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Measurement of Higgs boson mass using bosonic decay channels with the CMS detector

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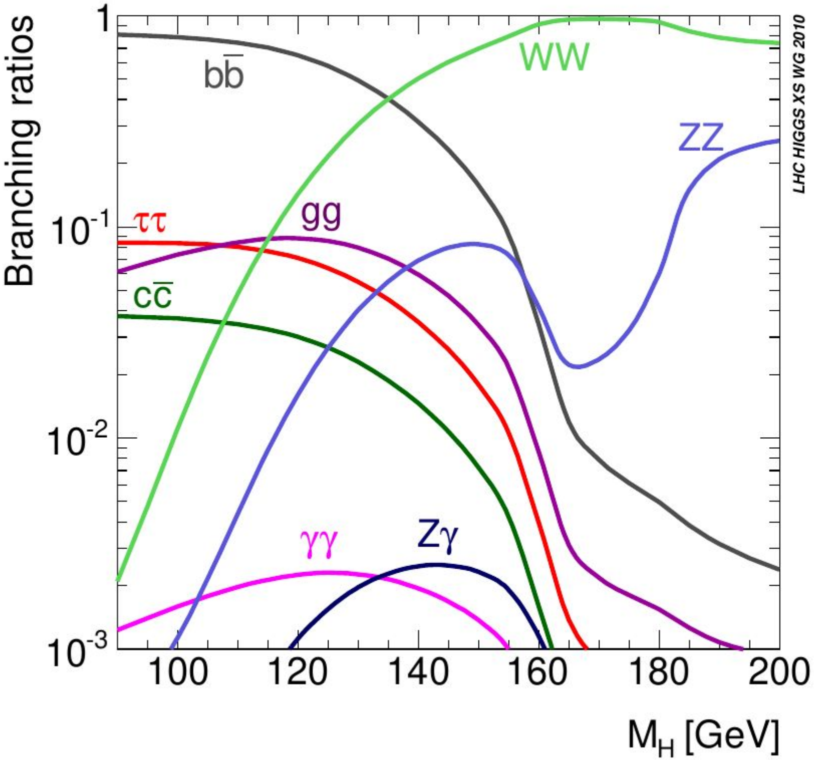
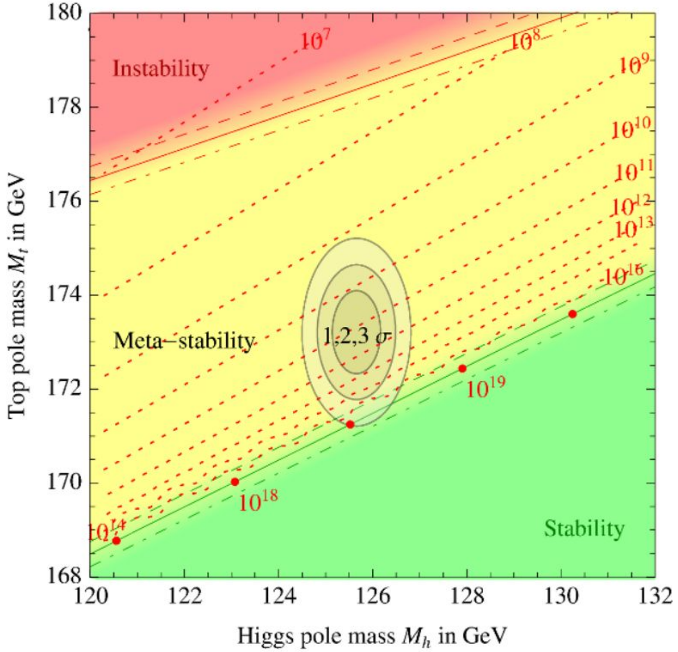
Introduction: Higgs boson mass

- 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**
- Measurement is carried in high resolution channels
  - H(γγ)
  - H(4L)



