OPERATIONS AND PERFORMANCE OF THE CMS ELECTROMAGNETIC CALORIMETER IN RUN 2 AND BEYOND

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ON BEHALF OF THE CMS COLLABORATION

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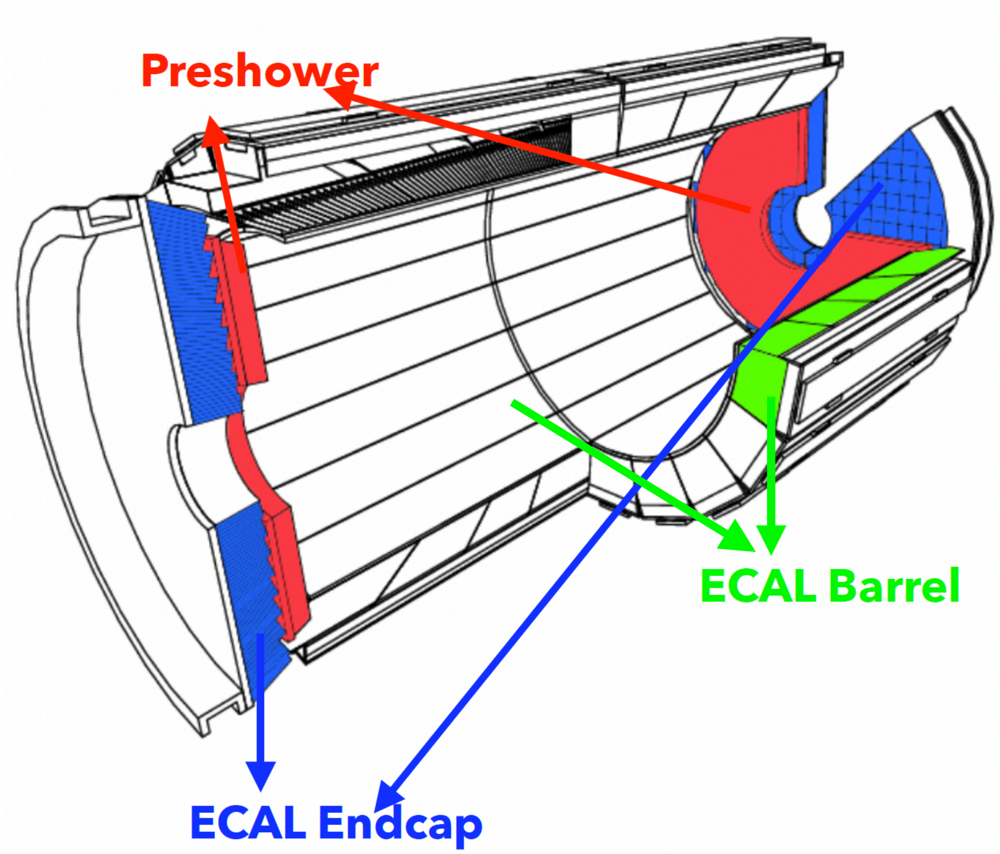
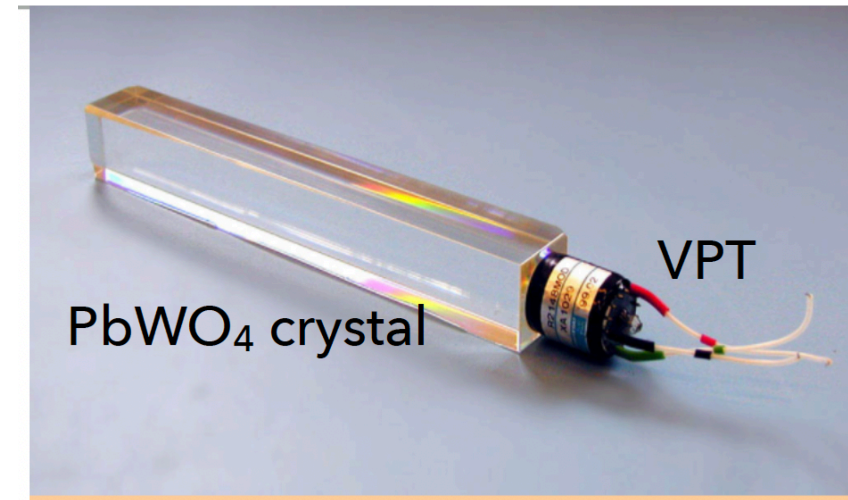
CMS Electromagnetic Calorimeter (ECAL)





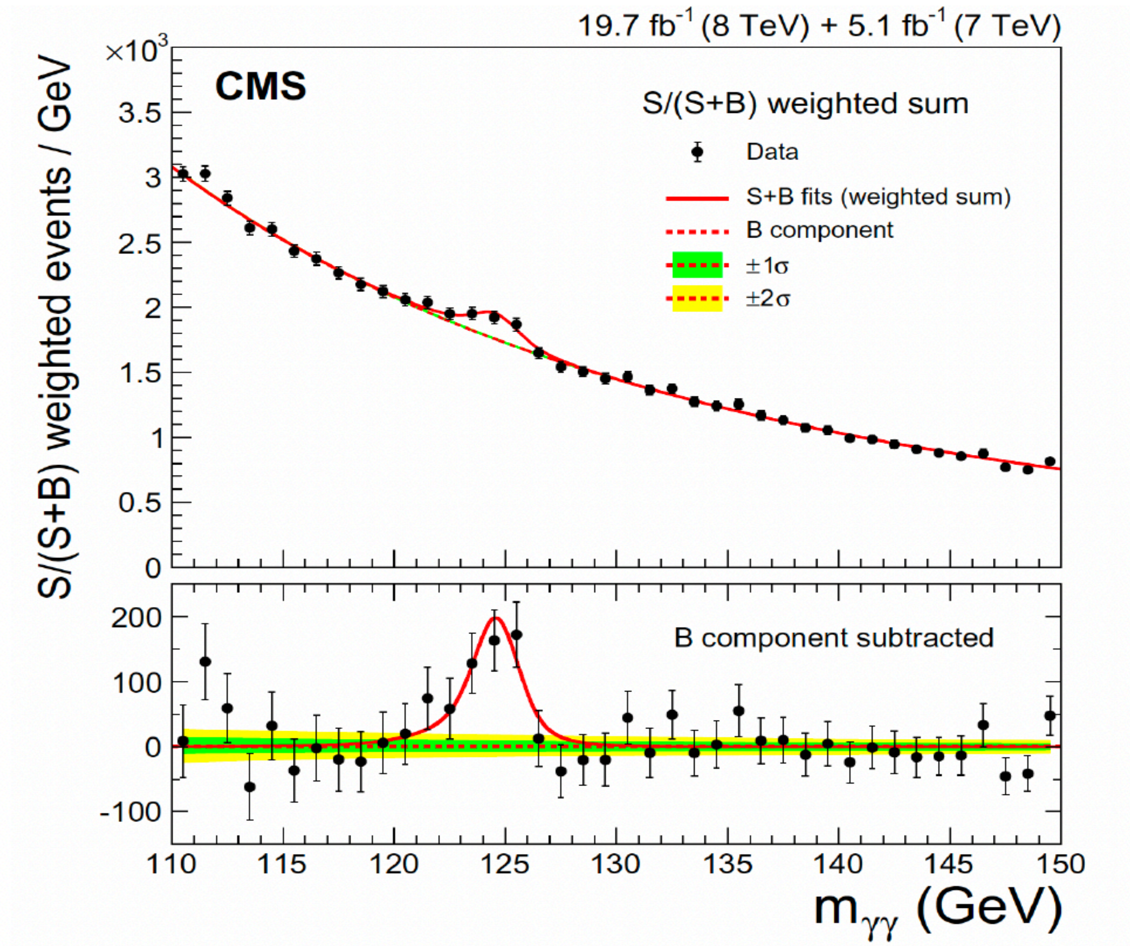
ECAL sits inside 3.8 T Magnetic field
This causes shower to spread in φ direction

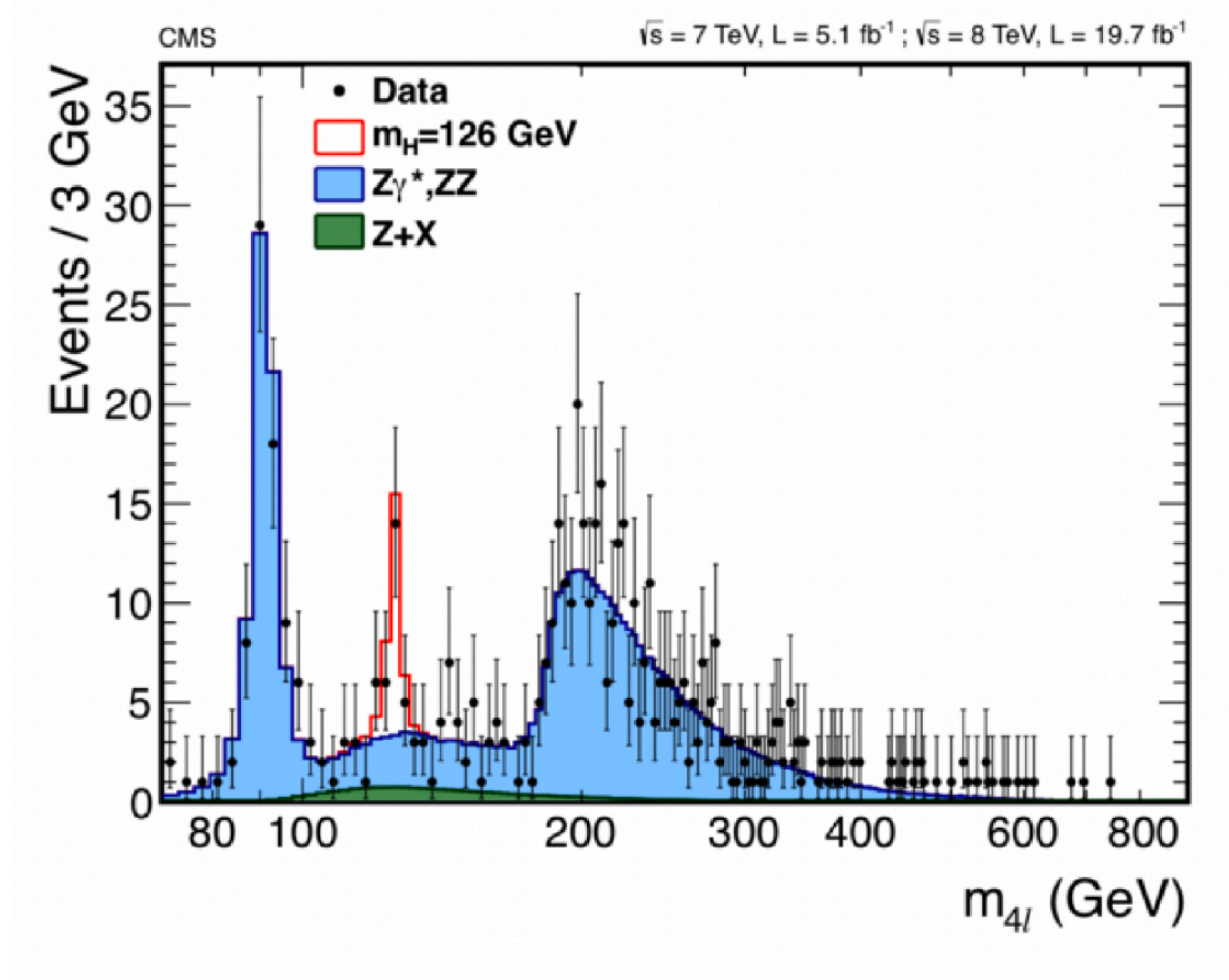
- **Excellent energy resolution:** for precision physics
- **High granularity:** relevant for position measurement and enabled merged photon searches
- **Compact:**
  - Small Molière radius = 2.19 cm
  - High density = 8.28 g/cm3
  - Short radiation length (X_0) = 0.89 cm
- **Excellent timing resolution** (~150 ps) for high energy showers - widened long-lived particle searches

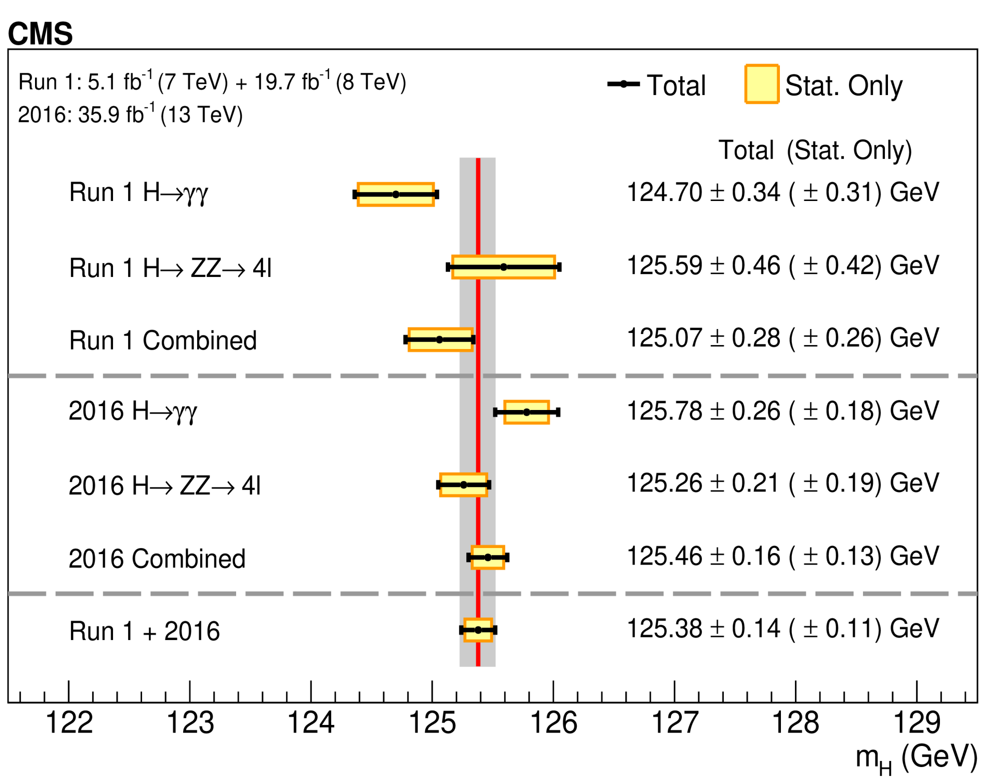
- Lead tungstate crystals ($PbWO_4$)
- Barrel ($|\eta| < 1.48$): 61200 crystals read by Avalance Photo-Diodes (APDs)
- Endcaps ($1.48 < |\eta| < 3$): 14648 crystals read by Vaccum Photo-Triodes (VPTs)
- Preshower ($1.65 < |\eta| < 2.6$): $3X_0$ of Pb/Si strips to discriminate between prompt photons and photons from π^0 decay

η is pseudorapidity

Importance of ECAL in searches, discoveries and precision measurements

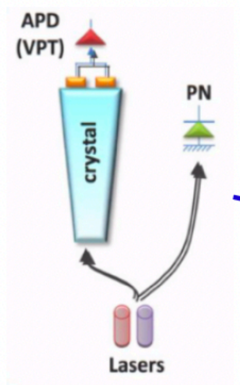


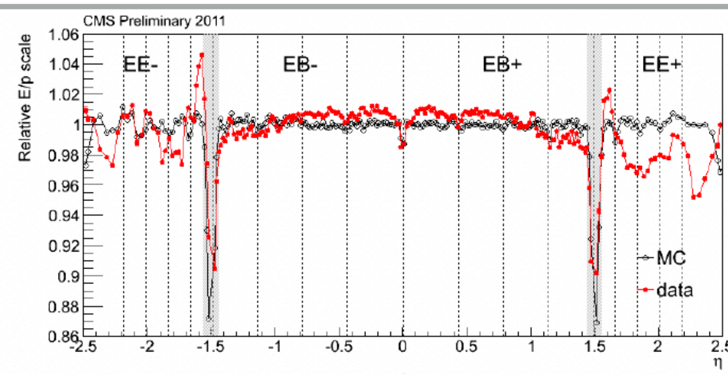


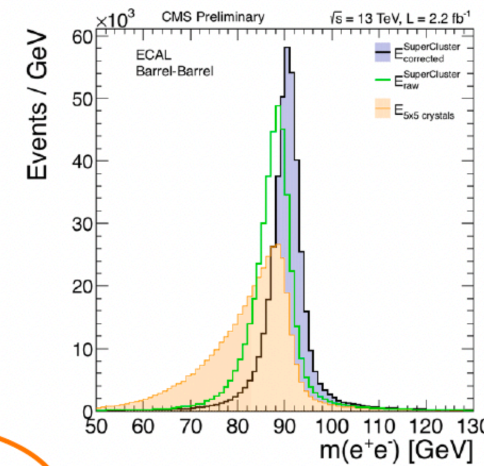


- Conception of ECAL was driven by H–>γγ search
  - Excellent energy resolution, and position resolution, led to the discovery of Higgs in H–>γγ and H–>ZZ channels
- And now after 11 years, we are in the precision physics era of Higgs physics using ECAL
- … and many other physics channels

