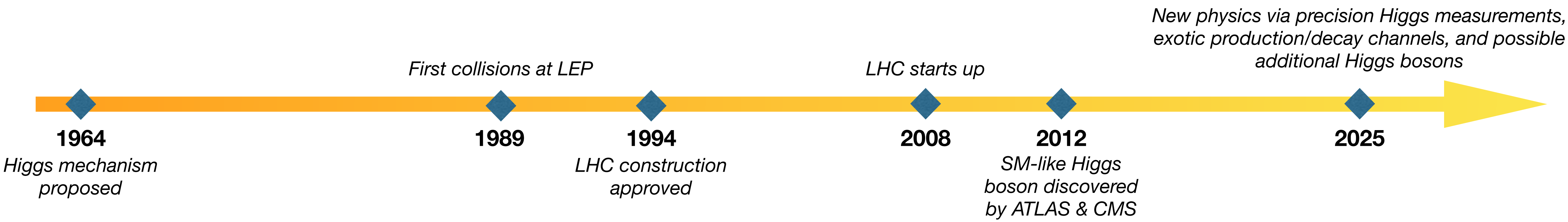
Higgs boson property measurements (mass, width, CP) - CMS

Amrutha Krishna (Northeastern University, Boston, USA),
on behalf of the CMS collaboration

15 July 2025
Higgs Hunting 2025

Introduction



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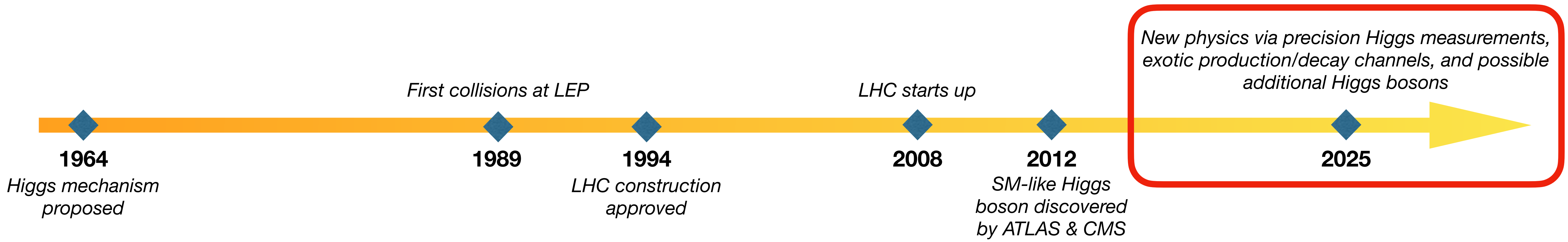
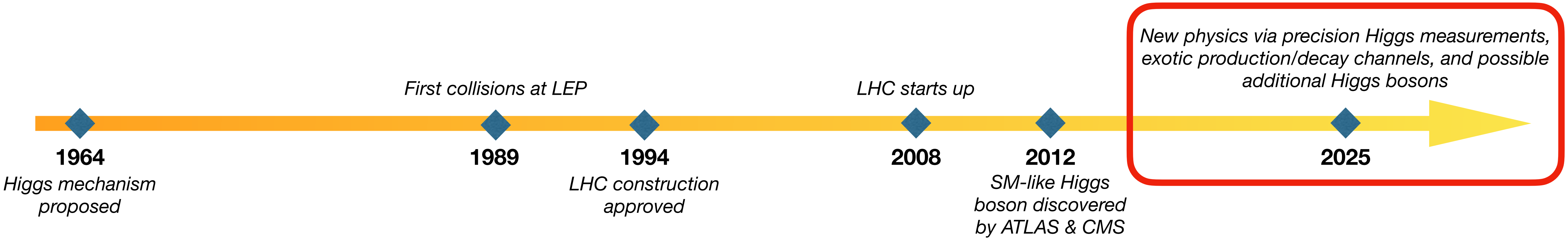


Introduction



- Precision measurement of m_H :
  - Only **free parameter** in the Higgs sector of the SM; all other Higgs properties depend on it.
  - Precise measurement of m_H using the high resolution decay channels: $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$.
- Precision measurement of Γ_H :
  - Predicted to be ~4.07 MeV for m_H = 125 GeV; any deviation points to invisible, BSM decays.
  - Direct measurement from the resonance limited by the detector resolution (~1 GeV), **indirect measurement strategies** used for better precision.
- Measurement of CP properties :
  - SM Higgs is CP-even; Probing **CP-violating, anomalous couplings** (ACs) in several Higgs production and decay channels.
  - Important to explain matter/anti-matter asymmetry in universe.

m_H measurement in $H \to \gamma\gamma$ channel

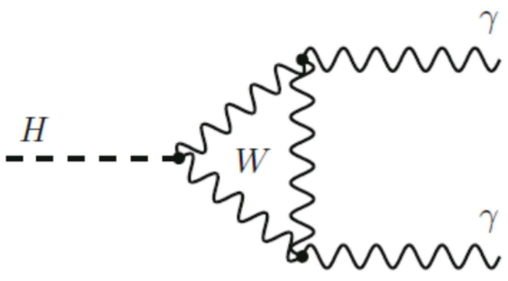
- Run 2 analysis using 36 fb^{-1} (**2016**) data: Phys. Lett. B, 805 (2020)

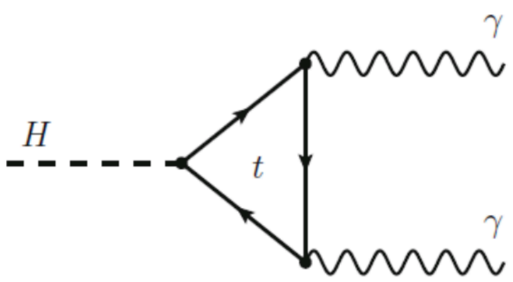
- Improved precision compared to previous analyses due to refinements in E_γ calibrations and better understanding of systematics:

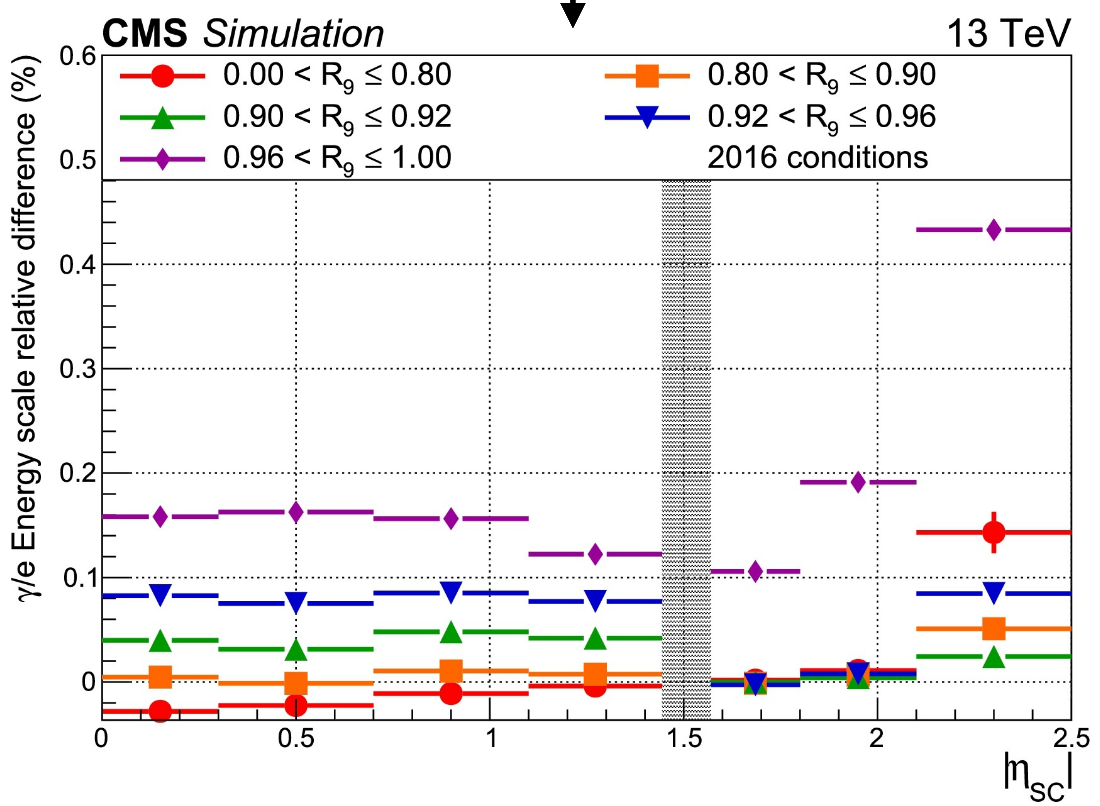
  - **Three-step residual scale and resolution corrections** to E_γ using $Z \to ee$ events with electrons reconstructed as photons.

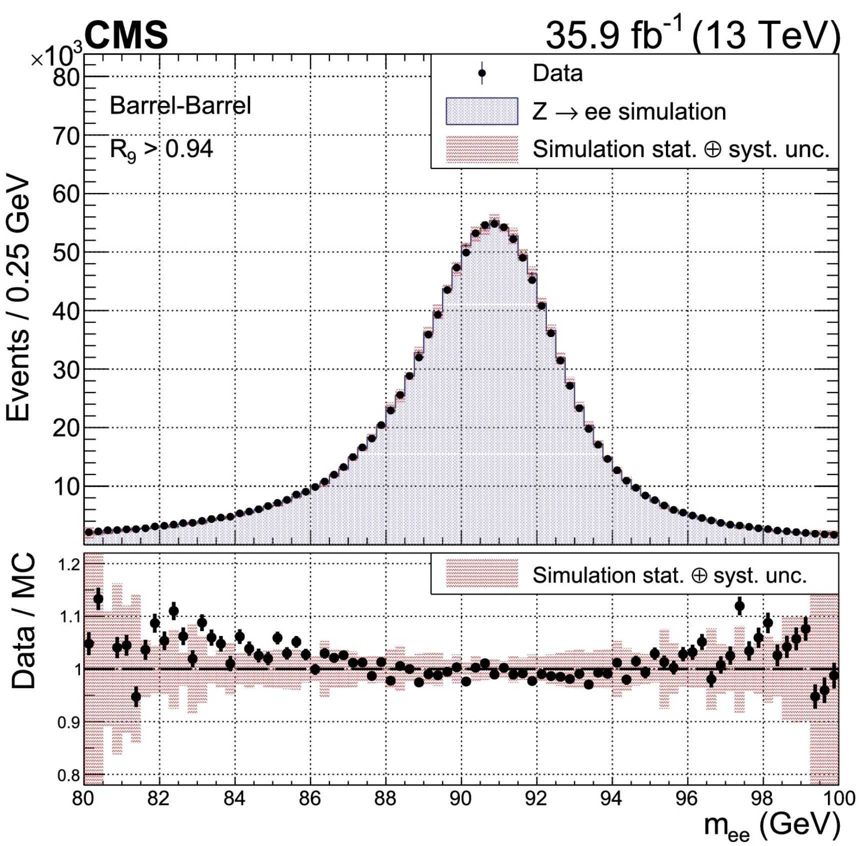
  - Scale (resolution) corrections in bins of η, R_9, p_T (η, R_9) with dedicated systematic uncertainties, including a residual uncertainty for any non-closure of corrections.

  - A method to estimate **systematic uncertainty** on E_γ scale **from non-uniformity in light collection** due to radiation damage along ECAL crystal depth using optical simulation.