Introduction: Higgs boson mass

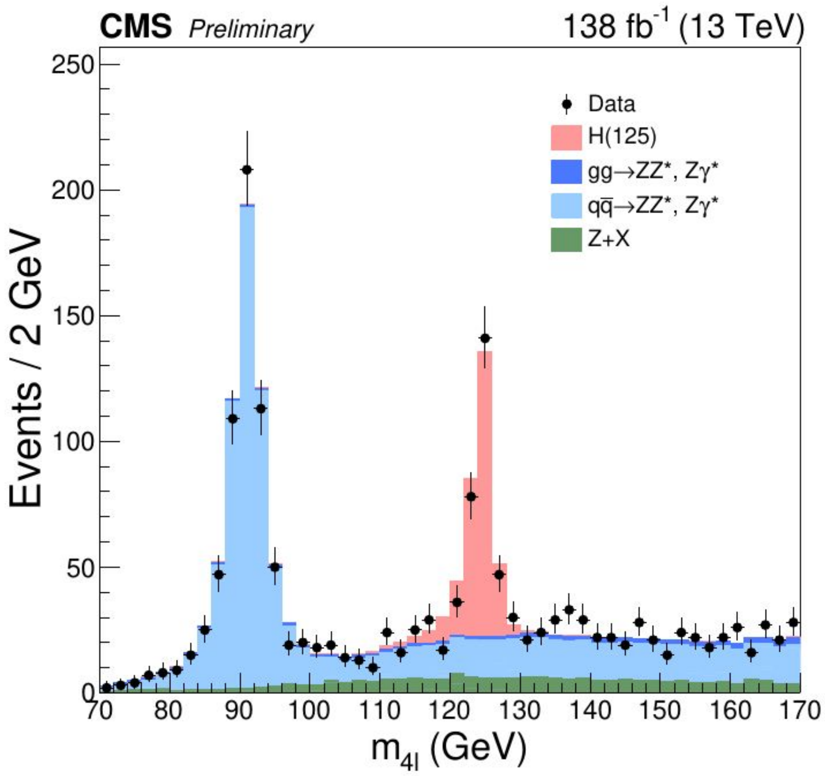
- m_H (and m_t) determine behavior of electroweak vacuum
  - **Cosmological implications** [1]
- Precise knowing of m_H leads to **overconstrained checks of SM** self-consistency



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

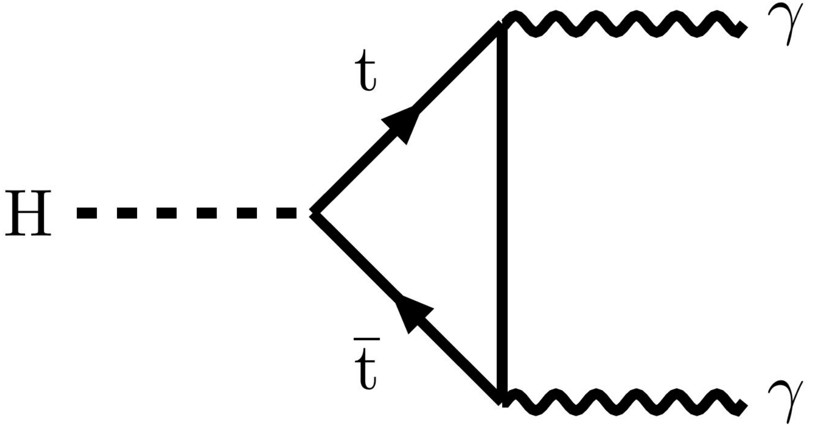
Introduction: γγ and 4L decay channels

- Higgs decays to γγ and 4L 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})
- Analysis strategy similar to previous CMS analyses [1]
- Measurement refined through **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

