Higgs boson properties with γγ decays in CMS

Fabio Iemmi [1]

on behalf of the CMS Collaboration

FCPPN/L workshop, Lyon, France
June 29th, 2026

[1] Institute of high energy physics (IHEP), Beijing, China

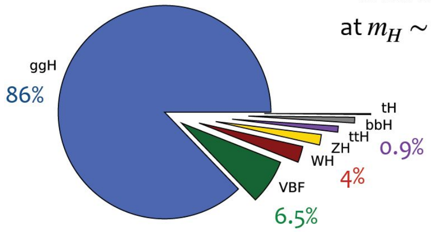
Outline

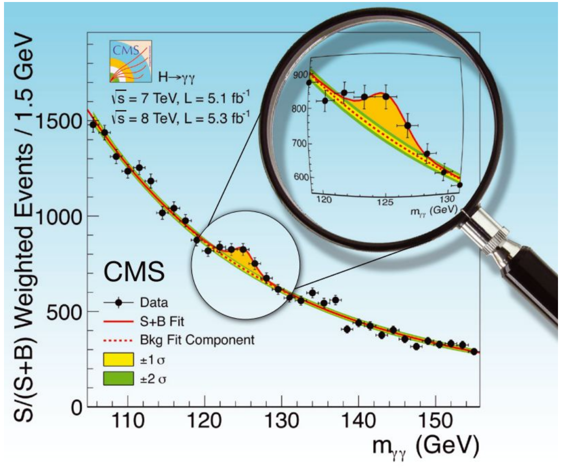
- **Introduction: H(γγ)**
- **Higgs boson mass measurement (new!)**
  - Dedicated calibration of photon energy scale
- **Higgs boson anomalous couplings**
  - New physics hiding in the Higgs sector?
- **Higgs boson natural width**
  - Alternative methods to direct measurement

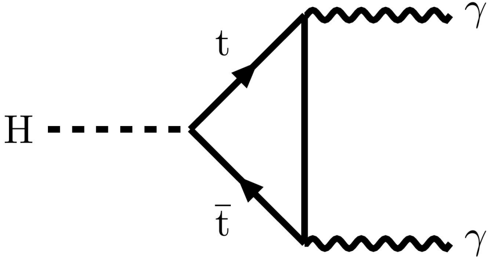
Introduction: H(γγ)

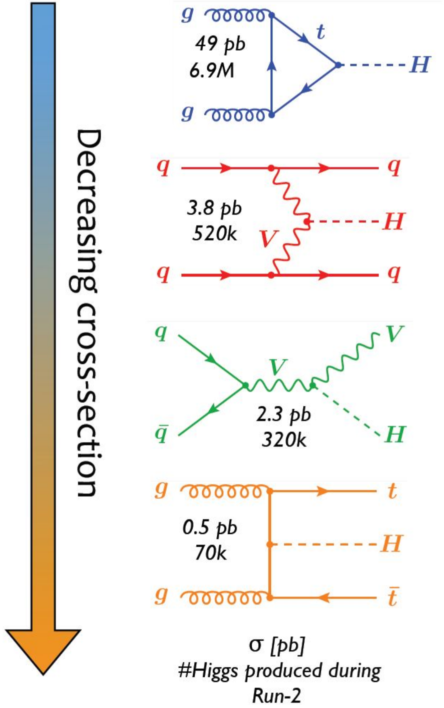
- **LHC is a Higgs factory**: O(8M) Higgs bosons produced in Run 2 for each experiment (138 fb^{-1})
- **H(γγ)** is one of the **golden channels** for discovery, measurements, and searches
  - Branching ratio somewhat small (~0.23%)
  - Relatively clean final state, fully reconstructable
  - **Excellent mass resolution**, O(1%)

Higgs production cross sections at $m_H \sim 125$ GeV









gluon fusion
ggH

vector boson fusion (**VBF**)

W,Z associated production
WH/ZH

$t\bar{t}H$ associated production

Introduction: H(γγ) analysis workflow

Online (trigger) selection

$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 30 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV
OR
$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 22 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV

Offline preselection (tighter than online)

$p_{T,1}$ > 35 GeV && $p_{T,2}$ > 25 GeV && $p_{T,1}/m_{\gamma\gamma}$ > ⅓ && $p_{T,2}/m_{\gamma\gamma}$ > ¼ && && isolation && loose photon ID

γγ vertex selection

Choose p-p vertex out of which the diphoton pair is produced

Diphoton BDT categorization (optional)

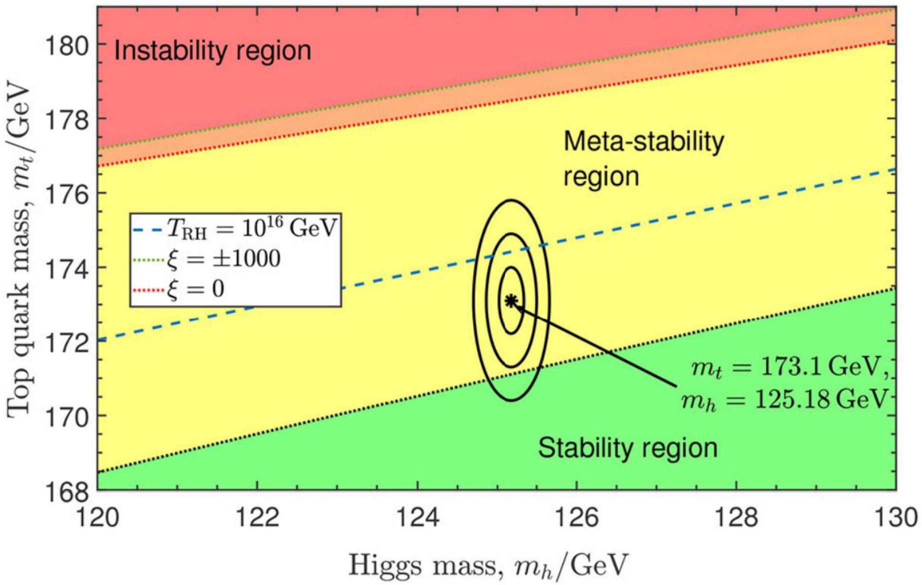
Identify diphoton pairs from Higgs decays

Categorize events based on BDT score

Signal and Bkg extraction:
Signal shape extracted from MC simulation
Background shape extracted from data

Higgs boson mass (m_H)

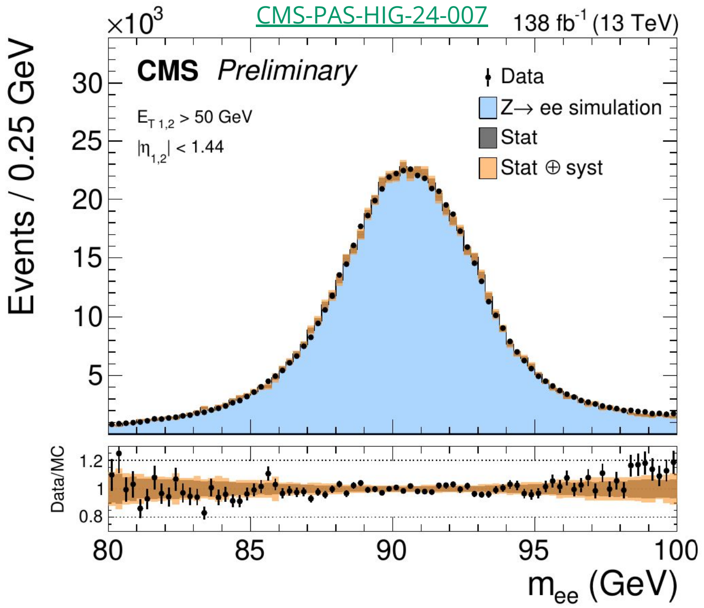
- m_H (and m_t) determine behavior of electroweak vacuum [1]
  - **Cosmological implications**
- Precise knowing of m_H leads to **overconstrained checks of SM** self-consistency [2]

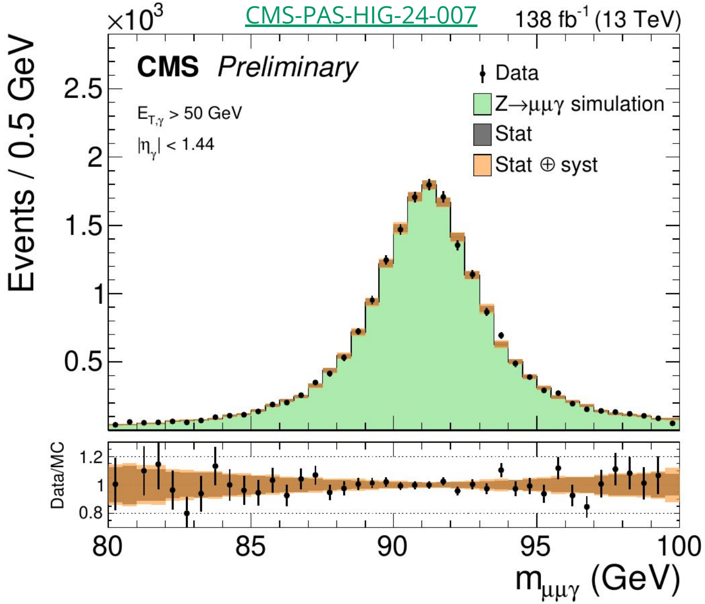


$$m_W = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W\sqrt{1 - f(m_t, \log(m_H))}}$$

m_H: photon energy calibration

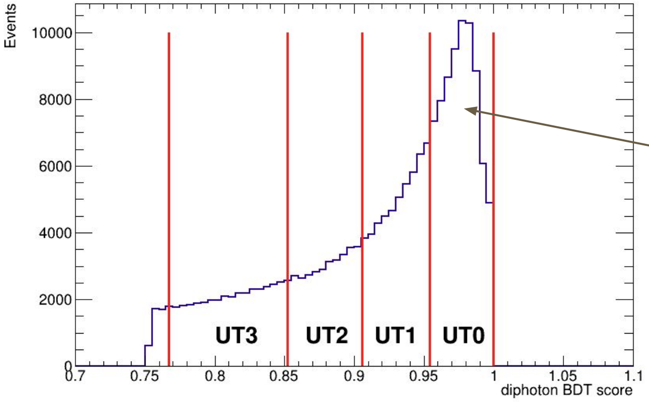
- Dedicated photon energy calibration in three steps
  - Energy scale correction derived from Z(ee) data
  - “Uniformity” corrections derived from simulation (accounts for radiation damage in CMS ECAL crystals). **New to this measurement (more in backup)**
  - Residual energy scale corrections derived in Z(μμγ) data. **New to this measurement (more in backup)**





