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Calibration and performance of the CMS electromagnetic calorimeter in LHC Run 2

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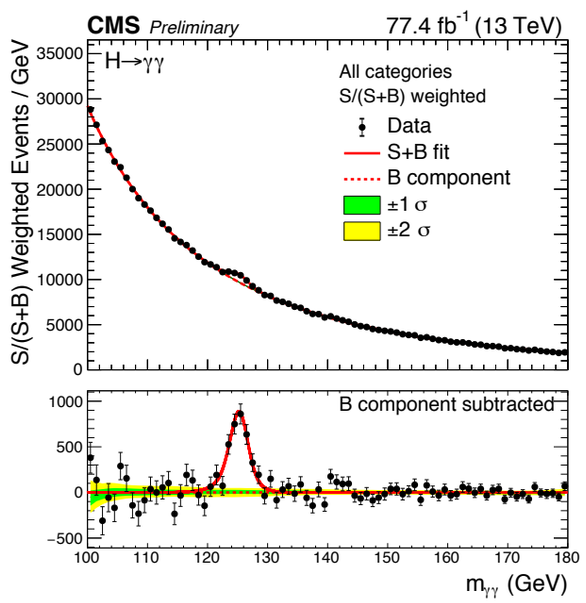
on behalf of the CMS Collaboration

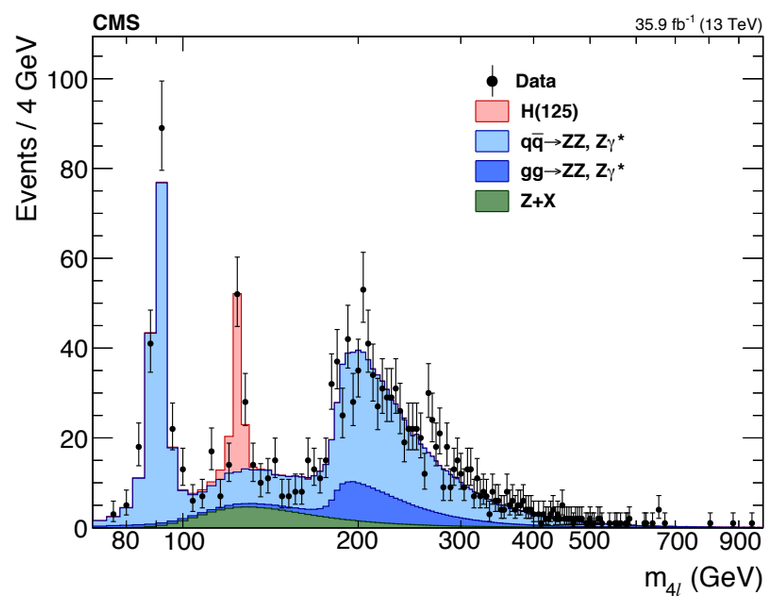
ECAL is crucial in CMS physics analysis

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

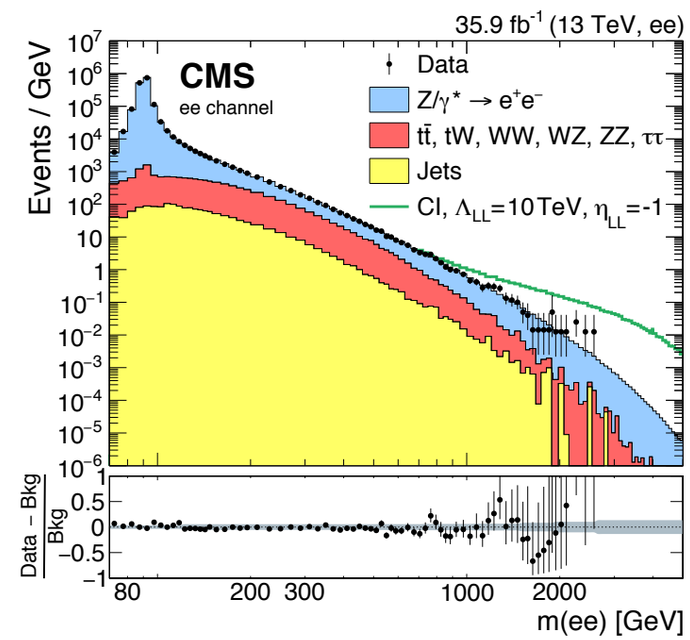
H→γγ



H→ZZ→4l



Z'→ee

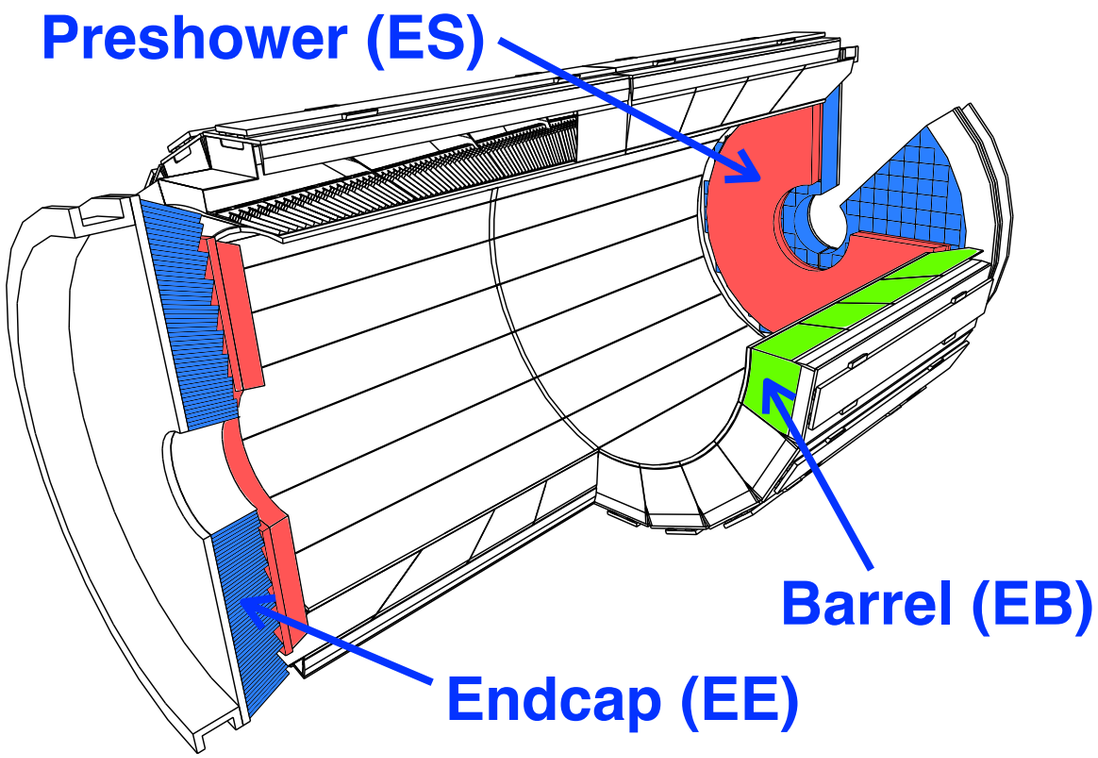


- high energy resolution
- position measurement

- 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)

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

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

Pulse Amplitude | η-scale | Preshower energy

- the optimal performance was achieved by exploiting full statistics of one year
- **CMS ECAL energy resolution :**
  - uniformity and stability resolution required *in situ* < 0.5%
  - in barrel, 1% energy resolution achieved in Run I for unconverted/late-converting photons