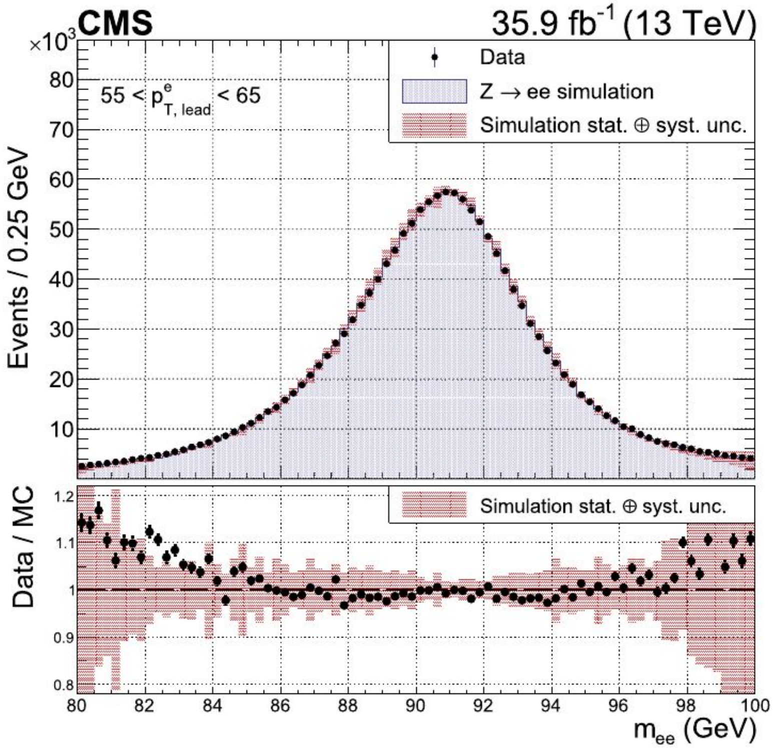
Photon energy (E_γ) calibration

- **Critical**: calibration of ECAL response to photons
- **First**: compute E_γ summing calibrated and corrected energies from ECAL deposits
- **Second**: multivariate regression [1] applied on top of E_γ from ECAL deposits. Corrects for:
  - Incomplete containment of EM showers
  - Energy losses from conversions upstream of ECAL
  - Pileup effects
- **Third**: correct for residual differences between data and MC in E_γ scale and resolution
  - Done in a three-step procedure

Residual scale and resolution corrections

- Residual corrections to E_γ scale and resolution **derived in Z(ee)**, with electrons reconstructed as photons

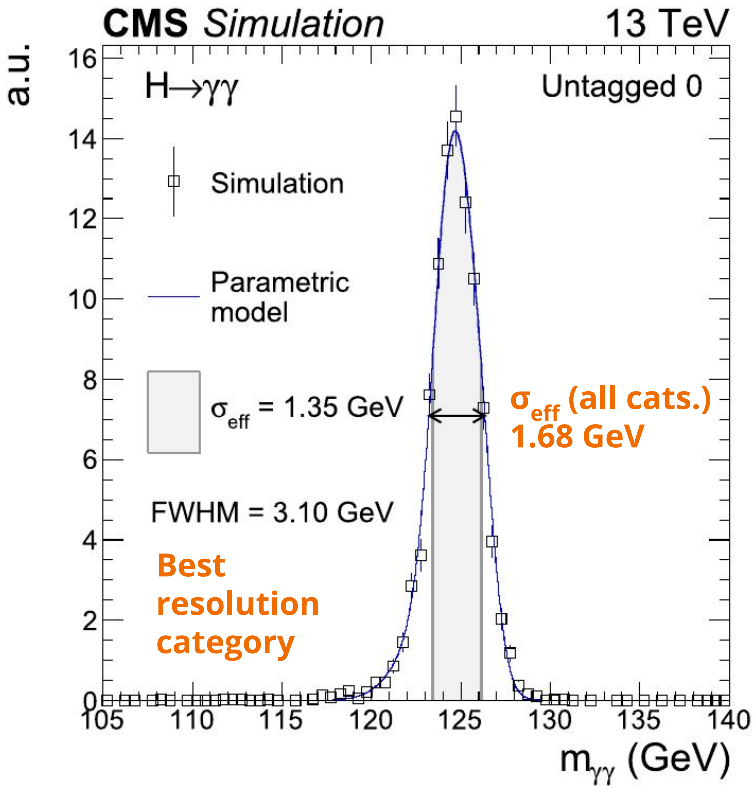
1. Correct for long-term shifts for E_γ scale (per LHC-fill)
2. Derive corrections for E_γ scale and resolution in bins of $|\eta|$, R9*
3. Derive corrections for E_γ scale in bins of $|\eta|$ and p_T
    a. Accounts for any small non-linear response of crystals with energy



