Institute of High Energy Physics
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Ultimate calibration and performance of the CMS Electromagnetic Calorimeter in LHC Run 2

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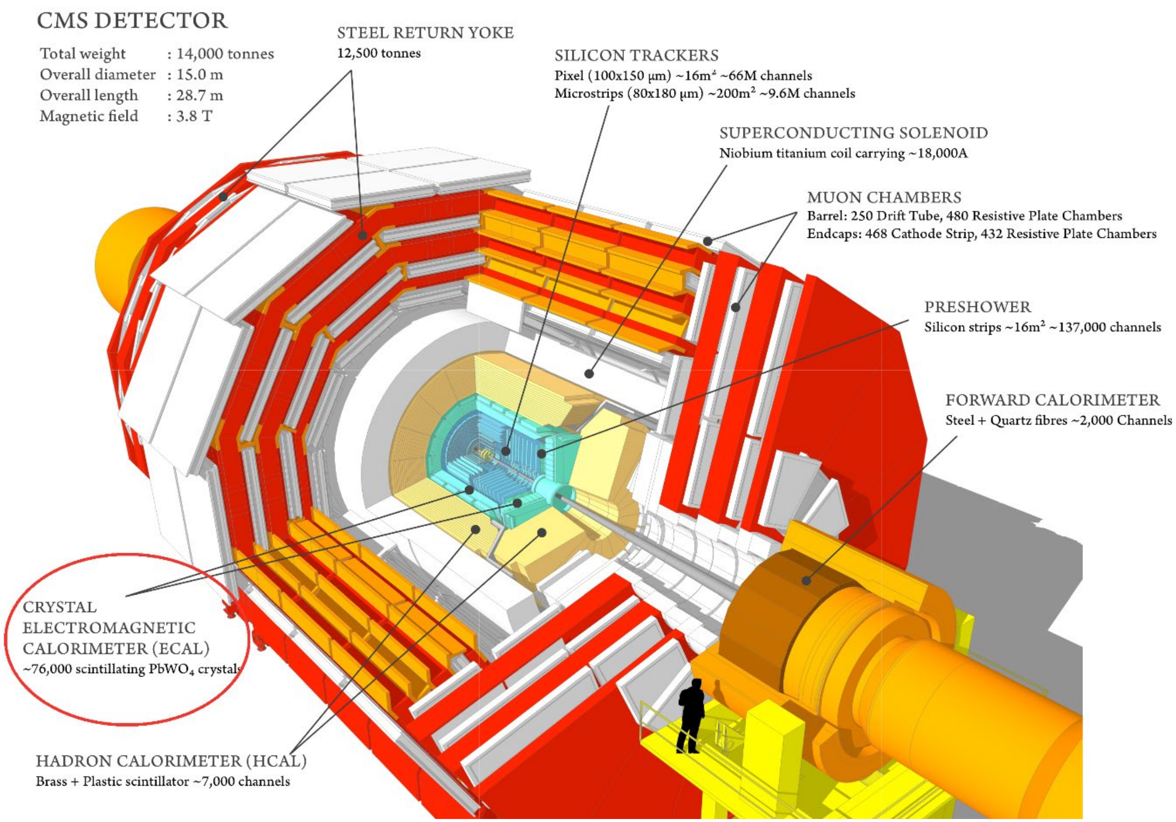
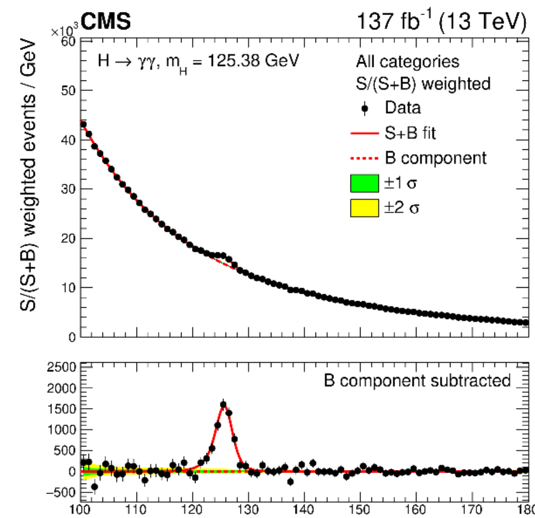
CMS Electromagnetic Calorimeter (ECAL)

- CMS is a general-purpose detector designed to
  - test Standard Model (SM) predictions
  - search for new physics beyond the SM





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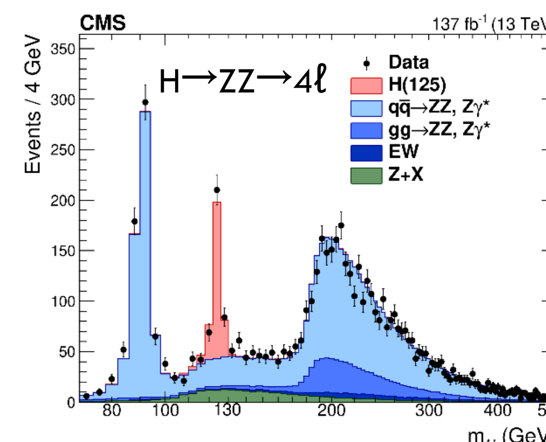

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- The electromagnetic calorimeter plays a crucial role in many CMS physics analyses that involve electrons/photons/jets

CMS Electromagnetic Calorimeter (ECAL)

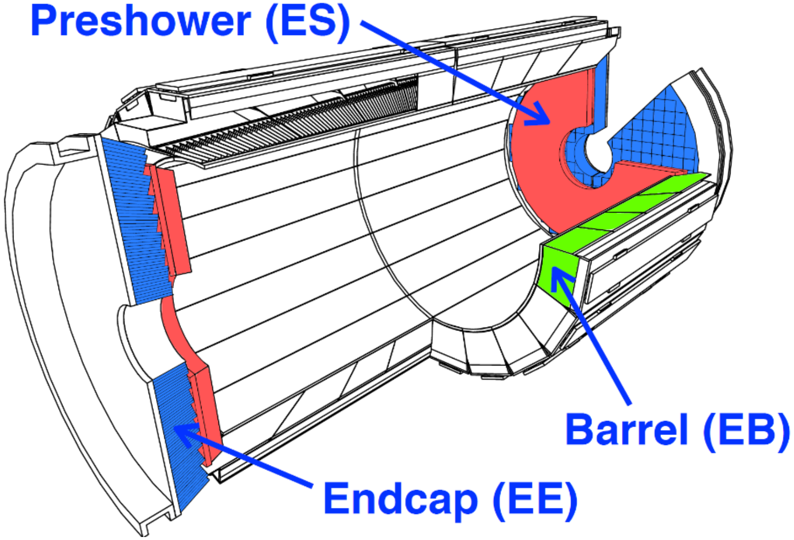
- **ECAL: compact, homogeneous, hermetic and fine-grain crystal calorimeter**
  - designed to provide highly efficient and accurate reconstruction of photons and electrons

- 75848 lead tungstate crystals $PbWO_4$
- high 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

Coverage:

Barrel (EB):	$\|\eta\| < 1.48$
Endcap (EE):	$1.48 < \|\eta\| < 3.0$
Preshower (ES):	$1.65 < \|\eta\| < 2.6$

(ES: discriminate between prompt photons and photons from π_0 decay)



ECAL challenges in LHC Run 2:

- higher pileup and noise, increased exposure to radiation
- a larger variation of the calorimeter response that must be corrected for

ECAL signal reconstruction

- Electromagnetic particles deposit their energy over several ECAL crystals.
  - dynamic clustering algorithms used to collect the energy deposits in ECAL

- The reconstructed energy of electrons and photons is estimated by:

cluster correction obtained from a regression method

the reconstructed signal amplitude

preshower energy

$$E_{e,\gamma} = F_{e,\gamma} \times \left[G \times \sum_i (A_i \times LC_i \times IC_i) + E_{ES}\right]$$

global scale factor for the ADC-to-GeV conversion

laser correction: correct for crystal transparency loss

intercalibration: equalize the channel response at same η

Signal amplitude reconstruction (A_i)

- 10 digitized ECAL pulse samples recorded for signal amplitude reconstruction
  - one in-time pulse and up to 9 out-of-time (OOT) pulses
  - Run 1: amplitude reconstructed from a weighted sum of samples
  - Run 2: 'multifit' reconstruction method used to mitigate higher pileup

