Measurements of the Higgs boson mass and width at CMS

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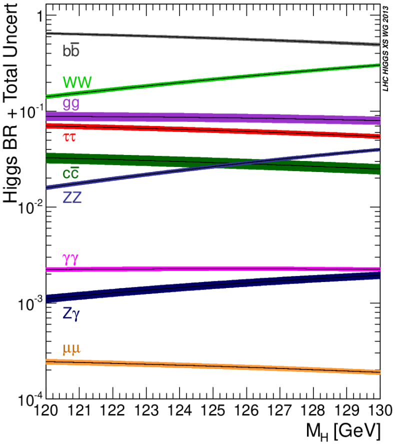
Introduction

- Higgs boson mass (m_H) not predicted by the Standard Model (SM)
- However, all Higgs boson characteristics depend on m_H
- Mass measured precisely in two channels: $H \to \gamma\gamma$ and $H \to ZZ \to 4l$

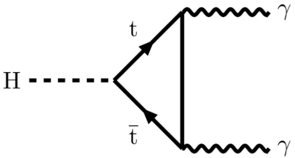
- Decay width (Γ_H) predicted precisely $\to$ deviations may hint at new physics
- Γ_H constrained with $H \to ZZ/WW$, both directly from lineshape and indirectly from off-shell measurements

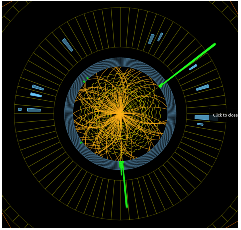


Mass measurement in $H \to \gamma\gamma$

- Clean final state with 0.23% branching ratio
- Early Run 2 analysis with 2016 data (36 fb^{-1}): Phys. Lett. B, 805 (2020)

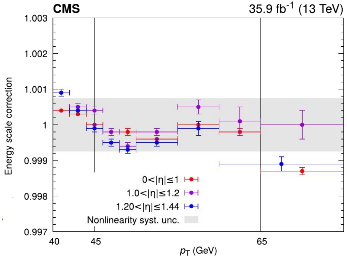
- After ECAL calibration of E_γ, MC correction (mainly for cluster containment) applied using multi-variate regression
- Data/MC residual corrections to E_γ scale and resolution derived from $Z \to ee$ treating e as γ:
  - $\to$ Per-LHC fill shifts in scale due to radiation
  - $\to$ η-cluster shapes dependence (R_9: high $R_9 \leftrightarrow \gamma$ conversions)
  - $\to$ η-p_T dependence (due to non-linearity)

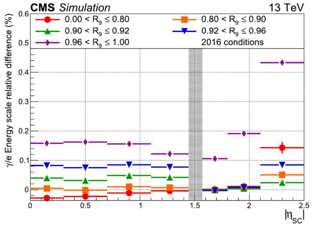




Systematic Uncertainties

- E_γ scale and resolution errors assessed by varying $Z \to ee$ selection criteria
- Residual p_T-dependent scale corrections errors:
  - $\to$ Corrections from $Z(ee)$ ($p_T \approx 45$ GeV) extended to $H \to \gamma\gamma$ ($p_T \approx 60$ GeV)
  - $\to$ Residual corrections reapplied $\to$ deviations from unity treated as systematic errors
- Non-uniformity of light collection caused by radiation damage on ECAL crystals:
  - $\to$ Photons (high R9) have deeper showers than electrons (used to calibrate)
  - $\to$ Error estimated with Geant4 + light-tracing simulations + test beam data with irradiated crystals



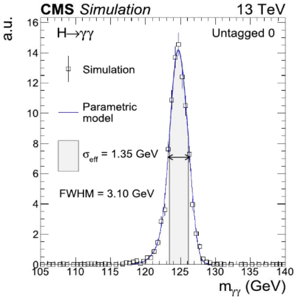


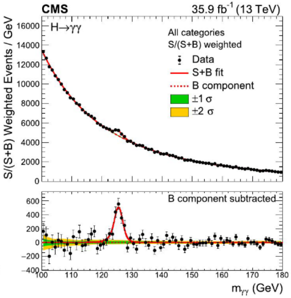
Results

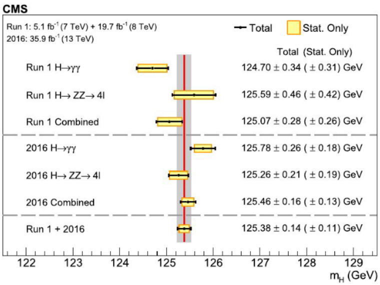
- Binned fit performed in 7 categories based on σ_m, with $\langle \sigma_m \rangle \approx$ 1.68 GeV and $\sigma_m = 1.35$ GeV in the best category
- Result:

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

- Measurement precision is at the per-mille level
- Large uncertainty (0.11 GeV) from light collection non-uniformity

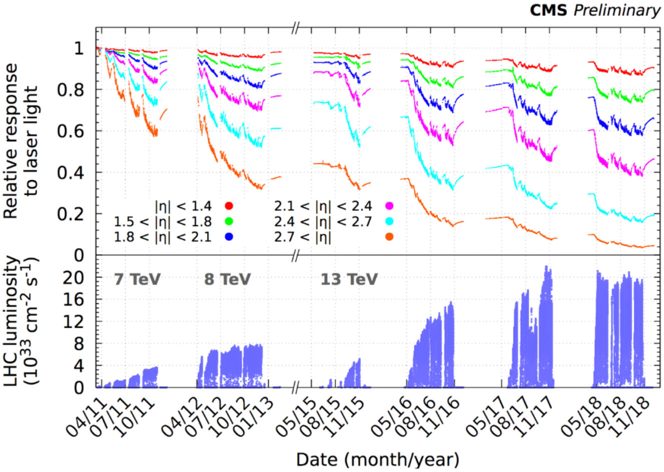






CMS ECAL transparency loss

- Scintillation light emitted by $\sim$ 20 cm long $PbWO_4$ crystals measured by APDs
- Photons showers start deeper ($\sim 9/7 X_0$) $\rightarrow$ differences w.r.t. $Z \rightarrow e^+e^-$



- Crystals not anymore transparent due to integrated dose
  - $\rightarrow$ Transparency measured online with a laser monitoring system
  - $\rightarrow$ Depending on the path inside crystals a different fraction of light is lost

Correction of light collection non-uniformity

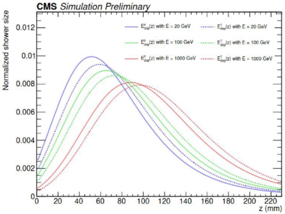
- In view of full Run 2 analysis this effect is corrected, otherwise its syst. uncertainty would dominate
- Light collection efficiency as a function of depth (z) simulated (CMS-DP-24-045) to determine energy scale corrections $\rightarrow$ dedicated uncertainty assigned to the correction

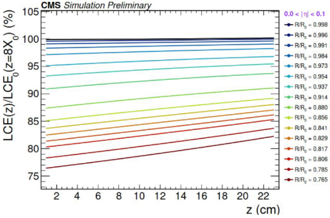
$$F = \frac{S^e}{S^\gamma} = \frac{\dfrac{\int E^e_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R}/\mathrm{R}_0, \eta)\, \mathrm{d}z}{\int E^e_{\mathrm{dep}}(z)\, \mathrm{d}z}}{\dfrac{\int E^\gamma_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R}/\mathrm{R}_0, \eta)\, \mathrm{d}z}{\int E^\gamma_{\mathrm{dep}}(z)\,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

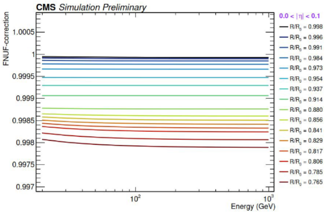
- S_e (S_γ): ECAL response to electrons (photons)
- $E_{dep}(z)$: shower profile in $PbWO_4$ (Geant4)
- $LCE(z)$: Light Collection Efficiency, simulated with Fluka+Light-tracing (Litrani code)
- R/R_0: ECAL laser response measured in data $\rightarrow$ per-run corrections possible

Correction of light collection non-uniformity

- Using crystal transparency measured online in data, corrections for light collection non-uniformity are evaluated
- This approach should significantly reduce uncertainty in full Run 2 mass measurement



