TIPP'17

Beijing, China
May 25, 2017

Performance of the CMS electromagnetic calorimeter during the LHC Run II

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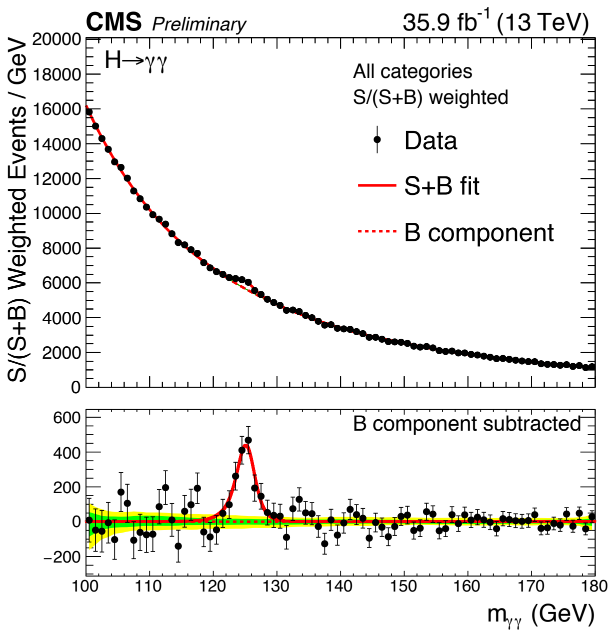
on behalf of the CMS Collaboration

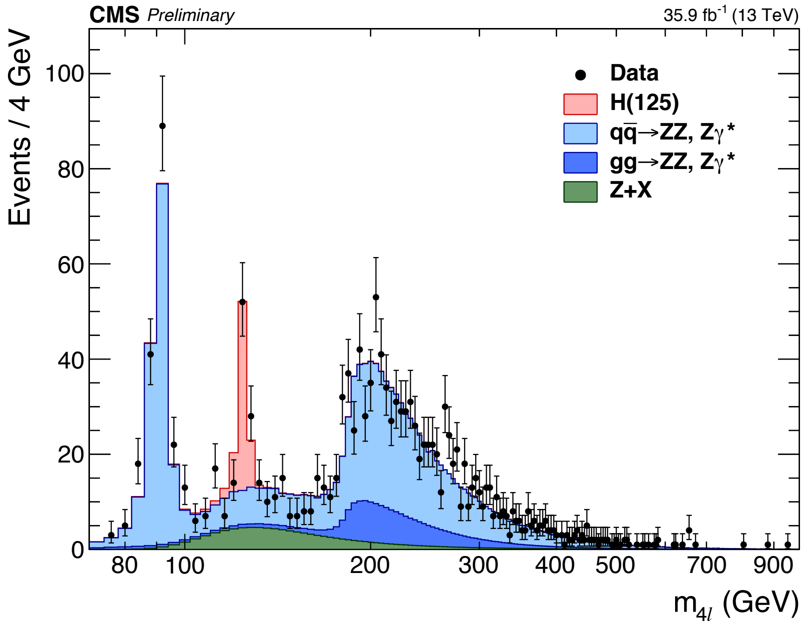
ECAL is crucial in CMS physics analysis

- New physics searches and Standard Model precision measurements with photons and electrons

