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Mass, width and CP measurements - CMS

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on behalf of the CMS Collaboration

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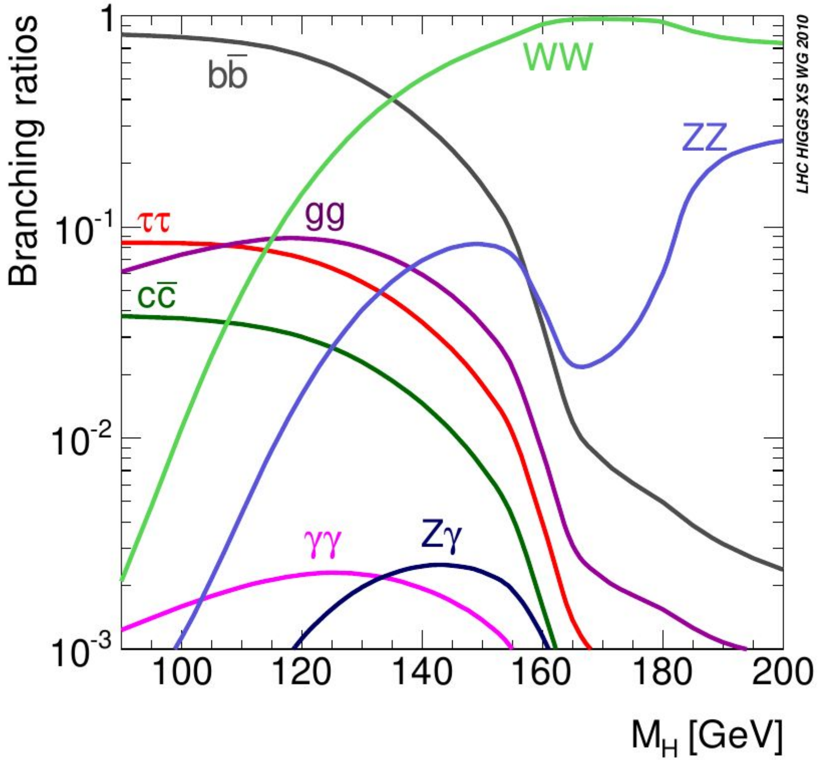
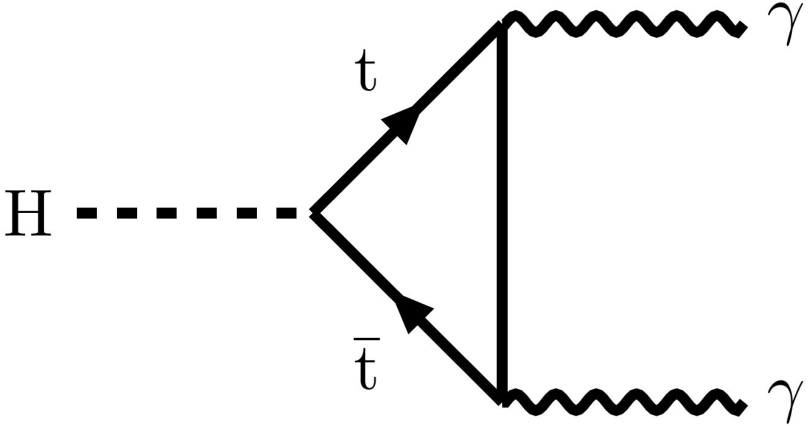
Introduction: Higgs boson mass

- 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)