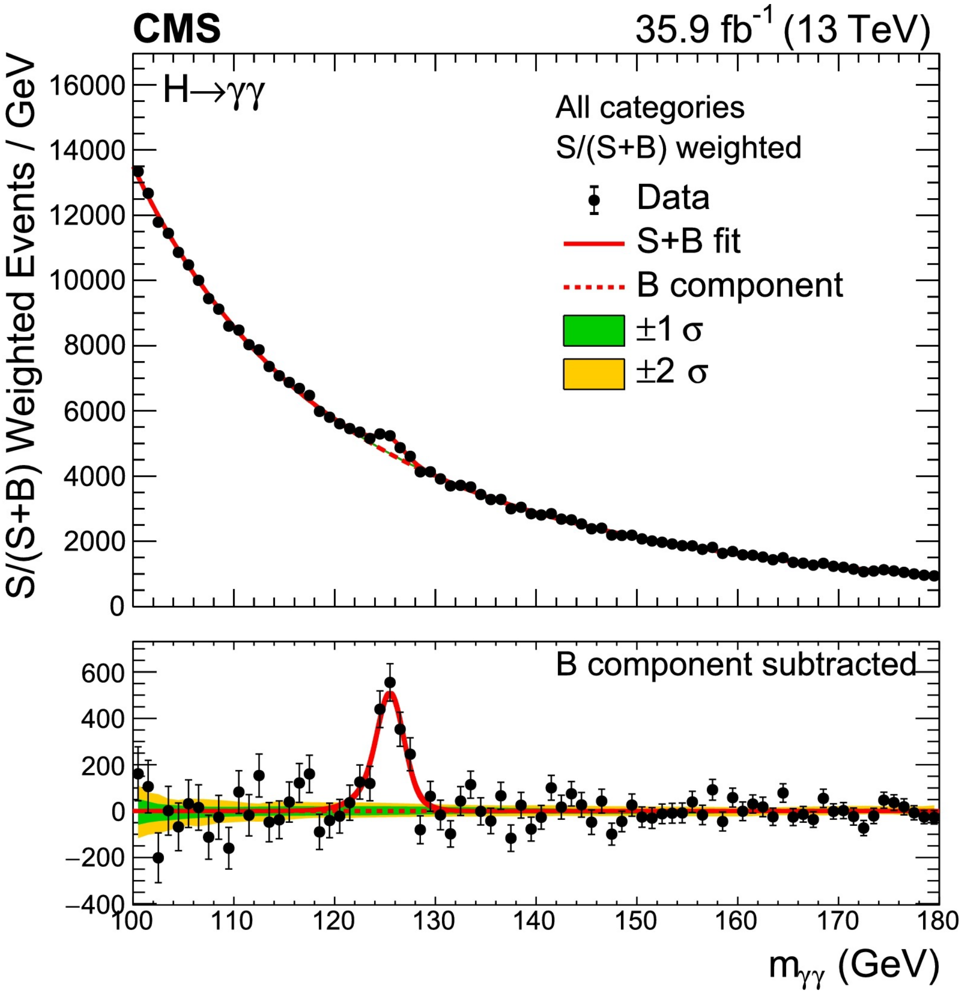


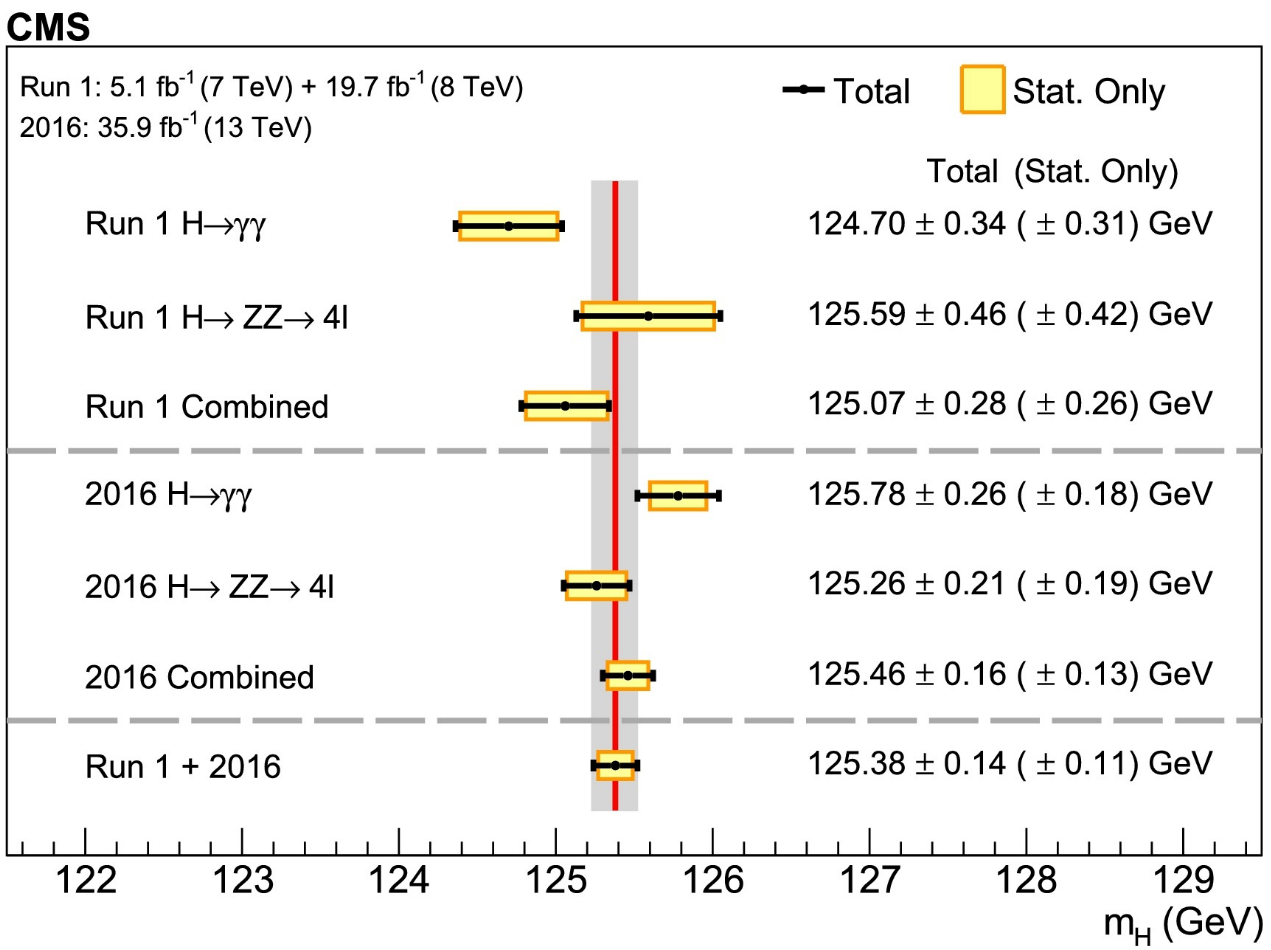


m_H measurement in $H \to \gamma\gamma$ channel

- Analysis performed using ggH and VBF production modes, VH and ttH are not considered as they add complexity to the analysis with negligible improvement in precision.
- 4 ggH + 3 VBF categories defined using a BDT that discriminates signal from background.
- Result:

$$m_H = 125.78 \pm 0.18\ (stat.) \pm 0.18\ (syst.)\ GeV$$





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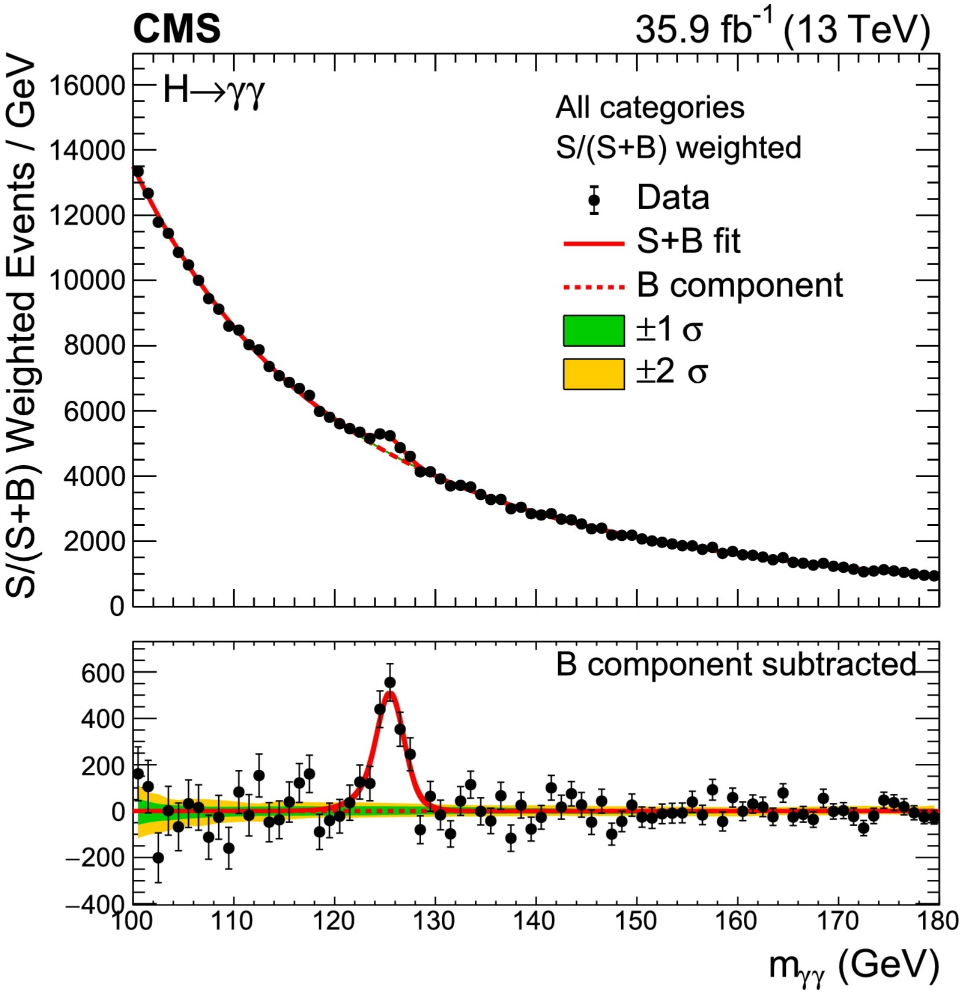

