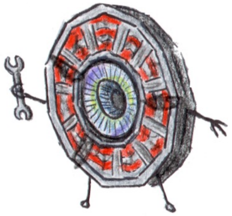
Performance of the CMS Electromagnetic Calorimeter in Run3



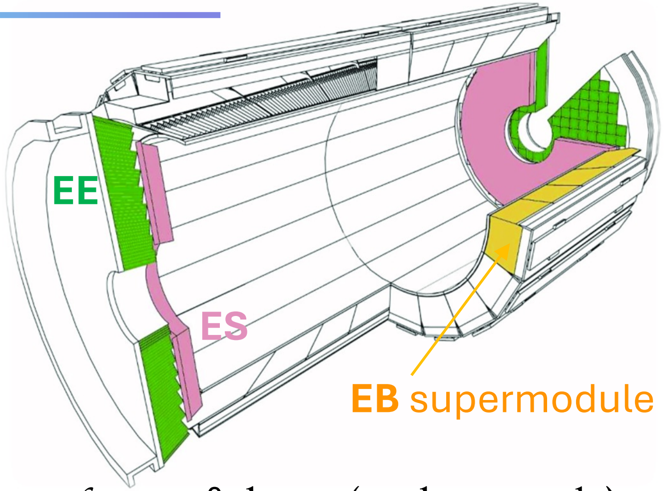
M.M. Obertino[1] on behalf of the CMS collaboration

[1] *Università di Torino and INFN*

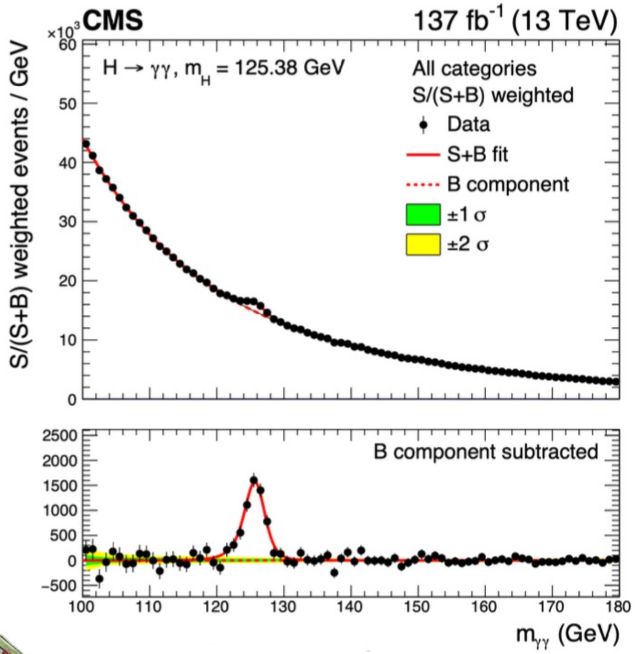
XIII International Conference
on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

ECAL, the CMS electromagnetic calorimeter

Homogeneous, hermetic, high-granularity $PbWO_4$ crystal calorimeter



- **Barrel (EB) – |η| < 1.48**
  61200 crystals in 36 super-modules, Avalanche Photo-Diode (APD) readout
- **Endcaps (EE) – 1.48 < |η| < 3**
  14648 crystals in 4-Dees, Vacuum Photo-Triode (VPT) readout
- **Preshower (ES) – 1.65 < |η| < 2.6**
  $3X_0$ of Pb/Si-strips to discriminate between prompt photons and photons from π^0 decay (endcaps only)



CMS-HIG-19-015

ECAL design goal

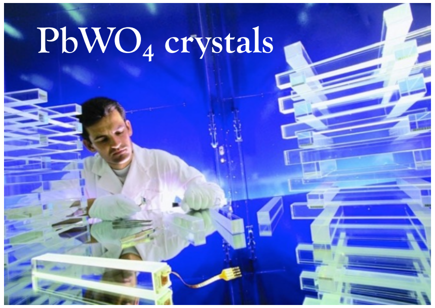
Running for 10 years at 14 TeV (L_{INT} : 500 fb^{-1}),
L_{INST} : 10^{34} $cm^{-2}s^{-1}$, PU~20
$\sigma_E/E < 1\%$ for ~60 GeV photons to achieve early Higgs discovery in γγ channel

ECAL has a crucial role in the CMS physics program, spanning from Higgs measurements to the exploration of new physics phenomena

ECAL main challenges

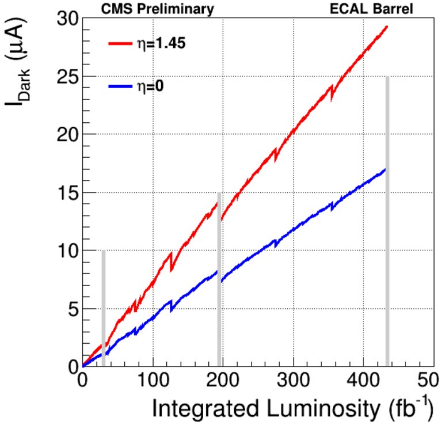
ECAL is the first crystal calorimeter installed at a hadron collider and the largest crystal calorimeter ever built for a high energy physics experiment.

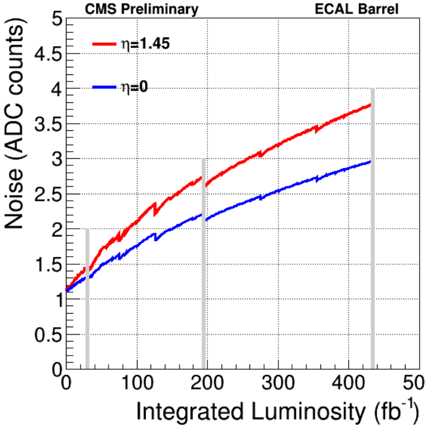
Operating ECAL to high precision in the LHC environment has been a demanding but exciting challenge


PbWO$_4$ crystals

→ Radiation-induced effects

- crystal transparency change
- channel pulse shape change
- APD dark current increase (i.e. electronics noise)

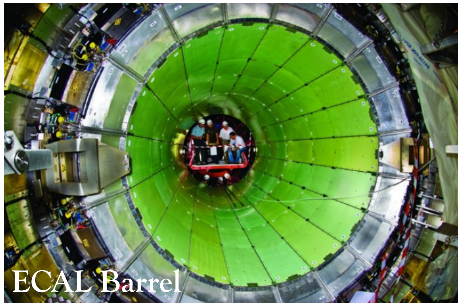


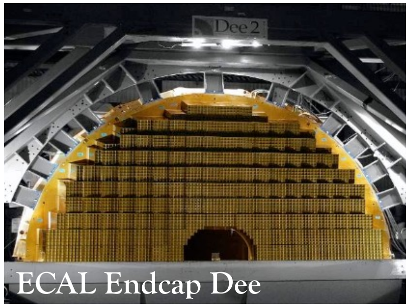


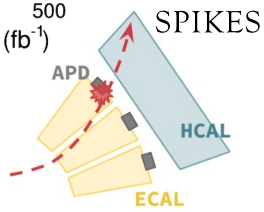
CMS-DP-2018-015

→ Response uniformity and stability

- crystal light yield (LY) spread ~10%
- endcap VPT response spread ~25%
- LY variation with temperature: ~ 2.2%/°C
- APD gain variation: −2.4%/°C, −3.1%/V


