The ultimate CMS ECAL calibration and performance for the legacy reprocessing of LHC Run 2 data

Raffaella Tramontano on behalf of the CMS collaboration
Sapienza Università di Roma & INFN

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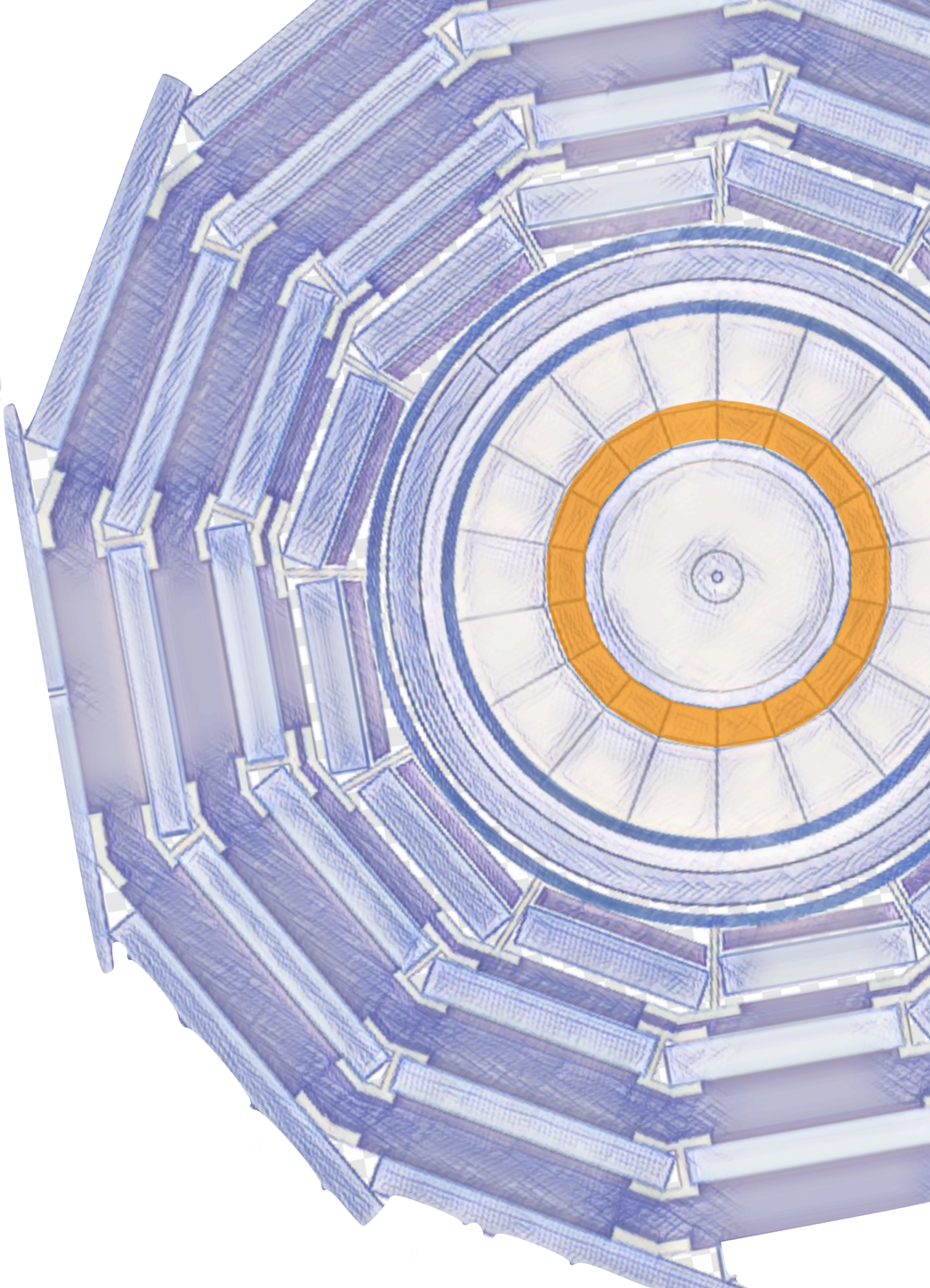
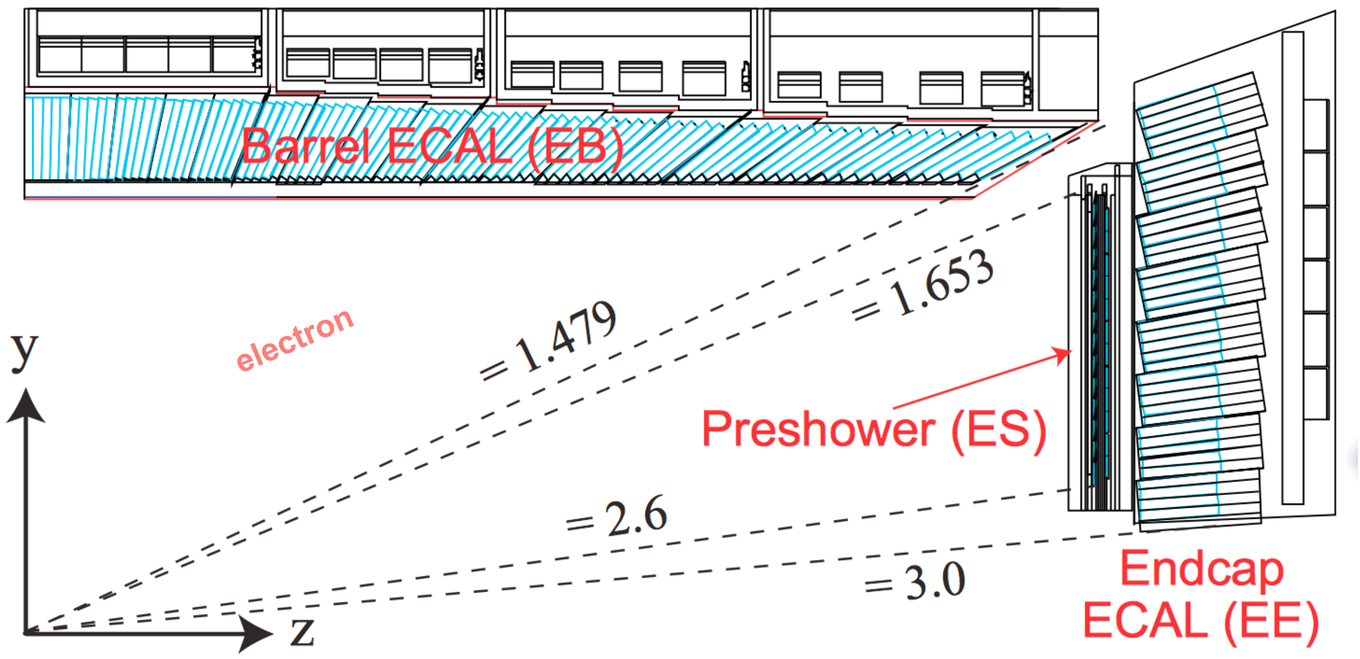
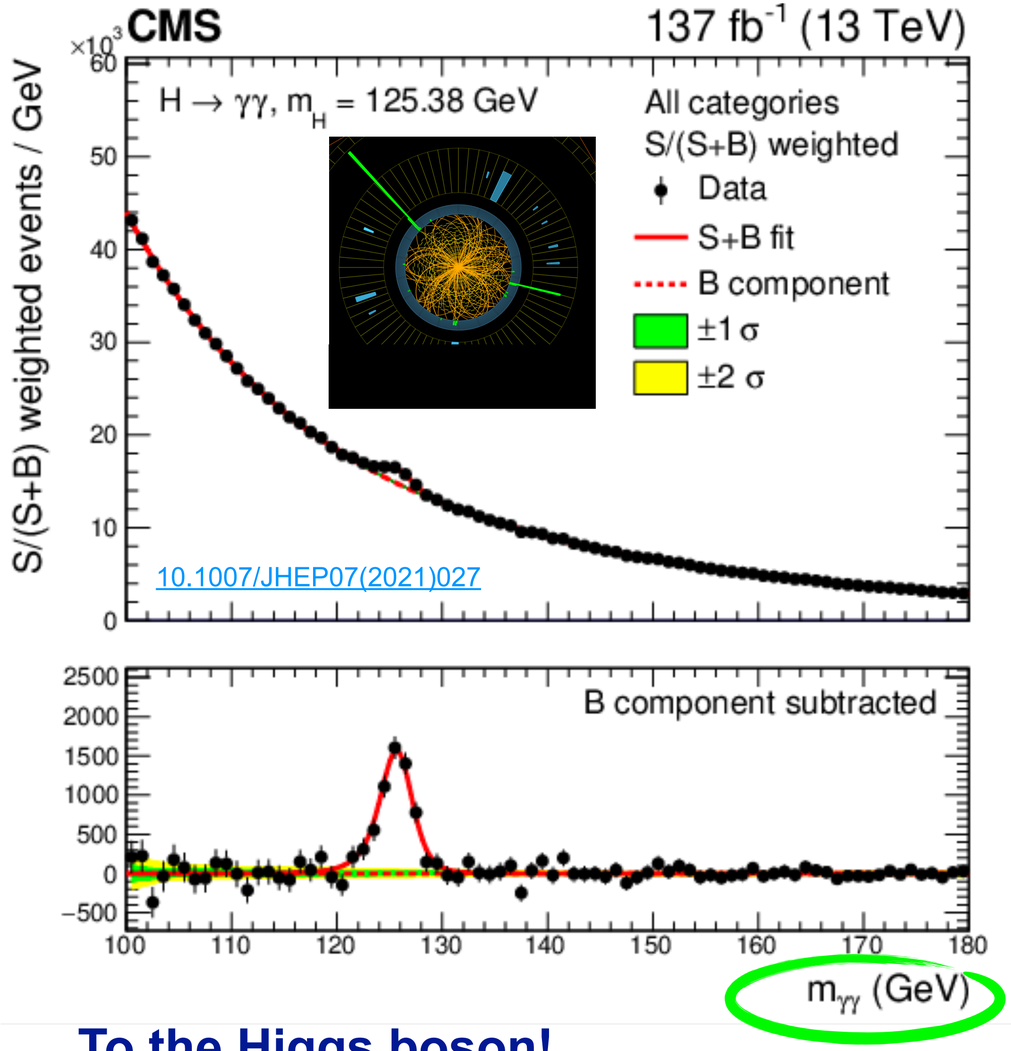