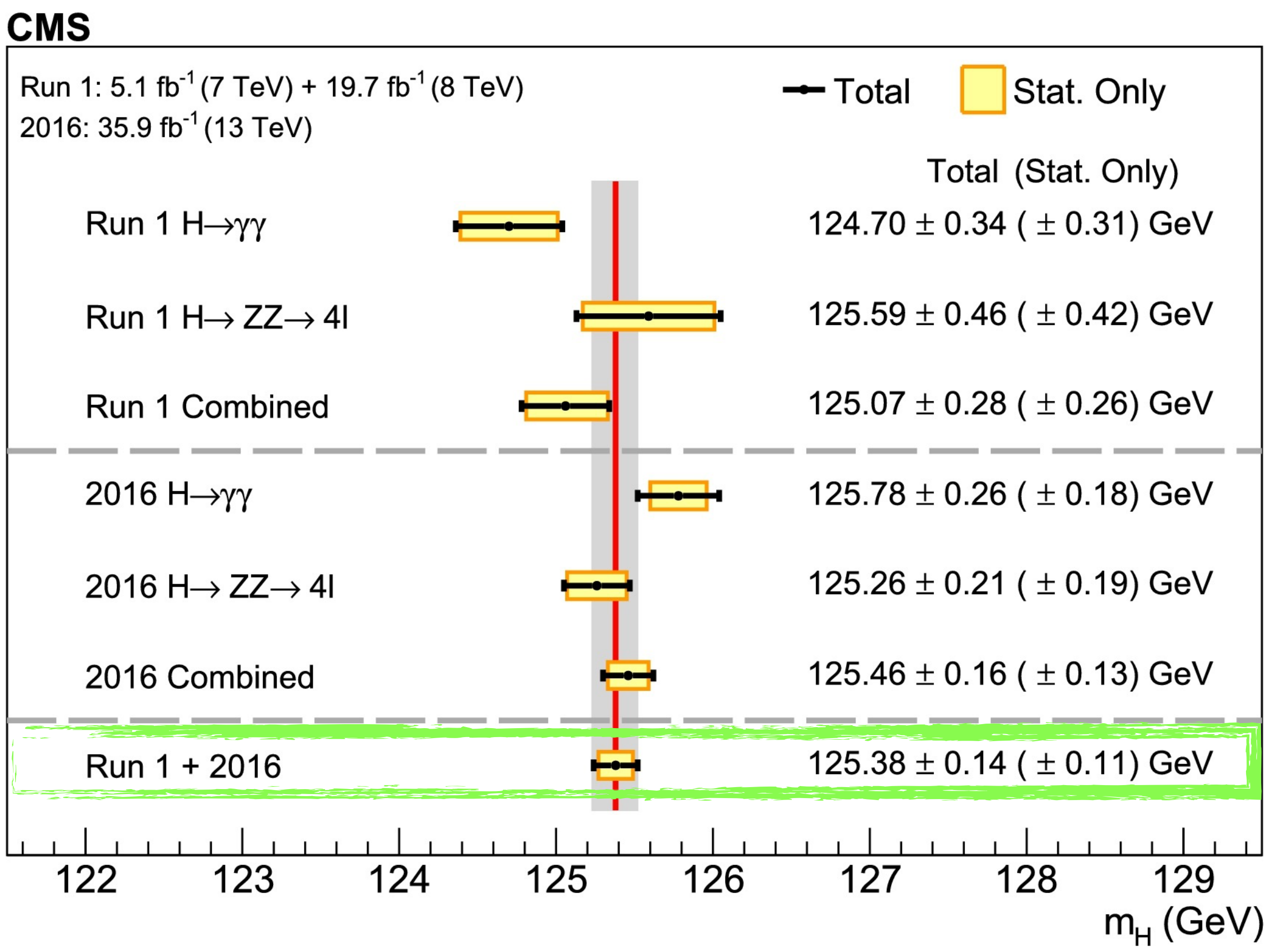

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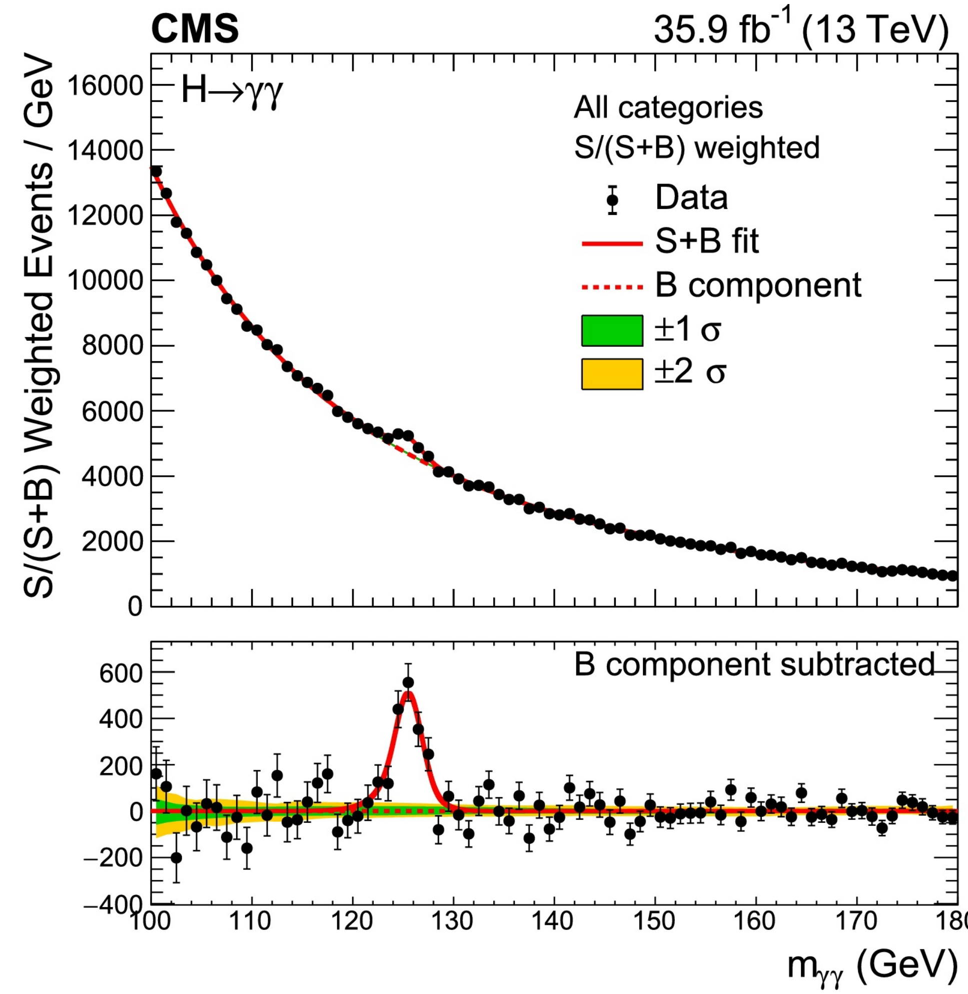
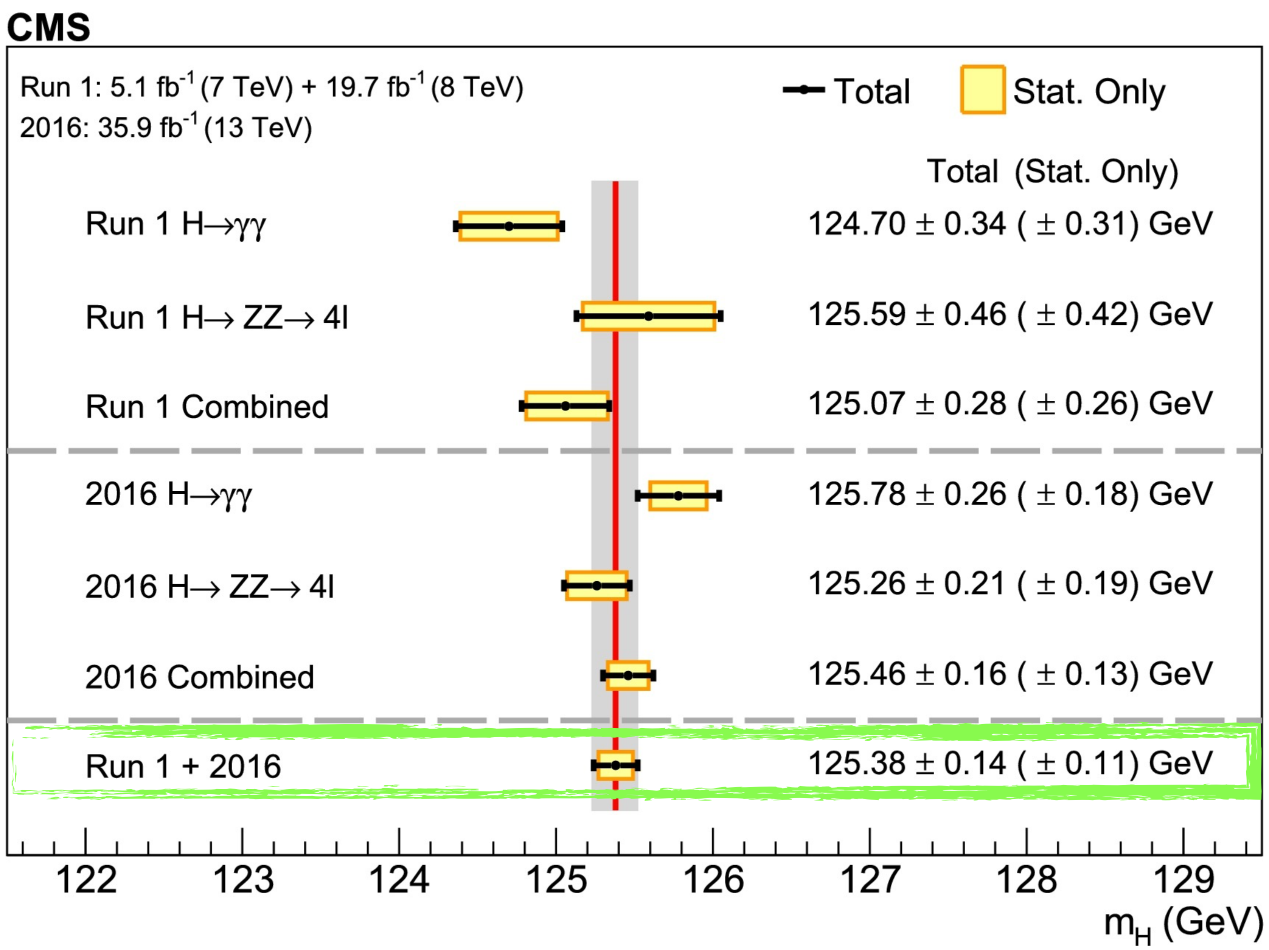
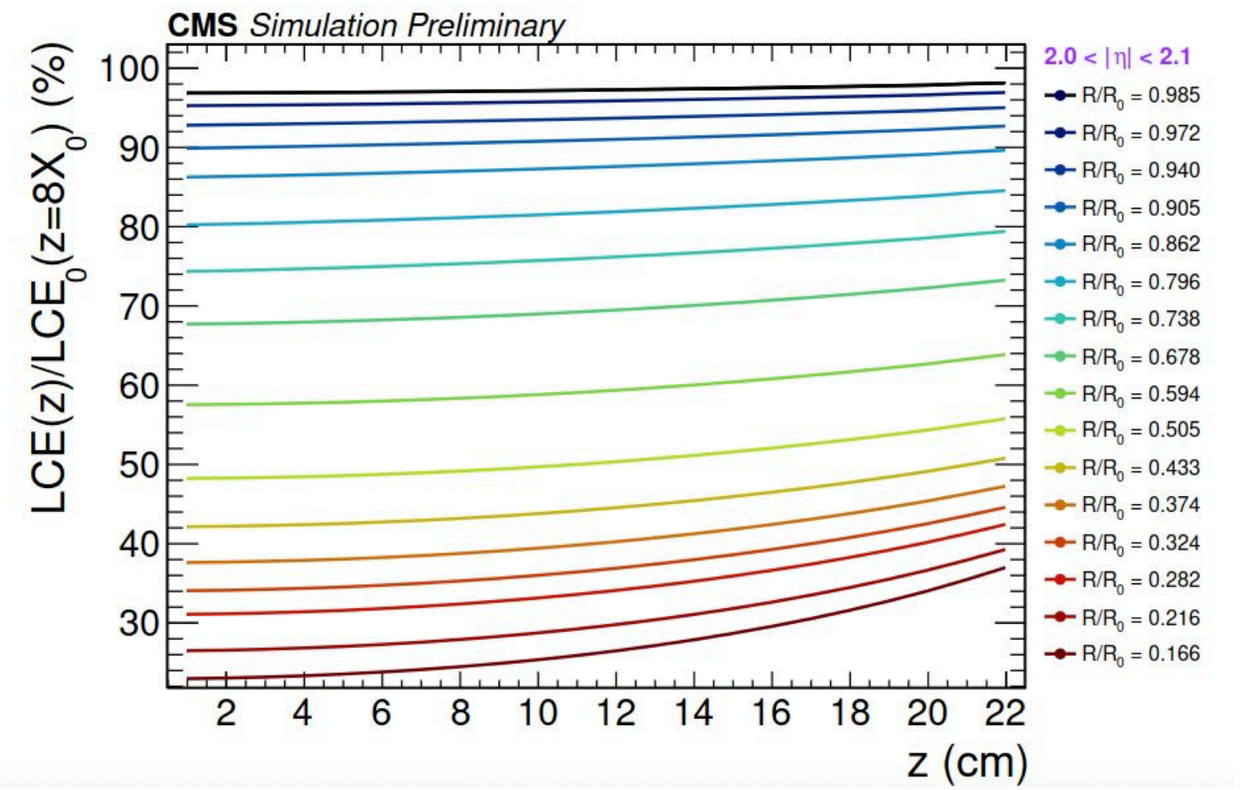




Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_T dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18

Towards full Run-2 $H \to \gamma\gamma$ m_H measurement

- Strategy to mitigate the syst. unc. from **non-uniformity of light collection** in ECAL:
  - Shower maximum of photons deeper than electrons of the same E by $0.85X_0$ in $PbWO_4$.
  - Bias in photon energy scale due to **non-uniform radiation damage** along crystal depth and applying $Z \to ee$ derived calibrations to photons.
  - **Correct photon energy scale** in data using a dedicated light collection efficiency (LCE) model (CMS-DP-24-045).