m_H analysis workflow: categorization

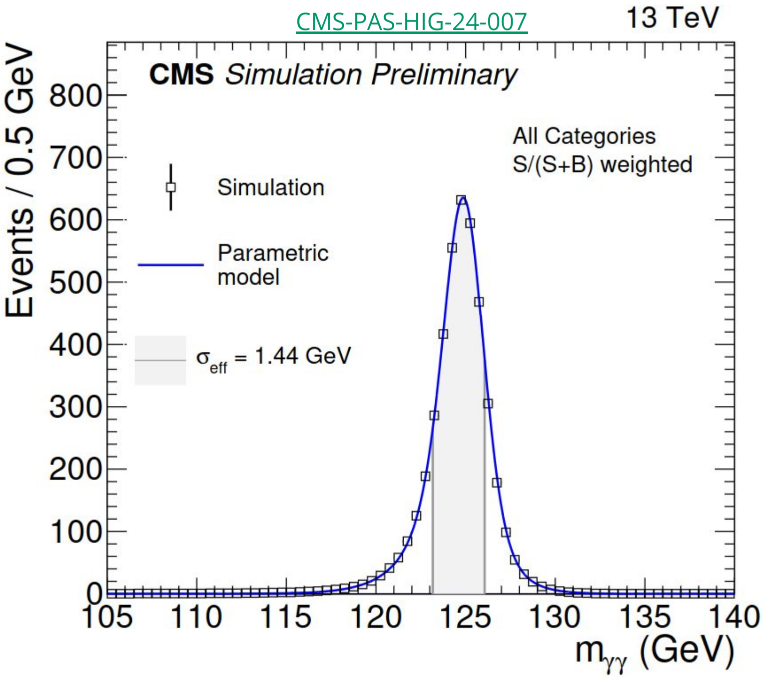
- Categorization criterion: create categories by placing boundaries on the diphotonBDT score
    - Irrespective of the production mode
    - **Separately for each era of data taking**
- Boundaries optimized by **maximizing $(m/\sigma_m) * (S/\sqrt{B})$**
    - **4 categories with both photons in the ECAL barrel**
    - **1 category**, with at least one photon in the endcaps

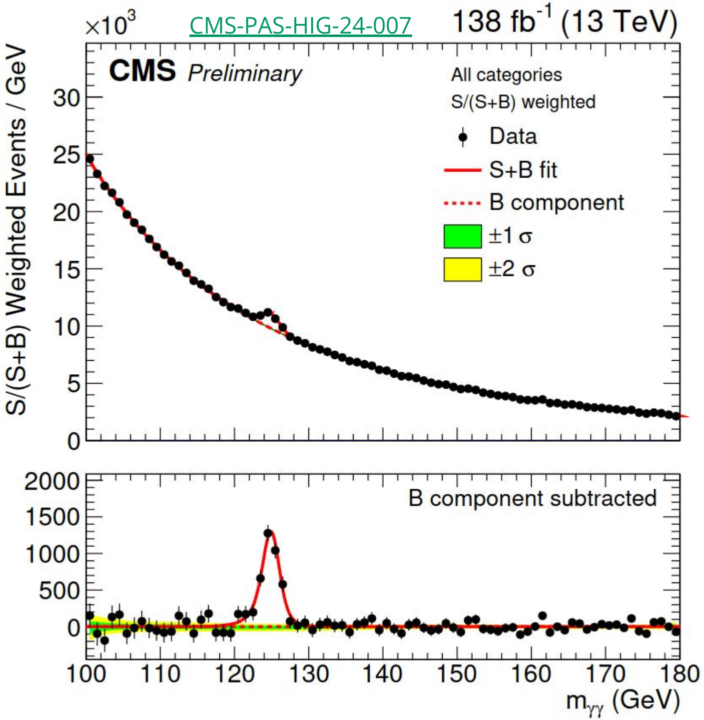


High diphotonBDT score events have the best mass resolution

- 5 categories x 4 eras of data taking: **20 signal categories in total**

Higgs boson mass: signal and background modeling

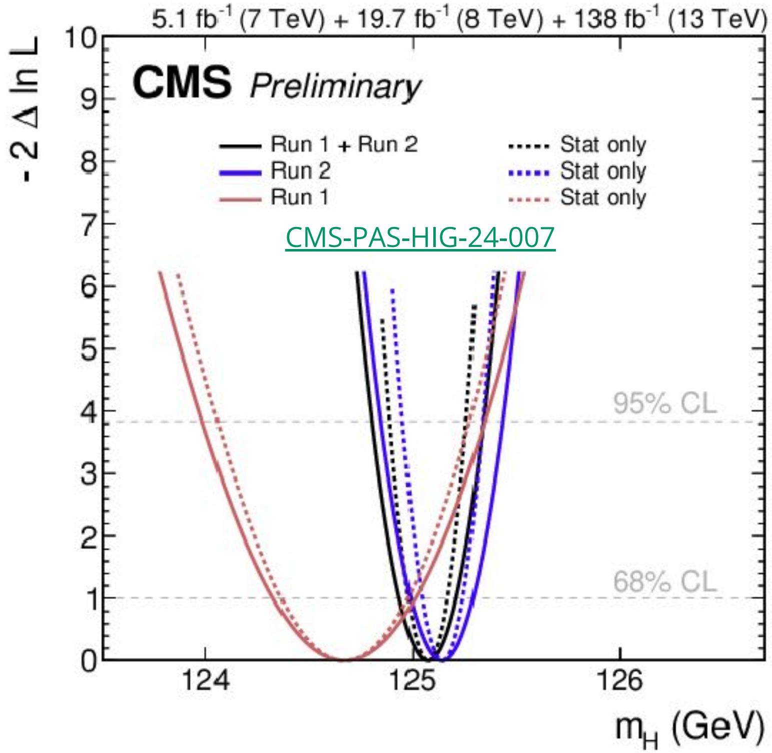




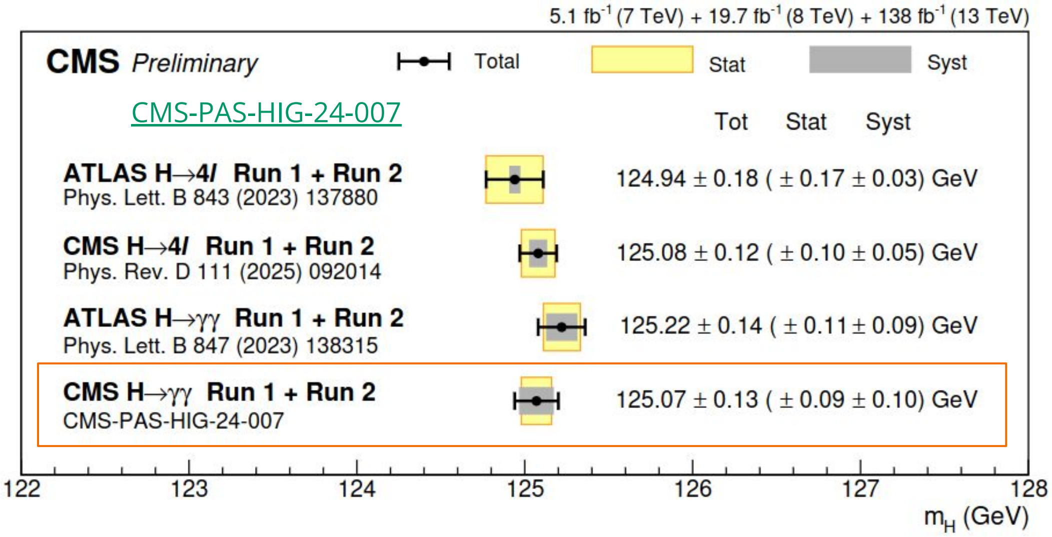
- Signal model obtained with sum of up to 5 Voigtian functions for each production mode and signal category
- Background model obtained with Discrete Profiling method [1]

m_H analysis workflow: measurement

- Simultaneous maximum-likelihood fit of all 20 signal categories to data



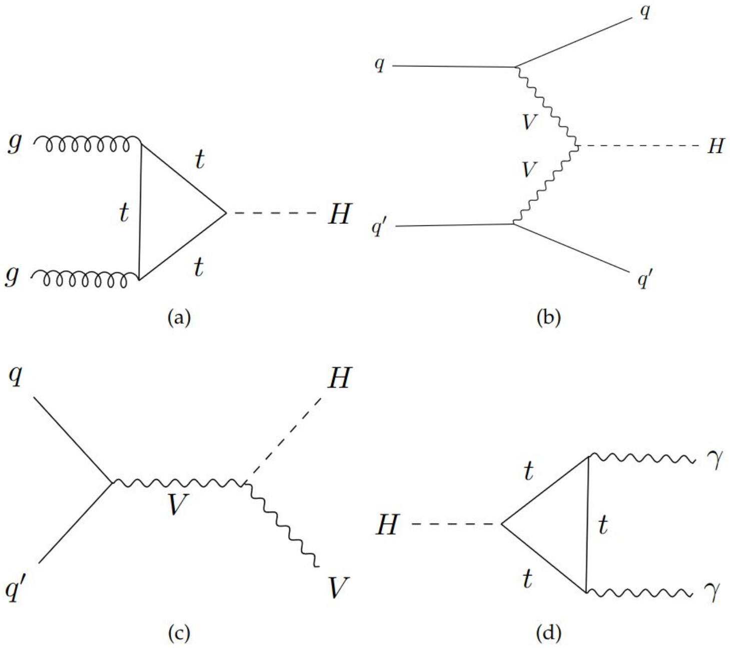
- **Run 2 result:** m_H = 125.14 ± 0.10 (stat) ± 0.11 (syst) GeV
- **Run 1 result:** m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV
- **Comb. result:** m_H = 125.07 ± 0.09 (stat) ± 0.10 (syst) GeV



Reached the per-mille precision

Anomalous, CP-violating Higgs couplings [CMS-PAS-HIG-24-006]

- In SM Higgs boson $J^{CP} = 0^{++}$.
- Limited precision of previous measurements **allow small anomalous couplings** and CP violation →Probe HVV couplings, through VBF and VH production, and Hff through ggH (in the loop)



- SM and Anomalous couplings between spin-0 H and VV (WW, ZZ, Zγ, γγ, gg)

$$\mathcal{A}(\mathrm{HV_1V_2}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