ECAL: CMS Electromagnetic CALorimeter

A homogeneus, hermetic, high granularity PbWO4 crystal calorimeter…

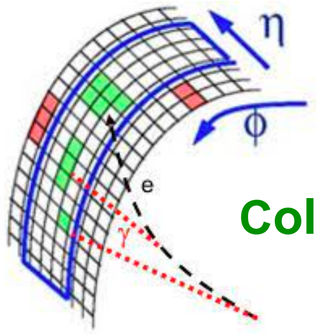


From EM showers in ECAL…



To the Higgs boson!

Path to ECAL energy measurements



Energy reconstruction

$A_i(t)$

Collect and measure energy deposits

More on clustering algos In Badder's talk

$C_i(t)$

Extracted signal behavior Homogeneus all over ECAL

$L_i(t)$

Account for radiation effects: Reduced crystal transparency

$G(\eta)$

Extracted signal reliable In terms of physics

Energy calibration

$F_{e,\gamma}$

Refinements:

Correct for shower leakage, material effects, death channels..

Today's aim:

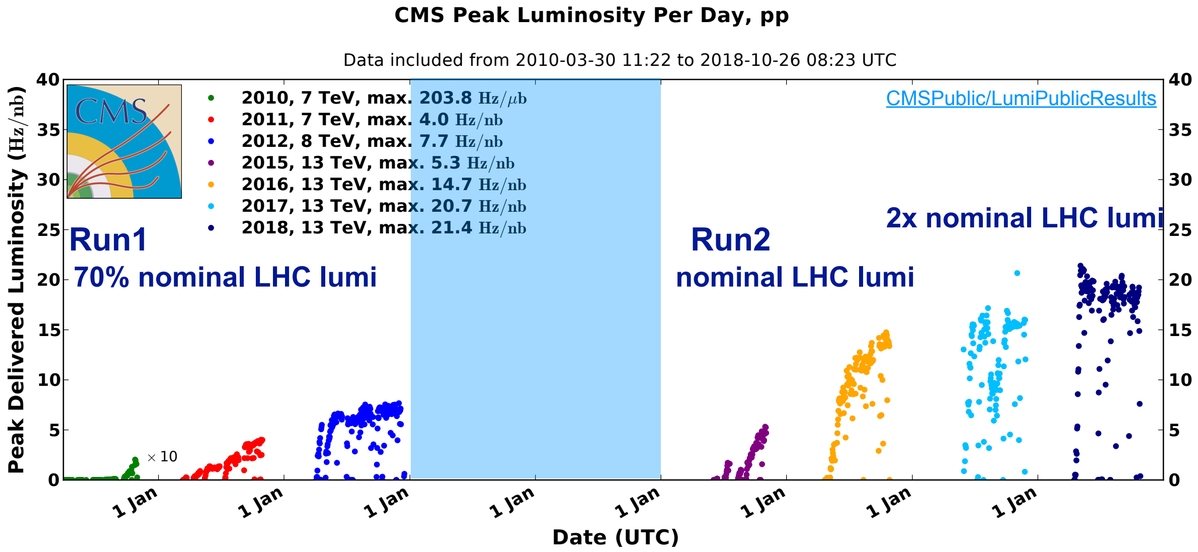
Walk through reconstruction & calibration

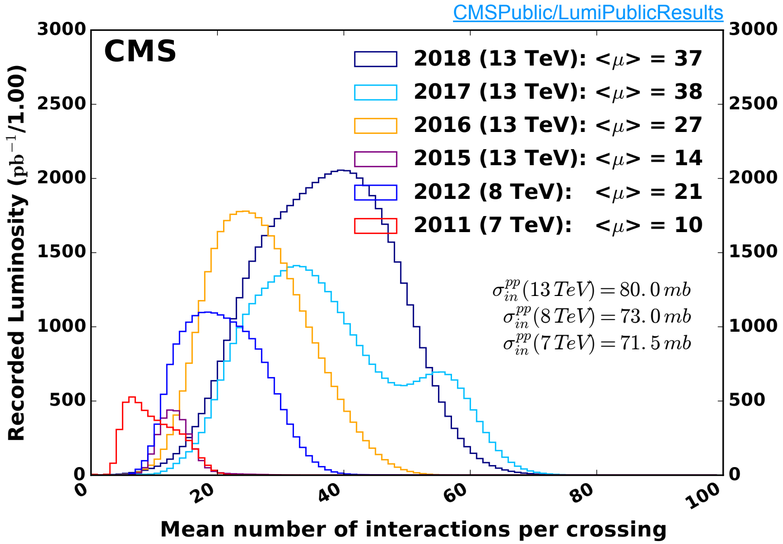
Legacy reprocessing for Run2 data

With an eye on the future Run 2 -> Run3

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

ECAL Run2 challenge: overlapping interactions





Nominal luminosity achieved by

focusing beams to enlarge collision probability

X

Halving time between collisions (50ns to 25ns)

Bigger number of **interesting events** produced

More vertexes to disentangle

X

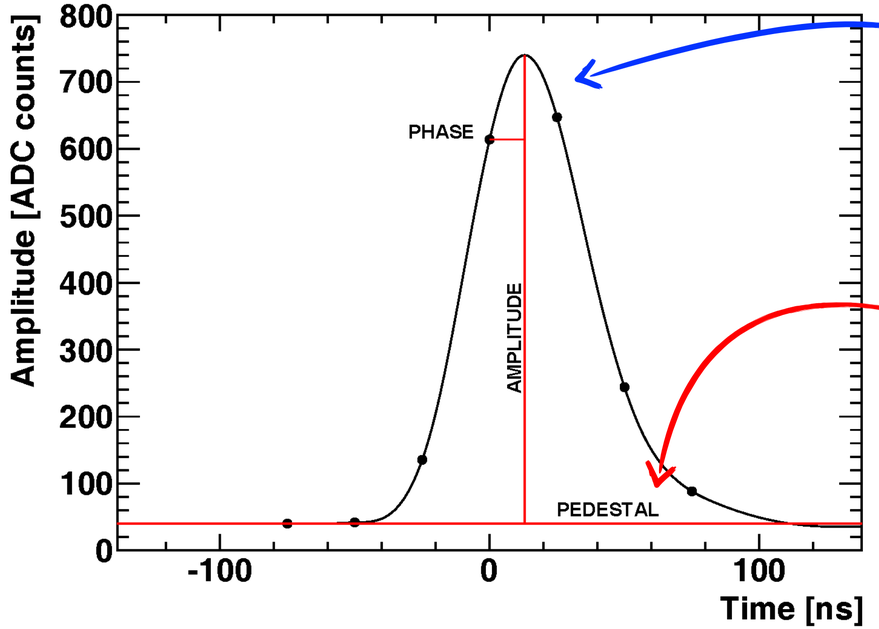
ECAL signal amplitudes last for O(100) ns