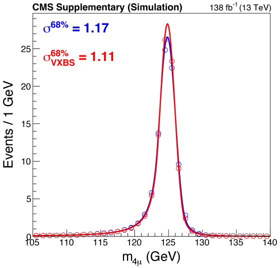


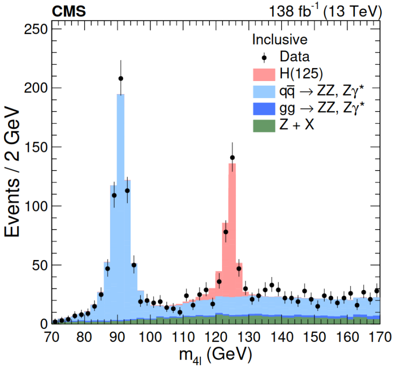


(shower profile) (light collection efficiency) (correction)

Mass measurement in $H \to ZZ \to 4l$

- Full Run 2 analysis (138 fb^{-1}) published in PhysRevD.111.092014
- Analysis improved from early studies:
  - 4-lepton tracks constrained to vertex within beam spot
  - One Z boson constrained to be on-shell
  - Categorization based on σ_m/m
  - Used kinematic discriminant to reduce background

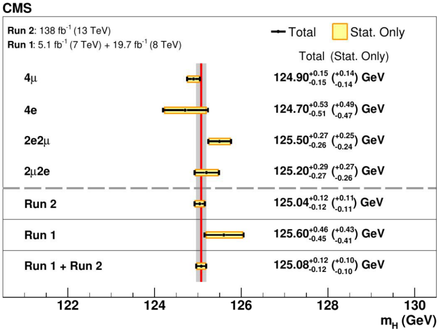




Results

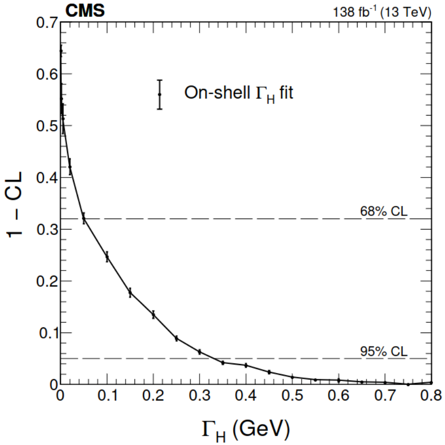
- Maximum likelihood fit performed using m_{4l} and a kinematic discriminant D_{bkg} to reduce background
- Major systematic uncertainties come from lepton scale (0.03% for μ and 0.15% for e)

- Result:
  $m_H = 125.04 \pm 0.11$(stat.) $\pm\, 0.11$(syst.) GeV
- Most precise single-channel Higgs mass measurement to date



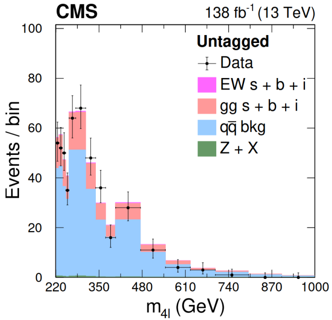
On-shell direct Γ_H measurement in $H \to ZZ \to 4l$

- Mass fit performed with Double Crystal Ball function convoluted with a Breit-Wigner to bound Γ_H
- $\Gamma_H < 50$ (330) MeV at 68 (95) % C.L.
- Direct measurement oof BW width Γ_H limited by mass resolution
- Reduced precision, but model independent



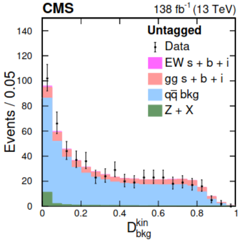
Off-shell indirect Γ_H measurement

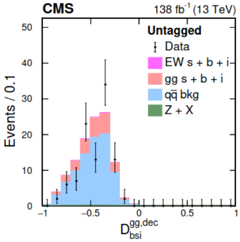
- Measurement performed by combining $4l$ and $2l2\nu$
- Off-shell method based on theory assumptions:
  - $\rightarrow$ Off-shell/on-shell coupling ratio known
    - $\rightarrow \mu_{off-shell} \propto \Gamma_H$
  - $\rightarrow$ ggH loops dominated by top (no BSM)
- Large interference between off-shell signal and continuum background