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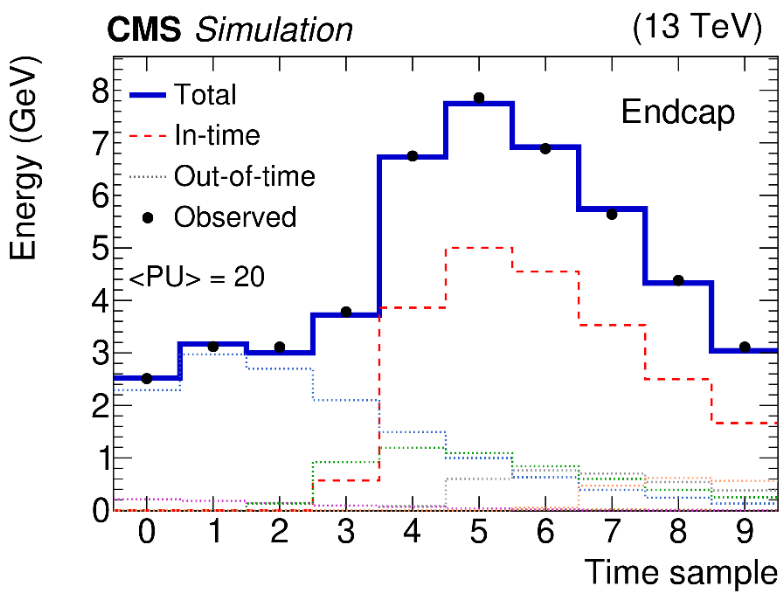

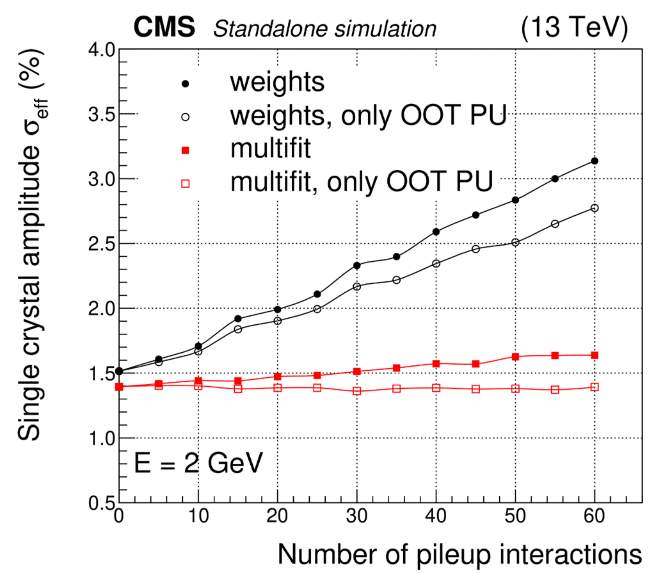

- The 'multifit' reconstruction method is robust against pile-up increase.

ECAL transparency loss

- ECAL channel response varies with time due to radiation-induced effects
  - crystal transparency changes over time
  - photocathode aging with accumulated charge

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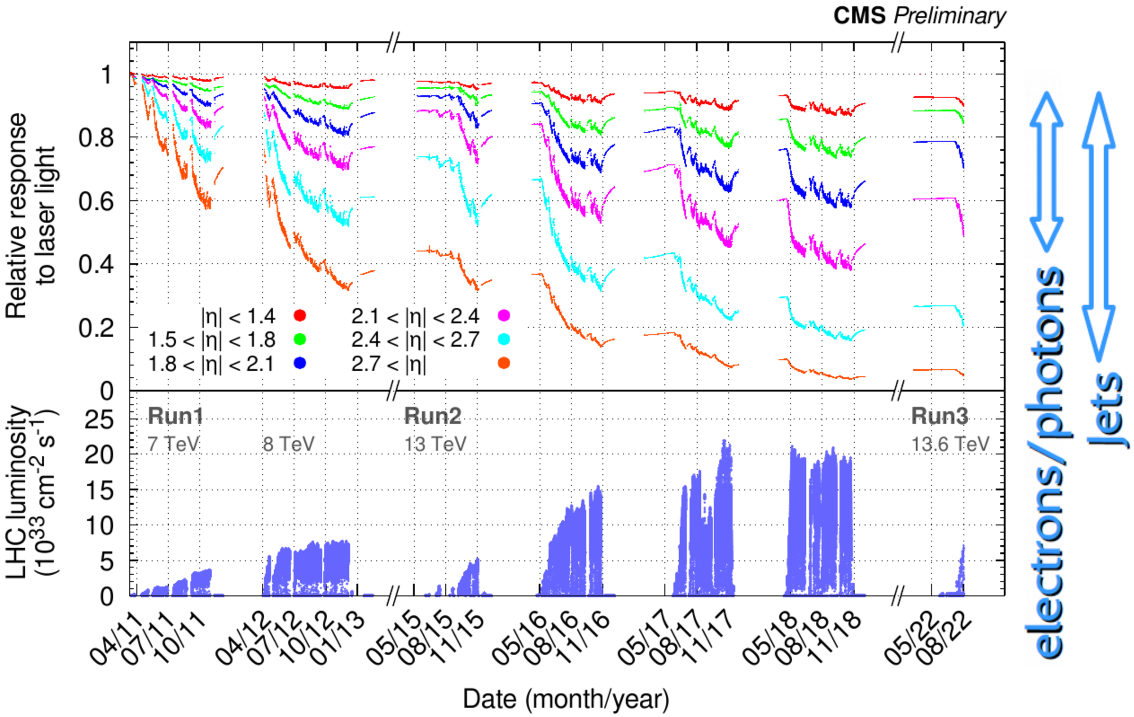


Transparency loss correction is crucial to maintain stable ECAL energy scale and resolution over time

Laser Correction (LC_i)

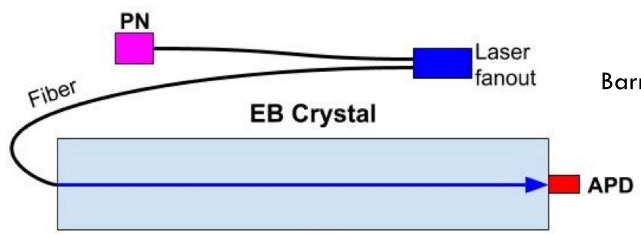
- A dedicated laser monitoring system is designed to provide corrections for transparency changes.
  - injects laser light with a wavelength of 447nm into each crystal
  - relates ECAL channel response variation to changes in the scintillation signal
  - measures the calibration point per crystal every 40 minutes
  - obtains and applies corrections within 48 hours for the prompt reconstruction

Correction for e/y scintillation

Response to injected laser

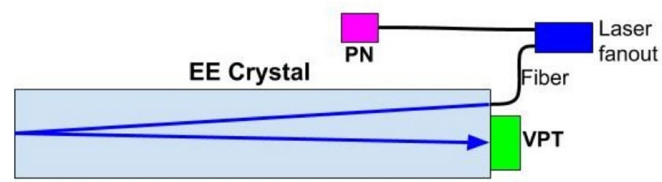
$$\frac{S(t)}{S_0} = \left(\frac{R(t)}{R_0}\right)^{\alpha}$$

α parameter



Barrel: Avalanche Photo-Diodes (APDs)

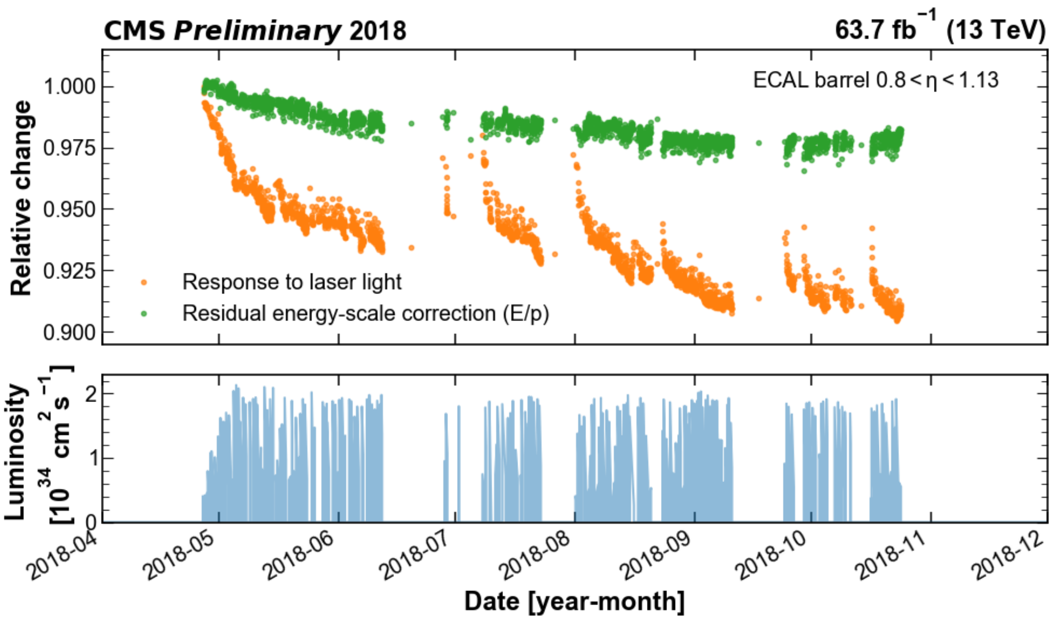
Endcaps: Vacuum Photo-Triodes (VPTs)



