Performance of the CMS electromagnetic calorimeter during the LHC Run II

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on behalf of the CMS collaboration

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https://indico.cern.ch/event/642256/sessions/272435/#20180521

Outline

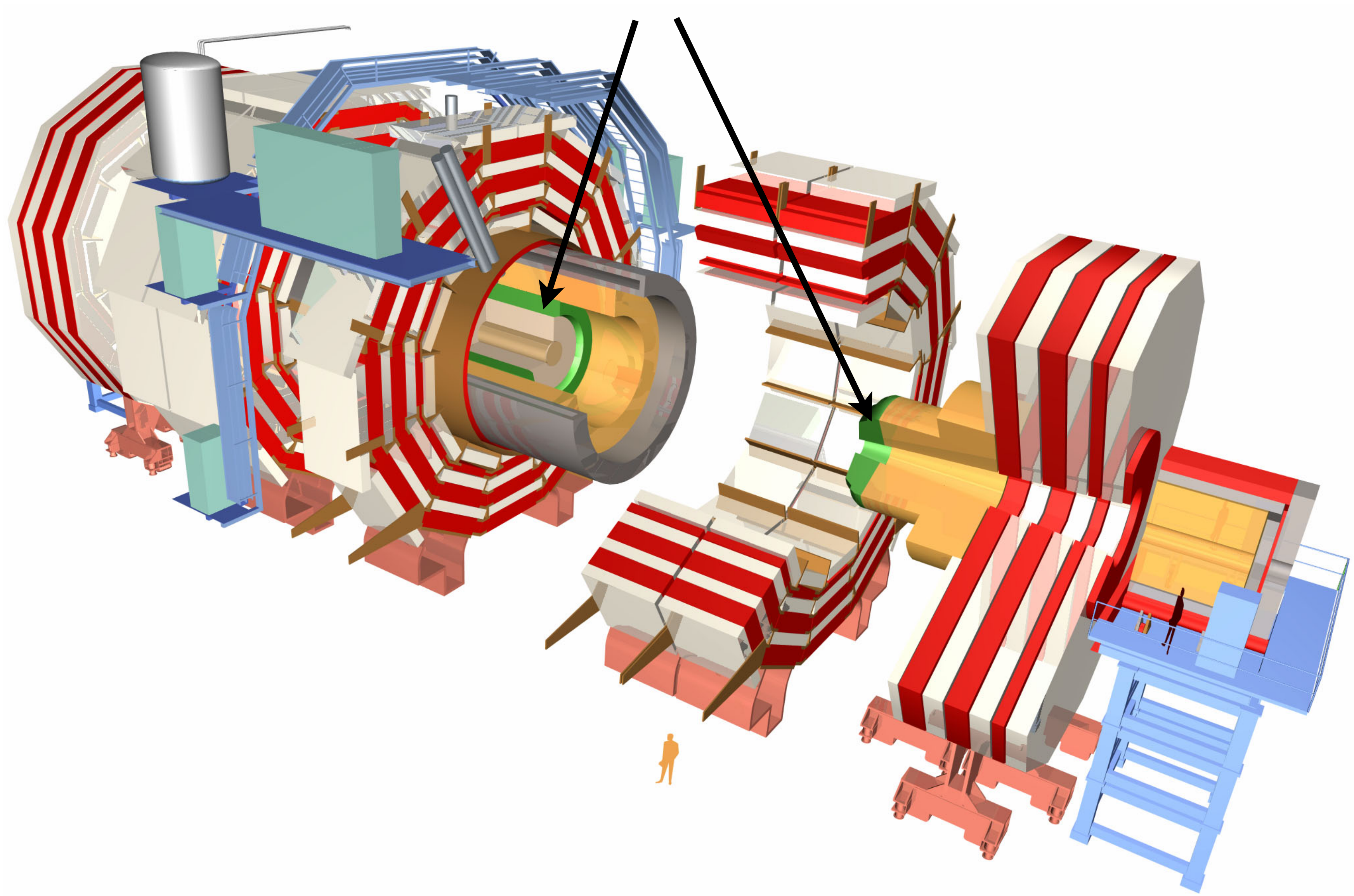
1. Description of the CMS Electromagnetic CALorimeter ECAL and Performance
2. Energy reconstruction with ECAL
3. Energy Resolution of ECAL during 2017 LHC Run II
4. Summary and prospects

