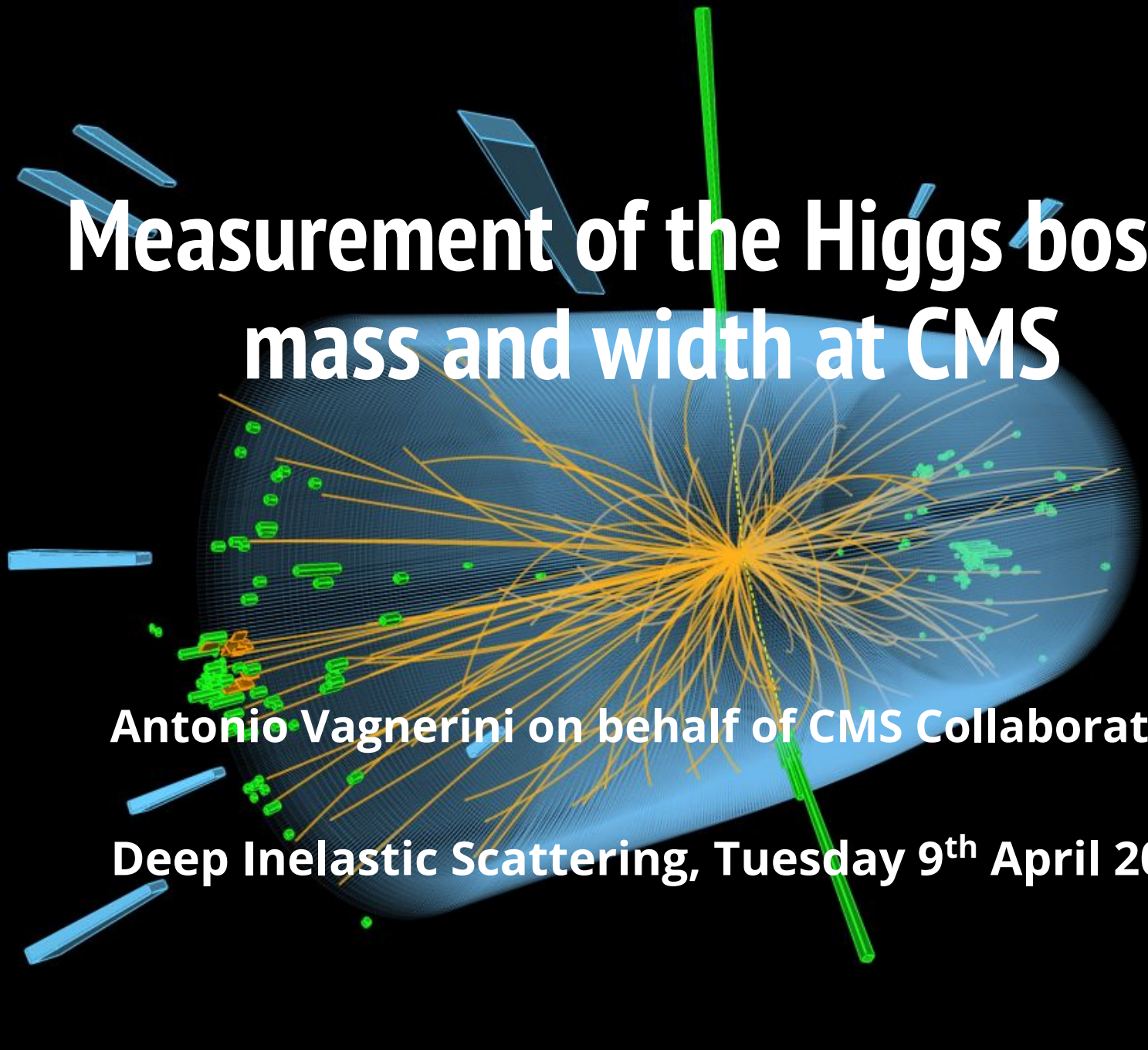
Measurement of the Higgs boson mass and width at CMS



