Measurements of the Higgs boson mass and width at CMS

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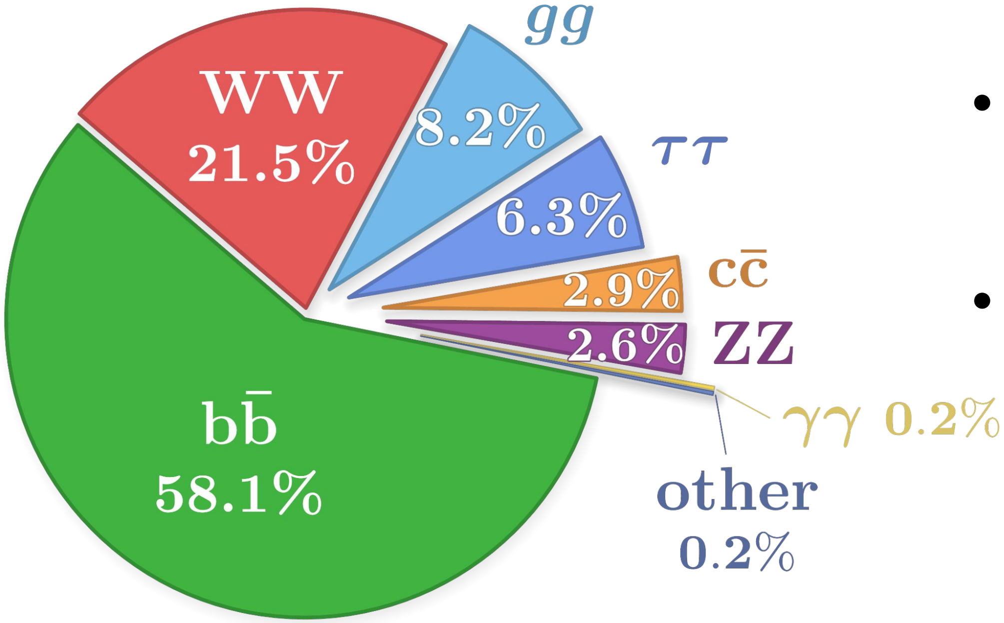


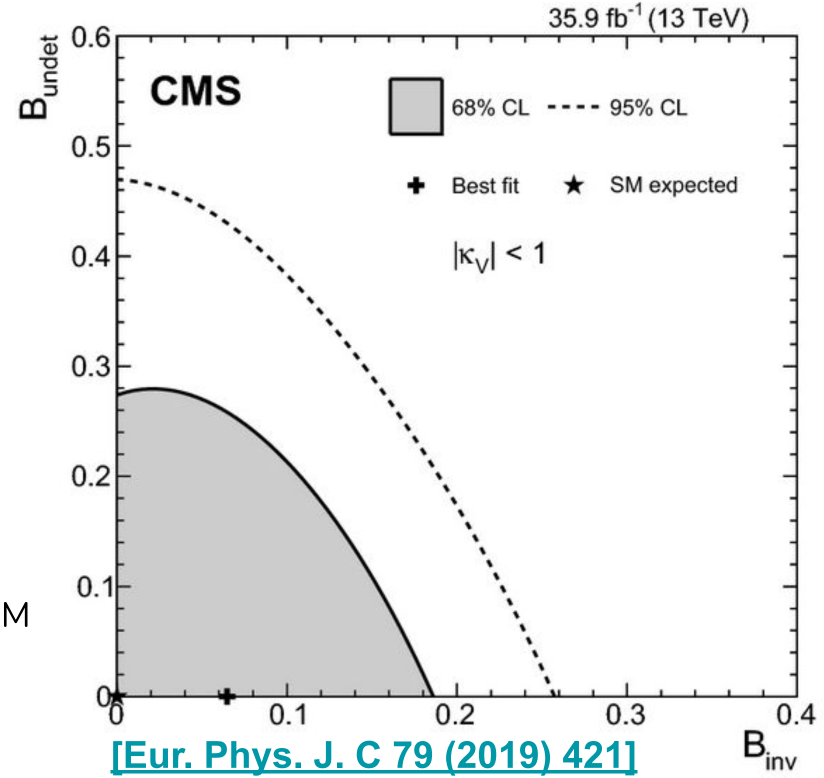
- Higgs boson mass (m_H) not predicted by the theory
- **All properties** of Higgs boson (couplings, branching ratios...) **depend on m_H**
  →Motivates precision measurements of m_H
- Mass and width measurements are carried in high resolution channels
  - H→4ℓ
  - H→γγ

- **m_H (and m_t) determine behavior of electroweak vacuum**
  →Cosmological implications [1]

- **Possibility of Higgs decay to BSM particles from Γ_H measurement:**
  - $Br_{BSM} \lesssim 30\%$ [2]
  - Given the small Γ_H~ 4 MeV, even small couplings with BSM particles,~O(10^{-2}), yield Br(h→BSM)=10%

- Precise knowledge of m_H leads to overconstrained checks of SM self-consistency:

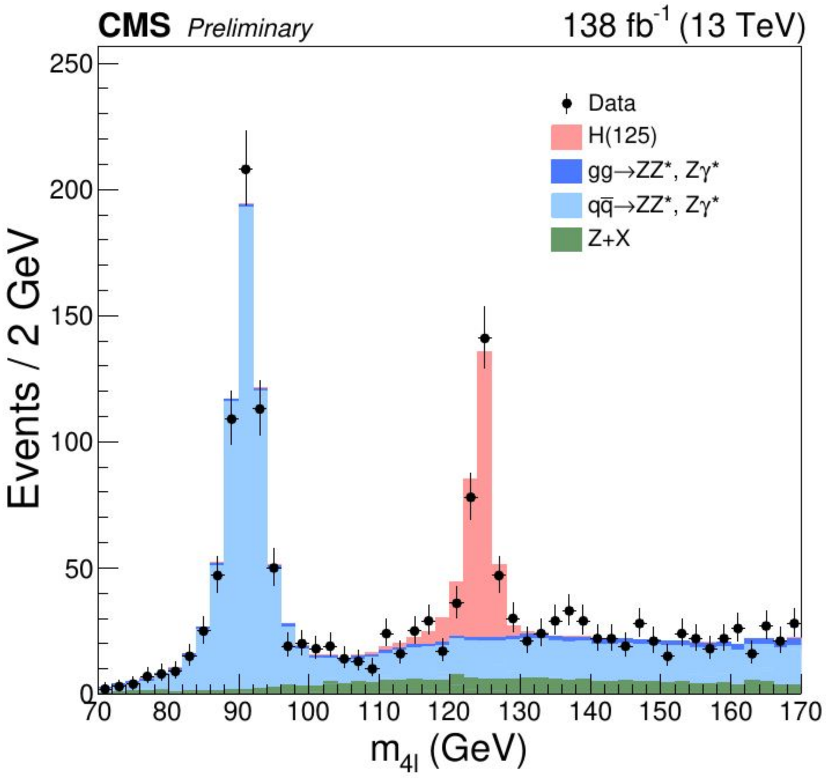
$$m_W = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W\sqrt{1 - f(m_t, \log(m_H))}}$$



[Eur. Phys. J. C 79 (2019) 421]

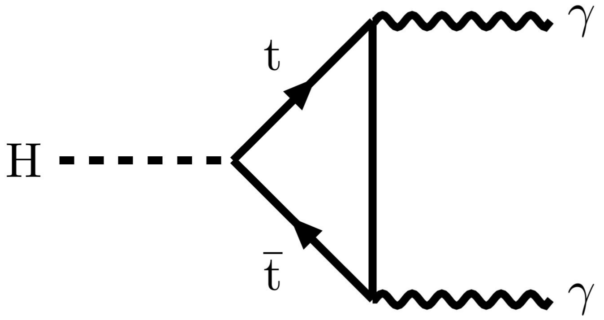
- Higgs decays to 4ℓ and γγ are best suited for mass measurements:
  - **Very clean final states, with good S/(S+B)**
- Properties of decay products can be known very precisely
- Natural width Γ_H predicted to be very small (~4 MeV) for m_H = 125 GeV
  - **Much below experimental resolution**

→Possible to measure Γ_H using off-shell decays



m_H in H→γγ: Phys. Lett. B, 805 (2020)

- **Small BR** (~0.23%) but **clean final state**
- Use **data collected in 2016** (36 fb^{-1})
- Previous CMS analysis [3]
- Measurement refined with **better detector calibration and understanding of systematics:**
  - Improved description of data-MC nonlinear discrepancies in energy scale
  - Developed a method to evaluate systematic due to radiation damage in ECAL
    → **Usable to reduce systematic uncertainty for the final full Run2 measurement**



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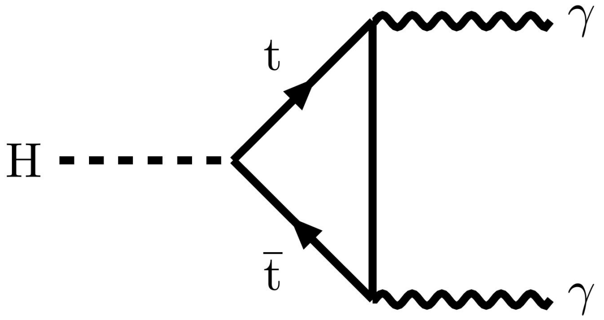