CMS Electromagnetic Calorimeter

ECAL

The CMS Detector and the ECAL

Electromagnetic calorimeter (ECAL)

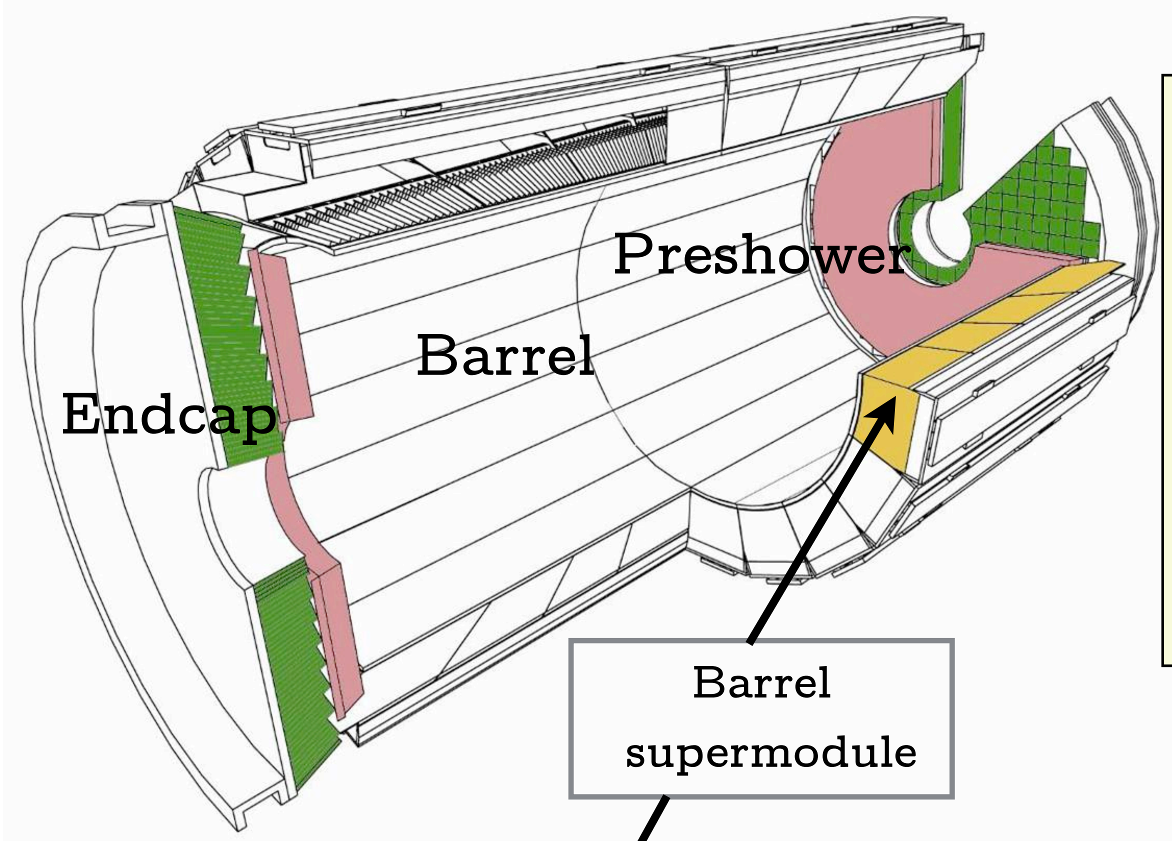


CMS:
Length: 21.5m
Diameter: 15m
Weight: 14kT
Magnetic field: 3.8T

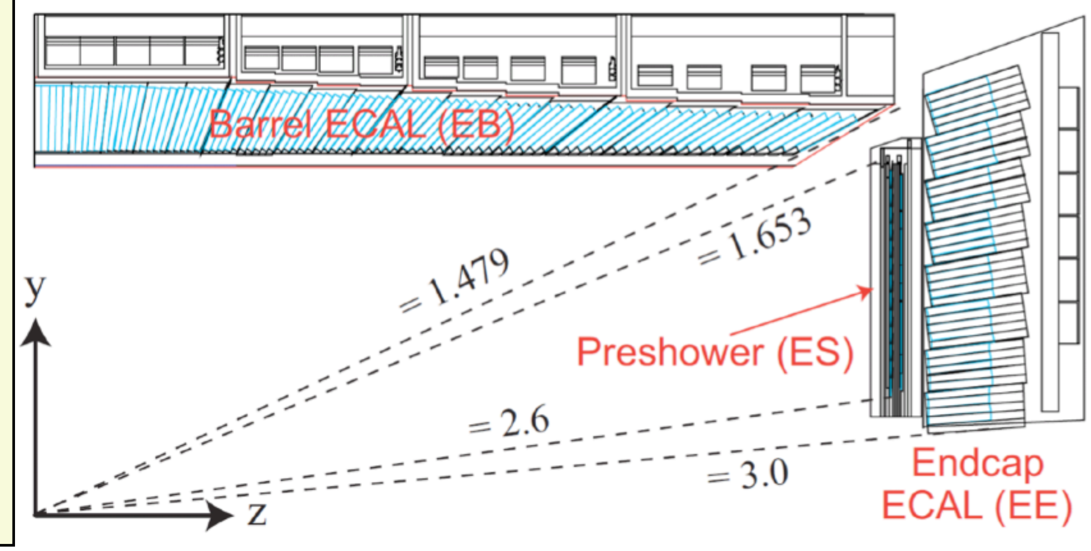