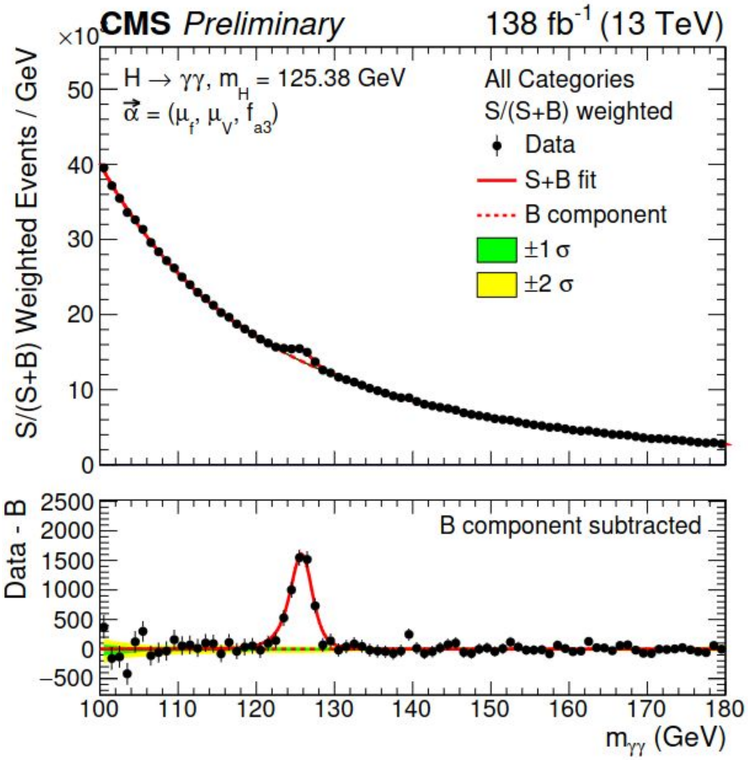
- For symmetry and gauge invariance: $a_1^{WW} = a_1^{ZZ}$, $a_1^{Z\gamma} = a_1^{\gamma\gamma} = a_1^{gg} = 1$, $k_1^{ZZ} = k_2^{ZZ}$, $k_1^{\gamma\gamma} = k_2^{\gamma\gamma}$, $k_1^{gg} = k_2^{gg} = 0$, $k_1^{Z\gamma} = 0$ → **13 independent paraments, in particular: a_3^{VV} is CP-odd mixed with CP-even**

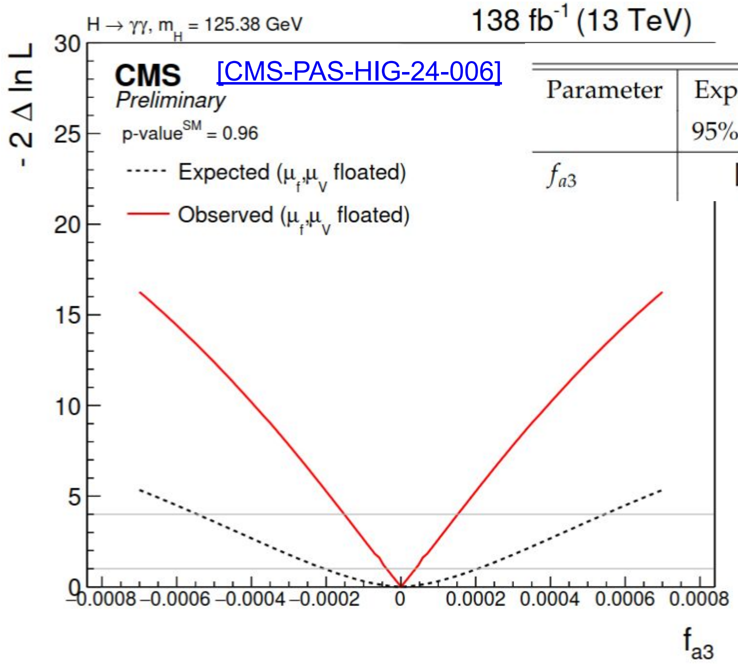
- For convenience, the effective cross sections are measured

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/(\Lambda_1)^2 + \tilde{\sigma}_{\Lambda_1}^{Z\gamma}/(\Lambda_1{}^{Z\gamma})^2} \times \mathrm{sgn}\left(\frac{a_i}{a_1}\right)$$

Anomalous, CP-violating Higgs couplings

- Categorization on Matrix Element VBF, VH and ggH discriminants is performed optimizing S/B:





Parameter	Expected/(10^{-4}) 95% CL H → γγ	Observed/(10^{-4}) 95% CL H → γγ
f_{a3}	[−5.4,5.4]	[−1.5,1.5]

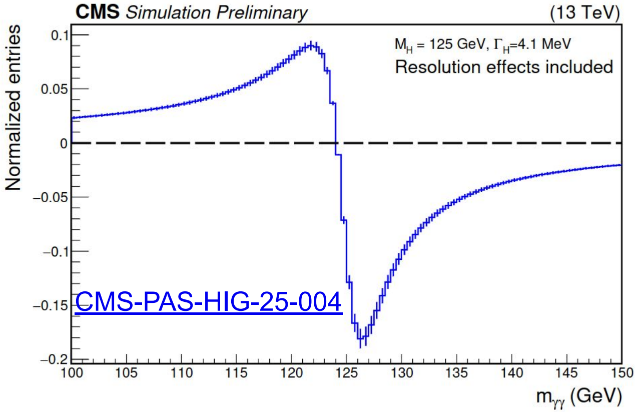
Higgs width from sig-bkg interference

CMS-PAS-HIG-25-004

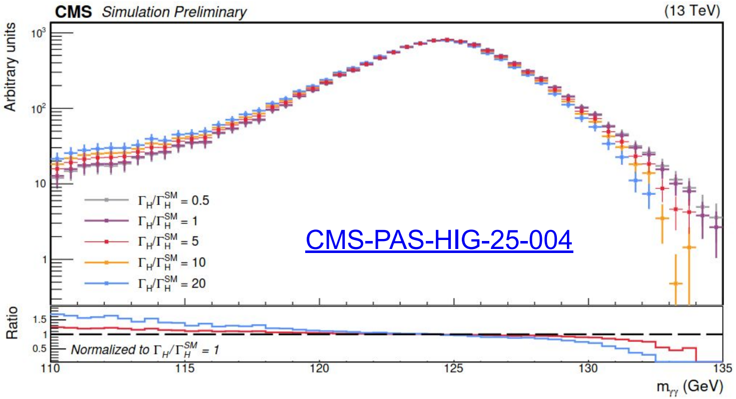
- Γ_H = 4.1 MeV in SM → **measurement limited by the detector resolution** (~1 GeV)
- On-shell and off-shell H→ZZ→4l measurements performed: on-shell Γ_H< 330 MeV and off-shell Γ_H< 7.9 MeV 95% CL [Phys. Rev. D 111 (2025) 092014]
- Γ_H measured **exploting the interference between signal gg→H→γγ and bkg gg→γγ, qg→H→γγ and qg→qγγ**

$$d\sigma_s^{ggH}/dm_{\gamma\gamma} + d\sigma_i/dm_{\gamma\gamma} = \mu_F \mathcal{S}_{ggH} + c_{g\gamma}\mathcal{I} = (\mu_F - c_{g\gamma})\mathcal{S}_{ggH} + c_{g\gamma}(\mathcal{S}_{ggH} + \mathcal{I})$$

$$c_{g\gamma} = \sqrt{\mu_F \Gamma_\mathrm{H} / \Gamma_\mathrm{H}^{SM}} \longrightarrow$$ Measure Γ_H from the measurement of this diff. cross-section



CMS-PAS-HIG-25-004



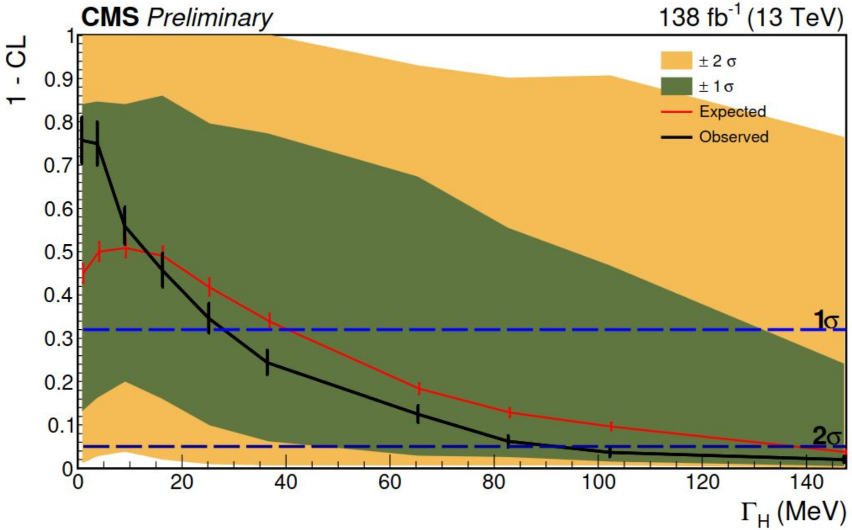
CMS-PAS-HIG-25-004

Higgs width from sig-bkg interference

- **Events are categorized:**
  - 10 categories for ggH production, based on diphoton-pt and diphotom-BDT
  - 1 VBF category to mitigate the dilution of the ggH fusion sample with events from VBF

- **Signal PDF modeled considering ggH, ggH+Interference, VBF and VH** (ttH negligible), with their own couplings:

$$\cdot\ \mu_V \quad , \quad \mu_{ggH} = \left(\mu_F - \sqrt{\mu_F \Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}^{SM}}\right) \quad , \quad \mu_{ggH+int} = \sqrt{\mu_F \Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}^{SM}}$$