ECAL challenge:
number of overlapping signals - pile up - increased

Signal amplitude - prepare for reconstruction

$A_i(t)$

- **Pedestals** to the pulse shape:
  - Recorded every **40 minutes** in Run2 using laser events
- **Pulse shape**
  - crystal template pulse shapes recomputed every 3-4 fb-1

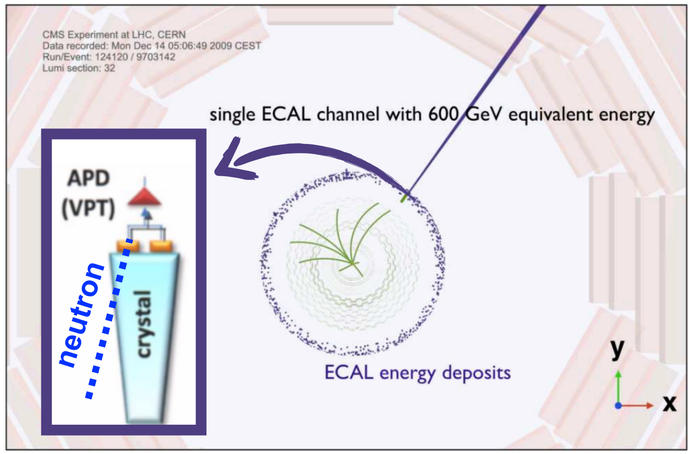


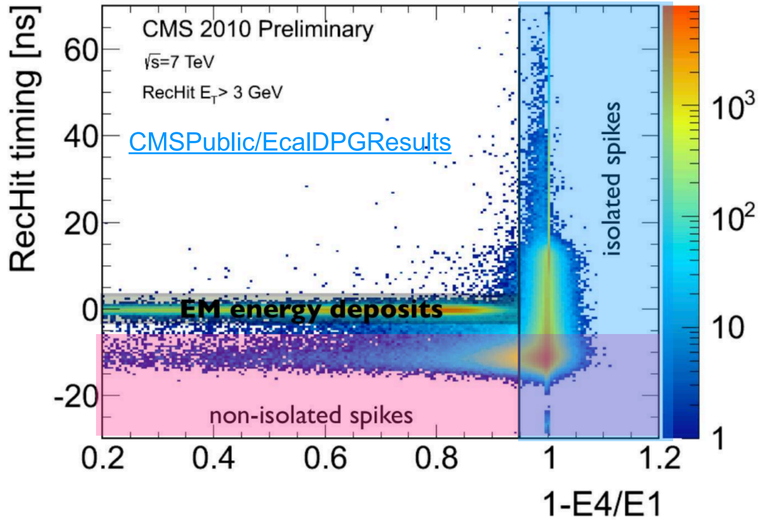
Shape changes with radiation damage

Pedestals change with time

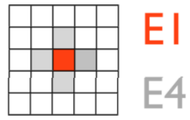
~ 40 MeV/year increase

- Catching **spikes - APD anomalous signals**





Swiss cross Variables



Checks single crystal energy Wrt to surroundings

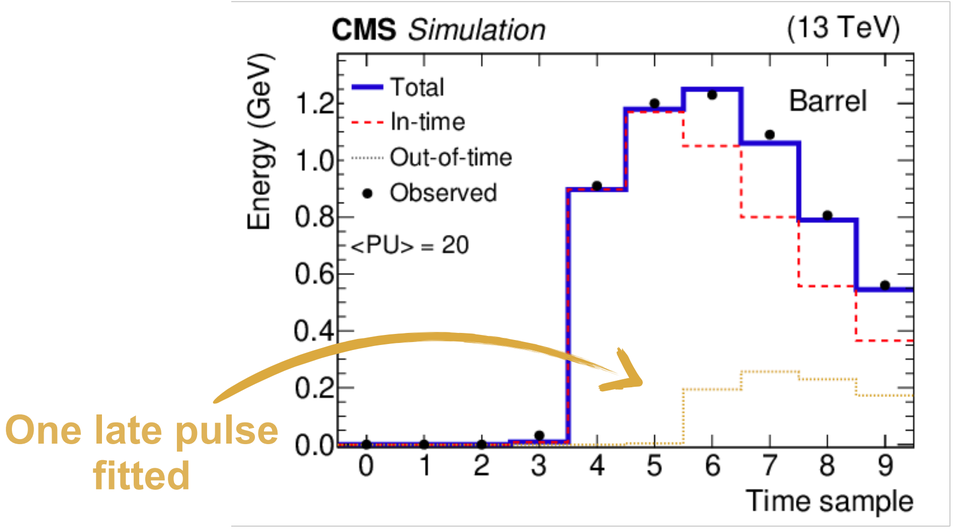
Early pulses - No scintillation

Signal amplitude reconstruction- algorithm

$A_i(t)$

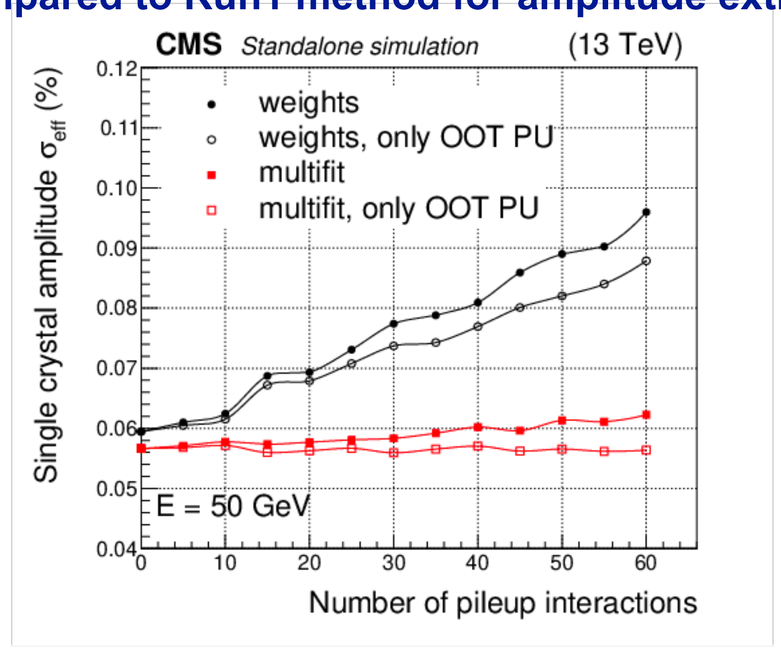
https://arxiv.org/abs/2006.14359

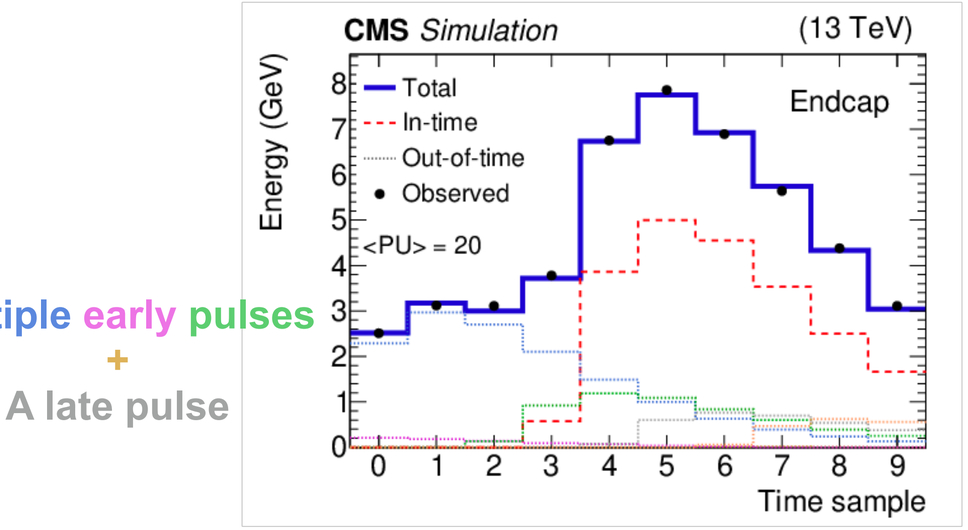
- **Multifit algorithm - treats out of time pile up**
  - Observed signal = 1 in time pulse + up to 9 out of time pulses
  - **Fixed pulses shapes, floating amplitude**



One late pulse fitted

Multifit performance for PU mitigation
Compared to Run1 method for amplitude extraction