ECAL: the main component of CMS to detect and precisely measure the energies of electrons and photons.

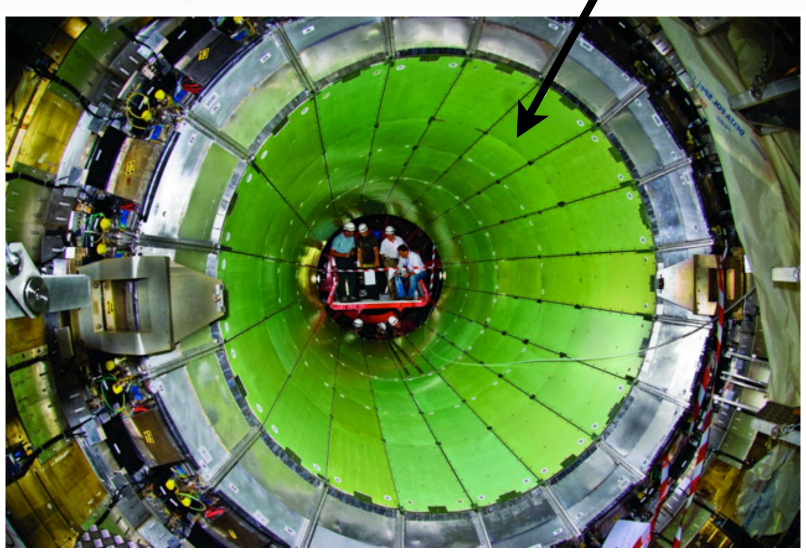
Goal: excellent di-photon mass resolution (~1%), needed for $H \to \gamma\gamma$ observation