Energy reconstruction in ECAL



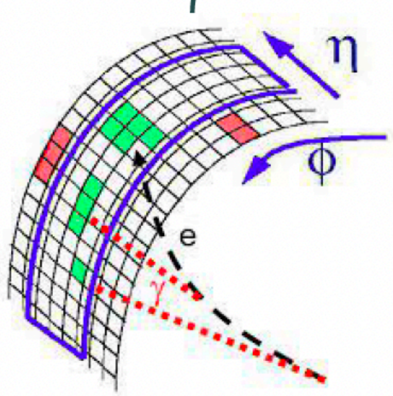


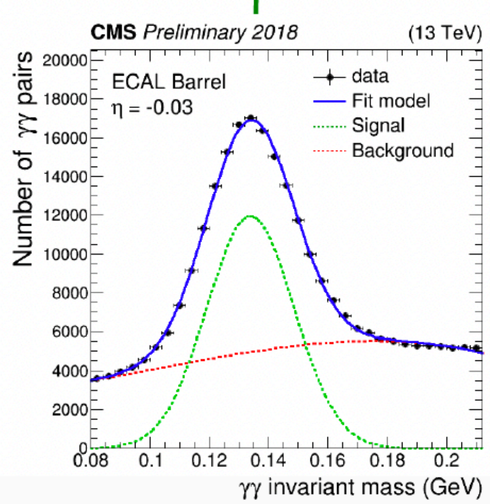


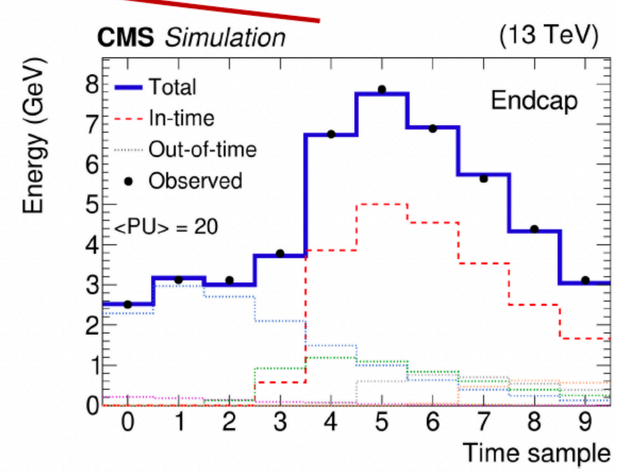
- Important to calibrate the ECAL detector well for precision physics and numerous searches

$$E_{e,\gamma} = \Sigma_i [L_i(t) \cdot C_i(t) \cdot A_i(t)] \cdot G(\eta) \cdot F_{e,\gamma}$$

Common to electron/photon and jet reconstruction

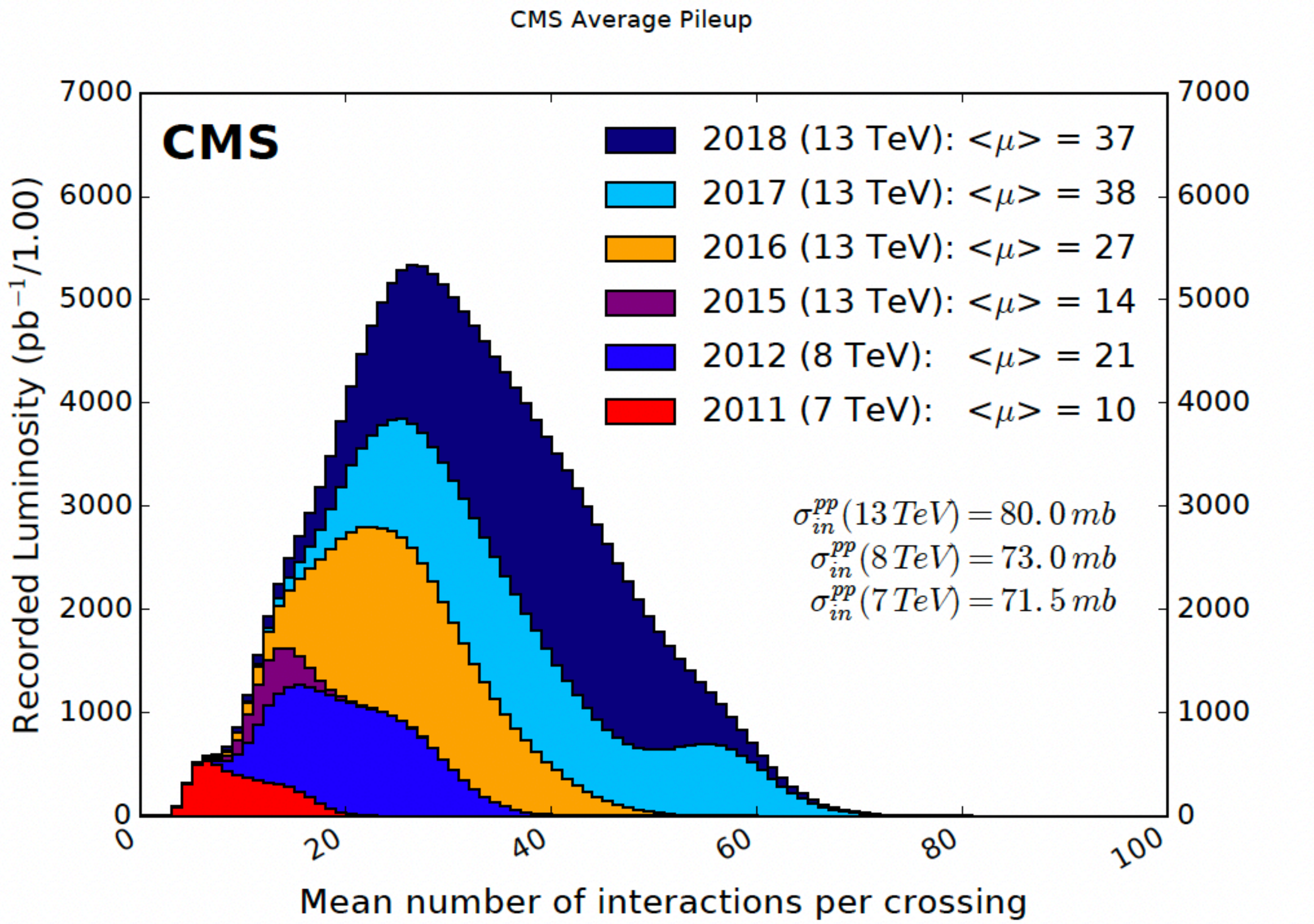




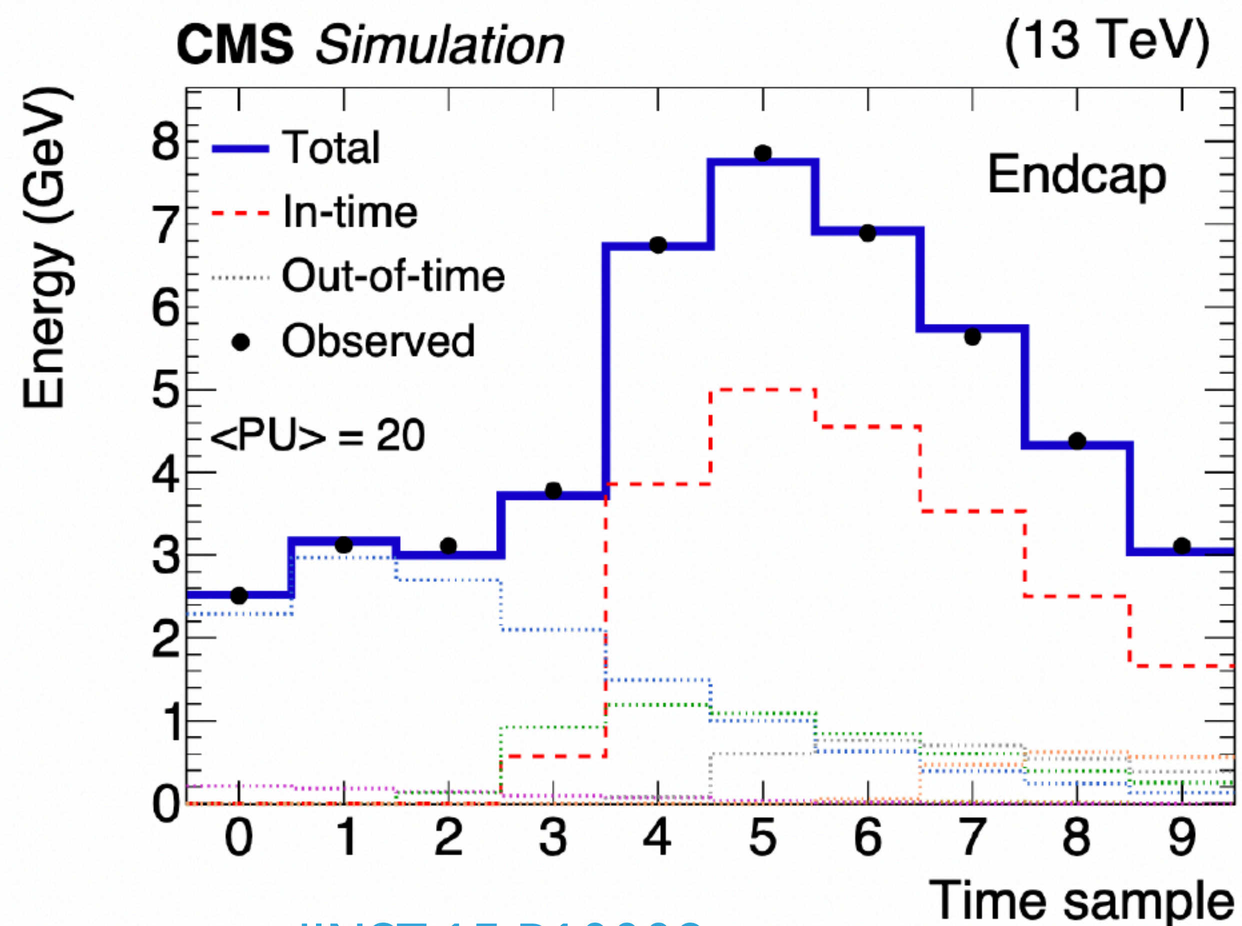


- e/γ energy is reconstructed in several crystals (more spread in φ)
  - ~97% energy is deposited in 3x3 array of crystals
- Dedicated clustering algorithms to collect the energy, thus forming **superclusters**
- ECAL calibration important for jet reconstruction as well ~30% of jet energy is deposited in ECAL

Challenges in ECAL energy measurement during Run 2: multi-fit method **($A_i(t)$)**



CMS Luminosity public results



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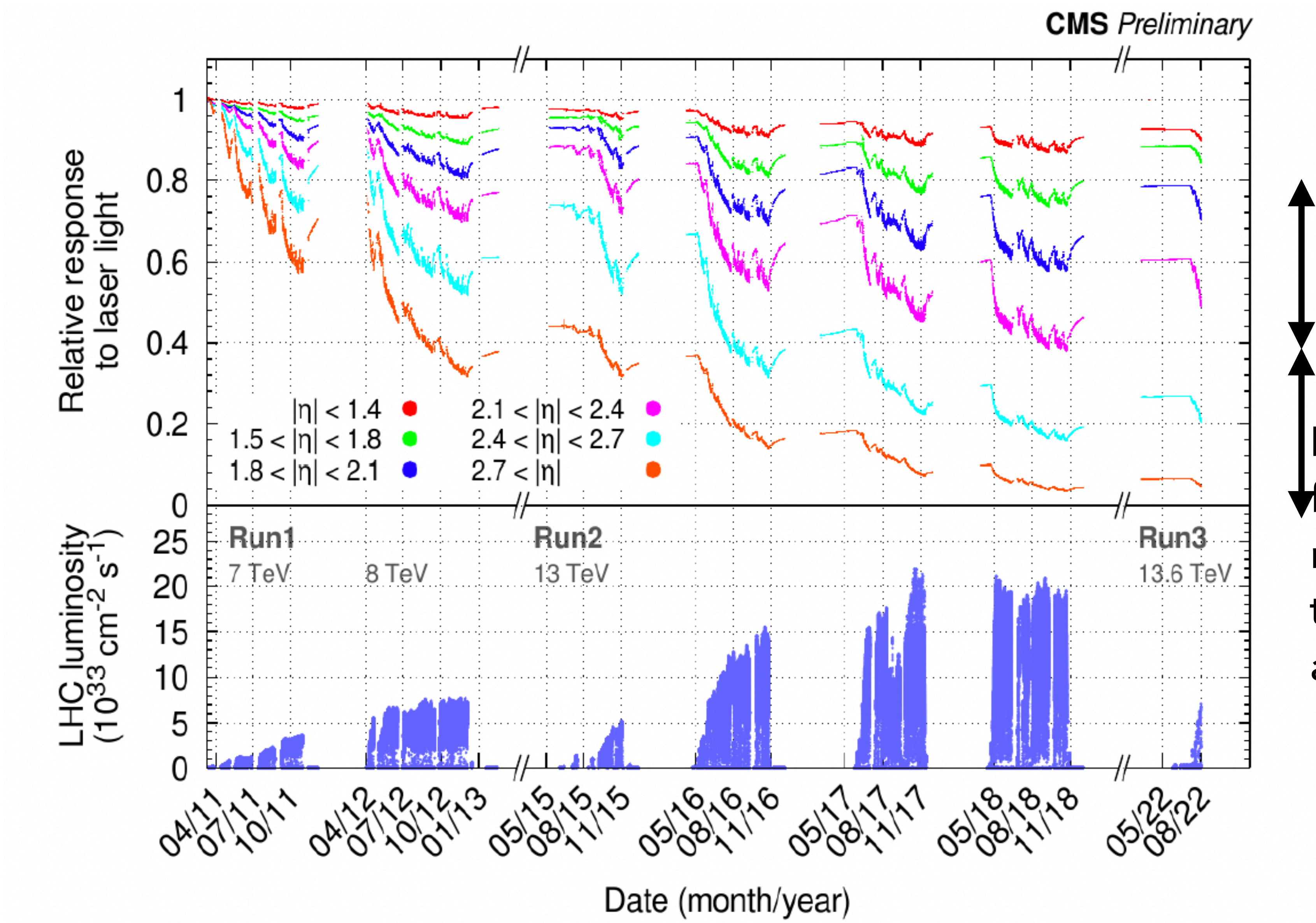
- Each pulse from APD/VPT is digitized in 10 samples
- Run 1: Amplitude was a weighted sum of all 10 samples
- **High pile-up during Run 2**
- Dedicated **multi-fit method to subtract the contributions from pile-up** in the ECAL pulse shape fit for energy

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

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

Challenges in ECAL energy measurement during Run 2: laser corrections ($L_i(t)$)



CMS DP-2022/042

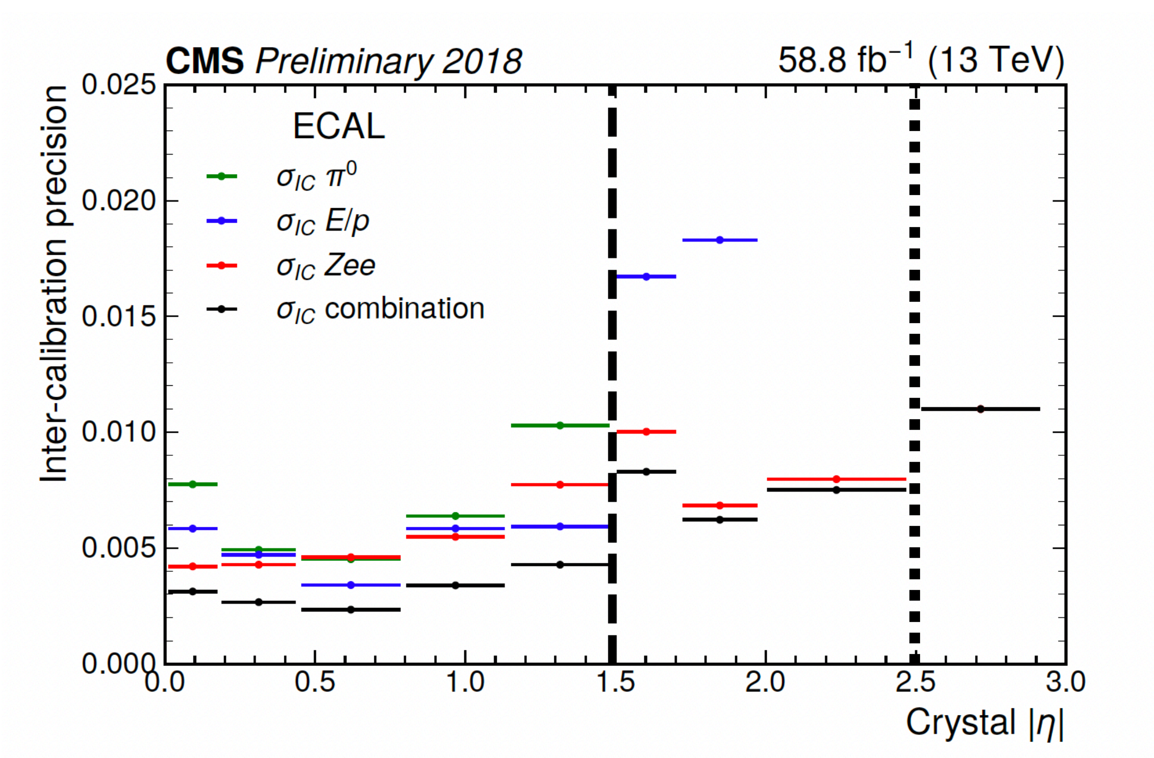
Endcap region covered by CMS tracker (62%)