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**

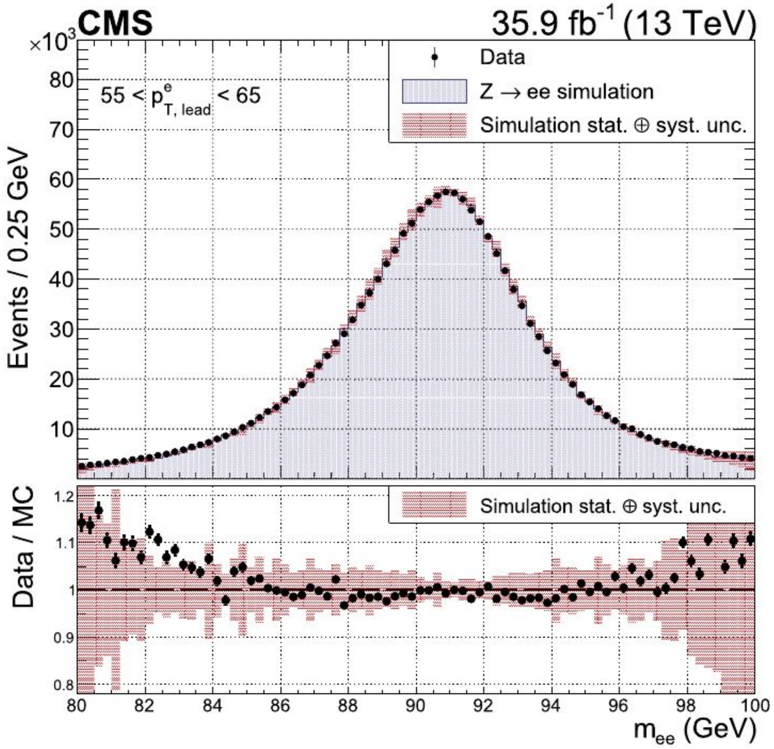


- Improved description of data-MC nonlinear discrepancies in energy scale

Residual scale and resolution corrections

- Compute residual corrections to E_γ scale and resolution after ECAL calibration and E_γ regression
- **Derived in Z(ee)**, with electrons reconstructed as photons

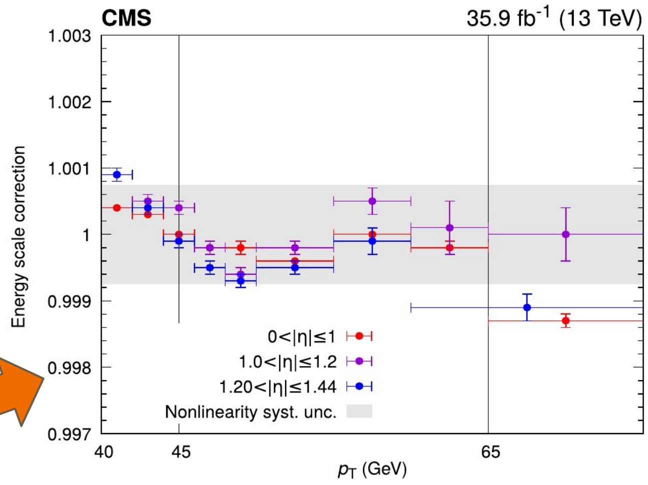
1. Correct for long-term shifts for E_γ scale (per LHC-fill)
2. Derive corrections for E_γ scale and resolution in bins of $|\eta|$, R9*
3. Derive corrections for E_γ scale in bins of $|\eta|$ and p_T
    a. Accounts for any small non-linear response of crystals with energy