Observed (expected) result:
$\Gamma_H < 92\ (138)$ MeV at 95% CL

Conclusions

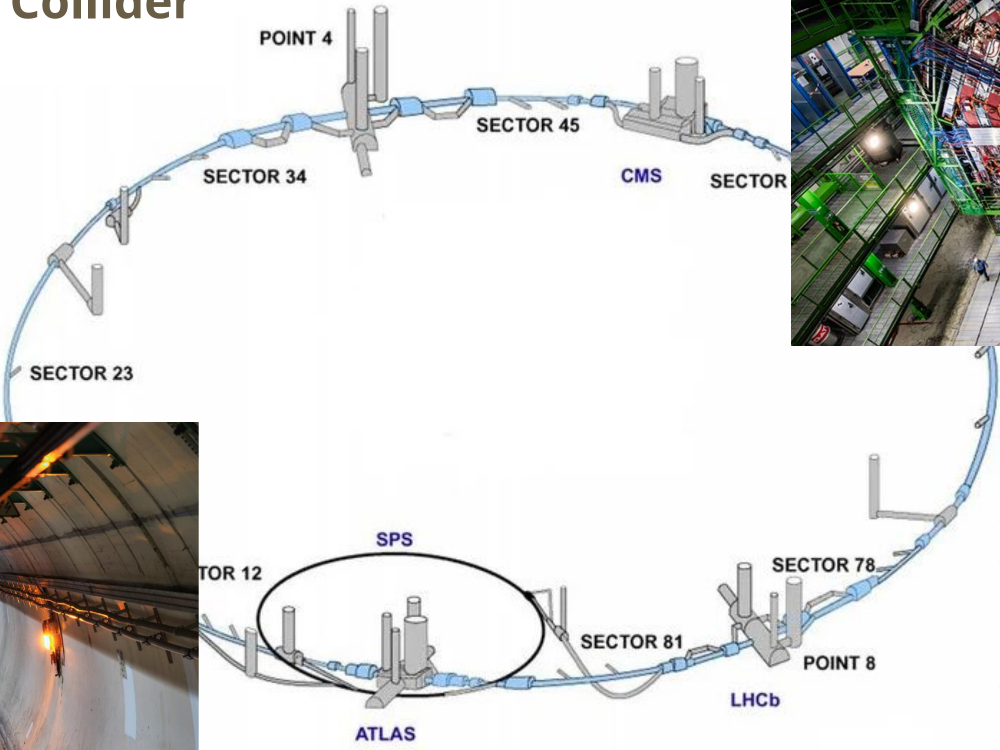
- The CMS Collaboration is actively measuring the **properties of the Higgs boson**
- H(γγ) is one of the driving decay channel in such studies
  - We **measured the Higgs boson mass** at the per-mille level
    - We foresee combinations with CMS H(4L) and ATLAS H(γγ) and H(4L) to achieve half per mille precision, a **benchmark measurement that will last for many years** to come
  - We searched for Higgs boson **anomalous, CP-violating couplings**. No evidence for new physics so far!
  - We constrained the **Higgs boson width** using the interference between the H(γγ) signal and the continuum background

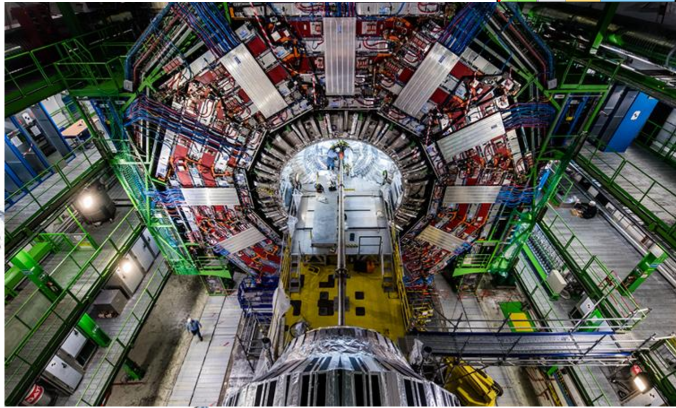
Thank you! Merci! 谢谢!

Backup slides

Introduction: LHC

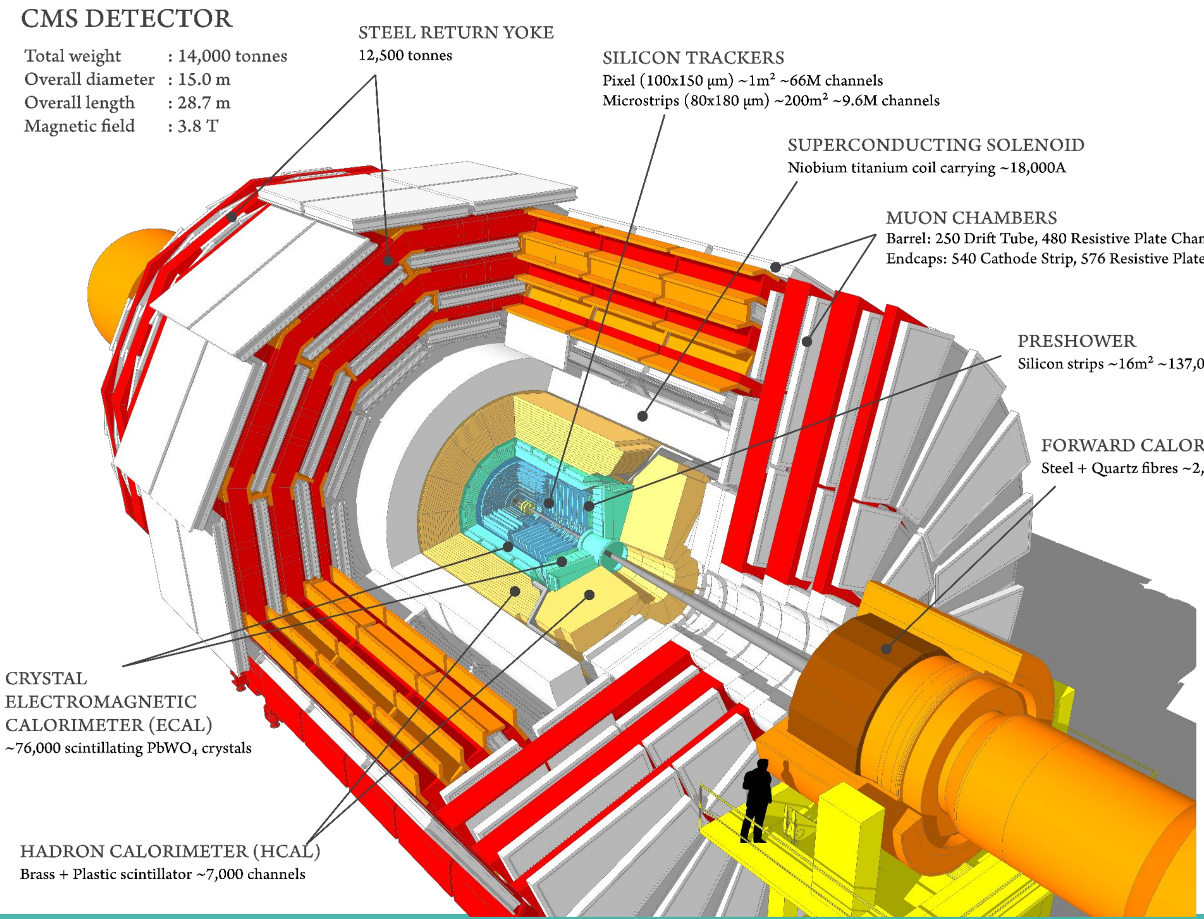
- **Large Hadron Collider**
  - p-p collider
  - L ~ 27km
  - T ~ 1.7K
  - B ~ 8.3 T





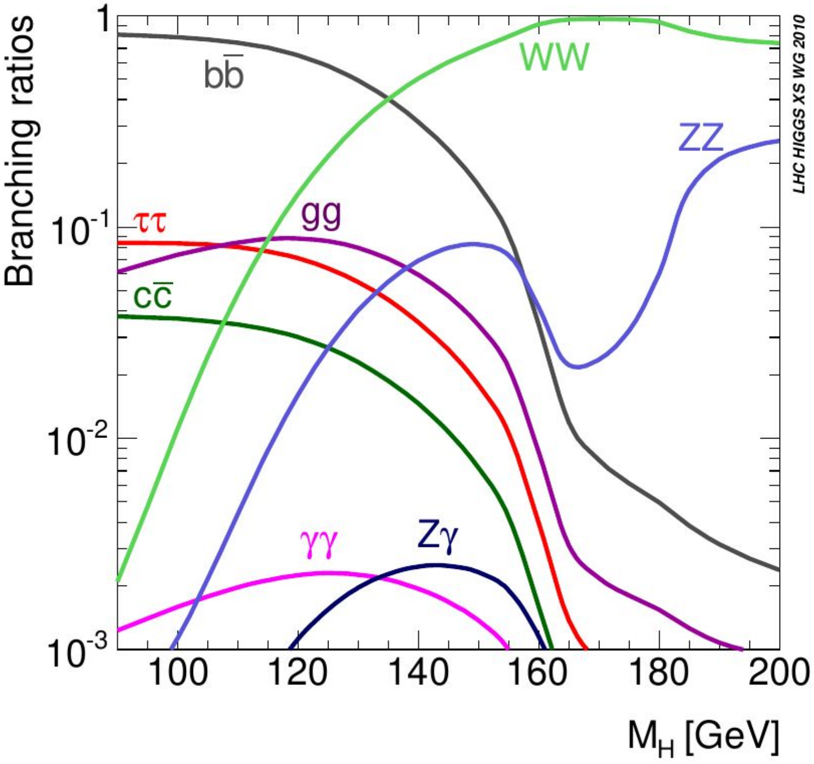
  - **Max. num. bunches:** 2808 (~1.6×10^{11} p)
  - **Bunch crossing:** 25ns
  - **Beam energy:** 7 TeV (2011), 8 TeV (2012), 13 TeV (Run2)
  - **Max. lumi in Run 2:** 2.1×10^{34} cm^{-2} s^{-1}

Introduction: CMS



Introduction: why the 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

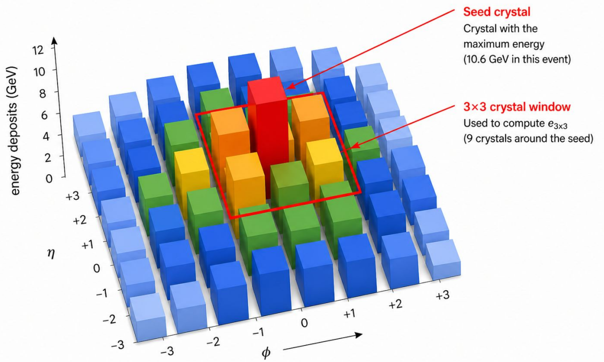


The CMS ECAL: electron/photon calibration

$$E_{e,\gamma} = \sum_i [A_i(t) \cdot L_i(t) \cdot C_i(t)] \cdot G(\eta) \cdot F_{e,\gamma} \cdot S_{Data\text{-}MC}(t)$$

- **$F_{e,\gamma}$: BDT regression**, trained on simulation to target generator-level energy
  - Account for shower leakage, material effect, dead channels, ...