- **Strategy:**
  - Preselection kinematic cuts on γγ pair
  - **VBF BDT to separates VBF from ggH , Diphoton-BDT to select signal-like with high resolution diphoton pairs:** first separate events in 3 VBF categories, then in 4 ggH categories using diphoton-BDT
  - **Sig-bkg models:**
    - **Signal:** sum of up to 4 gaussians
    - **Background:** using sideband data with discrete profiling method

m_H in $H \to \gamma\gamma$: photon energy calibration

- **Precise calibration of ECAL response to photons is fundamental**

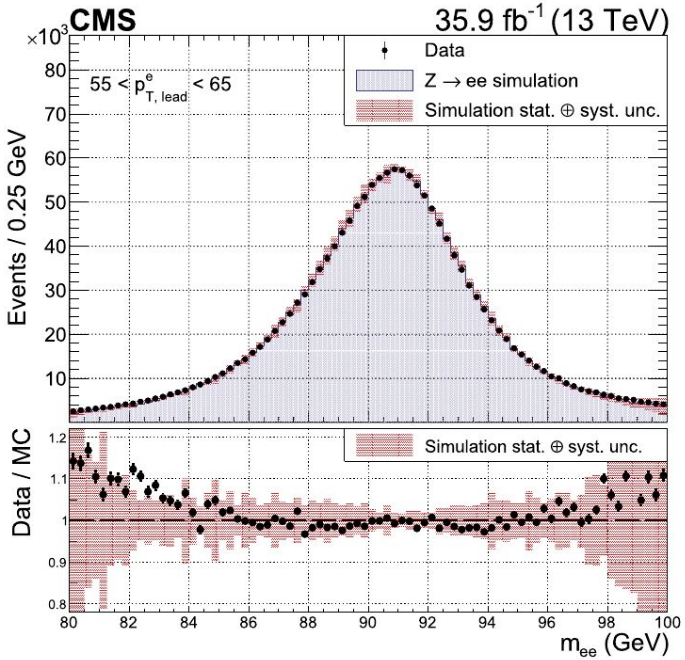
- **Done in steps:**

1. **Compute E_γ summing calibrated and corrected energies from ECAL deposits**

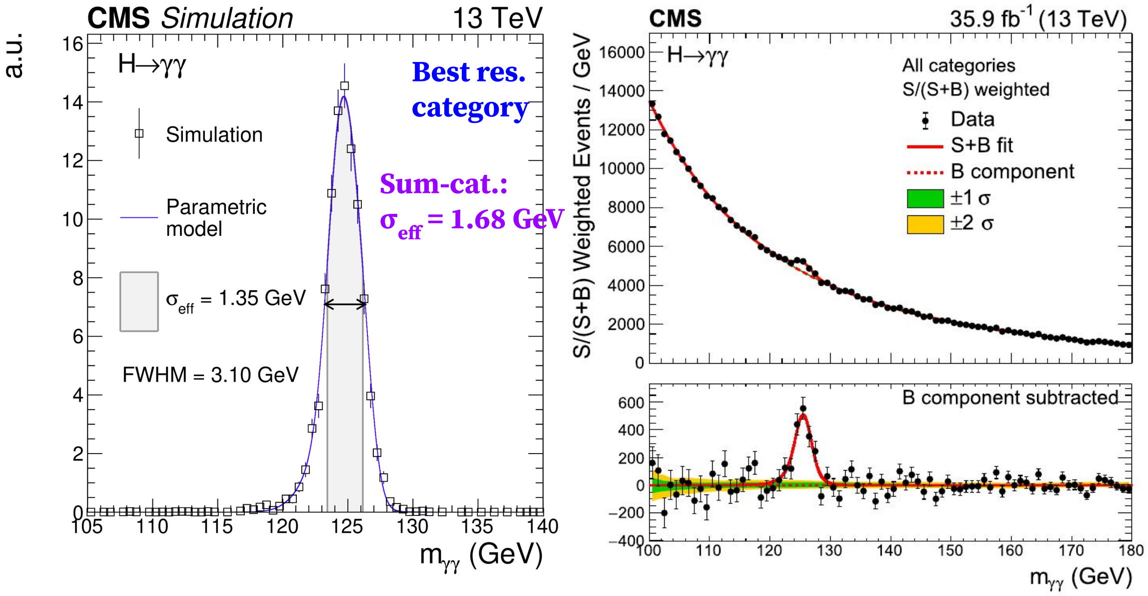
2. **Multivariate regression [4] applied on top of the energy** correcting for:
   →Incomplete containment of EM showers
   →Energy losses from conversions upstream of ECAL,
   →Pileup effects

3. **Correct for residual differences between data and MC in energy scale and resolution,** using Z→ee electrons reconstructed as photons:

   →Correct for long-term shifts of the energy scale (per LHC-fill)
   →Derive corrections for energy scale and resolution in bins of |η|, R9*
   →Derive corrections for energy scale in bins of |η| and p_T to account for residual non-linearities



