 1.81]	$1.00^{+1.05}_{-1.00}$ [0.00, 2.93]
$\mu_{\text{V}}^{\text{off-shell}}$	$0.69^{+1.32}_{-0.63}$ [0.00, 3.91]	$1.00^{+3.34}_{-1.00}$ [0.00, 7.65]

Conclusion

Higgs boson properties(mass/width), measured by the CMS collaboration have been presented.

The Higgs boson mass, free parameter of the SM, is measured with a precision of the order of 0.1% (@68% CL).

The best width measurement is extracted comparing on-shell with off-shell decay rates.

More on the way…

Thanks for your attention

Backup

Higgs boson mass: H→γγ

Latest result uses **2016 data + Run1**

- **Critical component** → energy calibration of the response of the detector to photons. Correction are derived using a multivariate regression technique

- **Dedicated method developed** → deals with residual differences between data and MC, after applying corrections:
  - Multistep method: uses Z→ee events (the electron showers are reconstructed as photons):
    - ✤ step 1: correction of the long-term drifts in the energy scale in data
    - ✤ step 2: correction of energy resolution in the simulation and the scale correction in data, simultaneously
    - ✤ step 3: correction for any nonlinear response of the crystals with energy

Higgs boson width

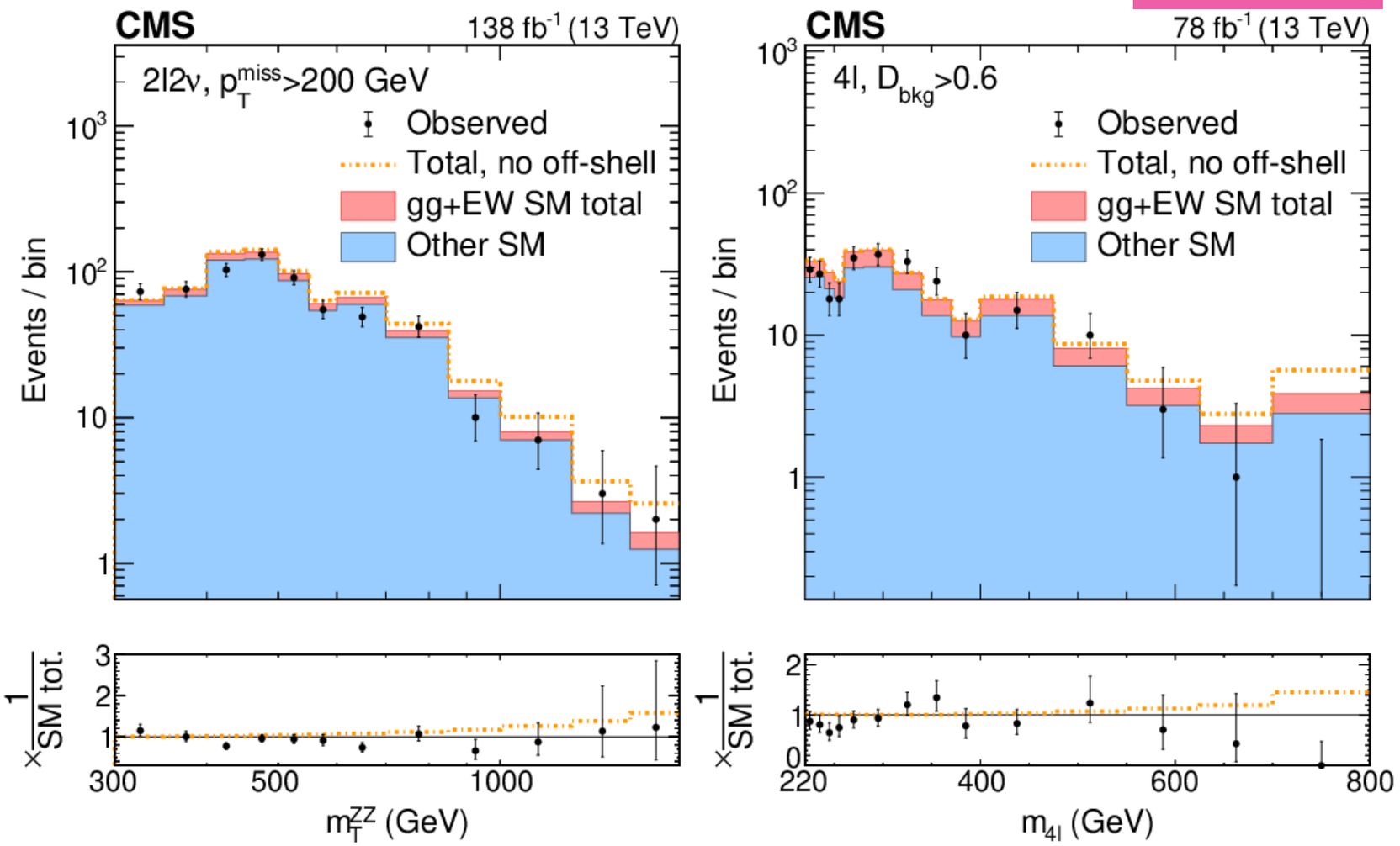
Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}$$