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

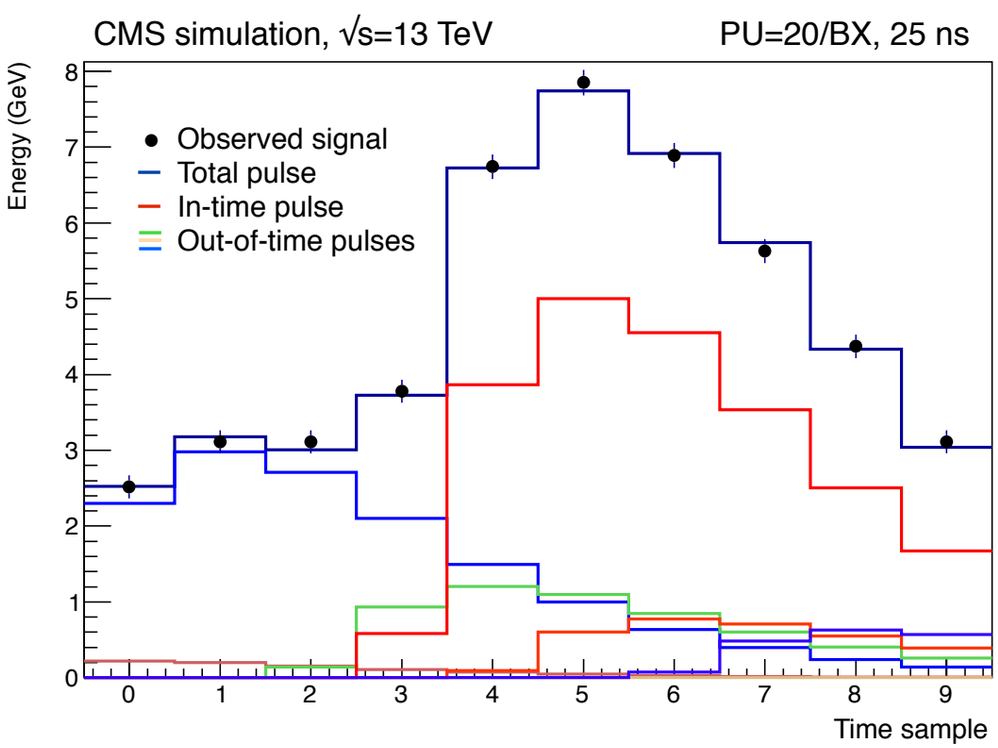
Pulse Amplitude

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

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

10 digitized signals are recorded and used for pulse reconstruction



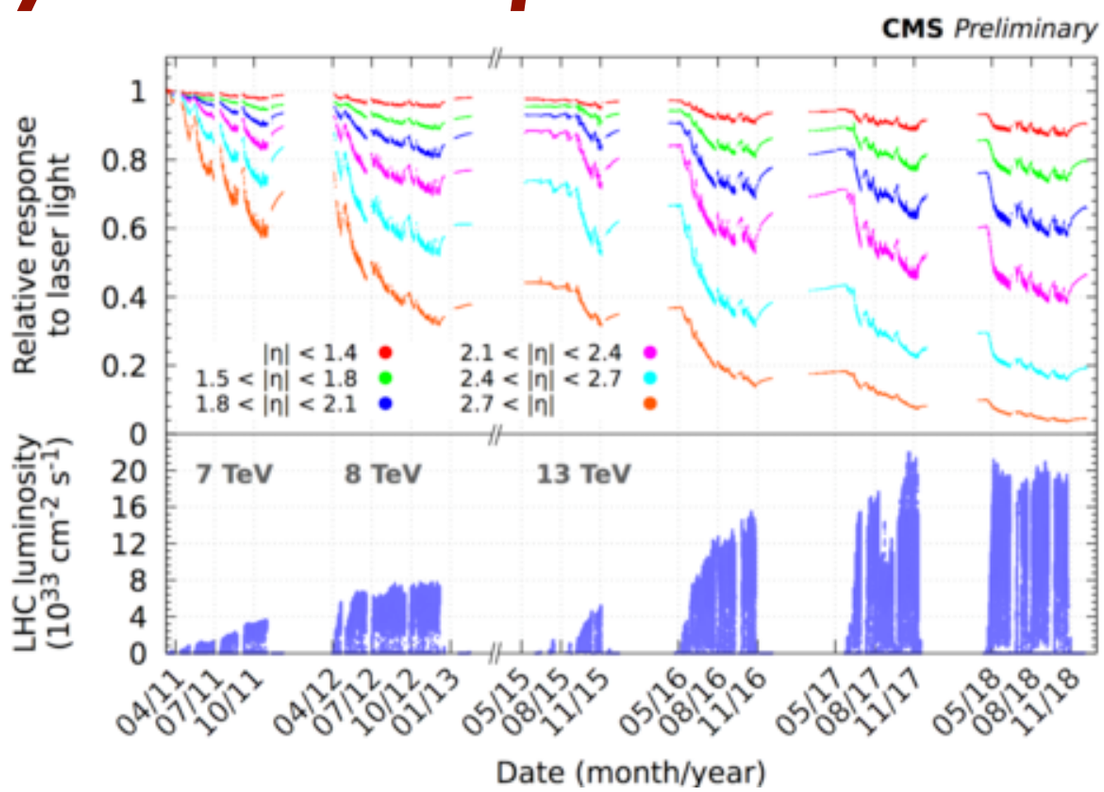
BX = 0, -4, -1, +1, etc. fitted

- up to 9 OOT pulses (one per time sample)
- minimize χ^2 distribution for best description of the in-time amplitude
- 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

Laser Monitoring

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

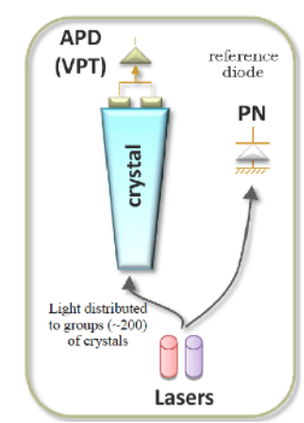
Crystal response monitoring (1/2)



tracker coverage → precision physics

high η (|η| > 2.5) → jet/MET 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>
  - change in crystal transparency
  - change in VPT response in endcaps
- 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