Relative response = APD(VPT) / PN

- α parameter depends on η and evolves with integrated luminosity
  - periodically re-computed to ensure energy scale stability and high resolution

Laser correction with E/p residual correction



CMS-DP-2019/030

- Orange: relative response variations to laser light injected in the ECAL crystals
- Green: the residual energy-scale correction after the application of the laser corrections
  - correction needed due to a drift of the response of the PN diode used in the laser-based calibration system, determined by comparison with the tracker-measured momentum of electrons from W/Z bosons (E/p ratio)
  - a few percent variation the whole year and independent of instantaneous luminosity

Intercalibration (IC_i)

- IC: equalize the ECAL response for different crystals at the same η coordinate.
- A combination of several methods based on different physics signals
  - π^0 mass: exploit reconstructed π^0 mass with its decay of photon pairs
  - E/p: comparison of the ECAL energy to the tracker momentum for isolated electrons from W/Z boson decay
  - Zee: exploit the invariant mass reconstructed with electron pairs from Z decays

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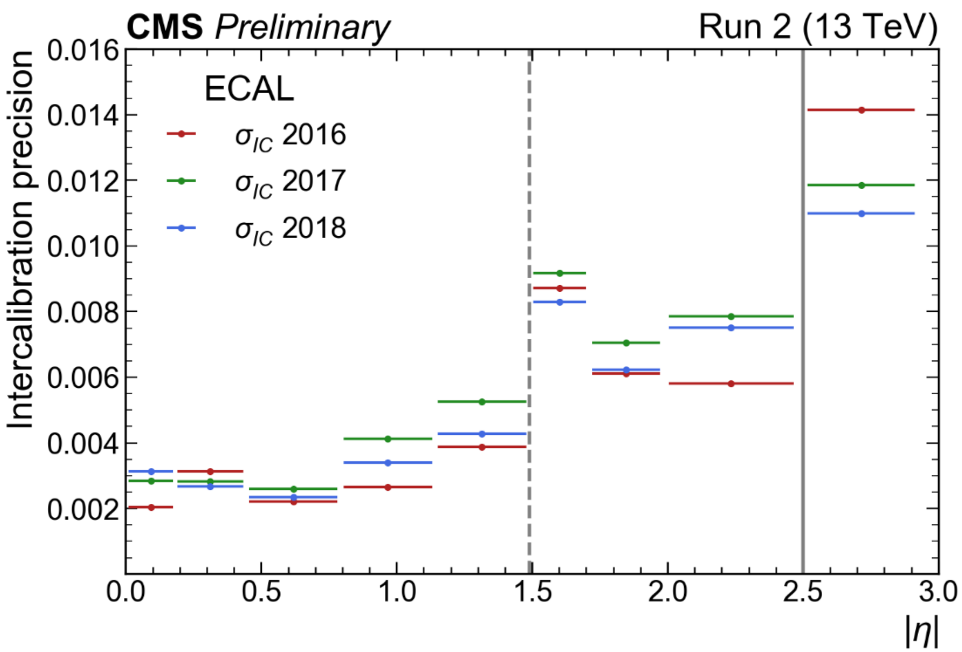

- Final intercalibration combines different methods by weighting their respective precision
  - precision evaluated with the relative energy resolution of Zee
- IC reaches very good precision
  - <0.5% at barrel region
  - <1% at endcap region

Preshower (E_{ES}) Calibration

- Preshower calibrated using minimum ionizing particles (MIPs)
  - channel by channel calibration
  - special runs taken for calibration every 10 fb^{-1}

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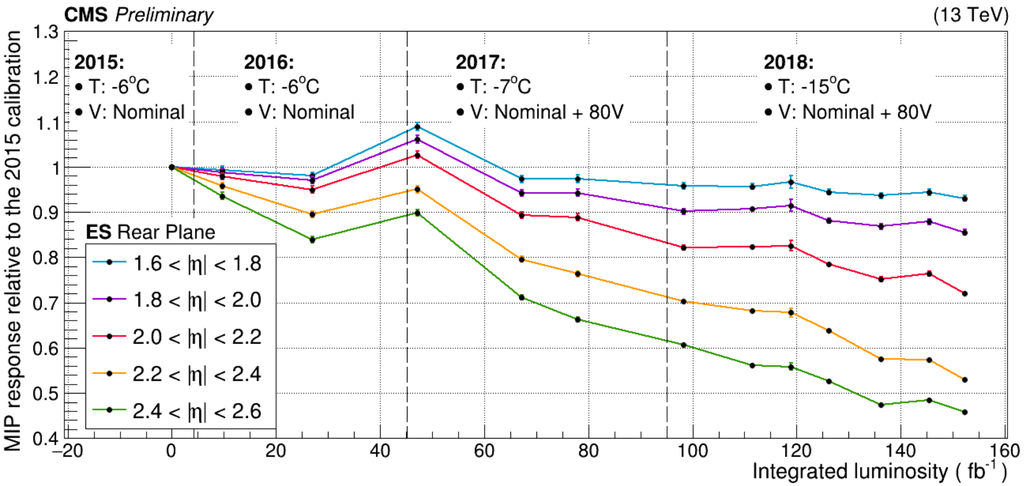
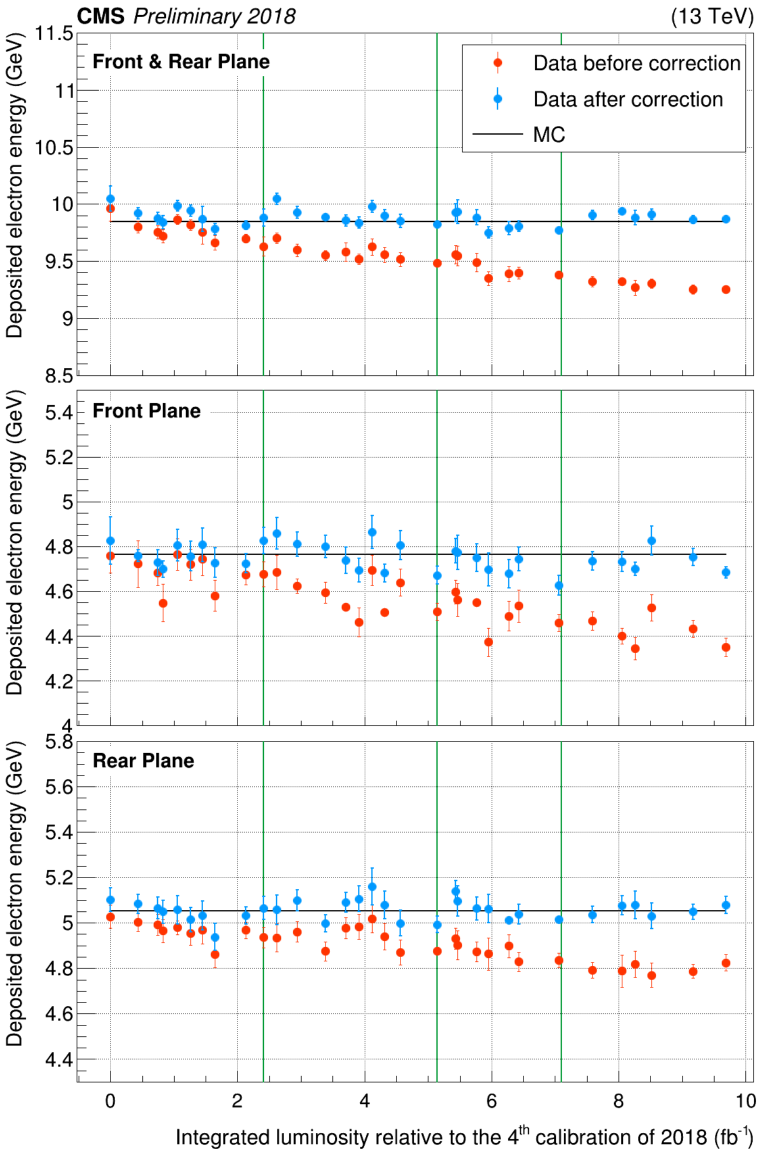
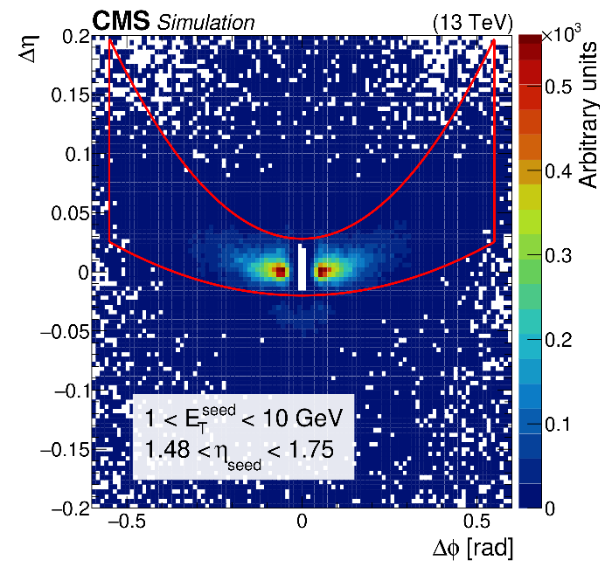