Multiple early pulses
+
A late pulse

Crystals ageing - transparency loss correction

$L_i(t)$

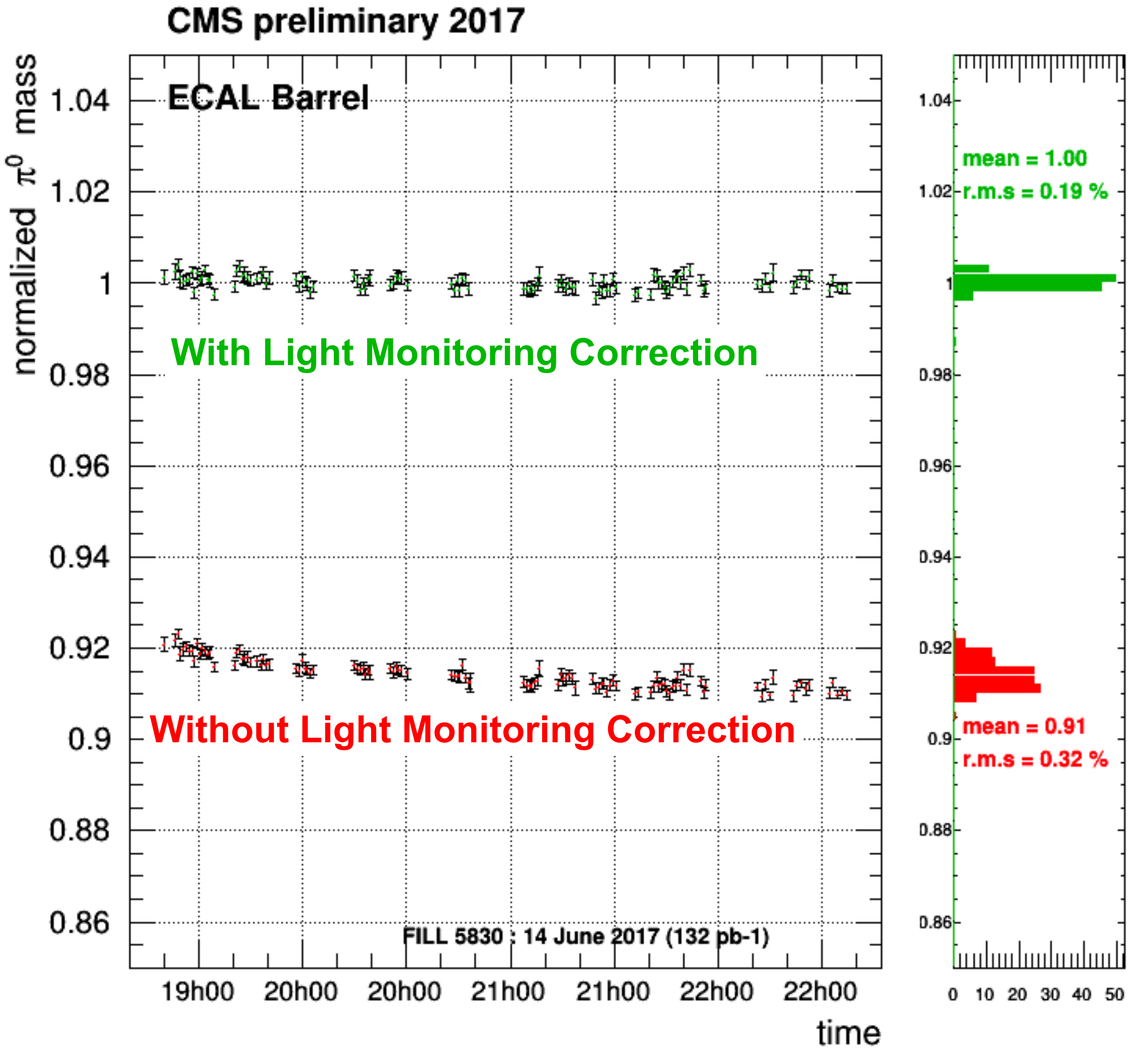
CMS DPNotes 2017-023

- Extreme radiation rates
  - Loss in transparency inevitable
- Laser crystal-by-crystal monitoring
  - Checks transparency evolution thought time
  - **laser system scans all crystals every 40 mins**

Crystal response

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

To EM showers To laser



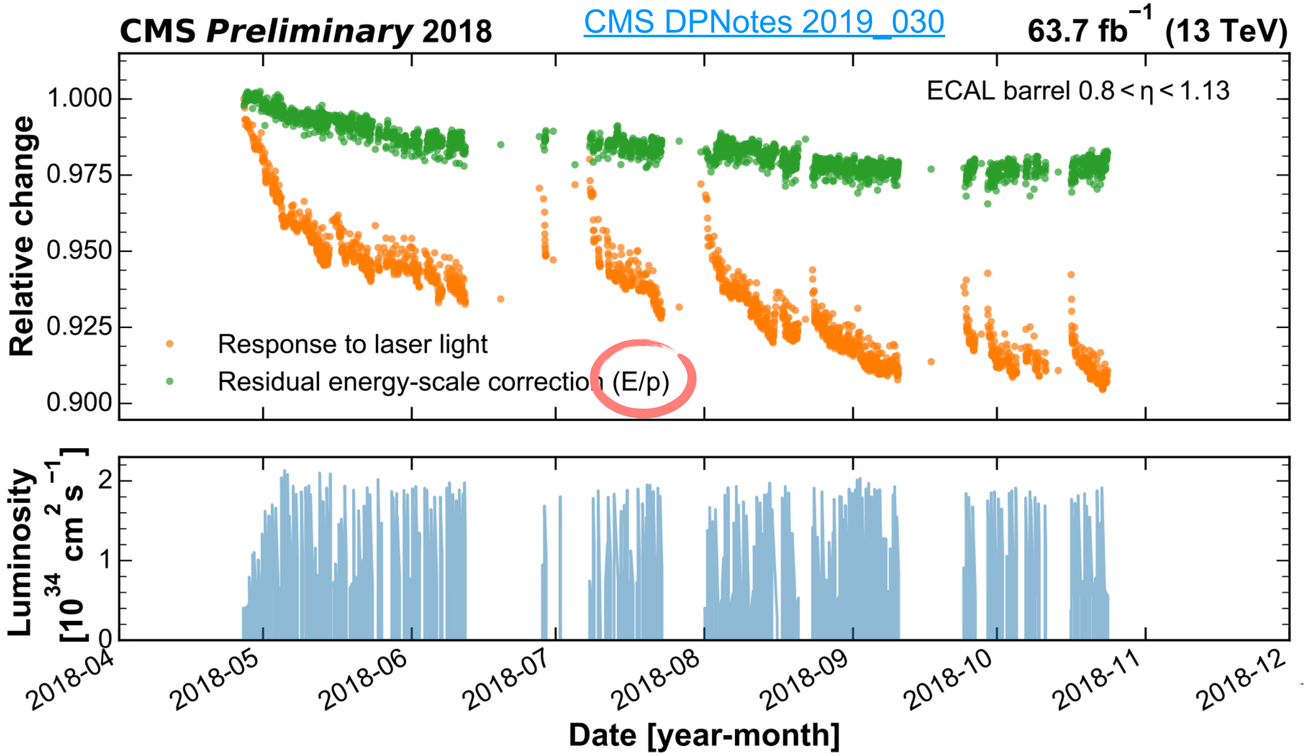
Monitoring the monitoring system:

Run 2 challenge:

- Bulk of light monitoring correction
- Residual worsening in corrected light output
  - Due to radiation damage on

    laser reference diode
    transmission fibers

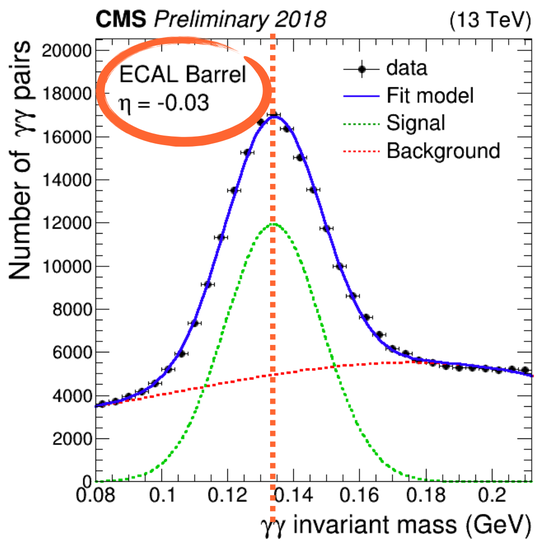
Correction
E/p with tracker momentum measurements of W/Z bosons electrons

