

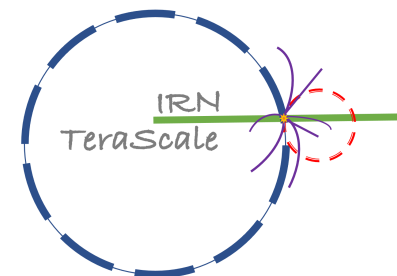
CMS Run 2 $H \rightarrow \gamma\gamma$ mass measurement and calibration improvements

Paul Gaigne, on behalf of the CMS collaboration



IRN Terascale - IJCLab Orsay

April 21, 2026



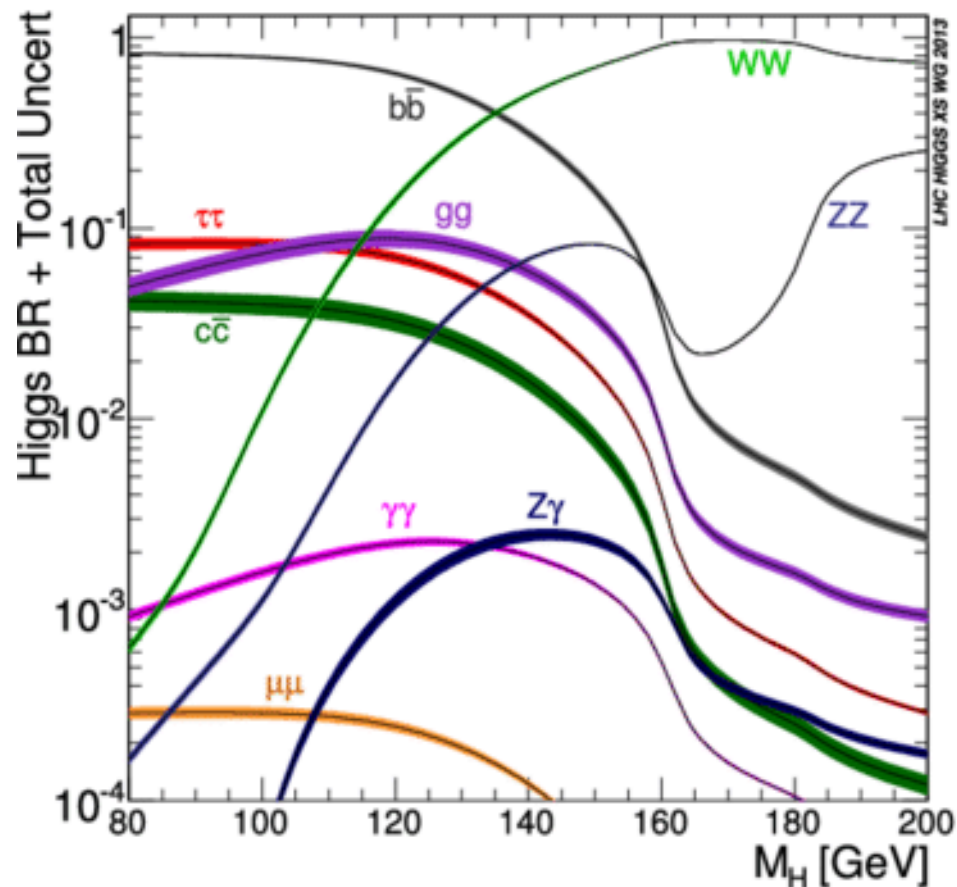
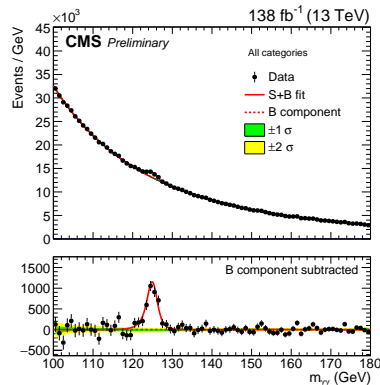
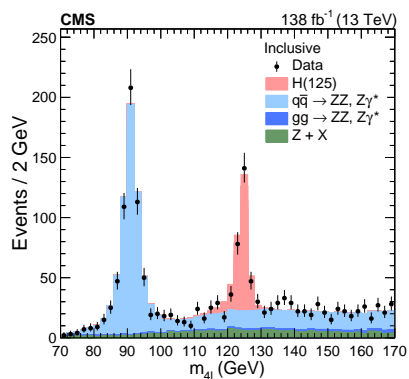
Introduction

Why measuring the Higgs boson mass (m_H) is important?

- ▶ Not predicted by the Standard Model but a free parameter
- ▶ Other properties of the Higgs boson depend on m_H (e.g. XS, couplings, BRs)

Can be measured with high precision in the two golden channels $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$

This talk will present the last CMS result using the full Run 2 dataset in the $H \rightarrow \gamma\gamma$ channel [1].



Higgs mass measurement in CMS

- ▶ The previous CMS mass measurement in the diphoton channel [1] using 2016 Legacy data.

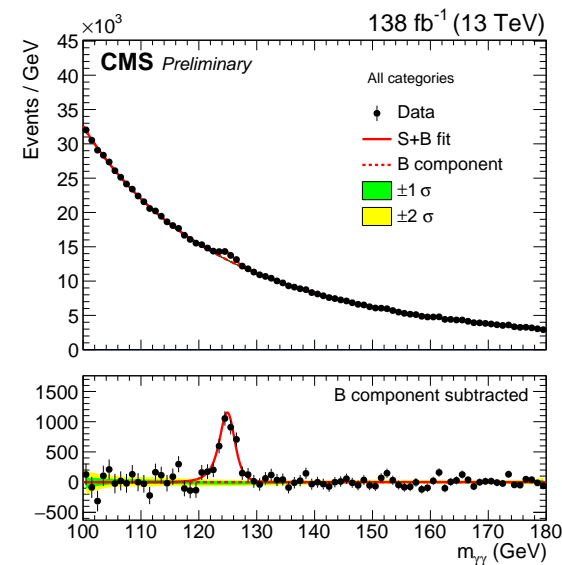
- $m_H = 125.78 \pm 0.18(\text{stat}) \pm 0.18(\text{syst})$

- ▶ The CMS mass measurement in the 4ℓ channel [2] using Run2-UL data:

- $m_H = 125.04 \pm 0.11(\text{stat}) \pm 0.05(\text{syst})$

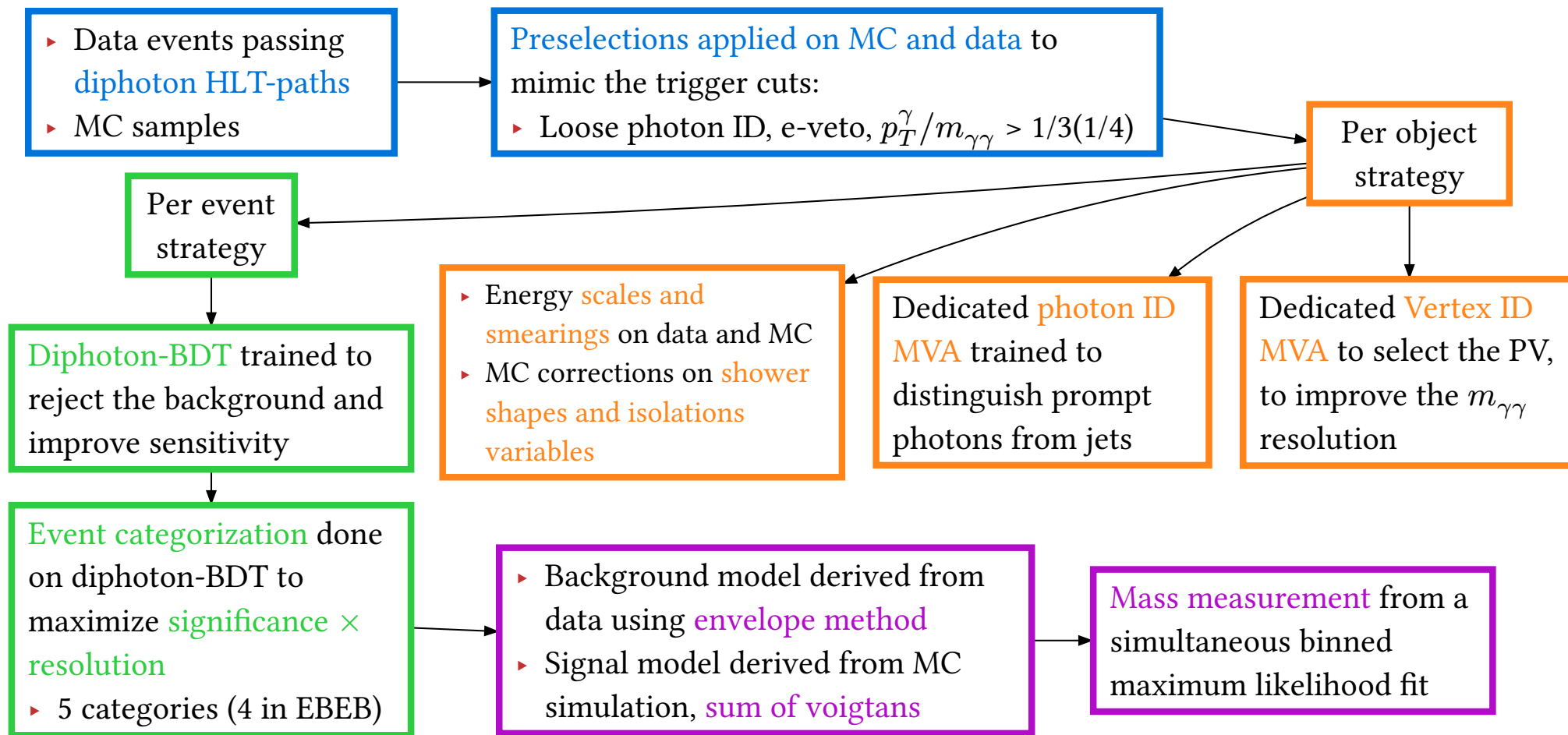
New features compared to the previous measurement in the diphoton channel:

- **More statistics** available 138 fb^{-1} vs 36 fb^{-1} .
- **Refined reconstruction** with fine-tuned calibration of the ECAL
 - ▶ Up to 15% improvement on the electromagnetic object energy resolution
- New photon energy scale and smearing corrections strategy in **three** stages:
 1. $Z \rightarrow ee$ calibrations with a **new framework** IJazZ2.0 [1]
 2. **Uniformity** corrections
 3. Residual **photon energy scale** corrections using true photons from data and simulation with $Z \rightarrow \mu\mu\gamma$ events
- Improvement from event categorization to maximize the **significance** \times **resolution**



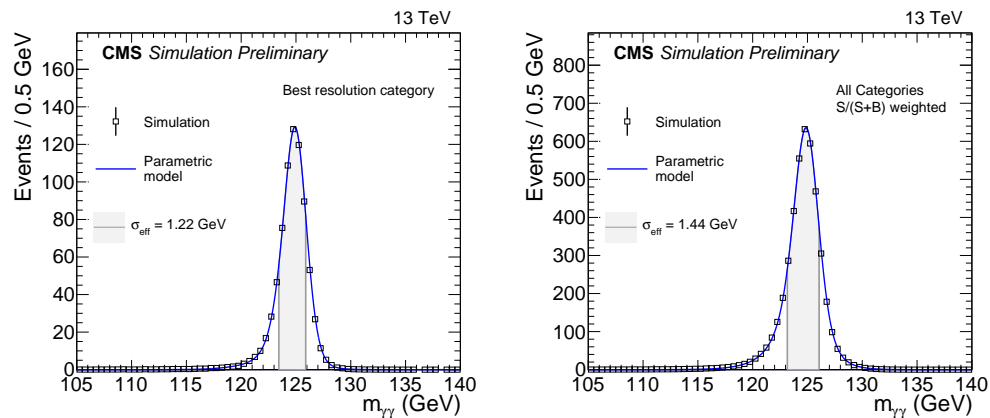
Invariant diphoton mass distribution using Run 2

Overall strategy for the analysis event selection and categorization



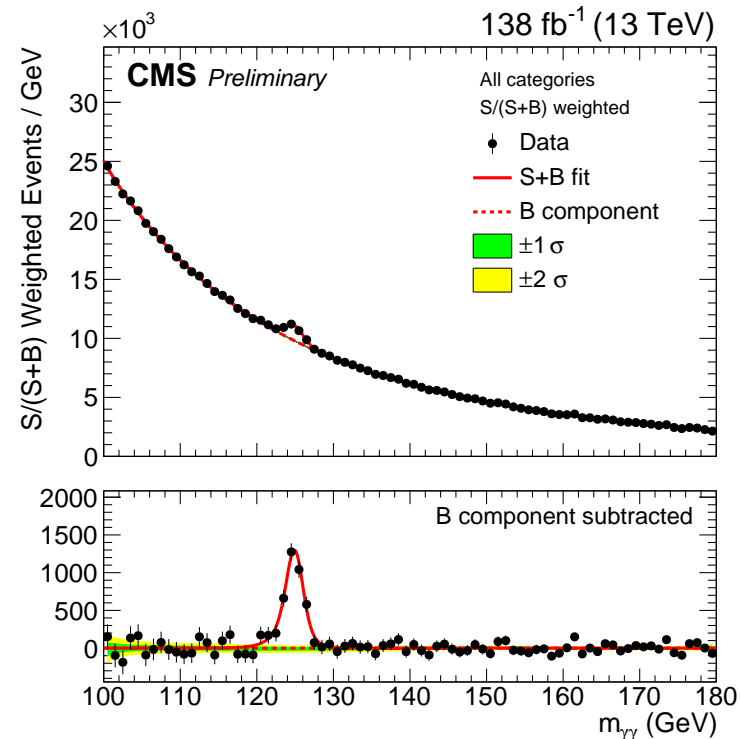
Run 2 $H \rightarrow \gamma\gamma$ mass result