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

Collected energy for damaged crystal

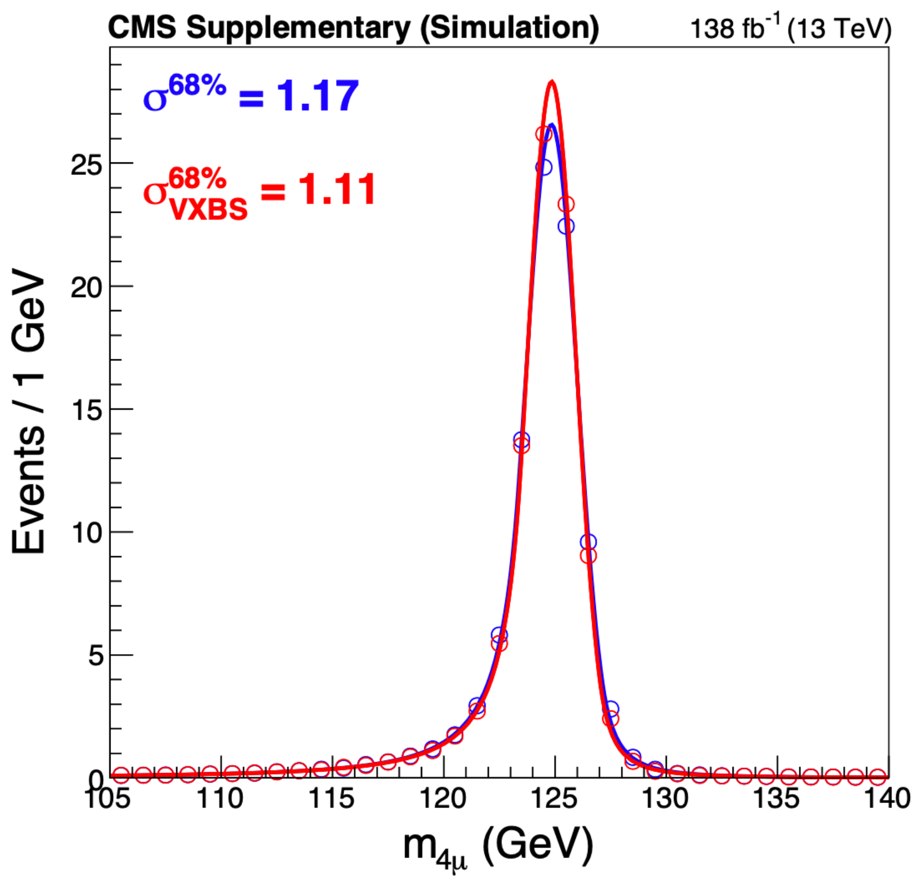
Collected energy for undamaged crystal

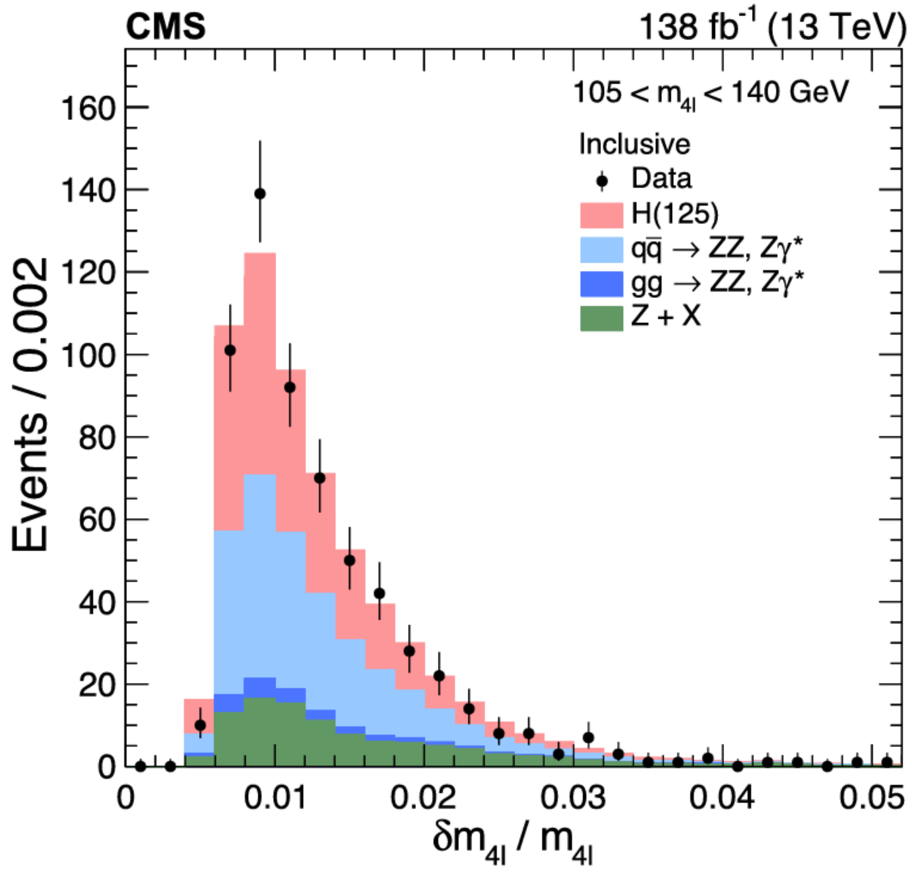
- $S^e(S^\gamma)$ = ECAL response to electrons (photons)
- $E_{dep}(z)$ = shower profile as a function of crystal depth (z) in non-irradiated $PbWO_4$ simulated using Geant4
- R/R_0 = ECAL crystal transparency measured per-run with a laser-based monitoring system

- Uncertainty in F evaluated from discrepancies between the LCE model and light output measurements on irradiated $PbWO_4$ in lab tests.
  - 20% in barrel and 35% in endcaps
- Significant reduction in the impact of this systematic uncertainty expected in full Run 2 mass measurement.

m_H and Γ_H measurements in $H \to ZZ^* \to 4l$

- **Full Run 2** analysis corresponding to 138 fb-1 of data (PRD 111 (2025) 092014).
- High precision through refinement of calibrations and analysis strategy:
  - $4l$ (4μ, $4e$, $2e2\mu$, $2\mu2e$) tracks constrained to a common vertex compatible with beam spot: 3-8% improvement in mass resolution depending on lepton flavor.
  - On-shell mass constraint applied to one Z boson.
  - Event categorization based on relative mass uncertainty of the four-lepton system ($\delta m_{4l}/m_{4l}$): 10% improvement in Higgs mass resolution.



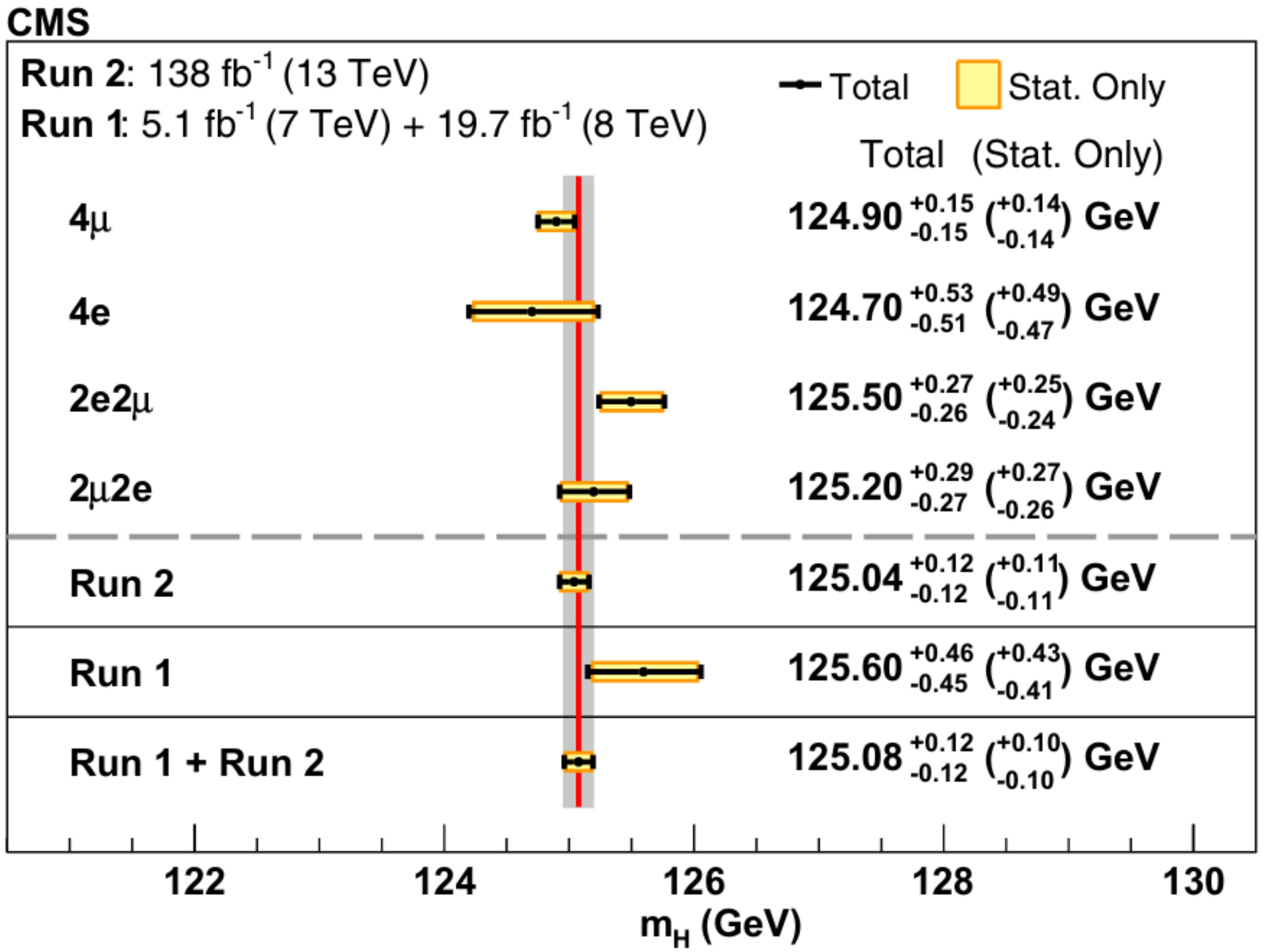


More details on the analysis methodology in Neha's talk!