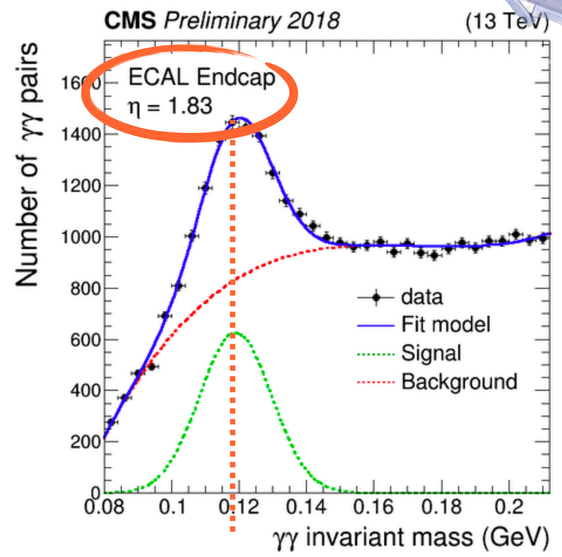


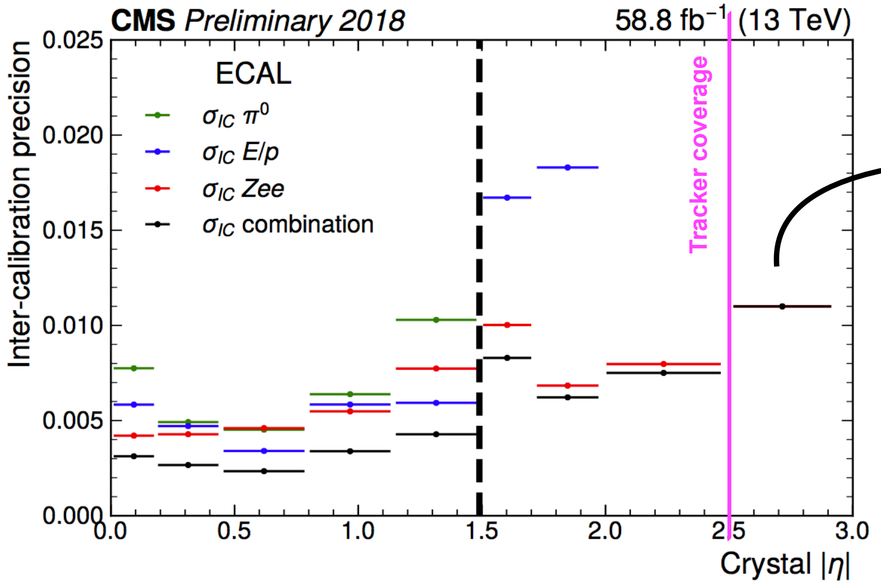
Energy calibration

CMS DPNotes 2019-038

- **Energy resolution**
  - Compare and correct signals output in η bins
  - **Reduce peak width**
  - Combining several correction methods
    - Peak widths $\pi^0 \to \gamma\gamma, Z \to e^+e^-$
    - **electrons**: E/p, momentum from tracker
- **Energy scale:** derived from $Z \to e^+e^-$
  - Peak position from ECAL deposits
    Corrected to match MC peak position
- **Inter-calibration precision better than 1% for e/γ**
  - **Better than 0.5% for $|\eta| < 1.5$**







Crucial for Jet energy reconstruction

Refinements:

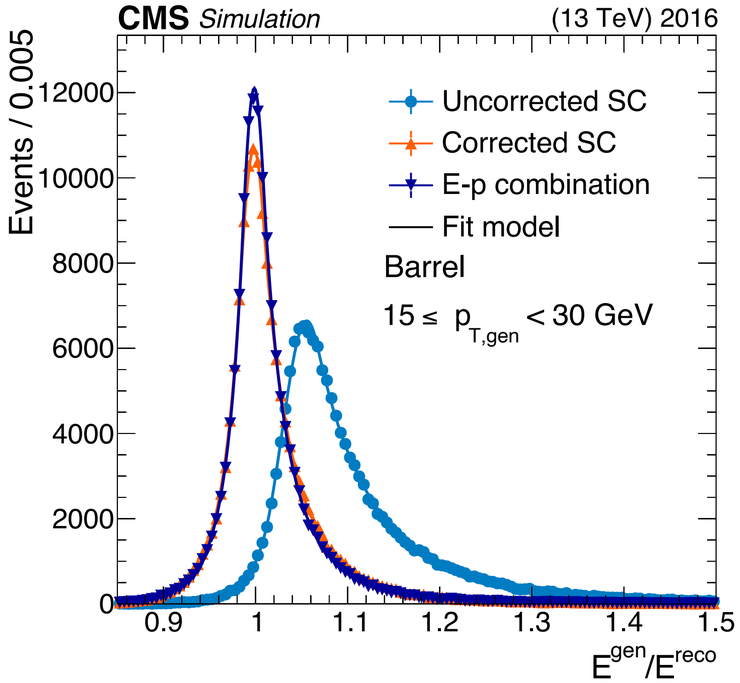
JINST 16 (2021) P05014

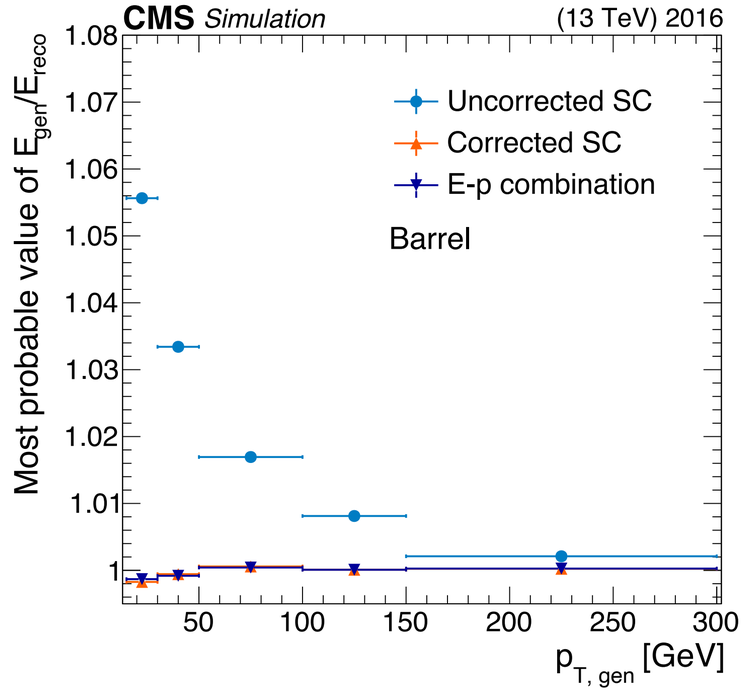
Semiparametric BDT to refine estimates

Accounts for leakage, material effects, dead channels..

Exploits variables related to:

- EM Shower shape/dimension
- Brehmstralhung energy losses
- **Electrons only**:
  - combination with angular tracker info