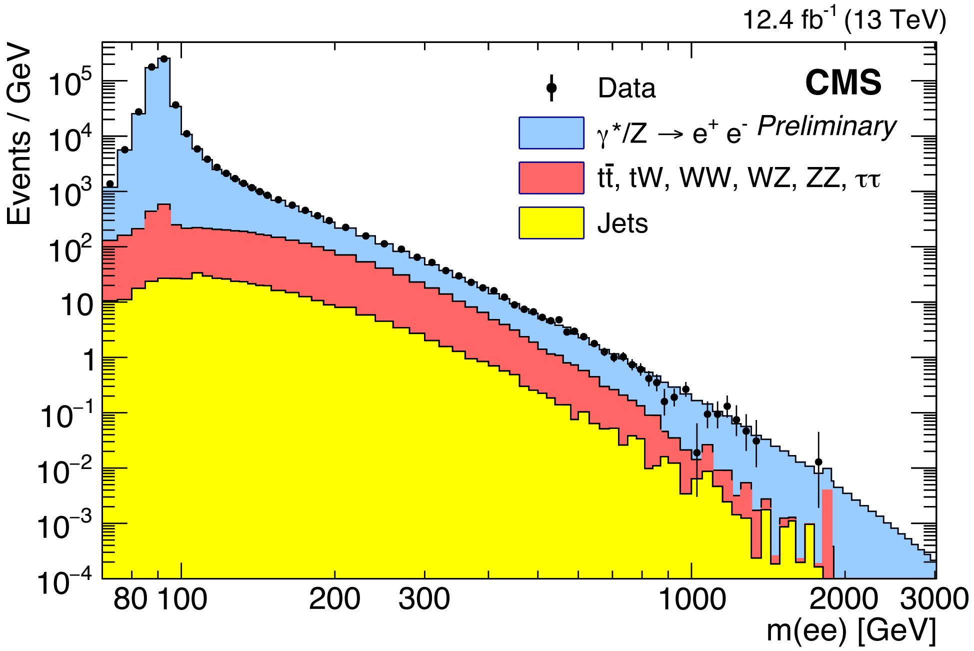
$H \to \gamma\gamma$



$H \to ZZ \to 4l$



$Z' \to ee$

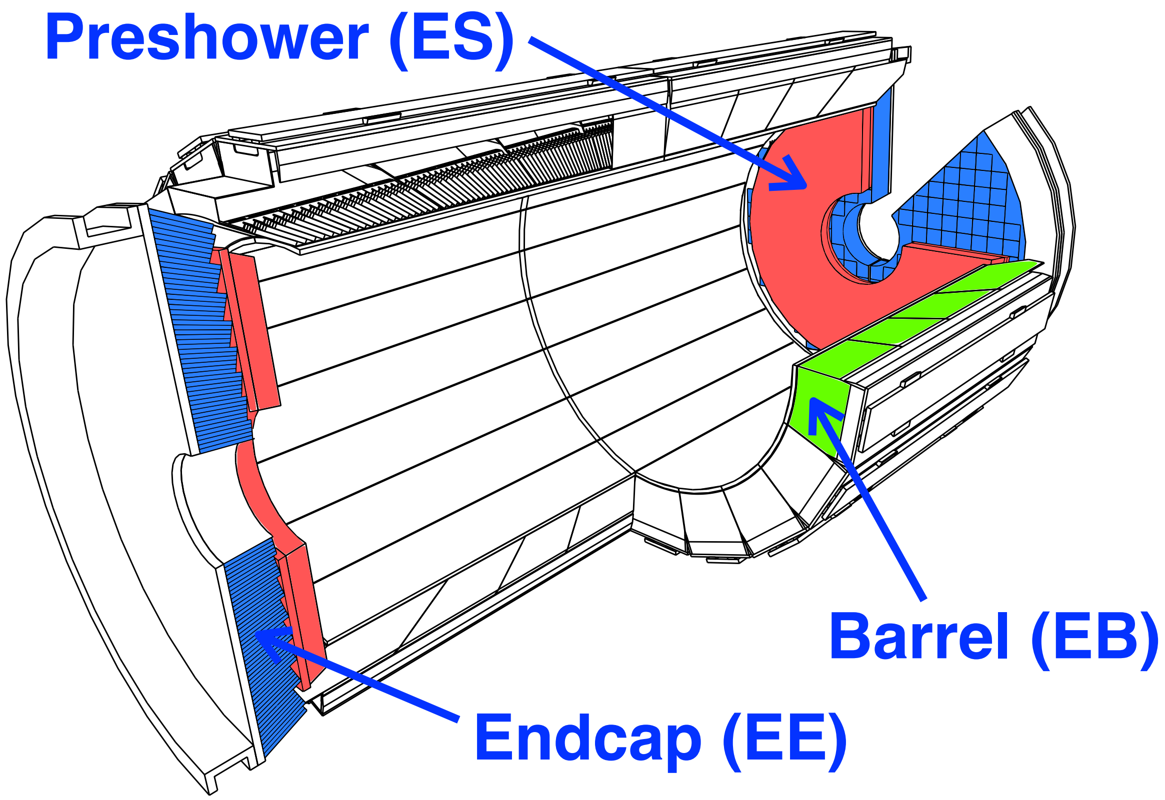


- high energy resolution
- position measurement

- a wide range of E_T

- high energy resolution
- energy linearity

CMS Electromagnetic Calorimeter



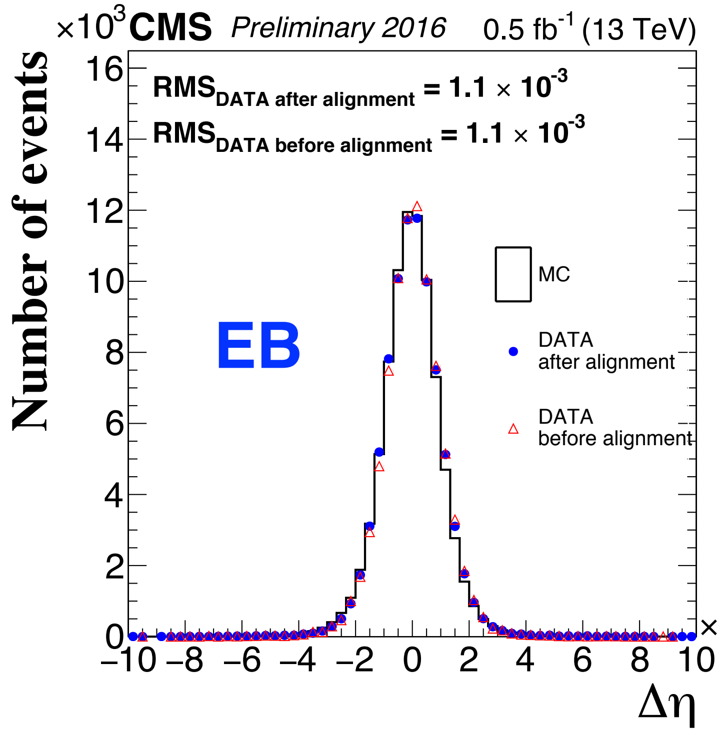
sub-detector	η-coverage	read-out channels	X_0
EB	$\lvert\eta\rvert < 1.48$	61200 crystals	~26
EE	$1.48 < \lvert\eta\rvert < 3.0$	14648 crystals	~25
ES	$1.65 < \lvert\eta\rvert < 2.6$	137216 Si strips	~3

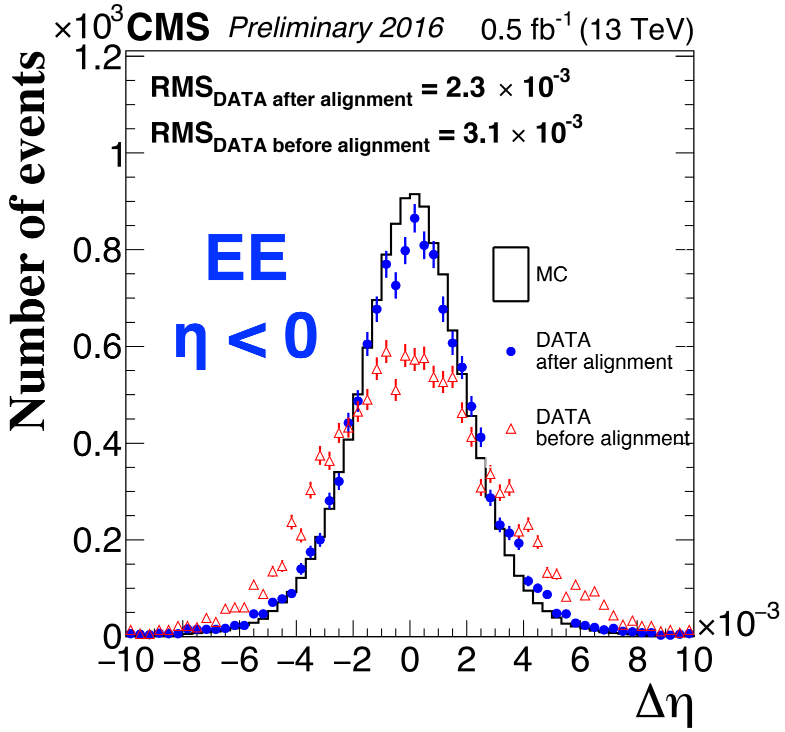
Compact enough to fit inside the 3.8T superconducting solenoid

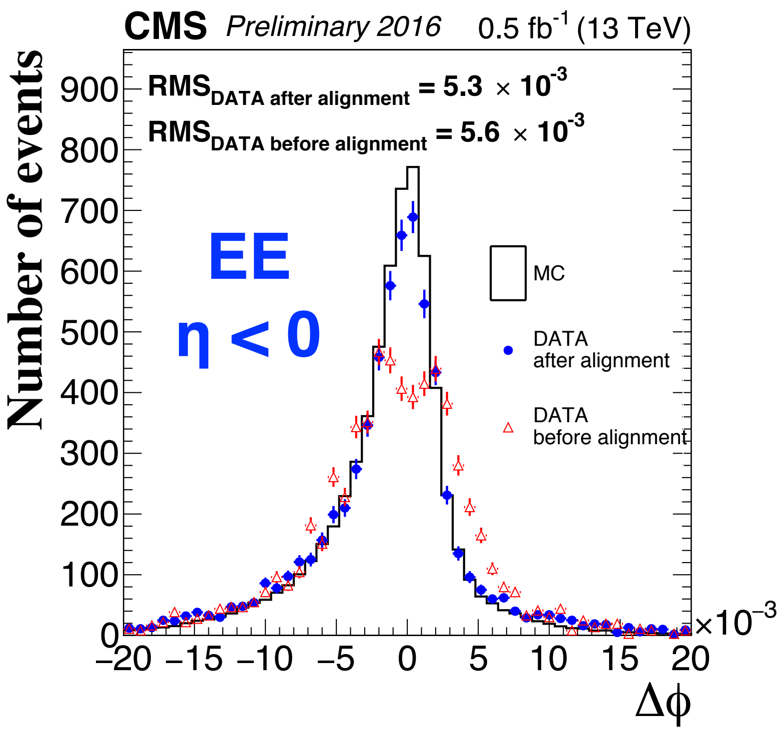
- **homogeneous, hermetic, compact, fine-grain** $PbWO_4$ crystal calorimeter
  - density of 8.3 g/cm^3
  - short radiation length 0.89 cm
  - small Moliere radius 2.2 cm
  - fast light emission : ~80% in ~25 ns
  - refractive index = 2.2
  - light yield spread among crystals 13% (RMS) from beam test
- **strengths :**
  - precise e/γ energy and position measurements
  - good timing resolution
  - fast and efficient readout for online selection (DAQ and trigger)

ECAL alignment

- position reconstructed from energy deposit exploiting ECAL high granularity
  - electron identification : prompt vs fake electrons
    - required matched measurements between ECAL and tracker is better than 0.02 radians in Φ and 0.004 units in η
  - measurement of photon direction : $H\to\gamma\gamma$
- procedure based on matching position reconstructed by tracker and ECAL with $Z\to ee$ events

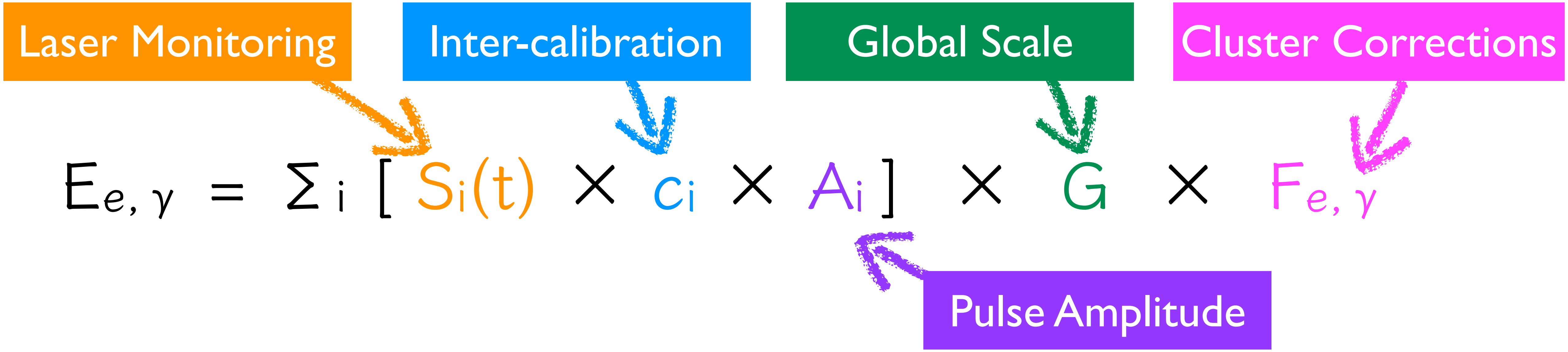






Energy reconstruction

- Electrons and photons deposit energy over several crystals (70% in one, 97% in a 3×3 array), spread in Φ, collected by clustering algorithms



Laser Monitoring

Inter-calibration

Global Scale

Cluster Corrections

$$E_{e,\gamma} = \Sigma_i \, [\, S_i(t) \times c_i \times A_i \,] \times G \times F_{e,\gamma}$$