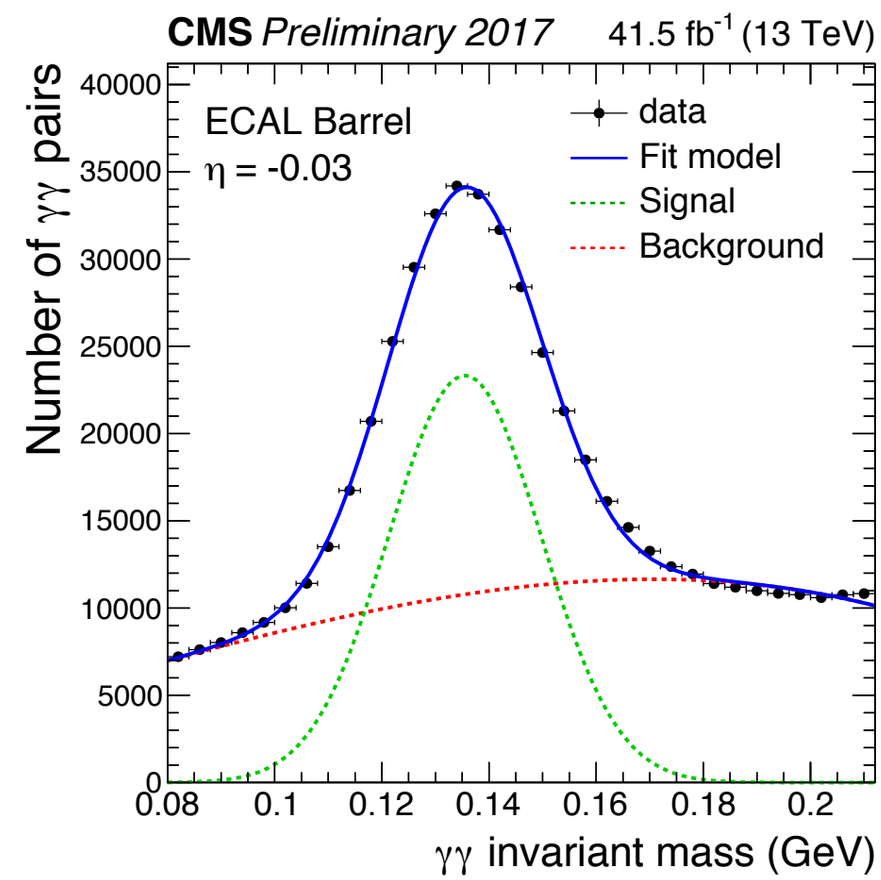
Inter-calibration

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

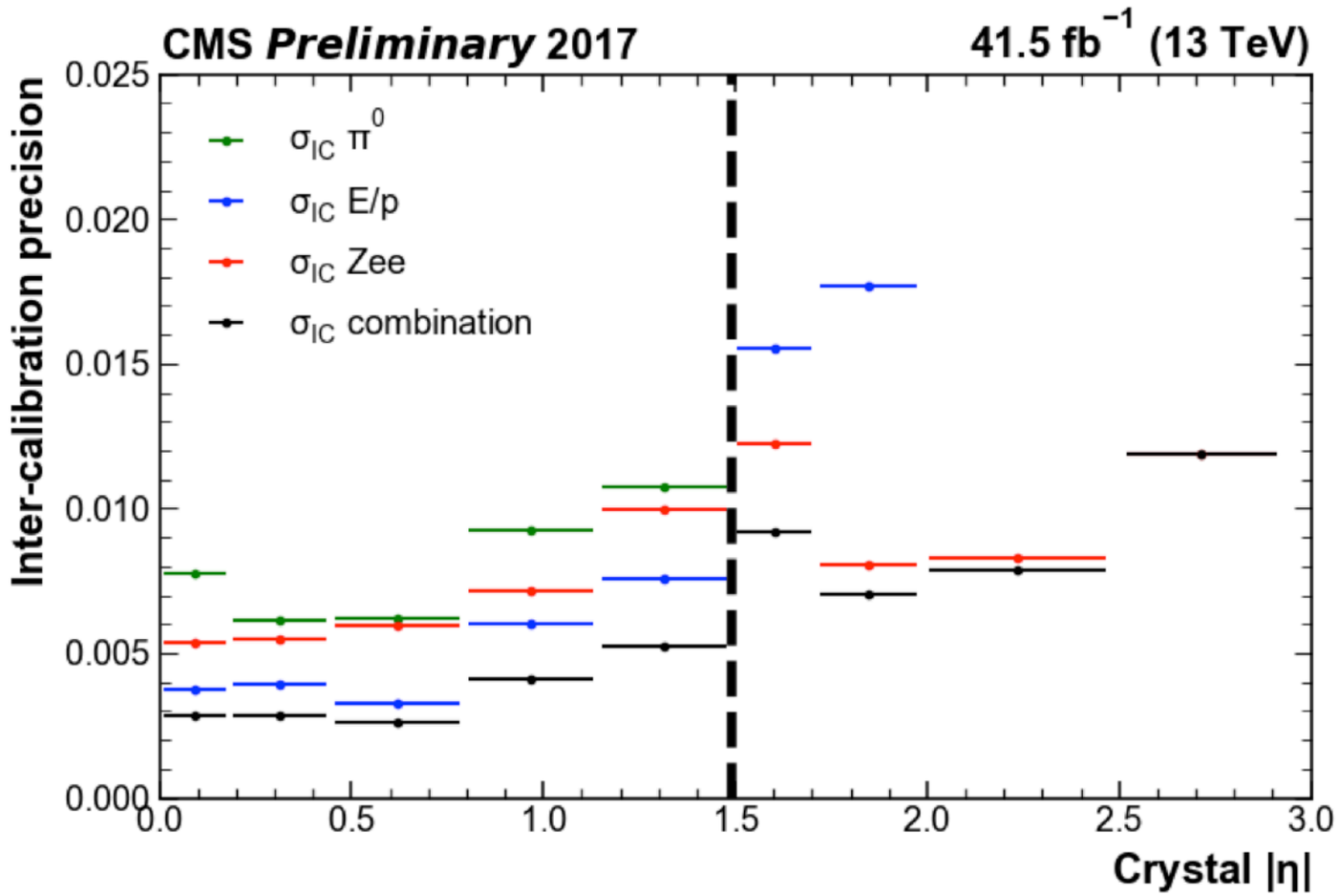
Inter-calibration (IC)

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

Method	Description
$\pi^0 \rightarrow \gamma\gamma$	In a Φ ring, use IC to improve $M_{\gamma\gamma}$ resolution for π^0 resonances
$Z \rightarrow ee$	Utilize the reconstructed invariant mass of Z bosons
electron E/p	Compare isolated electron energy from ECAL and tracker, compute IC to correct discrepancies
Φ-symmetry	Energy flux around Φ rings (constant η) should be uniform - IC corrects for non-uniformity [for monitoring purpose only]



Inter-calibration (IC): precision



- the precision of each IC method is evaluated with the relative energy resolution of Z→ee
- combined IC is obtained by weighting the respective precisions
- combined IC achieves the goal of 0.5% precision for the barrel region

ADC→GeV

Global Scale

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

η-scale

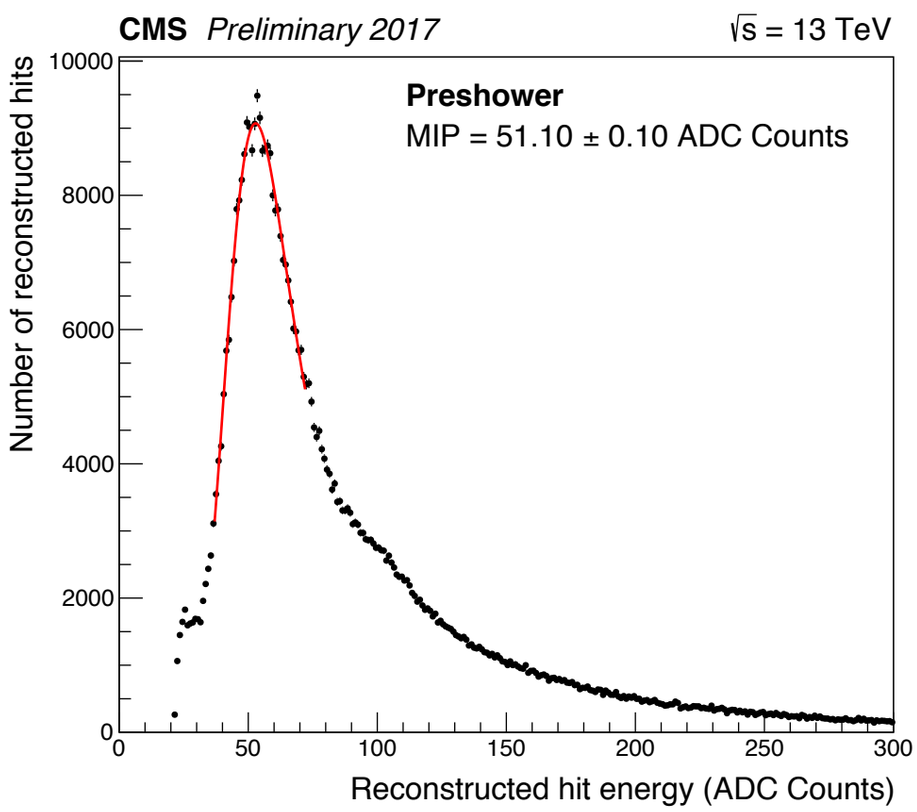
equalize ring
response wrt MC

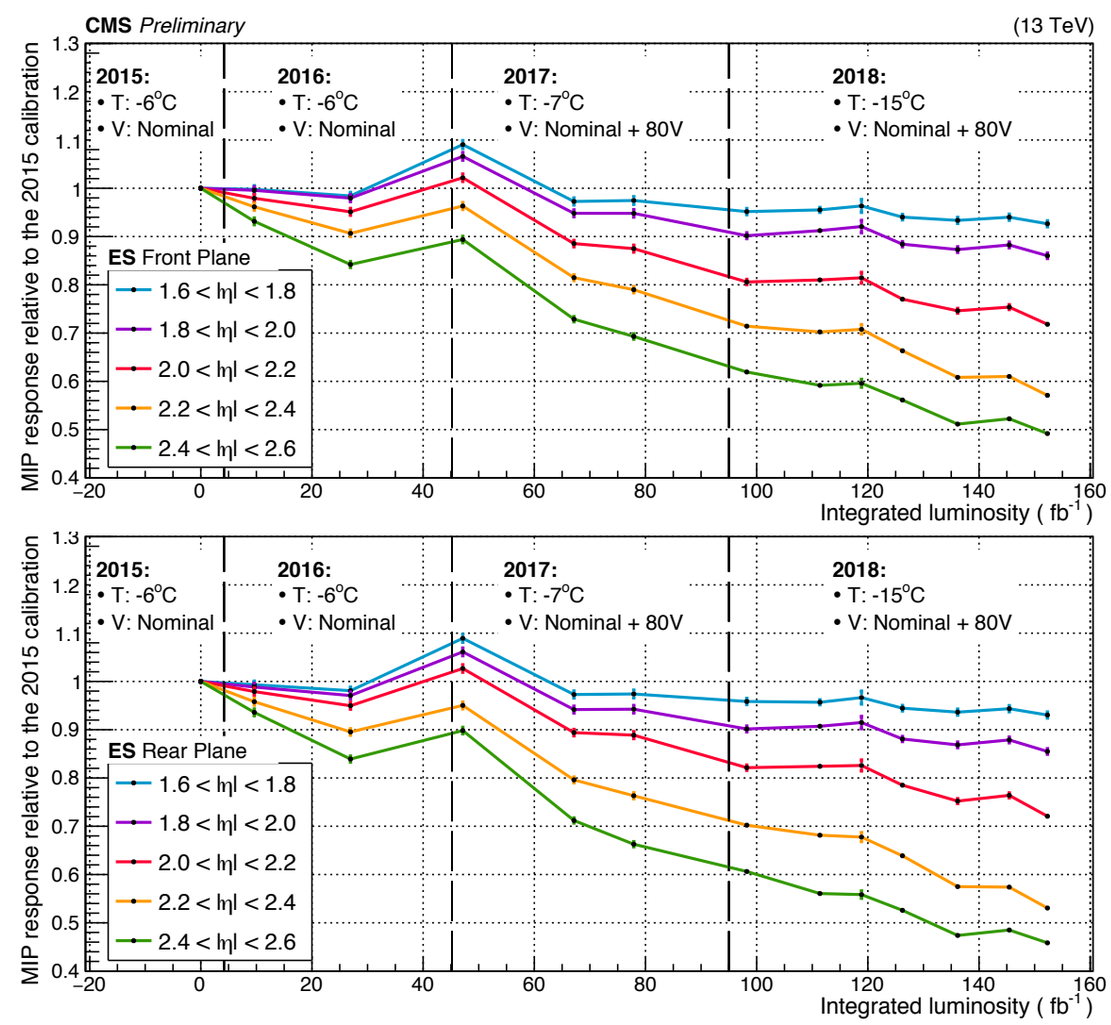
$$E_{e,\gamma} = [\Sigma_i (S_i(t) \times c_i \times A_i \times H_{i\eta}) \times G + E_{ES}] \times F_{e,\gamma}$$