m_H and Γ_H measurements in $H \to ZZ^* \to 4l$

- Maximum likelihood fit to m_{4l} and a background-reducing kinematic discriminant D_{bkg}^{kin}.
- Most precise single channel measurement:

$$m_H = 125.04 \pm 0.11\ (stat.) \pm 0.05\ (syst.)\ GeV$$ → *Stat. limited*



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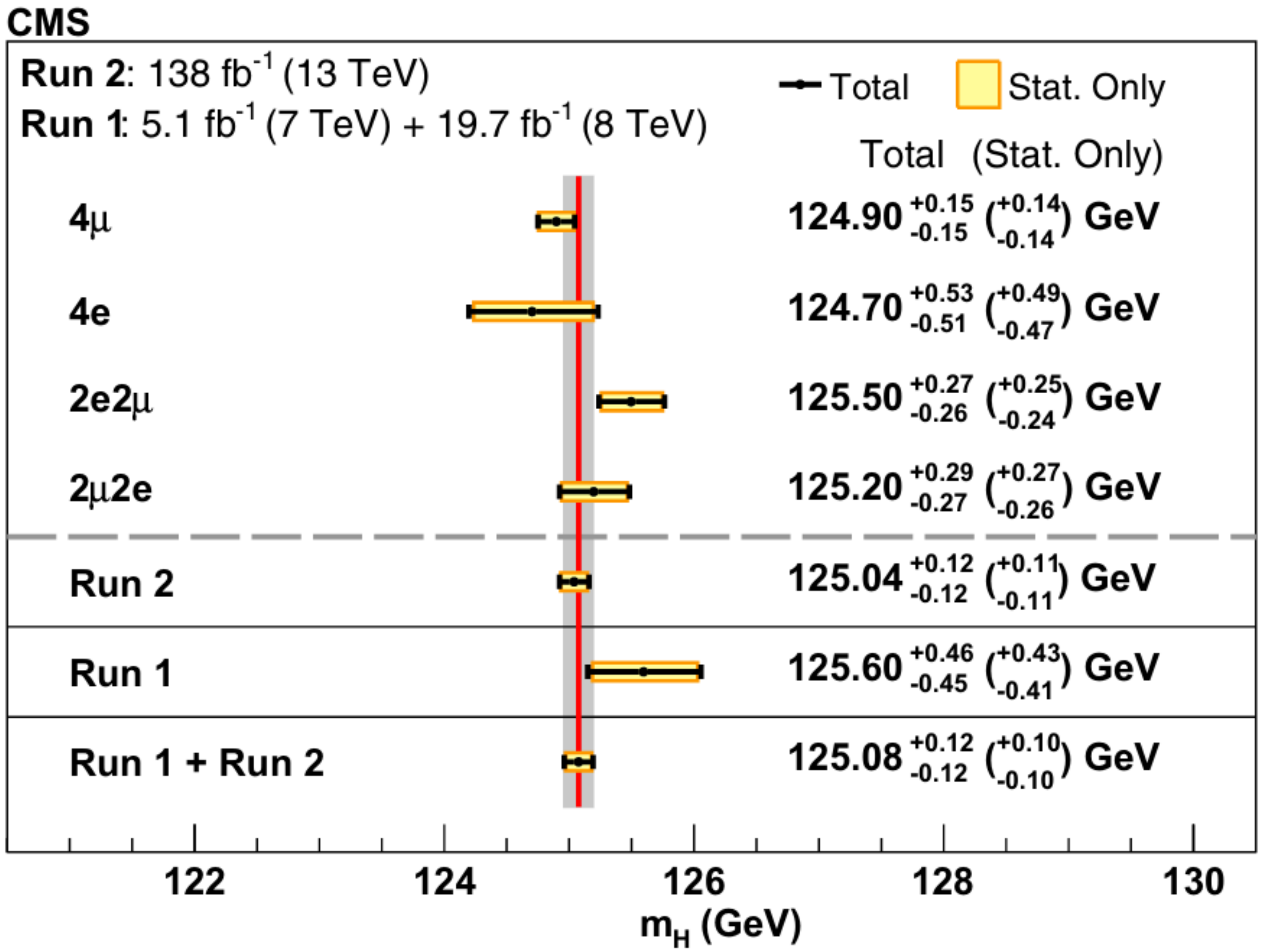
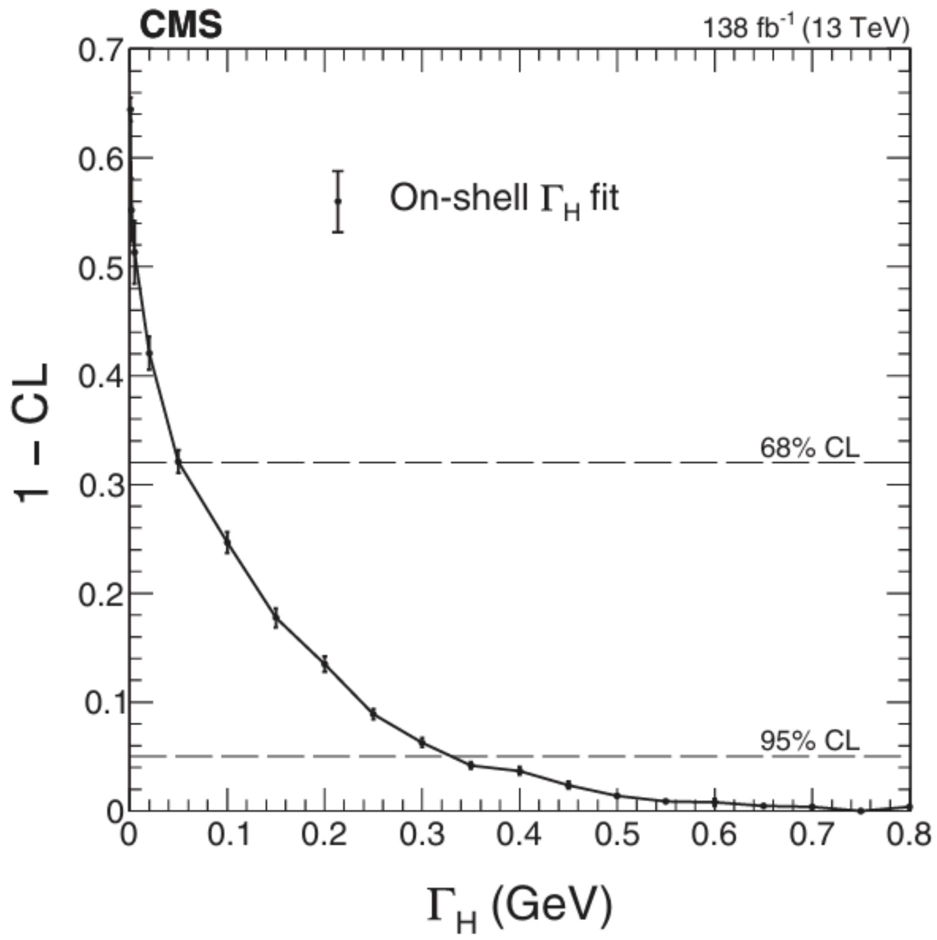




- Direct Γ_H from fitting the invariant mass distribution of $4l$ with a Breit-Wigner (BW) convoluted with a double sided Crystal Ball (DCB) function.
- Result:

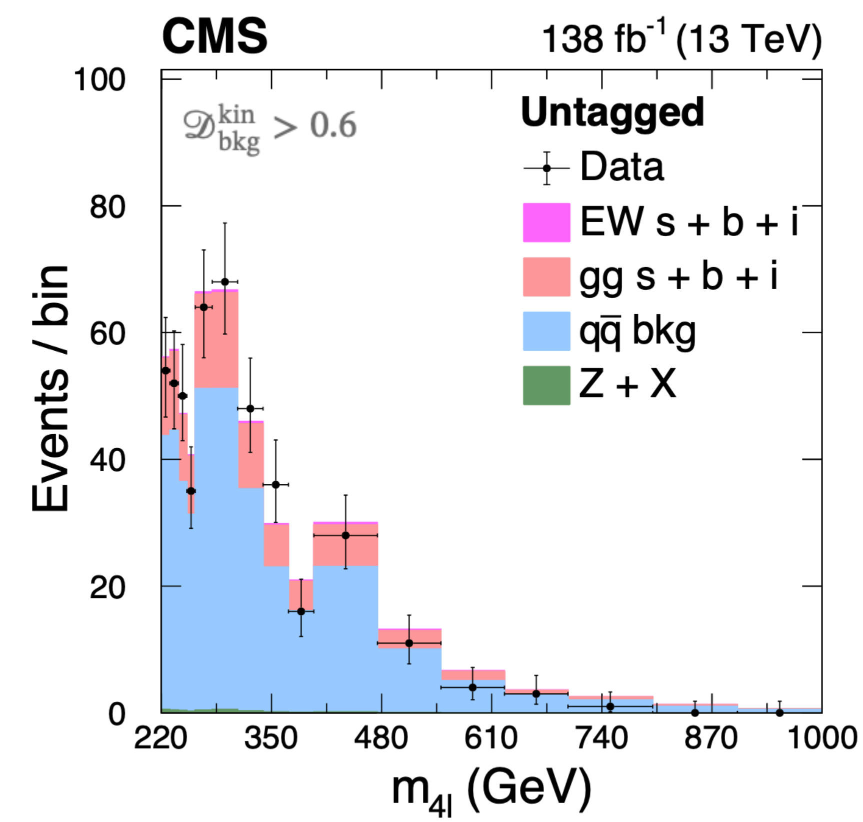
$\Gamma_H <$ 50 (330) MeV at 68% (95%) C.L.

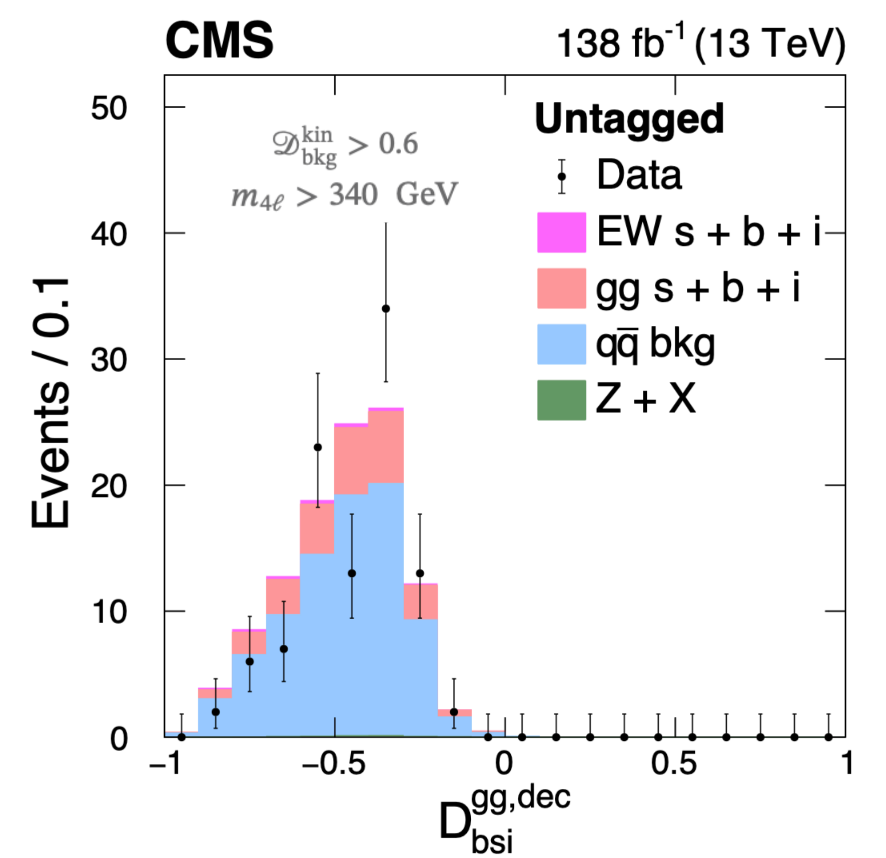
Off-shell Γ_H measurements in $H \rightarrow ZZ \rightarrow 4l$

- Utilizes the different dependence of on-shell and off-shell cross-sections on the width.

$$\frac{\sigma^{on-shell}_{gg \rightarrow H \rightarrow ZZ^*}}{\sigma^{off-shell}_{gg \rightarrow H^* \rightarrow ZZ}} \propto \frac{g_g^2 g_Z^2 / m_H \Gamma_H}{g_g^2 g_Z^2 / 4m_Z^2} \propto \Gamma_H$$

- **Assumes identical on-shell/off-shell couplings**, i.e., no new physics alters the coupling in off-shell case.
- Significant destructive interference between H signal and non-resonant $4l$ production in the off-shell region.
- Interference and cross contamination from on-shell H taken into account in the PDF describing data.
- Events separated based on production mode: VBF, VH & ggH.
- Two **kinematic discriminants** built to tag interference (D_{int}) and background events (D_{bkg}).
- Likelihood fit performed using observables: m_{4l} , D_{int} , D_{bkg}.