Pulse Amplitude

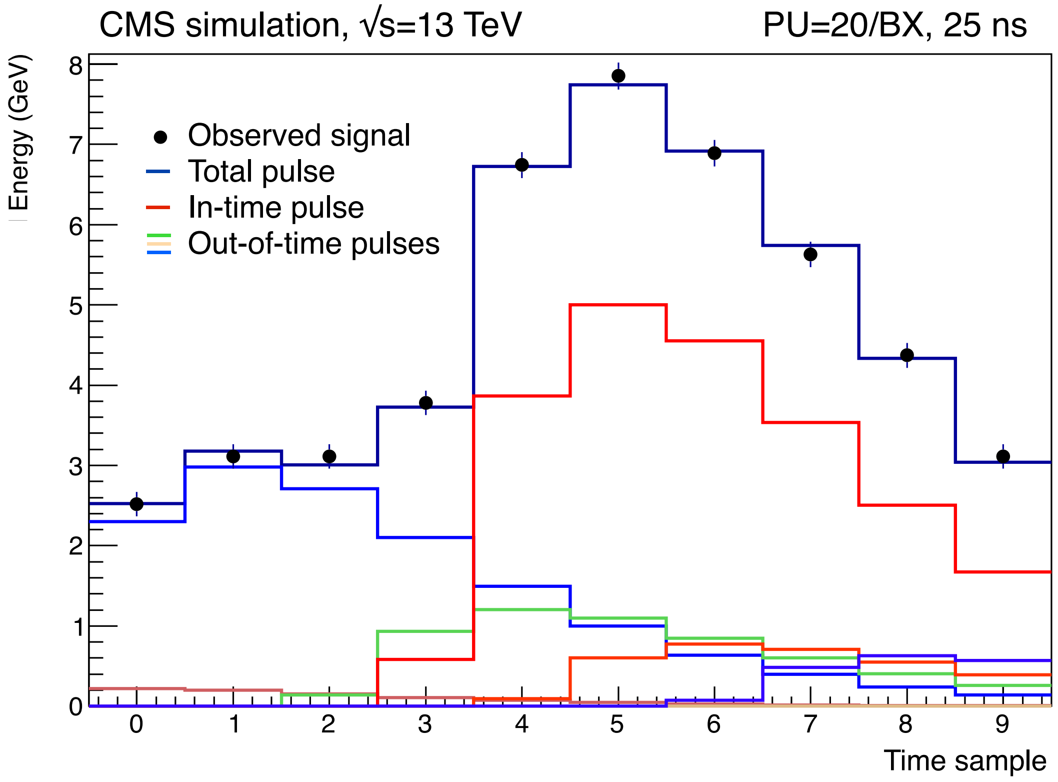
- **CMS ECAL energy resolution :**
  - uniformity and stability resolution required *in situ* < 0.5%
  - in barrel, 1% energy resolution achieved in Run-I and Run-II for unconverted/ late-converting photons

Pulse reconstruction

- When LHC runs with 25-ns bunch-spacing, the level of out-of-time (OOT) pile-up increases
- to mitigate this effect → **Multifit algorithm :** pulse shape is modeled as a sum of one in-time pulse pluses OOT pulses

$$\chi^2 = \sum_{i=1}^{10} \frac{(\sum_{j=1}^{M} A_j \times p_{ij} - S_i)^2}{\sigma^2_{S_i}}$$

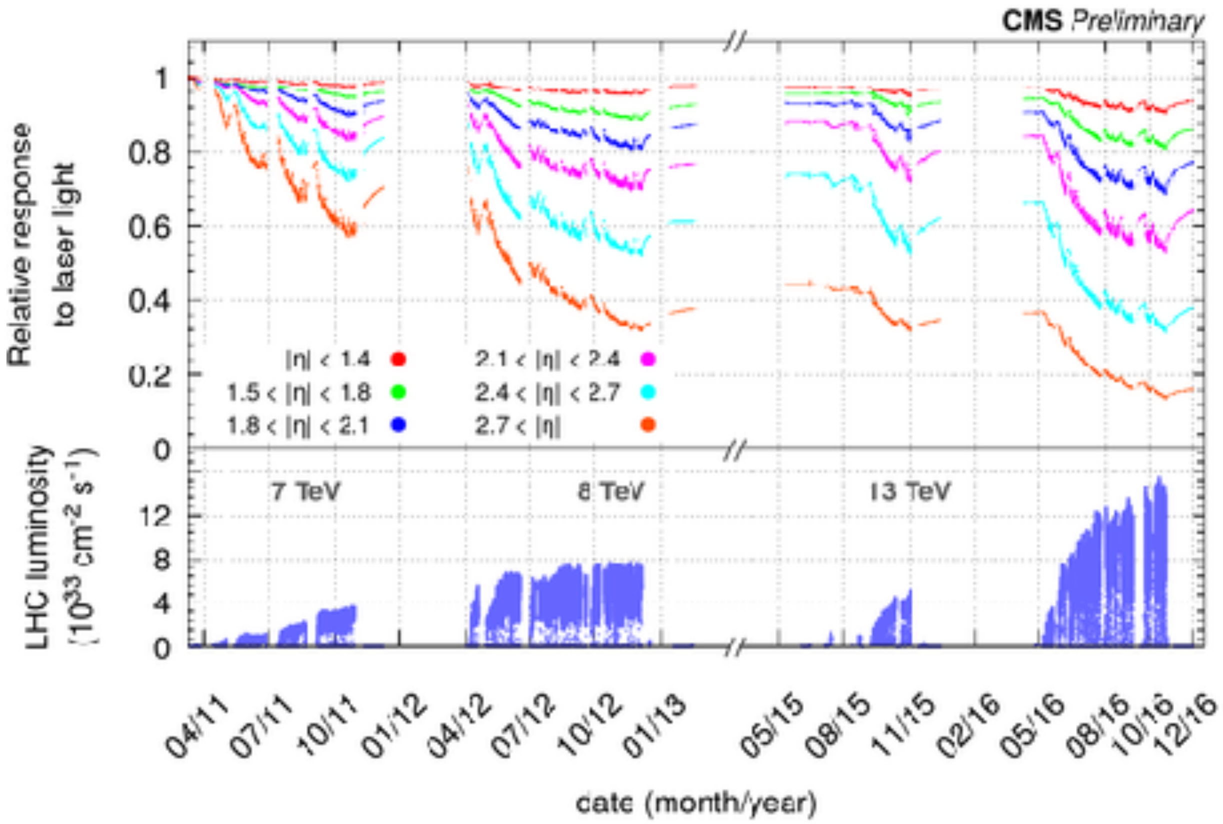
10 digitized signals are recorded and used for pulse reconstruction



BX = 0, -4, -1, +1, etc. fitted

- up to 9 OOT pulses (one per time sample)
- minimize χ^2 distribution for best description of the in-time amplitude
- LHC isolated bunches are used to extract the pulse shapes (binned templates) periodically
- baseline and electronic noise periodically measured from dedicated runs and used in the covariance matrix
- Minimization using non-negative least-squares : fast enough to be used both offline and online

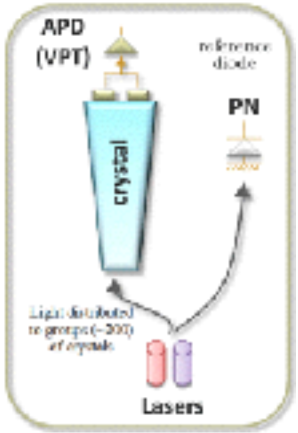
Crystal response monitoring



tracker coverage
→ precision physics

high η (|η| > 2.5)
→ jet physics

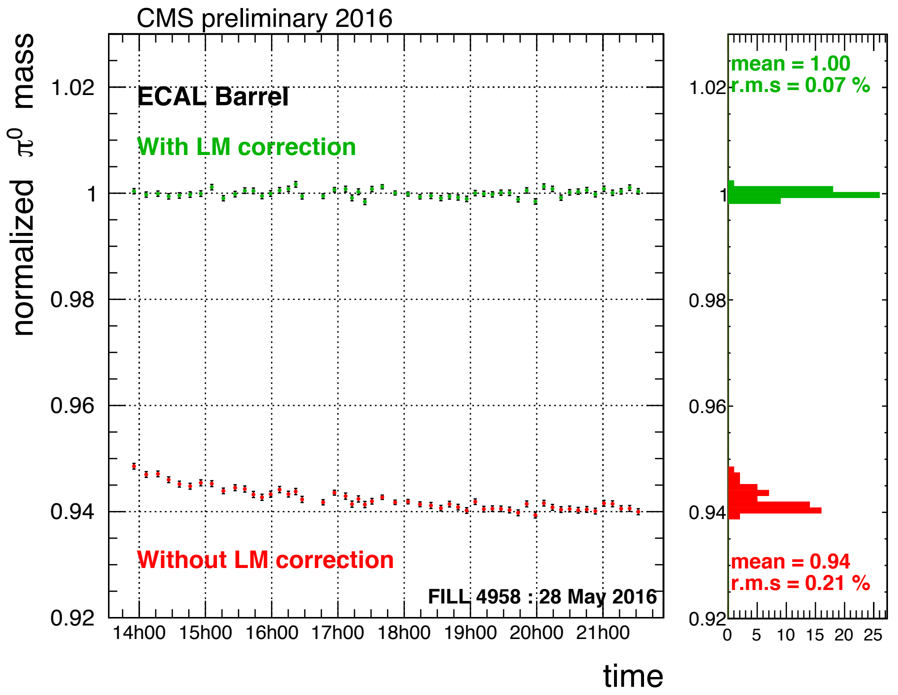
- Steady recovery during shutdowns and inter-fills
- In the regions close to beam pipe, not fully recovered