Antonio Vagnerini on behalf of CMS Collaboration

Deep Inelastic Scattering, Tuesday 9th April 2024

Outline

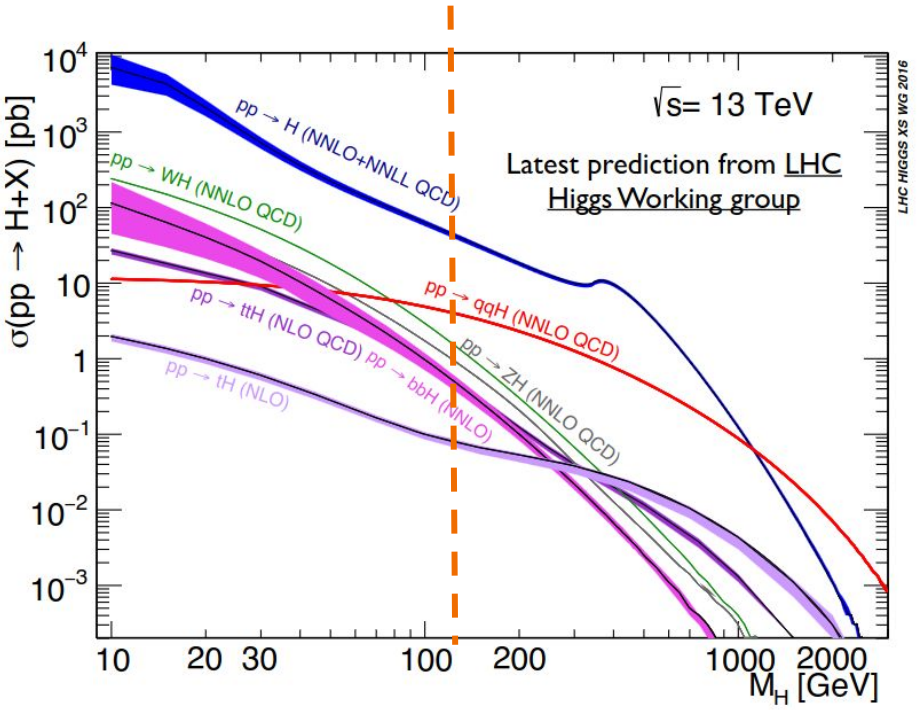
- Motivation for Higgs mass & width measurements
- Legacy Run 1 and projection for Run 2 results
- H->ZZ->4l mass measurement
- On-shell direct Higgs width constraints
- Off-shell indirect Higgs width measurements
- Summary & Outlook

Higgs boson mass measurement

- The Higgs boson mass m_H is a **free, fundamental parameter** in the SM
  - value must be determined **experimentally**

$$V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$$

- **Precision** mass measurement is a **crucial consistency** test of the SM
- Defines **phenomenology** of observed scalar in terms of **decays** and **production** modes
- Precision **cosmology**: determines **vacuum** stability
- Constrains potential **BSM** scenarios
  - e.g. **m >150GeV** would have rules out **MSSM**



Legacy Run 1 results and Run 2 expectation

- **Precision** measurement on $\mathbf{m_H}$ in the **"golden"** channels: **H->ZZ-4l** and **H->γγ**
  - better than **2 per-mille** in LHC Run 1 (CMS+ATLAS)

$$m_H = 125.09 \pm 0.21_{stat} \pm 0.11_{syst}\,GeV$$

Phys.Rev.Lett. **114 (2015) 191803**

- Parametric **uncertainty** on **BRs** and **prod**. **x-sec** lower than other uncertainties
- **Dominant** systematic uncertainties: **lepton** and **photon energy** scales
- Not a **limiting** factor of **global EW** fit