  - correction computed by minimizing the χ^2 value between the energy distribution of data and MC using Z→ee events
- Measured energy of ES cluster is stabilized by applying the correction.

Clustering and cluster energy corrections ($F_{e,\gamma}$)

- ‘mustache super-clustering’ method exploits to cluster hits and form physics objects
  - multivariate corrections applied to reconstruct the original deposited energy
- Energy thresholds for hits clustering re-tuned to mitigate pile-up and noise contamination
- Energy scale uncertainty smaller than 0.1 (0.3)% in the barrel (endcap) region in proton-proton collisions



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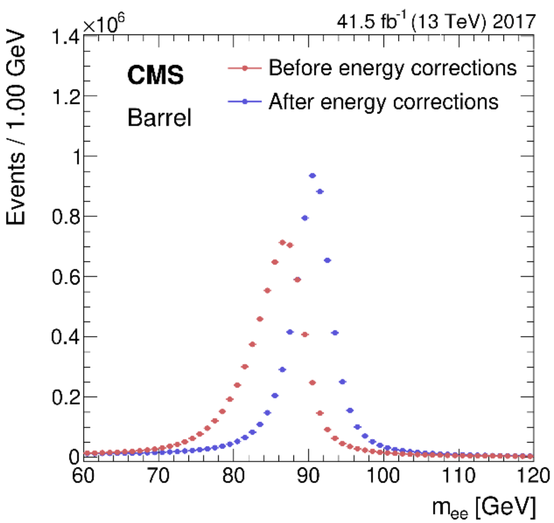
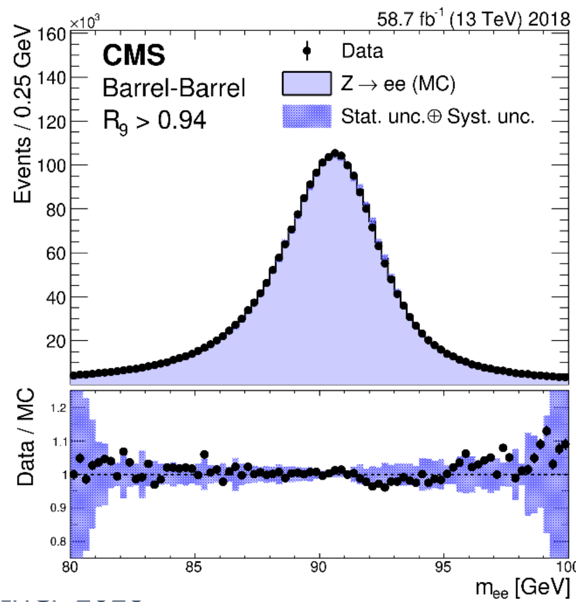
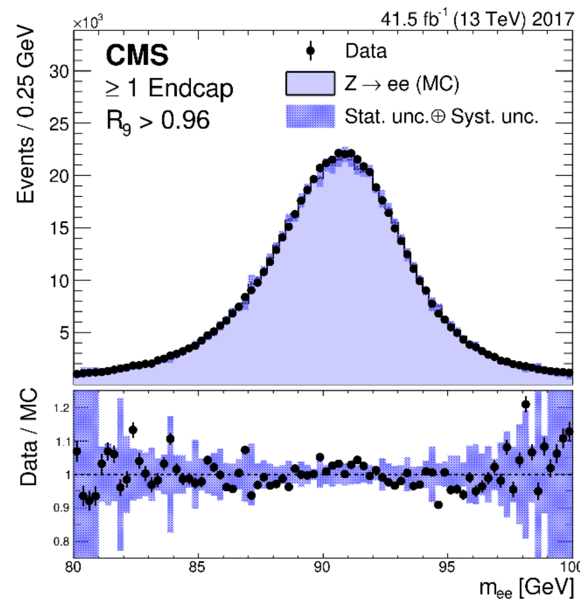
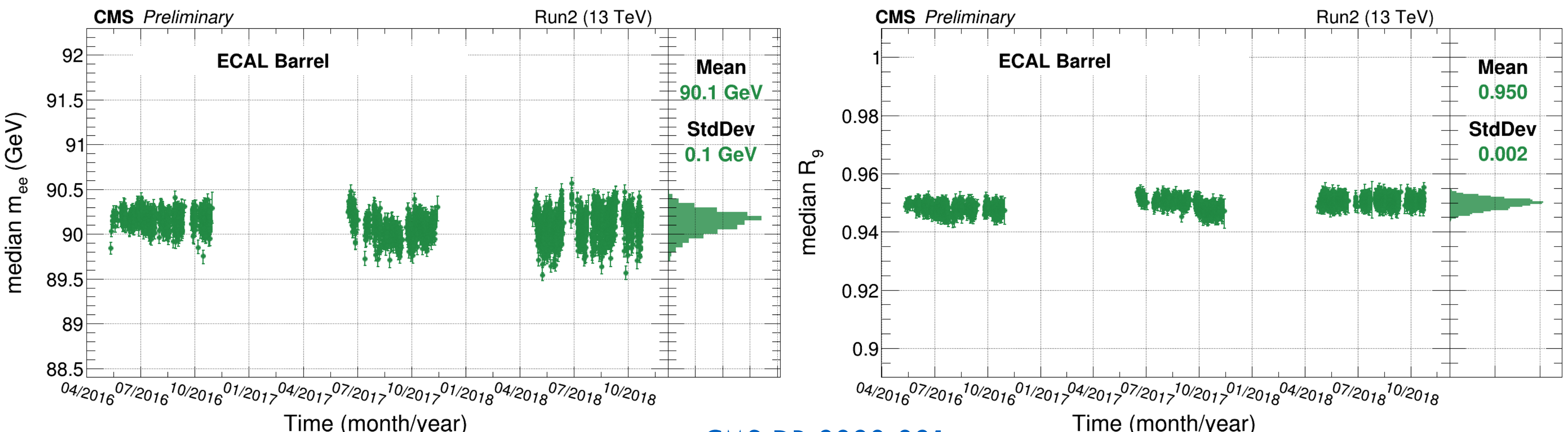






ECAL performance in Run 2

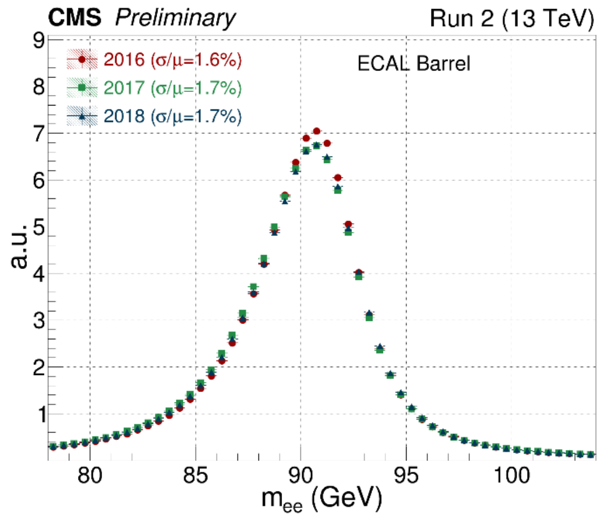
- ECAL response is stable over time after corrections
  - validated with Z→ee events