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

Analysis strategy for $4l$

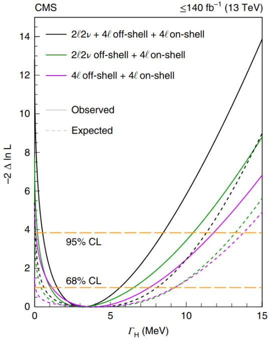


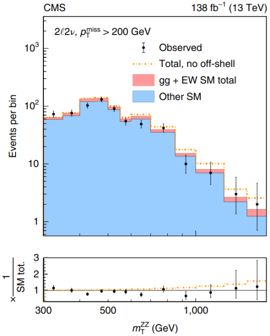


- Three kinematical discriminants built from matrix-elements to tag VBF, WH, ZH
- Events separated in VBF-Tagged, VH-Tagged and Untagged categories
- Two additional kinematical discriminants D_{bkg}, D_{int} build to tag interference and background
- Performed fit with observables: m_{4l}, D_{bkg}, D_{int}

Analysis strategy for $2l2\nu$

- $2l2\nu$ analysis published in *Nature Physics 18, 1329-1334, 2022*
- $2l2\nu$ not used on-shell because only p_T^{miss} is measured $\rightarrow m_{2l2\nu}$ not precise
- In off-shell Higgs boson production, Z bosons are on-shell and m_{ZZ}^T (using only p_T^{miss}) is sufficient to observe the final states (no peak at m_H)

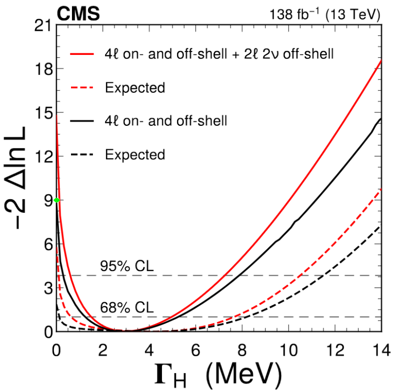


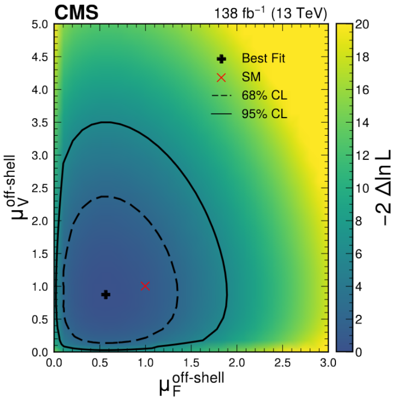


- Fit performed with 2 or 3 observables:
  - $\rightarrow m_{ZZ}^T$
  - $\rightarrow p_T^{miss}$, to reject Z+jets bkg
  - $\rightarrow$ a kinematical VBF-tagger D_{VBF} (only when $N_{jets} \geq 2$)

Results

- Best bound on Γ_H to date: $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV (Exp. 4.1 ± 4.0 MeV)
- $\mu_{off-shell}$ evaluated for both ggH (fermion coupling) and EW (boson coupling) Higgs production modes using different categories
- $\mu_{off-shell} = 0$ excluded at $> 3\sigma \rightarrow$ Evidence for off-shell production





Summary

- CMS measured Higgs boson mass and width with high-mass-resolution channels: $\gamma\gamma + ZZ$
- Most precise single-channel measurement on m_H in $H \to ZZ \to 4l$ made with full Run2 data
- Made studies to reduce uncertainty caused by light collection non-uniformity for full Run2 mass measurement in $H \to \gamma\gamma$
- Γ_H bounded effectively with off-shell Higgs boson production in $H \to ZZ$

Backup

$H \to \gamma\gamma$ systematic uncertainties impacts

- Leading sources of systematic uncertainty:
  - $\to$ electron energy scale and resolution correction
  - $\to$ residual p_T dependence of photon energy scale
  - $\to$ nonuniformity of light collection

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