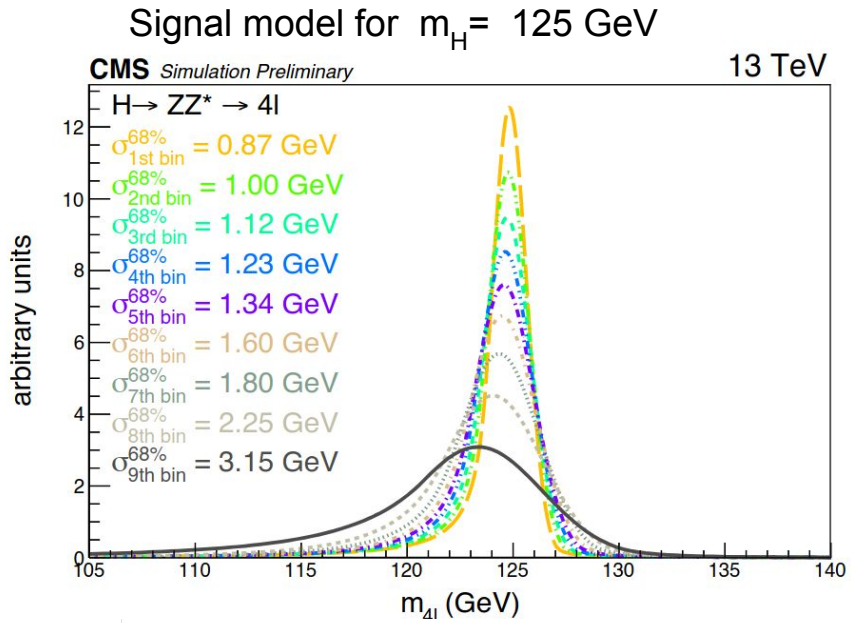
Expectation for **LHC Run 2 :**

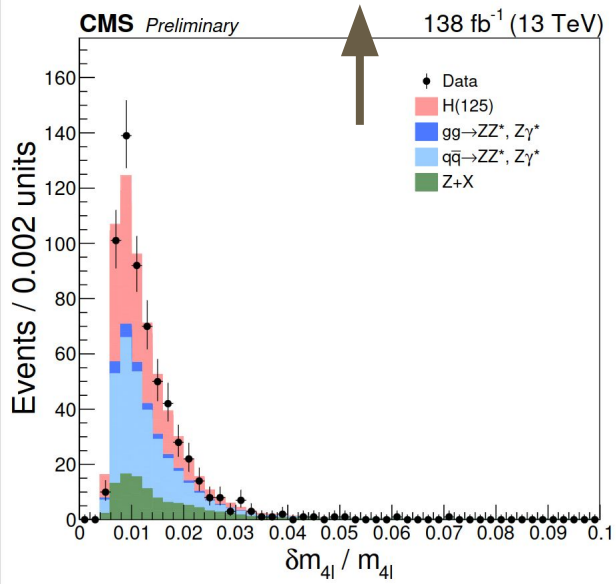
- **x5.6** increase in **luminosity**
- **x2.4** increase in **Higgs signal cross-section**
- **x2** increase in continuum **background**

Mass measurement with H->4l: Strategy

Several **improvements** in **strategy** wrt analysis with CMS 2016 data

- **Beamspot constraint** to adjust **μ momentum**:
  - all **4 lepton tracks** must come from common **vertex** compatible with **BS**
  - improvement in res. $\boldsymbol{\sigma_{m,4l}/m_{4l}}$ by 3-8%
- Per-event **uncertainty** $\boldsymbol{\delta m_{4l}}$ from **per-lepton** momentum uncertainty:
  - **μ**: track-fit covariance **matrix**
  - **e**: ECAL **energy** deposit and **track** $\boldsymbol{p_T}$
- Event **categorization**: 9 bins in $\boldsymbol{\delta m_{4\ell}/m_{4\ell}}$ equal signal
  - **isolate** events with better **mass** resolution to improve **lineshape**