Off-shell Γ_H measurements in $H \rightarrow ZZ \rightarrow 4l$

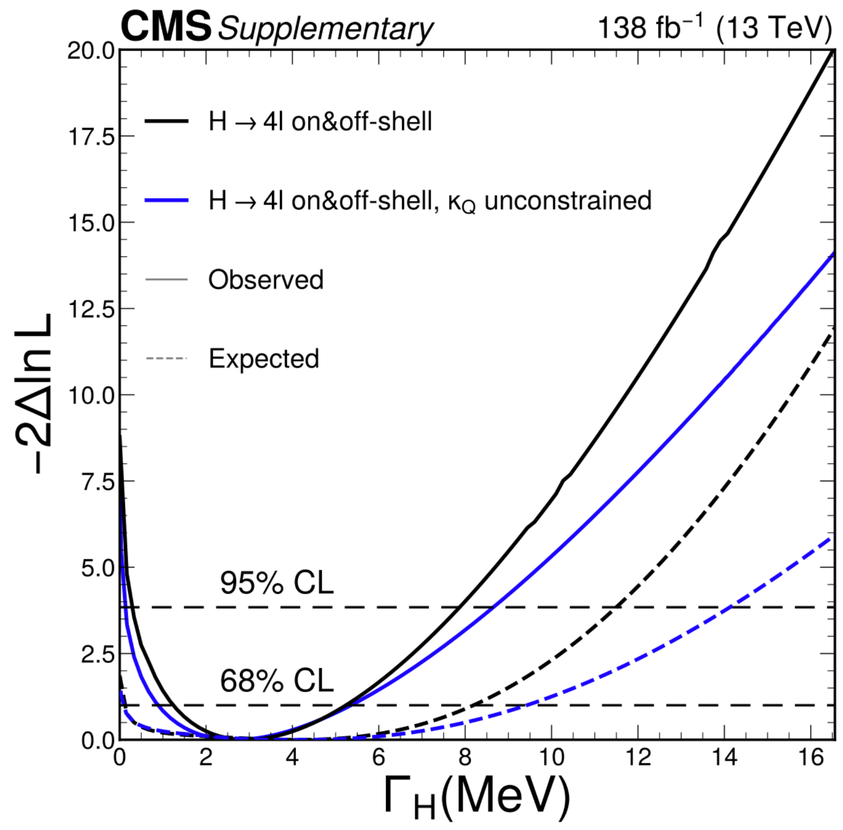
- Measurement compatible with SM:

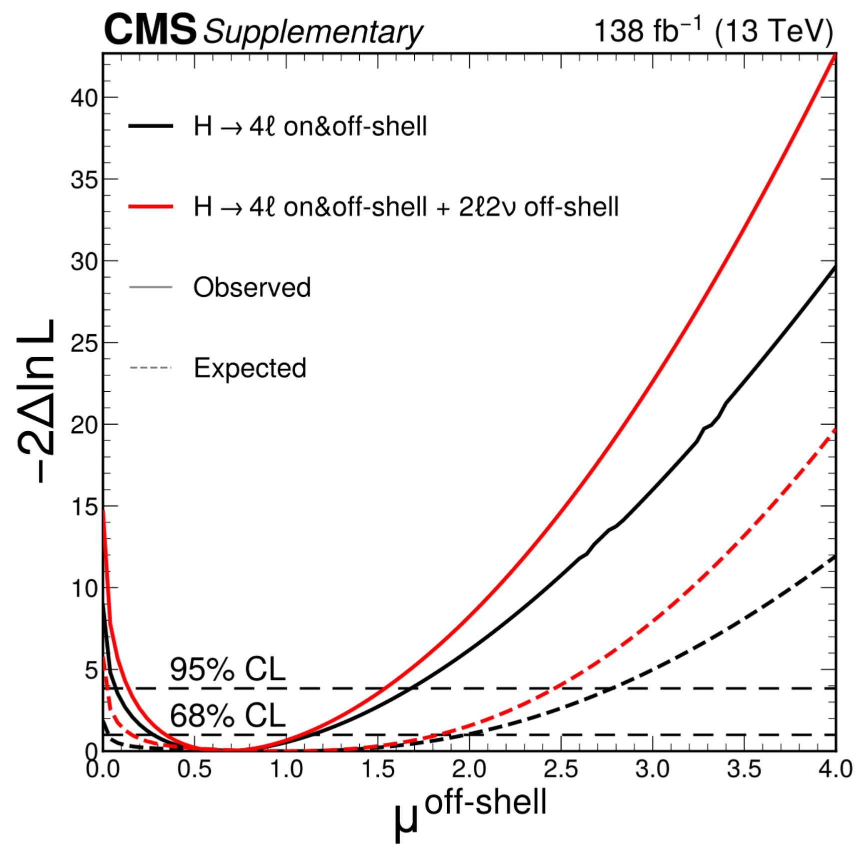
  $$\Gamma_H = 2.9^{+2.3}_{-1.7}\ MeV$$

- Combination with off-shell $2l2\nu$ channel ([Nature Physics 18, 1329-1334, 2022]()):

  $$\Gamma_H = 3.0^{+2.0}_{-1.5}\ MeV$$

- **SM dependency studied** by introducing a heavy quark Q in the ggH loop.
  - An unconstrained coupling strength κ_Q included in the PDF parametrization using EFT-based MC templates.
  - Value of κ_Q constrained by on-shell/off-shell data and bounds on Γ_H is less stringent but consistent with $\kappa_Q = 0$.
  - Stricter constraints on κ_Q possible with future combinations with other on-shell measurements.
- $\mu_{off-shell} = 0$ **excluded** with a CL corresponding to 3.8σ





AC measurements in $H \to \gamma\gamma$

- **New full Run-2** analysis (CMS-PAS-HIG-24-006).
- **HVV** ACs through $H \to \gamma\gamma$ events produced via VBF and VH modes, and **Hgg** AC through ggH + 2 jets events.
- As per usual practice, AC measurements expressed in terms of **cross-section fractions** (systematic uncertainties cancel out):

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

- Analysis categories defined and optimized using **MELA paired with ML** discriminants to maximize the sensitivity to a CP-odd signal.
- Four HVV and one Hgg AC cross-section ratios measured using a simultaneous maximum likelihood fit to the $m_{\gamma\gamma}$ spectra across all categories.
- Results **consistent with SM** as well as with previous measurements.

$$A(HVV) \sim \left[a_1^{VV} + \frac{k_1^{VV} q_{V1}^2 + k_2^{VV} q_{V2}^2}{(\Lambda_1^{VV})^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*\mu\nu(2)} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*\mu\nu(2)}$$

SM : VV = ZZ,WW

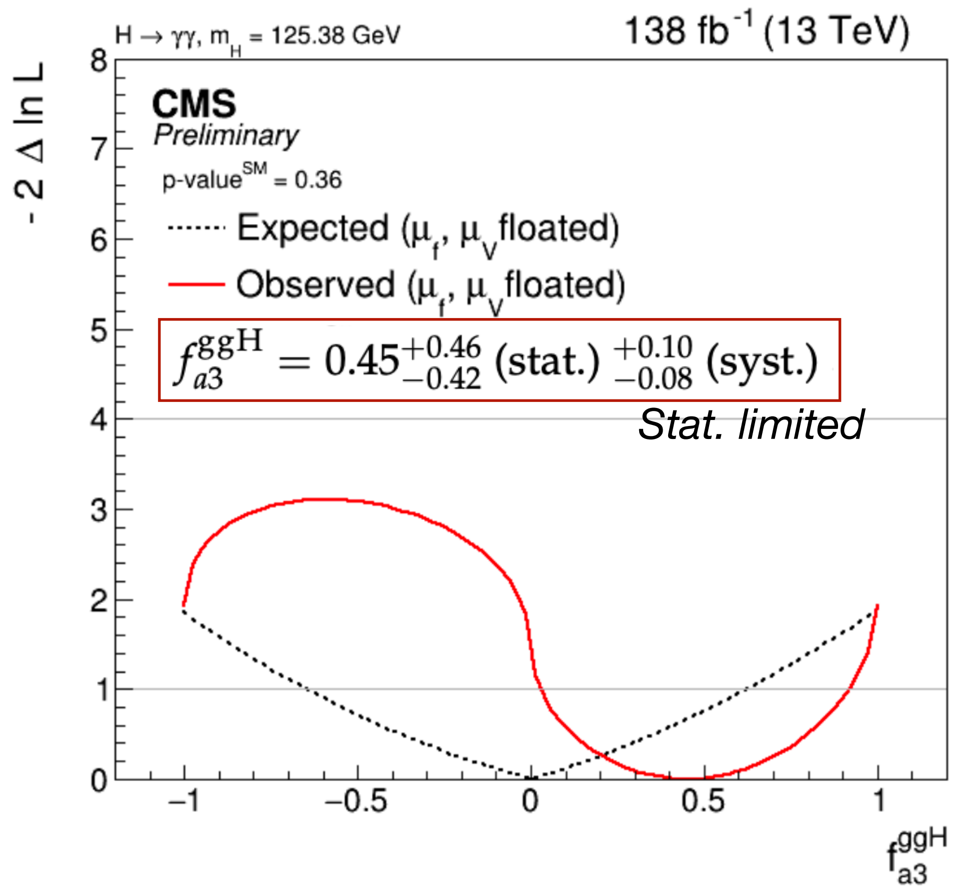
CP Even (higher order couplings) ($\Lambda_1 = 1 TeV$)

CP Even

CP Odd

Parameter	Expected/(10^{-4}) 95% CL $H \to \gamma\gamma$	Observed/(10^{-4}) 95% CL $H \to \gamma\gamma$
f_{a3}	[−5.4,5.4]	[−1.5,1.5]
f_{a2}	[−8.8,10]	[−5.5,1.2]
$f_{\Lambda 1}$	[−0.48,1.2]	[−0.36,0.17]
$f_{\Lambda 1}^{Z\gamma}$	[−9.5,9.9]	[−2.5,4.8]

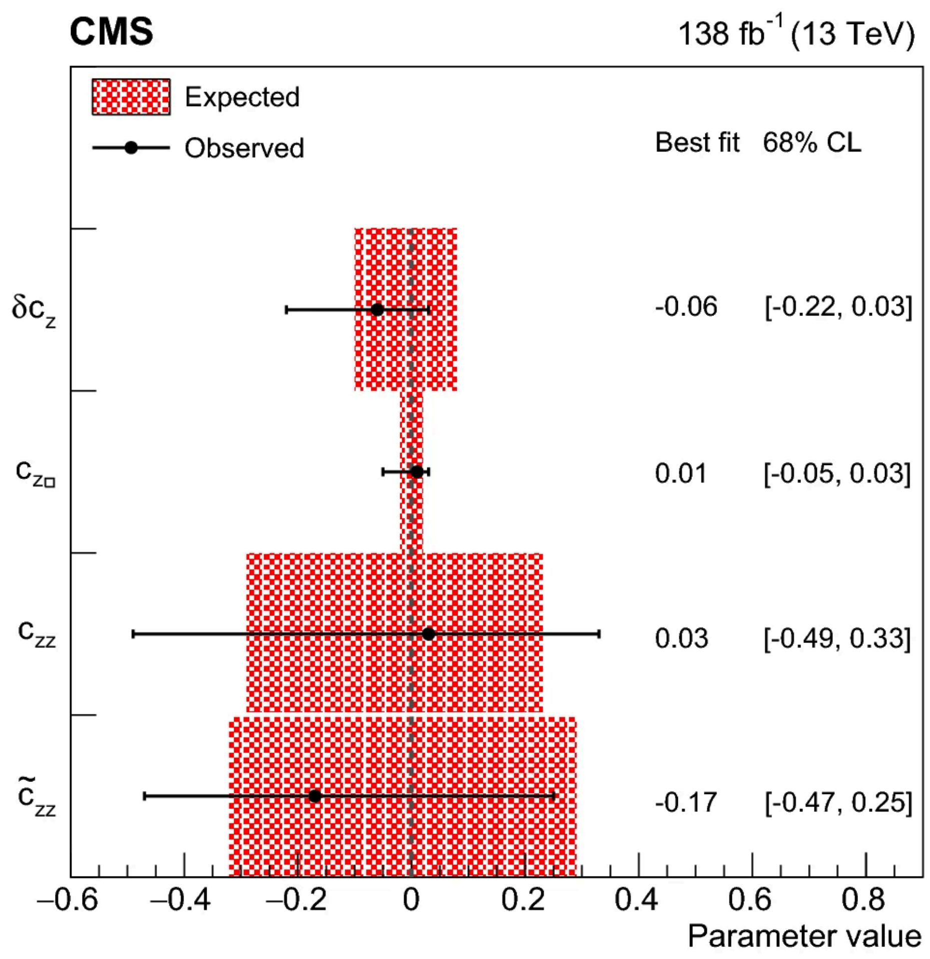
Some of the most stringent limits to date!