* Low/high R9: converted/unconverted photon

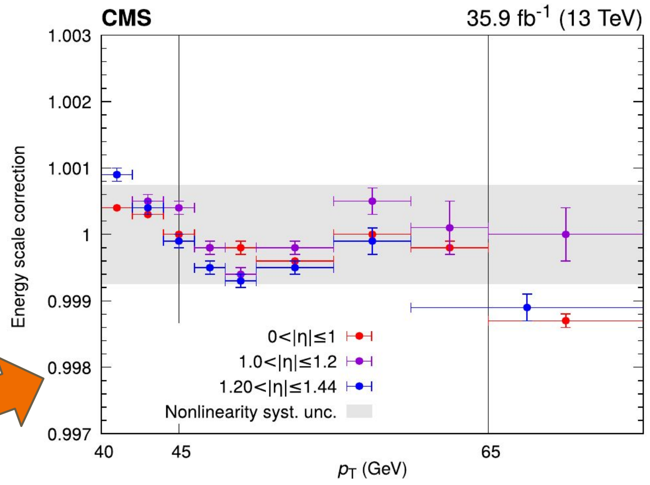
Event classification; signal & background modeling

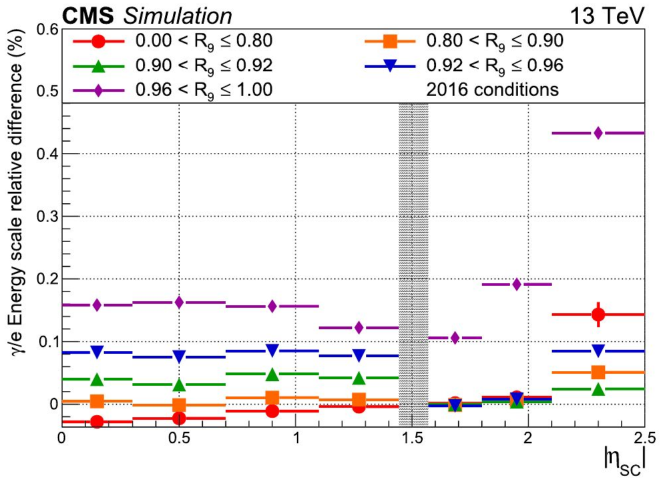
- Preselection kinematic cuts on γγ pair [1]
- Train **2 MVA algorithms**:
  - VBF BDT
  - Diphoton BDT
- **VBF BDT** separates VBF from ggH
- **Diphoton BDT**: assign high score to signal-like, high resolution diphoton pairs
- **First**: separate events in 3 VBF categories based on VBF BDT score boundaries
- **Second**: separate remaining events in 4 ggH categories based on diphoton BDT score boundaries
- **Signal model**: sum of <= 4 Gaussians for each production mode
- **Background model**: from sidebands in data, discrete profiling method



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 $\approx 1X_0$ more than electrons in ECAL crystals
  - Developed and validated dedicated light collection efficiency model [1, 2]