2016+2017 only



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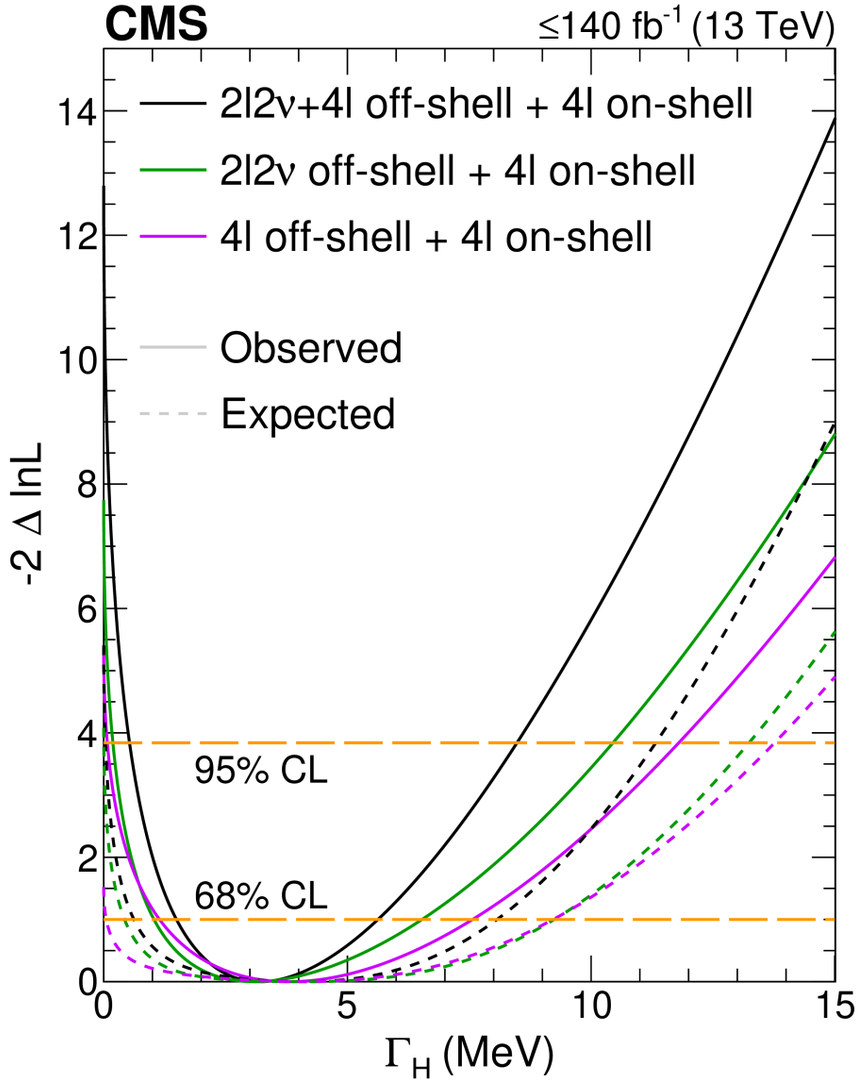
Higgs boson width

Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production, in different decay channels



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$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ MeV\ @68\,\%\,C.L.$$