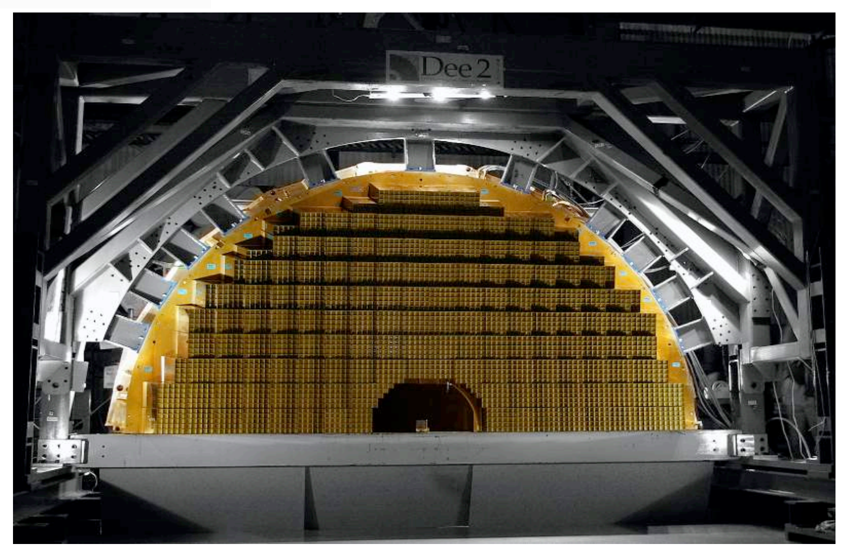
The CMS Electromagnetic Calorimeter

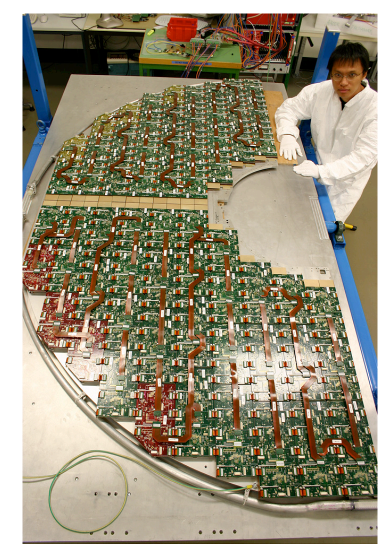


Lead Tungstate Crystal Barrel & Endcaps ($PbWO_4$) + Lead/Si Preshower









Barrel (EB)

36 supermodules (1700 crystals)
Total of 61200 $PbWO_4$ crystals
Avalanche PhotoDiode readout
coverage: $|\eta|<1.48$

Endcap (EE)

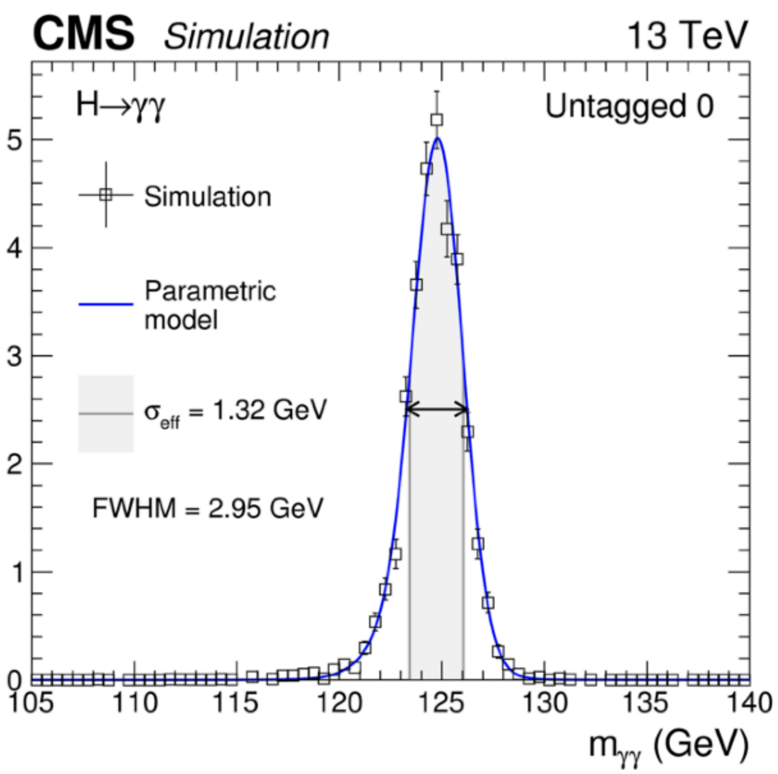
4 half-disk Dees (3662 crystals)
Total of 14648 $PbWO_4$ crystals
Vacuum PhotoTriode readout
coverage: $1.48<|\eta|<3.0$