CMS-DP-2020-021

- energy scale stable at ~1% level across 3 years
- shower shape variable (R_9) also stable over time with spread <<1%
  - R_9: ratio of the energy deposit in the 3x3 crystal matrix around the seed crystal to that in the supercluster
  - important variable for the electron and photon identification

ECAL performance in Run 2



- Energy and mass resolution with ECAL calibration

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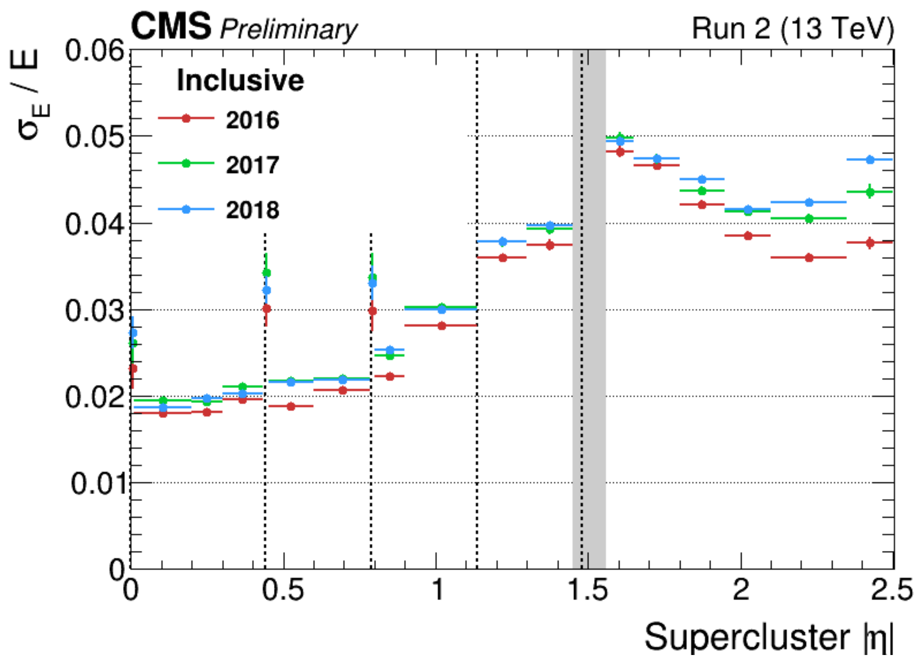
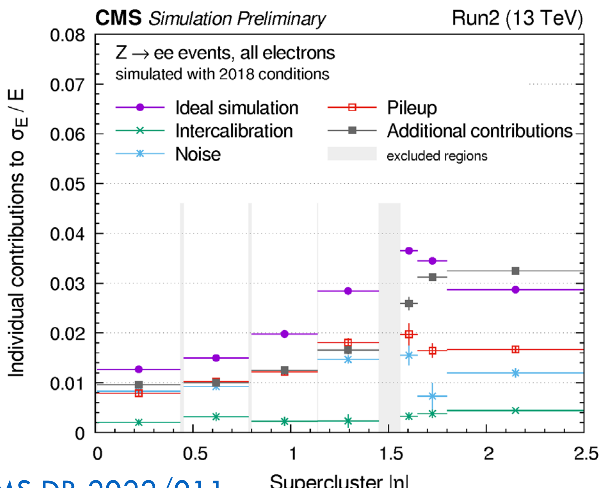




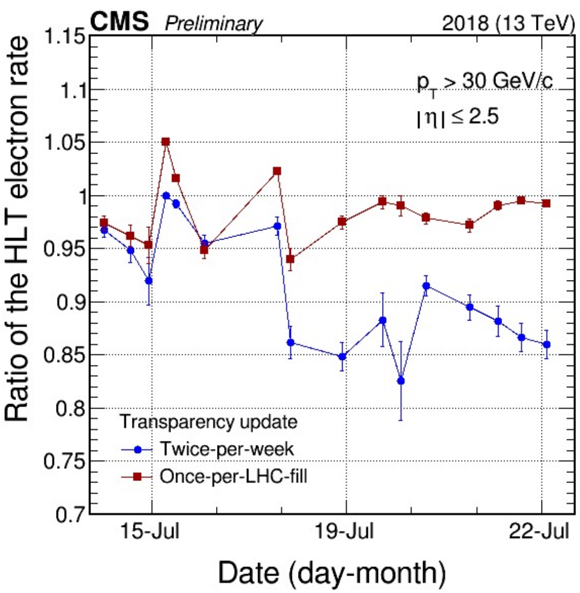
CMS DP-2022/011

Large impacts on resolution from pile-up and noise related effects

- Excellent ECAL performance throughout Run 2
  - resolution at ~2% in the central, <5% elsewhere
  - stable in different years in Run 2

ECAL calibration and performance towards Run 3

- New Graph Neural Network based algorithm for SuperClustering
  - more details in [poster(No.320)]
- Increased laser correction update from twice-per-week in Run 2 to once per-fill (~10h on average in 2022) in Run 3
  - nice tracking of the transparency for L1 and HLT during Run 3
  - improved HLT electron rates and resolution
- Developed ECAL calibration automation framework that integrates many ECAL calibration and monitoring methods
  - Including pulse shape updates, timing calibration, alignments, various steps in energy calibrations, performance monitoring …
  - optimized workflow for prompt ECAL calibration deployment
  - improves the quality of prompt reconstruction data



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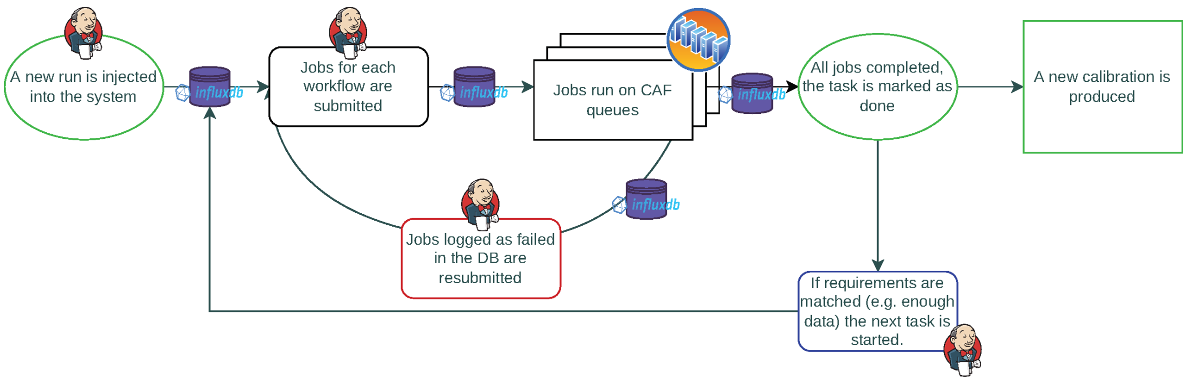


Summary

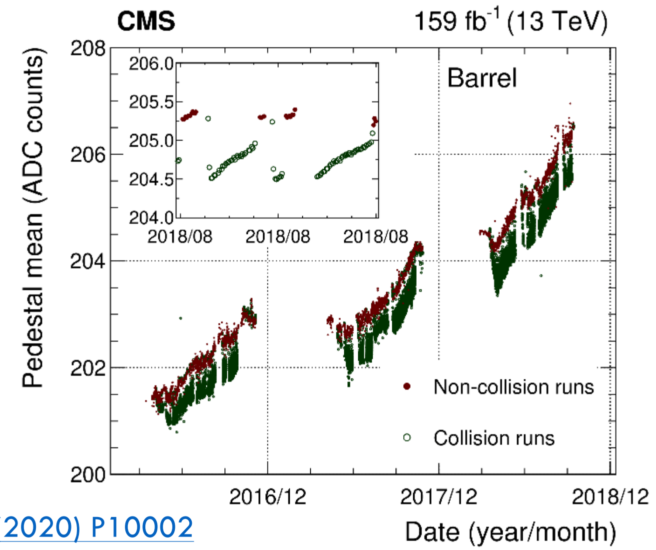
- A range of recalibration and optimization has been exploited in Run 2
  - challenging due to increased instantaneous luminosity and detector aging
  - new multifit method for amplitude reconstruction
  - frequent laser correction to stable ECAL response over time
  - combined intercalibration to stable crystal response at same η
  - dedicated corrections for measured energy in preshower
- Outstanding performance of the CMS ECAL in Run 2
  - stable ECAL response over time with spread at ~1% level
  - resolution of electrons between 2% and 5%
  - similar ECAL performance achieved in Run 2 in comparison with Run 1 despite much harsher environment
- ECAL group is constantly working to improve ECAL performance towards Run 3
  - more frequent laser condition updates, automation framework for prompt calibration, machine learning in clustering and monitoring etc..