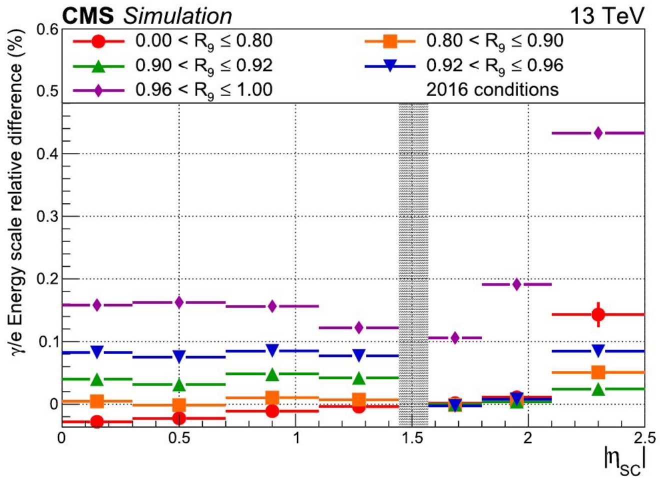


* Low/high R9: converted/unconverted photon

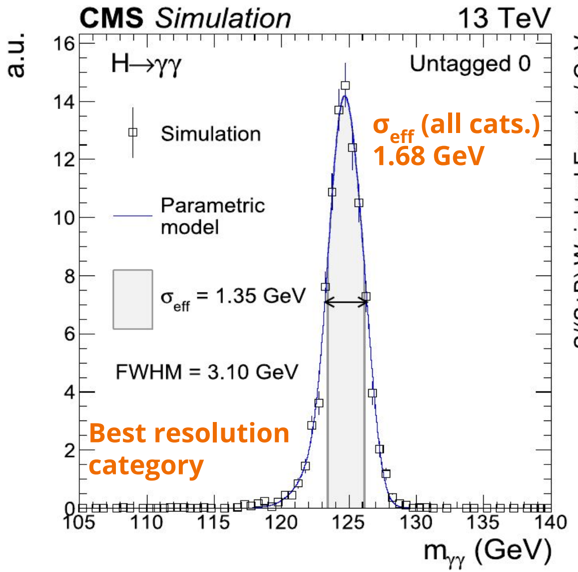
Systematic uncertainties

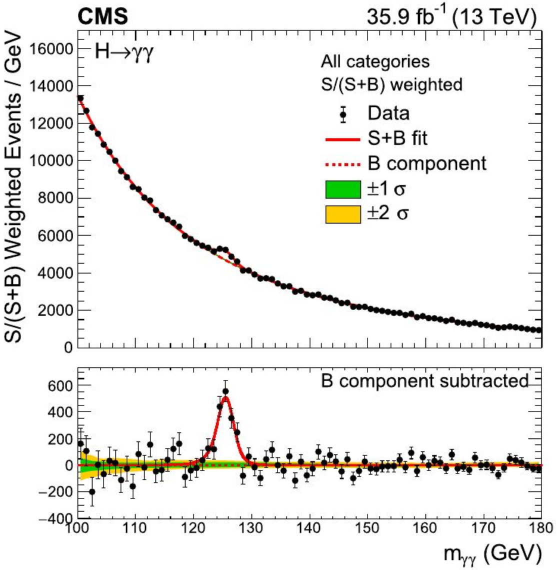
- **E_γ scale and resolution**: vary R9 distribution and selection criteria of Z(ee) electrons
- **Residual p_T dependance of scale corrections**
  - Corrections for Z(ee) electrons ($\langle p_T \rangle \approx 45$ GeV) used for H(γγ) photons ($\langle p_T \rangle \approx 60$ GeV)
  - Apply residual corrections a second time, 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 $0.85X_0$ more than electrons in ECAL crystals
  - Derived **uncertainty to cover for differences between electrons and photons** [1, 2]

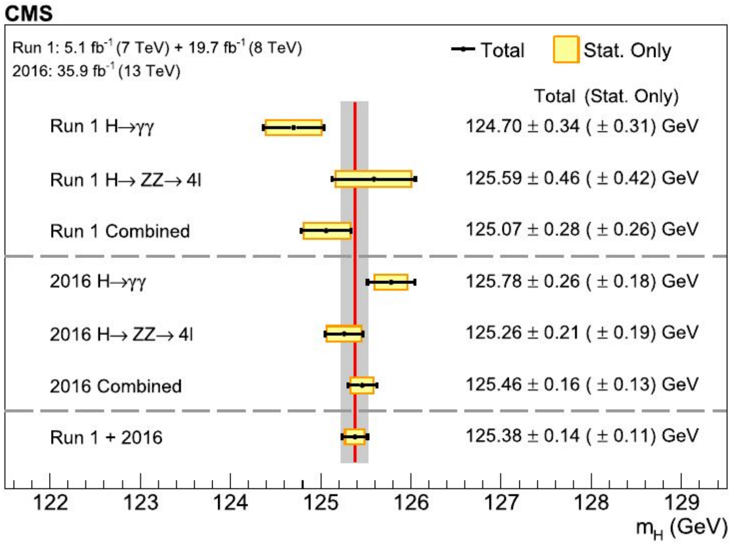




Results







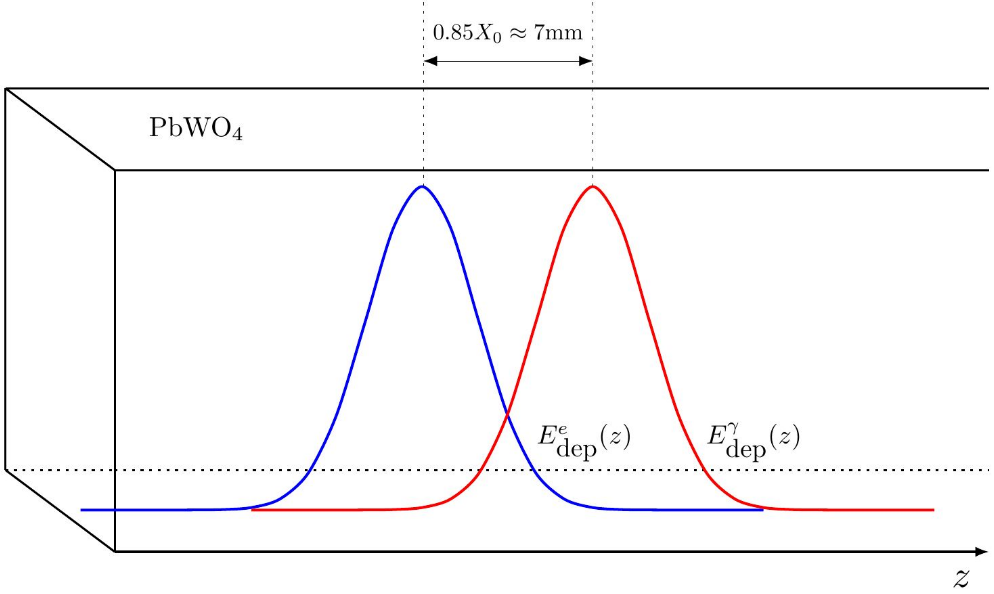
- Binned maximum likelihood to all 7 analysis categories