* Low/high R9: converted/unconverted photon

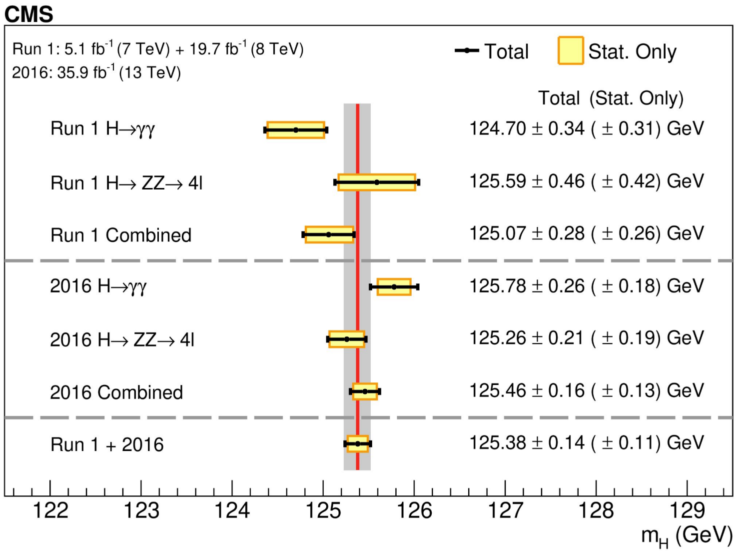


Binned maximum likelihood to all 7 analysis categories (2016 only):

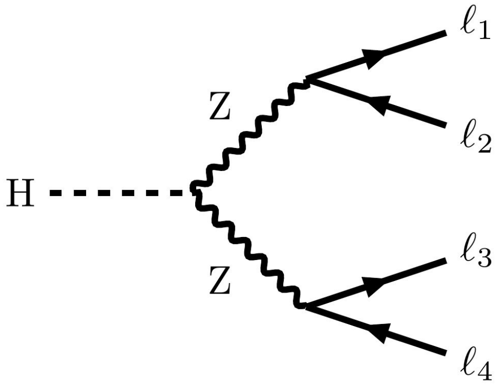
$$m_{\mathrm{H}} = 125.78 \pm 0.18(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})\ \mathrm{GeV}$$

→**Measurement precision at per-mille level**

combination with 2016 H→4ℓ and Run1



- **Very small BR** (1.24×10^{-4}) but **very clean final state**
- Use **data collected in Run2** ($138\ fb^{-1}$)
- Previous CMS analysis [5]
- Measurement of m_H refined through **better detector calibration, analysis strategy and understanding of systematics**



- **Measure** the Higgs boson natural width Γ_H **using on- and off-shell events**

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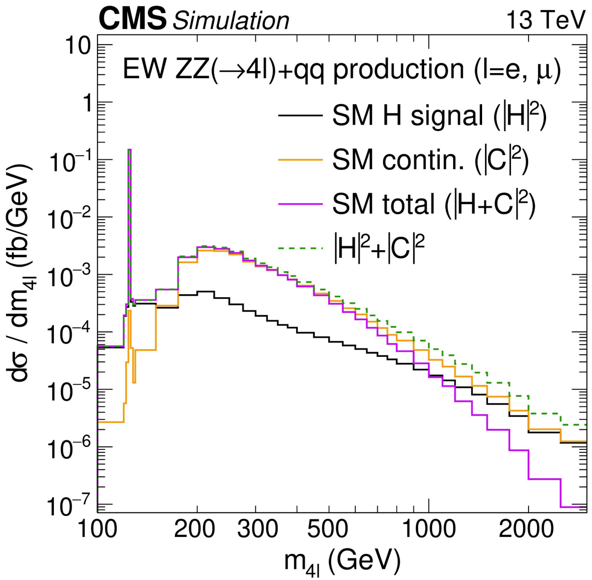
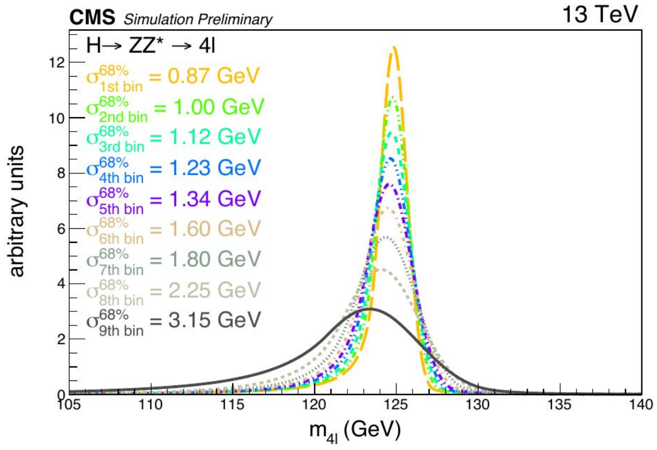
- **Measure** the Higgs boson natural width Γ_H **using off-shell events:** previous measurement by CMS [6]
  - Relying on **assumptions**
    - Knowledge of coupling ratios between on- and off-shell production
    - **ggH loop** production is **dominated by top and has no BSM** contributions
  - Off-shell region characterized by **sizeable interference between H boson signal and continuum background:** PDF taking into account for interference