Preshower energy

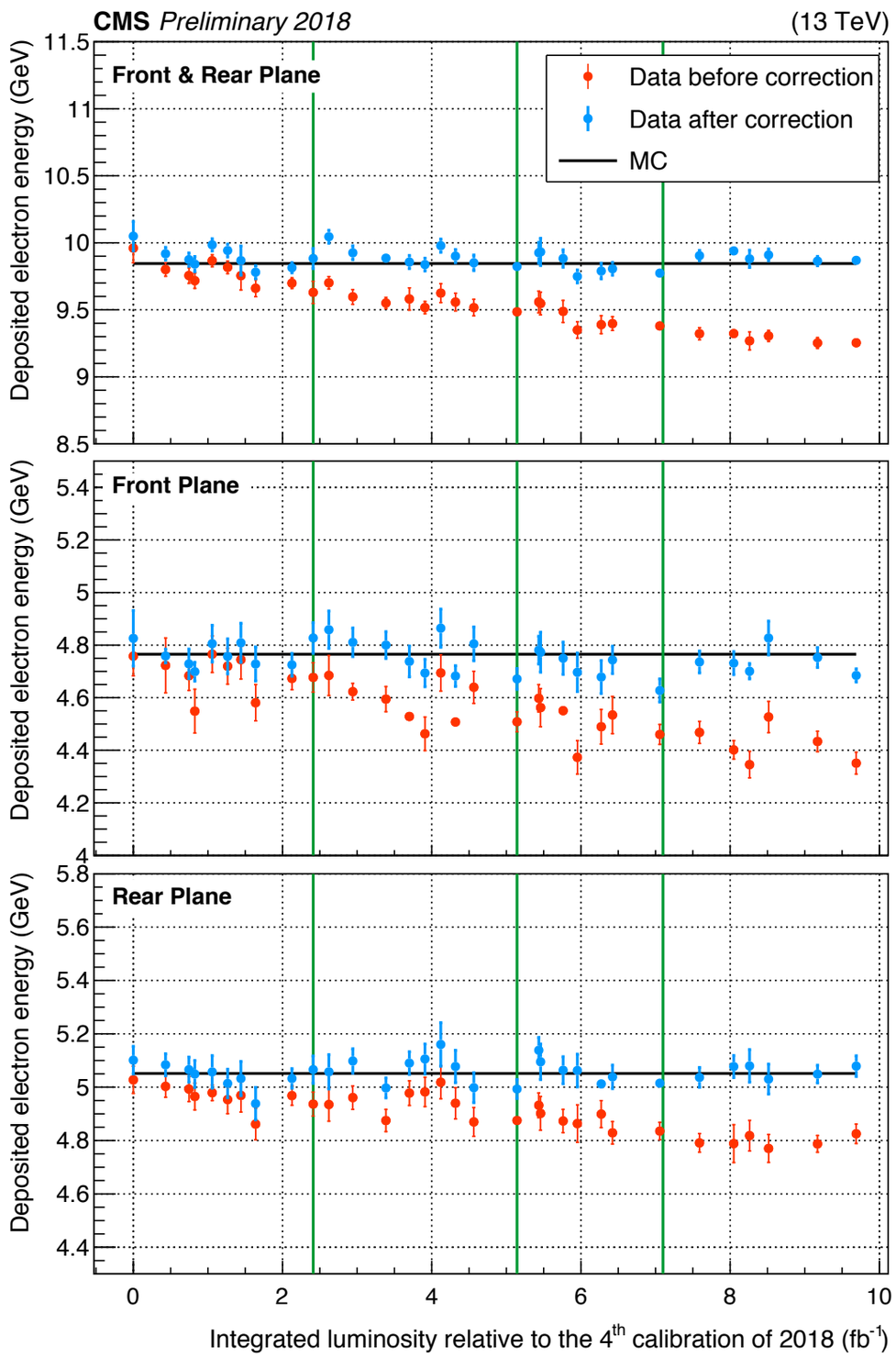
Preshower silicon sensors inter-calibration

- Preshower was operated in low gain mode (S/N ~ 3) for physics, but switched to high gain mode (S/N ~ 10) for calibration periodically (about every 10-20/fb)
- Charged particles produced in the collisions are used to calibrate





Preshower energy correction

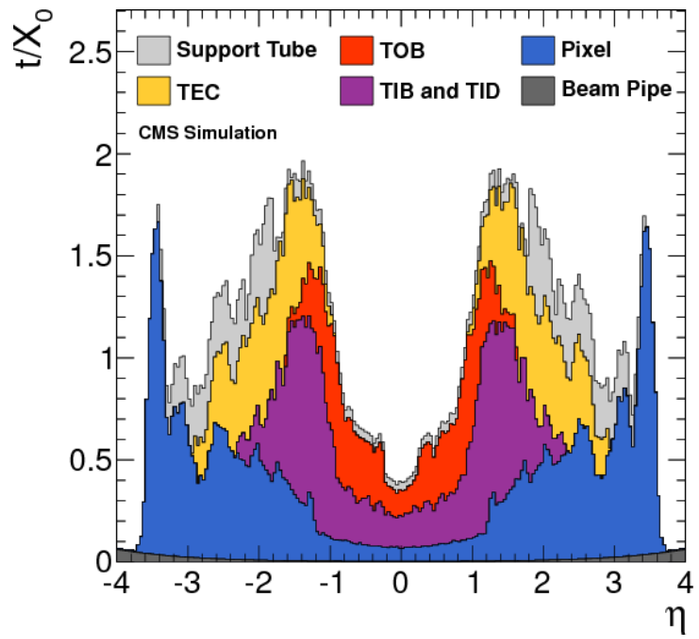


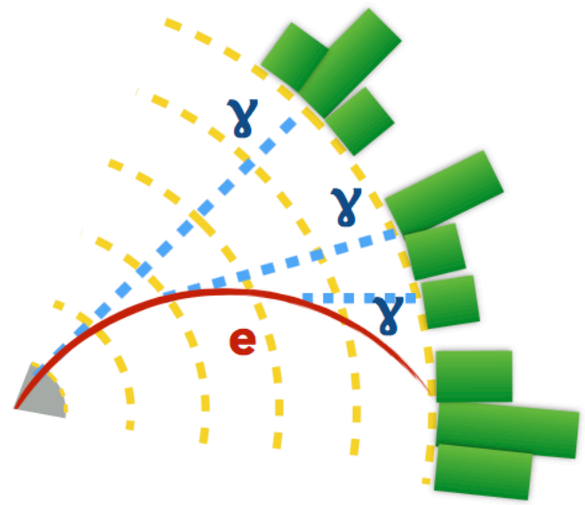
- the Preshower response decreases with time due to radiation damage
- the correction was computed by minimizing the X^2 value between the energy distribution of data and MC using $Z \rightarrow ee$ events
- after the correction, the Preshower energy measurement is stabilized