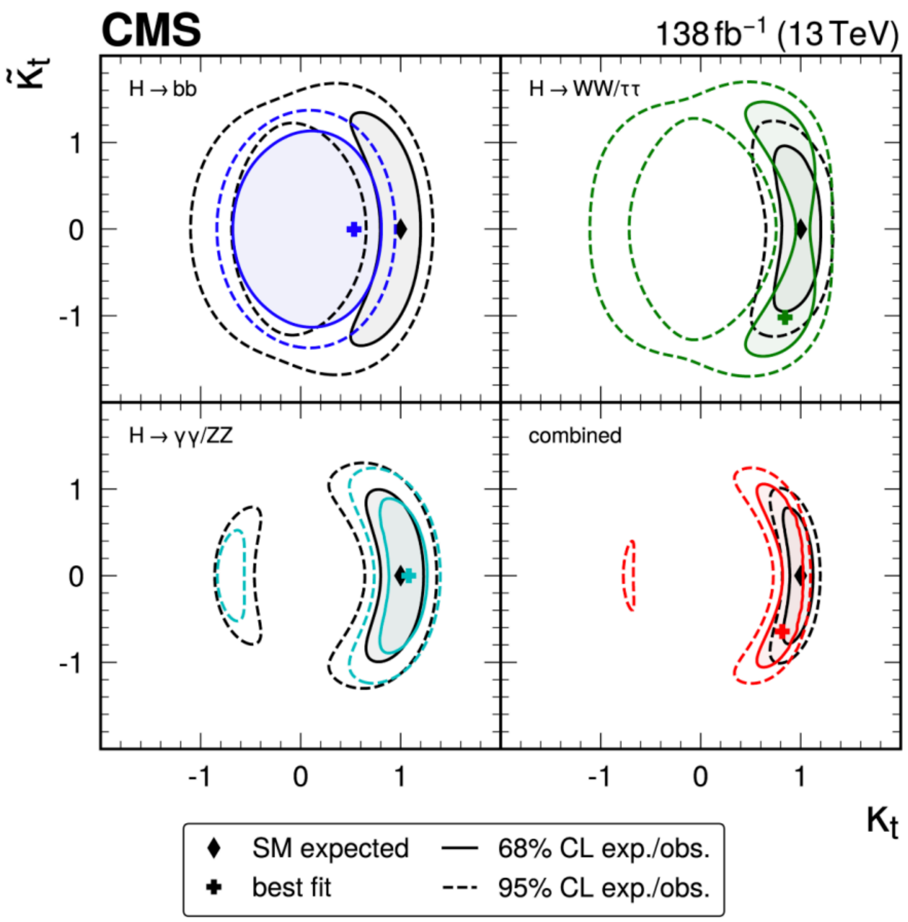


See Federica's talk for more details!

Other AC searches

- Search for anomalous HVV and Hgg couplings using $H \to WW$ production (VBF, VH, ggH + 2 jets) and decay (different-flavor dilepton final states) (EPJC 84, 779 (2024)).
- MELA-based kinematic discriminants to increase the sensitivity at the production vertex.
- AC measurements in terms of cross-section fractions.
- Additionally, a simultaneous measurement of four HVV ACs performed in the SMEFT framework.
- All results are consistent with the SM.





- AC search using ttH(bb) and tH production (JHEP 02 (2025) 097).
- top-Higgs coupling parametrized with purely CP-even (κ_t) and CP-odd ($\tilde{\kappa}_t$) terms.
- Best-fit values after combination with other H decay channels: $(\kappa_t, \tilde{\kappa}_t) = (0.82, -0.65)$

Summary

- Presented results of Higgs boson mass and natural width measurements in CMS using $H \to ZZ \to 4l$ and $H \to \gamma\gamma$ channels.
  - Most precise single channel m_H measurement using full Run2 $H \to ZZ \to 4l$ data:

    $$m_H = 125.04 \pm 0.11\ (stat.) \pm 0.05\ (syst.)\ GeV$$

  - Best constraints on Γ_H from indirect off-shell/on-shell cross-section ratio measurement in $H \to ZZ \to 4l$ channel:

    $$\Gamma_H = 3.0^{+2.0}_{-1.5}\ MeV$$

- Presented studies towards reducing systematic uncertainty due to non-uniformity of light collection in full Run2 $H \to \gamma\gamma$ mass measurement.
- Results of CP-violating, anomalous couplings searches presented in several Higgs production and decay channels — consistent with SM expectation of purely CP-even interactions.

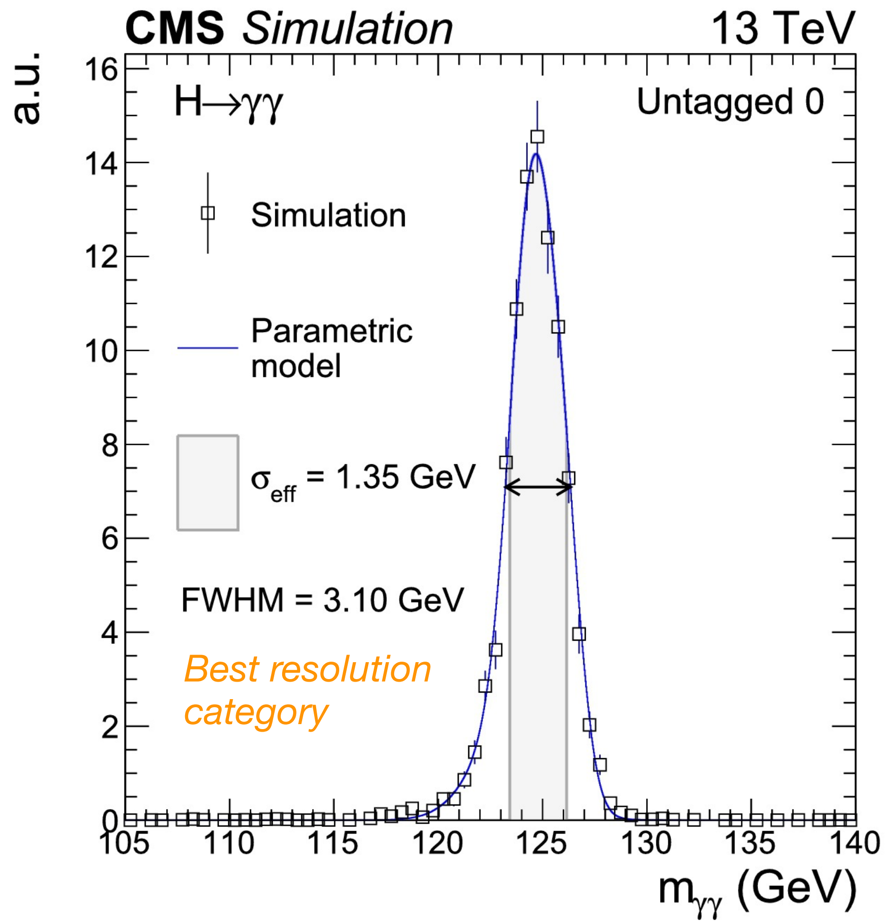
Backup

m_H measurement in $H \to \gamma\gamma$ channel

- **Multi-step residual scale and resolution corrections** to E_γ (following ECAL calibration and multivariate regression), using $Z \to ee$ events with electrons reconstructed as photons.
  - Per LHC-fill corrections to account for shift in E_γ scale due to ECAL radiation damage.
  - Scale & resolution corrections derived simultaneously in fine bins of R_9 (shower shape variable to distinguish converted/unconverted photons) and η.
  - Final scale corrections derived in bins of η and p_T to address residual non-linearity in ECAL response and differences in e/γ energy spectra between $Z \to ee$ and $H \to \gamma\gamma$ decays.
- Systematic uncertainty on E_γ scale and resolution corrections evaluated by varying R_9 and $Z \to ee$ event selections.
- Scale corrections re-applied to data and their deviation from unity applied as a residual uncertainty due to non-closure of corrections.
- Estimated **systematic uncertainty** on E_γ scale **from non-uniformity in light collection** due to radiation damage along ECAL crystal depth
  - derived from optical simulation and validated with test beam data on irradiated crystals.

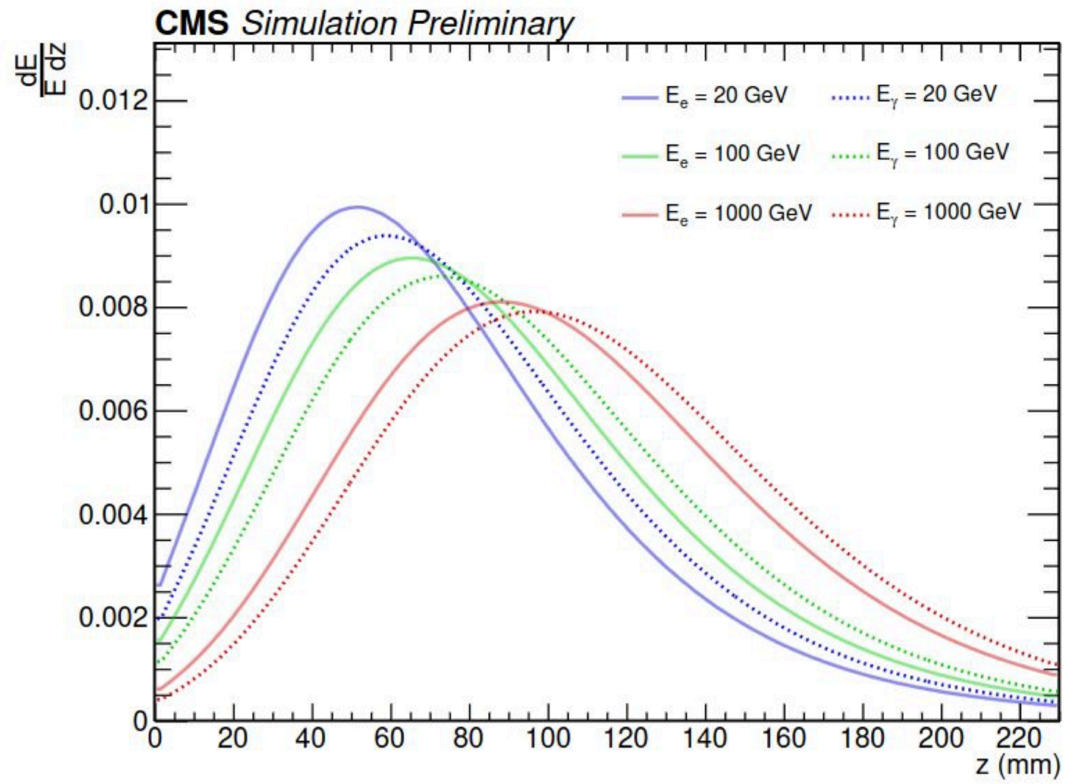
m_H measurement in $H \to \gamma\gamma$ channel