Mass extracted from the simultaneous fit to the diphoton invariant mass distribution in the 5 categories:



Run 2 $H \rightarrow \gamma\gamma$ mass result:

$$m_H = 125.14 \pm 0.10(\text{stat}) \pm 0.11(\text{syst}) \text{ GeV}$$
$$= 125.14 \pm 0.15 \text{ GeV}$$

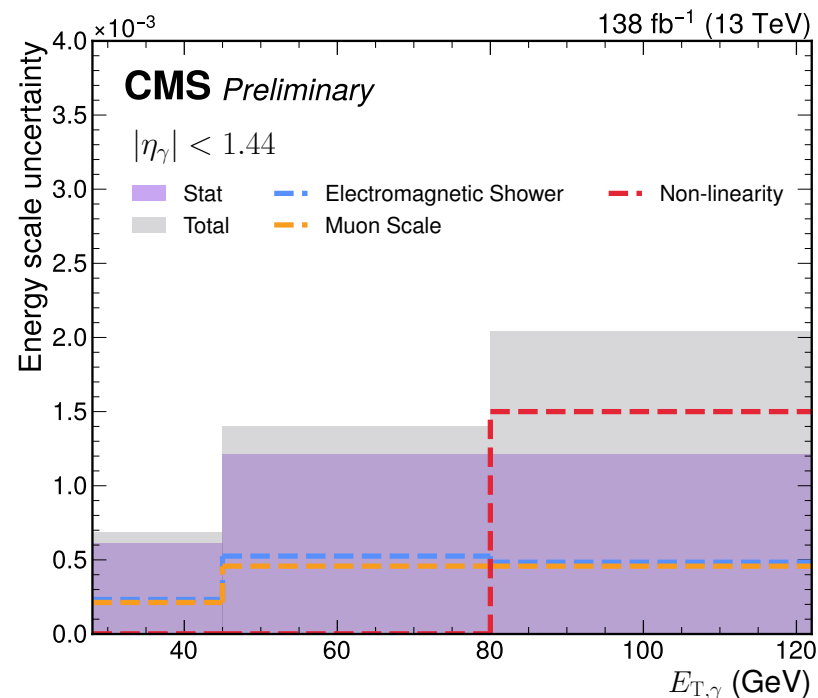


Systematic uncertainties on the photon energy scale

New strategy given the additional corrections using true photons:

- ▶ The **electron to photon extrapolation** uncertainties are no longer considered
 - 110 and 30 MeV in CMS-HIG-19-004.
- ▶ Photon scale uncertainty limited by **Z → μμγ statistics**

Source	Impacts (MeV)
Energy scale	
▶ Statistical uncertainty	75
▶ Residual non-linearity at high E_T	64
▶ Muon momentum scale uncertainty	38
▶ EM shower	23
Energy resolution	7
Interference	27
Other sources	13
Total systematic uncertainty	112
Statistical uncertainty	100
Total uncertainty	150



Combined diphoton mass result

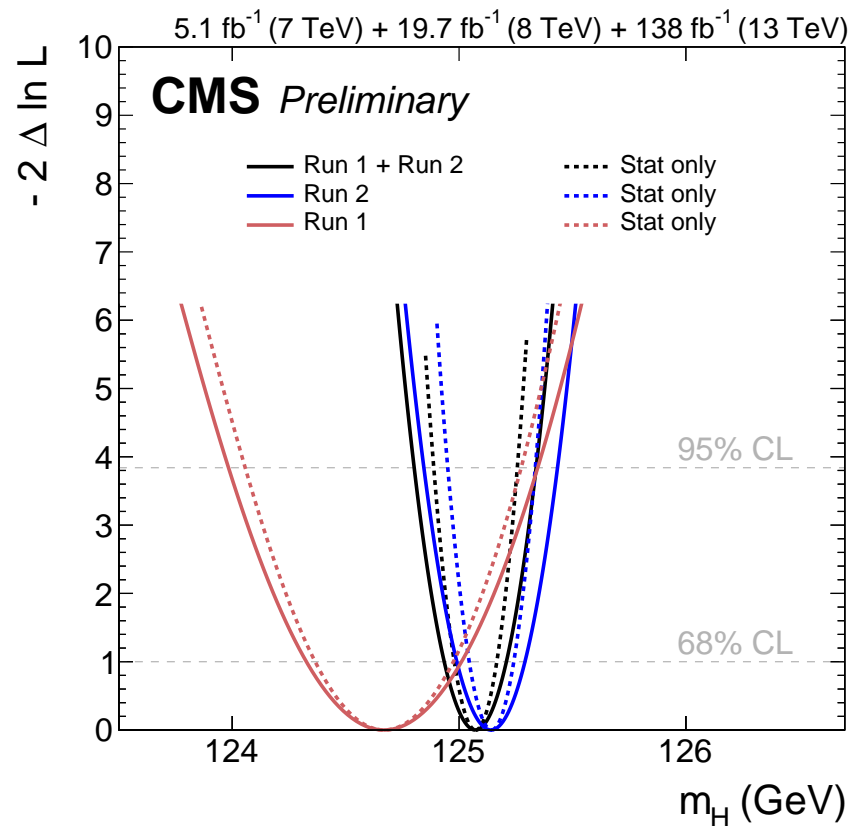
The result is combined with the Run 1 measurement [1]:

$$m_H = 125.07 \pm 0.09(\text{stat}) \pm 0.10(\text{syst}) \text{ GeV}$$

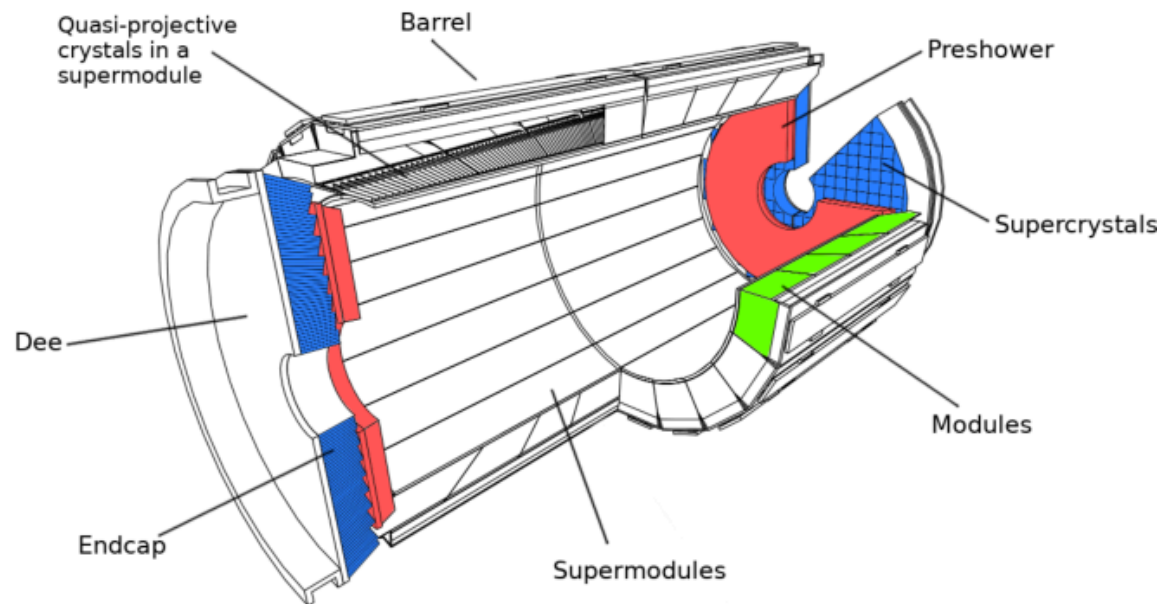
CMS $H \rightarrow \gamma\gamma$	m_H	stat	syst	Total
Run 1	124.70	0.31	0.15	0.34
Run 2	125.14	0.10	0.11	0.15
Run 1 + Run 2	125.07	0.09	0.10	0.13

Which can be compared to the ATLAS combined measurement of m_H using Run 1 and Run 2 datasets in the $H \rightarrow \gamma\gamma$ channel [2]:

$$\begin{aligned} m_H &= 125.22 \pm 0.11(\text{stat}) \pm 0.09(\text{syst}) \text{ GeV} \\ &= 125.22 \pm 0.14 \text{ GeV} \end{aligned}$$



ECAL refined energy calibration



- ▶ High resolution: for precision physics
- ▶ High granularity
- ▶ Complex calibration procedure for maintaining good performance

Homogeneous calorimeter composed of 75848 lead tungstate scintillating crystals (PbWO_4) $\sim 25X_0$

- ▶ **Barrel:** 61200 crystals read out by avalanche photodiodes (APDs)
- ▶ **Endcaps:** 14648 crystals read out by vacuum phototriodes (VPTs)

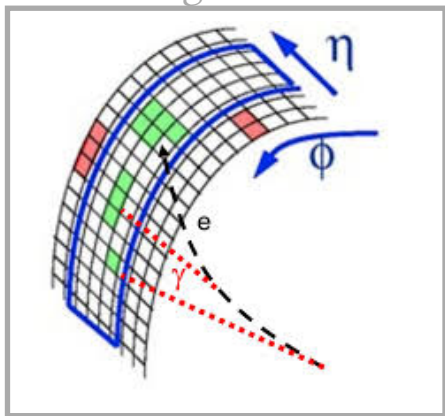
Multi-gain preamplifier: 12, 6 and 1



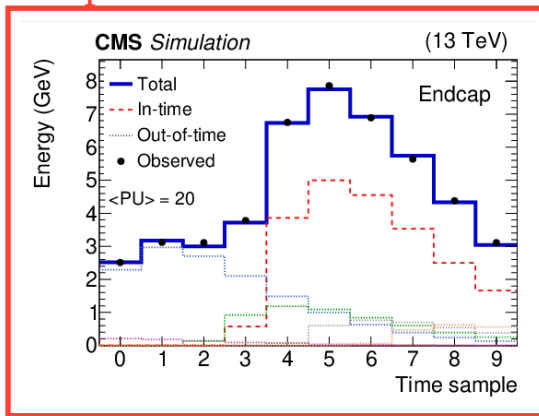
Preshower: $3X_0$ of Pb/Si strips

ECAL refined energy calibration

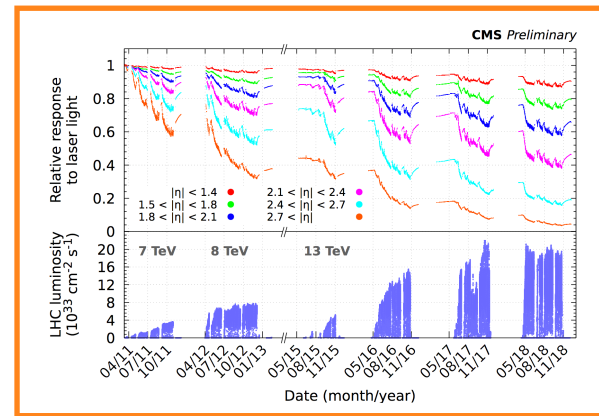
Clustering



Amplitude fit



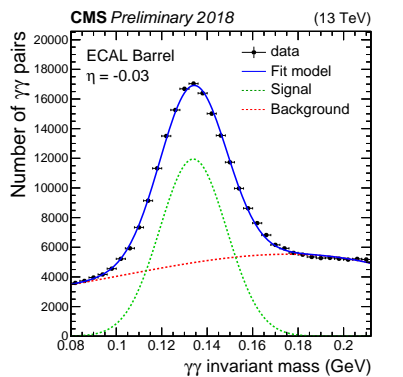
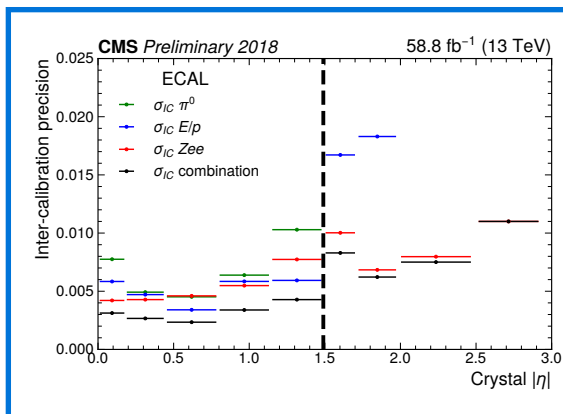
Laser correction