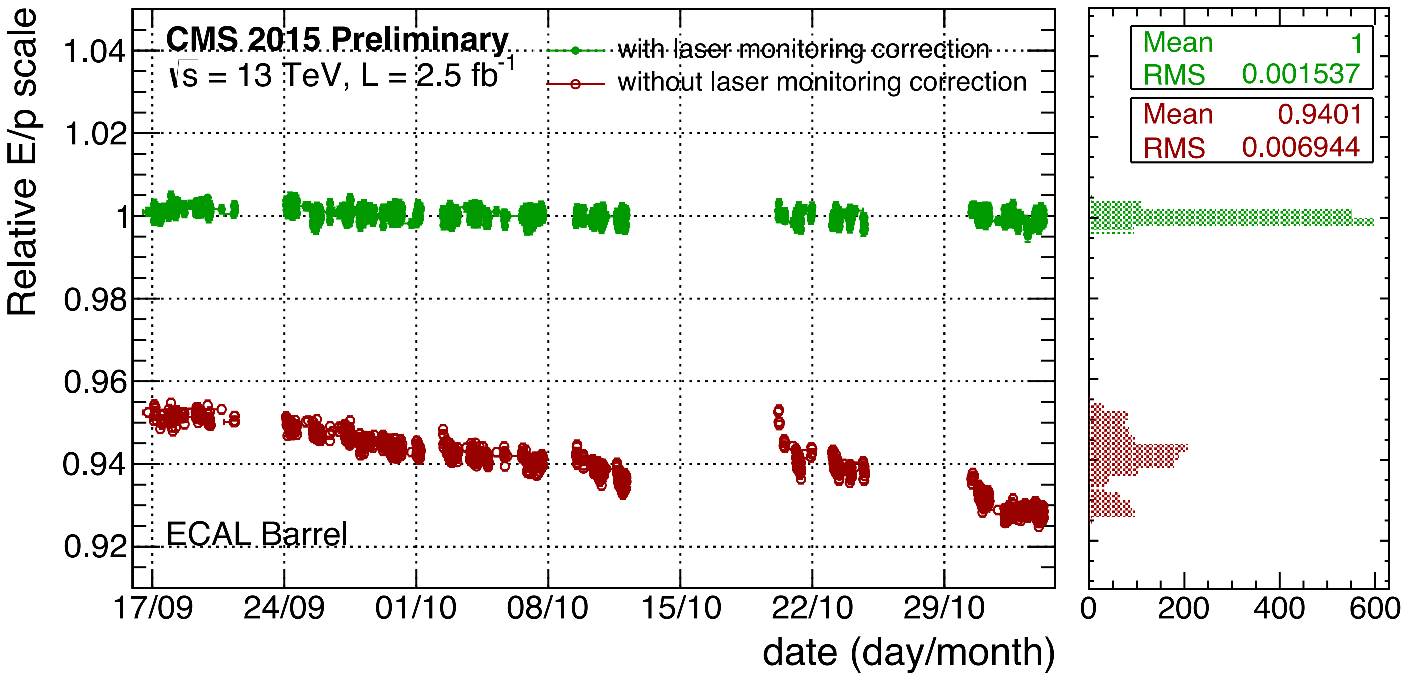
- ECAL radiation-induced effects, <u>heavily η dependent</u>
  - crystal transparency changes
  - VPT photocathode aging with accumulated charge
- channel response is constantly monitored with a laser system injecting light in every ECAL crystal
  - 1 calibration point per channel every 40 mins
  - corrections obtained and applied in ~48 hours for prompt reconstruction

Validation of response monitoring

- Response stability after corrections validated with physics signals:
  - the stability of π^0 invariant mass
  - E/p relative scale of isolated electrons from W decays



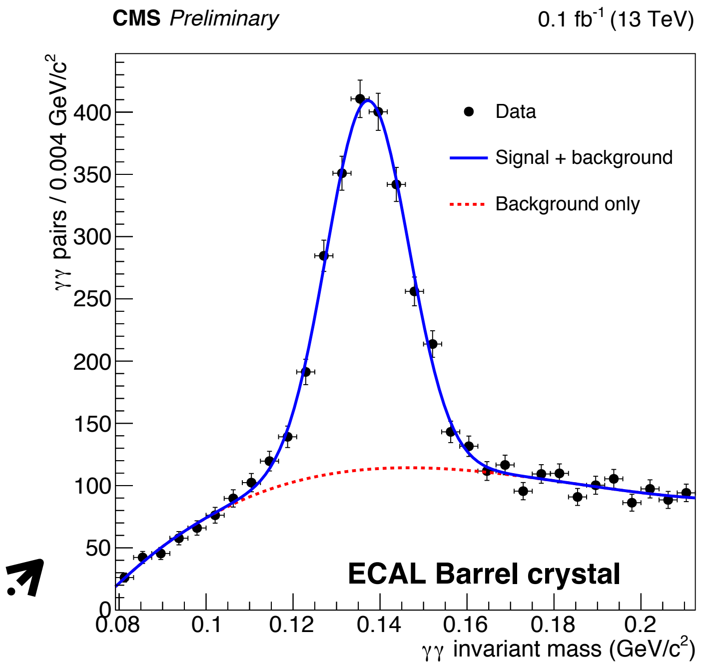
- π^0 mass history in barrel in 1 fill
  - <signal loss> ~1%
  - RMS after laser monitoring corrections : ~0.07%
  - very fast monitoring : 1 point/8-min

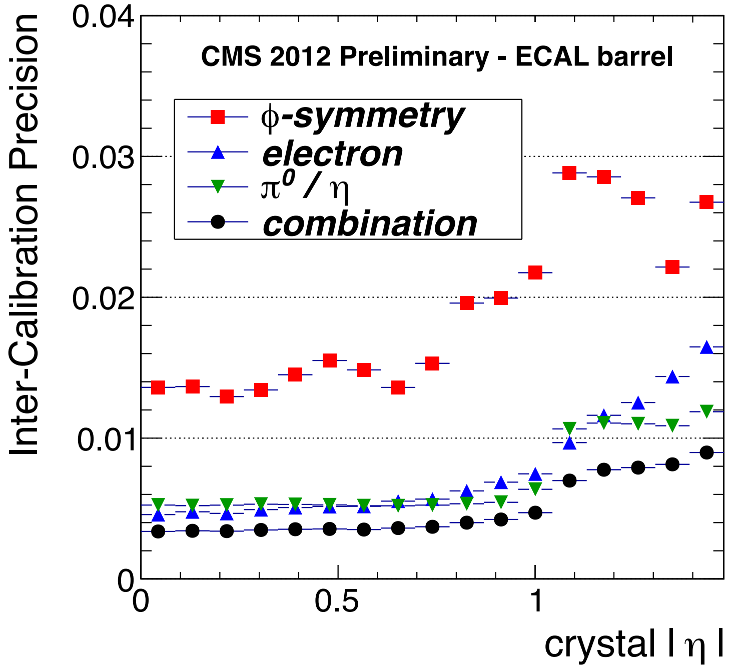


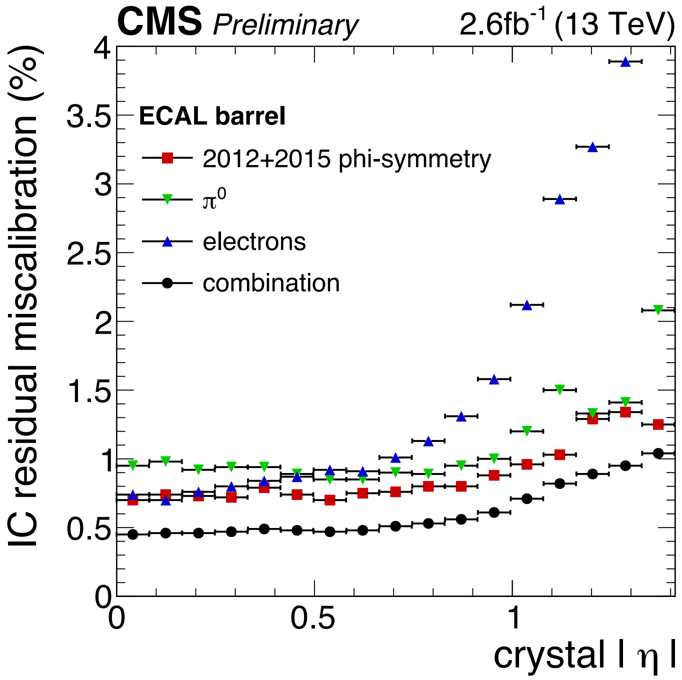
- Electrons E/p history in barrel in 2015
  - <signal loss> ~6%
  - RMS after laser monitoring corrections : ~0.15%