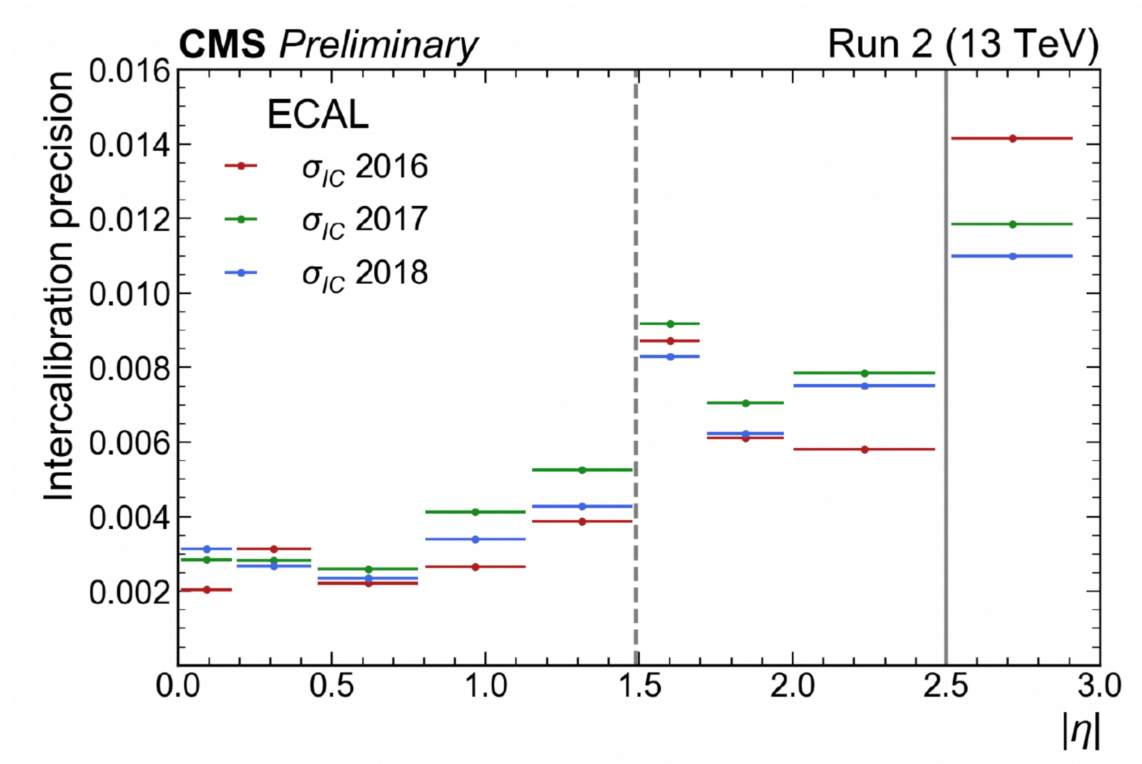
Endcap region relevant for forward jets. Low response (loss ~96%) due to ageing induces amplification of noise

- Detector ageing: **Significant reduction in crystal transparency** and increased APD noise
- **Dedicated laser system** to monitor each channel every 40 minutes
- Crucial to **maintain stable ECAL energy scale and resolution** over time

Single Channel Inter-calibration (**$C_i(t)$**)

- Equalize response of different crystals at the same η combining different methods
  - Z–>e+e- , W–>eν and π⁰–>γγ (effectively reducing the peak width)
- Energy scale VS η corrected in data to match simulation using Z–>e+e- mass peak (essentially adjusting the peak position)





CMS-DP2019-038

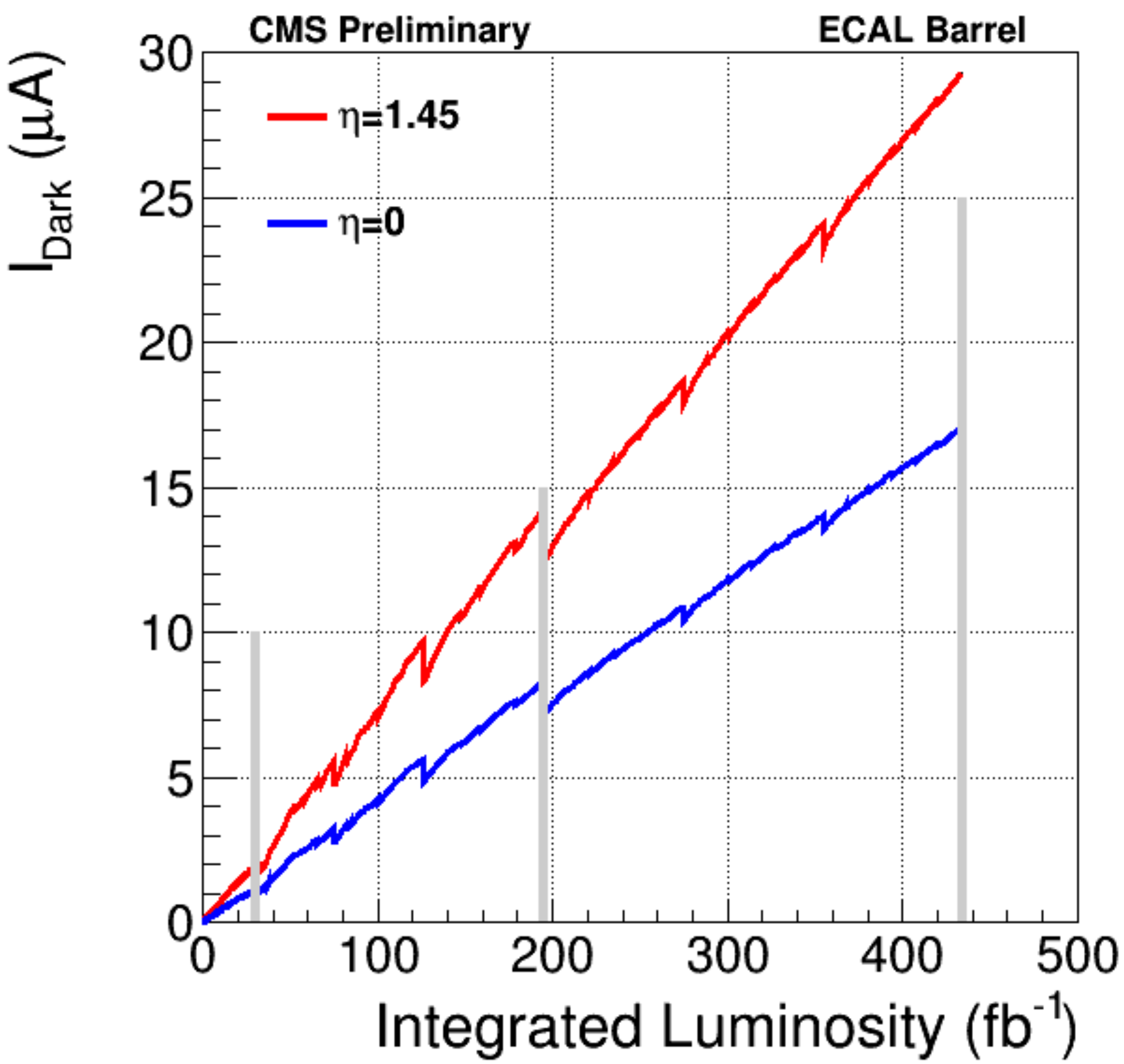
CMS-DP2020-021

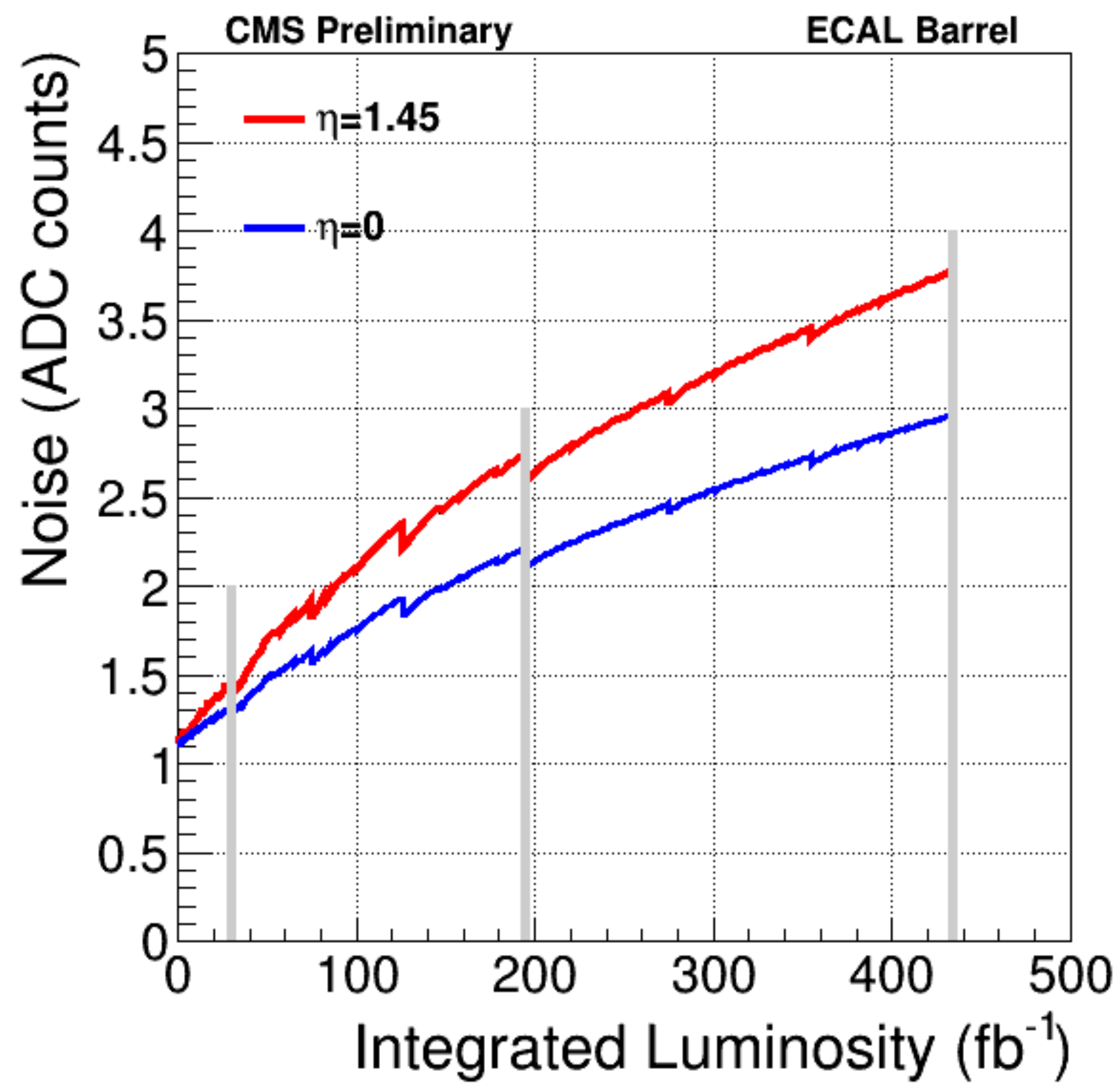
High precision achieved in all the regions

Barrel ($|\eta| < 1.5$):$< 0.5\%$

Endcaps ($|\eta| < 2.5$) $< 1\%$

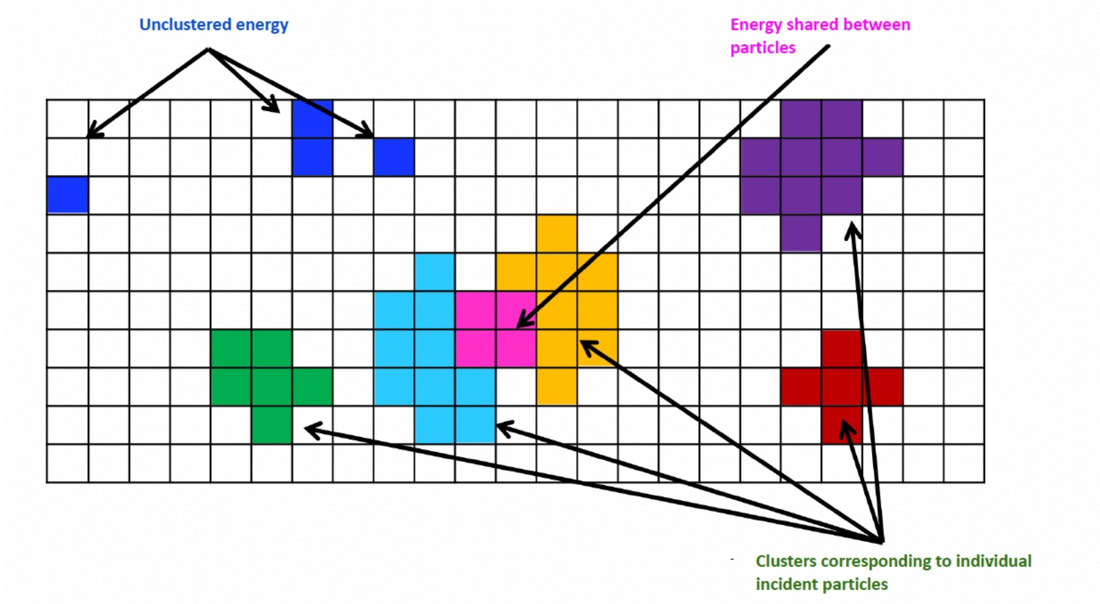
Evolving noise

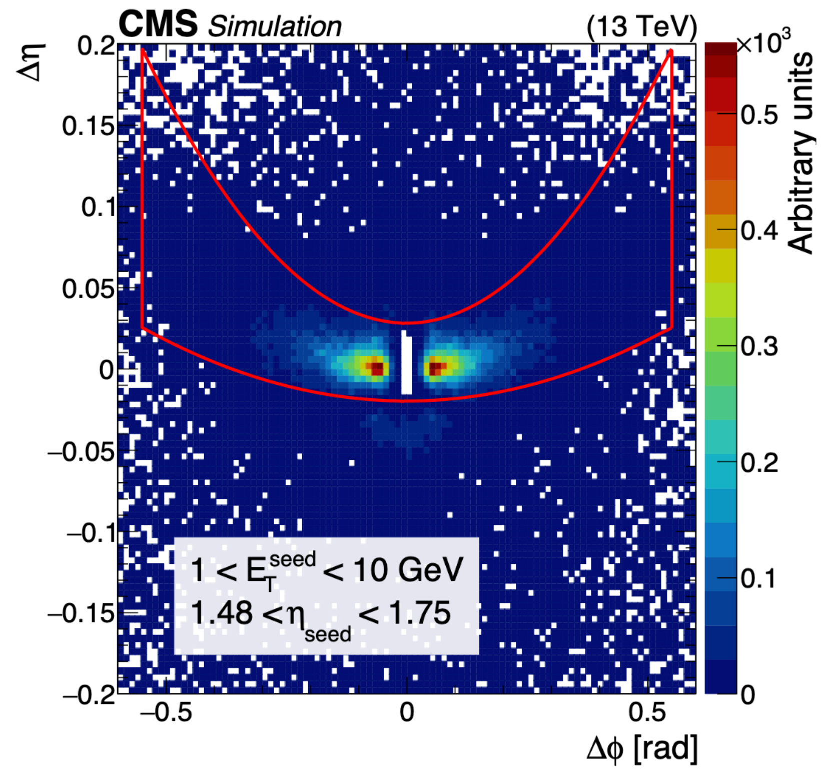




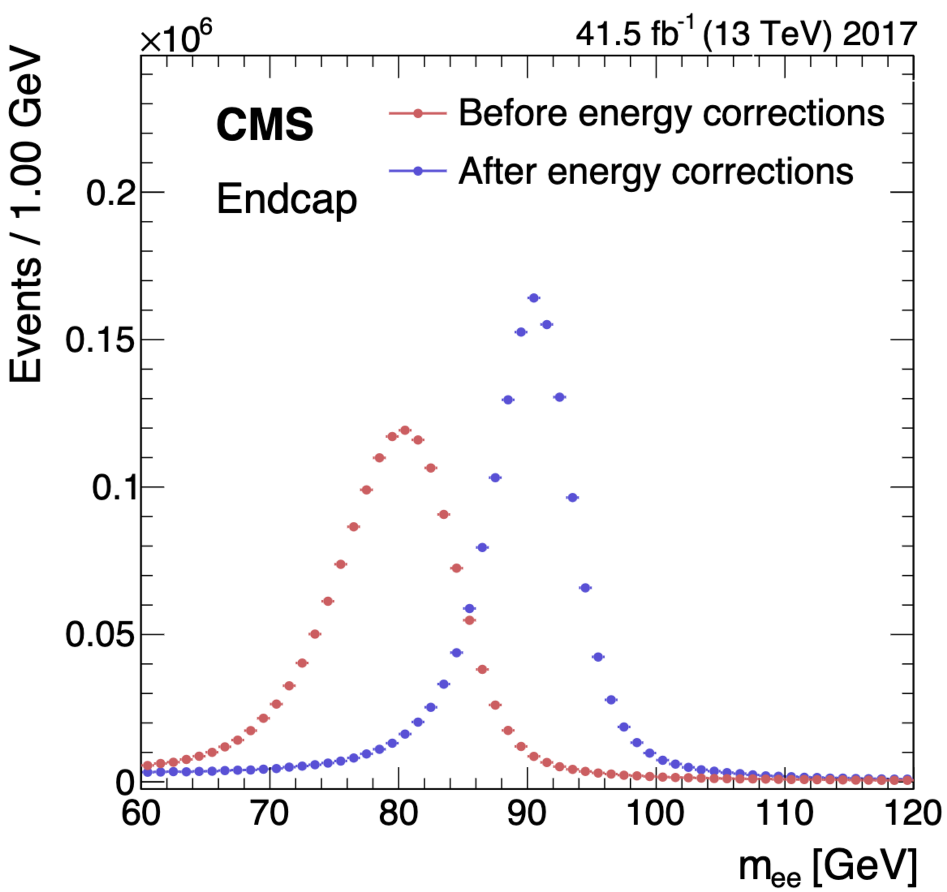
- Predictions for the APD leakage current due to hadron damage for an operational temperature of 18 degrees.
- As a result of **increased leakage current of APD, detector noise increases**
- **Dedicated energy thresholds are applied for clustering** the hits to mitigate pile-up and noise

Clustering and Energy corrections of the clusters for physics objects ($\mathbf{F_{e,\gamma}}$)