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

- Precision of measurement at the per-mille level
- **Dominant uncertainty:** non-uniformity in light collection

Developments: non-uniformity of light collection

- **Developed new treatment for uncertainty due to non-uniformity of light collection**
- Calibrations performed with Z(ee) electrons, applied to photons
- **Photons** penetrate $0.85X_0$ deeper than **electrons** of the same energy in $PbWO_4$
- Non-uniform radiation damage along crystal depth → **bias in photon energy**, as non-uniformity is neither simulated nor corrected by E_γ regression



Developments: non-uniformity of light collection

- 2016 analysis: do not correct for bias, assign uncertainty covering for this
  - Resulted in dominant uncertainty: **revised in light of full Run2 analysis**
- **Rely on simulation of light collection efficiency (LCE) instead** (CMS-DP-24-045): apply energy scale correction and dedicated uncertainty on the correction

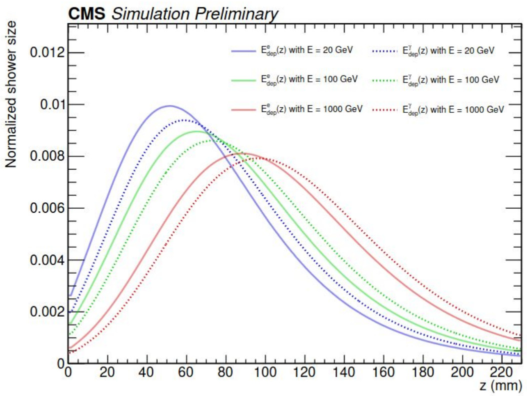
$$F = \frac{S^e}{S^\gamma} = \frac{\dfrac{\int E^e_{\rm dep}(z) \times {\rm LCE}(z;\, {\rm R}/{\rm R}_0, \eta)\, {\rm d}z}{\int E^e_{\rm dep}(z)\, {\rm d}z}}{\dfrac{\int E^\gamma_{\rm dep}(z) \times {\rm LCE}(z;\, {\rm R}/{\rm R}_0, \eta)\, {\rm d}z}{\int E^\gamma_{\rm dep}(z)\, {\rm d}z}}$$

← Collected energy for damaged crystal

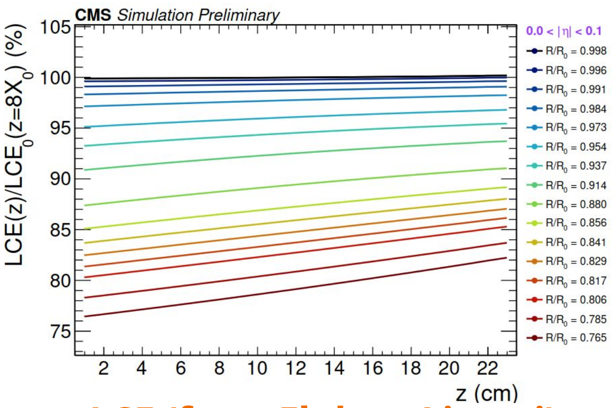
← Collected energy for undamaged crystal

- S^e (S^γ) ≡ ECAL response to electrons (photons)
- E_{dep} ≡ shower profile in $PbWO_4$ as a function of depth (Geant4)
- LCE ≡ Light Collection Efficiency as a function of depth, simulated with Fluka+Litrani
- R/R_0 ≡ ECAL laser response **measured in data —> can correct with per-run granularity**