Inter-calibration (IC)

- Equalizes the response of each single crystal to the deposited energy



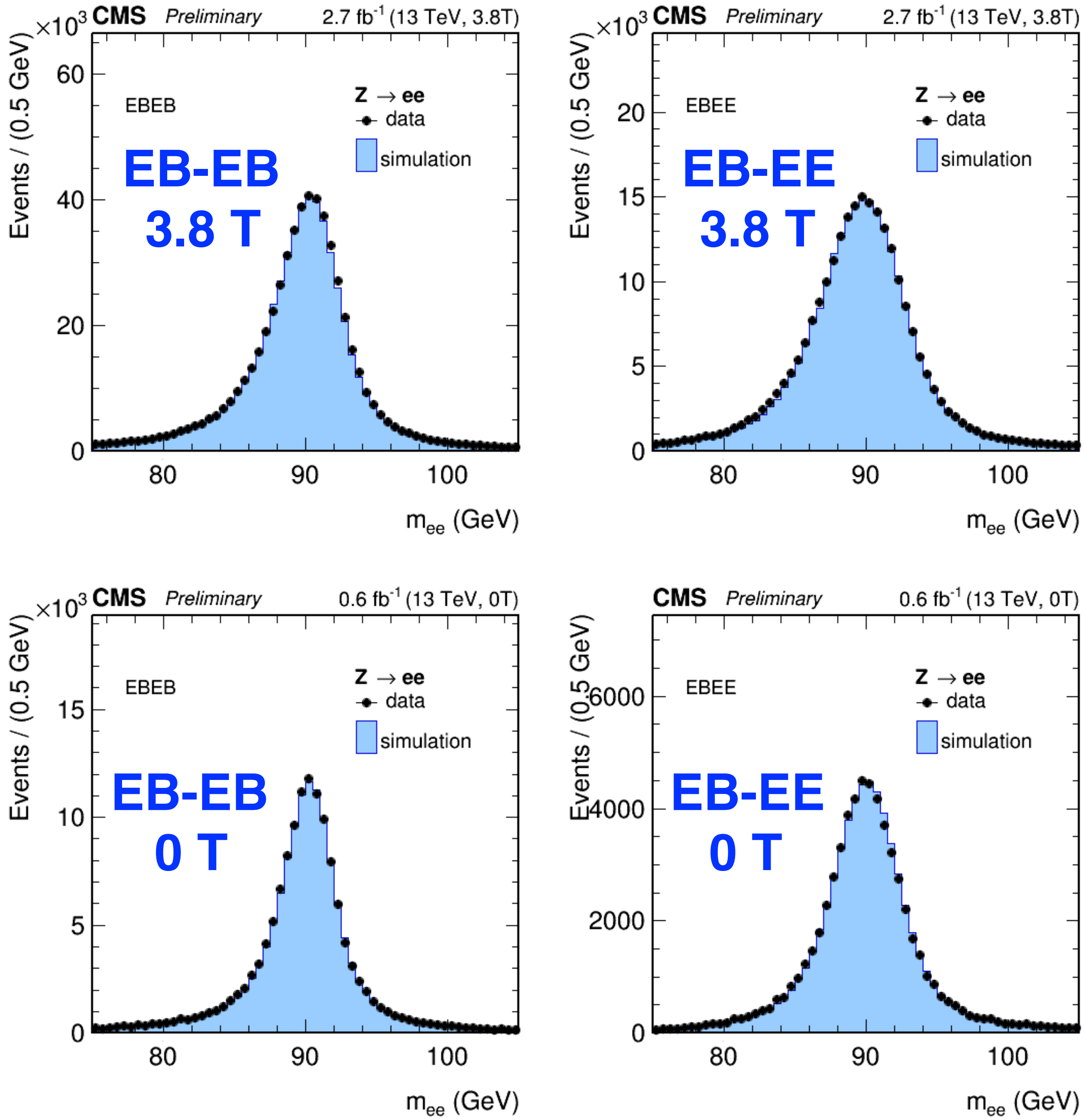




Method	Description	Run-I precision
Φ-symmetry	Energy flux around Φ rings (constant η) should be uniform - IC corrects for non-uniformity	1-3% in EB 3-5% in EE
$\pi^0/\eta \rightarrow \gamma\gamma$	In a Φ ring, use IC to improve $M_{\gamma\gamma}$ resolution for π^0 and η resonances	0.5% in EB 3% in EE (|η<2|)
electron E/p	Compare isolated electron energy from ECAL and tracker, compute IC to correct discrepancies	0.5% in EB 2% in EE

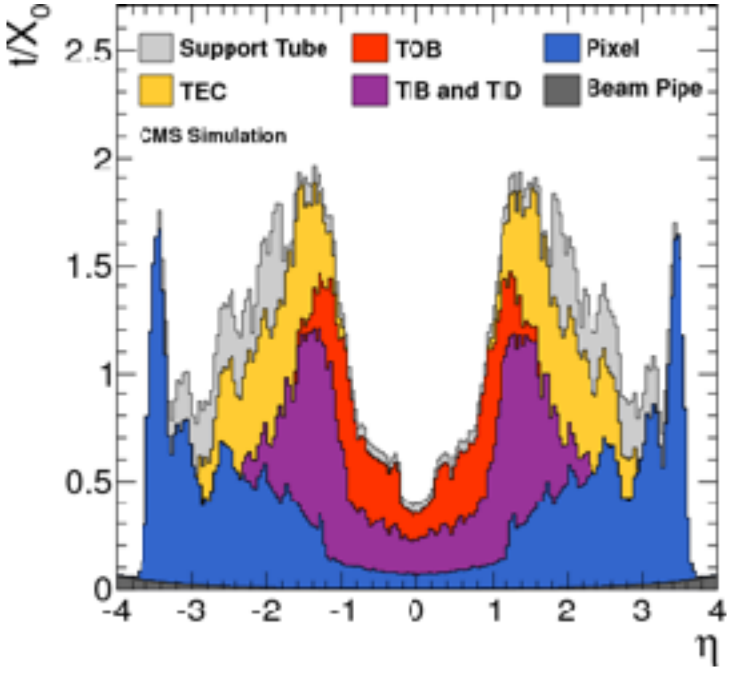
η scale and absolute calibration

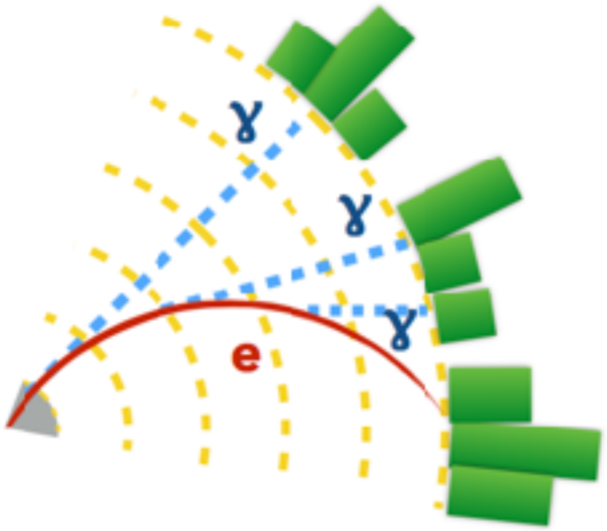
- the η dependence of the energy reconstruction and its absolute scale are calibrated with electrons from Z decays
- Z peaks in a single η-ring are used to correct the relative scale between different η-rings
- The Z peak is used again to fix the overall absolute calibration, matching data to a detailed simulation of the detector
  - separate absolute calibrations for 3.8 and 0 T data