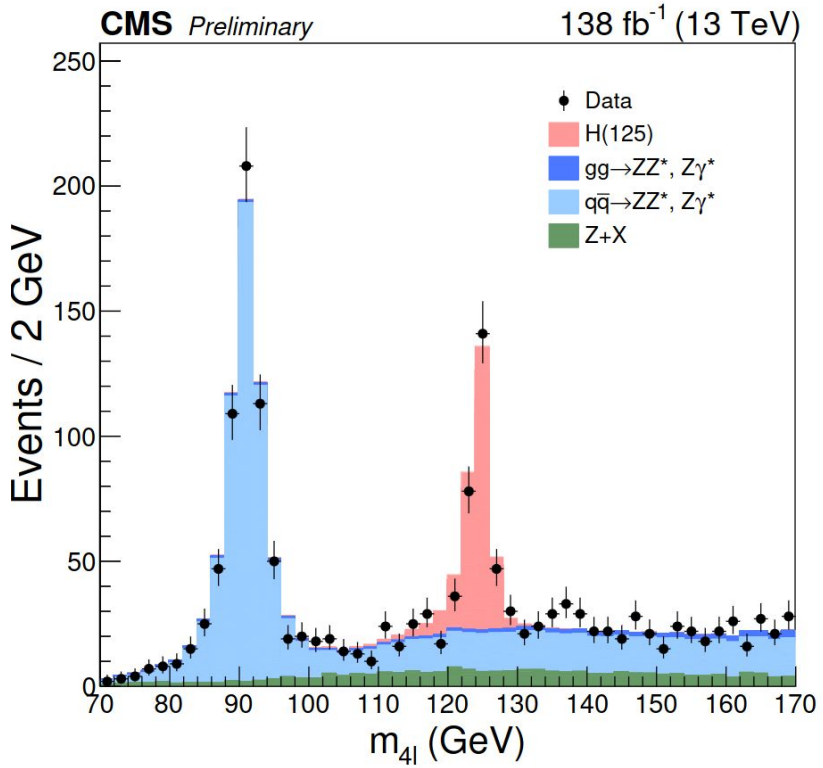




Mass measurement with H->4l: Discriminants

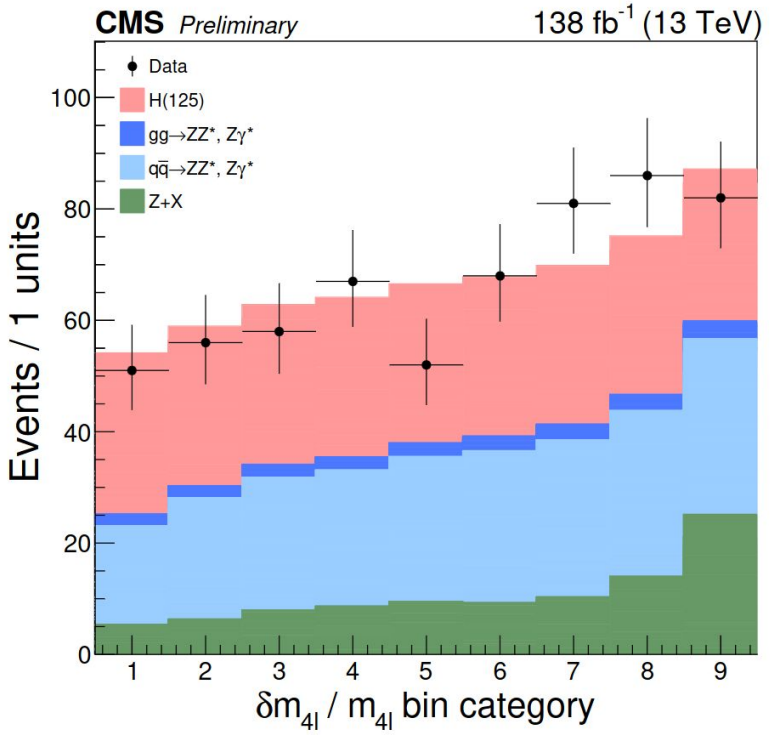
Two main observables $\mathbf{m_{4l}}$ and **MELA** kinematic **discriminant** for the likelihood **fit:**

9 $\delta m_{4\ell}/m_{4\ell}$ bin x 4 final state by flavour [4μ;2e2μ;2μ2e;4e] x data-taking period



$$\mathcal{D}_{\text{bkg}}^{\text{kin}} = \frac{\mathcal{P}_{H\to 4\ell}}{\mathcal{P}_{H\to 4\ell} + \mathcal{P}_{q\bar{q}\to 4\ell}}$$

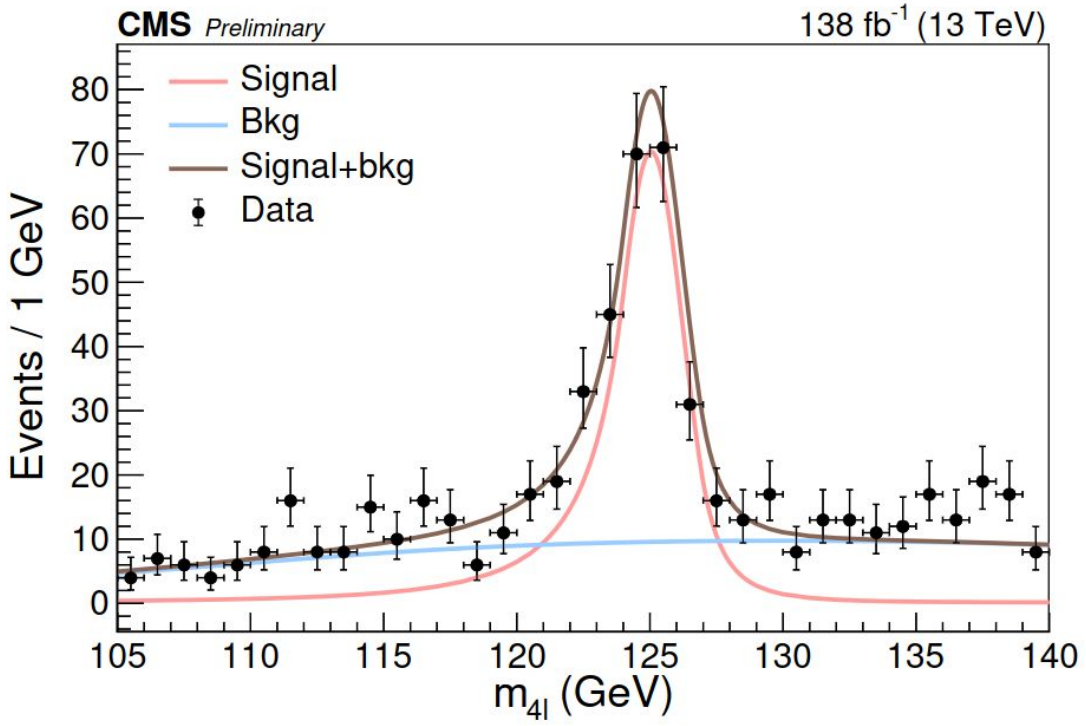
$$\Omega^{\text{dec}} \supseteq \{m_{12}, m_{34}, \theta_1, \theta_2, \Phi\}$$



P : «probability» from Matrix Elements (MELA) with kinematic Ω info as input

Mass measurement with H->4l: Final Fit

- Simultaneous **signal extraction fit** in all categories
  - total signal yield 258 events