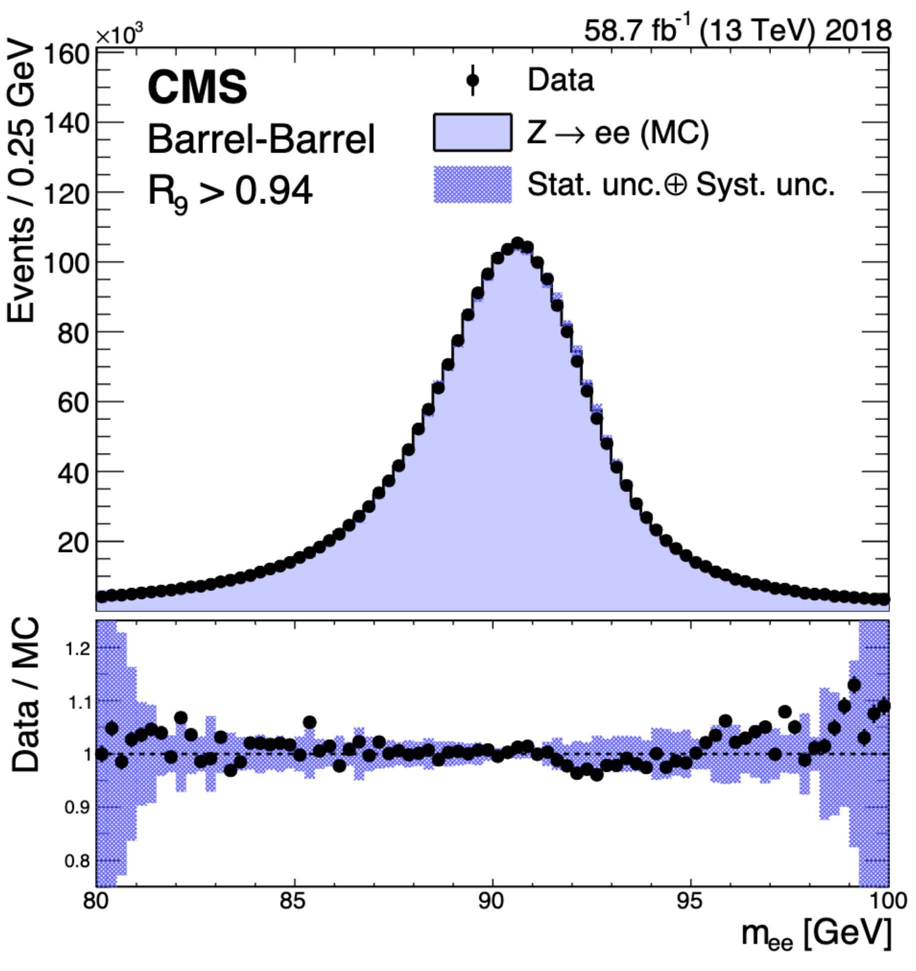


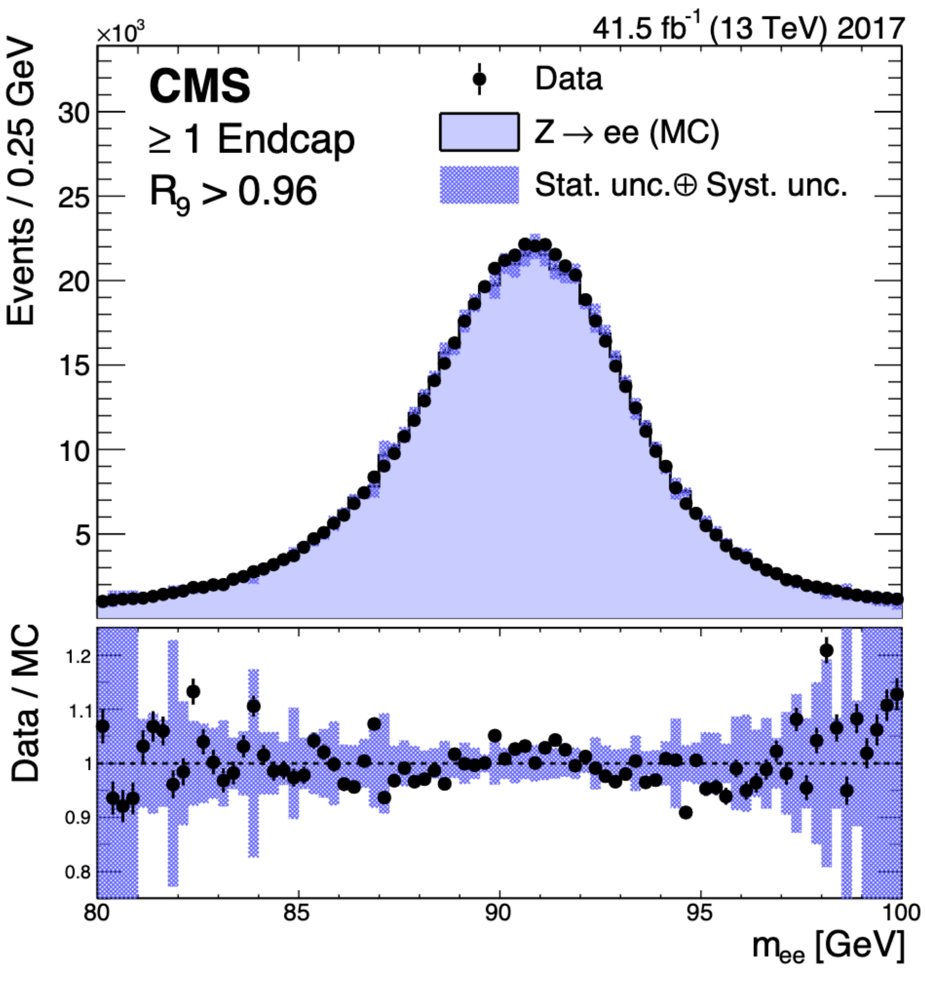
Due to the magnetic field, shower spreads in φ



- Dedicated 'mustache super-clustering' method to cluster hits and form physics objects (more on this in slide later)
- Clustering is still affected by leakage, PU and other effects
- Dedicated multivariate corrections applied to reconstruct the original deposited energy of the particle
  - Provides substantial improvements by accounting for event-by-event fluctuations in the shower

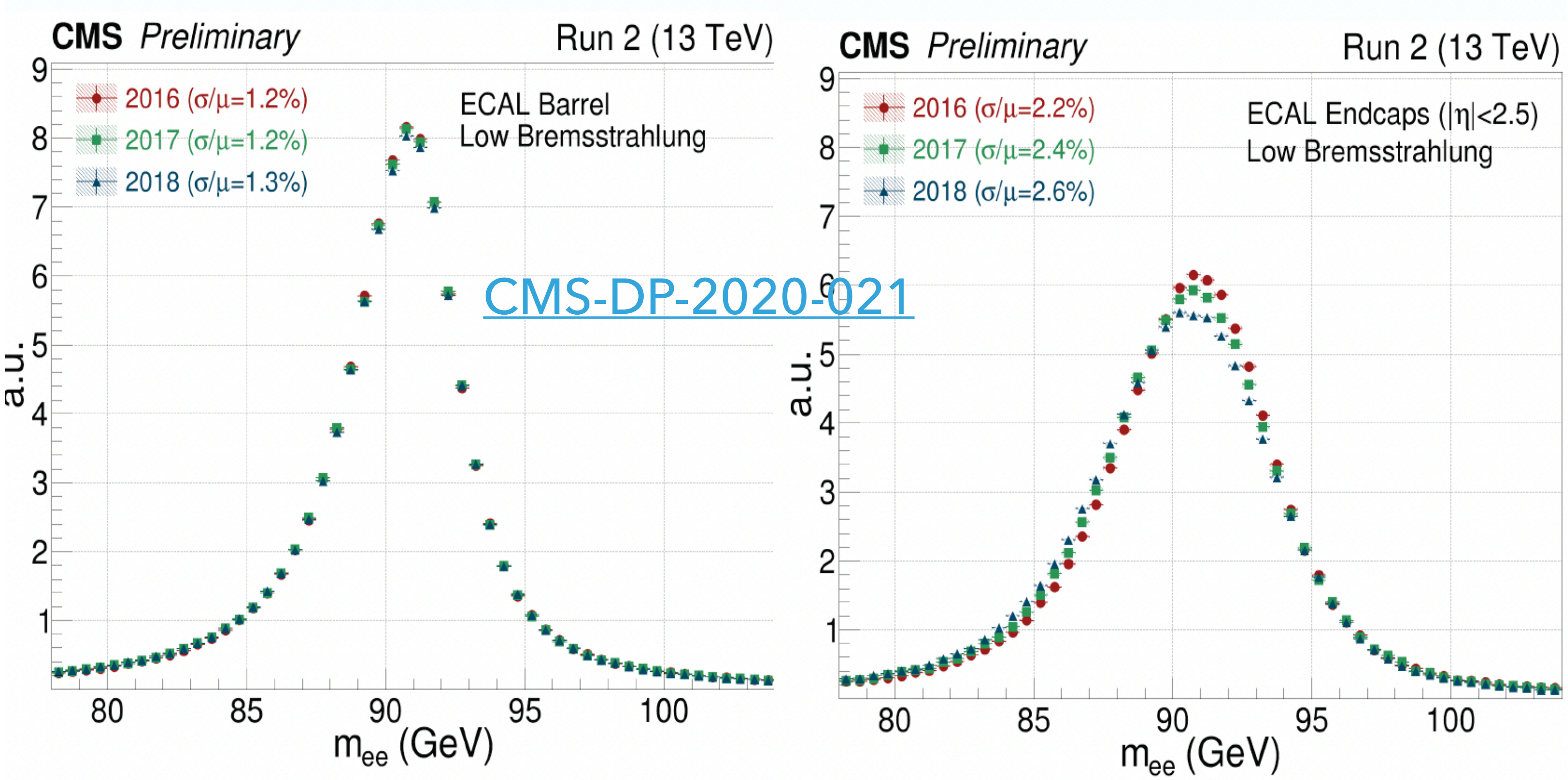
Absolute energy scale (G)





- There are time dependent drifts after all the corrections are applied
  - Divided in time bins, P_T, η and $R_9(=E_1/E_{3x3})$
  - Corrected using Z–>ee electrons in data
- Uncertainty on energy scale is 0.05-0.1% in the EB and 0.1-0.3% in the EE

Energy performance during run 2



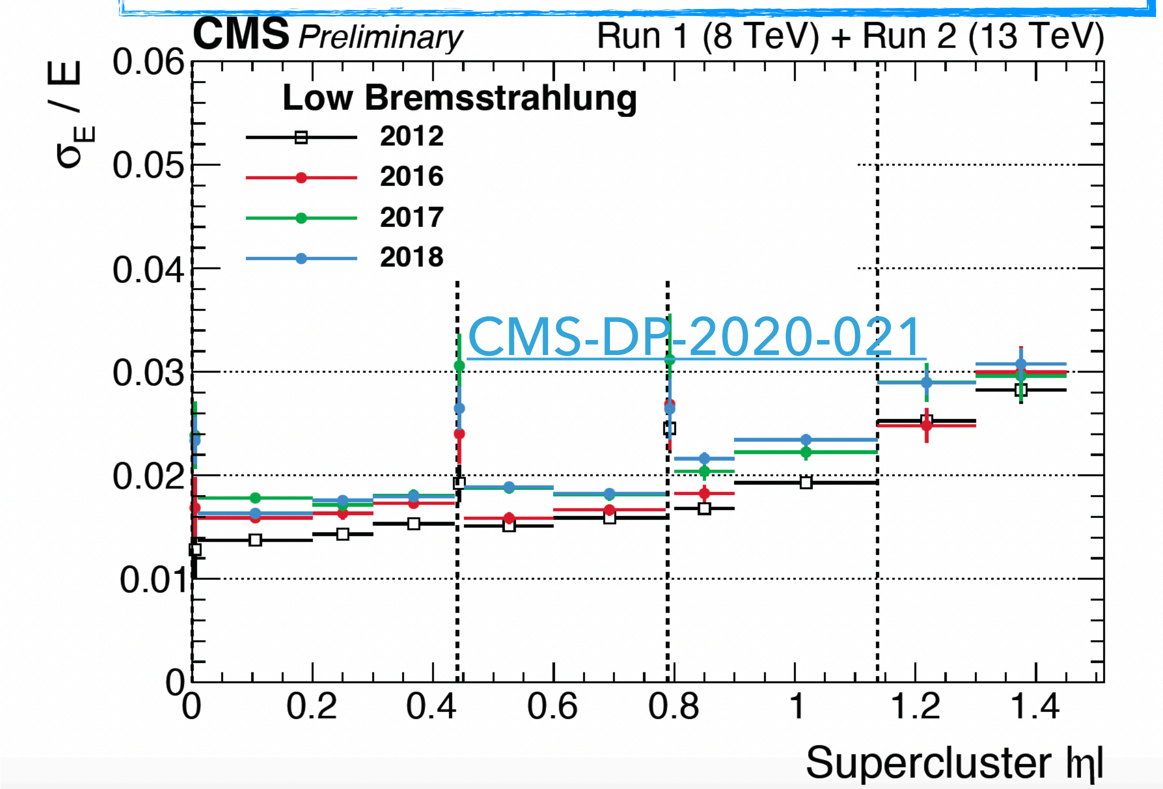
CMS-DP-2020-021

CMS-DP2018-015

Di-electron invariant mass distributions using Z–>ee low-bremsstrahlung electrons

Retained performance throughout Run 2

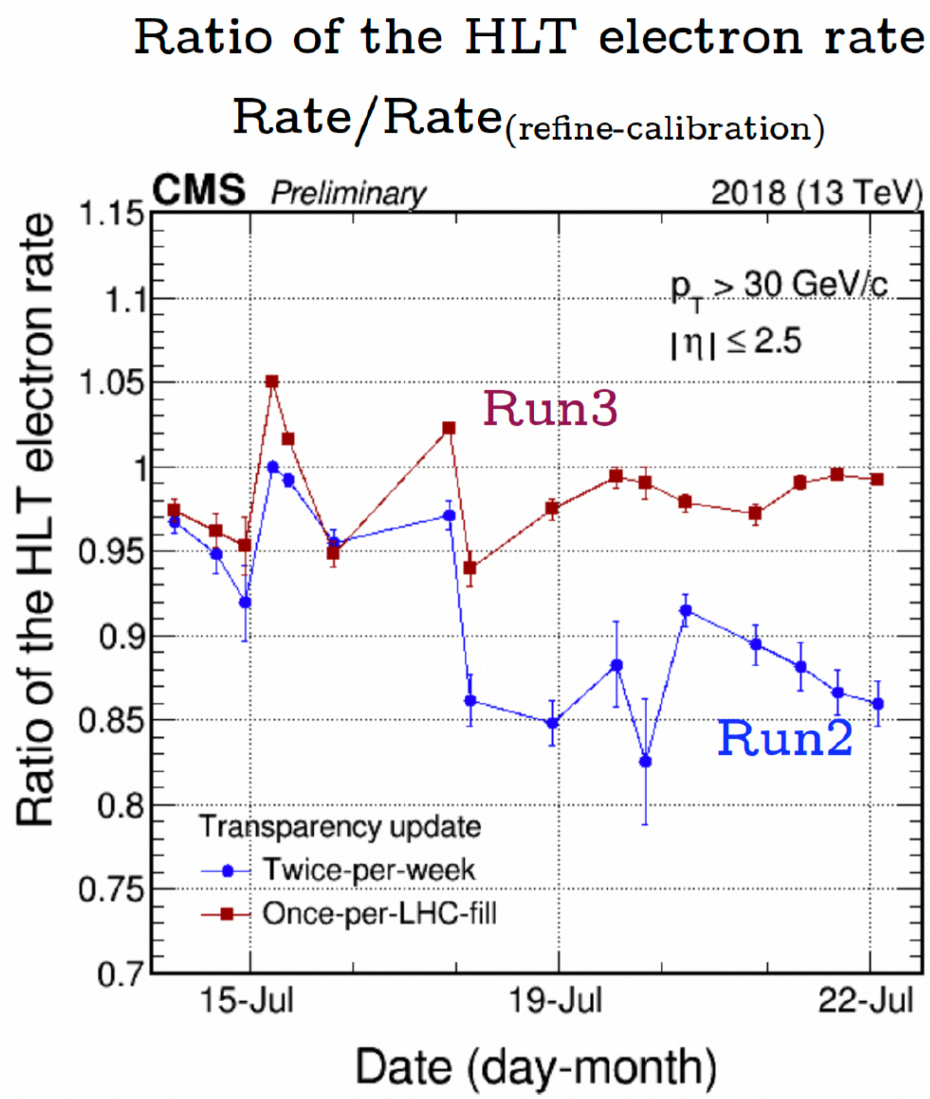
Energy resolution using Z–>ee electrons



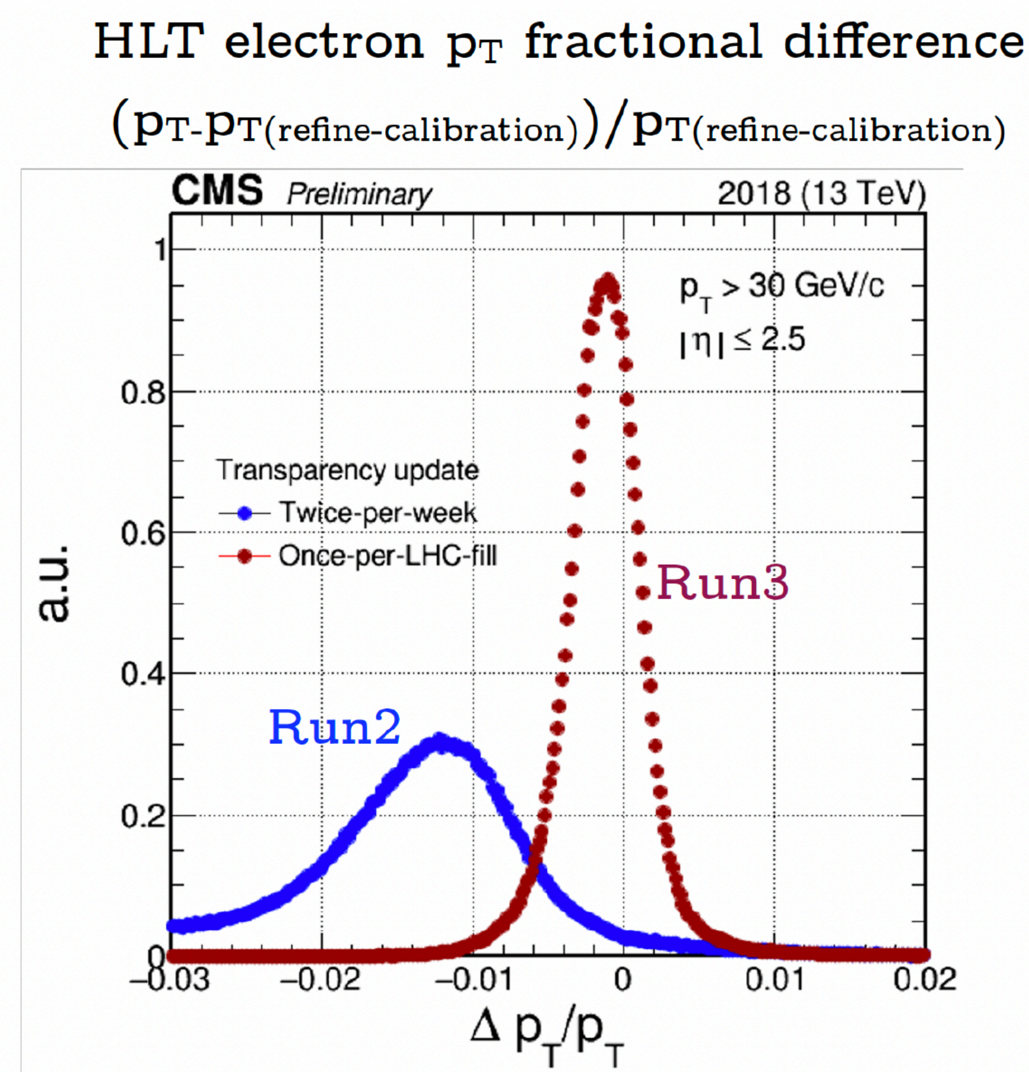
CMS-DP-2020-021

- Refined calibration done at the end of Run 2
- Similar performance achieved as in Run 1 inspite of harsher environment in terms of radiation level (and hence detector ageing) and pile-up