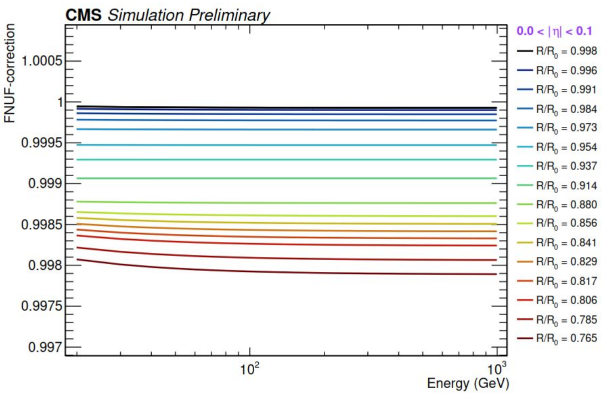
Developments: non-uniformity of light collection



E_{dep} (from Geant4)



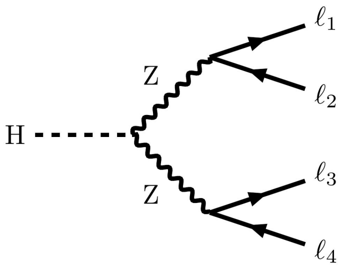
LCE (from Fluka + Litrani)



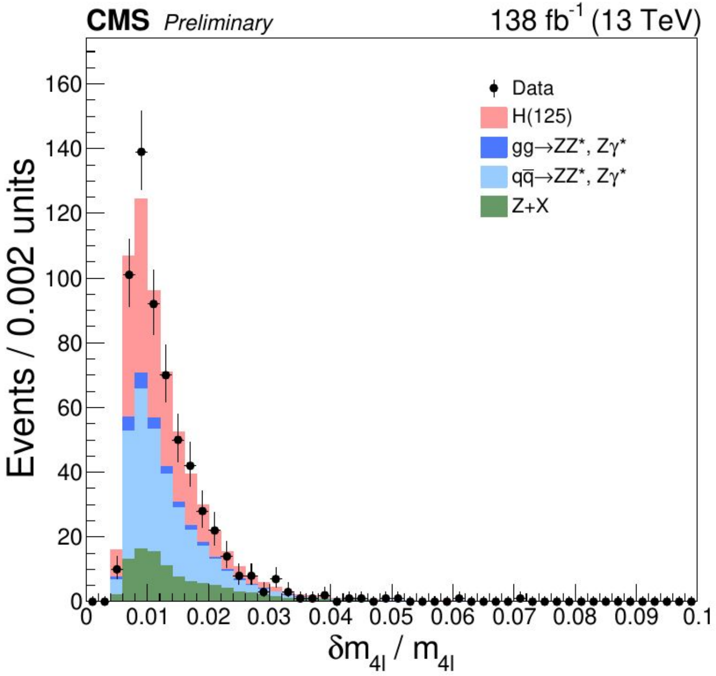
Correction

- Ingredients: e/γ shower profiles in ECAL (Geant4) and LCE in ECAL (Fluka + Litrani)
- Expect to strongly reduce uncertainty due to light collection efficiency in full Run2 measurement

m_H and Γ_H in H(4l): Submitted to PRD



- Full **Run2 data** (138 fb^{-1})
- Analysis strategy refined through **better calibrations, analysis strategy** and **understanding of systematics**
- **Vertex-beamspot constraint**: 4L tracks constrained to common vertex compatible with beam spot
  - 3–8% mass resolution improvement
- **Constraint on 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
  - ≈ 10% mass resolution improvement



m_H results

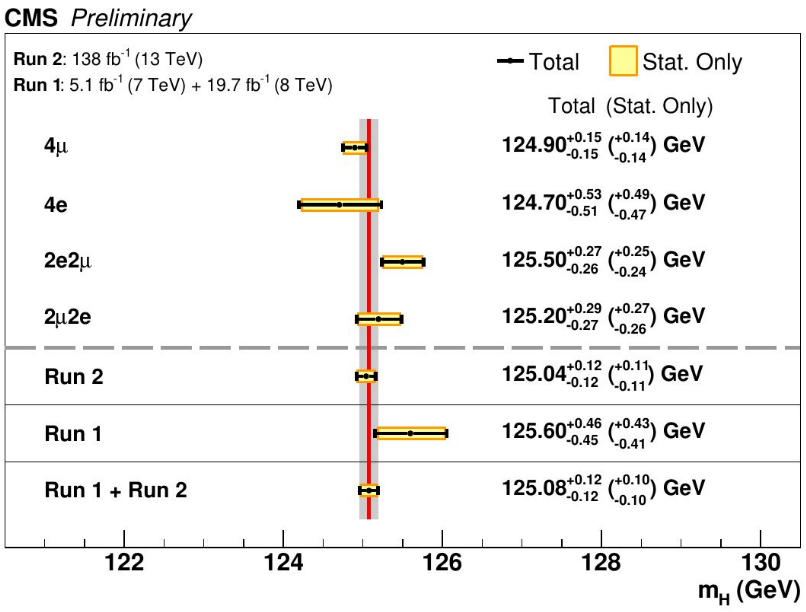
- Maximum likelihood fit to m_{4L} and kinematic discriminant D_{bkg}