F. Errico, ICNFP2024

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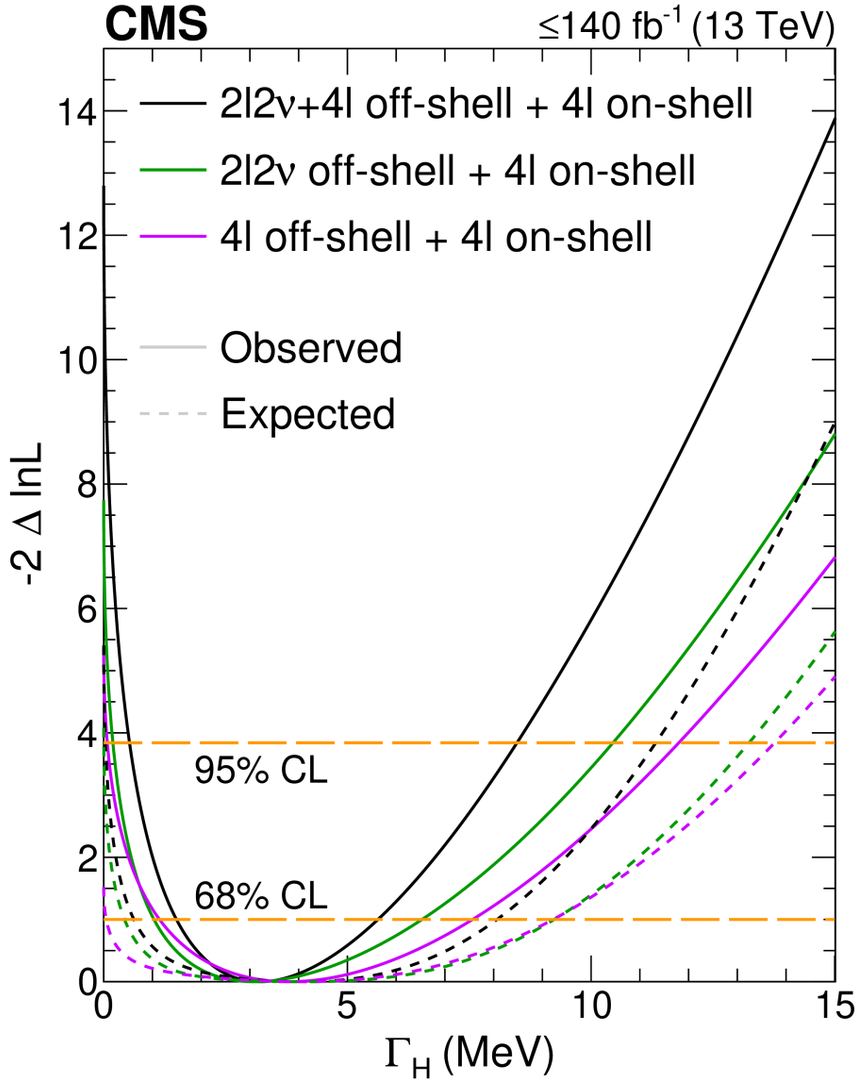

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No off-shell scenario ($\mu^{\text{off-shell}} = 0$ or $\Gamma_H = 0$) is excluded at a p-value of 0.0003 (3.6 standard deviations)

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F. Errico, ICNFP2024

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- 3 exclusive categories
- Profit of several kinematic discriminant (sig vs bkg and also for interference)

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$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \frac{\mu_j \Gamma_{\mathrm{H}}}{\Gamma_0}\,\mathcal{P}^{\mathrm{sig}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \sqrt{\frac{\mu_j \Gamma_{\mathrm{H}}}{\Gamma_0}}\,\mathcal{P}^{\mathrm{int}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mu_j\,\mathcal{P}^{\mathrm{cross}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mathcal{P}^{\mathrm{bkg}}_{jk}(\vec{x};\vec{\xi}_{jk}),$$

Higgs boson width

Difficulties in directly measuring the width (4.07 MeV*) due to detector resolution.

Measured in the **H→ZZ** channel, full Run 2 data, comparing on-shell and off-shell production

– The VBF-2jet category requires exactly four leptons. In addition, there must be either two or three jets of which at most one is b-tagged, or at least four jets and no b-tagged jets. Finally, $\mathcal{D}_{2\text{jet}}^{\text{VBF}} > 0.5$ for the VBF production is required.

– The VH-hadronic category requires exactly four leptons. In addition, there must be either two or three jets, or at least four jets and no b-tagged jets. Finally, $\max\left(\mathcal{D}_{2\text{jet}}^{\text{WH}}, \mathcal{D}_{2\text{jet}}^{\text{ZH}}\right) > 0.5$ for the VH production is required.

– The Untagged category consists of the remaining events.

$$\mathcal{D}_{\text{alt}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})}{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega}) + \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\boldsymbol{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})\ \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}},$$

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