Run 3: Online calibration



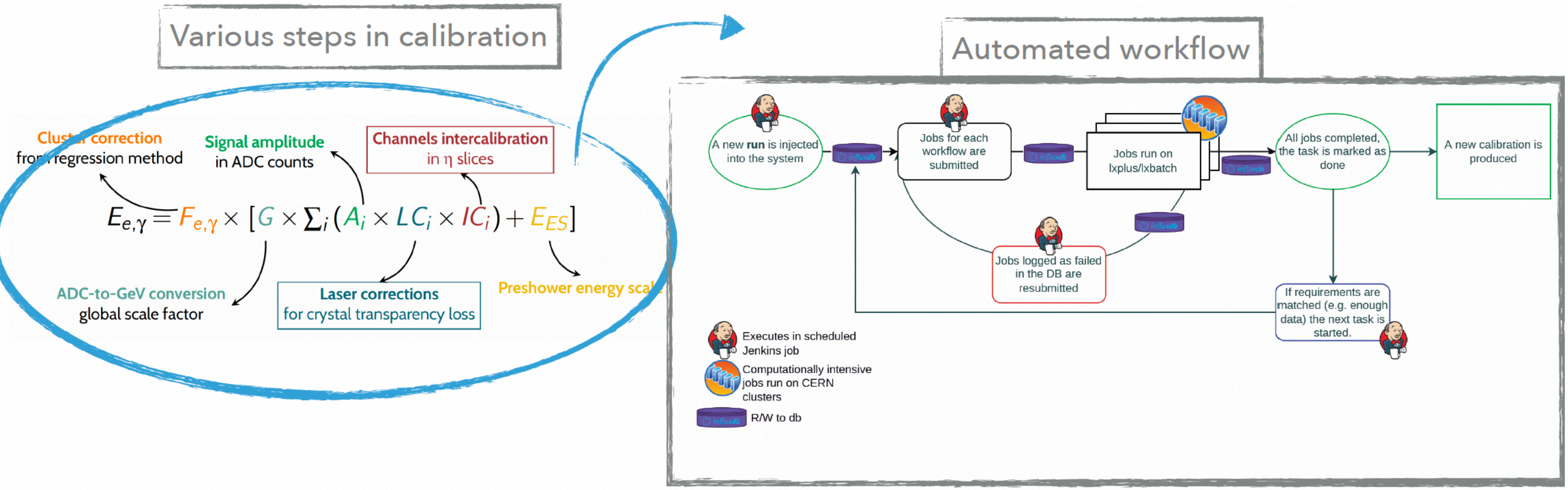
CMS-DP2022-042



- For Run 3, at L1/HLT **frequency of laser updates has been increased** from twice-per-week (Run 2) to once per-fill** (Run 3) (frequency of offline update is 40 minutes - used in refined calibration)
  - Checked on Run 2 data with **Run 2** and **Run 3** conditions applied and compared with the refined calibration
  - Faster processing of laser data enabled frequent updates
- **Improved HLT electron rates and resolution**

** In 2022, a fill is 10 hrs long on an average

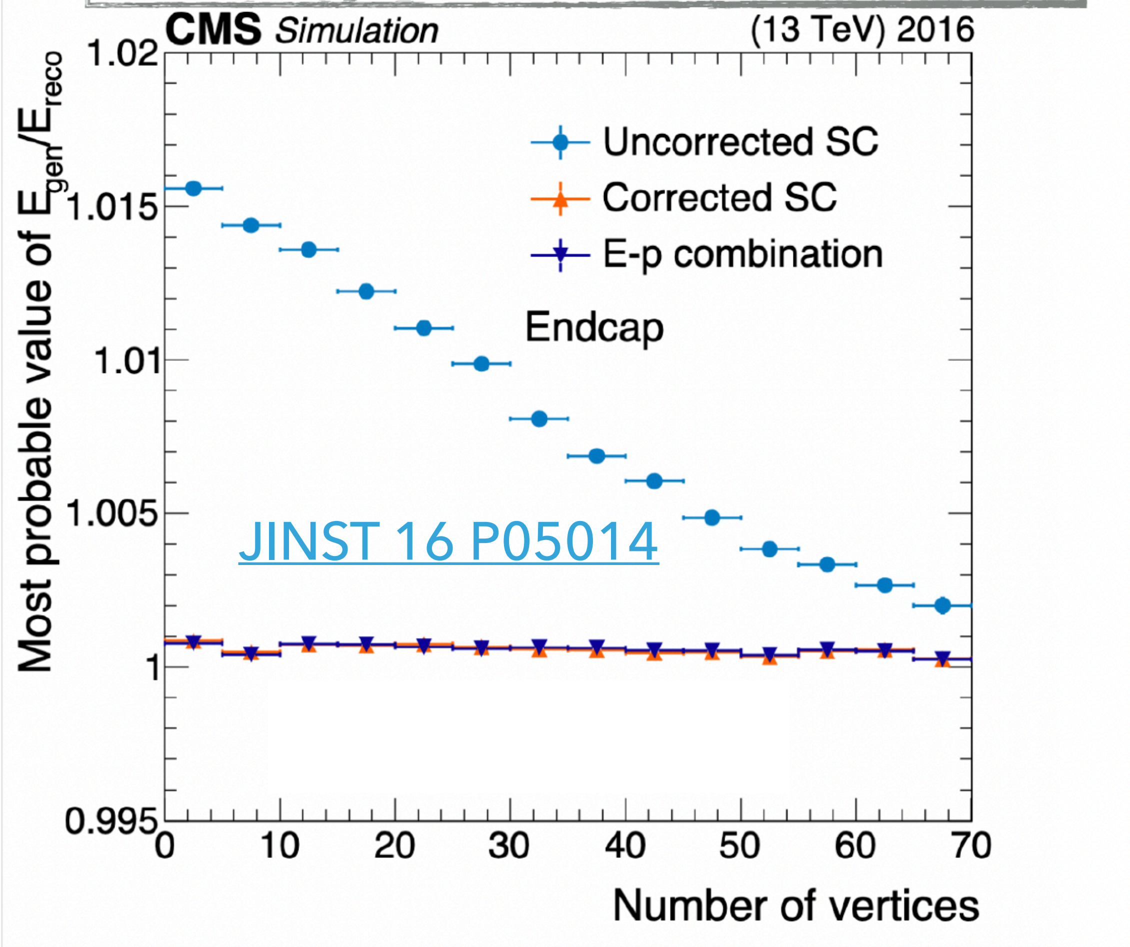
Run 3: Offline calibration - Quick delivery via automation



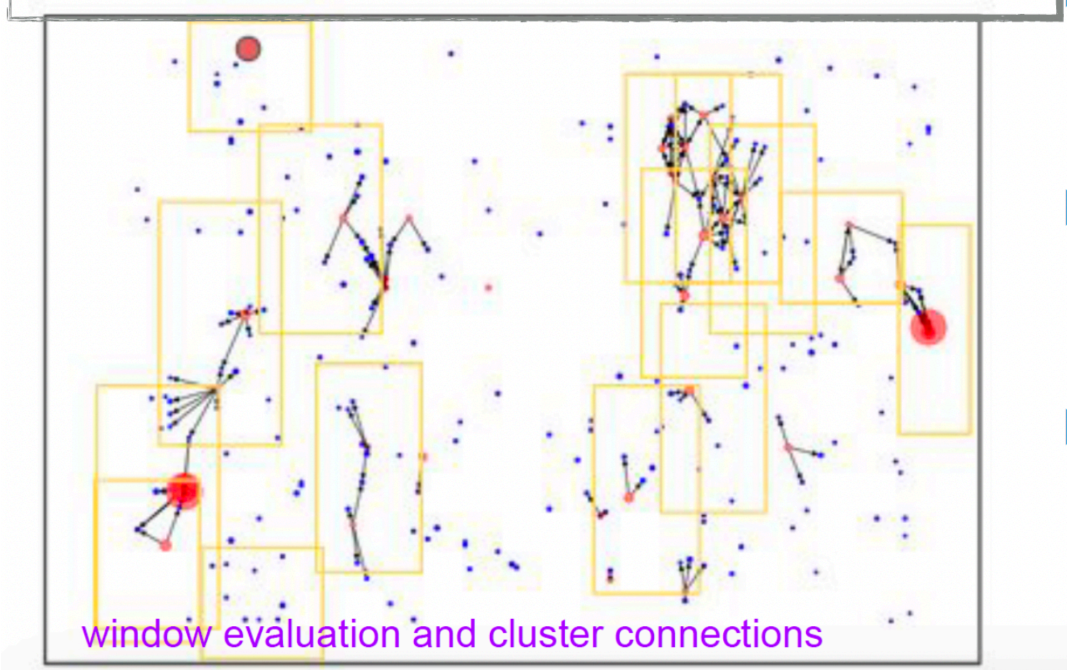
- **Constant monitoring and fine time granularity** is needed for calibration to mitigate radiation damage effects and **achieve improvement at the level of Legacy calibration at the end of Run 2**
  - Tracking the response evolution over time is the main challenge
- Automated calibration framework developed during Run 3 using a framework of finite state machine through Jenkins and influxdb + Grafana for monitoring
  - **Get the calibration from data as soon as it is available**
- Timing calibration (ECAL timing shifts due to irradiation), pulse shape updates, various steps in energy calibrations, alignment …

Run 3: ECAL super-clustering using GNN

Performance in Run 2 after regression

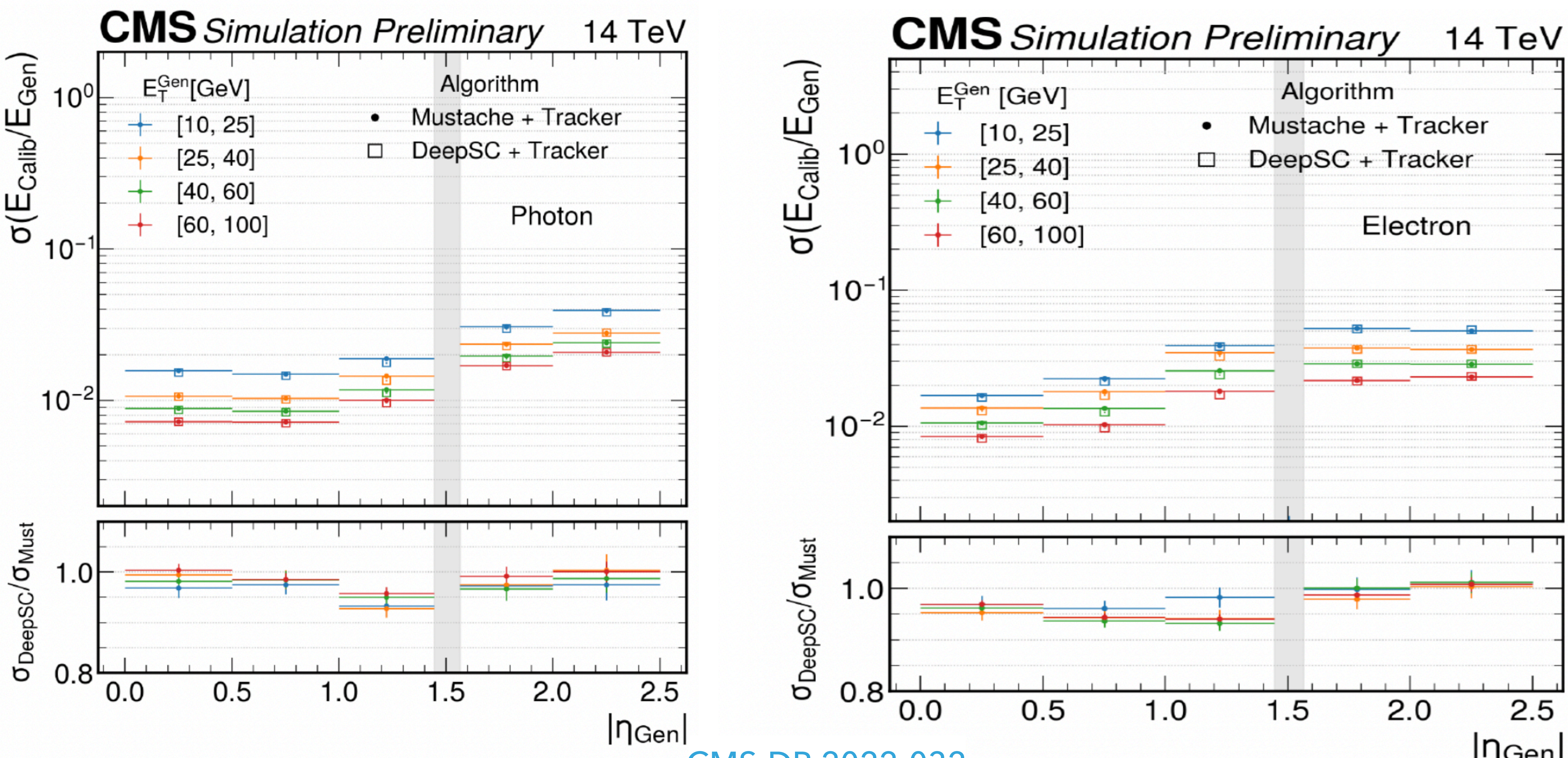


Approach for Run 3: Graph Neural Network



- **Run 2 (a.k.a Mustache super-clustering): Purely geometrical** approach of hit collection within a certain window motivated by the spread of shower along φ
  - High efficiency - gathers even low energy clusters
  - Downside: suffers from pileup (PU) and noise contamination
  - Dedicated regression is applied to correct for these effects on an average
- New development ongoing for **Run 3** based on **Graph Neural Network**
- **Input features include information from clusters and its crystals (rechits)**
- **Multiple outputs:** Cluster classification (whether in/out of SC) object identification (electron/photon/jet), and energy regression

Run 3 future: ECAL super-clustering using GNN



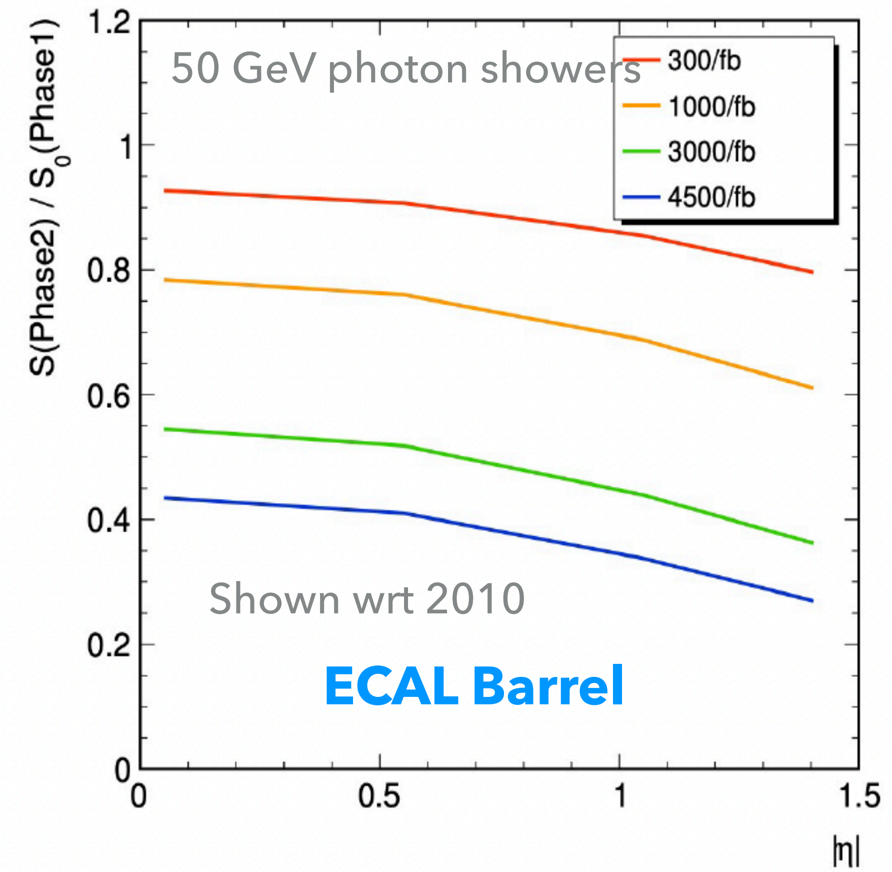
CMS-DP-2022-032

- Response estimated by fitting the calibrated electron/photon energy divided by the true energy with a Cruijff function
- **Resolution better** in most of the cases compared to the **current algorithm developed during Run 2**