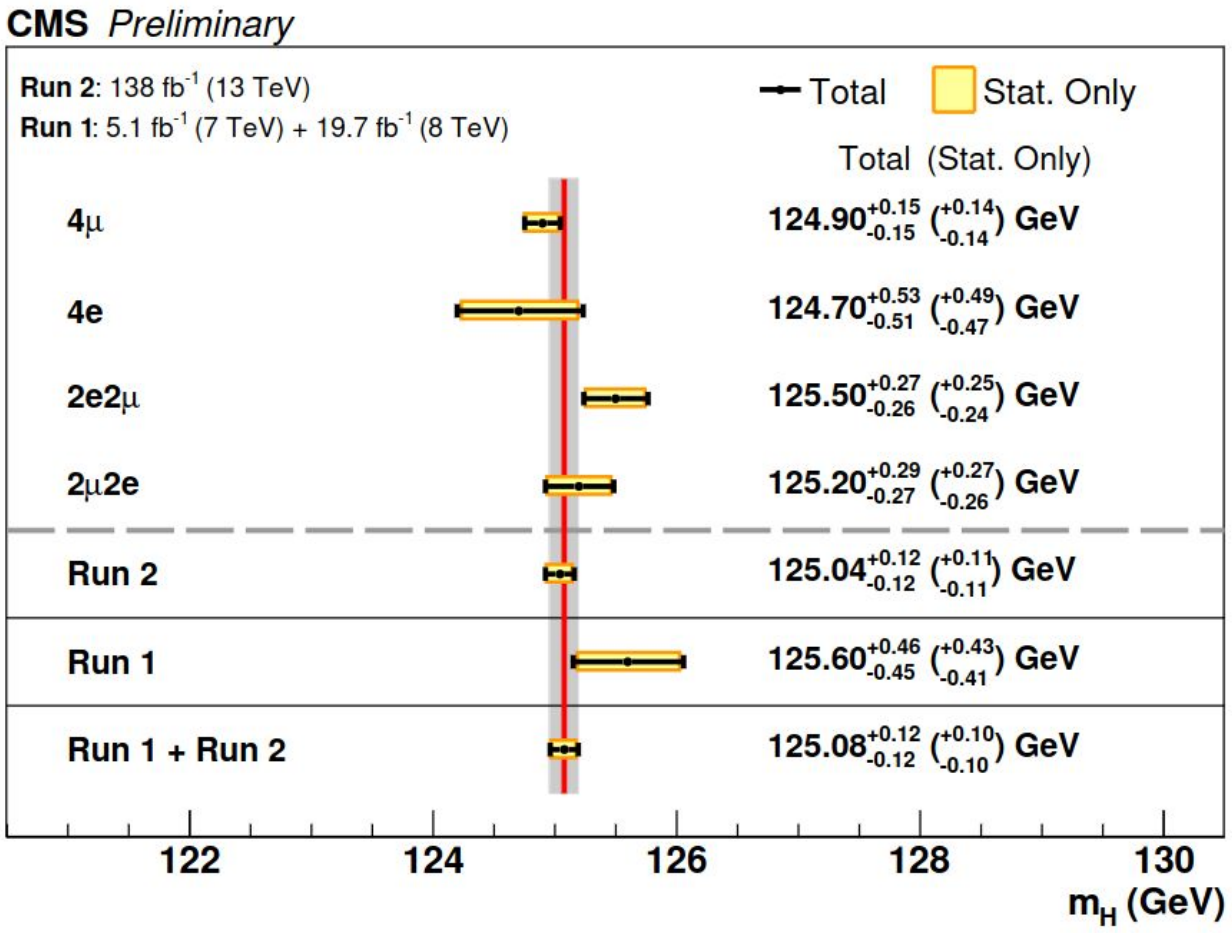


- **Improvements** wrt naive **1D model**
  - Z_1-mass +BS constraint: 15%
  - Per-event error modelling: 10%
  - $\mathscr{D}_{bkg}$ kinematic observable: 4%

- Similar methodology wrt ATLAS in FSR recovery and Z-mass constraints
  - variations in treatment in per-event lepton uncertainties
  - *70% lower stat. uncertainty* due to higher B-field in CMS

Mass measurement with H->4l: Combination

- Most **precise** individual **mass** measurement: $m_H = 125.04 \pm 0.11_{stat} \pm 0.05_{syst}$ GeV
  - uncertainties from **lepton** energy scale 30(40 MeV) for μ(e)



- **Run 2** precision improved by xfactor **4** wrt **Run 1**
- Most sensitive channel 4μ due to higher reconstruction efficiency for muon

Direct constraints on Higgs width: On-shell

- SM particles couple to Higgs via their **mass** and only **small** couplings for the observed **SM** “accessible” decay modes
  - **narrow width** predicted in SM: Γ_{SM} **= 4.1 MeV**
  - **BSM particle** could enhance **Γ** e.g. Higgs portal models