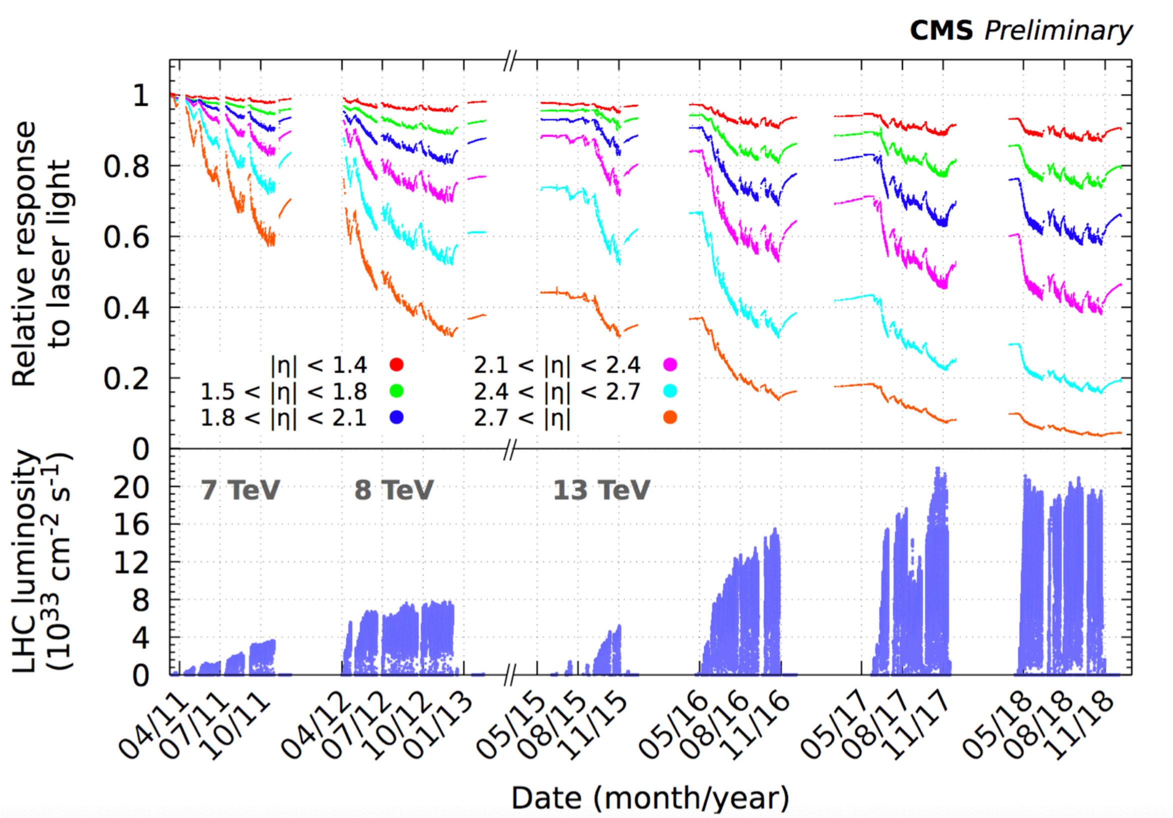
- Parametric signal model per production mode, category and right/wrong vertex scenario from MC — $m_{\gamma\gamma}$ distributions fitted with a sum of upto 4 Gaussians.
- Background models from fits to data side-bands — discrete profiling of plausible PDFs in the final likelihood fit.

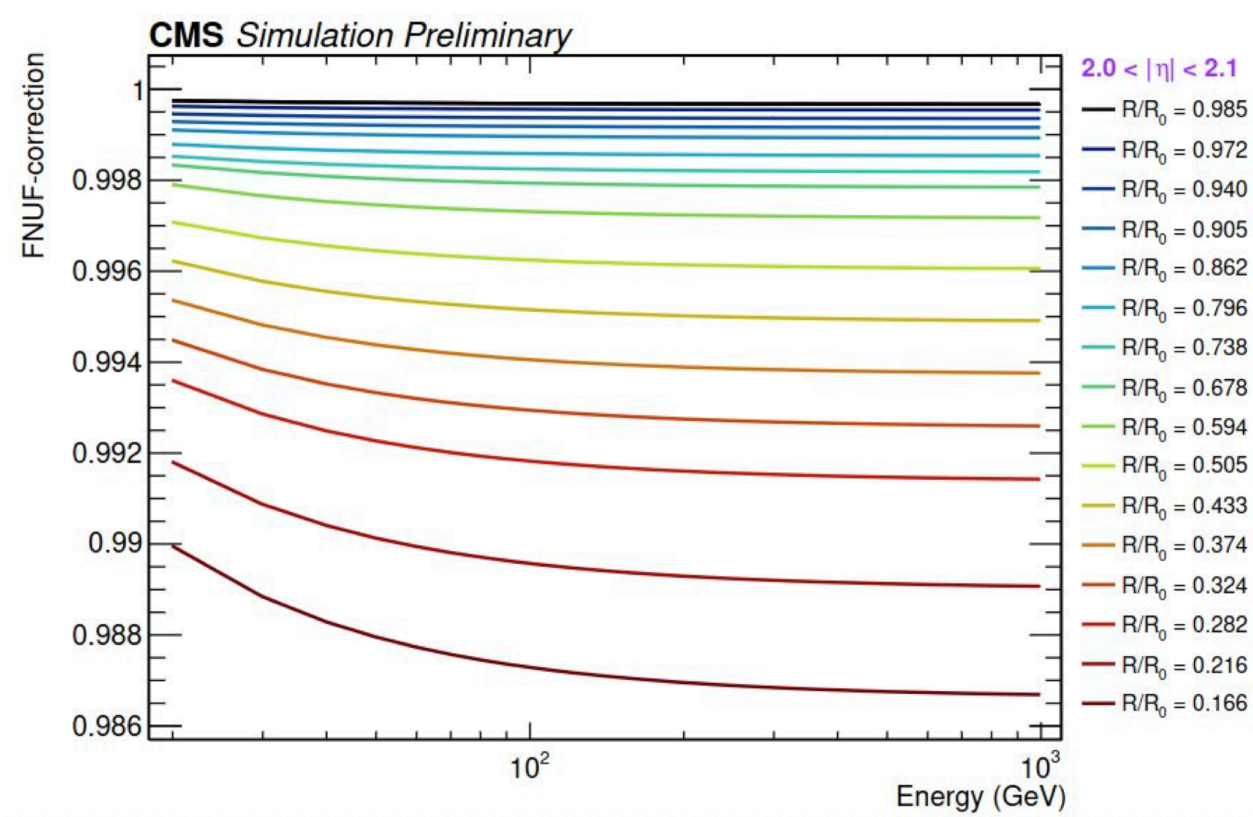


FNUF corrections

- Shower maximum of photons deeper than electrons of the same E by $0.85X_0$ in $PbWO_4$.
- Bias in photon energy scale due to **non-uniform radiation damage** along crystal depth and applying $Z \rightarrow ee$ derived calibrations to photons.
- Light collection efficiency (LCE) as a function of crystal depth (z), transparency loss (R/R_0) and η simulated using Fluka + Litrani.

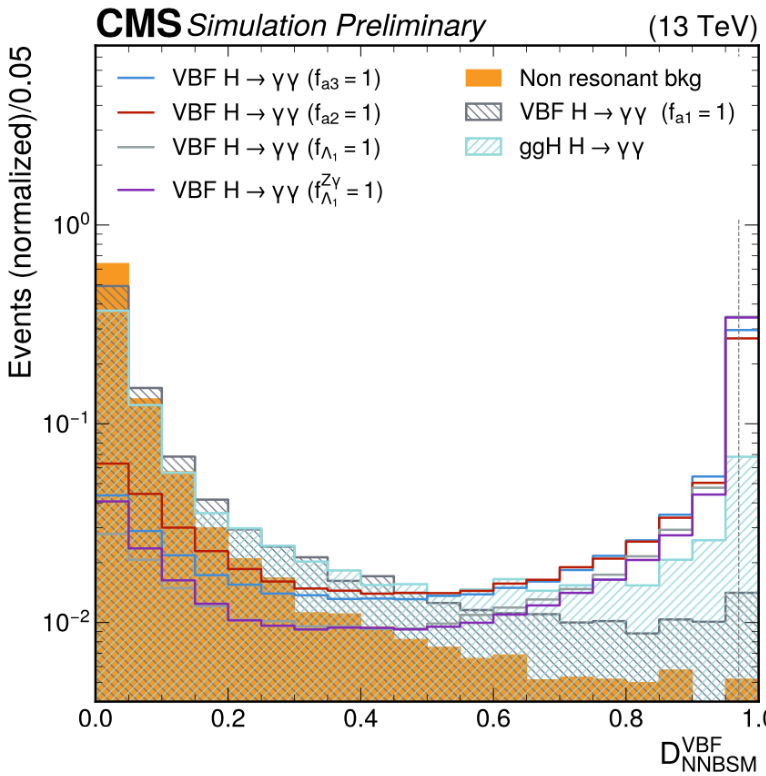






ACs

- **MELA discriminants paired with ML** algorithms for maximum sensitivity. For eg., VBF events divided into two bins in each of the following three discriminants:
  - D_{0-}^{VBF} (MELA-based, CP-even/CP-odd separation),
  - D_{NNBSM}^{VBF}, D_{NNbkg}^{VBF} (DNN-based, VBF sig/bkg separation, SM VBF/BSM separation)
- Categories optimized by scanning each discriminant to maximize the sensitivity to a CP-odd signal.



$$a_1^{\rm WW} = a_1^{\rm ZZ},$$

$$a_2^{\rm WW} = c_{\rm w}^2 a_2^{\rm ZZ},$$

$$a_3^{\rm WW} = c_{\rm w}^2 a_3^{\rm ZZ},$$

$$\frac{\kappa_1^{\rm WW}}{(\Lambda_1^{\rm WW})^2} = \frac{1}{c_{\rm w}^2 - s_{\rm w}^2}\left(\frac{\kappa_1^{\rm ZZ}}{(\Lambda_1^{\rm ZZ})^2} - 2s_{\rm w}^2\frac{a_2^{\rm ZZ}}{m_{\rm Z}^2}\right),$$

$$\frac{\kappa_2^{\rm Z\gamma}}{(\Lambda_1^{\rm Z\gamma})^2} = \frac{2s_{\rm w}c_{\rm w}}{c_{\rm w}^2 - s_{\rm w}^2}\left(\frac{\kappa_1^{\rm ZZ}}{(\Lambda_1^{\rm ZZ})^2} - \frac{a_2^{\rm ZZ}}{m_{\rm Z}^2}\right),$$

→

$$\delta c_{\rm z} = \frac{1}{2}a_1^{\rm ZZ} - 1,$$

$$c_{\rm zz} = -\frac{2s_{\rm w}^2 c_{\rm w}^2}{e^2}a_2^{\rm ZZ},$$

$$\tilde{c}_{\rm zz} = -\frac{2s_{\rm w}^2 c_{\rm w}^2}{e^2}a_3^{\rm ZZ},$$

$$c_{\rm z\Box} = \frac{m_{\rm Z}^2 s_{\rm w}^2}{e^2}\,\frac{\kappa_1^{\rm ZZ}}{(\Lambda_1^{\rm ZZ})^2},$$