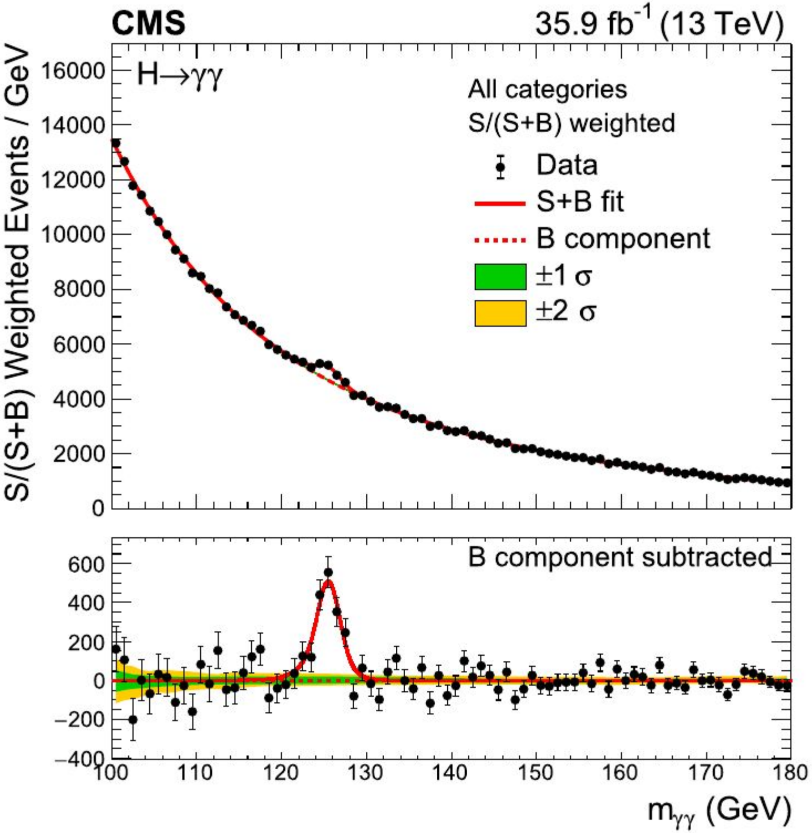


Results

- Binned maximum likelihood to all 7 analysis categories

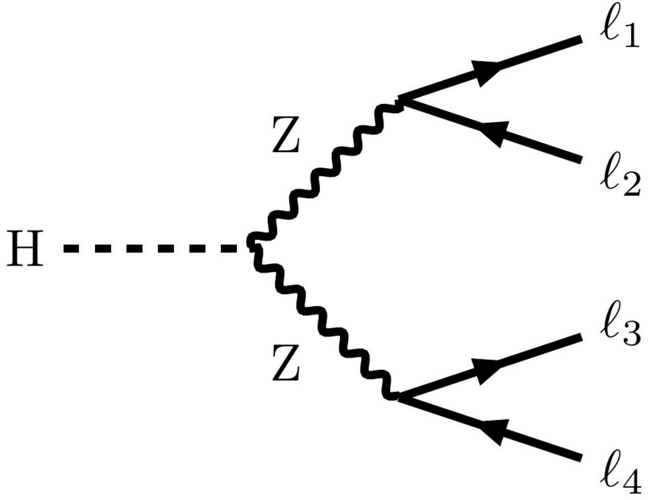
$$m_{\mathrm{H}} = 125.78 \pm 0.18(\mathrm{stat.}) \pm 0.18(\mathrm{syst.})\ \mathrm{GeV}$$

- **Precision of measurement at the per-mille level**



m_H and Γ_H in H(4l): CMS PAS HIG-21-019

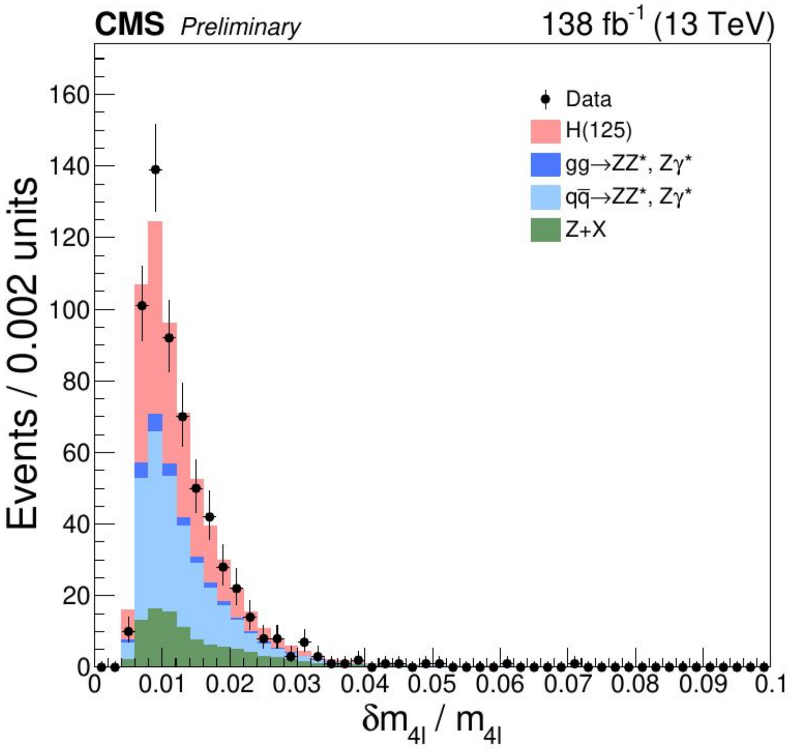
- **Very small BR** (1.24 x 10^{-4}) but **very clean final state**
- Use **data collected in Run2** (138 fb^{-1})
- Analysis strategy similar to previous CMS analyses [1]
- Measurement of m_H refined through **better detector calibration, analysis strategy and understanding of systematics**