- **Input variables**:
  - SC raw Energy
  - SC η
  - Shower-shape variables such as
    - R_9 = e3x3 / SC raw Energy
    - S_4 = e2x2/e5x5
  - HCAL-energy/ECAL-Energy in a cone around the particle
  - Pile-up related variables



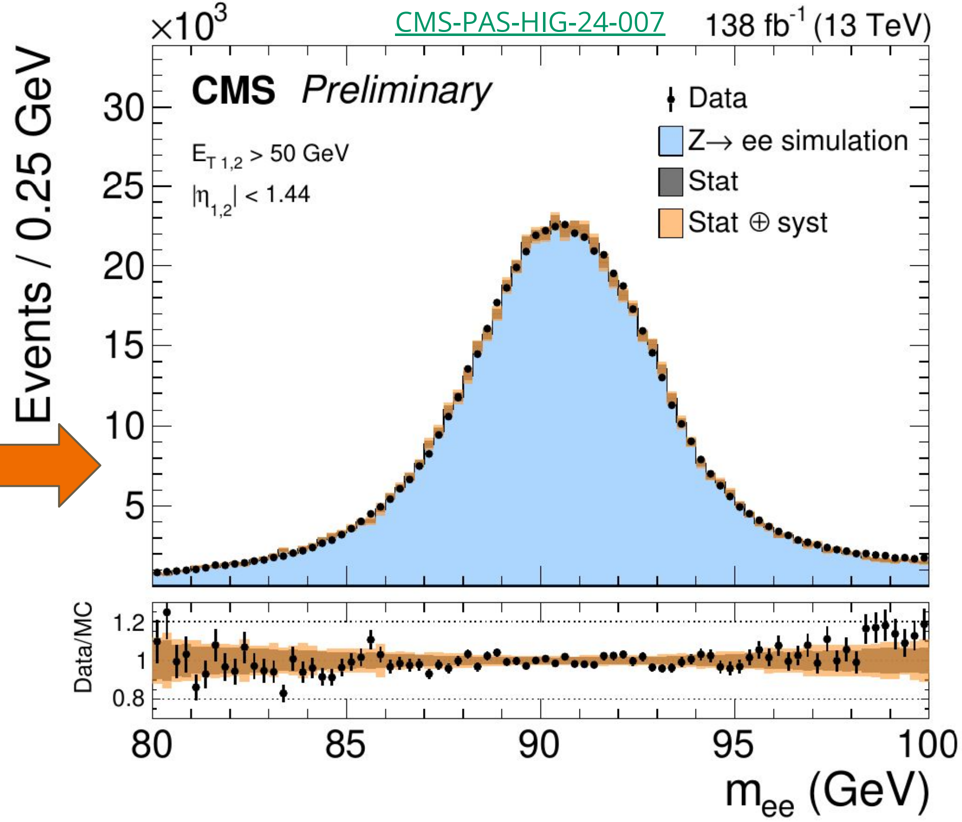
The CMS ECAL: electron/photon calibration

$$E_{e,\gamma} = \sum_i [A_i(t) \cdot L_i(t) \cdot C_i(t)] \cdot G(\eta) \cdot F_{e,\gamma} \cdot \; S_{Data\text{-}MC}(t)$$

- **$S_{\text{Data-MC}}(t)$**: residual data-MC **scale and smearing corrections**
    - **Derived using Z(ee)** decays and “electrons reconstructed as photons”: remove tracker information and only use ECAL energy deposits
    - Adjust energy scale in data and MC to have Z mass peak position and width to agree
    - **Can be seen as a calibration of the BDT energy regression**
    - Derived in sequential steps with fully analytical minimization method [1]
    - Highly granular **corrections in bins of p_T, η, R_9**, for smearing and additionally **time** and ECAL **crystal gain** for scale

The CMS ECAL: electron/photon calibration

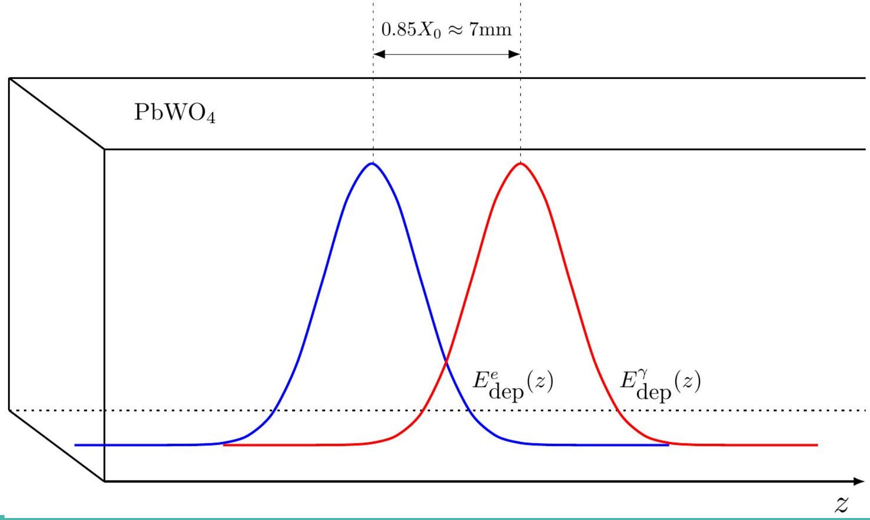
- **$S_{\text{Data-MC}}(t)$**: residual data-MC **scale and smearing corrections**
- Validated in many electron p_T and η bins
- Most relevant bin: both electrons in ECAL barrel, both with $p_T > 50$ GeV
    - Phase space where most of the Higgs boson decays are expected
- **Endpoint of calibration in previous mass measurements**



The CMS ECAL: electron/photon differences

- **Calibrations** performed with Z(ee) electrons, **eventually to be applied to photons**
- **Photons** penetrate $0.85X_0$ deeper than **electrons** of the same energy in $PbWO_4$
- With **non-uniform radiation damage** along crystal depth, **expect bias in photon energy**
- Correct for this bias: **uniformity correction**, derived and applied for the **first time in CMS**

Front face of ECAL crystal



The CMS ECAL: uniformity correction

- **Rely on ECAL Longevity Model (ELM) instead**: use FLUKA [1] to predict fluencies in CMS and Litrani [2] to model light propagation in $PbWO_4$ and **obtain Light Collection Efficiency**

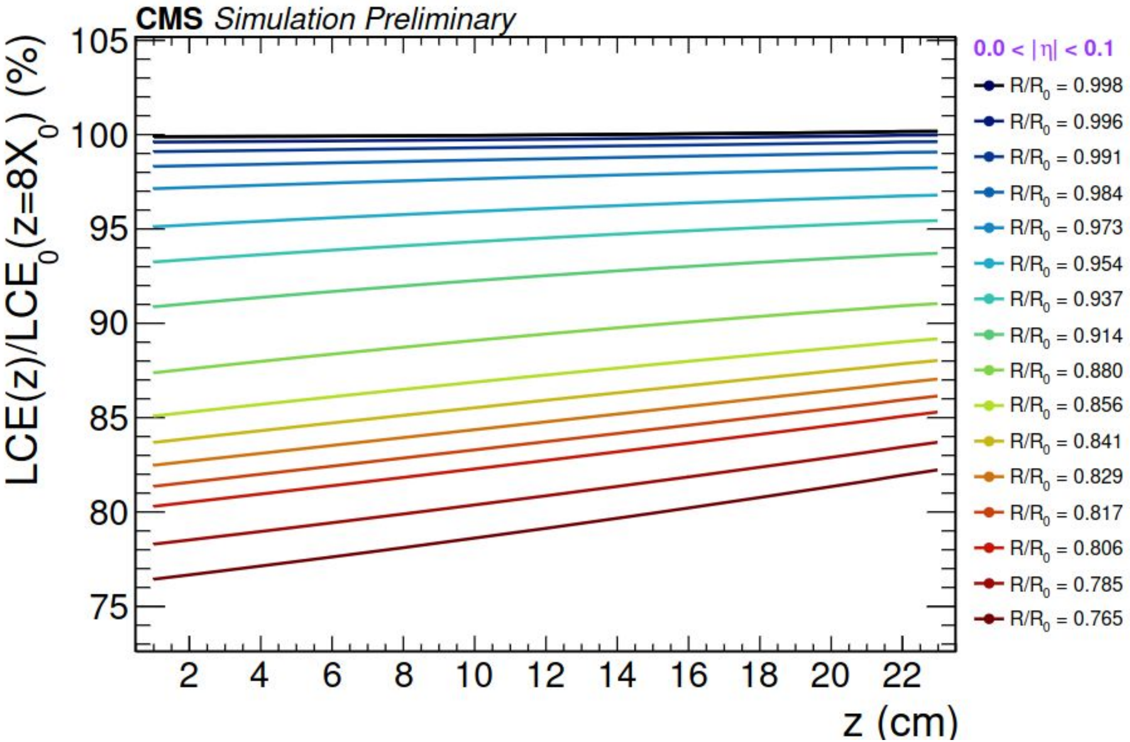
$$F = \frac{S^e}{S^\gamma} = \frac{\dfrac{\int E^e_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R}/\mathrm{R}_0, \eta)\, \mathrm{d}z}{\int E^e_{\mathrm{dep}}(z)\, \mathrm{d}z}}{\dfrac{\int E^\gamma_{\mathrm{dep}}(z) \times \mathrm{LCE}(z;\, \mathrm{R}/\mathrm{R}_0, \eta)\, \mathrm{d}z}{\int E^\gamma_{\mathrm{dep}}(z)\,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

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 (from Geant4 [3])
- LCE ≡ Light Collection Efficiency as a function of depth, simulated with ELM
- R/R_0 ≡ ECAL laser response **measured in data → can correct with per-fill granularity**