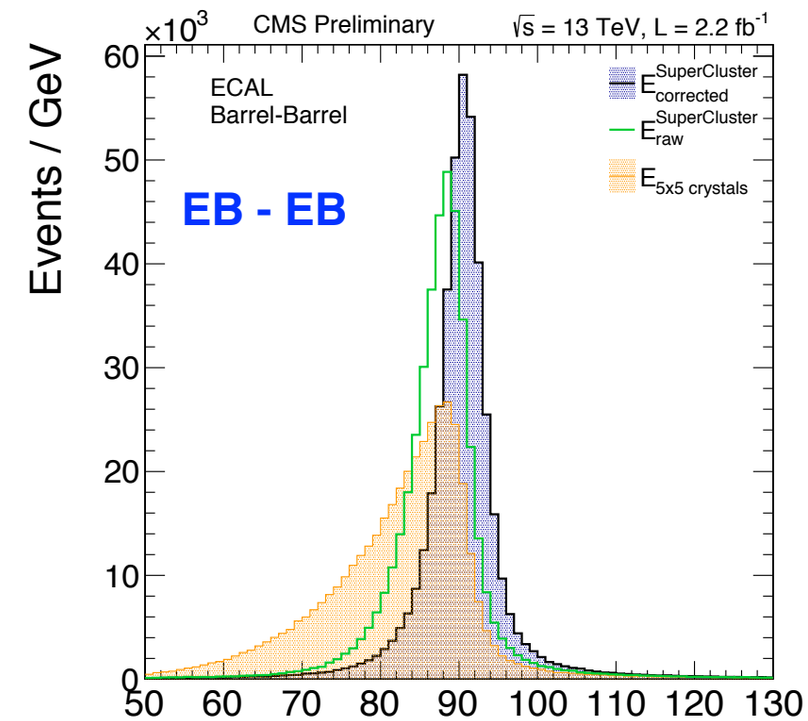
Cluster Corrections

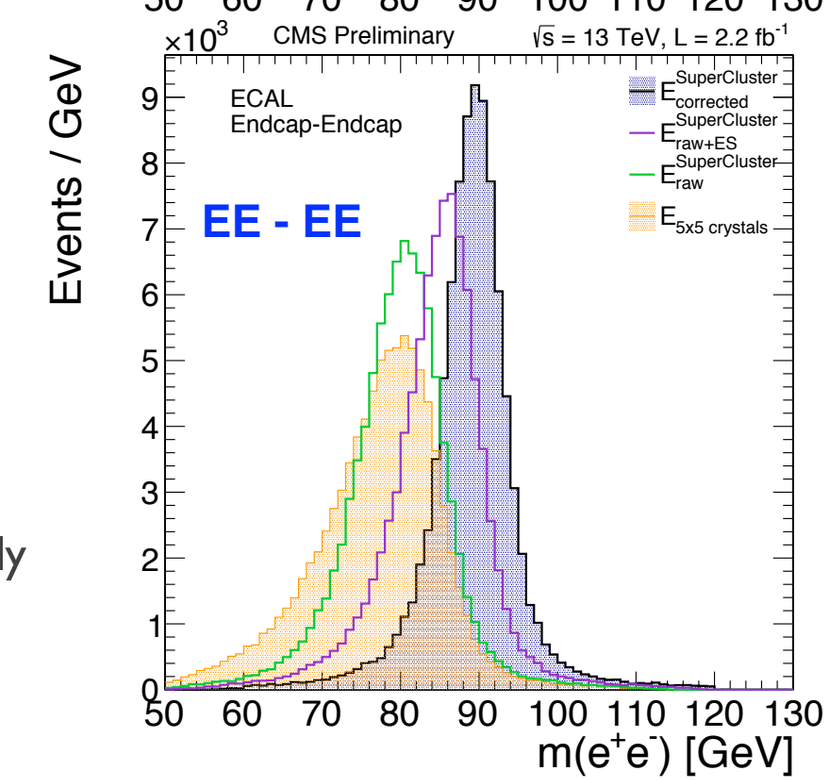
$$E_{e,\gamma} = [\Sigma_i (S_i(t) \times c_i \times A_i \times H_{i\eta}) \times G + E_{ES}] \times F_{e,\gamma}$$

Clustering and corrections





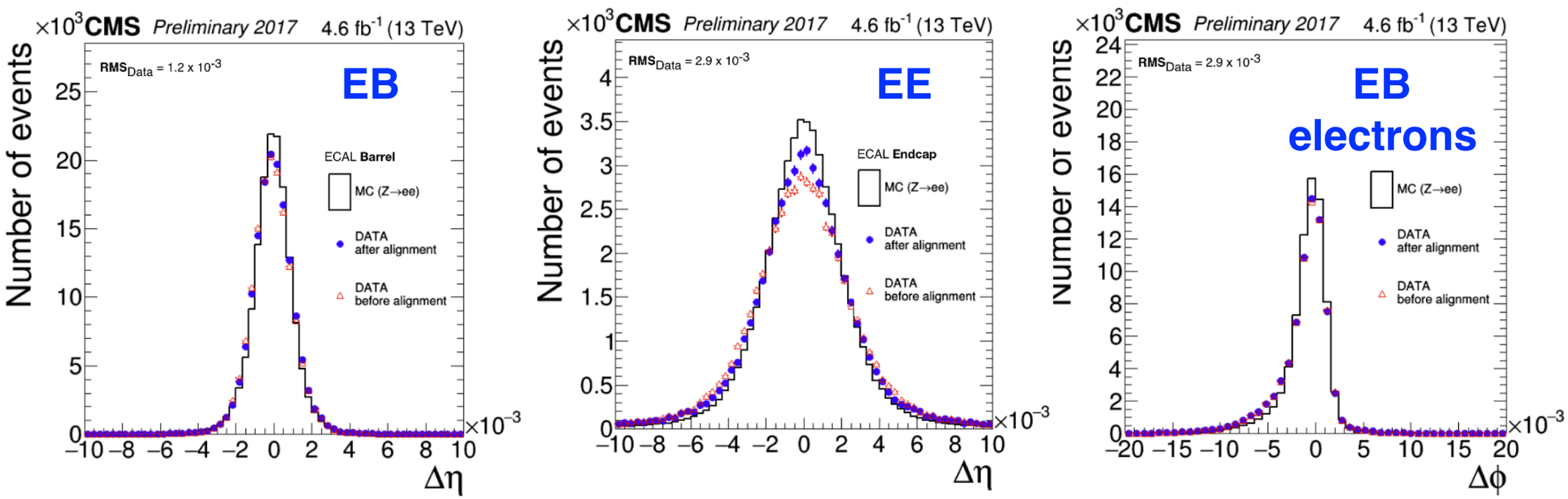




- large amount of material before ECAL
- dynamic clustering algorithm recovers energy radiated upstream of ECAL via bremsstrahlung or conversions
    - super-cluster (SC) of clusters along Φ (bending direction)
    - soft conversion legs/brem may not be included in SC
    - in the endcaps, preshower 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