Preshower (ES)

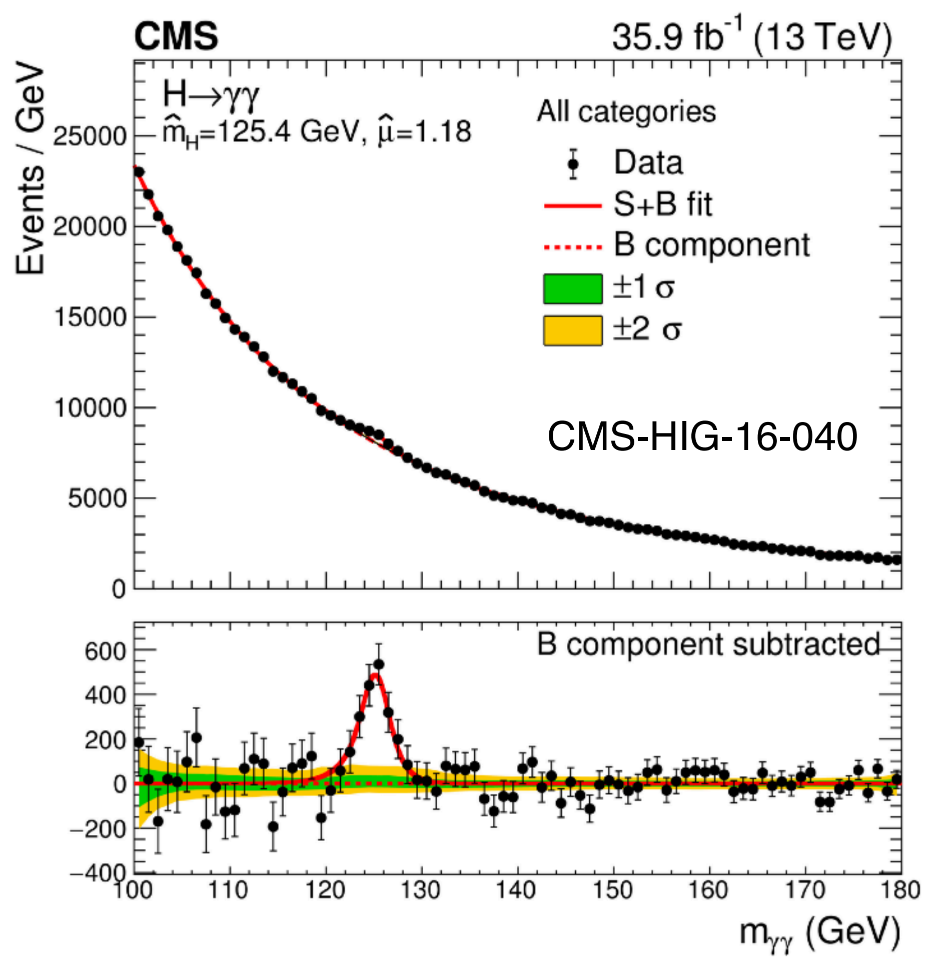
Two Lead/Si planes
137216 Si strips ($1.8x61mm^2$)
coverage: $1.65<|\eta|<2.6$