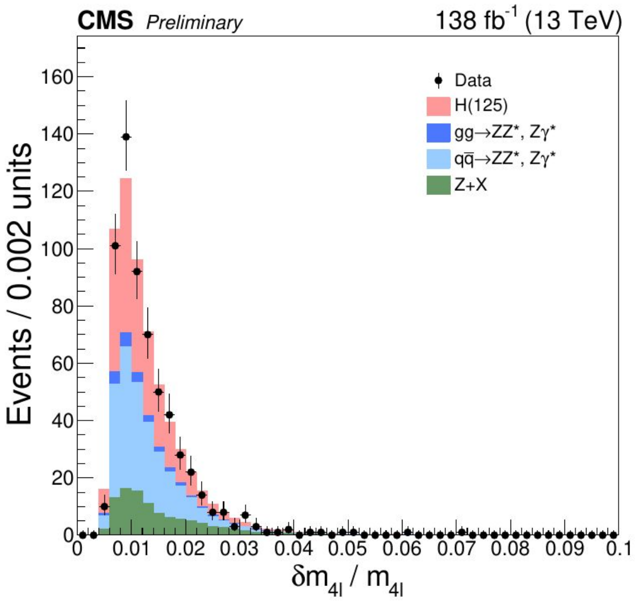


$$\frac{\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell}}{\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell}} \propto \Gamma_{\text{H}}$$

- **Vertex-beamspot** (VXBS) **constraint:** 4ℓ tracks constrained to common vertex compatible with beam spot: 3-8% mass resolution improvement

- **Constraint on intermediate on-shell Z with a kinematical-fit**: p_T of dilepton pair should give Z true lineshape

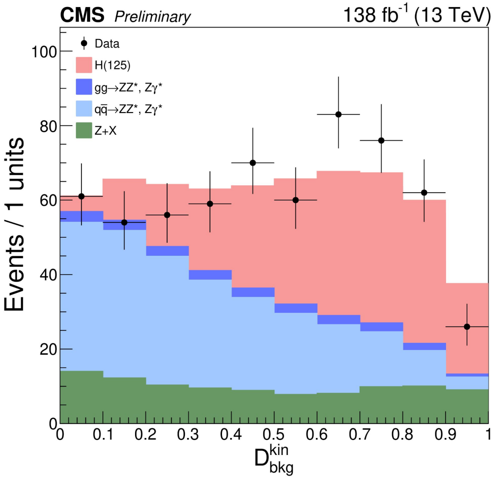




- Select 4 prompt isolated leptons and **split events in 9 categories based on mass uncertainty ($\delta m_{4\ell}/m_{4\ell}$):** isolate events with high mass resolution from the others (≈ 10% mass resolution improvement)

- **Sig.-bkg. models:**
  - **Signal:** DSCB + Landau (+ Breit-Wigner when measuring Γ_H)
  - **Background:**
    - Irreducible: from MC, Bernstein pol. degree 3
    - Reducible: from control region in data (fake-rate method), Landau

m_H and Γ_H in H→4ℓ: m_H results

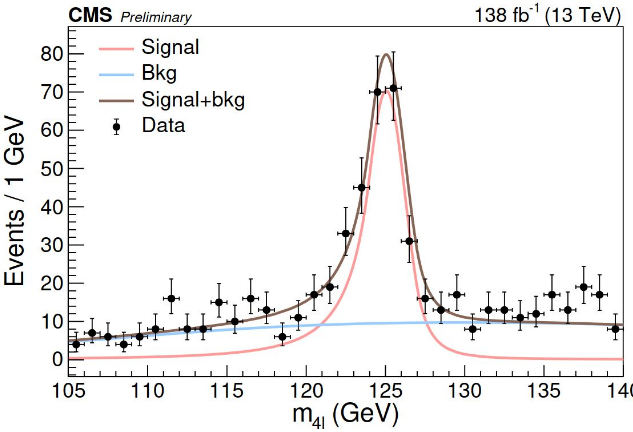


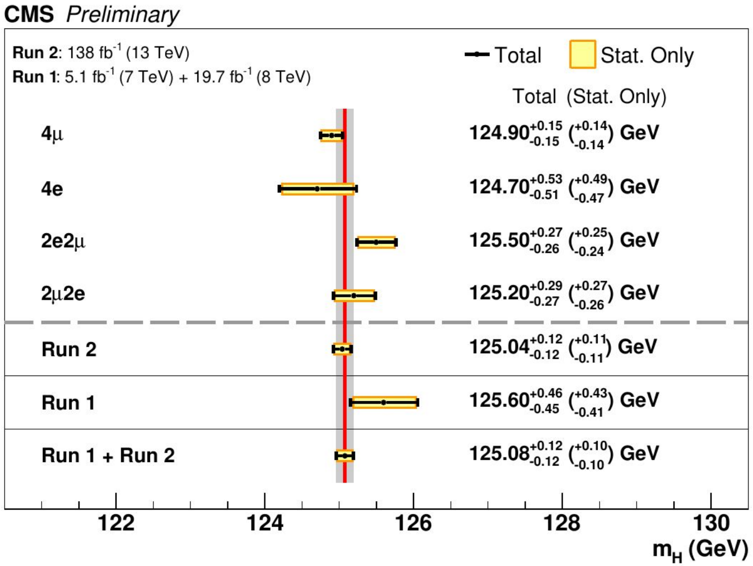
D^{kin}_{bkg} extracted using MELA [8] (Matrix Element Likelihood Analysis) approach exploiting 13 kinematical variables