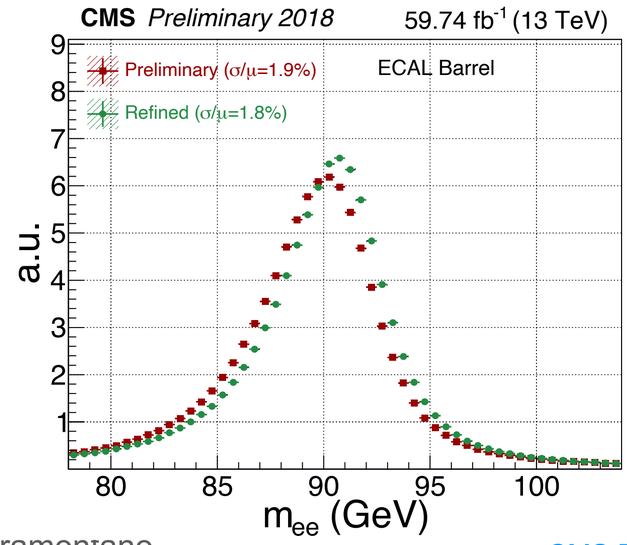


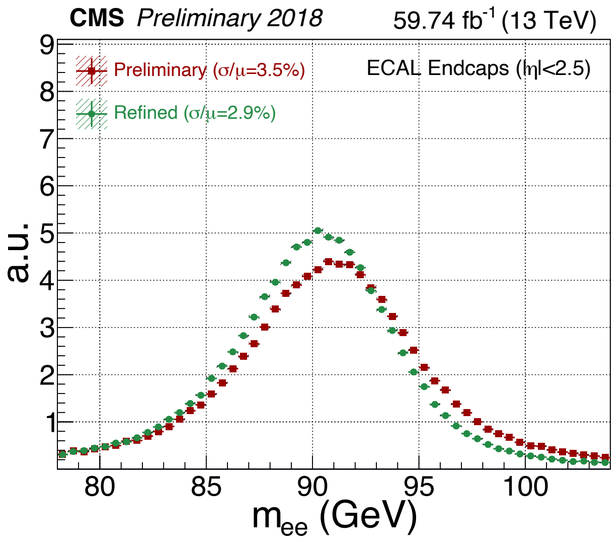
ECAL Run2 legacy reprocessing

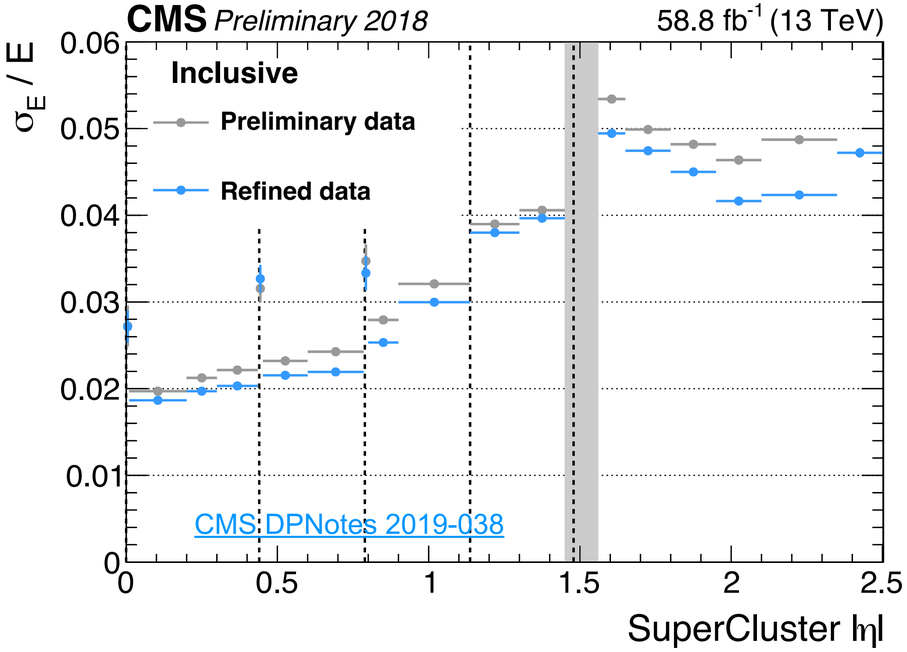
Standard calibration obtained by chunk of early data for each period

Legacy reprocessing: reconstruction & calibration using all Run2 data

- **smaller uncertainties**
- Higher sampling - **refined corrections for different data taking periods and conditions**
- **“integration”** of temporary inefficiencies, transient defects..







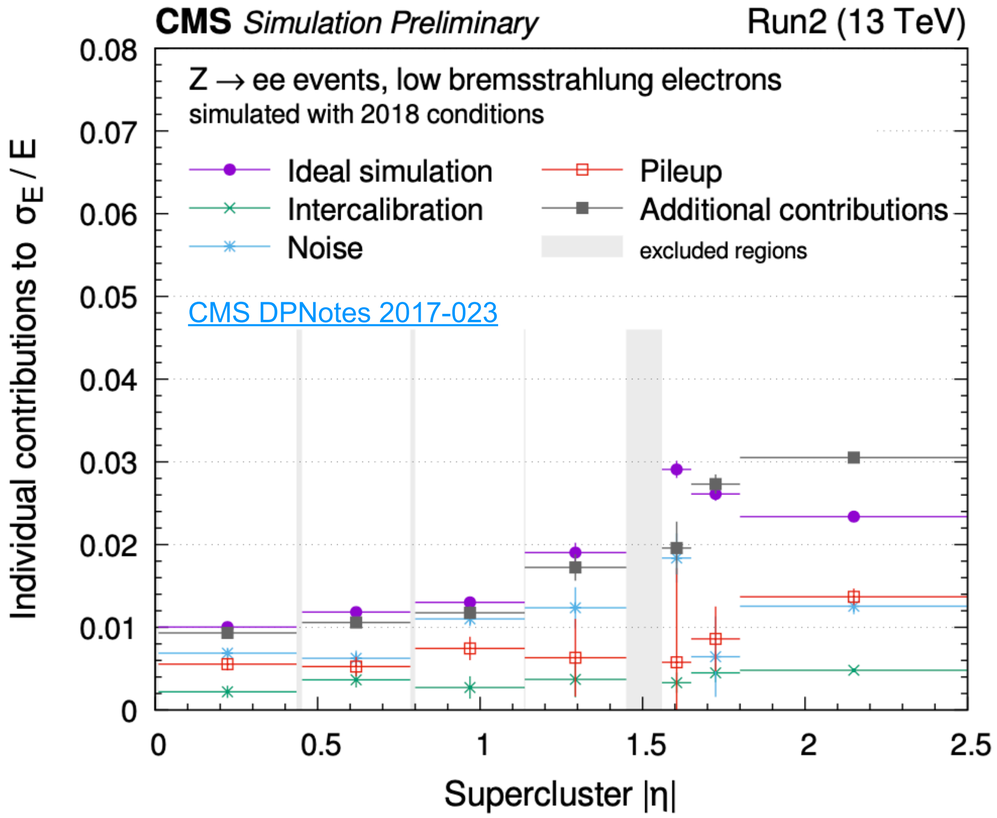
Ultimate performance
“Legacy” calibration ~40% better than preliminary!

CMS DPNotes 2019-038

Energy measurements wrap up

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

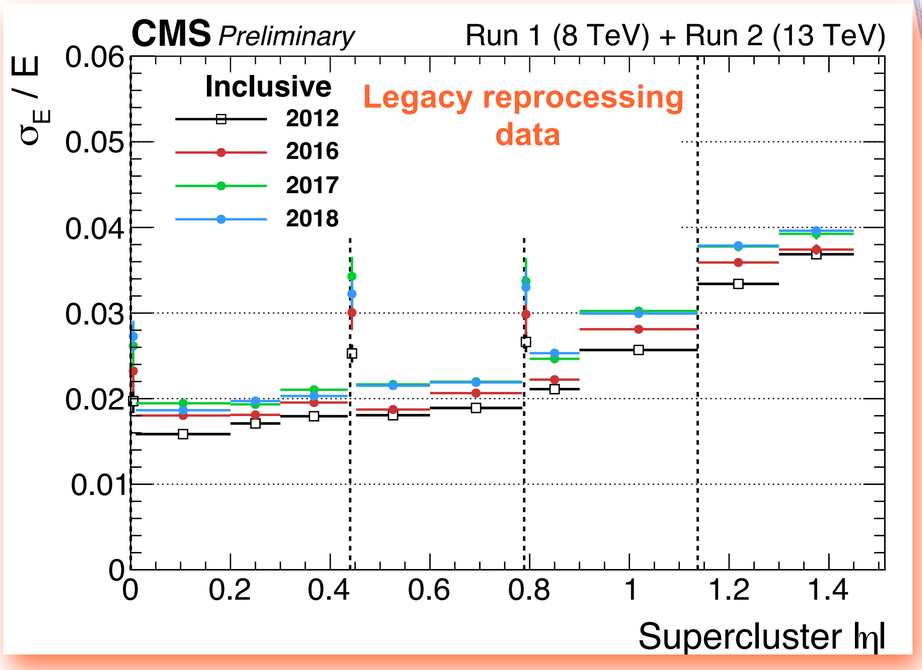
- **Contributions to resolution @ Run2:**
  - **Intercalibration** almost negligible
  - **Noise** and **pile up** significant and comparable:
    - **Run3**: ML algo to control under development
  - Contribution for unaccounted effects significant:
    - **Well described by gaussian smearing**
    - **Stable over time**