The CMS ECAL: uniformity correction

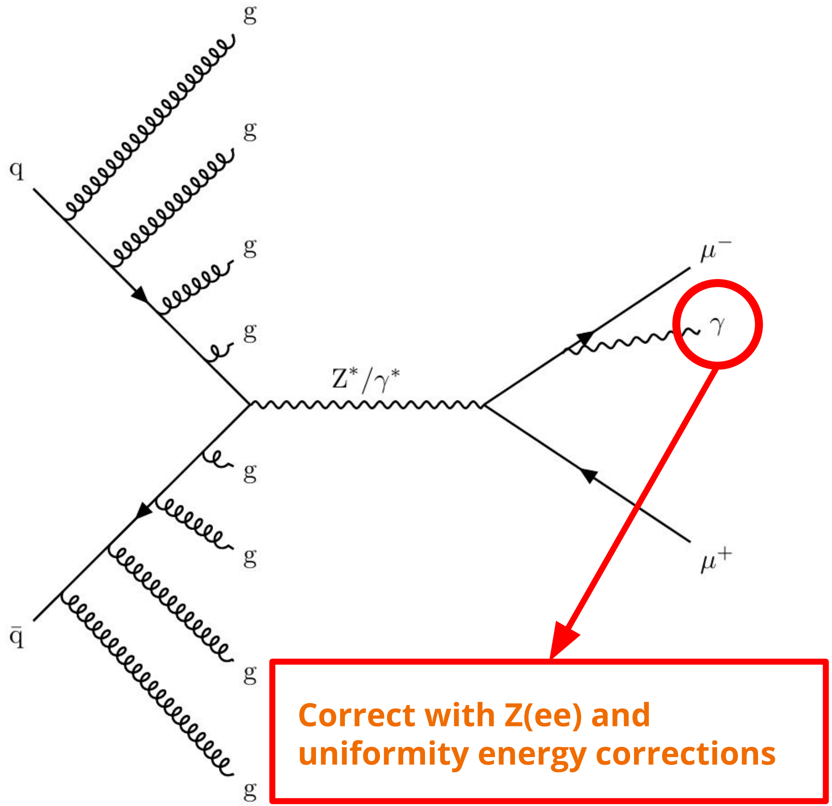


LCE (from Fluka + Litrani)

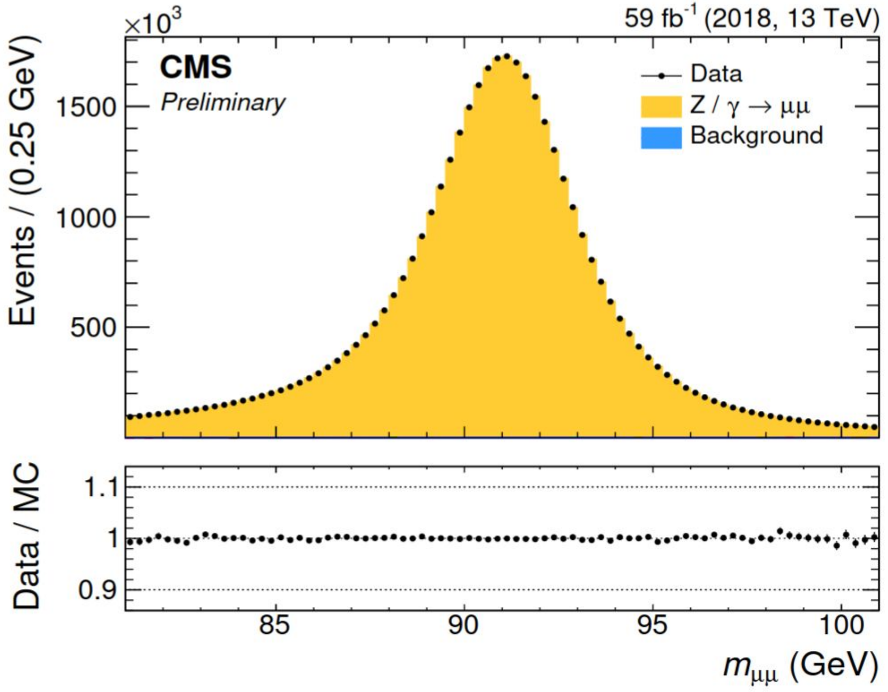
- Light collection efficiency degrades with radiation damage
- Light collection efficiency is higher at the rear face of the crystals

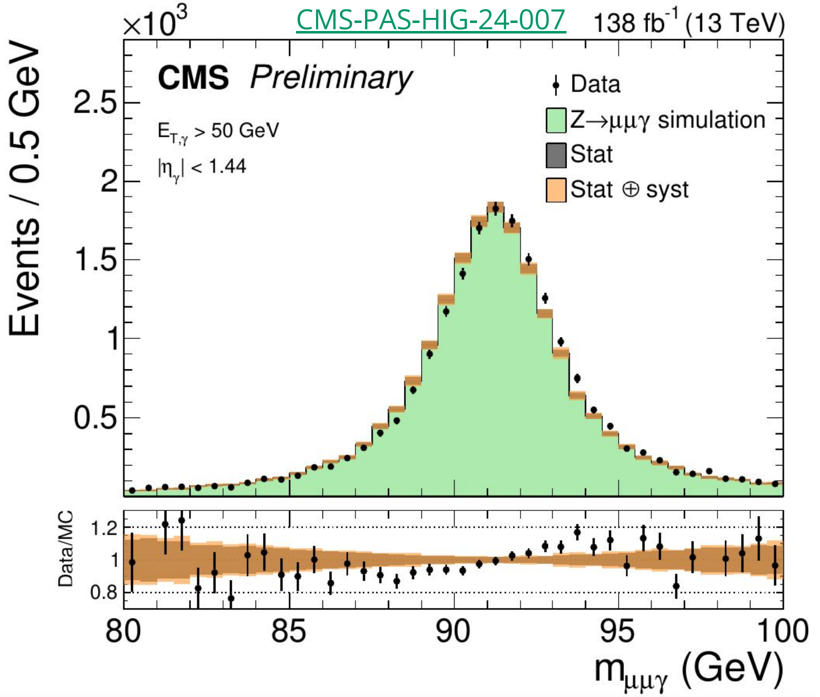
The CMS ECAL: electron/photon differences

- How to **validate energy corrections** on actual photons in data?
  - No high-mass resonance decaying to photons, other than the Higgs
- Use **radiative-Z** Drell-Yan events
- Final state consist of **two muons and a photon**
- **Apply energy corrections** to muons and to to photon, **check closure**



The CMS ECAL: electron/photon differences

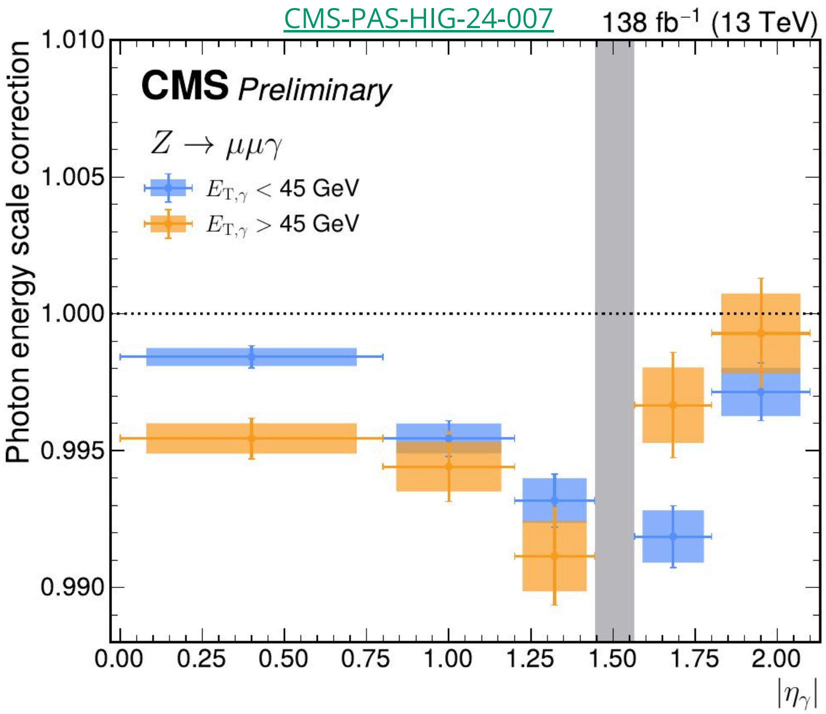




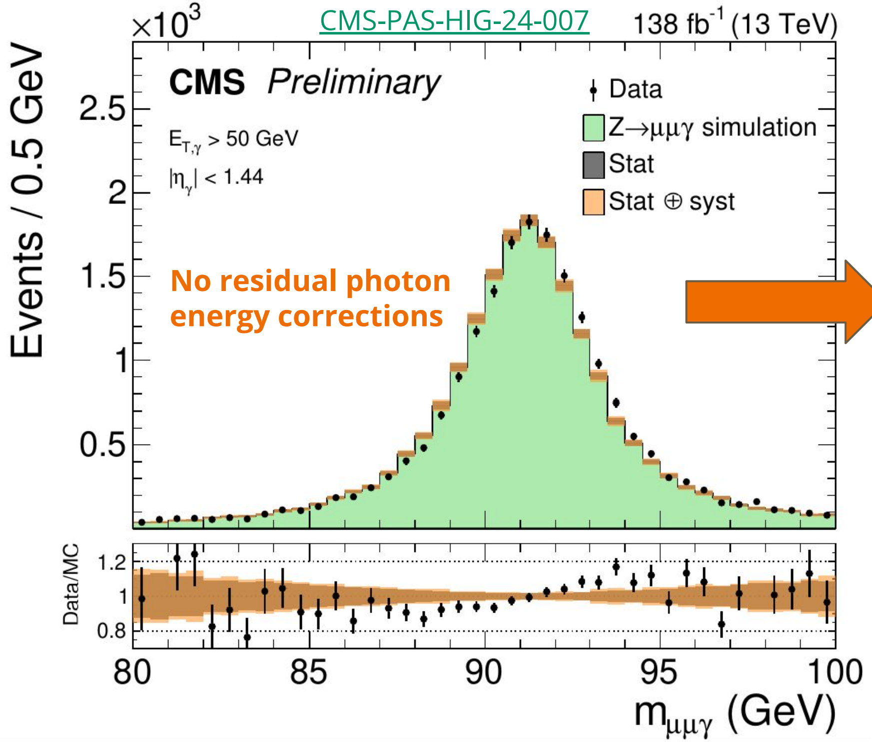
- Excellent closure of muon energy corrections when applied to Z(μμ)
- **Residual non-closure** when applying muon and Z(ee) and uniformity energy corrections to Z(μμγ)