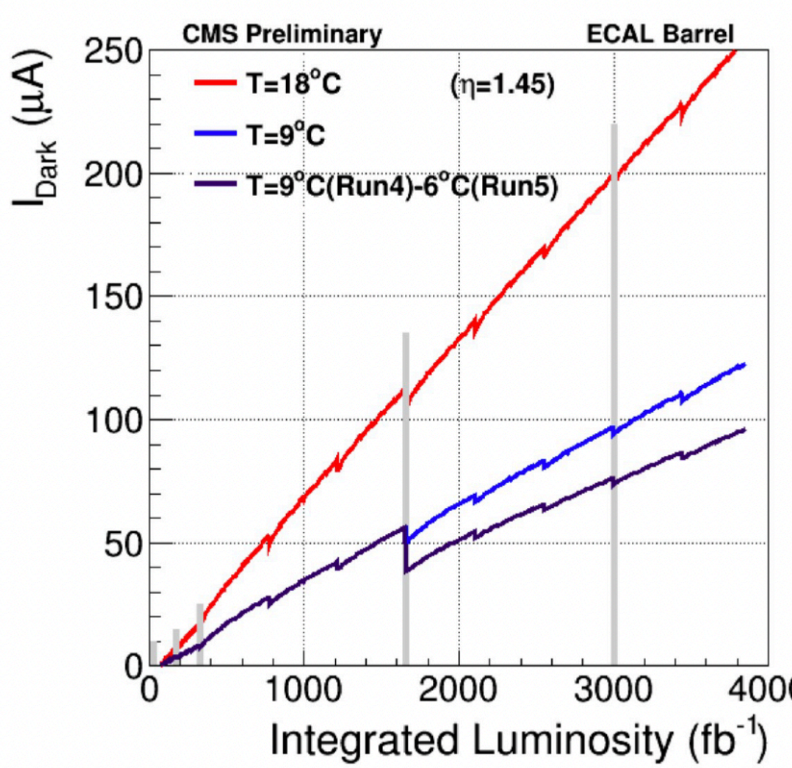
Upgrade for HL-LHC (Phase II)

- HL-LHC is expected to deliver a total integrated luminosity of 4500 fb^{-1} with a peak luminosity of 7.5 x 10^{34} $cm^{-2}s^{-1}$ and for 200 pile-up interactions
- ECAL Barrel (|η|<1.48) will retain significant light output and will be retained for HL-LHC operation
- ECAL Endcap (|η|>1.48) will suffer significant radiation damage after ~500 fb^{-1}
    - Replaced by High Granularity Calorimeter - not covered in this talk

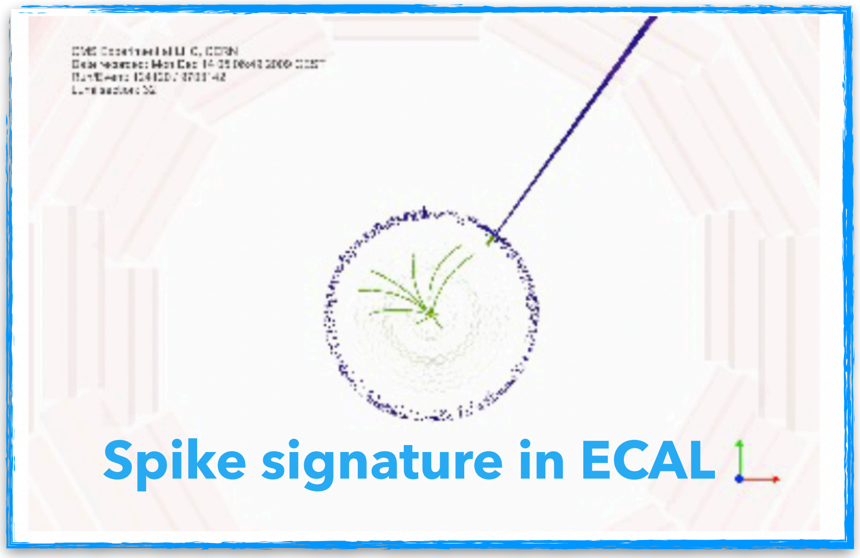
Prediction of transparency

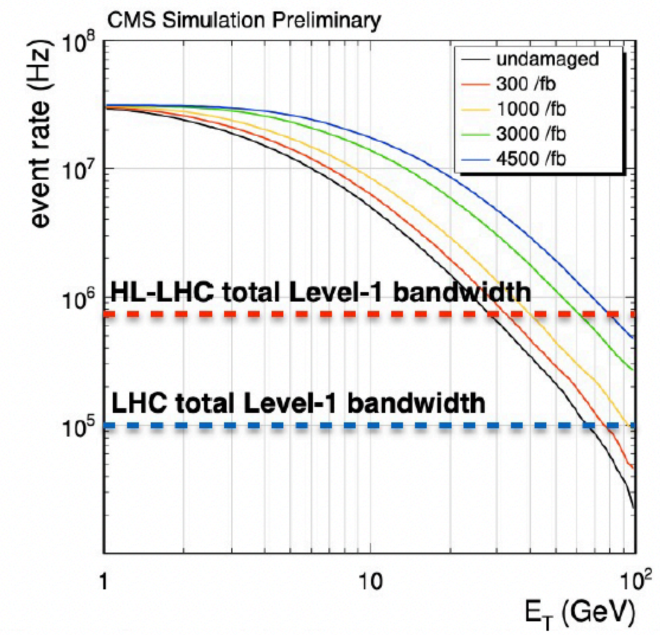


High APD leakage current –> high noise



High spike rate: > 1 MHz for E_T > 20 GeV - unmanageable at L1

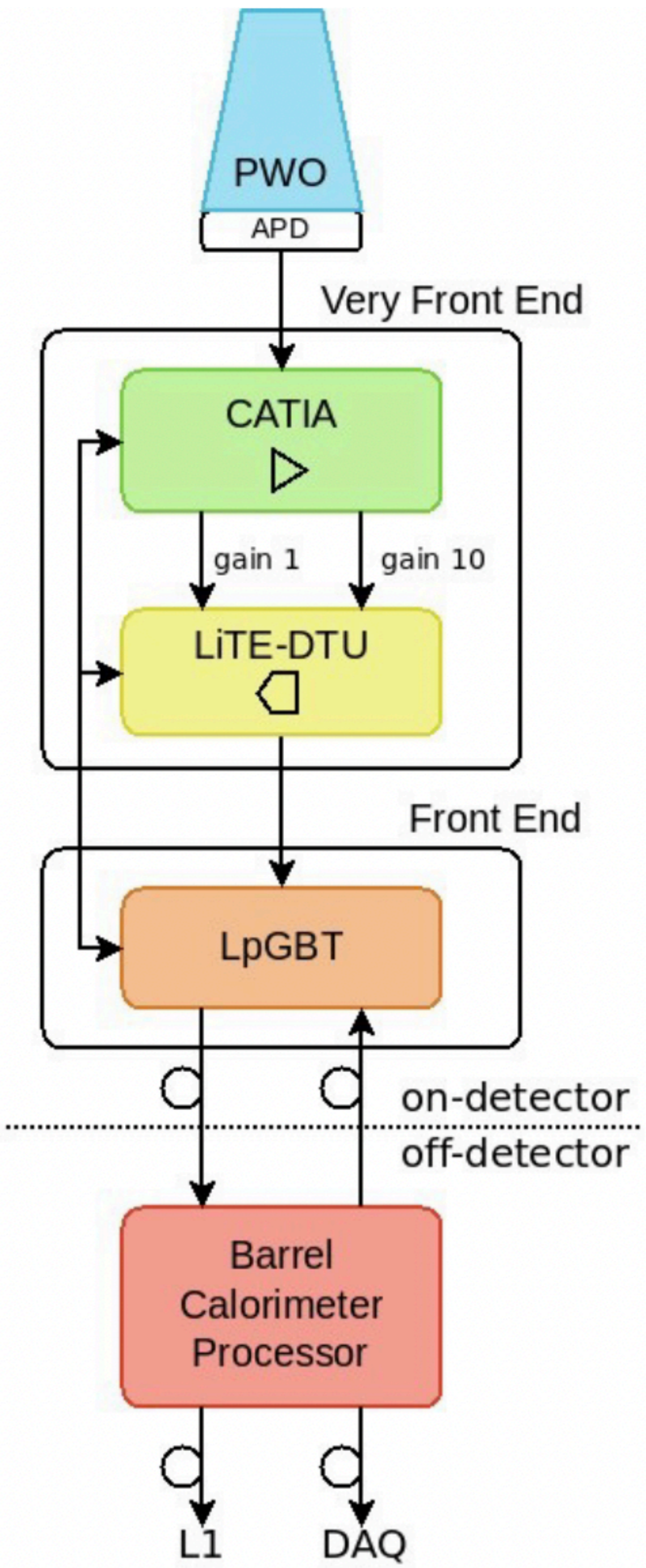




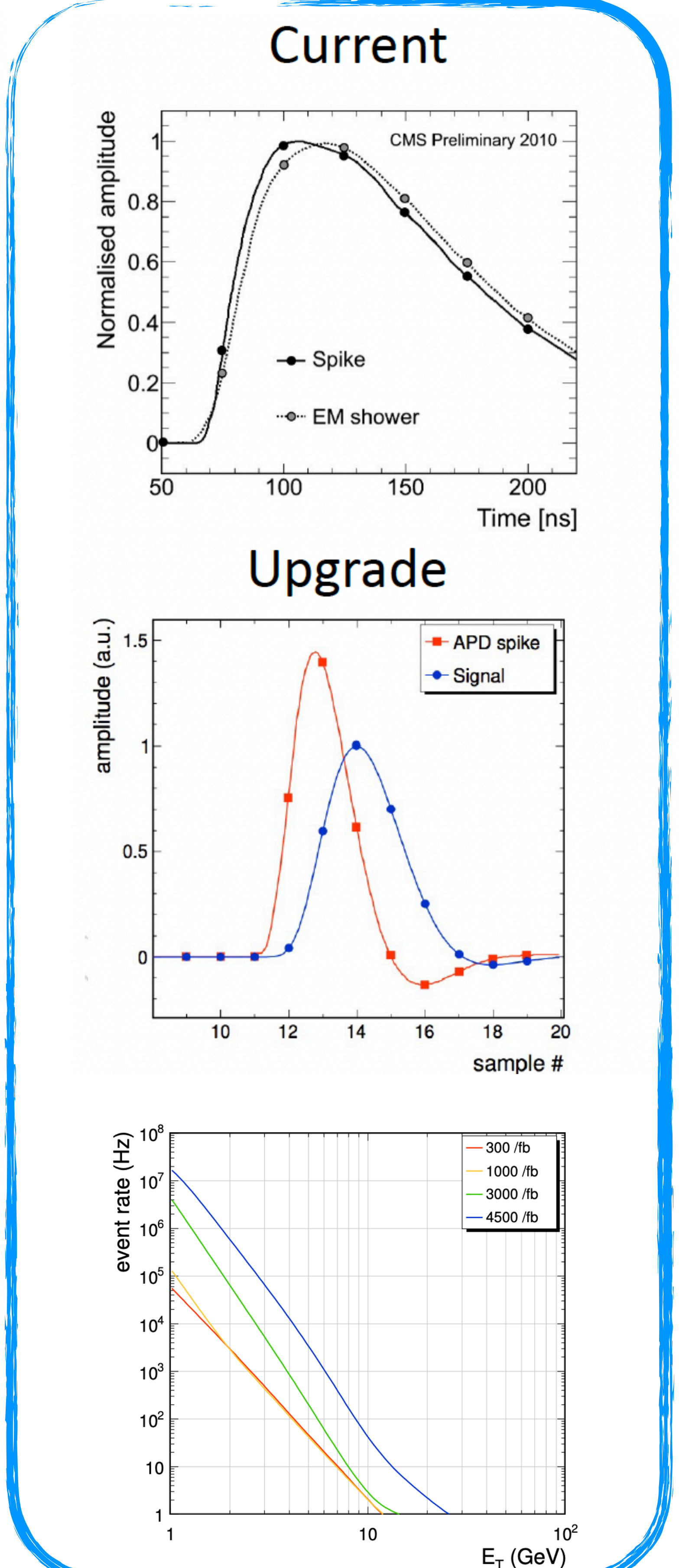
Spike rate vs Et threshold

Need spike rejection efficiency better than 99.9%

Plans of ECAL Barrel upgrade for HL-LHC



Spikes rejection



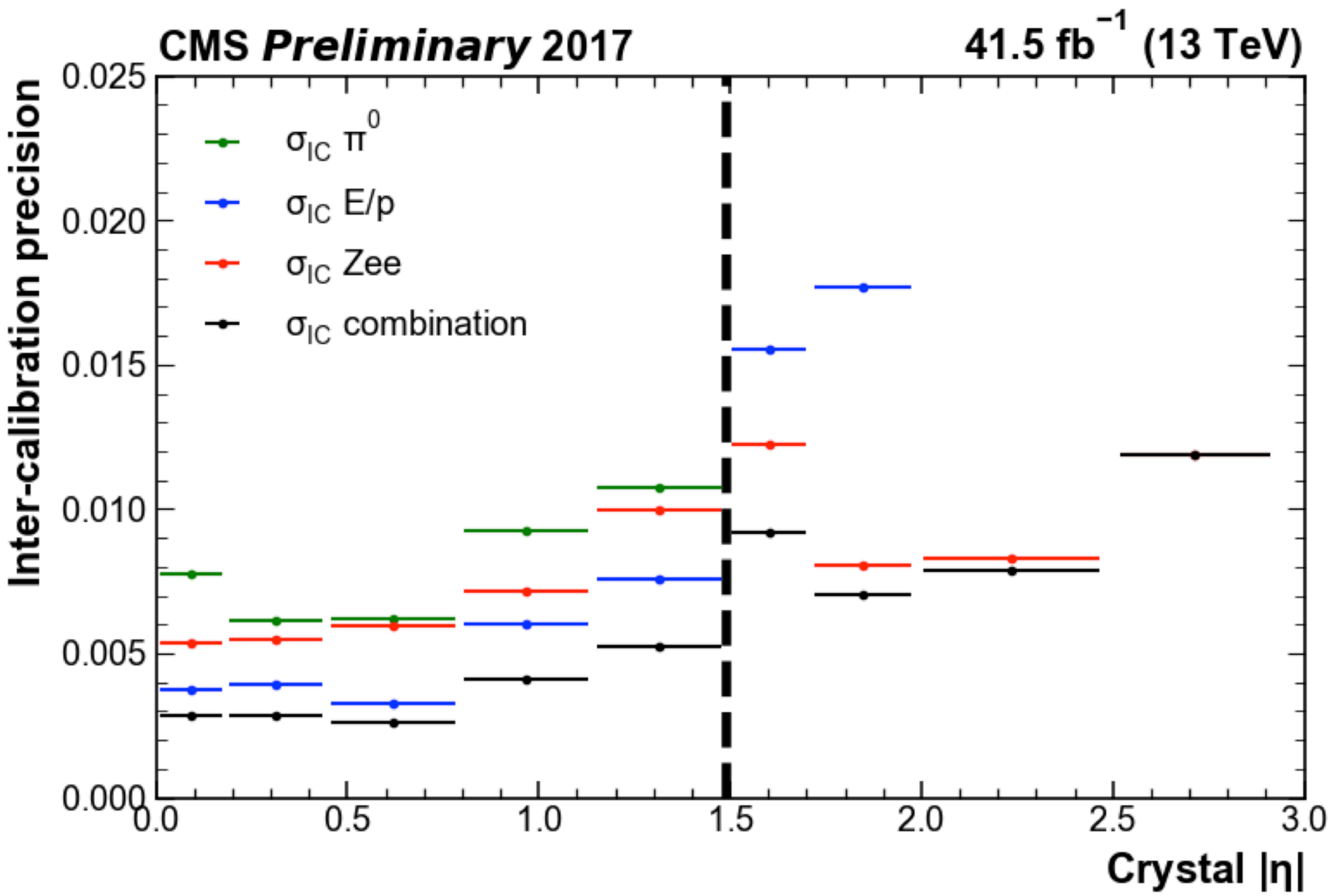
- Refurbish ECAL barrel super-modules during Long Shutdown 3 (2026-2028)
- Keep the lead tungstate crystals and APDs in the barrel
  - Reduce temperature from 18⁰C to 9⁰C to keep the noise well below 250 MeV
- Replace the on and off detector electronics
  - Use new radiation hard ASICs with faster pulse shaping and factor of 4 increase in the sampling rate:
    - Reduce impact of out of time pileup and limit increase in APD noise effect which increases with the shaping time
    - Provide improved spike rejection via pulse shape discrimination
      - spikes rates above 20 GeV drop to 0.5-0.75 MHz
    - Provide 30 ps timing resolution for E > 50 GeV
- Streaming Front-end board providing single crystal info to trigger via high speed radiation hard optical links (lpGBT)
  - More advanced algorithms in off-detector FPGAs