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

- 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)
  - Partial dataset for 4L
- Measurement of Γ_H from off-shell measurements relies on **assumptions**
  - Knowledge of coupling ratios between on- and off-shell production

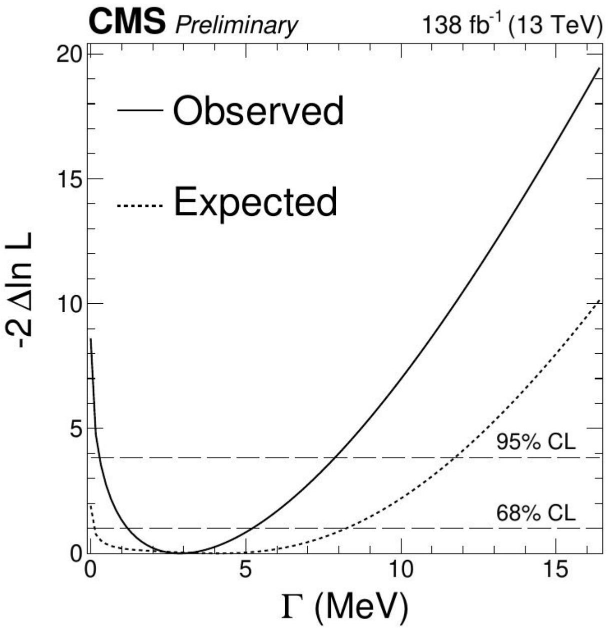
$$\frac{\sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell}}{\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell}} \propto \Gamma_{\text{H}}$$

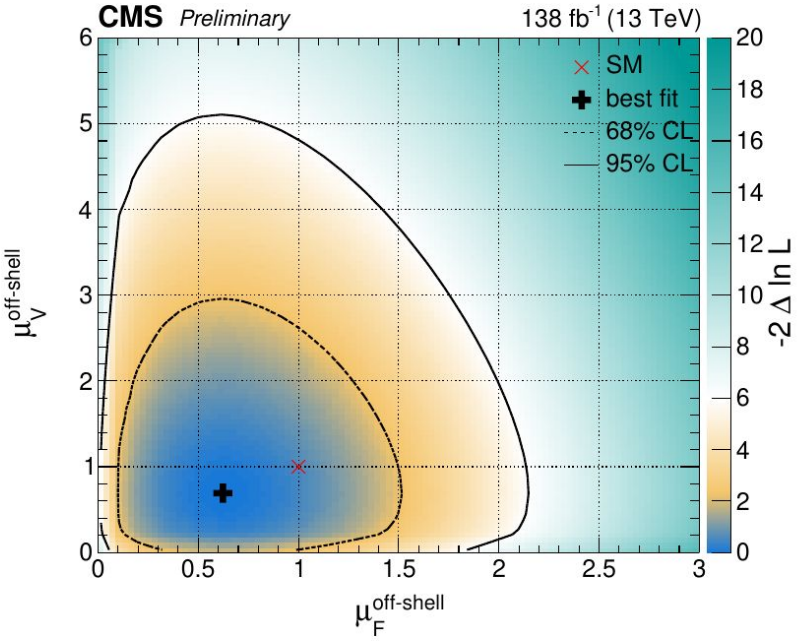
  - **ggH loop** production is **dominated by top and has no BSM** contributions
- **Sizeable interference** between H boson signal and continuum background
- PDF describing data **accounts for interference and cross-feeding**