- **Measure** the Higgs boson natural width **Γ_H using on- and off-shell events**
- Γ_H precisely predicted by SM (≈ 4 MeV)
- Modified Higgs couplings or undiscovered decays could modify Γ_H
  - Important to measure

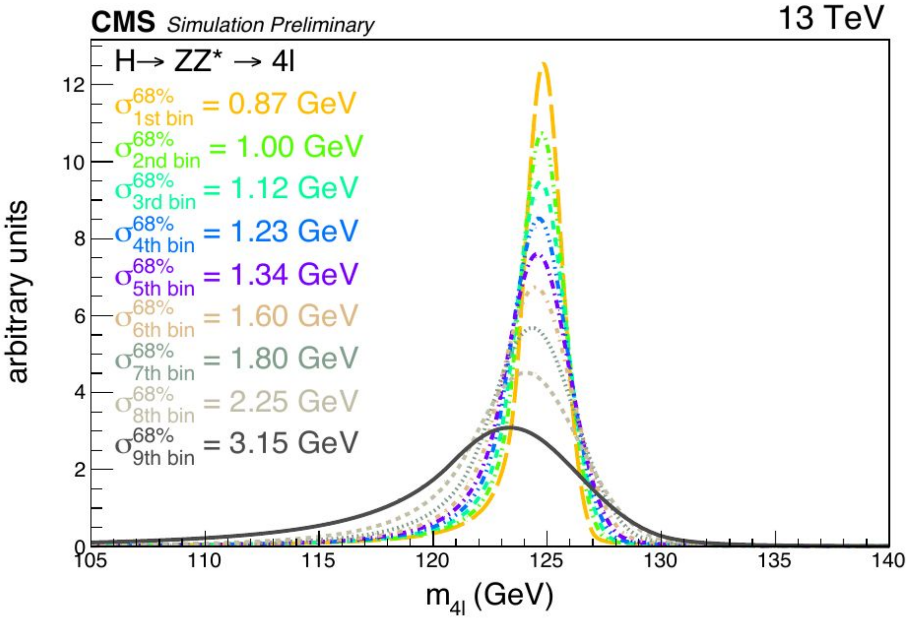
Improvements in m_H measurement

- **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**: p_T of dilepton pair should give Z true lineshape
- **Categorize events based on $\delta m_{4L}/m_{4L}$**: isolate events with high mass resolution from the others
  - ≈ 10% mass resolution improvement



Event classification; signal & background modeling

- Select 4 prompt isolated leptons
  - Build Z candidates and H candidate
- Split events in **9 categories based on $\delta m_{4L}/m_{4L}$**
  - Equal amount of signal events in each
- **Signal model**: DSCB + Landau
  - + Breit-Wigner when measuring Γ_H
- **Background model**
  - Irreducible: from MC, Bernstein pol. degree 3
  - Reducible: from control region in data (fake-rate method), Landau



m_H results

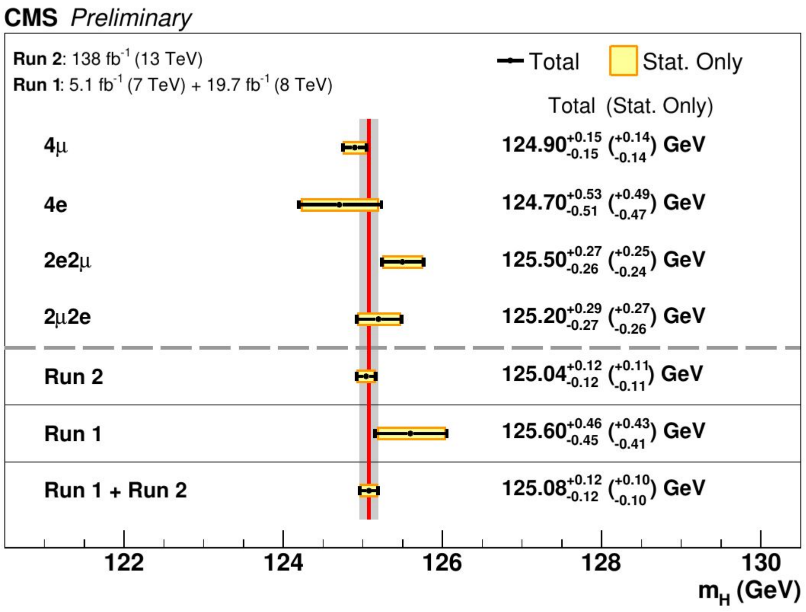
- Maximum likelihood fit to m_{4L} and kinematic discriminant D_{bkg}