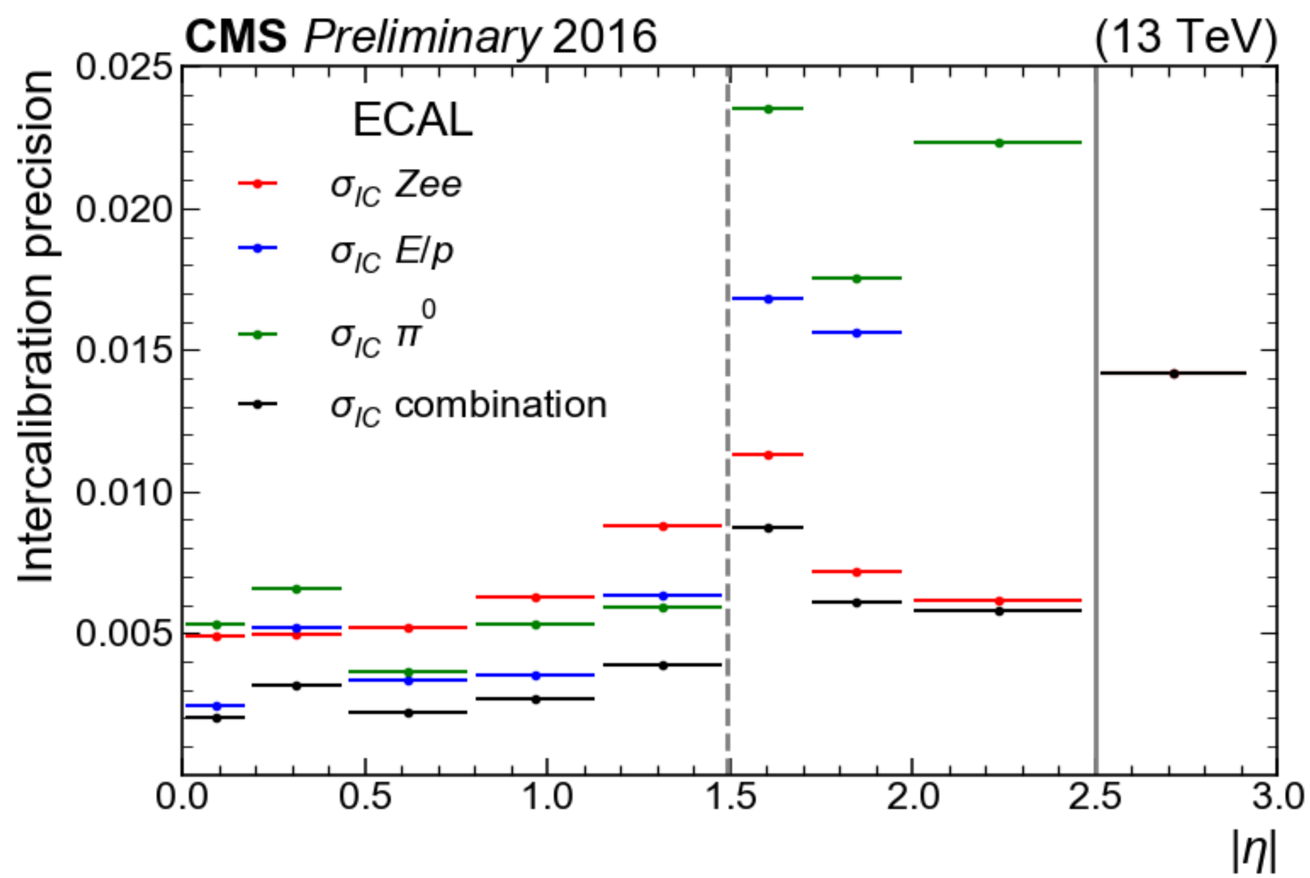
Outlook

- Outstanding performance of the CMS ECAL in Run 2 as in Run 1 in-spite of harsher environment
- Developments done for Run 3 at both online and offline levels
  - Stable rates, better resolution
  - Automated calibration workflow - fast and continuous tracking of the detector calibration with time
  - ML based super-clustering methods show improvement and more resistance towards pile-up and noise
- In view of HL-LHC (phase II), both on and off detector electronics will be replaced in the CMS ECAL to maintain the current performance
  - Reduced noise, better spike rejection, better timing and hence better pile up rejection

Backup

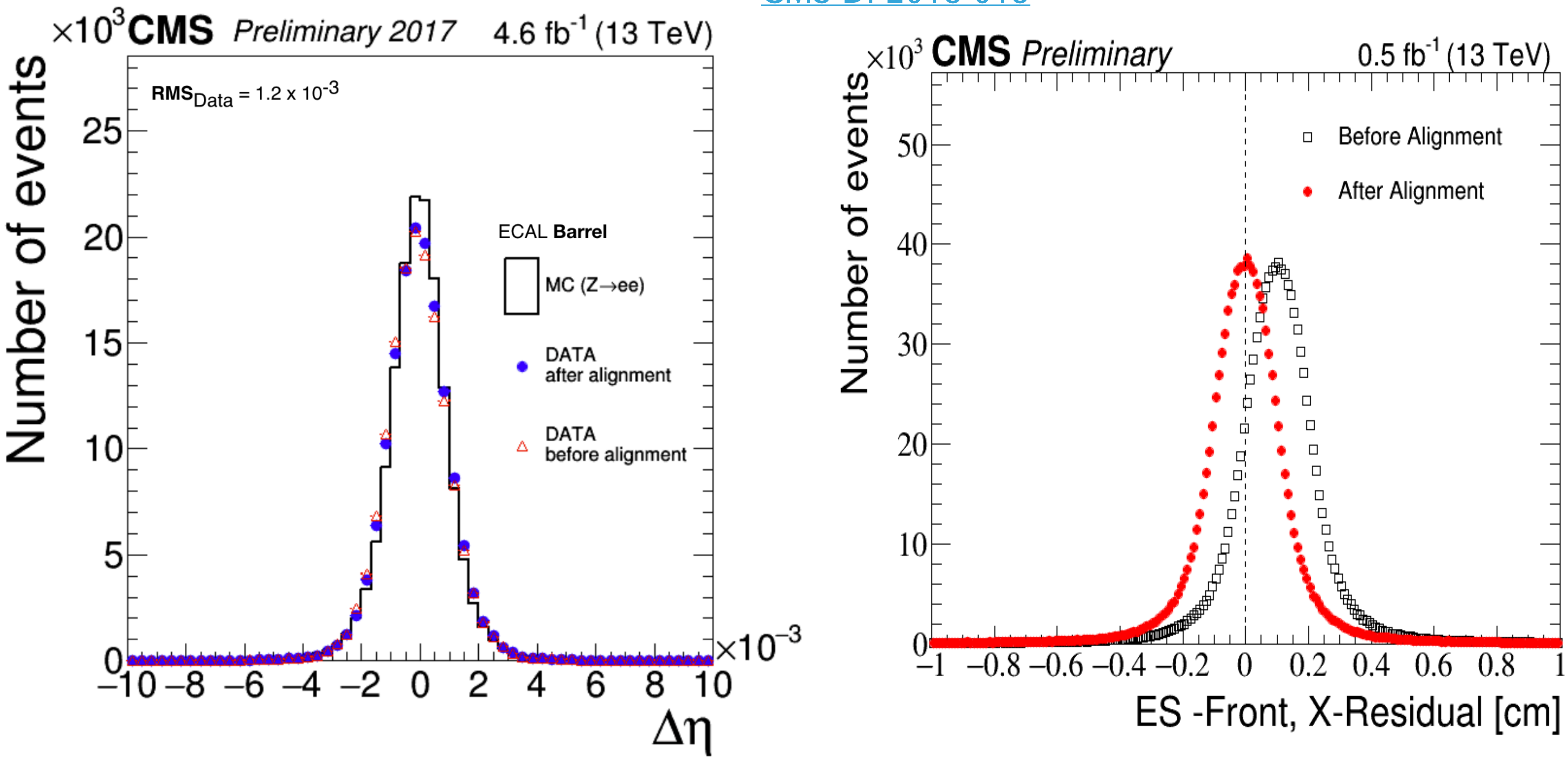
IC precision for Run 2





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

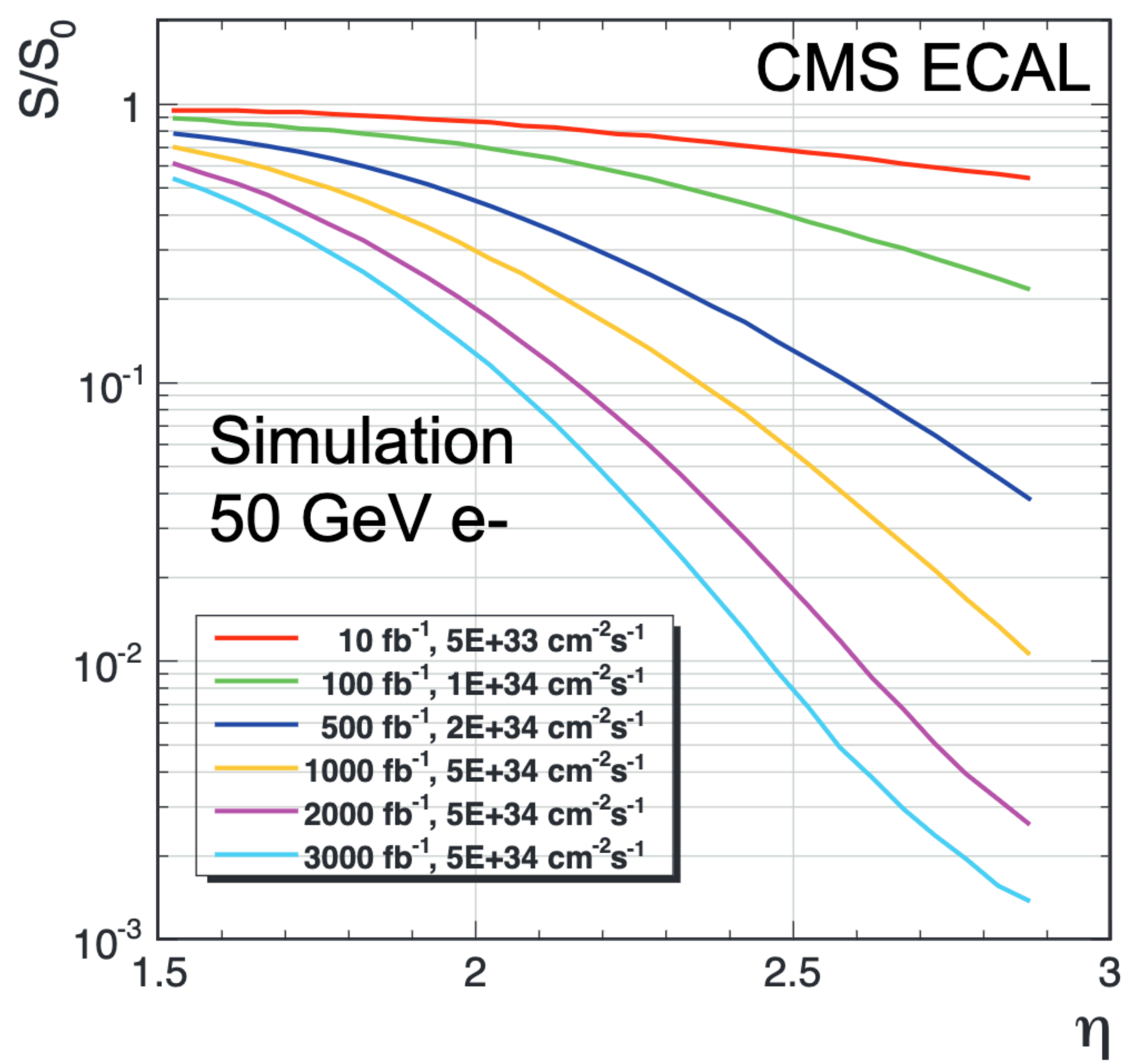
CMS-DP2018-015



- **Alignment between ECAL/ES and tracker is necessary for electron reconstruction and identification**
- Done using Z–>ee electrons for ECAL and using charged particle tracks for the ES
  - ECAL-tracker: Performed by minimising the difference in the η/φ between the ECAL super-cluster and the extrapolated track position using the closes approach to the super-cluster
  - ES-tracker: Again a minimization of the expected hit in the ES and the extrapolated track

ECAL Endcap during HL-LHC

ECAL Endcap

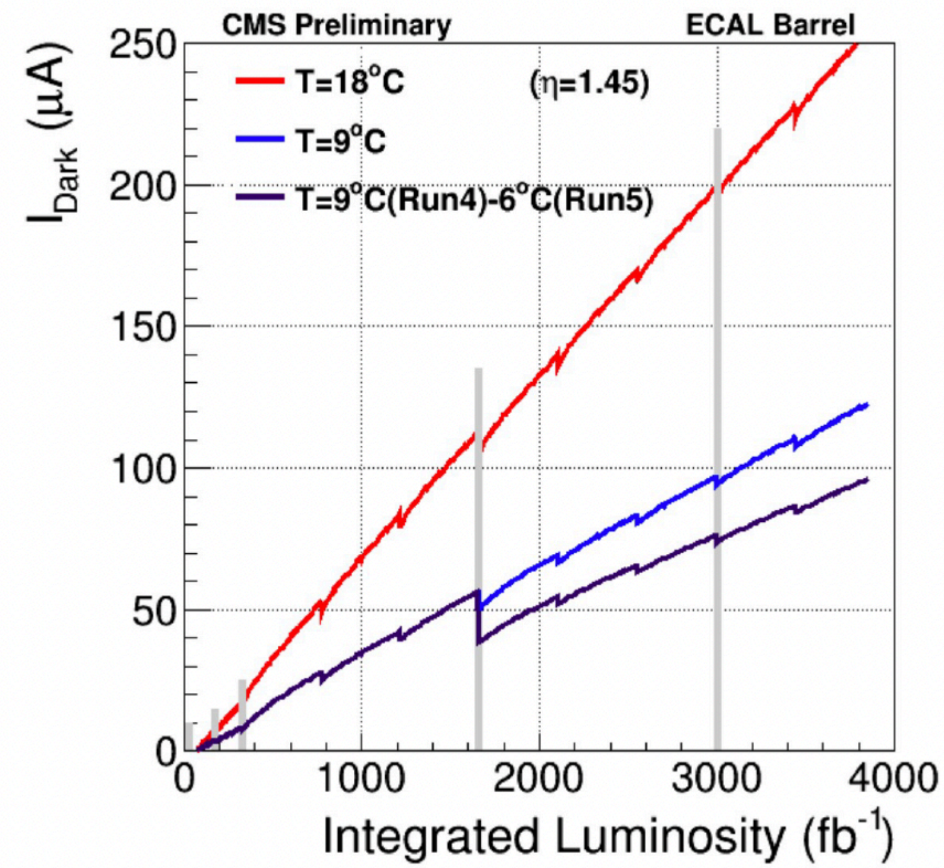


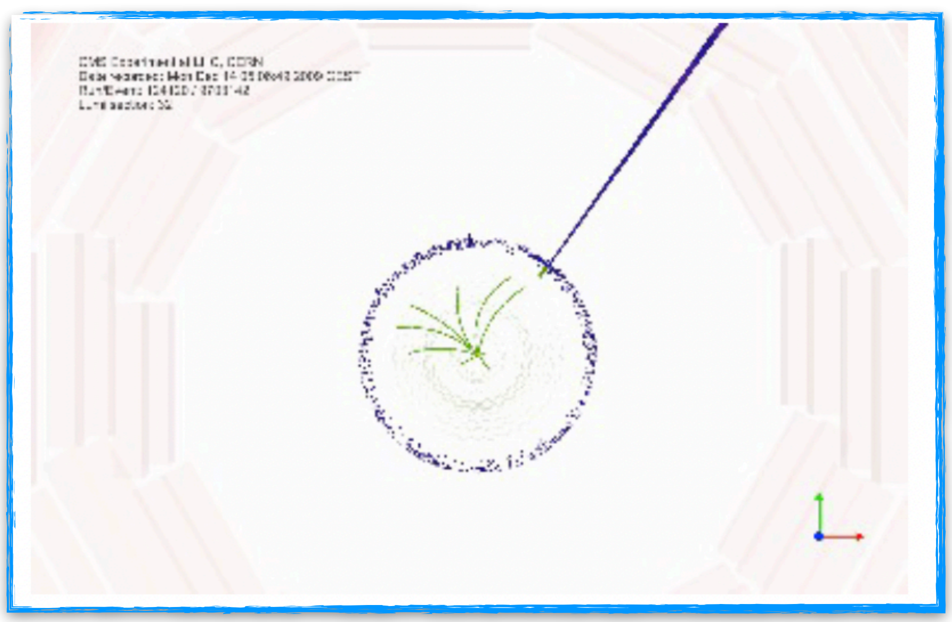
LHCC-P-008

- Transparency evolution for ECAL Endcap during HL-LHC
- This will be replaced by High Granularity Calorimeter

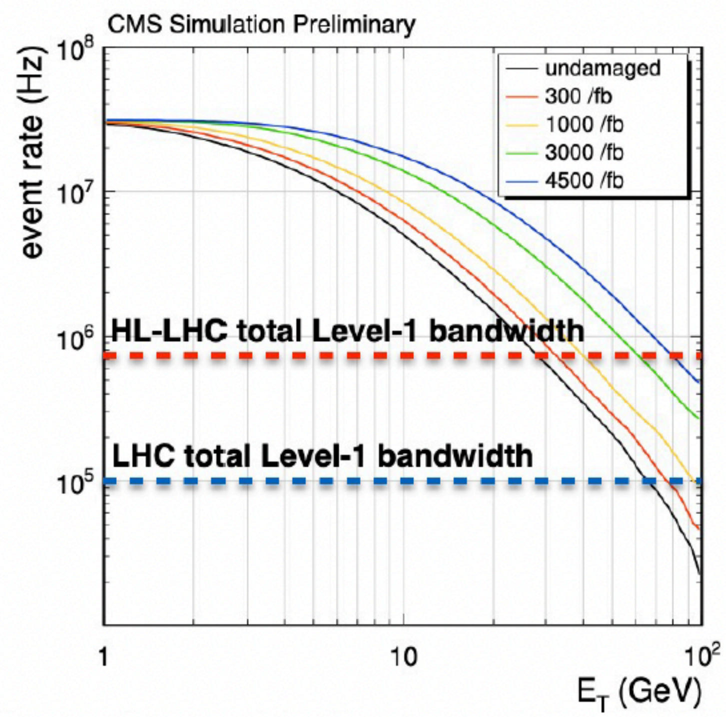
Additional challenges for HL-LHC

- More radiation and hence more APD leakage current (and hence noise)
- Increase rate of anomalous signals ("spikes" - isolated large signals, look like real EM signal) caused by hadrons impacting directly on the APDs
  - Increases the trigger rates
  - Spike rate > 1 MHz for E_T > 20 GeV
  - Would saturate the available Phase-2 Level-1 bandwidth
  - Need a spike rejection efficiency better than 99.9%