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

Γ_H off-shell measurement

- 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



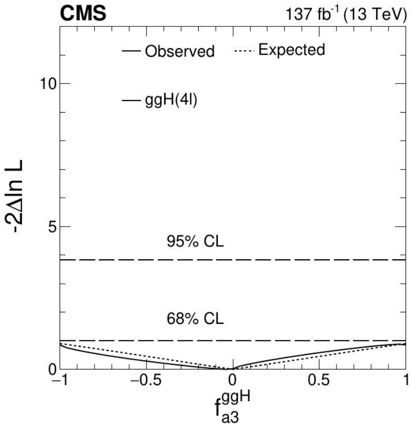


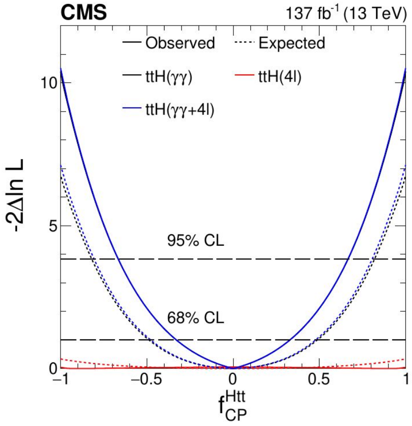
CP properties

- So far, properties of Higgs boson found to be consistent with SM
- In particular, $J^{CP} = 0^{++}$
- **Limited precision allows for CP-violating anomalous couplings**
    - E.g., CP-odd coupling to top quarks or new BSM interactions would result in CP violation
- Anomalous, CP-violating couplings (ACs) studied in large spectrum of production and decay modes
- Events categorized based on matrix-element discriminants (MELA, [1]) or on advanced Machine Learning techniques
- Results usually expressed in terms of cross-section ratios f_{ai} , depending on ACs a_i

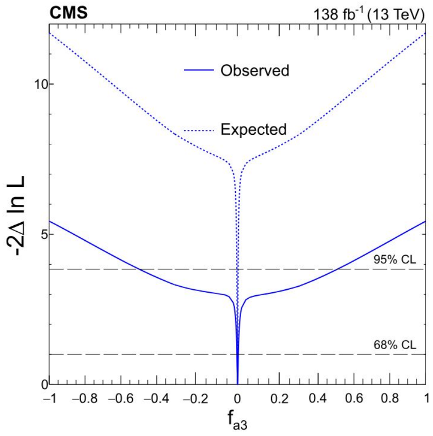
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \operatorname{sign}\left(\frac{a_i}{a_1}\right)$$

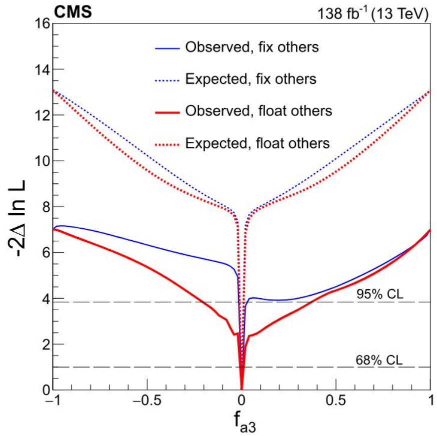
CP-violating ACs: results





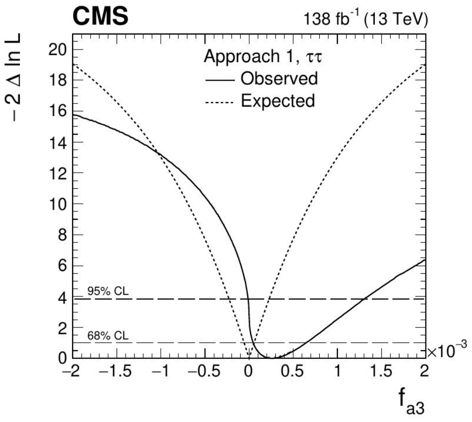
- H→4L decay ([PRD 104, 052004]())
- AC with gluons f^{ggH}_{a3} consistent with 0
- Combining with ttH(γγ) ([PRL 125, 061801]()), CP-odd excluded at 3.2σ
- Similar studies on HVV couplings in papers

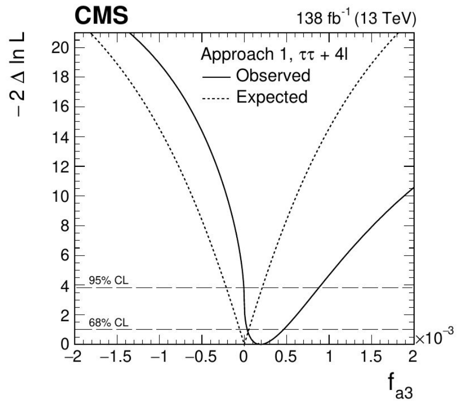




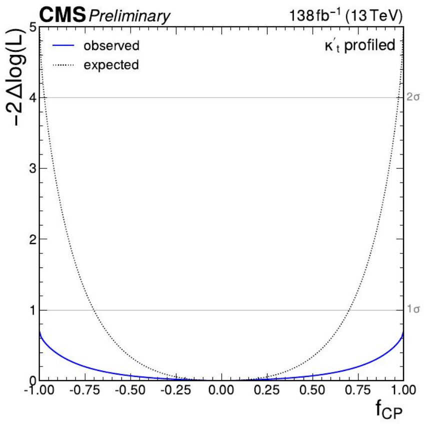
- H→WW decay ([EPJC 84, 779 (2024)]())
- Study HVV ACs in two approaches
  - Impose $a_i^{WW} = a_i^{ZZ}$, study cross section ratios independently (left)
  - Impose SU(2) x U(1) symmetry, analyze a_i independently (left) or simultaneously (right)
- Value of CP-violating AC f_{a3} is found to be consistent with 0