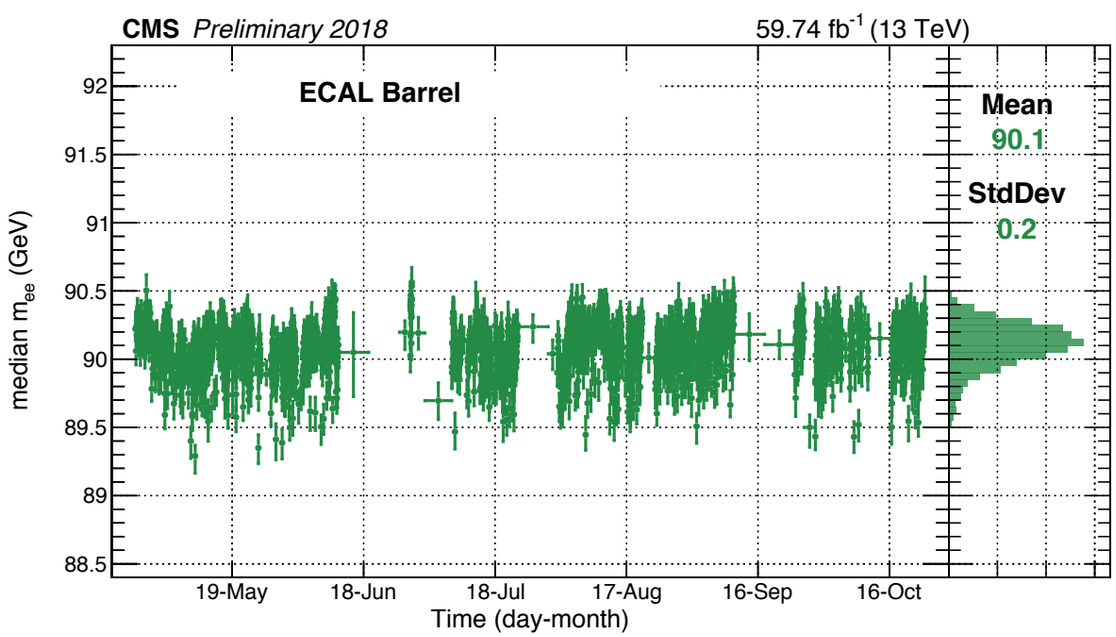
ECAL alignment

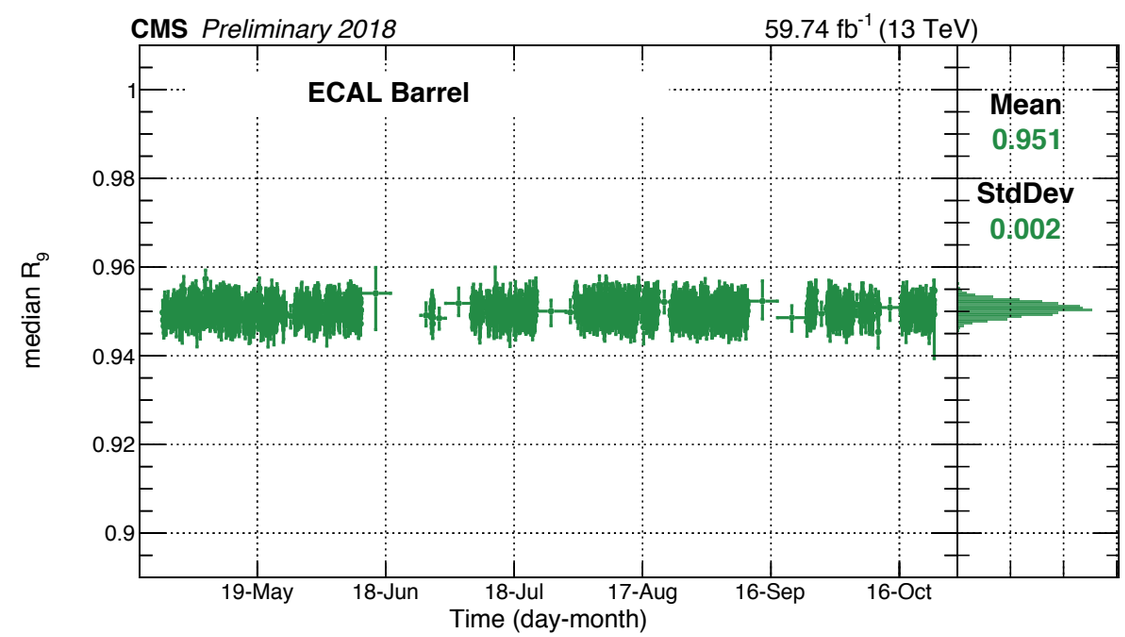
- position reconstructed from energy deposit exploiting ECAL high granularity
  - electron identification: prompt vs fake electrons
  - measurement of photon direction: $H \rightarrow \gamma\gamma$
- procedure based on matching position reconstructed by tracker and ECAL with low bremsstrahlung electrons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



Response stability

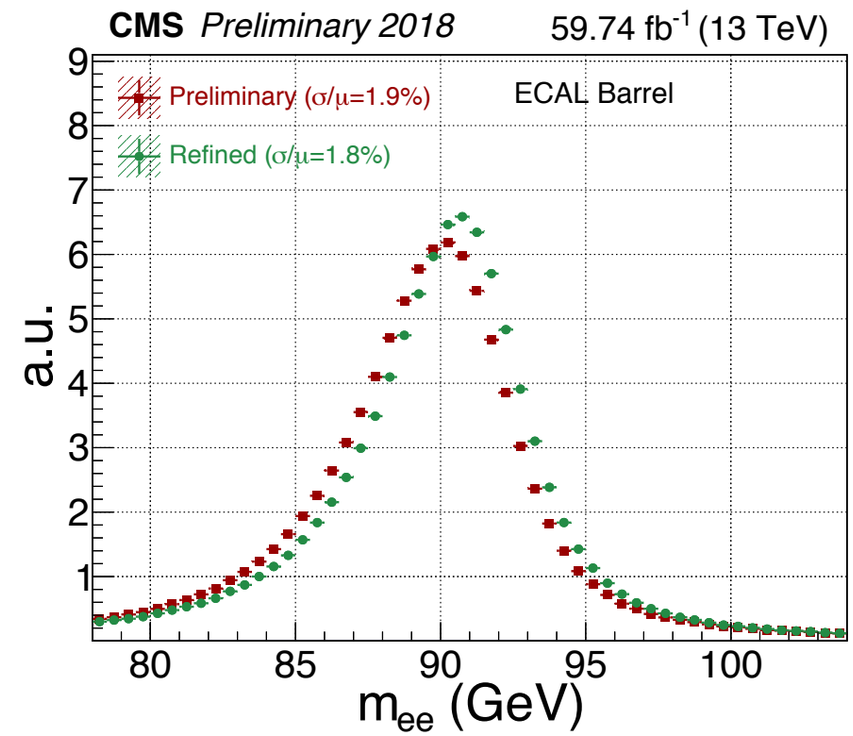
- response stability after corrections validated with physics signals, $Z \rightarrow ee$ events
- stable response over time ~0.2%
- the shower shape variable $R_9(E_{3x3}/E_{SC})$, important for the electron and photon identification, is also found to be stable (relative spread < 0.25%)