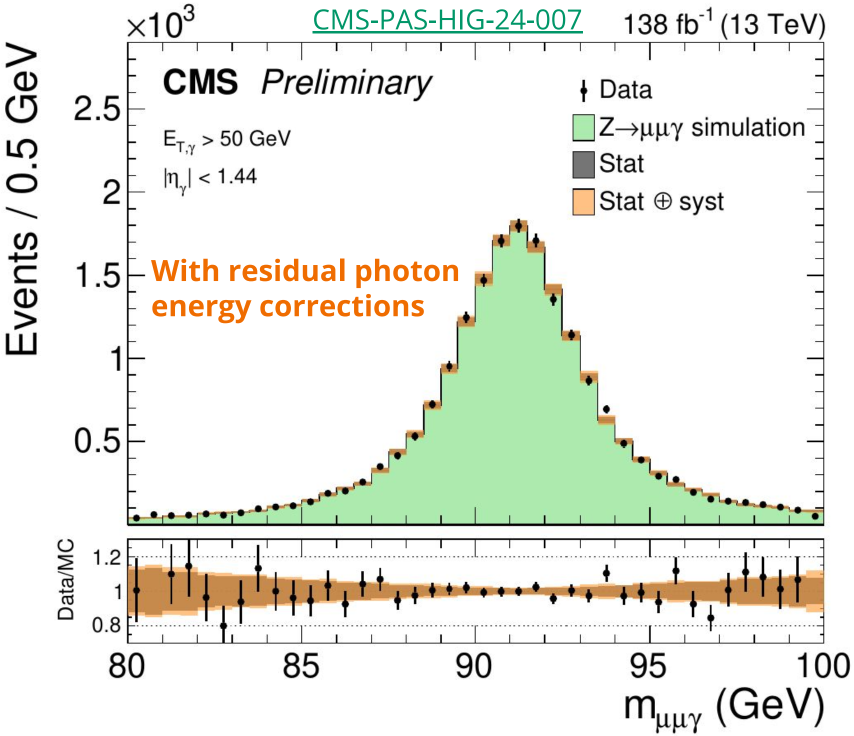
Residual photon energy corrections

- Derive additional set of **residual photon energy corrections** using Z(μμγ) events
  - Capture any possible residual difference between electrons and photons
- Use full Run 2 data (138 fb^{-1}) to have sufficient statistics
  - 5 bins in $|\eta_\gamma|$
  - 2 bins in R_9
  - 2 bins in p_T
- **Final energy corrections in 3 steps:**
  - Z(ee)
  - Uniformity
  - Z(μμγ)



Residual photon energy corrections



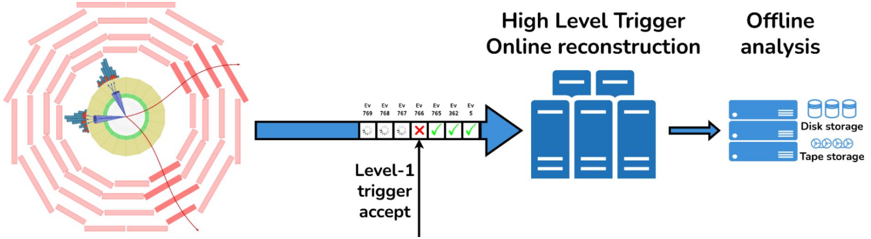


- **Very good closure after full energy correction chain** Z(ee) + uniformity + Z(μμγ)

m_H analysis workflow

Online (trigger) selection

$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 30 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV
OR
$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 22 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV



- LHC collides protons every 25ns (40 MHz)
- Too much data to be saved anywhere
- **Two-staged trigger system**
  - Level-1 trigger (100 kHz)
  - High Level trigger (1 kHz)

m_H analysis workflow

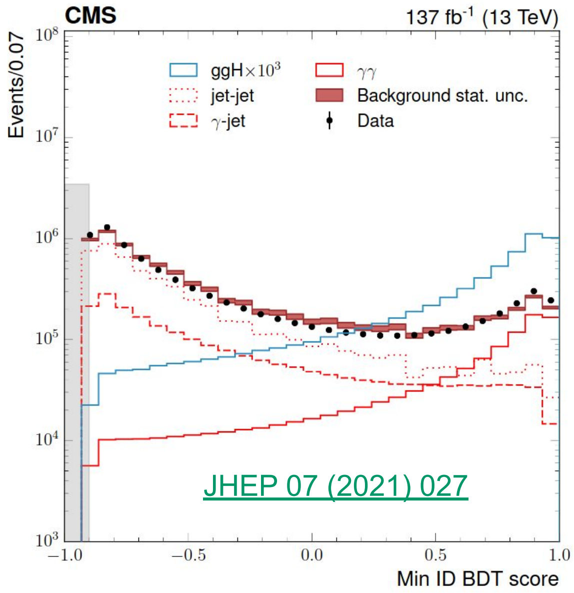
Online (trigger) selection

$p_{T,1} > 30$ GeV && $p_{T,2} > 30$ GeV && loose isolation && $m_{\gamma\gamma} > 90$ GeV
OR
$p_{T,1} > 30$ GeV && $p_{T,2} > 22$ GeV && loose isolation && $m_{\gamma\gamma} > 90$ GeV

Offline preselection (tighter than online)

$p_{T,1} > 35$ GeV && $p_{T,2} > 25$ GeV && $p_{T,1}/m_{\gamma\gamma} > 1/3$ && $p_{T,2}/m_{\gamma\gamma} > 1/4$ && && isolation && loose photon ID

- **Photon ID**: BDT trained to **separate real photons** (“prompt”, p) **from jets** misidentified as photons (“fake”, f)
- Trained on simulated γ+jets samples
  - Positive class: photons
  - Negative class: jets
- **Input features**: isolation variables, shower shape variables, energy, η, pileup-related variables
- Validated on simulated signal and main backgrounds (pp, pf and ff)



m_H analysis workflow

Online (trigger) selection

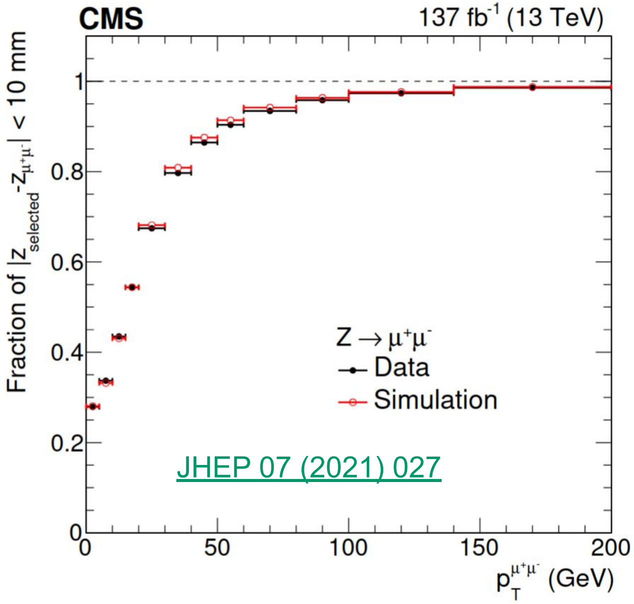
$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 30 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV
OR
$p_{T,1}$ > 30 GeV && $p_{T,2}$ > 22 GeV && loose isolation && $m_{\gamma\gamma}$ > 90 GeV

Offline preselection (tighter than online)

$p_{T,1}$ > 35 GeV && $p_{T,2}$ > 25 GeV && $p_{T,1}/m_{\gamma\gamma}$ > ⅓ && $p_{T,2}/m_{\gamma\gamma}$ > ¼ && && isolation && loose photon ID

γγ vertex selection

Choose p-p vertex out of which the diphoton pair is produced



- **Diphoton mass resolution depends on vertex choice:** $m_{\gamma\gamma} = \sqrt{2E_1E_2\cos(1-\phi)}$
- Main CMS vertex: vertex with greatest sum of p_T^2 of tracks
- Photons have no tracks
- **Train a BDT** (using ggH events) with recoil tracks **to identify the diphoton vertex**
- Validated in Z(μμ) with stripped tracks

m_H analysis workflow

Online (trigger) selection

$p_{T,1} > 30$ GeV && $p_{T,2} > 30$ GeV && loose isolation && $m_{\gamma\gamma} > 90$ GeV
OR
$p_{T,1} > 30$ GeV && $p_{T,2} > 22$ GeV && loose isolation && $m_{\gamma\gamma} > 90$ GeV

Offline preselection (tighter than online)

$p_{T,1} > 35$ GeV && $p_{T,2} > 25$ GeV && $p_{T,1}/m_{\gamma\gamma} > 1/3$ && $p_{T,2}/m_{\gamma\gamma} > 1/4$ && isolation && loose photon ID

γγ vertex selection

Choose p-p vertex out of which the diphoton pair is produced

Diphoton BDT categorization

Identify diphoton pairs from Higgs decays

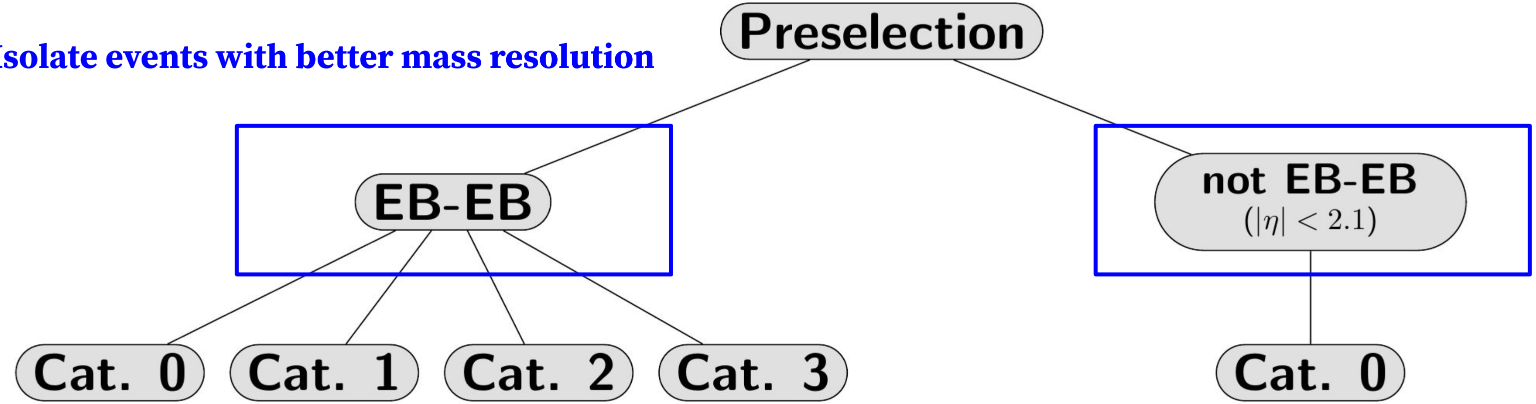
Categorize events based on BDT score

- **Diphoton BDT**: trained to separate signal diphoton pairs from background
- pf and ff backgrounds are estimated directly from data [1]
- A weight is assigned to high mass resolution events to increase their importance. **High BDT score ↔ high mass resolution**