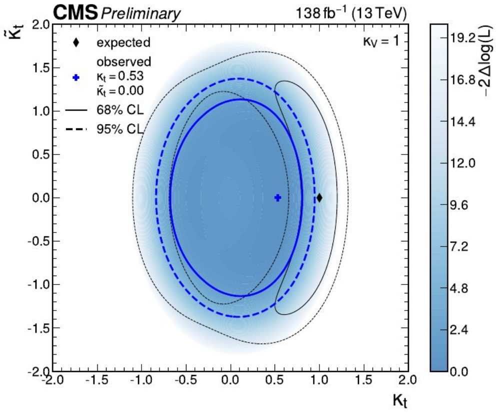
CP-violating ACs: results





- H→ττ decay (PRD 108, 032013)
- Value of CP-violating AC f_{a3} is found to be consistent with 0
- Combined result with 4L analysis (cfr. previous slide) consistent with 0 as well.





- ttH(bb) (submitted to JHEP)
- Higgs-top CP coupling parametrized with purely CP-even and -odd terms $\kappa_t, \tilde{\kappa}_t$ as well as cross section ratio f_{CP}
- Results compatible with purely CP-even coupling
- $\kappa_t, \tilde{\kappa}_t$ result compatible with SM at the level of 2σ

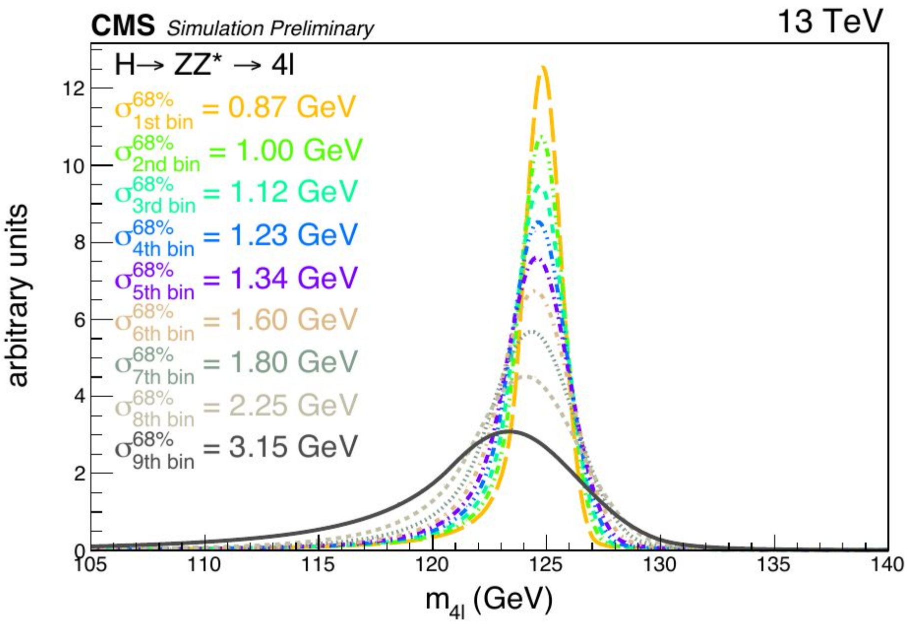
Conclusions

- The CMS Collaboration is measuring the Higgs boson mass and natural width using the canonical high-mass-resolution channels: γγ and 4L
- **Most precise single-channel measurement on m_H in H(4L)** decay channel, using full Run2 dataset
- Intensive work to **reduce uncertainty** due to non-uniformity of light collection in sight **of full Run2 H(γγ) mass measurement**
- Measured Γ_H using off-shell events in H(4L) decay channel
- Anomalous, **CP-violating couplings** (ACs) **studied** in large spectrum of production and decay modes
    - Results are consistent with SM expectation of purely CP-even interactions

Backup slides

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



Γ_H off-shell measurement

- Select region **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