Spike signature in ECAL

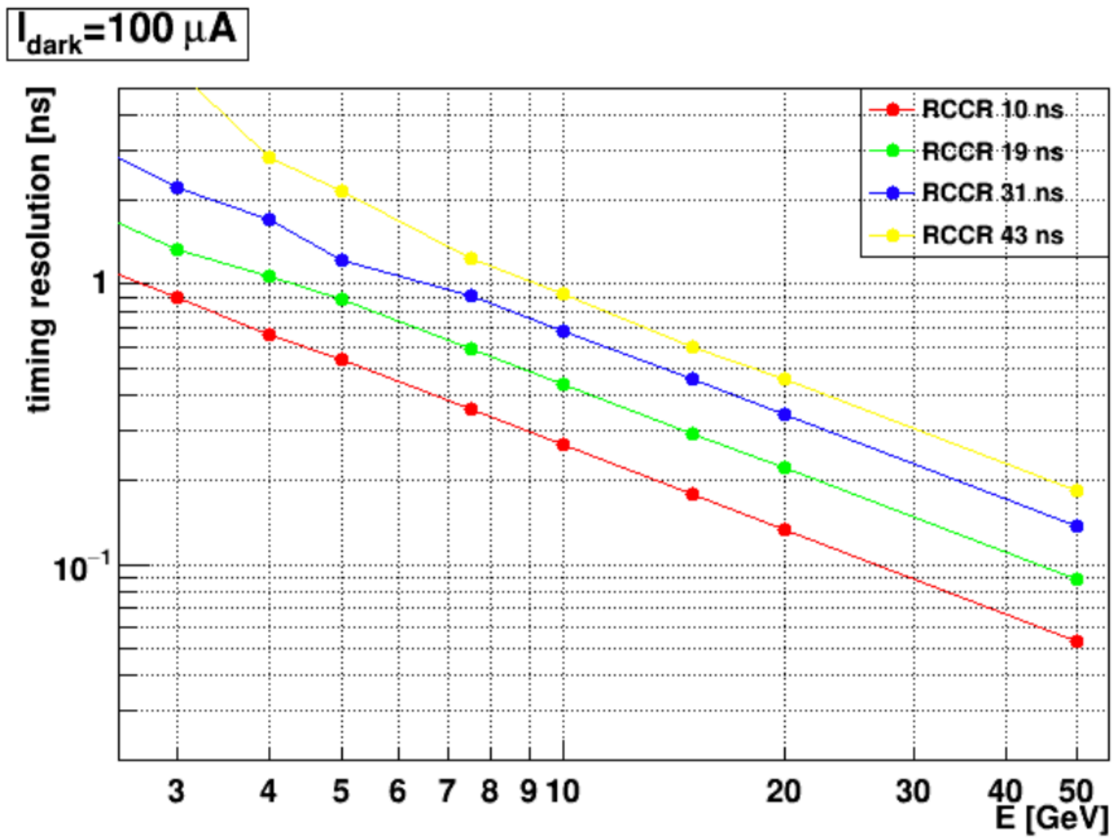


Spike rate vs Et threshold

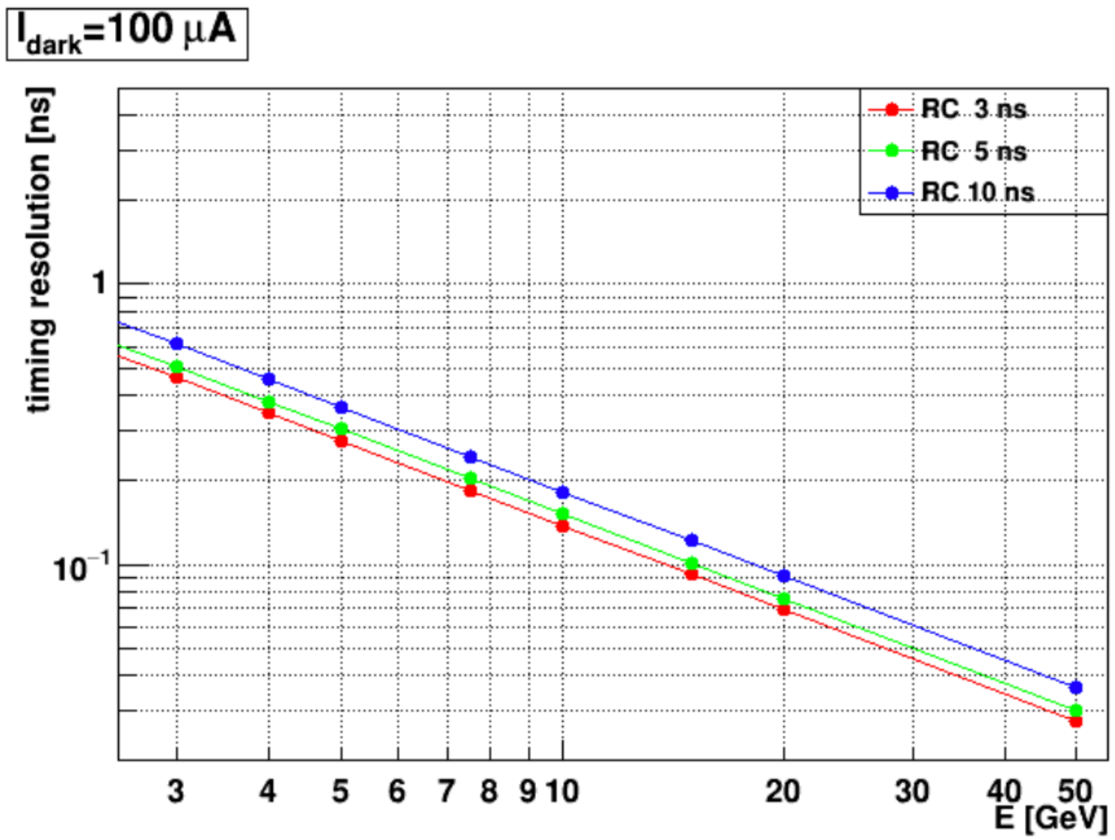
ECAL Barrel will be upgraded depending on the requirements

- APD noise that can be tolerated
- Maximum acceptable signal amplitude (50 MeV - 2 TeV)
- Timing resolution
- Spike rate
- etc

Charge amplifier VS current amplifier for the upgrade



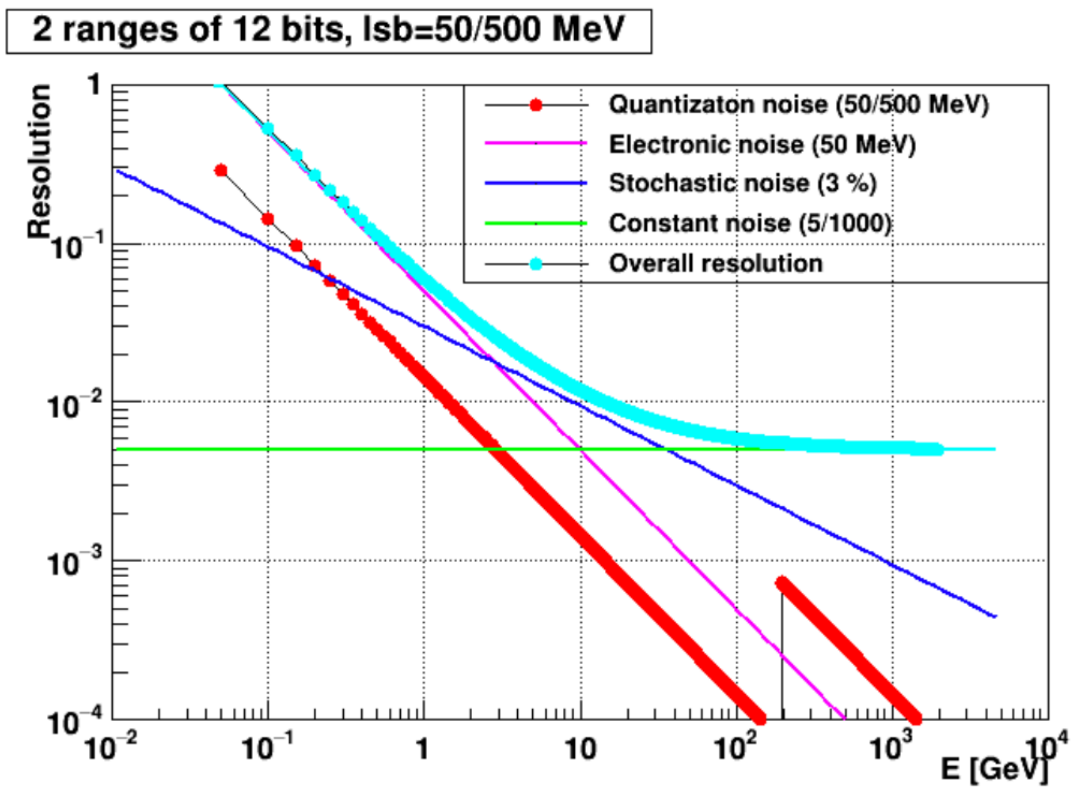
Charge Amplifier

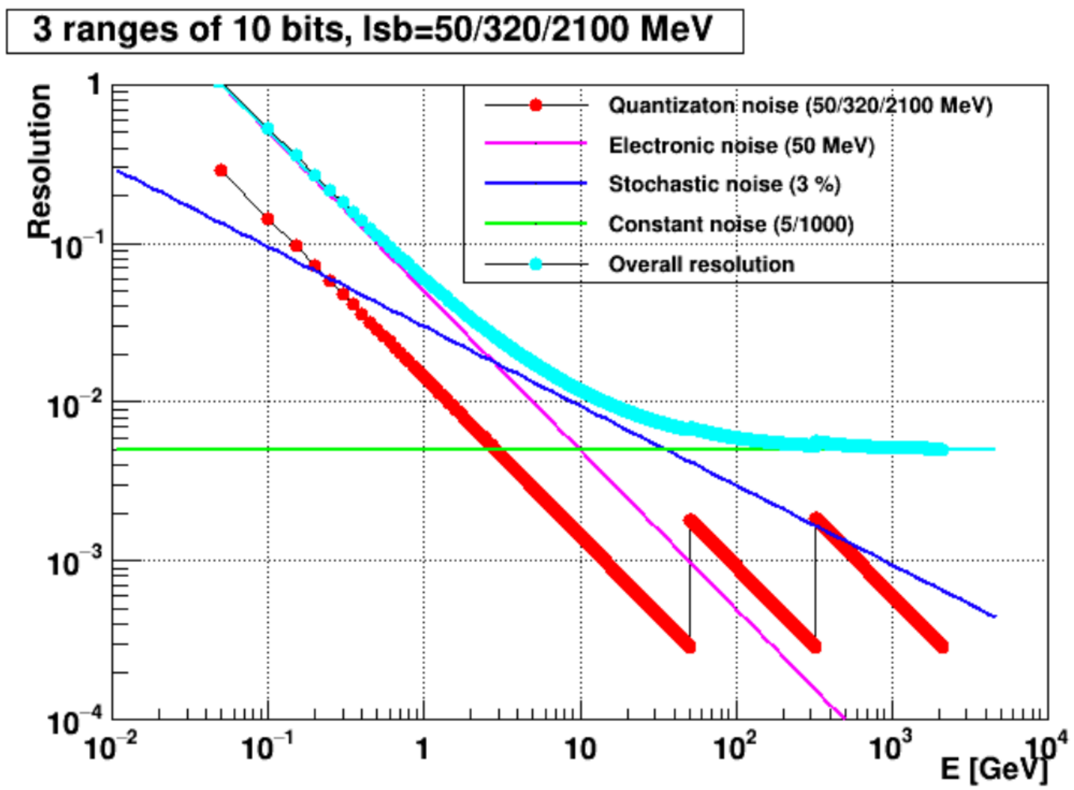


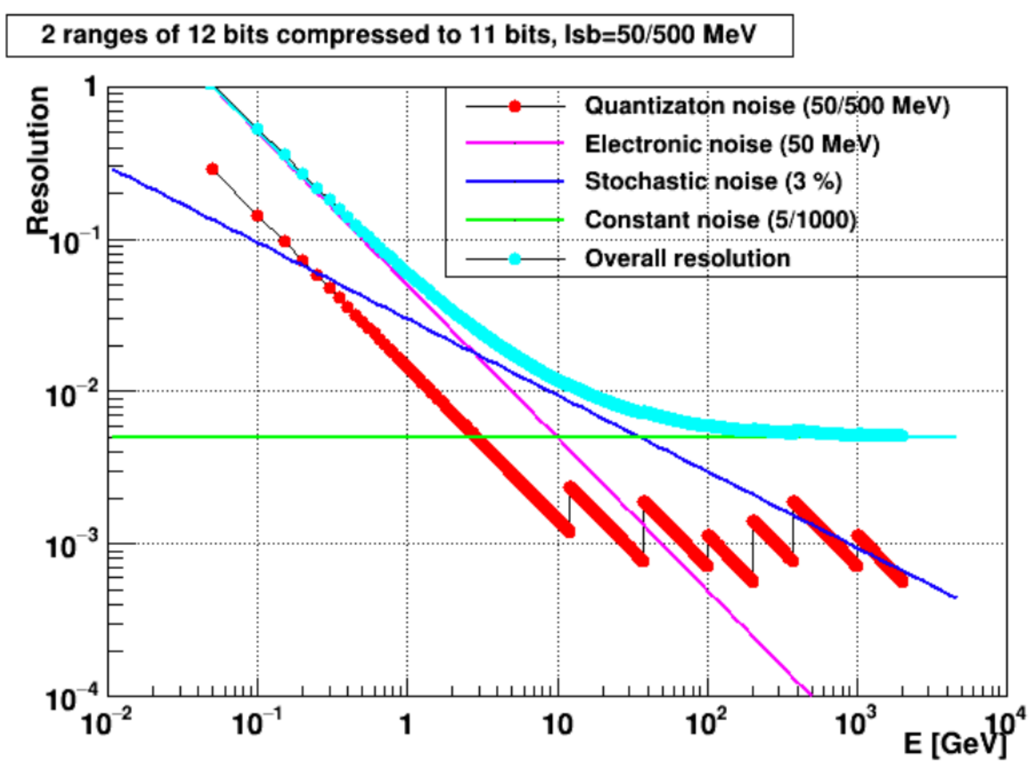
Current Amplifier

- Target timing resolution is ~30 ps for 50 GeV showers
- Current amplifier is much better able to achieve this target as opposed to charge amplifier

Upgrade: 12 bit ADC with 2 gains VS 10 bit ADC with 3 gains

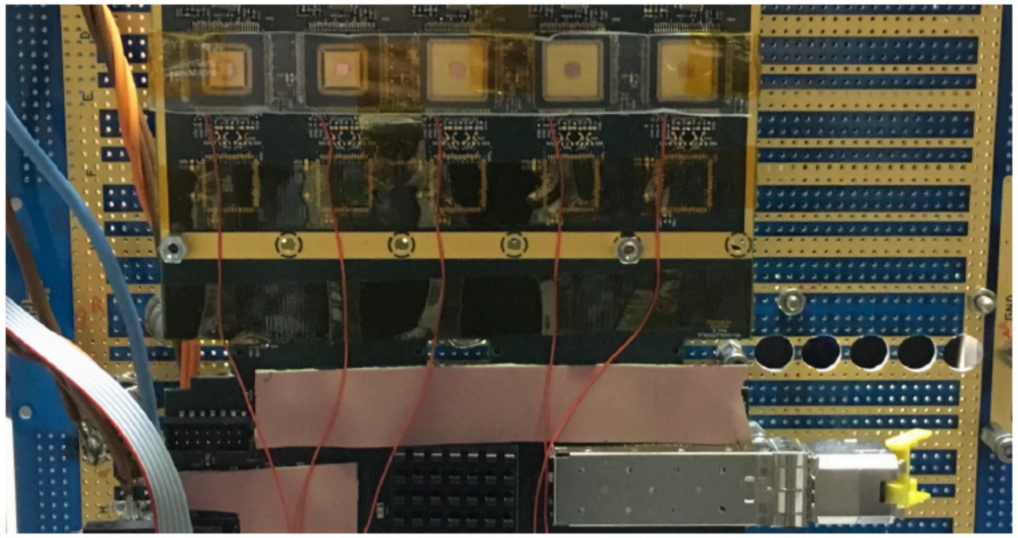




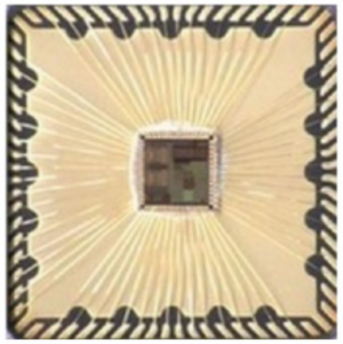


- In order to avoid gain switching for photons from precision physics (such as H–>γγ decays), the two gain 12-bit ADC has been chosen as the baseline
- Since the quantization noise is small, compression of the data from 12 to 10 bits is possible using non-linear digital transformation without loss in the resolution

Front-end chips



- CATIA
  - Pre-amplifier ASIC: Calorimeter Trans-Impedance Amplifier (CATIA) architecture with minimal pulse shaping
  - Faster pulse shaping is important for precise timing and improved spike rejection capabilities
  - 2 output gain values: x1 and x10
- LiTE-DTU
  - Data conversion, compression and transmission ASIC
  - Two 12-bit ADCs, lossless data compression due to small quantization noise
    - 50 MeV resolution up to 200 GeV. Thereafter resolution of 500 MeV up to 2 TeV
  - Look-ahead algorithm: sample saturation check prevents mixing samples from different gains in the same APD signal timeframe



Backend Electronics

- Run 2 off-detector electronics cannot sustain the expected high L1 rate (750 kHz)
- Replaced by Barrel Calorimeter Processor (BCP) using commercially available powerful FPGAs and high speed optical links
- Combines trigger and DAQ functionalities and provides clock and control signals to the FE electronics
- Each board handles signals from 600 crystals
- Algorithms developed using high level synthesis
  - Rejection of spikes
  - Conversion of digitized pulse into transverse energy
  - Basic clustering of localized energy
  - Formation of trigger primitives