ECAL Barrel


ECAL Endcap Dee

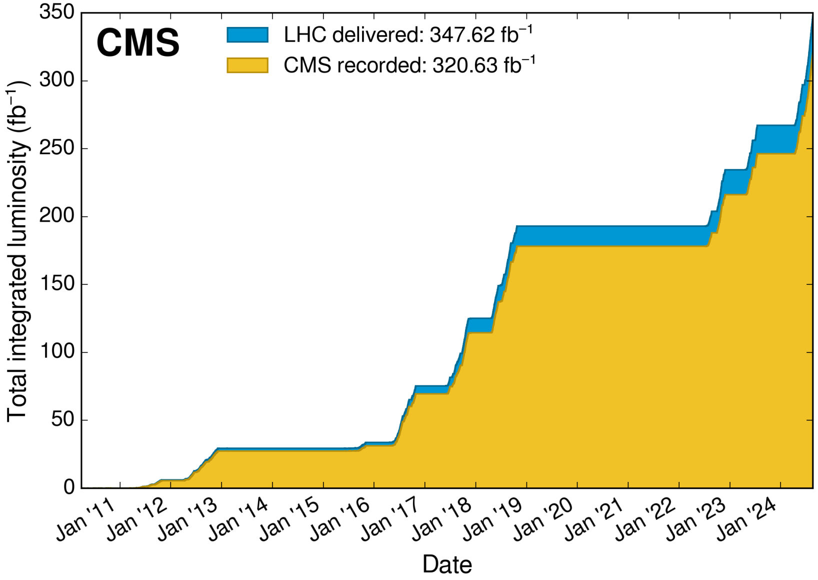


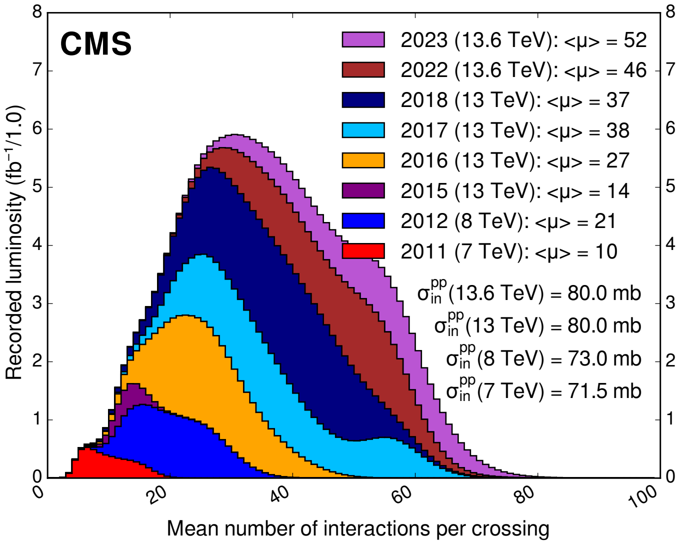
→ Direct ionization signal in the APD

→ Increasing number of simultaneous pp interactions (pile-up, PU) up to 60-70

Not expected/completely foreseen in the design phase

LHC Run3: more than what ECAL was designed for





	Run1	Run2	Run3
Peak-luminosity (10^{34} cm^{-2} s^{-1})	0.8	2	2.6
Recorded Luminosity (fb^{-1})	30	140	200*
Average pile-up	20	35	50
L1 trigger rate (kHz)	100	100	115

* expected

Peak luminosity increased up to 2.6 10^{34} cm^{-2} s^{-1}
CMS mean pile up: 46 in 2022 and 52 in 2023
2024: lumi-levelling at PU 62,
L1 trigger rate of 115 kHz

ECAL has to cope large radiation doses and high PU and maintain performance

- Full control of the environmental conditions
- Continuous correction and equalization of the channel response
- Mitigation of pile-up effects

ECAL operations in Run3

Despite the challenging environment, ECAL is behaving well in Run3

- ✓ **Temperature stability** at 18◦C **a factor of two better than required** (<0.05◦C for EB, <0.1◦C for EE)

- ✓ **High-voltage stability** better than the measurement sensitivity and well **below the required 60 mV**
  - → regular calibration of the channels to adjust the APD bias (once per year)

- ✓ **DAQ extremely reliable**
  - → automatic recovery from single event upset improved in Run3 (recovery time reduced from ~ 30 s in Run 2 to 12 s in Run 3)
  - → reduced configuration time and improved monitoring programs

- ✓ Very limited failures overtime, mainly in HV and LV power supplies

- ✓ **Stable number of active channels**: >98.7%(EB), >97.8%(EE)

Successful heavy ion data taking in 2023: ECAL managed to cope with the larger event size of ion collisions keeping an excellent data quality thanks to optimised zero-suppression settings

ECAL at Level 1 and High Level triggers (L1 and HLT)

ECAL sends energy sums to L1 @ 40 MHz; trigger primitives (TPs) are combined with HCAL to form electrons/photons, jets and tau candidates, and to compute transverse energy sums.

ECAL trigger system is operating with high reliability in Run 3

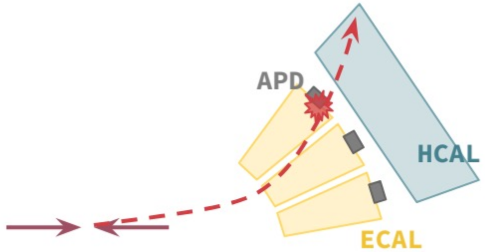
ECAL TP regularly calibrated to maintain stable rates at L1 and HLT

✓ Channel response corrections, intercalibration constants and pedestals update necessary

Noisy/problematic trigger towers automatically masked

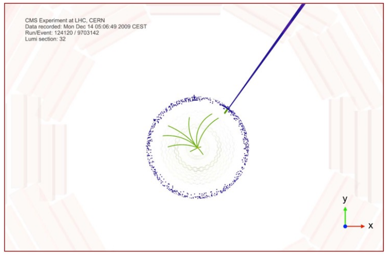
Spike rejection necessary to avoid saturating the L1 rate at high E_T

Spike: large signal in a single crystal coming from direct ionization of APD by hadrons from CMS interaction point.



Spikes removed at L1 looking for isolated energy hits above a certain threshold (**spike killer - SK**).

>95% of spikes above 8 GeV rejected with minimal impact on electron trigger efficiency



SPIKE EVENT DISPLAY

SK performance kept high thanks to a threshold retuning before Run 3 to cope with higher PU and APD noise

EM Objects Energy Measurement & Calibration

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

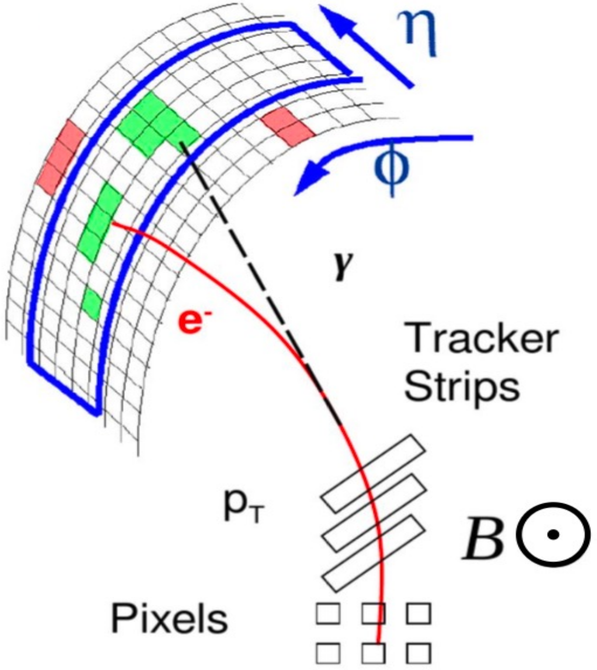
FROM RAW DATA TO CALIBRATED ENERGIES

$$E_{e,\gamma} = F_{e,\gamma} \boxed{G(\eta, t) \sum_i c_i(t)\, s_i(t)\, A_i(t)}$$

Different time granularity

- $A_i(t)$: channel signal amplitude [ADC count]
- $S_i(t)$: time-dependent corrections for radiation induced response variations
- $c_i(t)$: intercalibration factor, to equalize the response of all ECAL channels
- $G(\eta,t)$: energy scale, i.e. conversion factor between ADC counts and energy prior to any radiation damage – about 40 (60) MeV/ADC in EB (EE)
- $F_{e,\gamma}$: particle energy correction including η and ϕ dependencies, material effects and differences for e, γ