ECAL performance

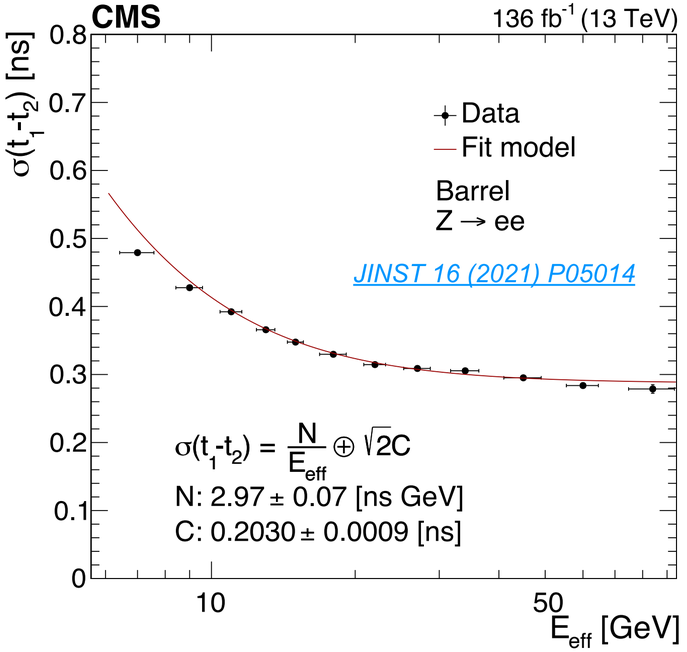
- **Run 2 Legacy reprocessing:**
  Fine grained calibration in:
  - detector volume
  - **time/luminosity**
    Essential to the highest quality resolution
  - **Run3 Goal**: automatize calibration methods involving data
    - **Corrections specific for each data taking period**

CMS DPNotes 2020-021



+ ECAL Timing - more in Stefano's talk

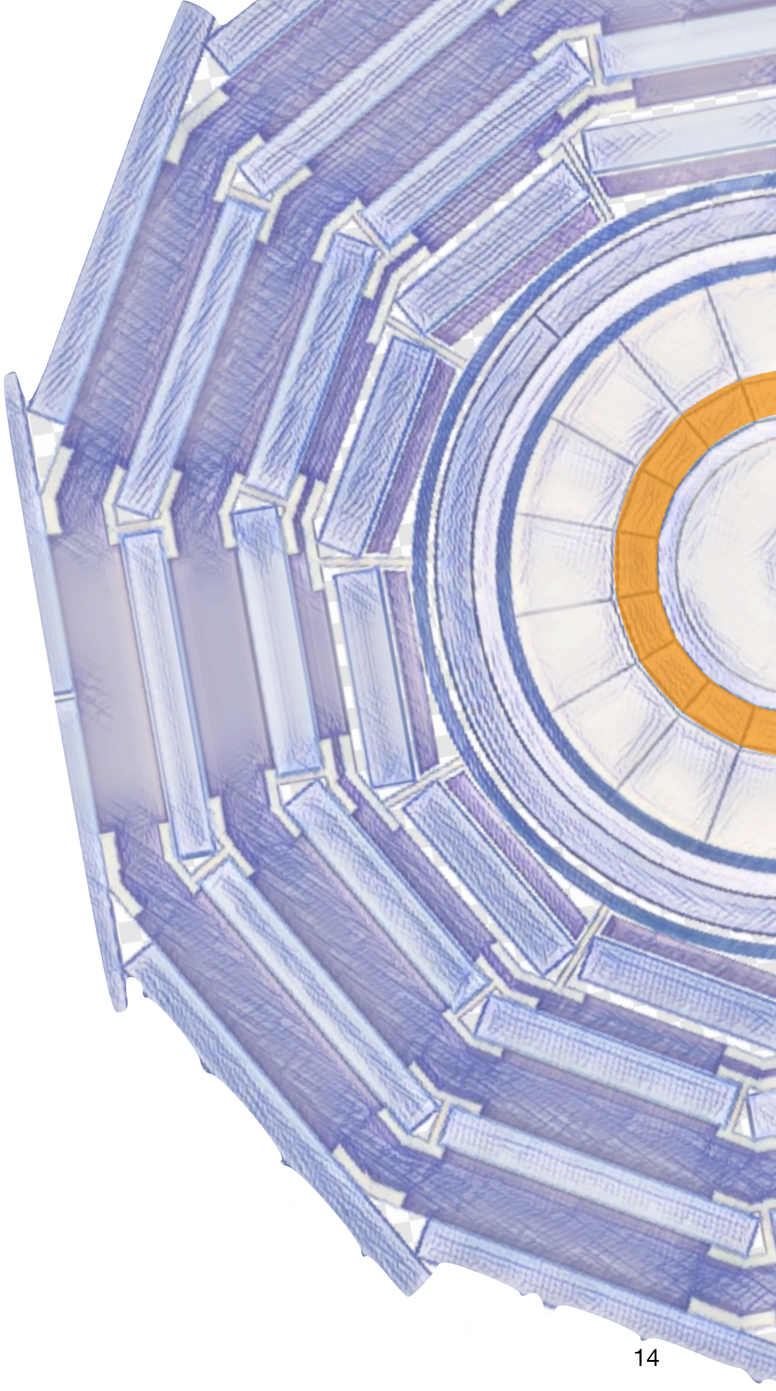
- **Excellent timing performances**
  - **Already exploited in LLP searches, spikes hunt**
  - **Pivotal in HL-LHC for rising pile up rejection**



Summary

ECAL reconstruction and calibration are crucial to deliver and preserve ECAL optimal performance

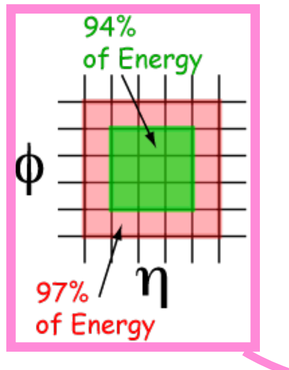
- **Proven as a continuous, meticulous job but extremely rewarding challenge**
  - Run2 Legacy reprocessing:
    ~ 1 year of work = 40% better overall performance
- **Challenges ahead of us:**
  - Noise and Pile Up increasing levels
  - Automatisation of calibration
  - ECAL HL-LHC upgrade
  - Barrel electronics substitutions:
    - Cope with HL radiation rates
    - Better exploit timing measurements



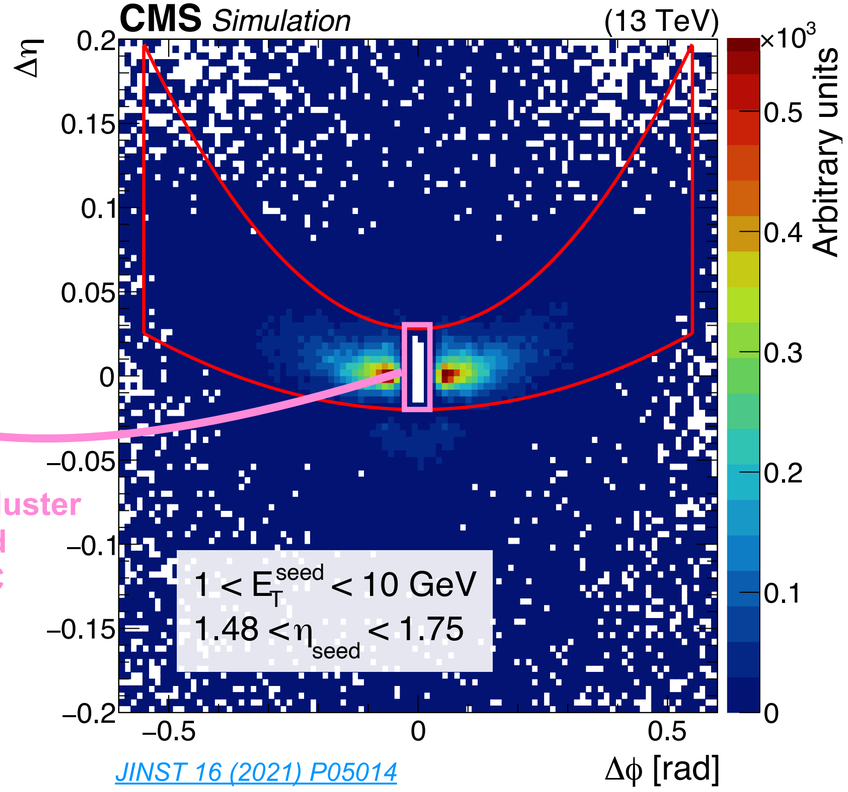
Backup

Signals localization: clustering algorithms

An **unperturbed** photon/electron EM shower in ECAL crystals array



photon/electron showers within CMS
Shower is spread due to e/γ interactions with tracker Material effects..