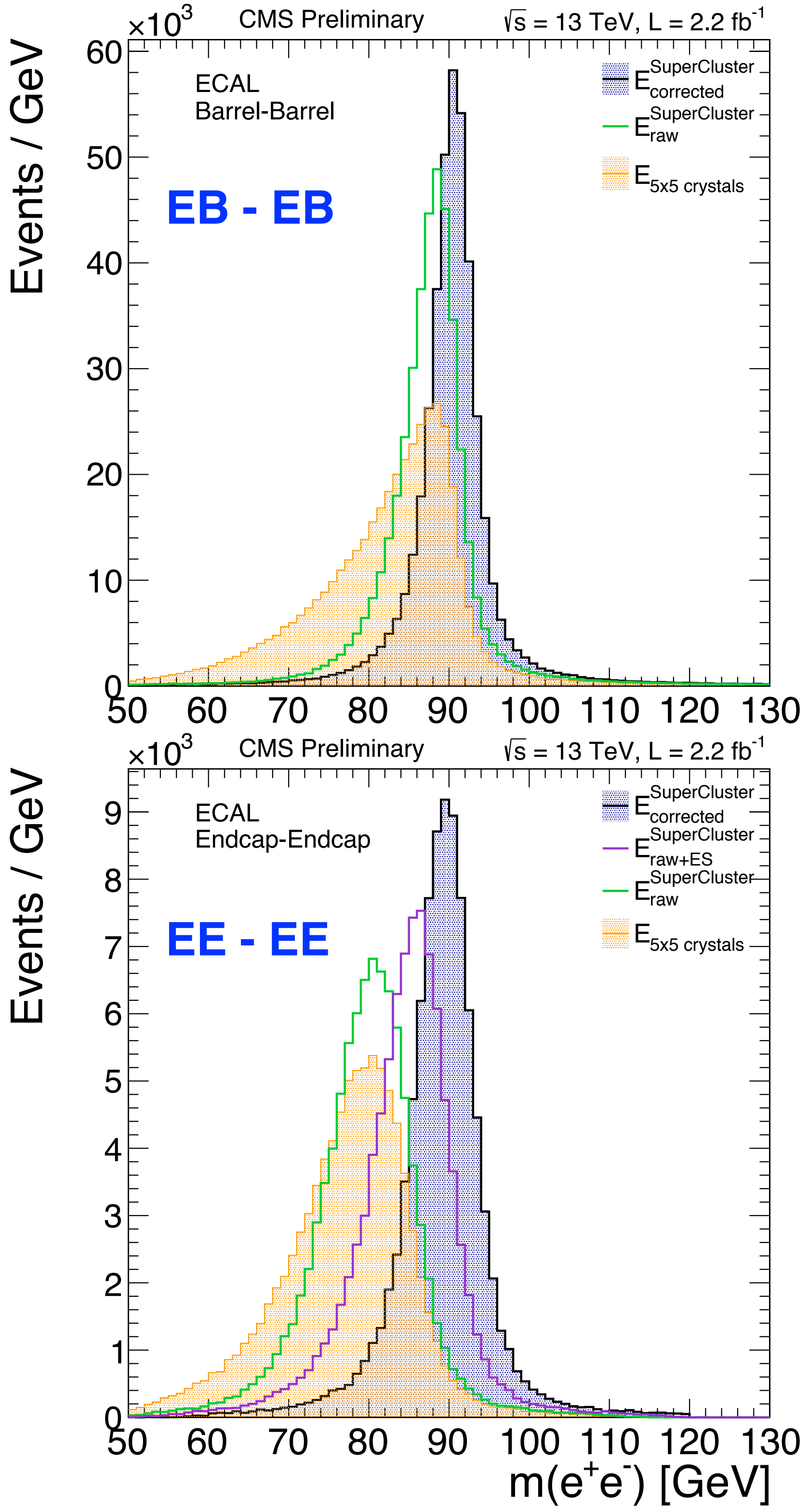


The inclusion of 0T data improved the search sensitivity of X→γγ by ~10%

Clustering and corrections



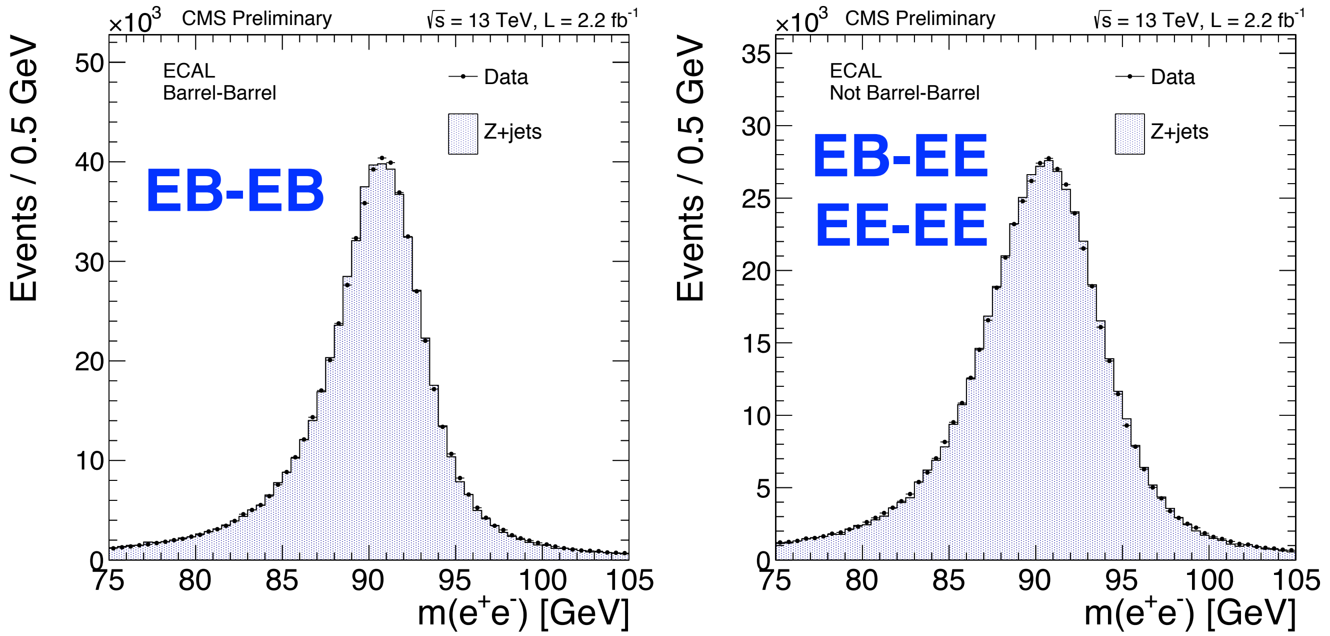




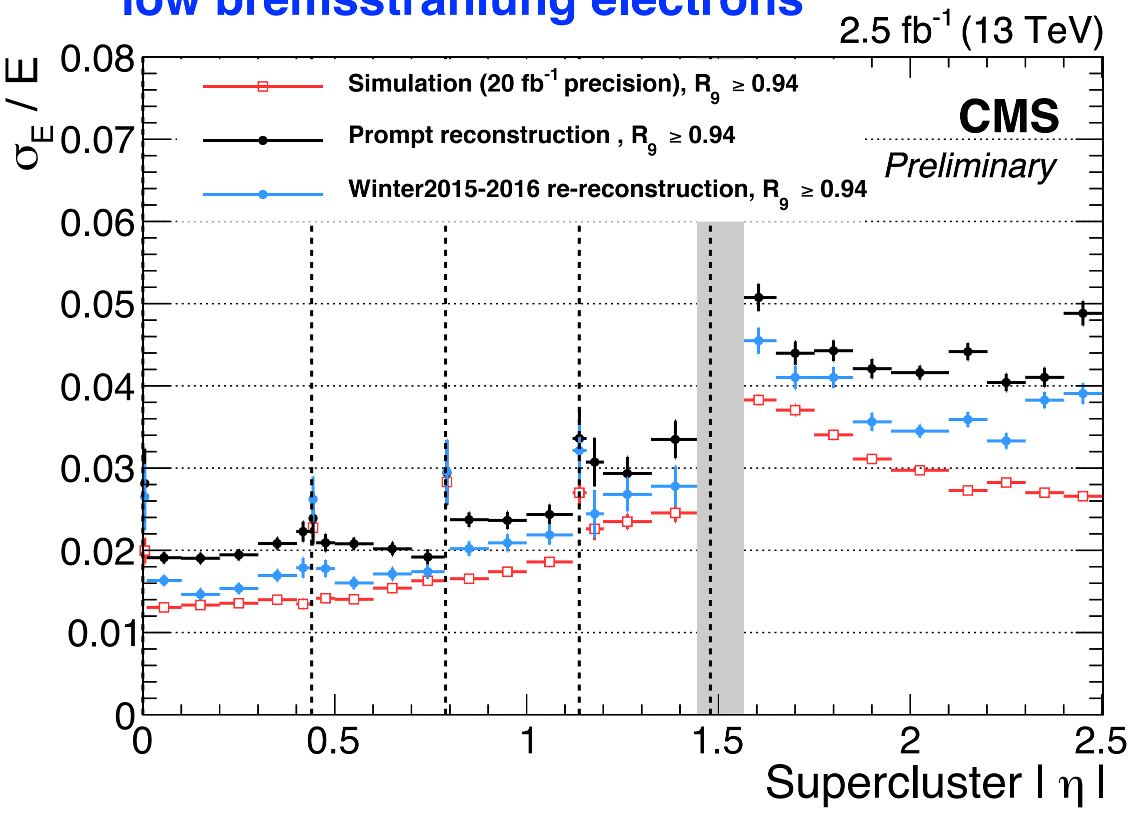
- large amount of material before ECAL
- dynamic clustering algorithm recovers energy radiated upstream of ECAL via bremsstrahlung or conversions
    - super-cluster (SC) of clusters along Φ (bending direction)
    - soft conversion legs/brem may not be included in SC
    - in the endcaps, preshower energy is also considered
    - additional energy from pileup contaminates the shower
- the energy of supercluster is corrected using a multivariate approach that maximally exploits the information of the events → tuned on MC, validated on data
- Reconstructed Z mass in data with different levels of energy reconstruction and corrections