ECAL sits inside 3.8 T magnetic field
Showers to spread in ϕ direction



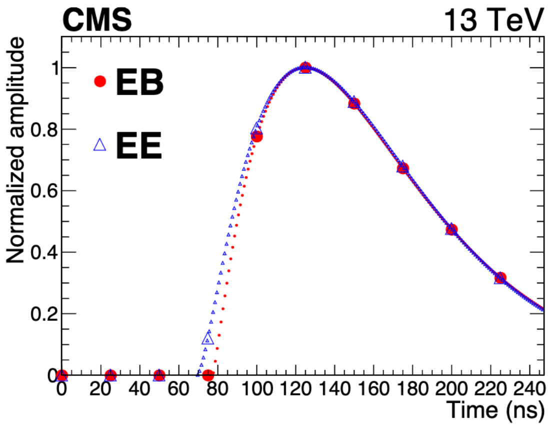
NEXT TALK

A_i(t): the signal amplitude

A(t): signal amplitude reco from 10 digitized samples @ 40 MHz

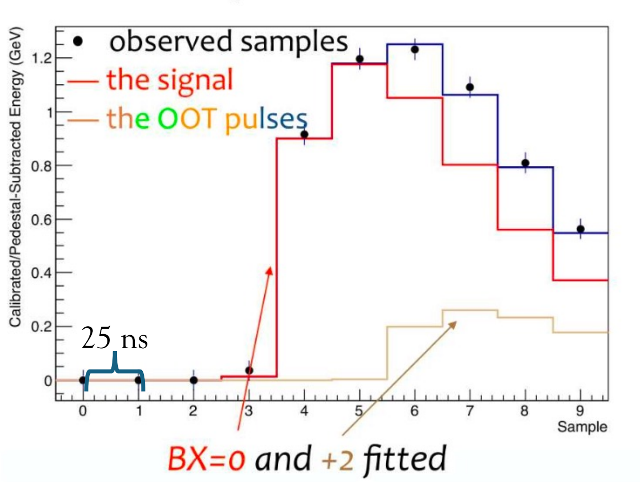
Innovative algorithm (Multifit) introduced to reduce the effect of out-of-time (OOT) pileup [2020 JINST 15 P10002]

- Template fit (1 template per channel), with 10 free parameters corresponding to the amplitudes of signals in different BXs
- Prior knowledge of the pedestals/noise needed



Introduced already at the start of Run2 for both the offline and online event reconstruction; working efficiently in Run 3 conditions

example fit on a barrel hit



$$\chi^2 = \left(\sum_{j=0}^{N_{\mathrm{BX}}} A_j \vec{p}_j - \vec{S}\right)^T \mathbf{C}^{-1} \left(\sum_{j=0}^{N_{\mathrm{BX}}} A_j \vec{p}_j - \vec{S}\right)$$

1. Multifit: pulse shape is modeled as in-time pulse plus up to 9 out-of-time (OOT) pulses
2. Minimizing χ^2 to get best estimate of in-time pulse amplitude
3. Contamination from OOT pulses effectively removed

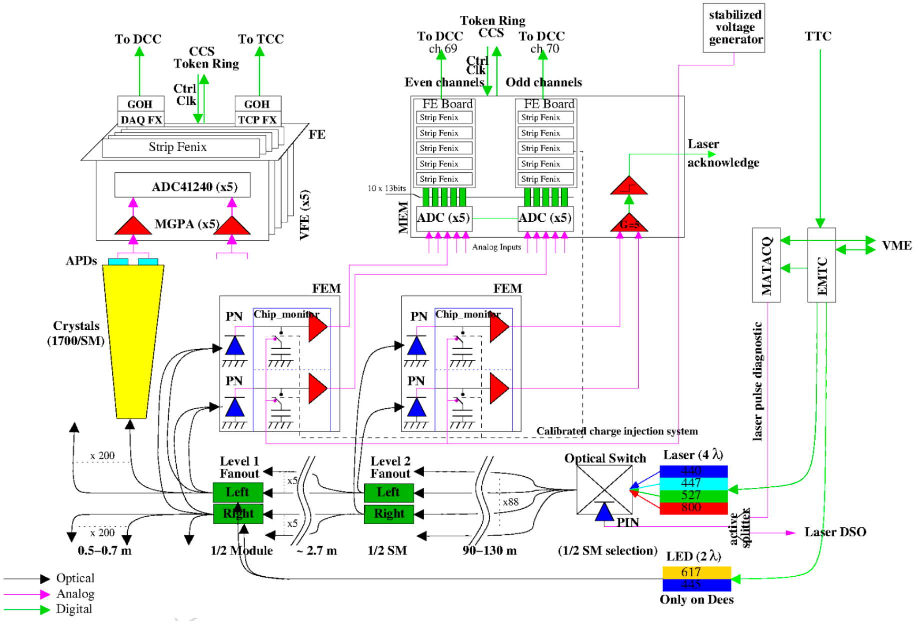
Regular updates of pulse shape templates and input parameters to ensure the stability of energy reconstruction over time:

- Pedestals measured every 40 minutes
- 1 per week update of pulse shape template and time shift (due to transparency losses)

In-time pile-up: irreducible, can be removed on average from the energy density in an event

$s_i(t)$ and the ECAL laser monitoring system

The Laser Monitoring System (LMS) constantly monitors and allows to correct for changes in the crystals transparency and photodetector response.



88 laser monitoring regions, 2 in each EB SM + 4 per Dee in the Endcaps

Light from a laser source sent to each crystal with a multi-level system of optical fibres and, simultaneously, to reference PN diodes (2 PN per region of 100-200 crystals, called harness).

Two lasers (blue@447 nm, close to scintillation peak, and green@527 nm) continuously sweep the ECAL laser monitoring regions: **one measurement every ~40 minutes**

LMS 100% reliable over the whole LHC running period, single measurement precision < 0.2%

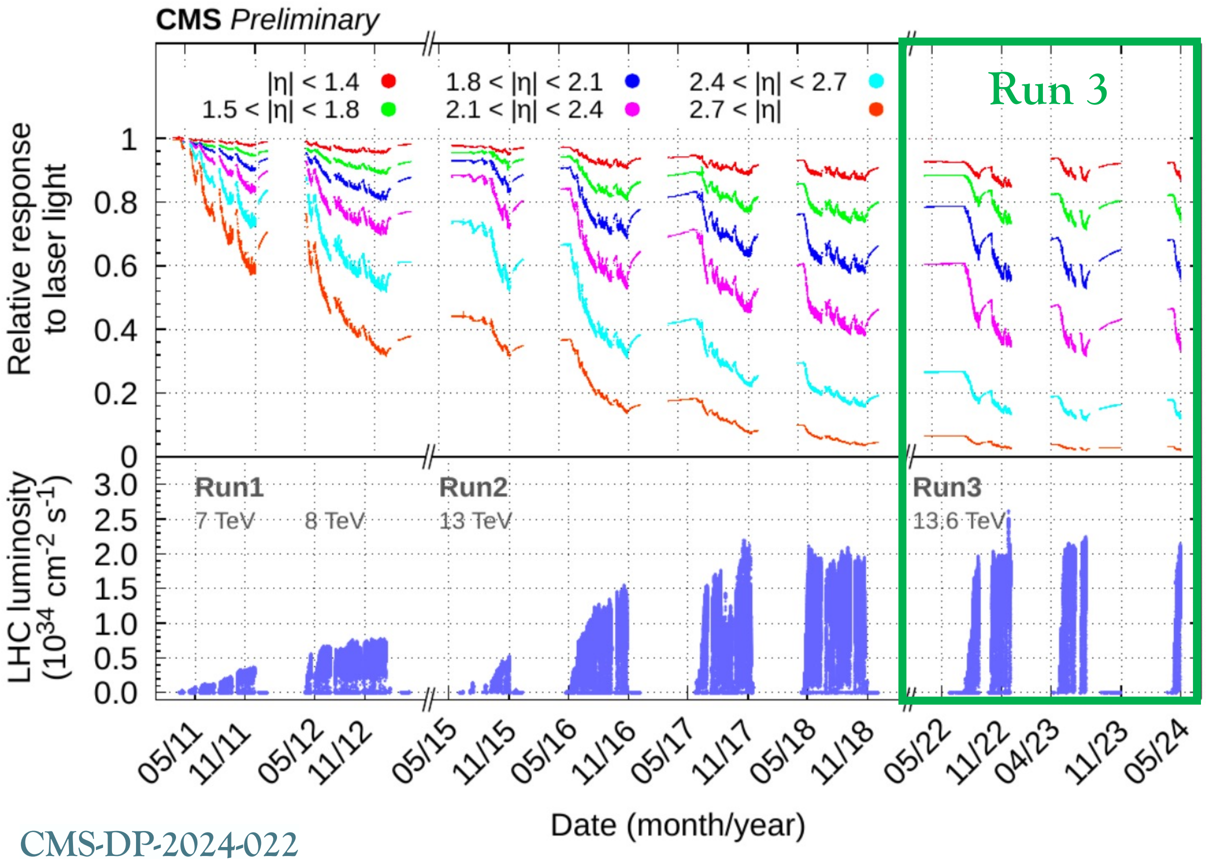
Response to laser light R/R_0 and to EM showers S/S_0 related by a power law, at first order:

$$S/S_0 = (R/R_0)^\alpha$$

Corrections provided within 48 hours for the prompt reconstruction of the CMS data and updated at trigger level for each beam fill (increased from 2 per week in Run 2).

Transparency loss history

Evolution of the ECAL response to laser light, measured by the LMS



CMS-DP-2024-022

Barrel

Endcap region covered by CMS tracker

Endcap region relevant for forward jets

Observed response change:

- up to 15% EB
- up to 70% at |η| ≈ 2.5
- up to 99% in the region closest to the beam pipe.

ECAL endcaps will suffer from high transparency loss especially in the regions at highest pseudorapidity and in the last years of Run3. **New, more powerful (18 mJ pulse energy wrt 1 mJ) green laser running in the calibration sequence since beginning of 2024.**

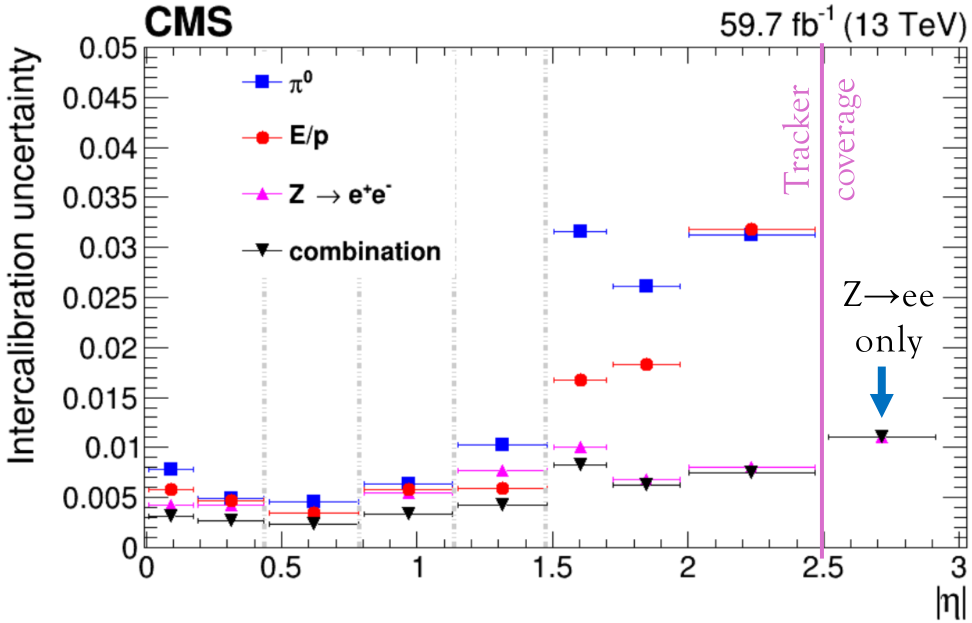
Single channel intercalibration $c_i(t)$ and energy scale $G(\eta,t)$

Several calibration methods combined to equalize response of channels at same η

- **π^0 method**, based on the invariant mass of photons from π^0 decays
- **E/p method**, based on the ratio between the energy in the calorimeter and the momentum of electrons from W or Z decay
- **$Z \rightarrow e^+e^-$ method**, based on the invariant mass of electron-positron pairs from Z decays

ICs calculated by each method combined using an estimate of their overall precision.

Precision and methods evolved from Run1 to Run3 due to different running conditions.



Z→ee only

Legacy Run2 plots

Precision of the different IC methods and of their combination.

CMS-EGM-18-002

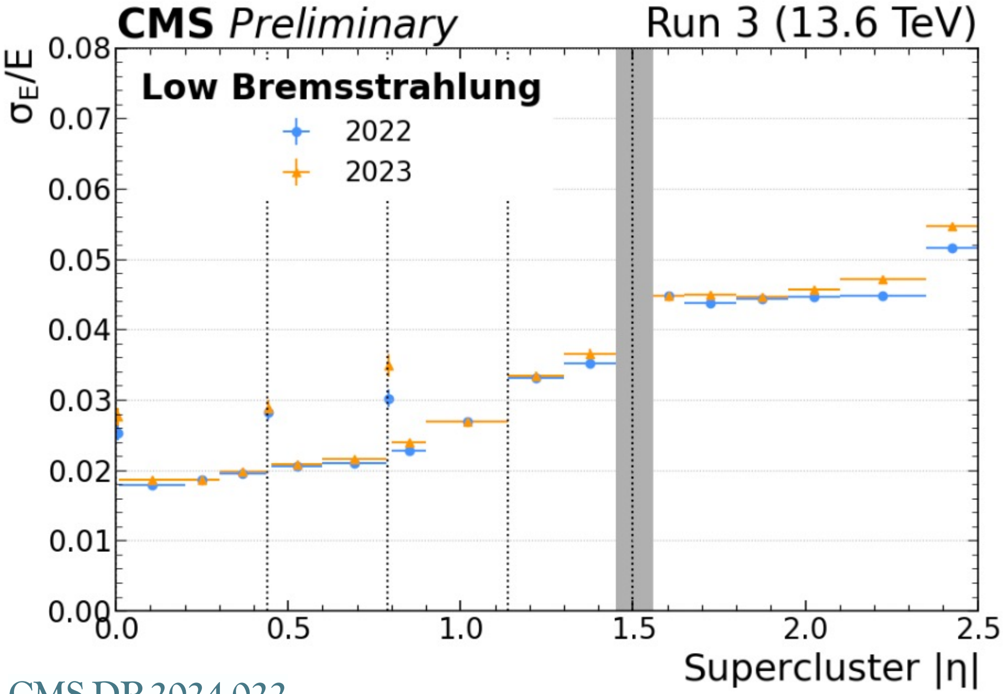
High precision in all regions: <0.5% in EB, <1% in EE