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

- Results are combined with Run1 data [1]

$$m_{\mathrm{H}} = 125.08 \pm 0.10(\mathrm{stat.}) \pm 0.05(\mathrm{syst.})\ \mathrm{GeV}$$

- **Most precise single-channel measurement to date**



Γ_H off-shell measurement

- Previous measurement by CMS [1] in Z(2L2ν) and Z(4L)
- Measurement of Γ_H from off-shell measurements relies on **assumptions**
  - Knowledge of coupling ratios between on- and off-shell production

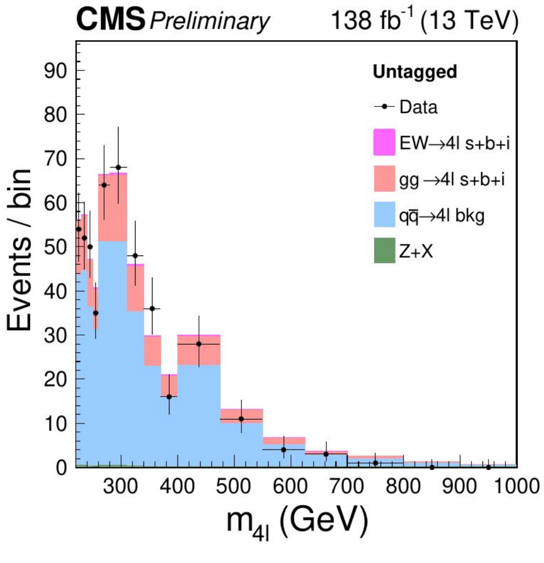
$$\frac{\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to 4\ell}}{\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to 4\ell}} \propto \Gamma_{\text{H}}$$

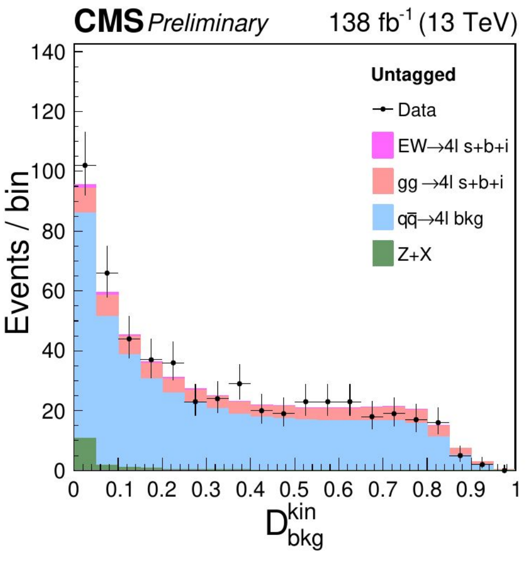
  - **ggH loop** production is **dominated by top and has no BSM** contributions
- Also, off-shell region characterized by **sizeable interference between H boson signal and continuum background**
- PDF describing data must **account for interference and cross-feeding**

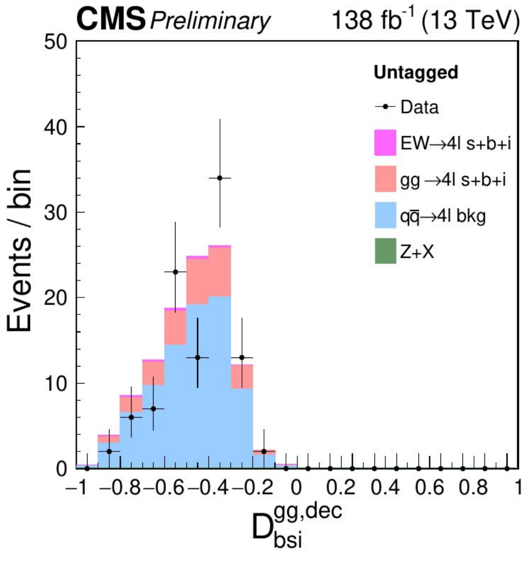
$$\mathcal{P}_{jk}(\vec{x};\vec{\xi}_{jk},\vec{\zeta}) = \frac{\mu_j \Gamma_{\text{H}}}{\Gamma_0}\mathcal{P}^{\text{sig}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \sqrt{\frac{\mu_j \Gamma_{\text{H}}}{\Gamma_0}}\mathcal{P}^{\text{int}}_{jk}(\vec{x};\vec{\xi}_{jk}) + \mu_j \mathcal{P}^{\text{cross}}_{jk}(\vec{x};\vec{\xi}_{jk})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