Energy and mass resolution

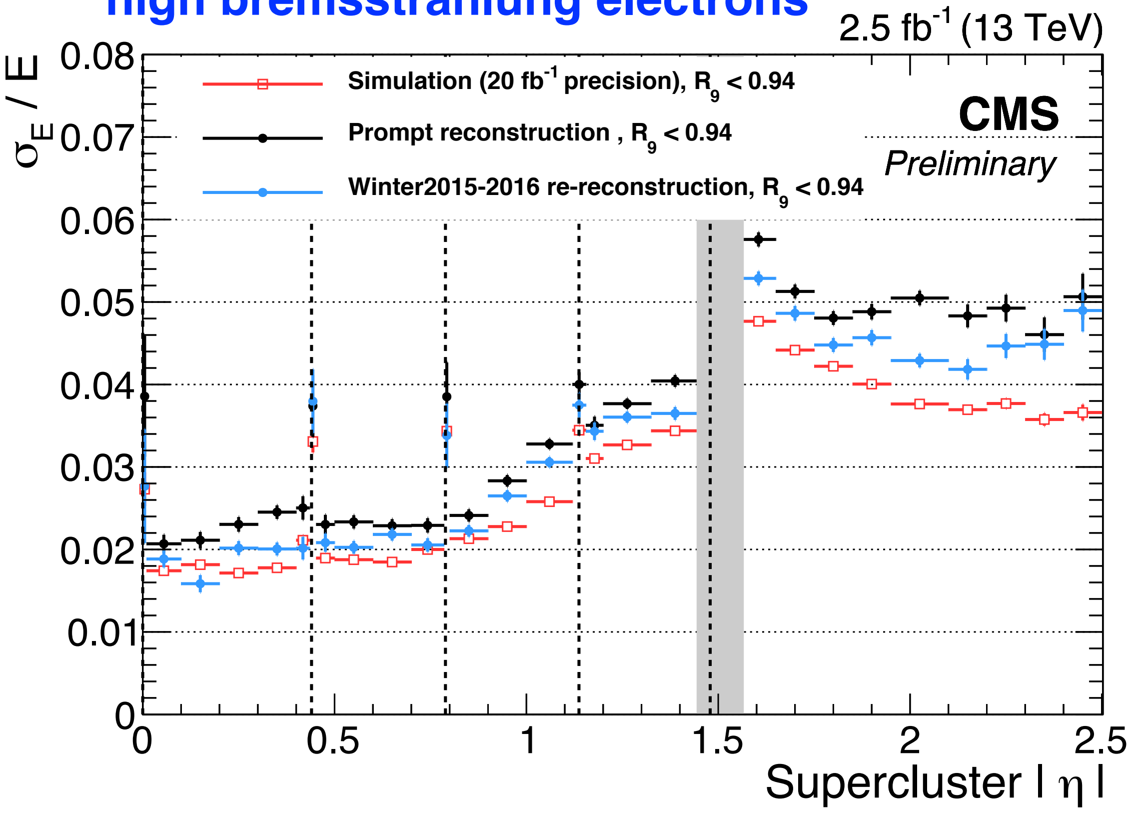
- derive electron energy resolution from Z→ee peak width
- improvement from prompt to refined conditions
    - for |η| < 1, precision at the level of Run-I
- simulation tuned to match resolution observed in data



low bremsstrahlung electrons



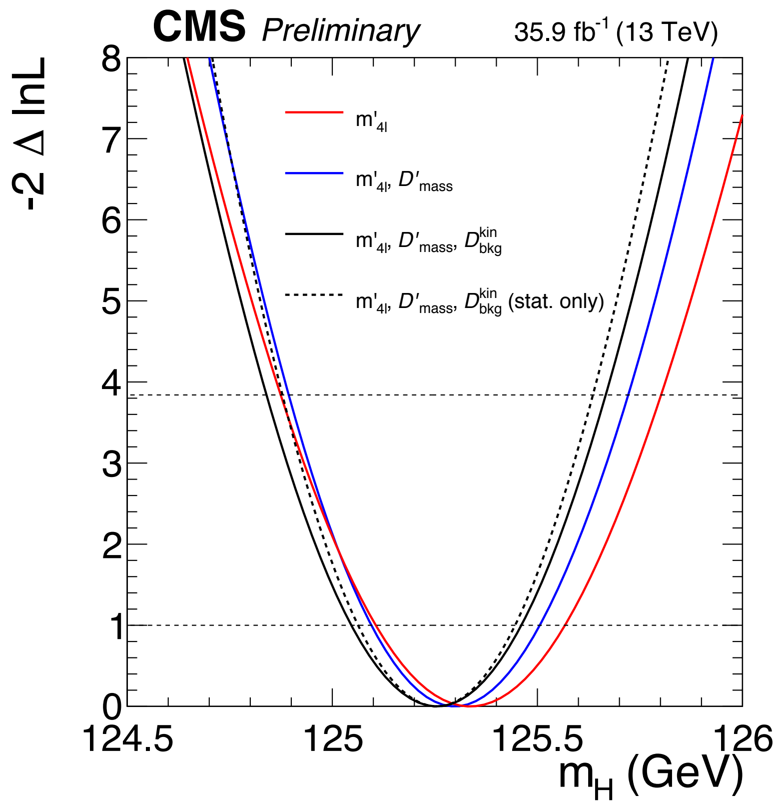
high bremsstrahlung electrons



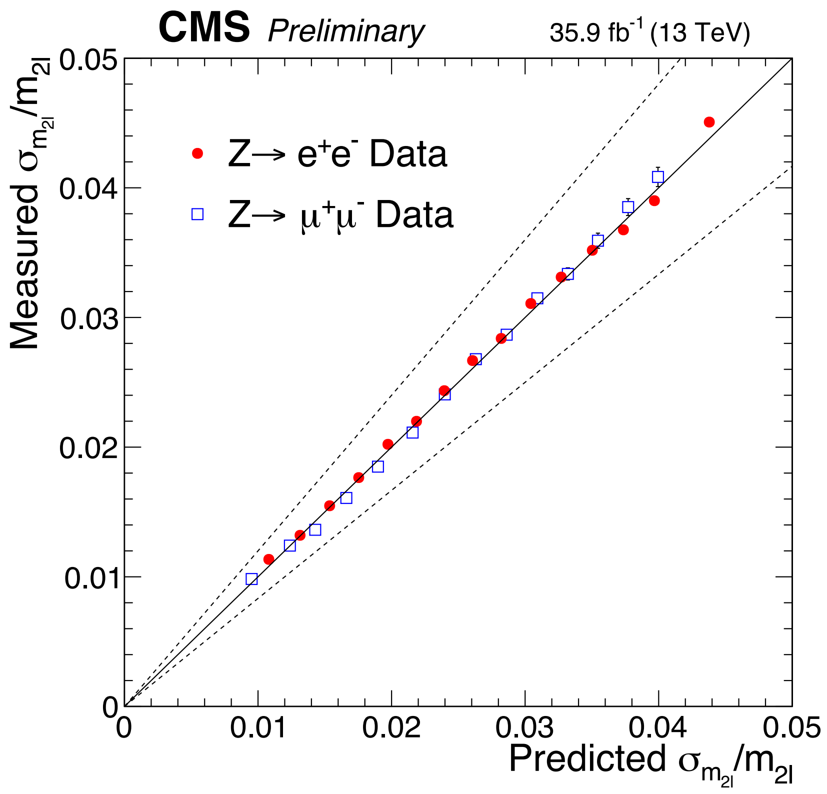
Estimation of single e/γ resolution

- per-electron or per-photon resolution used to build a per-event mass resolution (σ_m/m), utilized to make optimal use of the highest resolution events
  - H→ZZ→4l : per-event mass resolution used as a variable in the fit for mass measurement
    - validated in data with fits to Z→ee by comparing the predicted σ_{m2l}/m_{2l}
  - H→γγ : used to classify in several "untagged" categories for $m_{\gamma\gamma}$ fit