- $\Gamma_{SM} << \sigma_m/m$ experimental resolution for $m_{\gamma\gamma}$ or $m_{4\ell}$ **~ 𝒪(1-2 GeV)**

- **On-shell direct constraint** from reconstructed **lineshape: challenging** modelling of **resolution** uncert. and **interference** between signal & continuum bkg

CMS : Γ < 330 MeV @ 95% CL (~ 80×Γ_{SM}) ***CMS-PAS-HIG-21-019 (2023)***

- Lower limit **Γ> 3.5 MeV** from **Higgs lifetime** from **displaced 4l vertex** from **BS** at CMS

CMS: $c\tau_H$ < 57(56) μm ***Phys. Rev. D98, 3, 030001 (2018)***

Indirect Higgs width measurement: Theory

- Indirect **constraint** on Γ_H from the **off-shell/on-shell** event **yield ratio**
  - **on-shell** yield ~ $k^2_{g,on\text{-}shell} / \Gamma_H$
  - **off-shell** yield ~ $k^2_{g,off\text{-}shell}$

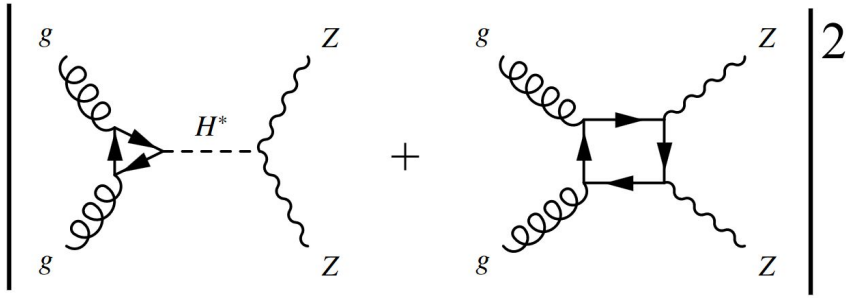
assuming $[g_i\, g_f]$ off-shell = $[g_i\, g_f]$ on-shell

$$\Gamma/\Gamma^{SM} = \frac{\mu_{off-shell}}{\mu_{on-shell}}$$

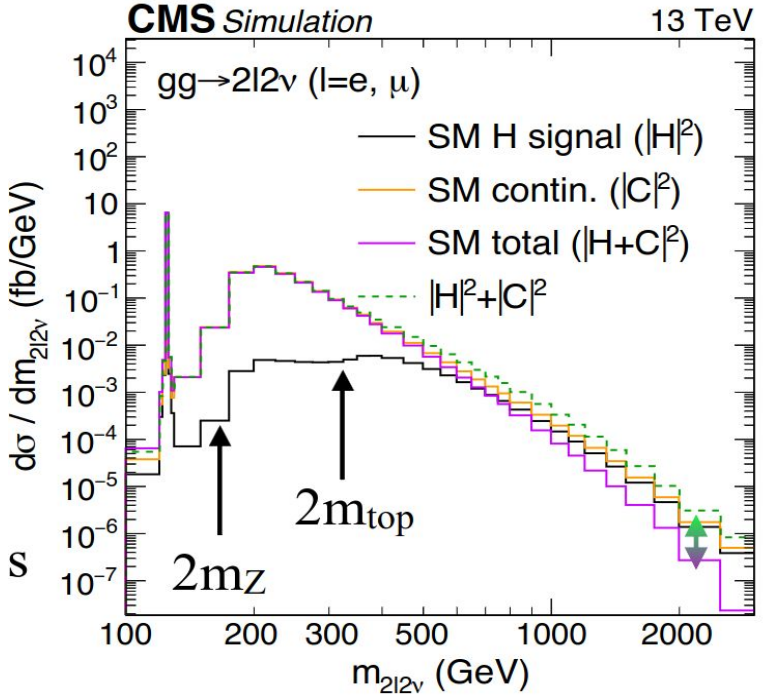
- First study m_{4l} **spectrum** & measure total **signal** strength in **off-shell** region

$$\frac{\sigma(pp \to H^* \to ZZ, m_{ZZ} > 2m_Z)}{\sigma(pp \to H^{(*)} \to ZZ)} \sim 8\%$$

- Large interference with continuum bkg (**gg→ZZ**)



In SM, ***deficit*** of events wrt bkg-only expectation



Indirect Higgs width measurement: Strategy

- State-of-the-art **estimate** of main non-interfering bkg (**qq → ZZ)**
- **Excellent modelling** of signal and **interfering** background **gg → ZZ**

$$N_{gg\to(H^*)\to VV} = \mu_{\text{off-shell}} N_{gg\to H^*\to VV} + \sqrt{\mu_{\text{off-shell}}} N_{\text{int}} + N_{gg\to VV}$$