Γ_H off-shell measurement

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

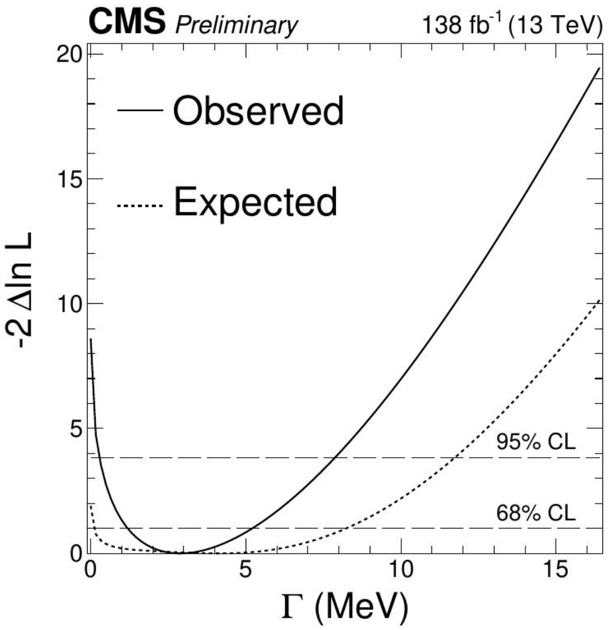


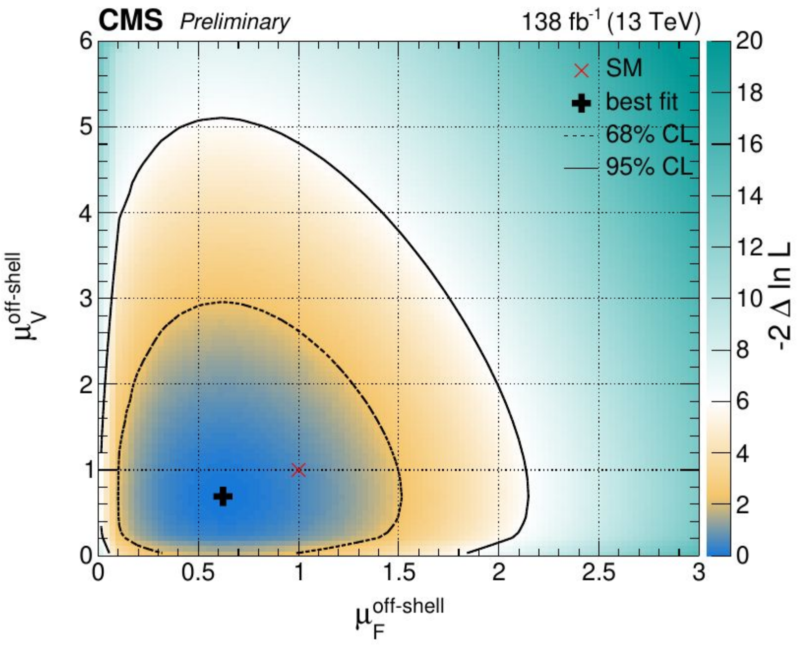




Γ_H off-shell measurement

- Extract Γ_H: $\Gamma_{\mathrm{H}} = 2.9^{+2.3}_{-1.7}\ \mathrm{MeV}$
- Off-shell μ_F, μ_V in agreement with SM prediction





Conclusions

- The CMS Collaboration is measuring the Higgs boson mass and natural width using the canonical 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, using full Run2 dataset
- Measured Γ_H using off-shell events in H(4L) decay channel
- Other efforts are ongoing

Stay tuned!

Backup slides