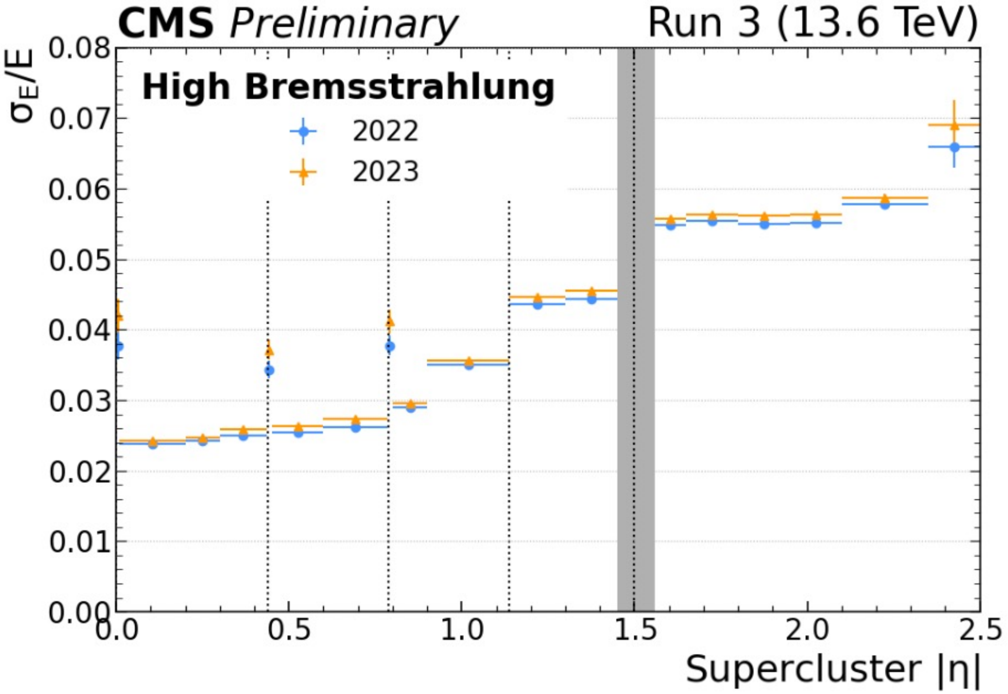
Energy scale vs η corrected in data to match MC using $Z \rightarrow e^+e^-$ mass peak

ECAL performance in Run 3: energy resolution

Energy resolution with not yet final conditions for Run3

- Energy scale updated every 2 fb^{-1}
- Channel inter-calibration computed for 2022 and 2023 with $Z \rightarrow e^+e^-$ method (1 IC/year)
- Intercalibrations with π^0 and E/p available for future improvements





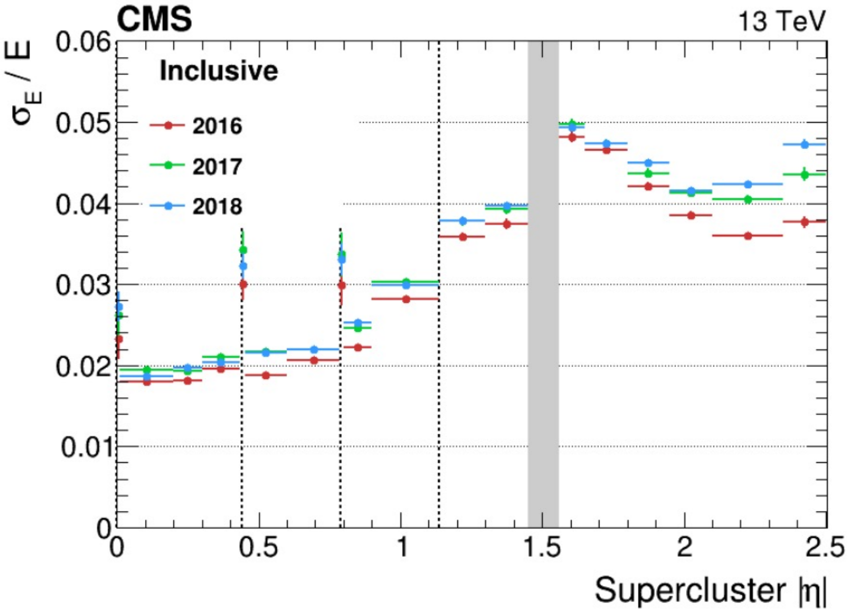
CMS-DP-2024-022

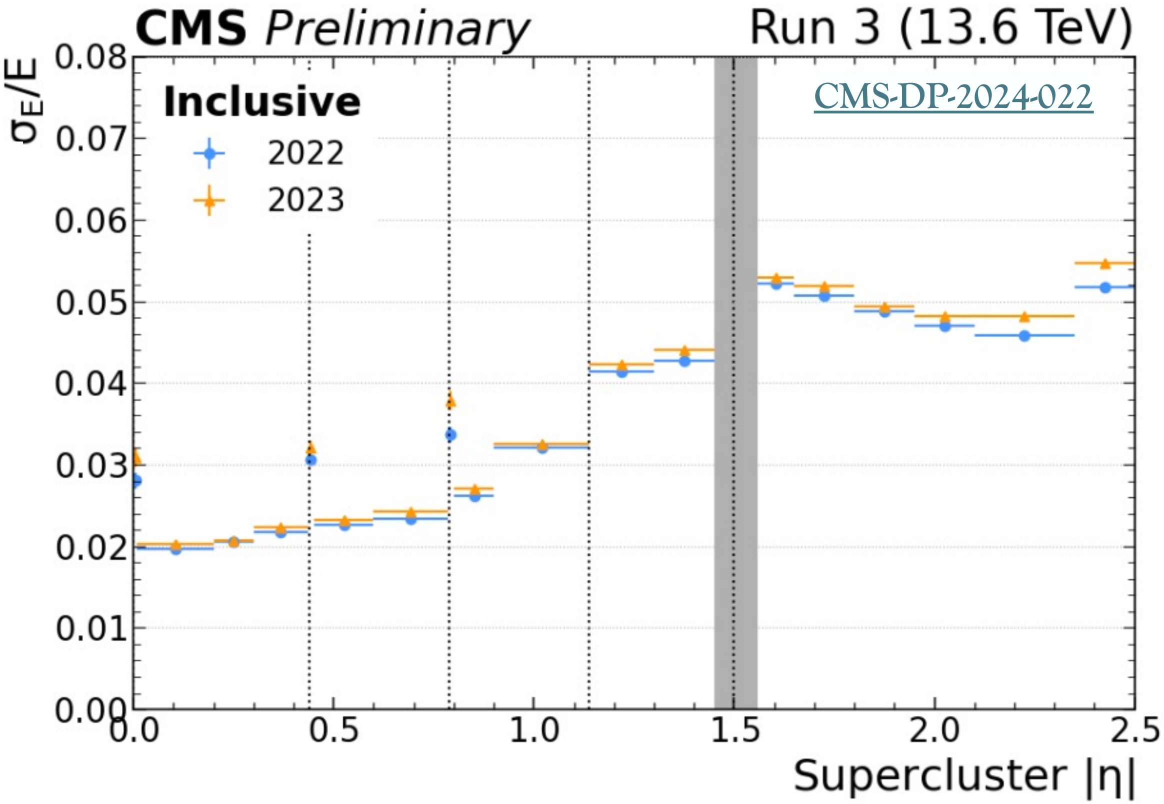
A stable ECAL energy resolution is observed between 2022 and 2023 despite the increased LHC luminosity and the ageing of the detector.

ECAL: Run3 vs Run2

CMS-EGM-18-002

Legacy Run2





CMS-DP-2024-022

Energy resolution of Run 3 already similar to legacy Run 2 despite harsher conditions.