- Maximum likelihood fit to m_{4l} and kinematic discriminant D^{kin}_{bkg} (template) combining all $\delta m_{4l}/m_{4l}$ categories:

$$m_{\mathrm{H}} = 125.04 \pm 0.11(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})\,\mathrm{GeV}$$

- Results are combined with Run1 data [7]
  →**Most precise single-channel measurement to date:**
  precision < per-mille level

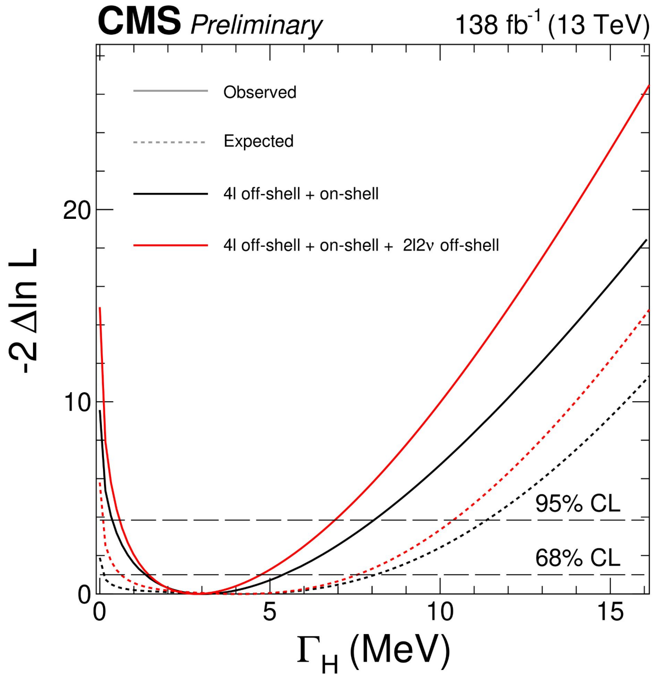


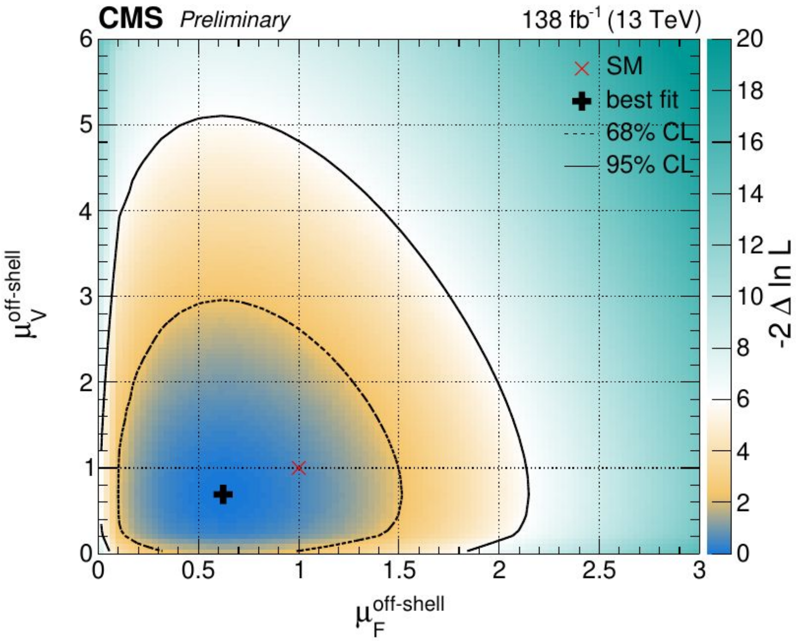


m_H and Γ_H in $H \rightarrow 4\ell$: Γ_H off-shell results

- **Strategy:**
  - Select region **$m_{4\ell}$ > 220 GeV**
  - **3 exclusive categories:** VBF tagged, VH tagged, untagged
  - **Fit 3 observables (templates)**: $m_{4\ell}$+2 kinematic discriminants
  - Model with 4 parameters of interest: m_H, Γ_H, μ_F, μ_V

- **Results:**
  - Extracted: $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV
  - On-shell: Γ_H < 60 MeV (68% CL)
  - Off-shell μ_F, μ_V in agreement with SM prediction