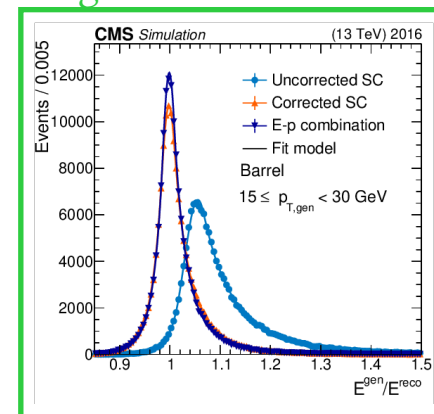
$$E_{e,\gamma} = \sum_i (A_i \times C_i \times LC_i \times G) \times F_{e,\gamma}$$

ADC to GeV

Intercalibration

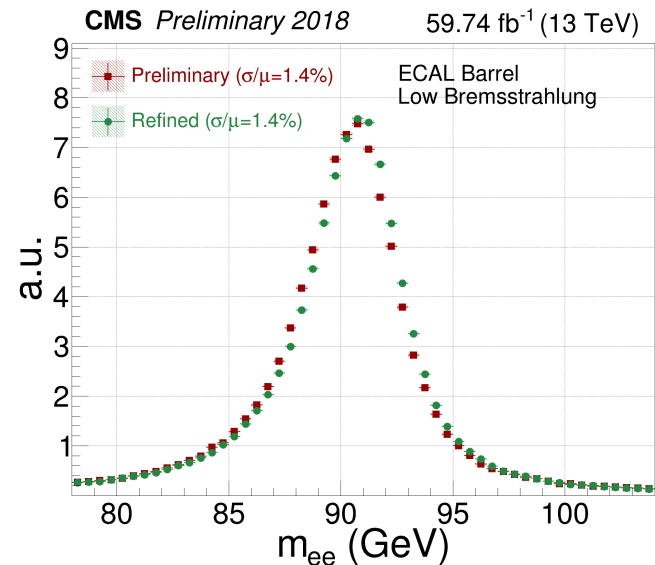
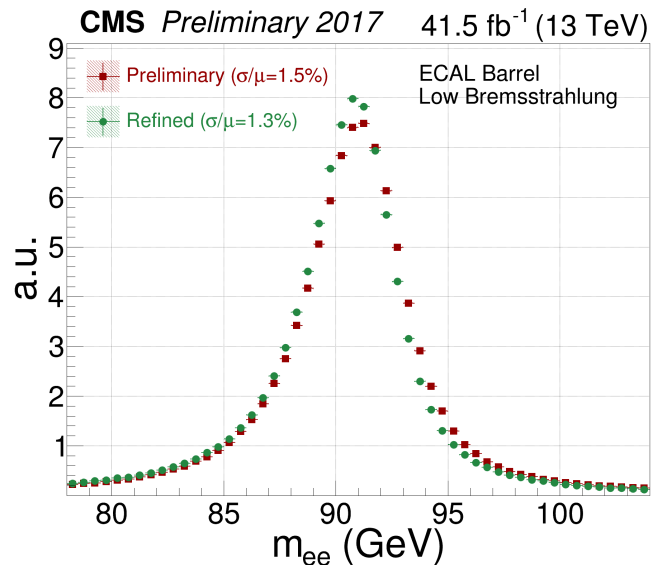
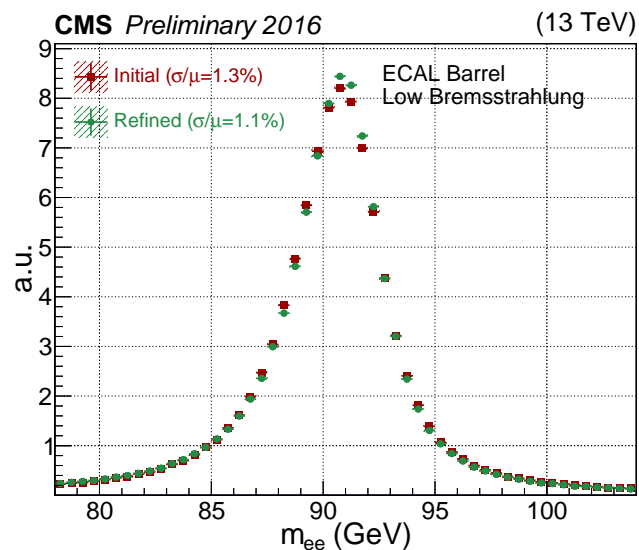


Regression



ECAL refined energy calibration

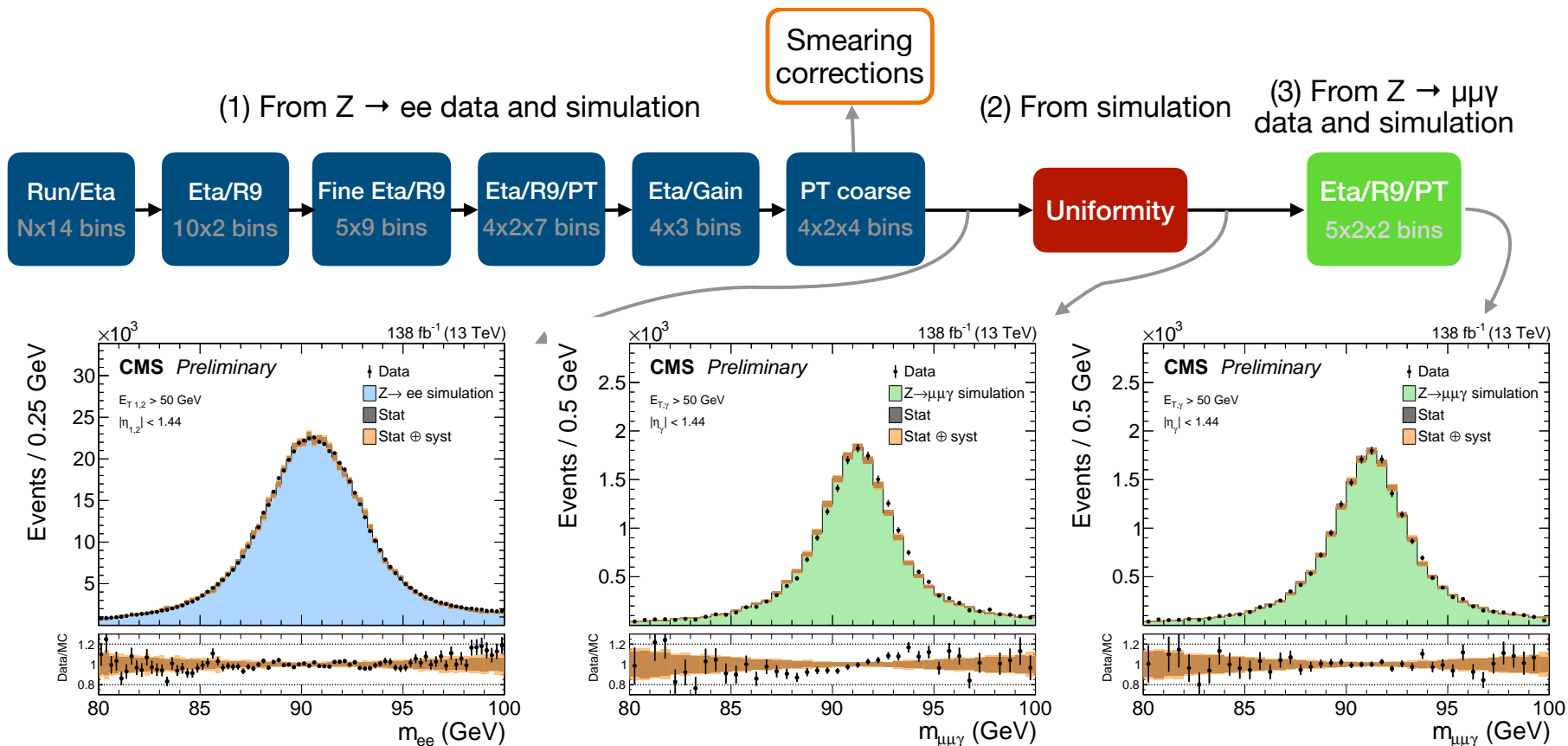
Improvement of the energy resolution thanks to the refined reconstruction [1]:



- ▶ Thanks to this effort the effective sigmas of the signal model is reduced by 15%:
 - Legacy 2016: 1.68 GeV
 - Run 2: **1.44 GeV**

Photon energy scale and smearing corrections

Differences between data and simulation in both the photon energy scale and the energy resolution are corrected using a **three-stage** calibration procedure:



Binned energy scale and smearing corrections

IJazZ2.0 [1]: new method for lepton energy calibration

▶ **Goal:**

- match Data/MC invariant mass distribution using $Z \rightarrow \ell\ell$ events

▶ **Method:**

- Per-lepton corrections: $E_{\text{corr}}^{\text{mc}} = E_{\text{raw}}^{\text{mc}} \times r_{\ell}(\vec{X}) \times \mathcal{N}(1, \sigma_{\ell}(\vec{X}))$
 - ▶ **scale** (r_{ℓ})
 - ▶ **smearing** (σ_{ℓ})

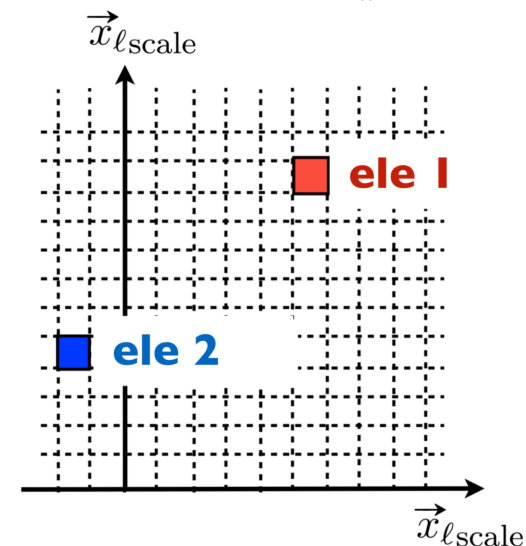
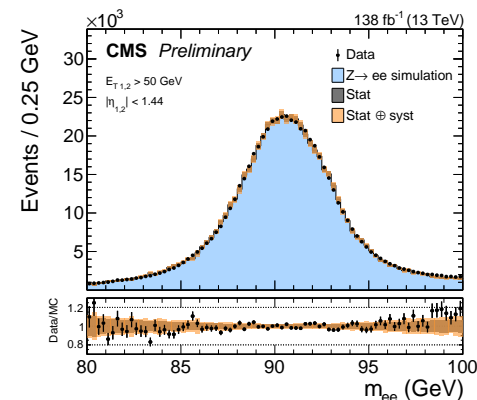
▶ **Implementation:**

- Events categorized in pair of bins (b_1, b_2)
 - ▶ bins defined as a function of η, R_9, p_T and gain
- $N_C \equiv \frac{N_B \times (N_B + 1)}{2}$.

Per category $c = (b_1, b_2)$ parameters:

- ▶ $r_{\ell\ell_c} = \sqrt{r_{\ell b_1} \times r_{\ell b_2}}$
- ▶ $\sigma_{\ell\ell_c} = 0.5 \times \sqrt{\sigma_{\ell b_1}^2 + \sigma_{\ell b_2}^2}$

affecting the mass distribution: $m_{\ell\ell}^{\text{mc,corr}} = m_{\ell\ell}^{\text{mc}} \times r_{\ell\ell_c} \times \mathcal{N}(1, \sigma_{\ell\ell_c})$



Binned energy scale and smearing corrections

Key idea of the IJazZ2.0 [1] method:

- ▶ Smearing modeled analytically
 - no random sampling
 - enabling the construction of a fully analytic likelihood

Method:

- ▶ Predict migration between bins given the **scale** and **smearing** parameters:

$$\alpha_{ijc}(r_{\ell c}, \sigma_{\ell c}) = \frac{1}{2} \left[\text{Erf} \left(\frac{b_i^u / r_{\ell c} - b_j^{\text{mc}}}{\sqrt{2} \sigma_{\ell c} b_j^{\text{mc}}} \right) - \text{Erf} \left(\frac{b_i^d / r_{\ell c} - b_j^{\text{mc}}}{\sqrt{2} \sigma_{\ell c} b_j^{\text{mc}}} \right) \right]$$