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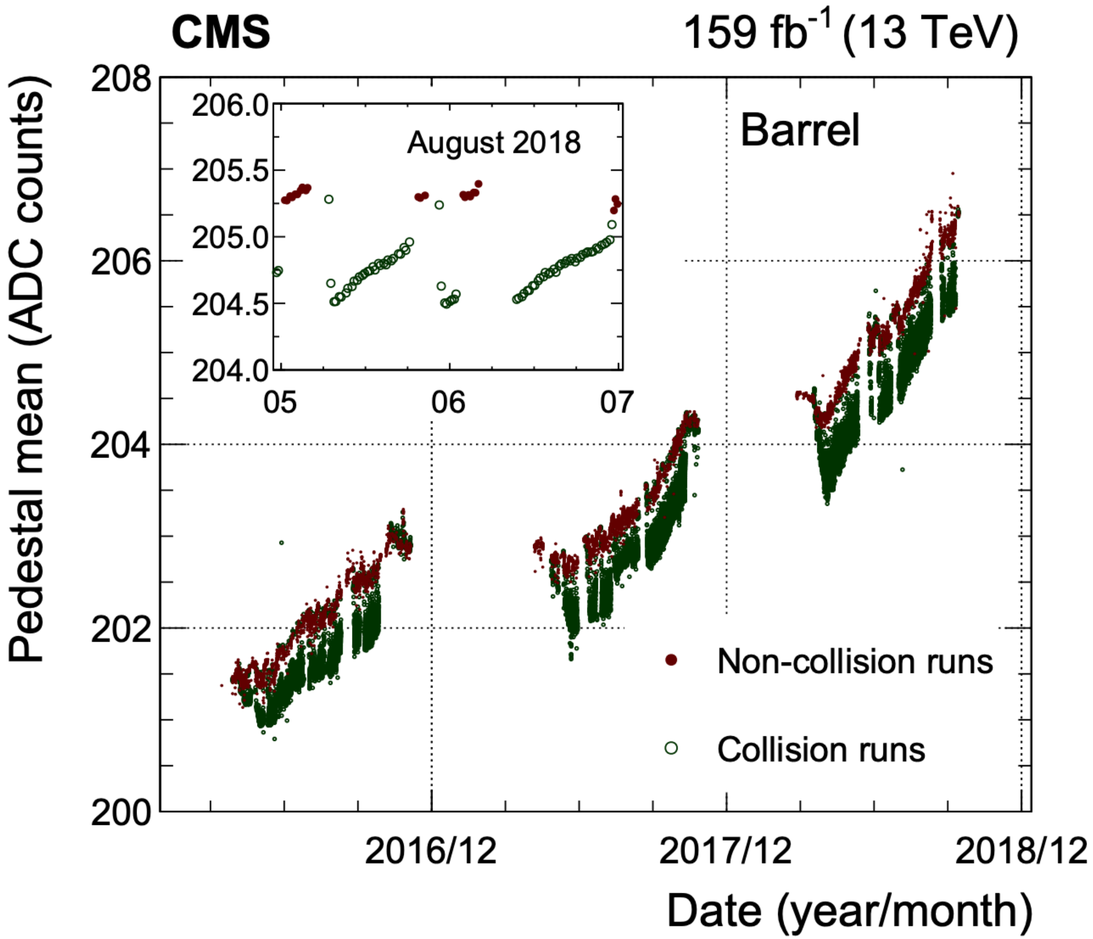
The elementary cluster is just a seed to the full SC

ES + ECAL clusters above a certain energy threshold = **seed clusters**

- Algorithm hunts for nearest to seed clusters
  - Why a moustache: CMS solenoidal magnetic field spreads radiated energy more in φ than in η
- Refining algorithm on top of mustache SC:
  - ECAL x other detectors info
- **Run2:**
  - Threshold for hits clustering **retuned**
    - Pile up mitigation
    - Noise contamination
  - ES adjusted to cope with **increasing irradiation**

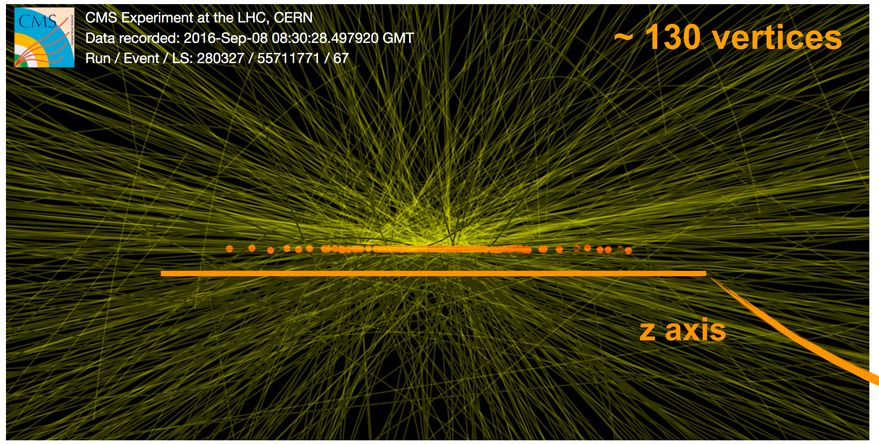
Pedestals behavior through time



1 ADC ~ 40 MeV

Towards higher luminosities

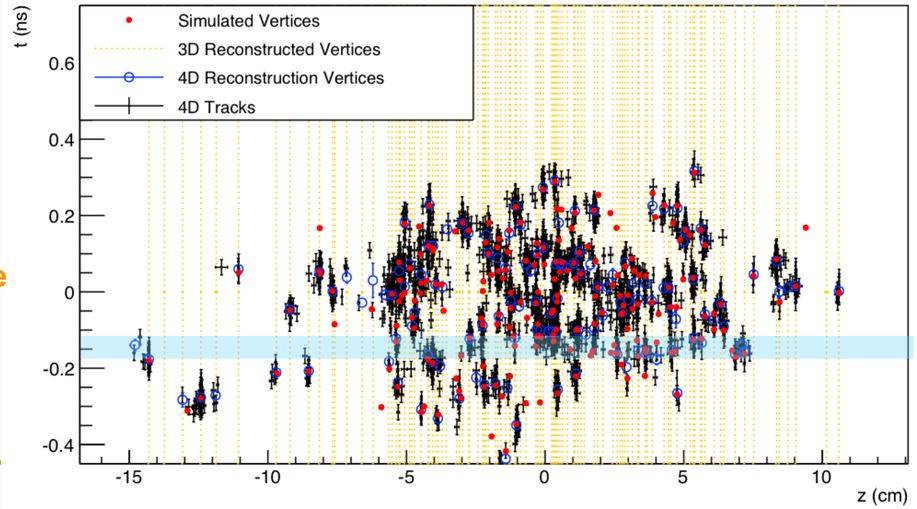
HL-LHC: LHC to overcome nominal LHC luminosity by a factor 5 to 7.5



Event recorder @ CMS in 2016 with pile up conditions similar to HL-LHC

Expand vertex in the time dimension

Slice collisions time In windows To reach lower Pile up levels

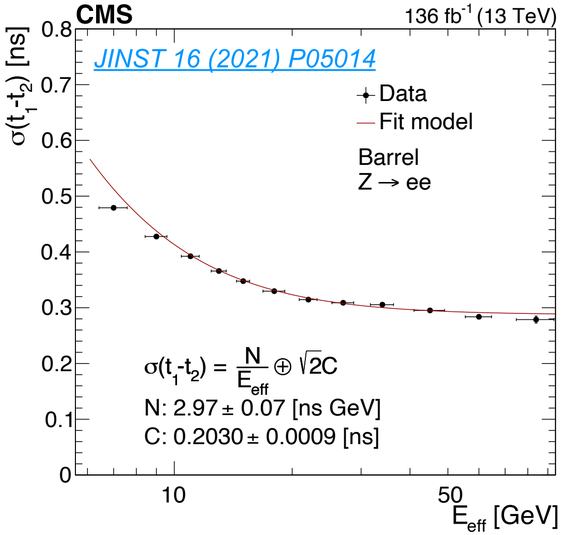


@ 30 ps Window holds ~ 40 vtxs

ECAL timing developments - more about this in Badder's talk

Fundamental for HL -LHC

Timing info
To be combined with timing
From novel MTD detector
(Expected reso ~40ps)



Excellent time resolution for Run1+ Run2 data already plenty exploited:

- LLP searches
- Trigger driven spikes hunt

Refinements: ES for basic ID

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ES: counter for charged particles

Essential for
Photons/neutral hadrons separation

Run2: to cope with irradiation

MIP response tuning:

in dedicated short runs
With high gain for MIP sensitivity