- **Include EWK** production signal strength modifiers $\mu_{F,\text{off-shell}}$**(ggF)** and $\mu_{V,\text{off-shell}}$ **(EW)** using 3 **categories**: VBF-tagged, VH-tagged and ggF (untagged)

- Discriminant $\mathcal{D}^{\text{kin}} = \mathscr{P}_{\text{target}} / (\mathscr{P}_{\text{target}} + \mathscr{P}_{\text{ggF+2jets}})$ for either VBF or VH-category

- In last step, **combine off-shell** with **on-shell** measurements to obtain Γ_H

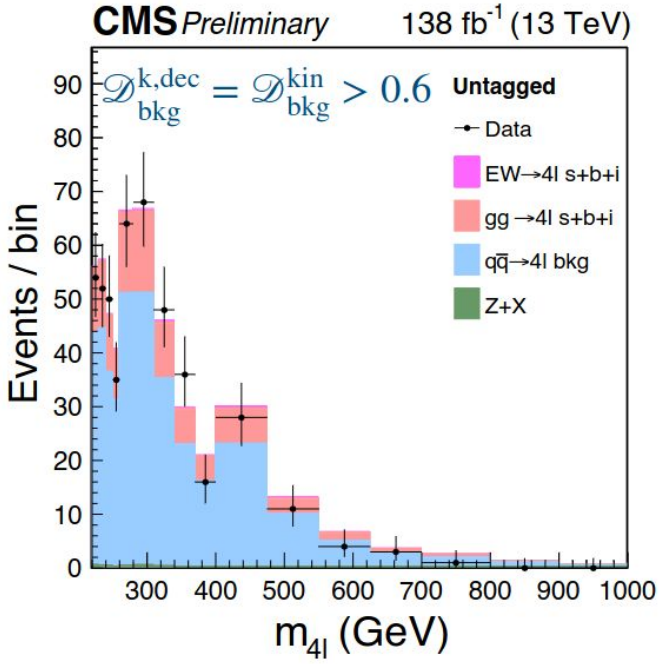
Indirect Higgs width measurement: Final Fit

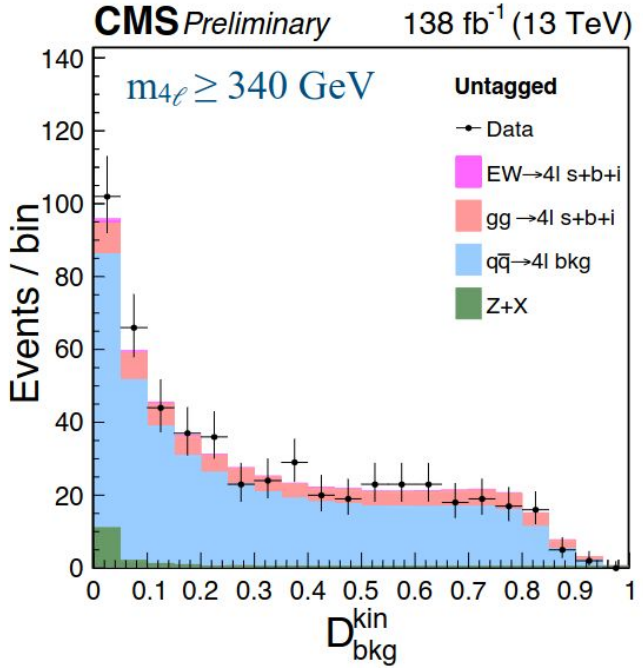
- **Three-dimensional** categorisation for **likelihood fit** with 3 **observables**:

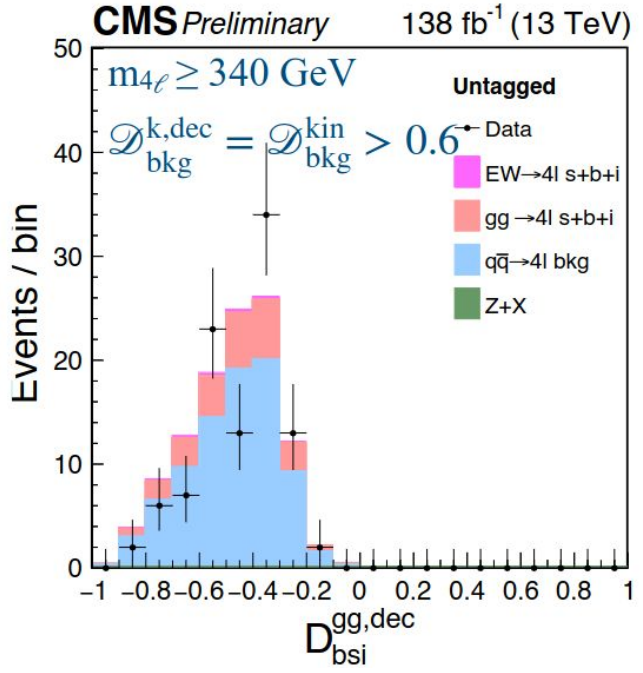
  $m_{4\ell}$(>220 GeV) ; $\mathfrak{D}^{kin}$ bkg (signal vs bkg) ; $\mathfrak{D}^{kin}$ bsi (interference vs pure bkg or signal)

$$\mathscr{D}_{bsi}^{k,dec} = \frac{\mathscr{P}_{int}}{2\sqrt{\mathscr{P}_{i\to H^*+X\to ZZ+X} \times \mathscr{P}_{i\to ZZ+X}}} \quad \in[-1,1]$$