m_H analysis workflow: categorization

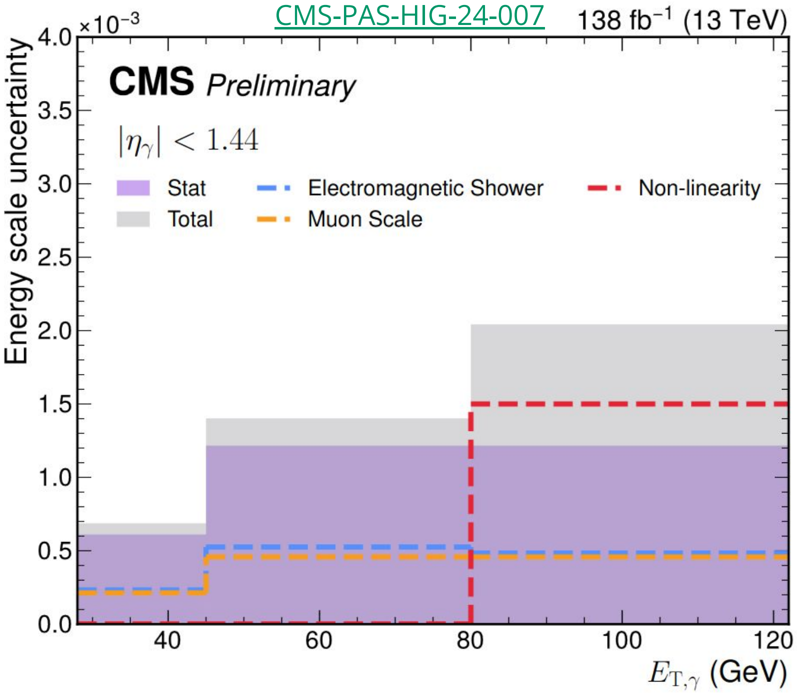
- First categorization criterion: **split events in barrel-barrel and not-barrel-barrel photon events**

Isolate events with better mass resolution



Analysis sensitivity is driven by events in the barrel

Systematic uncertainties

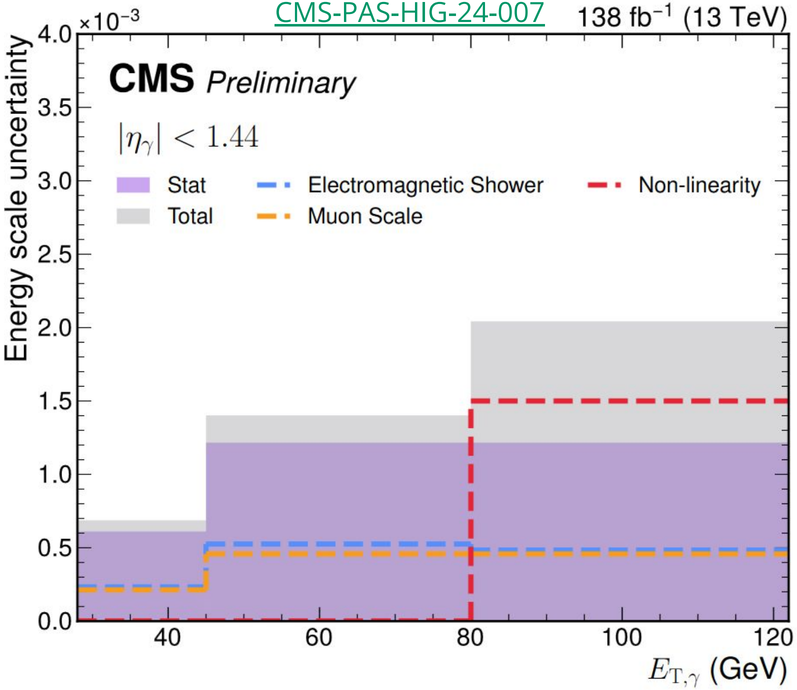


Source	Contribution (MeV)
Photon energy scale	
Statistical uncertainty of muon sample	75
Residual non-linearity	64
Muon momentum	38
Electromagnetic shower	23
Photon energy resolution	7
Interference between ggH signal and background	27
Other sources	13
Statistical uncertainty	100
Total uncertainty	150

- **Stat.**: limited size of Z(μμγ) sample in data and MC

Systematic uncertainties

CMS-PAS-HIG-24-007

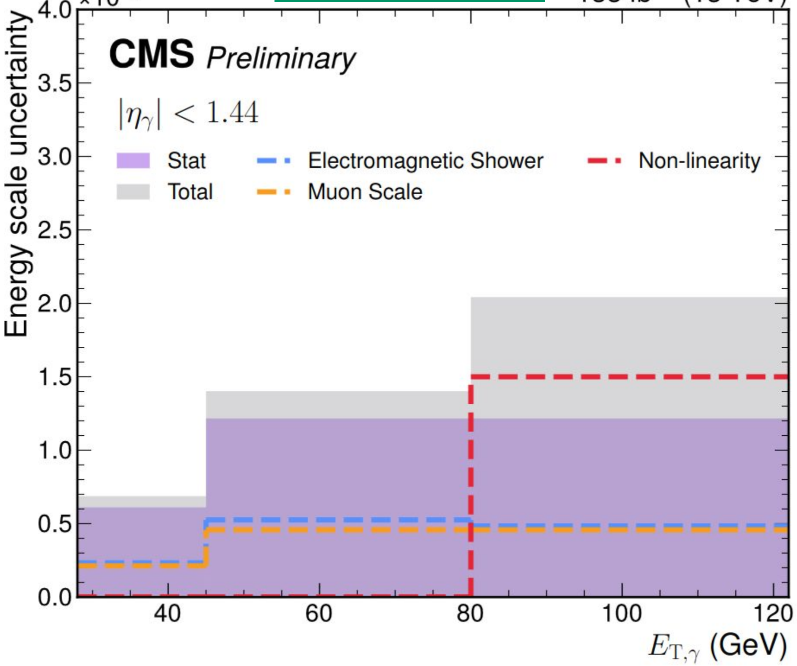


Source	Contribution (MeV)
Photon energy scale	
Statistical uncertainty of muon sample	75
Residual non-linearity	64
Muon momentum	38
Electromagnetic shower	23
Photon energy resolution	7
Interference between ggH signal and background	27
Other sources	13
Statistical uncertainty	100
Total uncertainty	150

- **Stat.**: limited size of Z(μμγ) sample in data and MC
- **Non-linearity**: not enough photons in Z(μμγ) above 80 GeV to precisely estimate scale correction

Systematic uncertainties

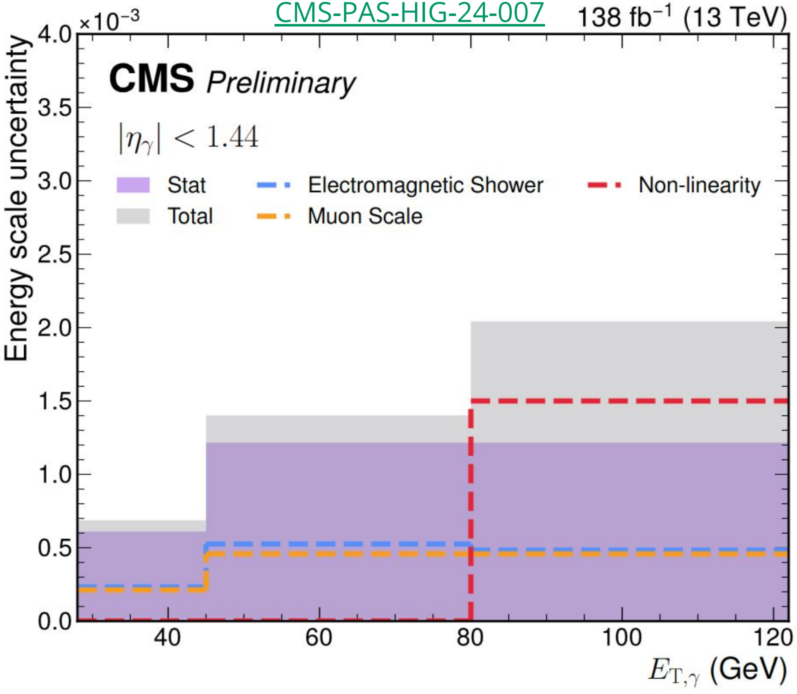
CMS-PAS-HIG-24-007



Source	Contribution (MeV)
Photon energy scale	
Statistical uncertainty of muon sample	75
Residual non-linearity	64
Muon momentum	38
Electromagnetic shower	23
Photon energy resolution	7
Interference between ggH signal and background	27
Other sources	13
Statistical uncertainty	100
Total uncertainty	150

- **Stat.**: limited size of Z(μμγ) sample in data and MC
- **Non-linearity**: not enough photons in Z(μμγ) above 80 GeV to precisely estimate scale correction
- **Muon scale**: impact of uncertainty on muon energy scale on derivation of photon energy scale correction

Systematic uncertainties



Source	Contribution (MeV)
Photon energy scale	
Statistical uncertainty of muon sample	75
Residual non-linearity	64
Muon momentum	38
Electromagnetic shower	23
Photon energy resolution	7
Interference between ggH signal and background	27
Other sources	13
Statistical uncertainty	100
Total uncertainty	150

- **Stat.**: limited size of Z(μμγ) sample in data and MC
- **Non-linearity**: not enough photons in Z(μμγ) above 80 GeV to precisely estimate scale correction
- **Muon scale**: impact of uncertainty on muon energy scale on derivation of photon energy scale correction
- **EM shower**: variation of scale correction as a function of cut on photon ID

Systematic uncertainties: final note

- Run 2 strategy adds two additional calibration steps: uniformity + Z(μμγ)
  - Implies additional uncertainties
- Last step of **run 2 strategy calibrates directly with photons in data**
- Allows to completely **drop uncertainties due to electron-photon differences**
  - They dominated the Run 1 measurement
- Example of ele/pho difference: **material budget**
  - Material upstream of the ECAL (tracking material) is imperfectly simulated
  - How does an uncertainty on the amount of material affect energy scale of e/γ? Does it affect them differently?
- **Uncertainty trade-off**, eventually in favor of Run 2 strategy

Eur. Phys. J. C **74**, 3076 (2014)

Source of uncertainty	Uncertainty in $\widehat{m}_H$ (GeV)
Imperfect simulation of electron–photon differences	0.10
Linearity of the energy scale	0.10
Energy scale calibration and resolution	0.05
Other	0.04
All systematic uncertainties in the signal model	0.15
Statistical	0.31
Total	0.34

Breakdown of uncertainties in Run 1