Back Up

Pedestal condition and timing calibration

- The signal pedestal and pulse shape are inputs to the amplitude reconstruction algorithm
  - Pedestal measured from laser events every 40 minutes.
  - Time shift due to irradiation corrected every year
    - towards negative times during collisions and towards positive times during recovery

Pedestal mean over time for ECAL barrel



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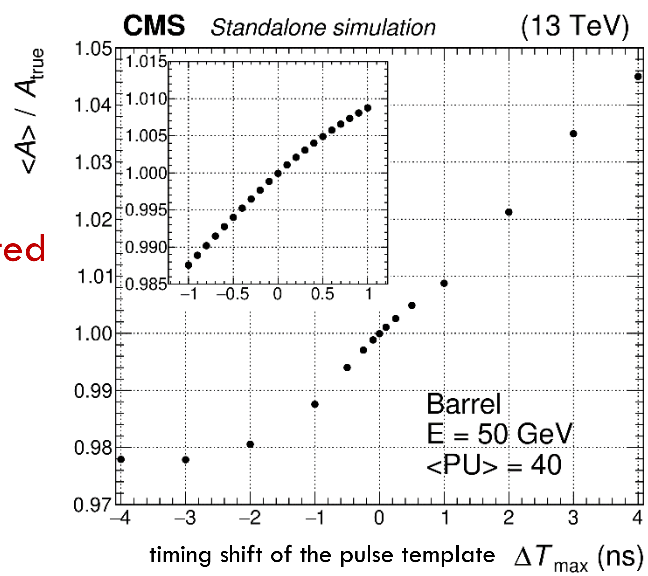
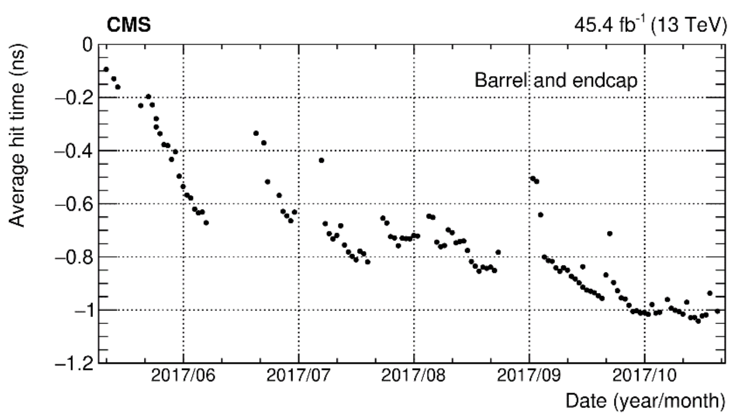
Good agreement between reconstructed amplitude over true amplitude



Average ECAL pulse timing in 2017



Intercalibration (IC_i)

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- A combination of several methods based on different physics signals
  - π^0 mass: exploit reconstructed π^0 mass with its decay of photon pairs
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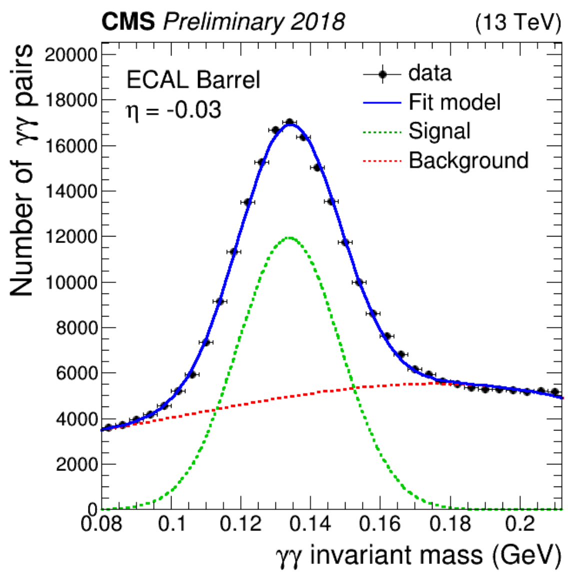
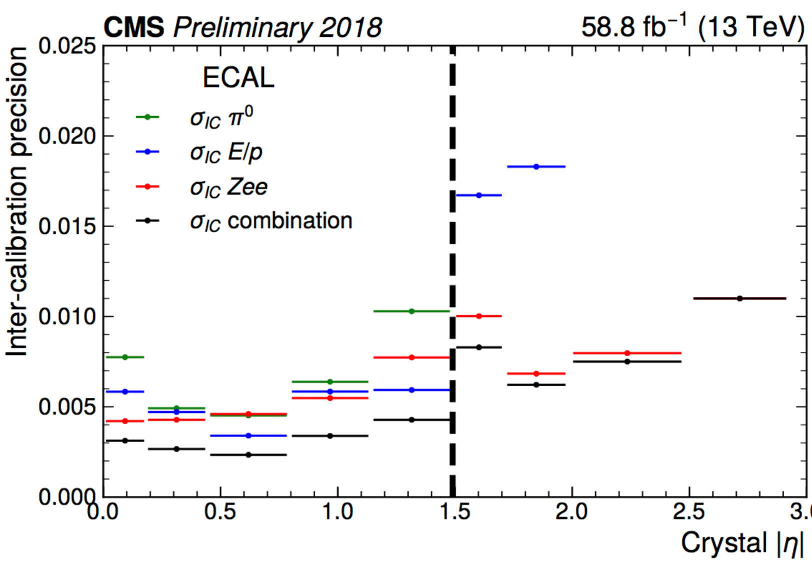
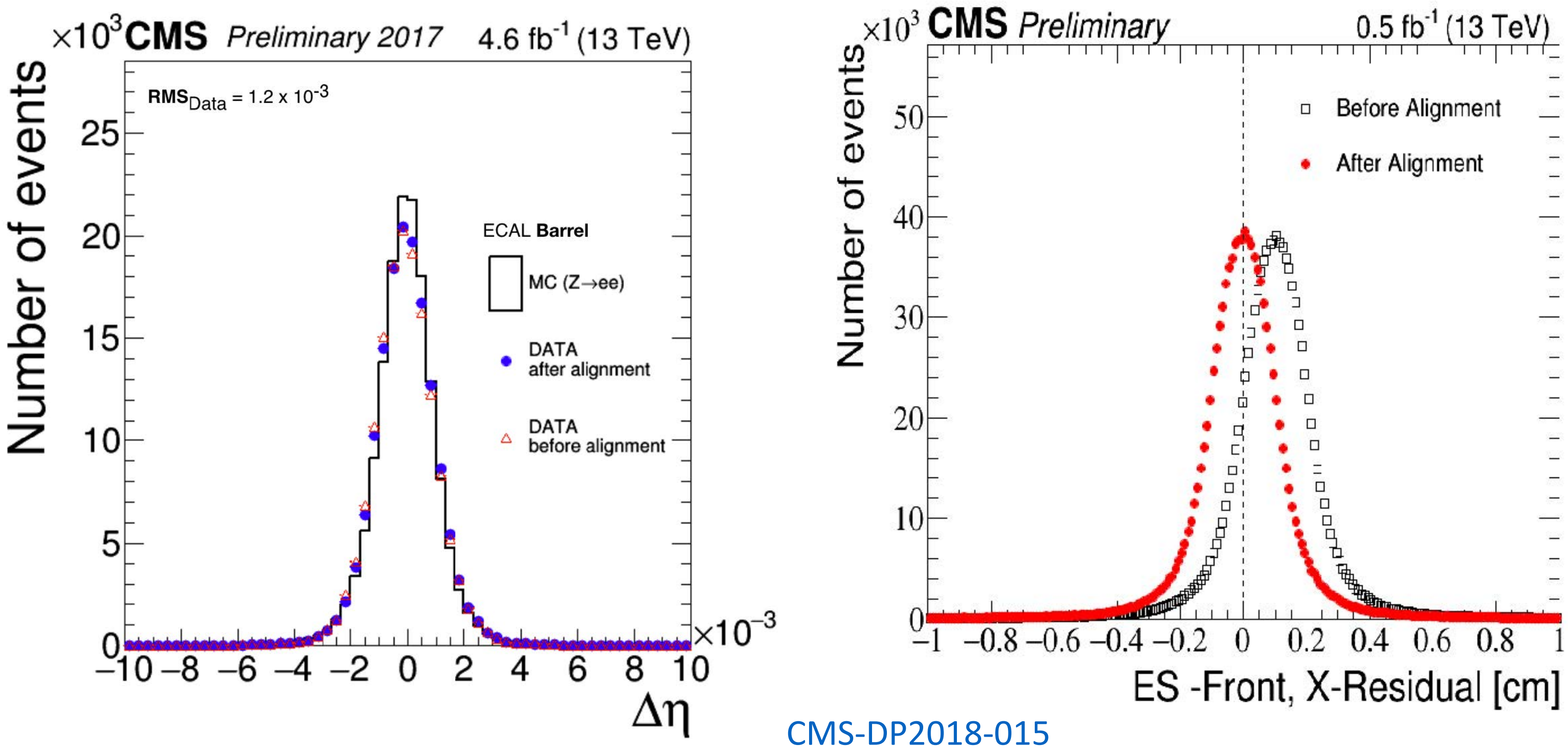
CMS-DP2019-038