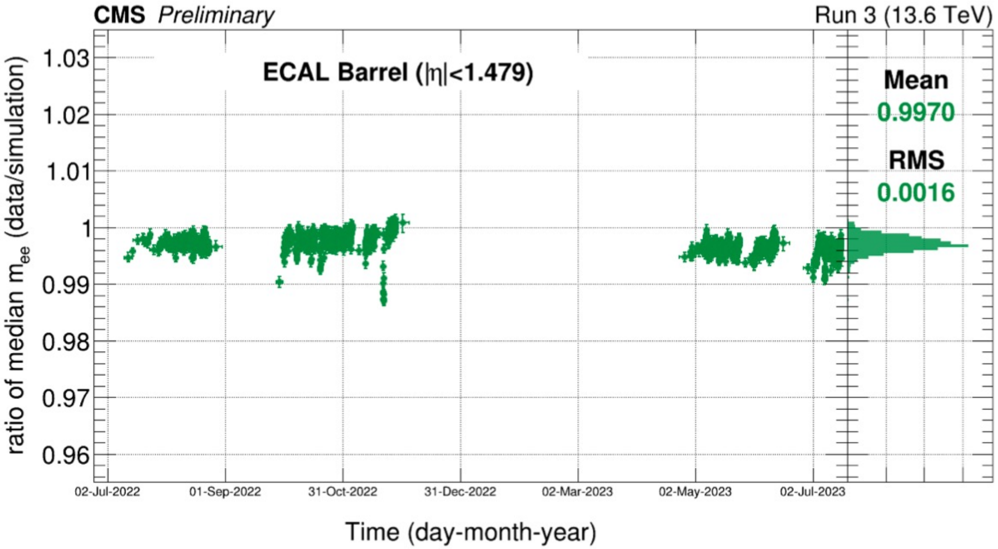
Improvement expected from:

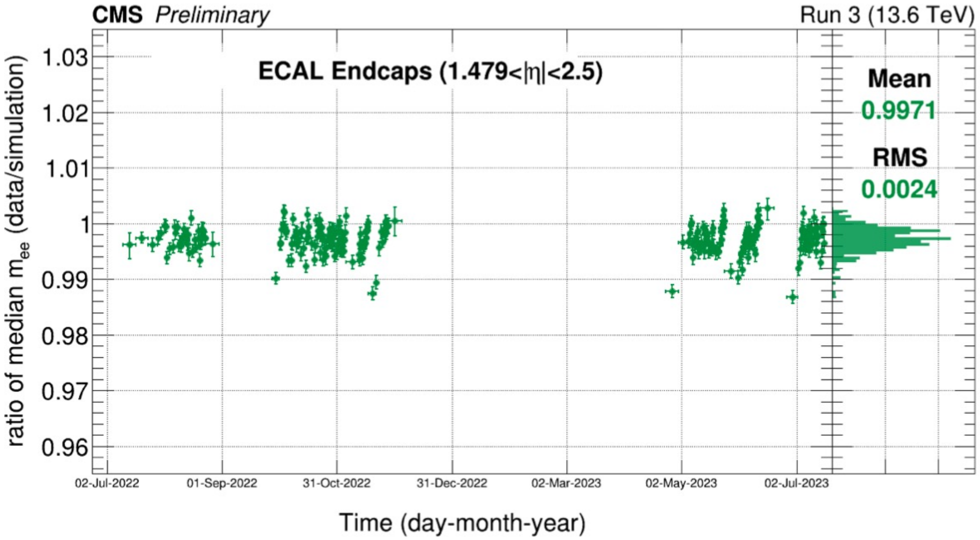
- ✓ improved intercalibrations (combination of different inter-calibration methods)
- ✓ better correction for losses in the detector and PU

NEXT TALK

ECAL response stability

Time stability of the Z peak over 2022 and 2023: stable response at per mille level using prompt calibrations





CMS-DP-2024-022

Spread of the median ratio is at 0.1% (0.2%) level in EB (EE) throughout 2022 and 2023

ECAL: time-of-flight reconstruction

- **Not within ECAL design goals**: better than 1 ns precision to avoid affecting energy measurement
- **Timing precision < 20 ps for large energy deposits** (E>50 GeV in EB) measured before Run 1 (test beam electrons, cosmics and beam splash event)
- In situ additional effects degrade this performance (variations in the clock distribution between different regions of the ECAL and different runs, pulse shape variation due to irradiation …). In **Run1** ECAL could achieve **–150 ps resolution for Δt between two different EM showers**.

Precise timing information from ECAL successfully used in the CMS physics program

→ jets/photon discrimination and BSM long-lived particles searches

Two methods developed to measure e/γ time of arrival in ECAL

Ratio timing algorithm

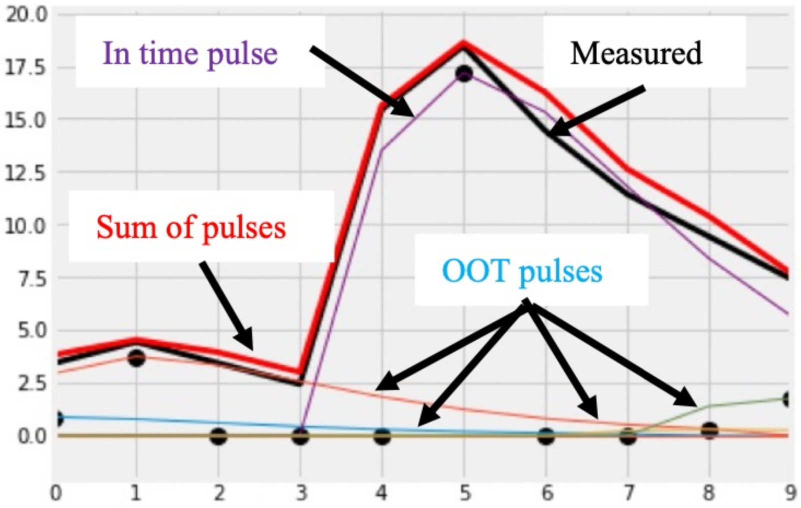
Ratio of any two consecutive amplitudes A(t) and A(t+25 ns) determines the timing of a pulse measured in a crystal wrt the LHC clock.

Default reconstruction algorithm in Run2 and in Run3 prompt reco

Cross-Correlation algorithm (CC)

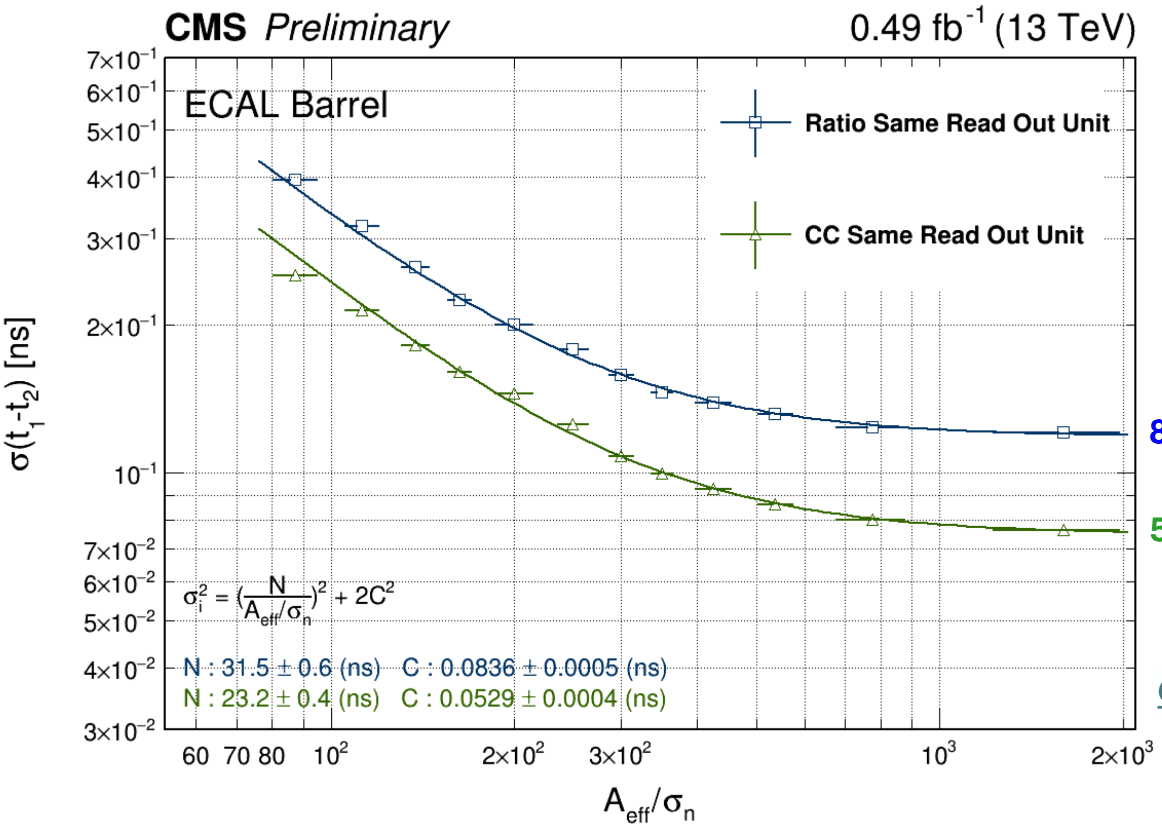
Similar to multifit: subtract/fit OOT pulses from the measured pulse, fit time shift for in-time pulse from a cross-correlation fit