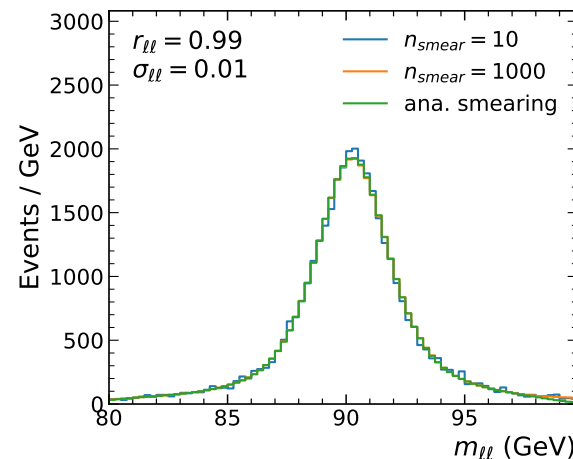
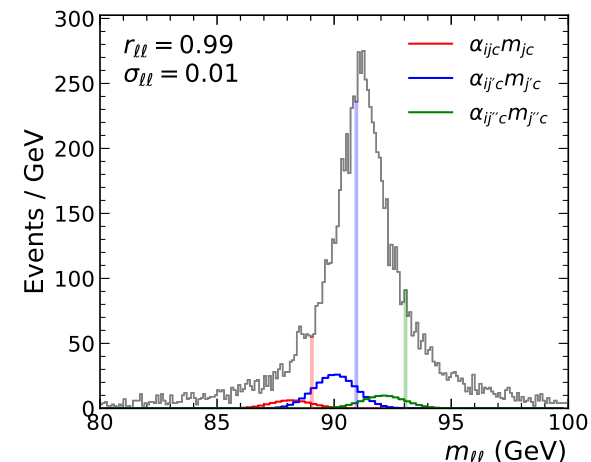
- ▶ Build **scaled** and **smear**ed mass distribution p_{ic} :

$$p_{ic} = \frac{\sum_j \alpha_{ijc} m_{jc}}{\sum_{i,j} \alpha_{ijc} m_{jc}}.$$

- ▶ Extract the **optimal parameters** (r_ℓ, σ_ℓ) to fit Data/MC:

$$NLL(n_{ic}; r_\ell, \sigma_\ell) = - \sum_{c=1}^{N_C} \sum_{i=1}^{N_I} n_{ic} \log(p_{ic}),$$

Thanks to this analytical approach, the derivation of the scale and smearing corrections is **much faster** (by a factor of ~ 1000).



Adaptation of the method to derive photon scale from $Z \rightarrow \mu\mu\gamma$ events

The IJazZ2.0 [1] method can be adapted to derive photon energy scale corrections from $Z \rightarrow \mu\mu\gamma$ events.

Method:

- Define a **new observable**:

$$V_{DY} \equiv \left(\frac{m_{\mu\mu\gamma}}{m_Z} - 1 \right) \frac{2}{1 - \frac{m_{\mu\mu}^2}{m_{\mu\mu\gamma}^2}}$$

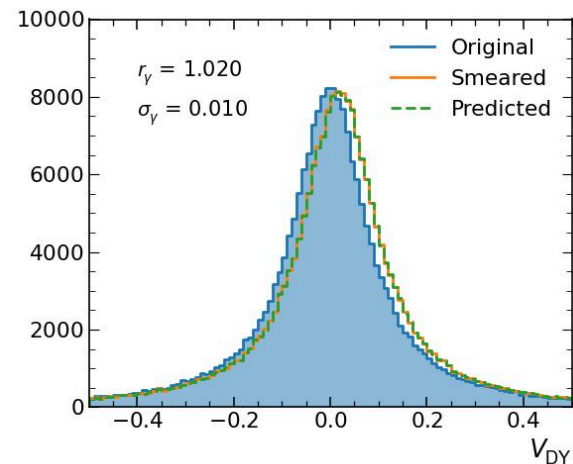
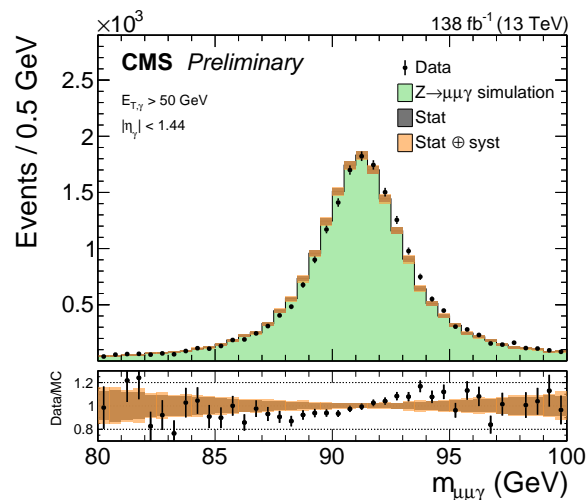
sensitive to residual **photon energy miscalibrations** (r_γ):

$$V_{DY}(r_\gamma) \approx V_{DY}(r_\gamma = 1) + (r_\gamma - 1).$$

Implementation:

- Adapt the **analytical likelihood** to derive photon scale corrections from $Z \rightarrow \mu\mu\gamma$ events

Used for the **first time** in this analysis.



Photon energy scale corrections from photons ($Z \rightarrow \mu\mu\gamma$)

Residual photon scale from $Z \rightarrow \mu\mu\gamma$:

- ▶ direct photon calibration
- ▶ independent of electrons
- ▶ removes extrapolation uncertainty

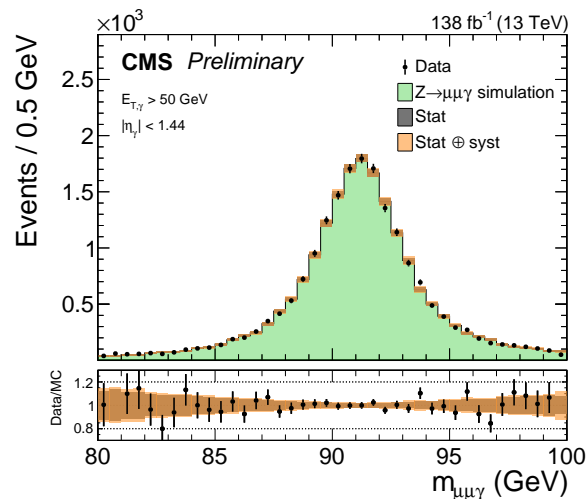
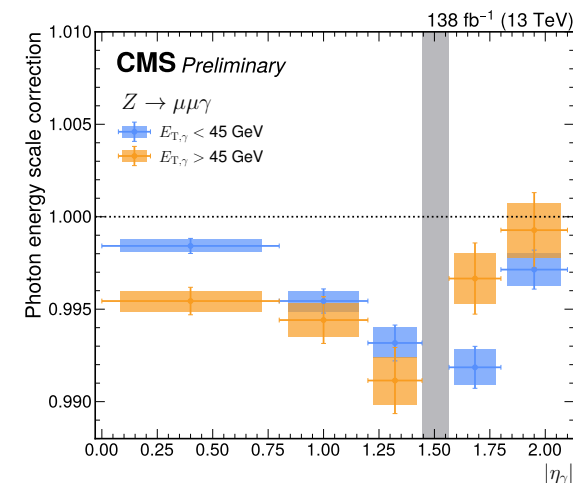
This correction is derived in:

- ▶ 5 bins in $|\eta|$
- ▶ 2 bins R_9
- ▶ 2 bins in p_T

Correction: 0.5% \rightarrow 0.8% (barrel)

Limitations:

- ▶ Limited statistics at high p_T^γ
 - Merging the full Run 2 dataset
- ▶ Dependence on muon momentum scale
 - Muon scale bias amplified by a **factor ~ 2** in photon scale

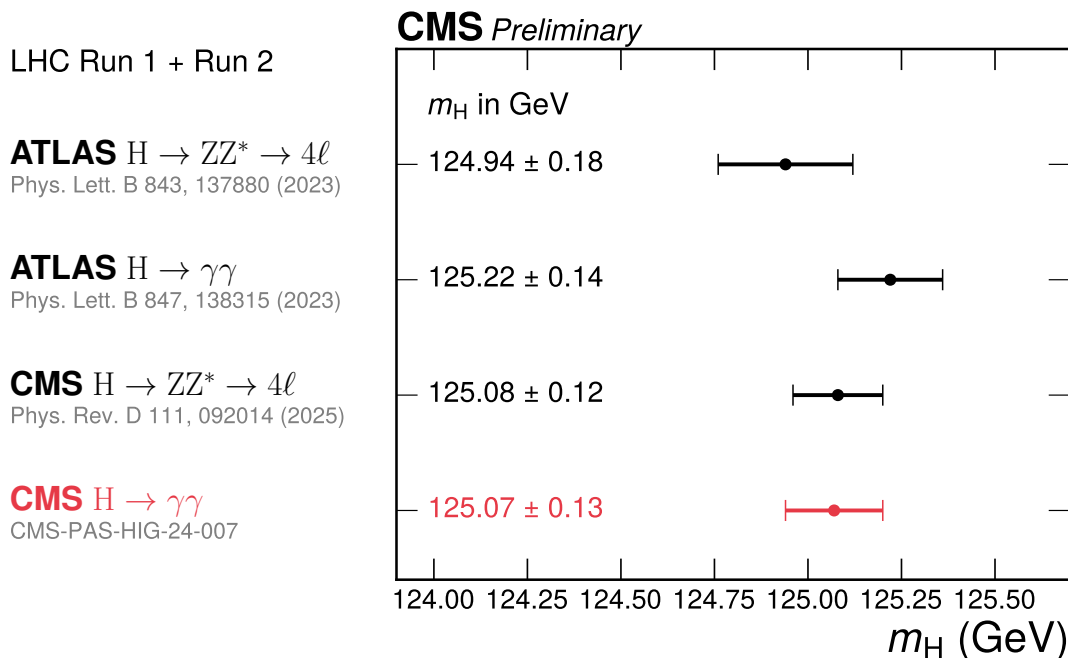


Summary

Refined ECAL calibration, improved scale and resolution methods, and an optimized analysis strategy lead to:

Full Run 2 $H \rightarrow \gamma\gamma$: $m_H = 125.14 \pm 0.10(\text{stat}) \pm 0.11(\text{syst}) \text{ GeV}$

Combined with Run 1: $m_H = 125.07 \pm 0.09(\text{stat}) \pm 0.10(\text{syst}) \text{ GeV}$



We are working on the combination with the $H \rightarrow 4\ell$ results [1] before combination with the ATLAS results [2]

Backup

Preselection, photon MVA ID, vertex identification and categorization

Preselection:

- ▶ A loose preselection is applied to data and simulation
 - $p_T^\gamma/m_{\gamma\gamma} > 1/3(1/4)$ for the leading (subleading) photon
 - $|\eta| < 2.1$ and EB-EE gap veto
 - Photon preselection to mimic the trigger selection
 - Loose photon ID MVA cut (>-0.9) and electron veto
 - Photon pairs are required to satisfy $100 < m_{\gamma\gamma} < 180$ GeV

Photon ID MVA:

- ▶ A dedicated TMVA BDT has been trained [1] to assign a higher score to the prompt photons than to non-prompt photons
- ▶ **Chained Quantile Regression** (CQR) method is used to correct the input features: shower shape and isolation variables, in MC, separately for each year

Vertex identification:

- ▶ A dedicated vertex identification method [2] has been used.
 - One MVA to identify the diphoton vertex
 - One MVA to estimate the probability of correct vertex assignment.

Overall efficiency within 1cm to true vertex $\sim 80\%$

Event categorization:

- ▶ An event classifier, **DiphotonBDT**, has been trained to reject SM diphoton continuum backgrounds:
- ▶ Nine input features (inspired by CMS-HIG-19-015):
 - $p_T^\gamma/m_{\gamma\gamma}$, η and mvaID score of each photon
 - Cosine of the angle between the two photons
 - Per-event probability estimate of PV
 - Relative mass resolution estimate w.r.t wrong vertex
- ▶ Data-driven prompt-fake (pf) & fake-fake (ff) backgrounds
- ▶ Event categories are defined by maximizing:

$$m_{\gamma\gamma}/\sigma_{m_{\gamma\gamma}} \times S/\sqrt{B}$$

- 4 categories for EBEB and 1 for notEBEB diphoton pairs
- ECAL barrel driven analysis (85% of the photons)

Uniformity energy scale correction (simulation only)

Motivation of this correction (CMS-DP-2024-045):

- ▶ Used as a systematic uncertainty in HIG-19-004.
- ▶ Photons develop showers **deeper** than electrons
- ▶ With non-uniform light collection due to radiation damage, we expect a **bias in the photon energy as the radiation damage is not simulated** and the first calibration stage is done with electrons.

Rely on ECAL Longevity Model (ELM):

$$F = \frac{S_\gamma}{S_e} = \frac{\int P_{\text{dep}}^\gamma(z, E) \cdot \text{LCE}(z; R/R_0, \eta) dz}{\int P_{\text{dep}}^\gamma(z, E) dz} \cdot \frac{\int P_{\text{dep}}^e(z, E) \cdot \text{LCE}(z; R/R_0, \eta) dz}{\int P_{\text{dep}}^e(z, E) dz}$$

- ▶ $P_{\text{dep}}(z, E)$ = energy dependent shower profile in PbWO4 as a function of the depth
- ▶ LCE = Light Collection Efficiency as a function of depth in the crystal, simulated with ELM (Fluka+Litrani)
- ▶ R/R_0 = ECAL laser response measured in data
- ▶ Correction ranges from $\sim 0.05\%$ in 2016 to $\sim 0.12\%$ at the end of Run 2 in the barrel