m_H in H→γγ: Dominant systematics

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

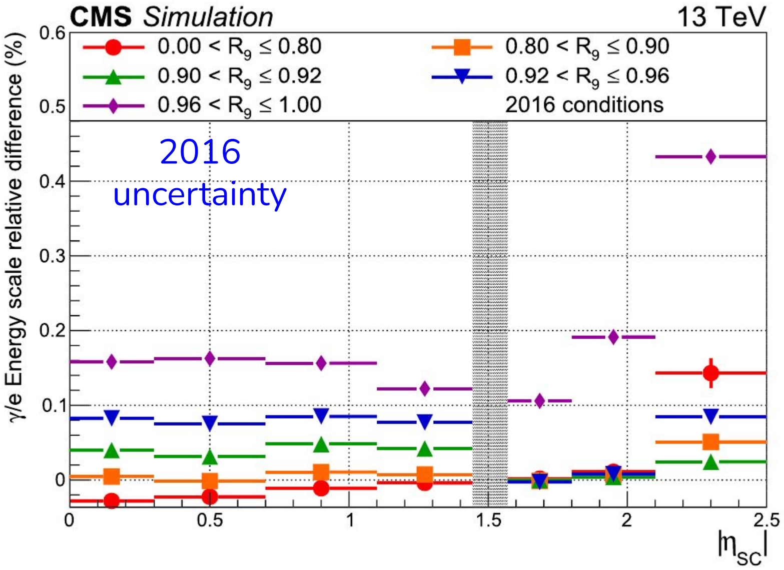
Dominant systematics:

→Residual energy scale

→**Non-uniformity of light collection**

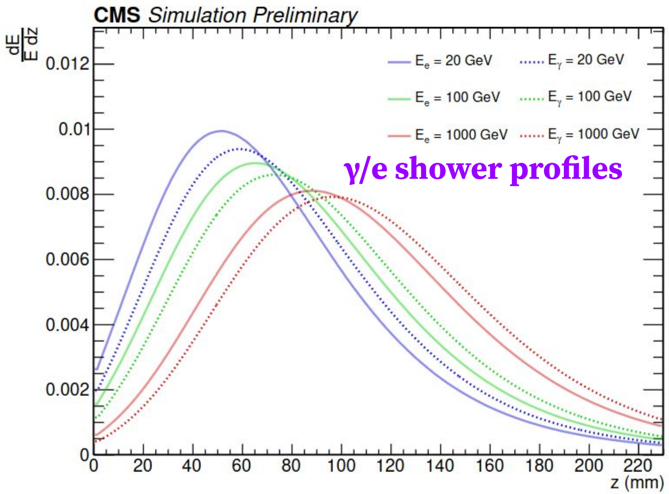
- **Non-uniformity of light collections** due to radiation damage:
  - Scale corrections derived in Z(ee) and applied to photons
  - Photons penetrate ≈ $1X_0$ deeper than electrons in crystals
  - **Radiation damage not simulated:**
    - Impact of γ/e shower profile difference cannot be corrected by the regression

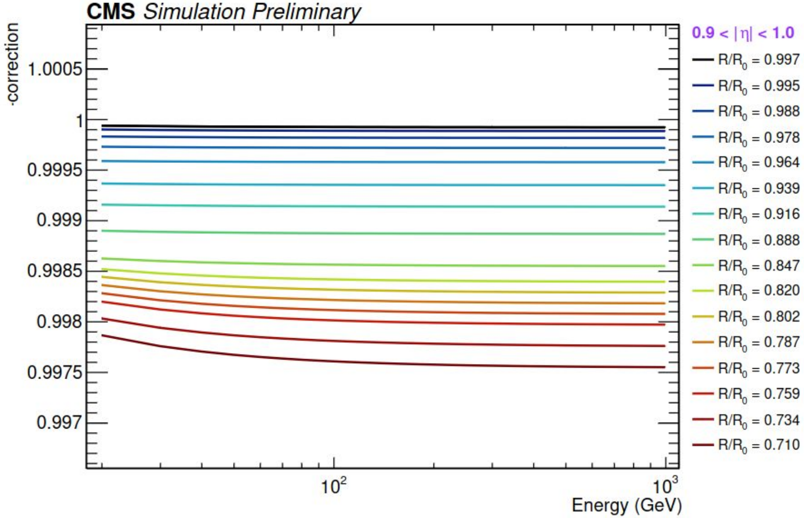
- Scale difference between electrons and photons computed → **difference assigned as systematic uncertainty**



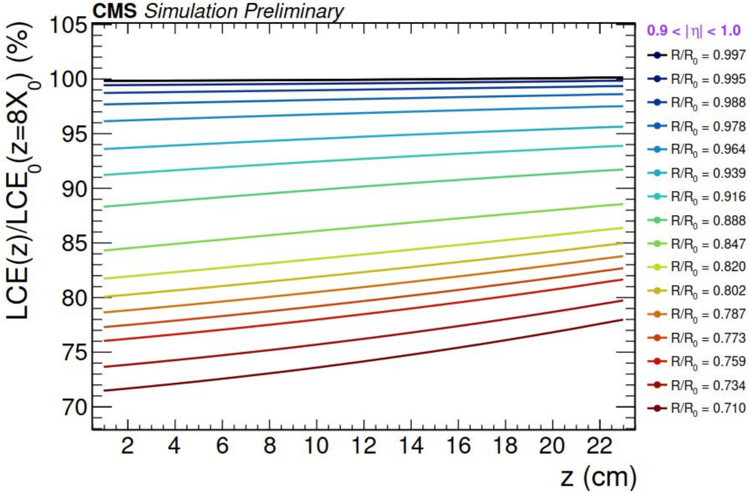
m_H in H→γγ: Non-uniformity of light collection