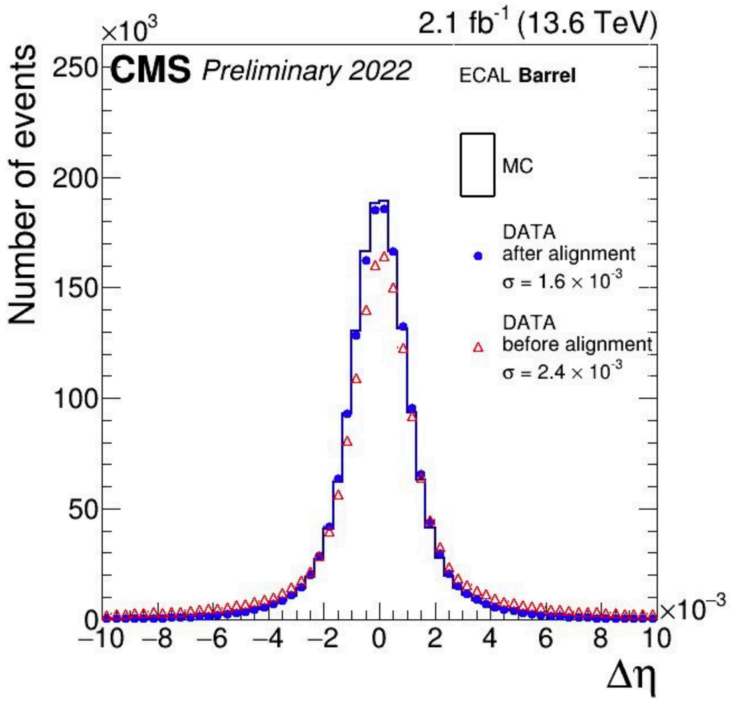
ECAL and Preshower (ES) alignment w.r.t the tracker in Run 2

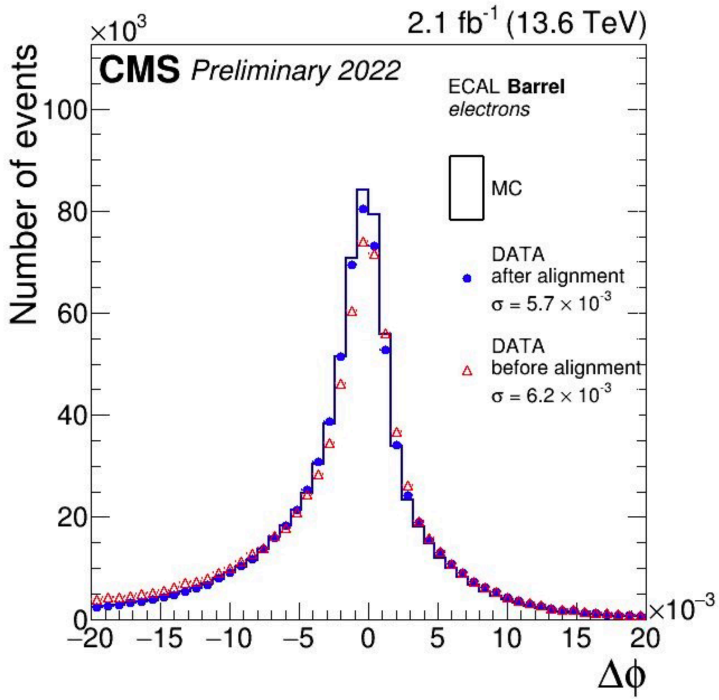


CMS-DP2018-015

- ECAL-tracker alignment: minimizing the difference in the η/φ between the ECAL super-cluster and the extrapolated track position
- ES-tracker: a minimization of the expected hit in the ES and the extrapolated track

ECAL alignment w.r.t. tracker in Run 3

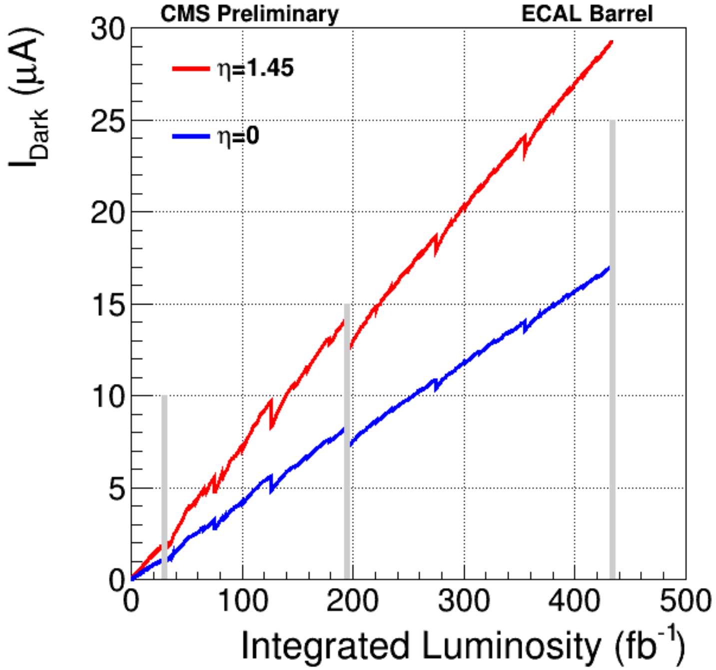


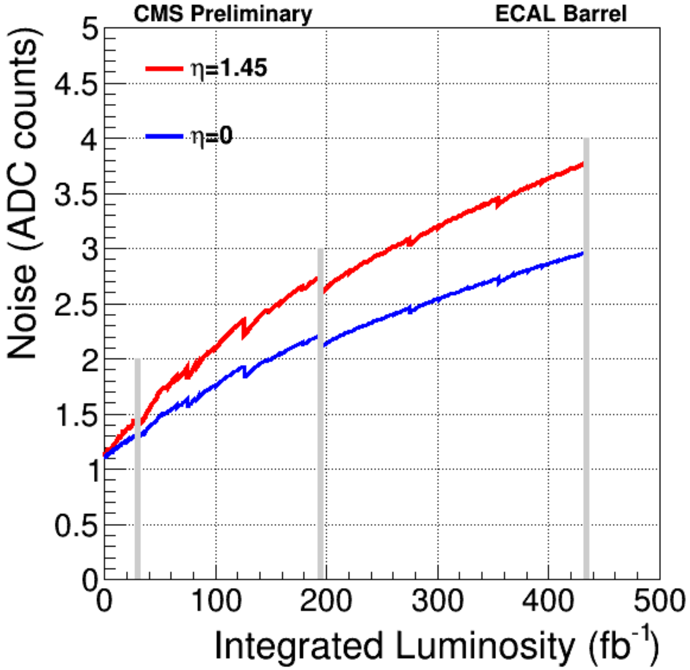


CMS-DP2023-001

- Relative alignment of ECAL crystals with the tracker detector using $Z \rightarrow e^+e^-$ events
  - For each e^+ and e^-, the distance between its track extrapolated from the tracker and its ECAL supercluster (SC) position is minimized along η and φ directions