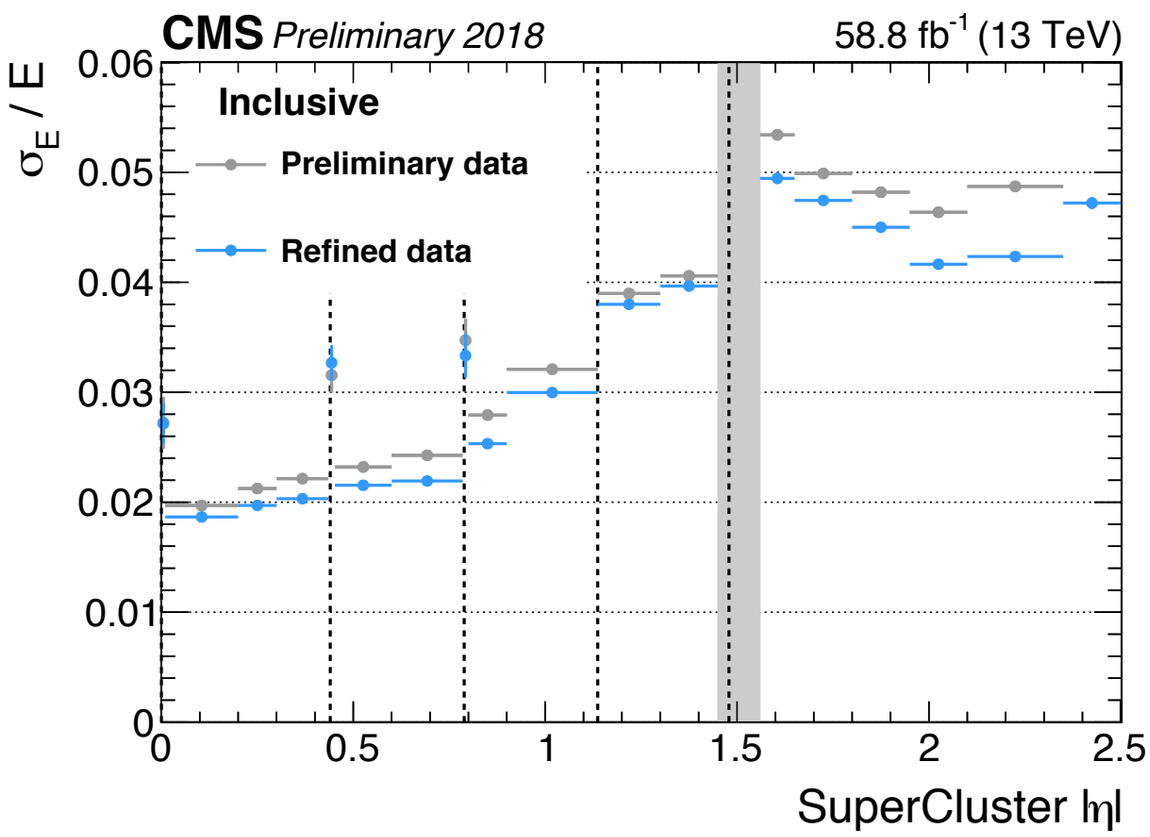


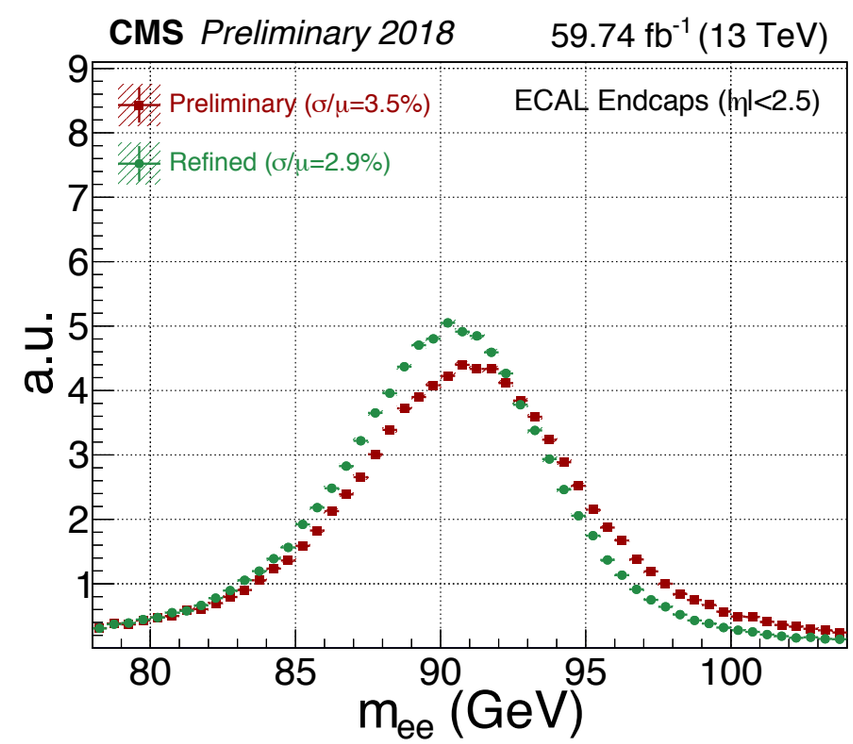


Energy and mass resolution

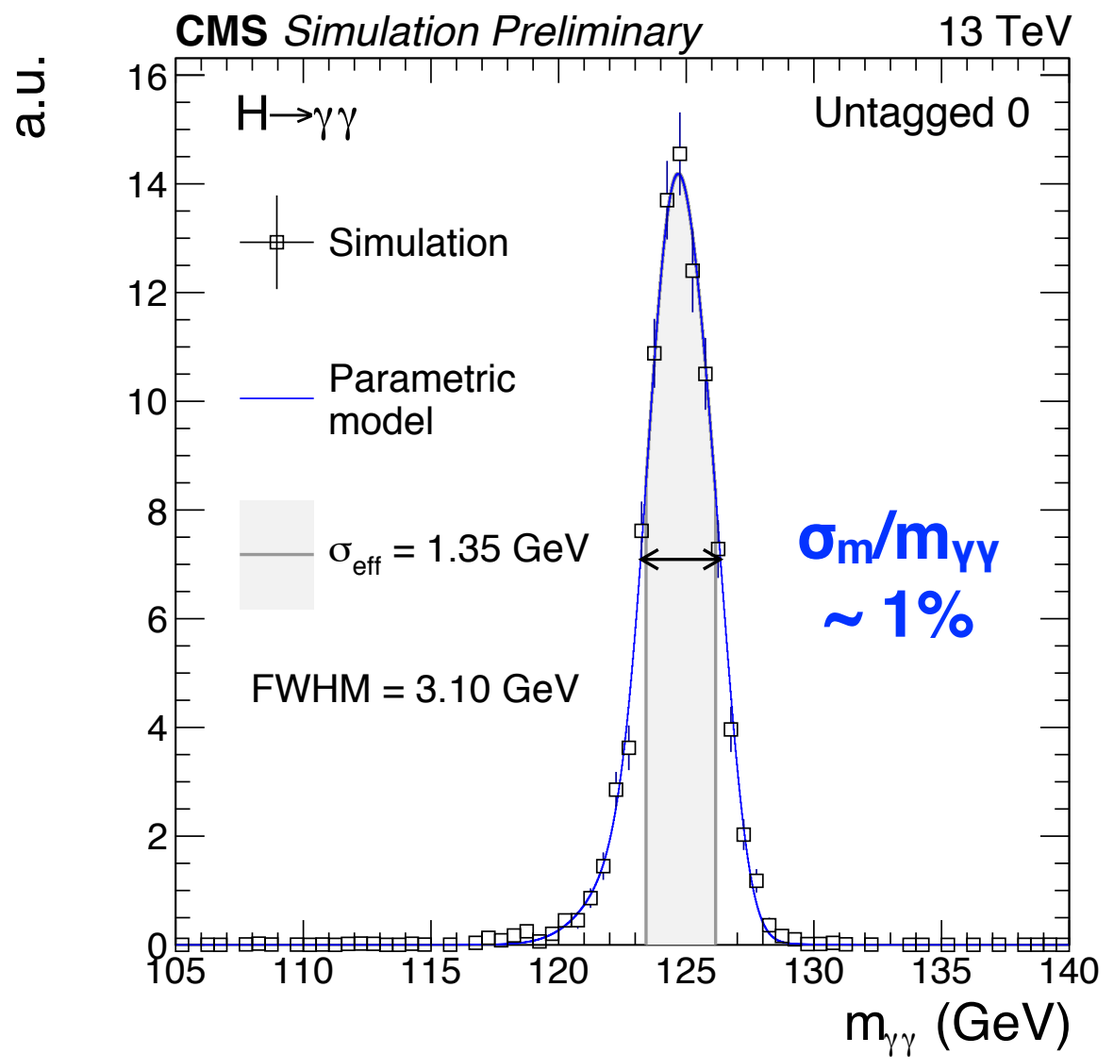
- derive electron energy resolution from Z→ee peak width
- energy resolution affected by the material budget in front of the ECAL
- signifiant improvement with the refined conditions obtained with the full dataset







Performance in the Higgs mass measurement



CMS HIG-19-004

- comparable to Run 1 performance despite more challenging conditions during data taking in Run 2

Conclusions

- The CMS electromagnetic calorimeter performs well during LHC Run 2 and plays a crucial role in physics beyond SM searches and precision measurements including Higgs physics
- More challenging conditions during data taking in Run 2 require to optimize the strategies for reconstruction and calibration
- Stable performance throughout Run 2
  - stable response
  - good energy resolution (2-4% in barrel and ~4% in endcap)
  - mass resolution of $H \rightarrow \gamma\gamma$ is comparable to Run 1