Developed and tested during Run2 to better cope with high PU



ECAL time resolution in situ

Time reconstruction comparison: CC algo demonstrates improved performance over Ratio algo



84 ps [Ratio]

53 ps [CC]

Time resolution vs effective amplitude for signals reconstructed in EB in 2018. Resolution estimated from Δt of the two most energetic neighboring crystals ("same read out unit") of photon/electron clusters, with a similar amount of energy.

CMS-DP-2024-061

Typical analysis relevant EM object resolutions observed in Run 2 (Ratio algorithm): 200-300 ps

Expected to achieved a resolutions of 100-200 ps in Run 3 with CC algorithm

Further improvements foreseen for HL-LHC thanks to electronics upgrade

G. LAVIZZARI TALK

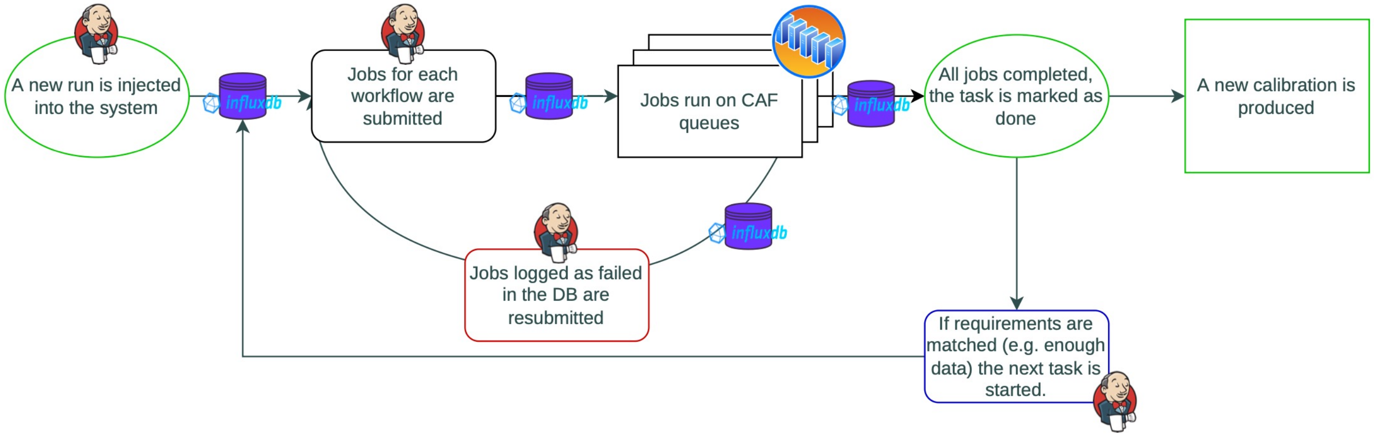
Automatic workflow framework

Tracking the response evolution over time is the main challenge for ECAL

Automated calibration framework developed during the LHC Long Shutdown 2 **using a framework of finite state machine through state-of-the-art software** for automatic data processing, visualization and monitoring (Jenkins and InfluxDB + Grafana for monitoring)

→ continuous processing of data reducing the person power needed to run the calibration

→ execute jobs regularly updating conditions when predefined conditions are met



ECAL workflows in production

- ✓ pulse shape templates
- ✓ timing calibrations (2 methods)
- ✓ E/p laser harness corrections
- ✓ energy scales as function of eta
- ✓ π^0 and m_{ee} monitoring
- ✓ alignment

System operated smoothly without interruption through the last 3 years of data taking (2022-2024), executing an average of 500 jobs per day.

Conclusions

The **CMS Electromagnetic Calorimeter (ECAL) is essential in the CMS physics program** thanks to its excellent measurements of energy, position and time of arrival of photons and electrons.

Precise calibration and continuous monitoring of the ECAL response are **key ingredients to achieve and maintain excellent performance** in terms of energy scale and resolution.

In Run 3 LHC reached the highest instantaneous luminosity to date: **ECAL demonstrated to achieve out-of-the-box performance comparable to legacy Run2, despite detector ageing.**

Applied strategy:

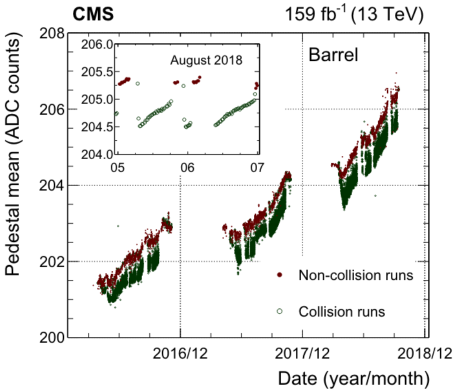
- ✓ Implementation of new measures to improve operations efficiency and face new challenges
- ✓ New automation workflow, running continuously Run 2 algorithms and calibrations
- ✓ Development of new tools for reconstruction procedures suffering from degradation due to pile up

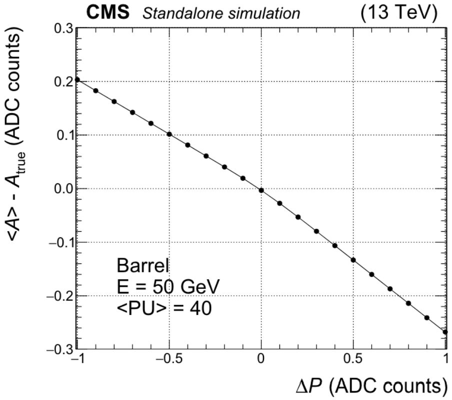
More to come: stay tuned for the next talk!

SPARES

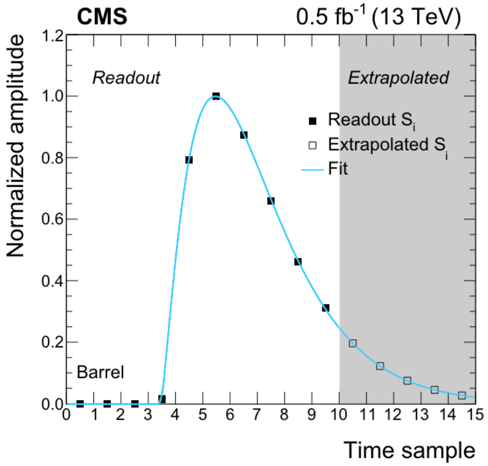
Signal amplitude reconstruction: regular updates needed

Regular updates of pulse shape templates and input parameters necessary to ensure the stability of energy reconstruction over time.