- Model developed to predict light collection efficiency (LCE) using FLUKA+LITRANI [CMS-DP-2024/045]
- **New approach to reduce uncertainty for full Run2 analysis,** as the radiation damage increase during Run2 and Run3
  - **Compute and apply a correction to photons in data:**
    - Assign an uncertainty to the correction
      →Smaller than 2016 analysis uncertainty





corrections and LCEs for different transparency scenarios (R/R_0)



Conclusions

- The CMS Collaboration measured the Higgs boson mass and natural width using the standard high-mass-resolution channels: γγ and 4ℓ

- **Per-mille level of precision on m_H in H→γγ** decay channel, using 2016 data

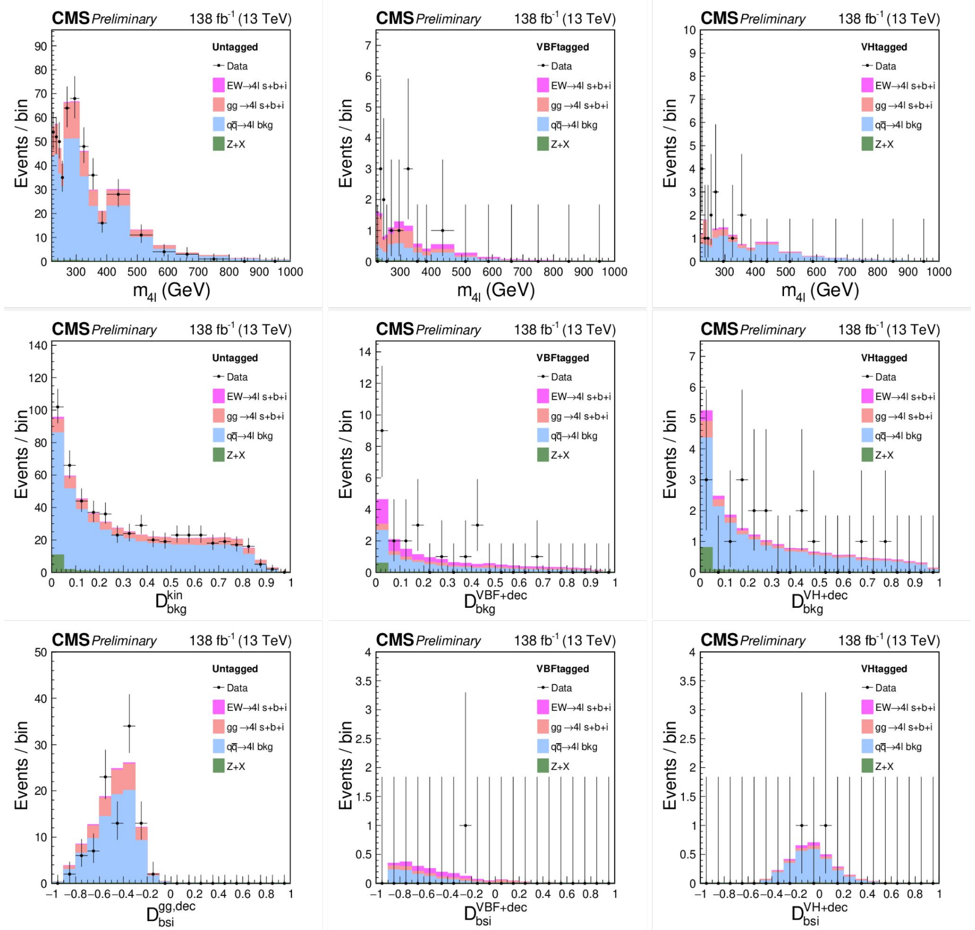
- **Most precise single-channel measurement on m_H in H→4ℓ** decay channel, combining Run1+Run2 measurements
  →Very precise Γ_H measurement using off-shell events in H→4ℓ decay channel

- **Efforts are ongoing to reduce the uncertainties on full Run2 H→γγ:**
  - Uncertainties on the energy scale thanks to refined calibration and optimized residual corrections
  - Uncertainty on the non-uniformity of light collection thanks to the new approach

Stay tuned!

BACKUP

m_H and Γ_H in H→4l: Γ_H off-shell observables



m_H in H→γγ: Systematic uncertainties

- **E_γ scale and resolution**: vary R9 distribution and selection criteria of Z(ee) electrons

- **Residual p_T dependance of scale corrections**
  - Corrections for Z(ee) electrons ($\langle p_T \rangle \approx 45$ GeV) used for H(γγ) photons ($\langle p_T \rangle \approx 60$ GeV)
  - Apply residual corrections a second time over corrected data and re-obtain corrective factors; deviations from unity taken as systematic

- **Non-uniformity of light collections** due to radiation damage
  - Scale corrections derived in Z(ee), applied to photons
  - Photons penetrate ≈ $1X_0$ more than electrons in ECAL crystals
  - Developed and validated dedicated light collection efficiency model [1, 2]