- **Representative** plots for the **ggF** (untagged) category



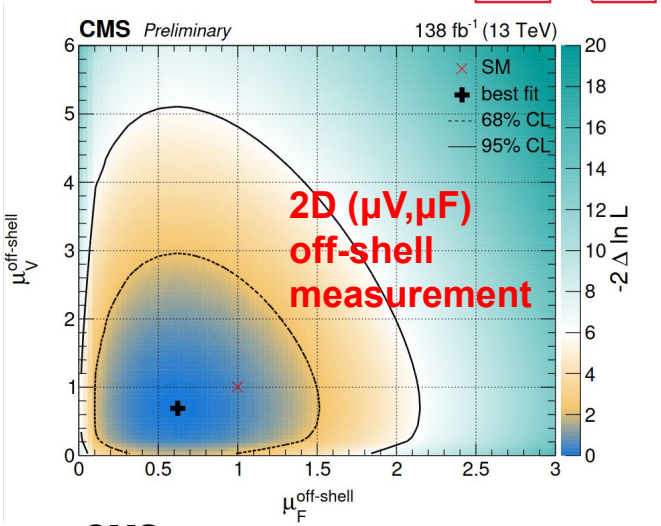




Higgs width measurement: Result

- Higgs **off-shell** width measurement **statistically limited**
  - main uncertainty from bkg modelling qq →(Z/γ*)(Z/γ*) → 4ℓ

$$\mu_{\text{off-shell}} = 0.64^{+0.50}_{-0.37}, < 1.69 \,@\, 95\,\%\ \text{CL}\ (\text{expected} : 1^{+0.99}_{-0.97})$$

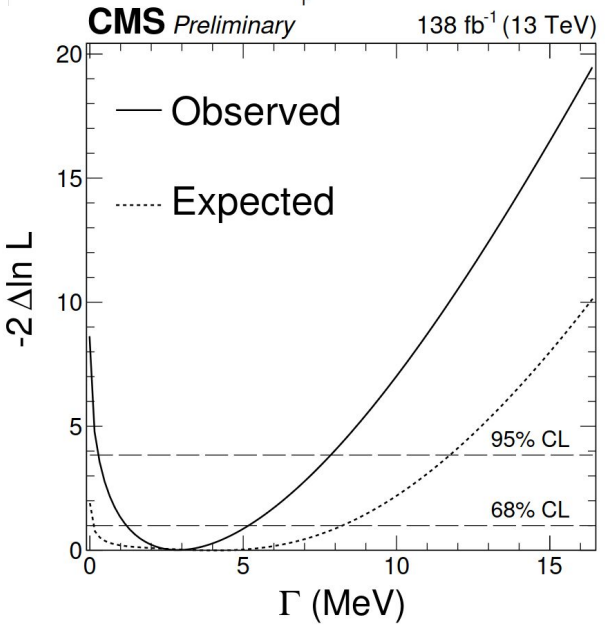


- Combination with 2l2ν analysis + on-shell assuming identical couplings **[g_i g_f] off-shell = [g_i g_f] on-shell**

NEW!

$$\Gamma = 2.9^{+1.9}_{-1.4}\ \text{MeV}, \in [0.6,7.0]\ \text{MeV}\ @\ 95\,\%\ \text{CL}$$

$$(\text{Expected} : \Gamma = 4.1 \pm 3.5\ \text{MeV}, \in [0.1,10.5]\ \text{MeV}\ @\ 95\,\%\ \text{CL})$$



Conclusion

- **CMS collaboration** made huge **progress** in reducing **lepton/photon energy scale**-related **systematic** uncertainties **during Run 2**

- This reflects on **excellent precision** in Higgs **mass** measurement of the **$\mathcal{O}(10^{-4})$** , which is dominated by the H → 4μ, 2e2μ channels

- **Higgs** boson **width** determination is **challenging** at a **hadron** collider
  - with reasonable **theory** assumptions it can be constrained to < $3\Gamma_{SM}$ expectation

- By performing a naive uncertainty **extrapolation** to the **HL-LHC** phase
  - **precision** of the order **$\mathcal{O}$(20MeV)** for m_H and of **$\mathcal{O}$(20%)** for Γ_H could be achieved by a CMS-like experiment 1902.00134