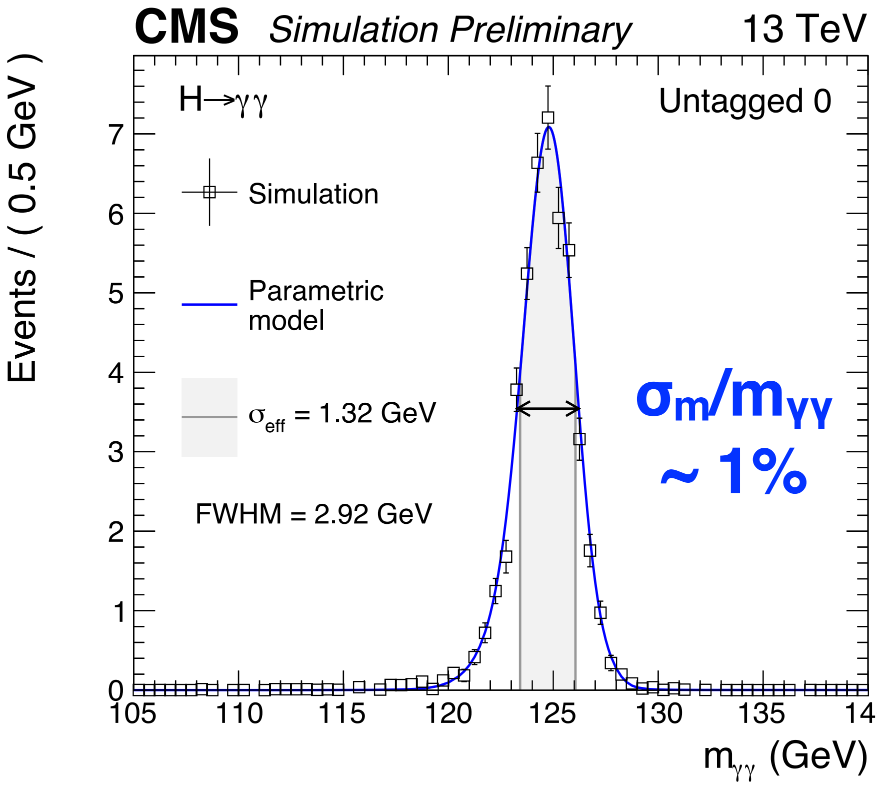
H→ZZ→4l mass likelihood



observed vs predicted σ_m



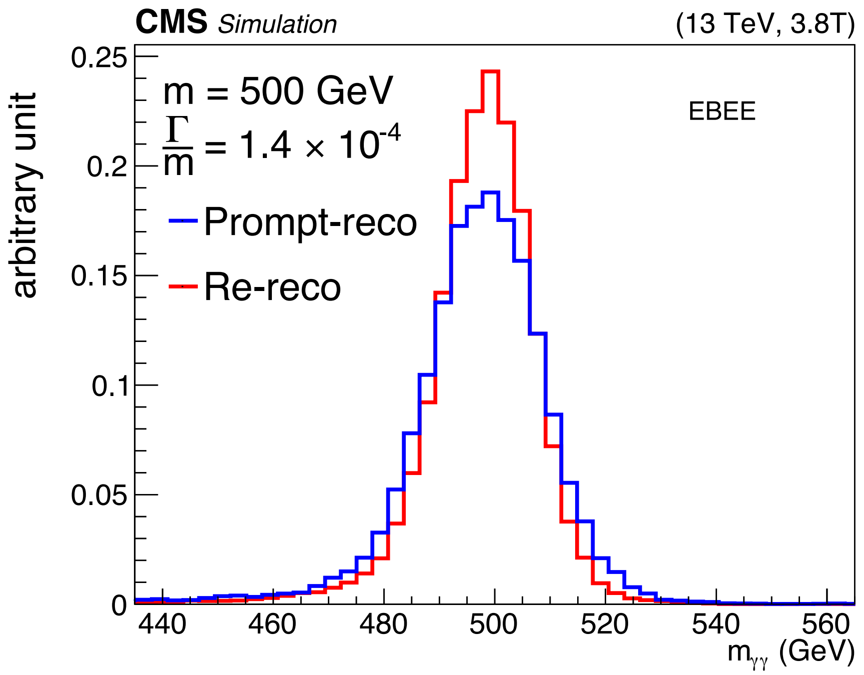
H→γγ best category

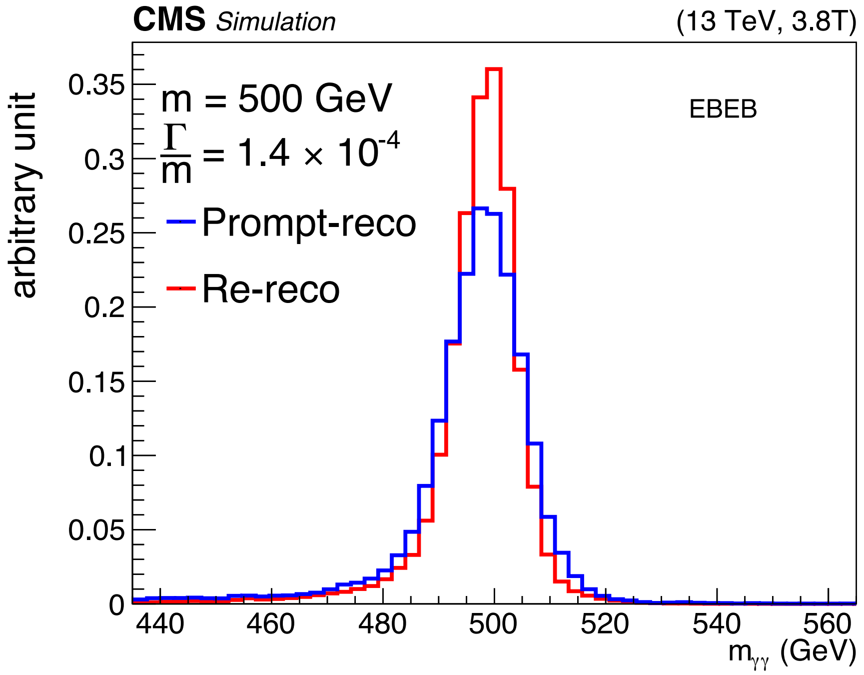


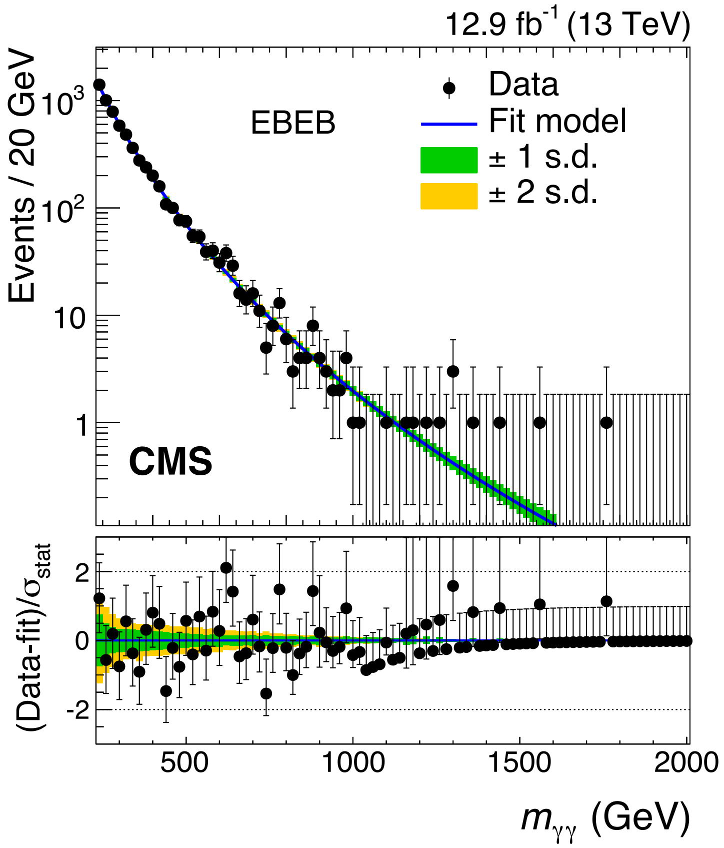
$\sigma_m/m_{\gamma\gamma}$ ~ 1%

Energy resolution for high energy photons

- recalibration also has an important impact on high energy photons
- saturation effects of electronics corrected with multivariate approach
    - single channel saturation in barrel : E ~ 1.6 TeV
    - impact on energy scale < 2%
- residual non-linearity checked with boosted Z→ee : < 0.5% (0.7%) for photons up to 150 GeV in the barrel (endcap)







Conclusions

- The CMS electromagnetic calorimeter performs well during LHC Run-II and plays a crucial role in physics beyond SM searches and precision measurements including Higgs physics
- Continuous developments and understandings of the detector details
  - new amplitude reconstruction algorithm in place to cope with ~40 pileup interactions
    - ready for even higher values expected in 2017
  - in barrel, 1% energy resolution achieved in Run-I and Run-II for unconverted/late-converting photons
- re-calibration with 2016 data is ongoing → stay tuned with m_H measurement in $\gamma\gamma$ final state with Run-II dataset