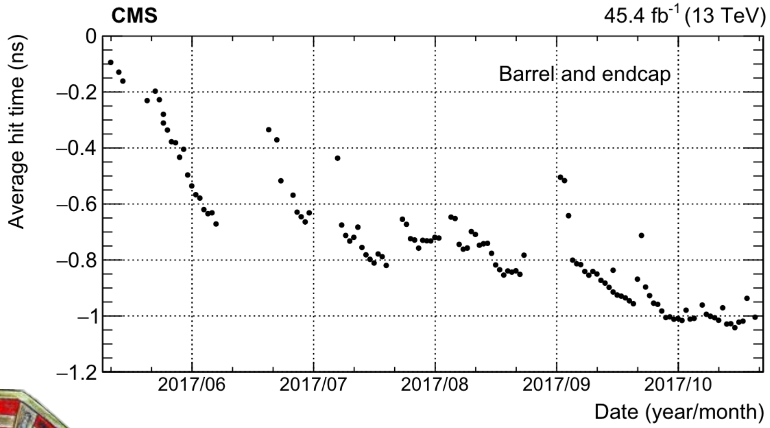


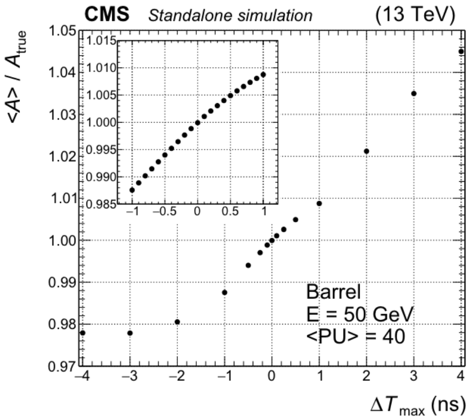


Pedestals measured from laser events every 40 minutes and every week during no beam periods



Pulse templates constructed from collision data (events recorded with a dedicated high-rate calibration data stream)



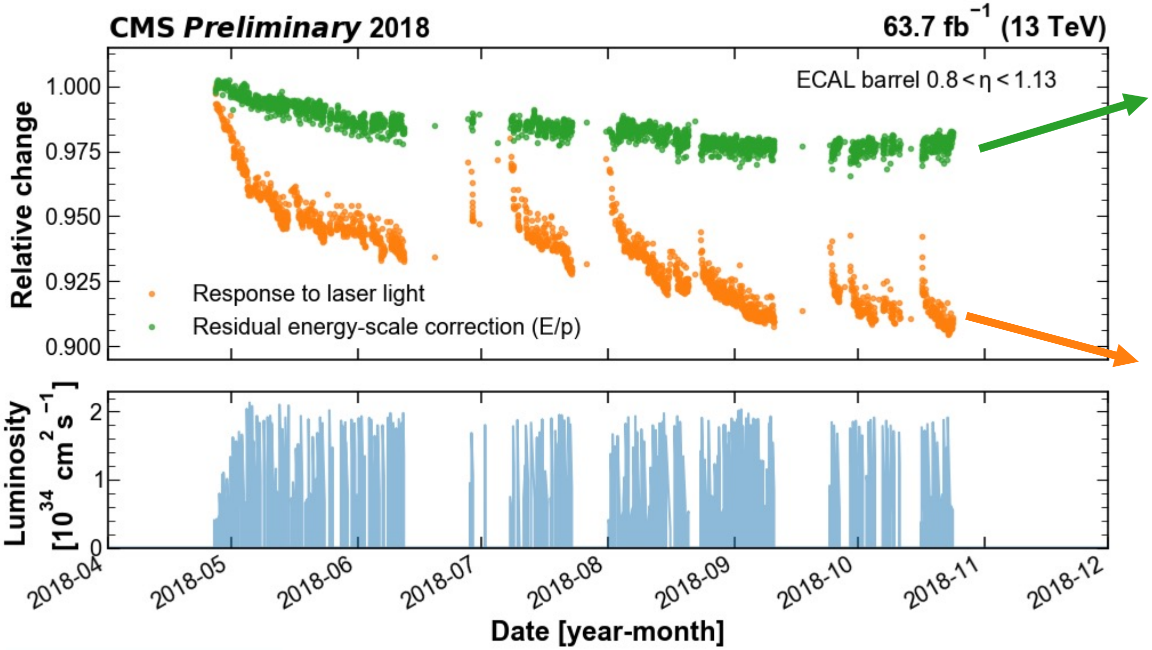


Regular updates (~once a week):

- pulse shape template
- time shift (due to transparency losses)

Radiation damage to LMS

Sizable radiation damage in laser transmission fibers and reference diodes observed in Run2.



Residual energy-scale corrections determined by the energy-to-momentum ratio (E/p) of electrons from W and Z decays after the application of the transparency corrections

Relative response to laser light measured by the LMS

Plot from 2018 – similar situation in Run3

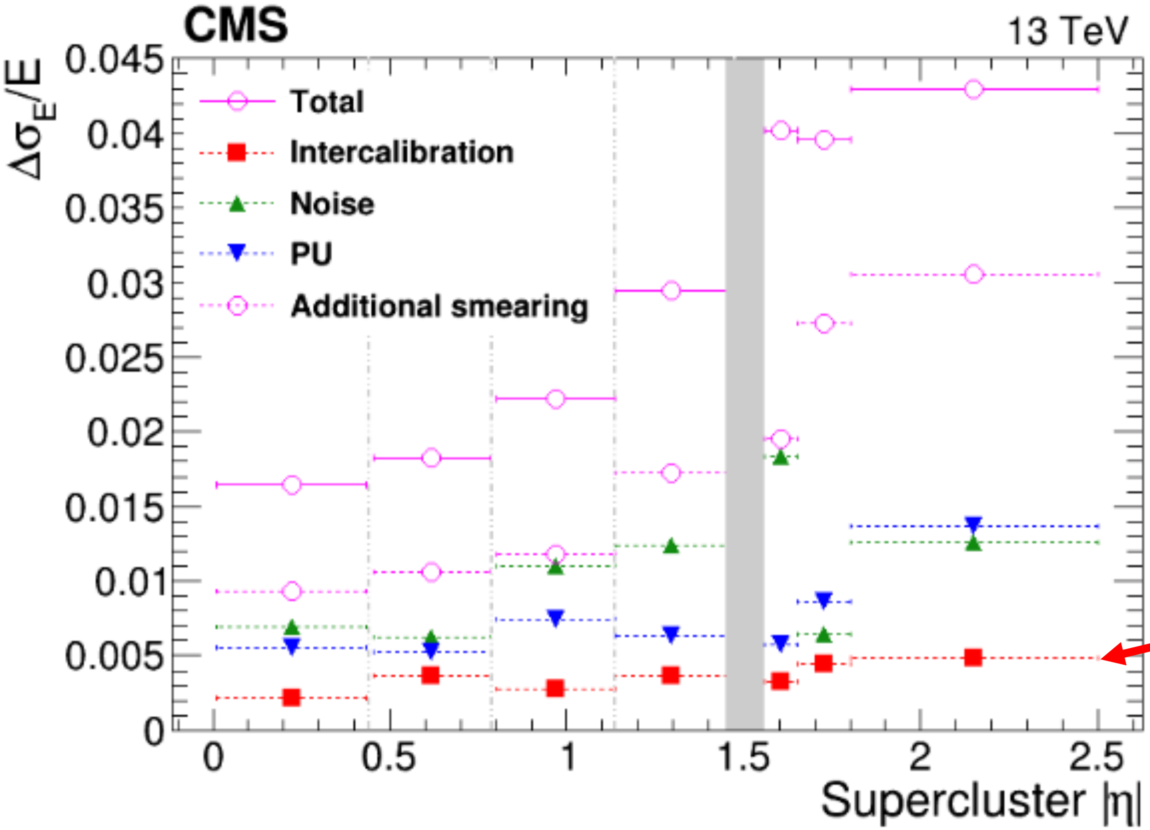
CMS-DP-2019-030

Residual corrections derived from E/p of electrons from W/Z decays at harness level every ~2 fb^{-1}

Given the layout of the light distribution system with the fibres behind the crystals for EE, and in front (closer to the interaction point) for the EB, the LMS for the **EE is exposed to less radiation and the drifts in the energy scale are not noticeable.**

Single channel intercalibration

Contributions of different effects (intercalibration accuracy, noise, PU) to the ECAL energy resolution (total resolution also reported)



Legacy Run2 plots

CMS-EGM-18-002

Impact on the energy resolution from IC precision < 0.5%