Spares

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

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

Pulse Amplitude | η-scale | Preshower energy

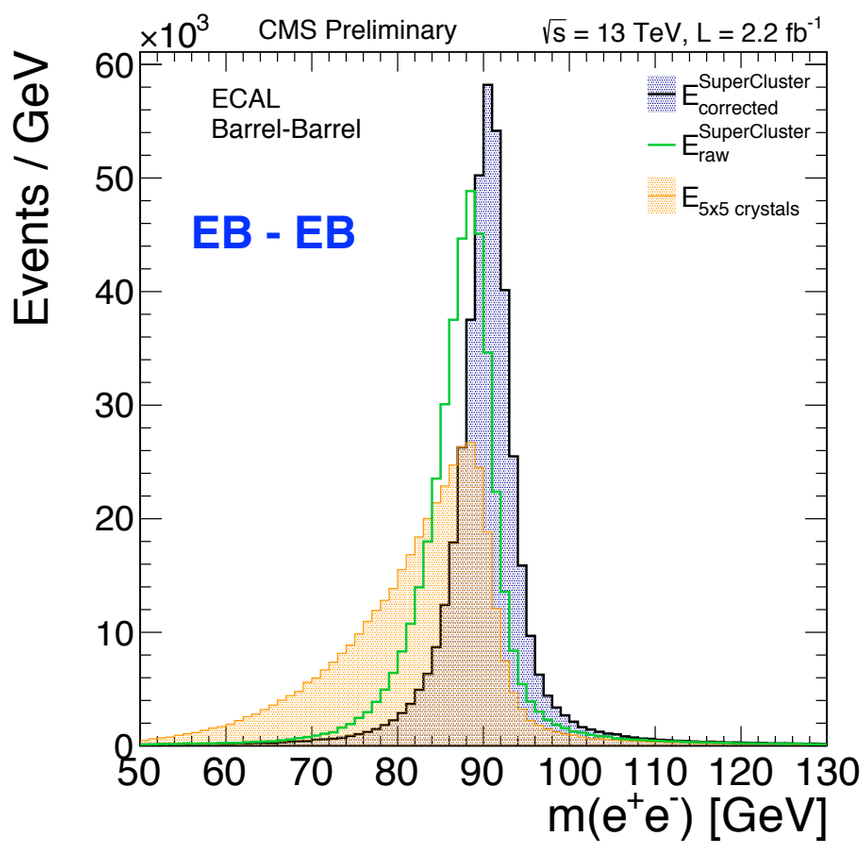
- **Qualification in beam tests :**
  - No magnetic field, no material upstream of ECAL, no radiation damage, negligible systematic term from channel response variations

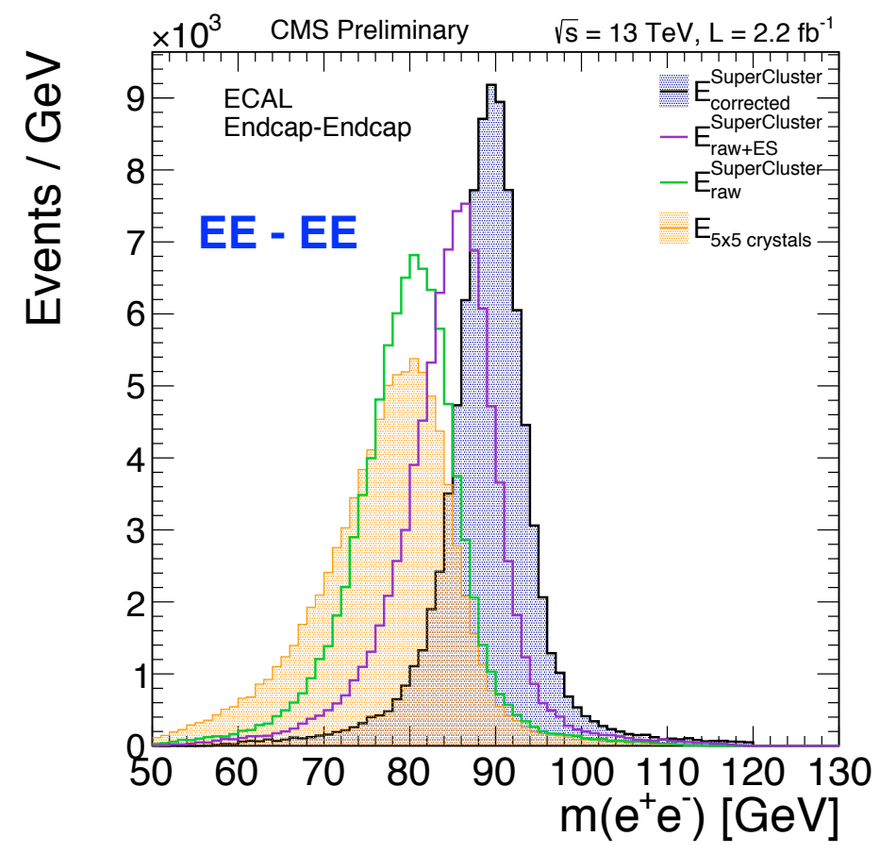
$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(GeV)}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

- uniformity and stability resolution required *in situ* < 0.3%
- in barrel, 1% energy resolution achieved in Run-I for unconverted/late-converting photons

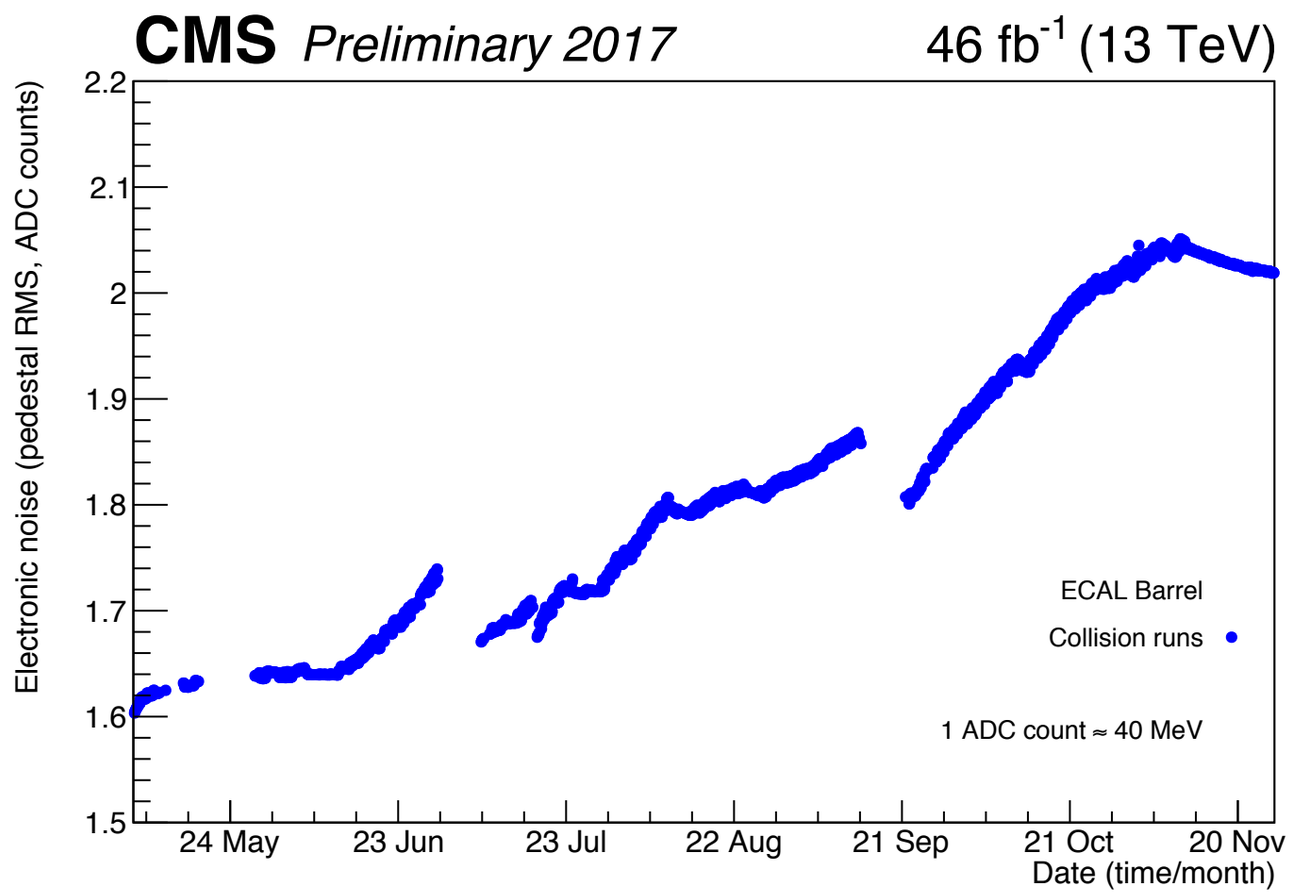
Cluster energy in data

- Reconstructed Z mass in data with different levels of energy reconstruction and corrections
  - the long tail of lower E_{5x5} in EB is due to the high fraction of showering electrons in the high-material region at $|\eta| > 1$
  - the energy scale is improved by adding the preshower energy to the crystal energy





Crystal response monitoring (2/2)



- the increase of the electronic noise was observed related to the increase of the APD dark current due to irradiation
- this effect is modeled in MC by taking the average performance over the year