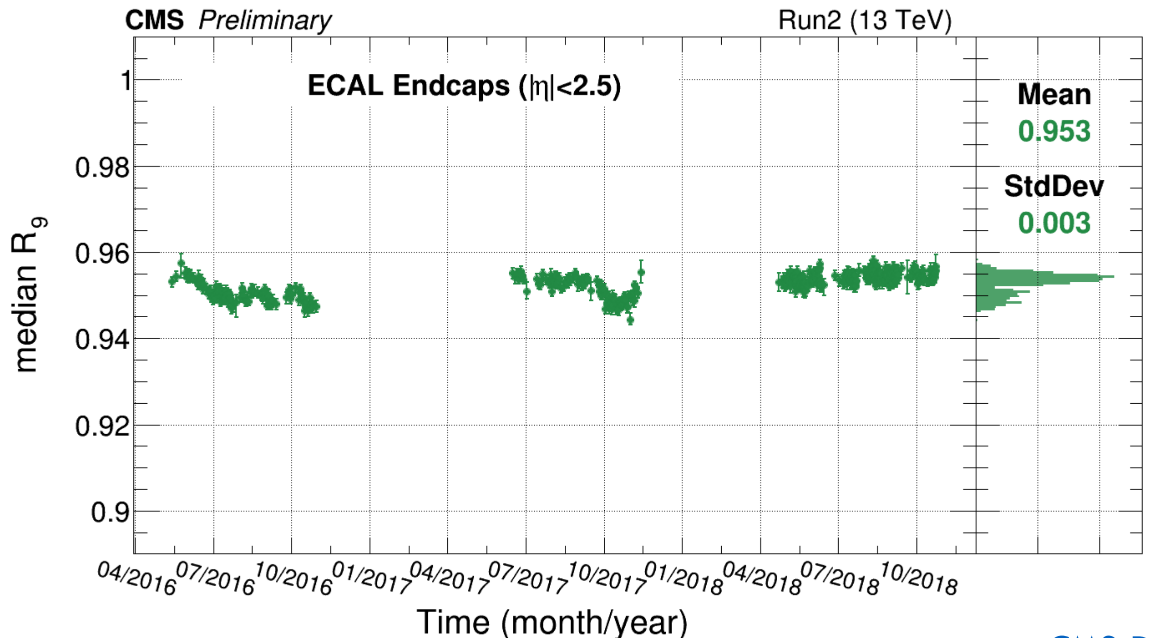
Evolving noise in ECAL





- The leakage current in the ECAL Barrel APDs increases due to radiation-induced hadron fluence.
- The noise increases due to the increase of the APD leakage current.

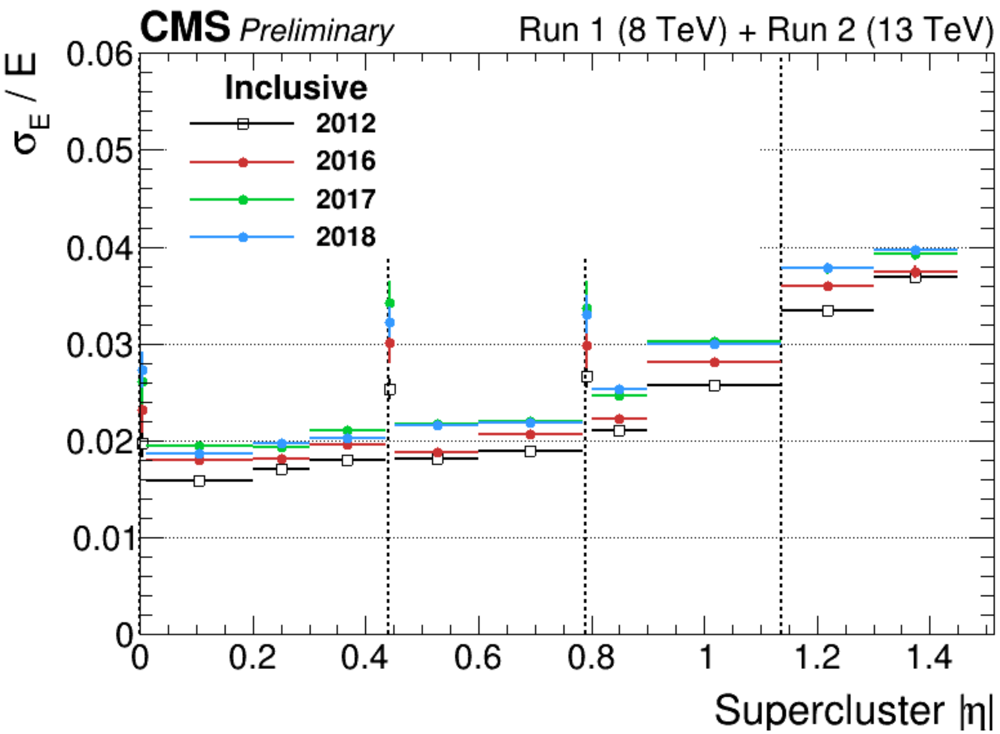
ECAL time stability in endcaps



CMS-DP-2020-021

The shower shape is measured by the variable R_9, defined as the ratio of the energy deposit in the 3x3 crystal matrix around the seed crystal to that in the supercluster. R9 is responsive to changes in pedestal and noise.

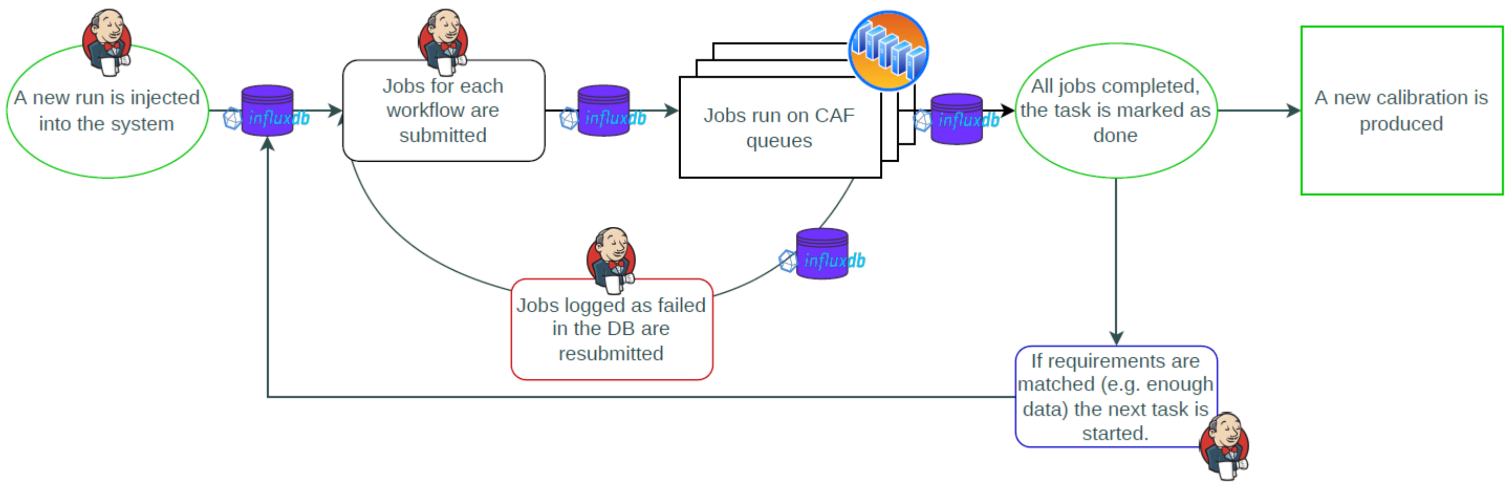
ECAL performance in Run 2

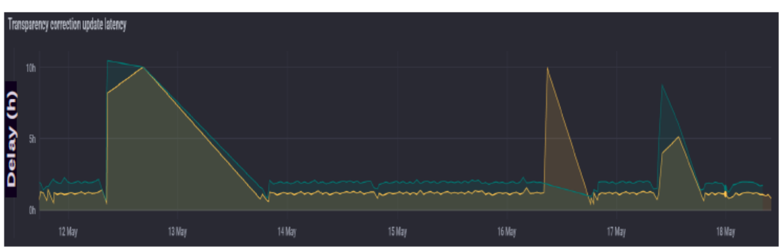


- Similar performance in Run 2 and Run 1

Calibration of prompt reconstruction in Run3

- Implement each calibration workflow as a finate state machine
- Execute jobs regularly updating conditions with predefined conditions
- Constant monitoring and update calibration with fine time granularity





System successfully deployed in Run 3