Physics output

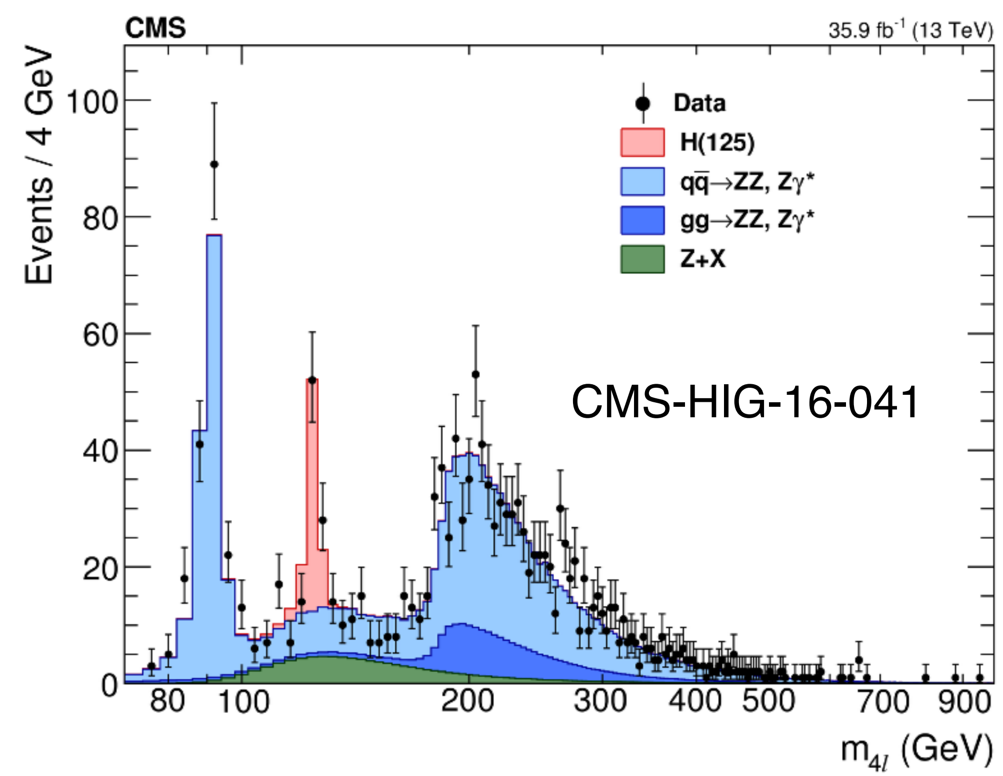
H→γγ



Mass resolution in best category ~1%



H→ZZ→4l



The excellent resolution and electron/photon ID of the CMS ECAL was crucial in the discovery and subsequent characterization of the 125 GeV Higgs Boson

The continued excellent performance of ECAL in the entire pseudorapidity range is a key component of many searches for new Physics

Overall ECAL Performance during 2017 Run

1. LHC delivered almost $50fb^{-1}$ during 2017
2. Beam intensities reached $1.7x10^{34}$ $cm^{-2}s^{-1}$ and peak pileup up to 60
3. ECAL performed smoothly throughout 2017 with
   - Up-time > 99%
   - Data certified as good : 99.5 %
   - Active channels EB+EE: 99% and ES: 99.9%
4. Our online and offline procedures have constantly been improved to cope with increasing LHC beam intensities, and the effects of detector aging

Online Performance: ECAL Trigger

ECAL provides important information to the CMS trigger system

- Trigger primitives for e/γ, jet, τ candidates and calorimeter energy sums
- Rejection of direct signals in the barrel APDs (“spikes” - see C. Schiber’s talk)

Recent improvements

- Regular corrections applied to account for detector aging (crystals and photodetectors) $\rightarrow$ stable L1 calorimeter trigger rates
- Account for aging effects in front-end electronics $\rightarrow$ to maintain optimal spike rejection
- Suppression of η-dependent noise in the forward regions of ECAL (intrinsic noise amplified by detector aging corrections)
- Recovery from Single Event Upsets (due to higher beam intensities in Run II) with automatic detection and masking of problematic channels

e/γ Energy Reconstruction

e/γ Energy Reconstruction

EM energy is reconstructed with a dynamic clustering algorithm to form a basic cluster

1. ECAL crystal transverse size chosen as ~R_M (Molière Radius of $PbWO_4$) so EM showers spread over several crystals
2. Basic clusters are extended in Φ direction to form superclusters (SC) to recover additional energy spread due to magnetic field, photon conversion/electron bremsstrahlung

Reconstructed e/γ energy is the sum over all crystals in a supercluster (SC)

global scale

inter calibration

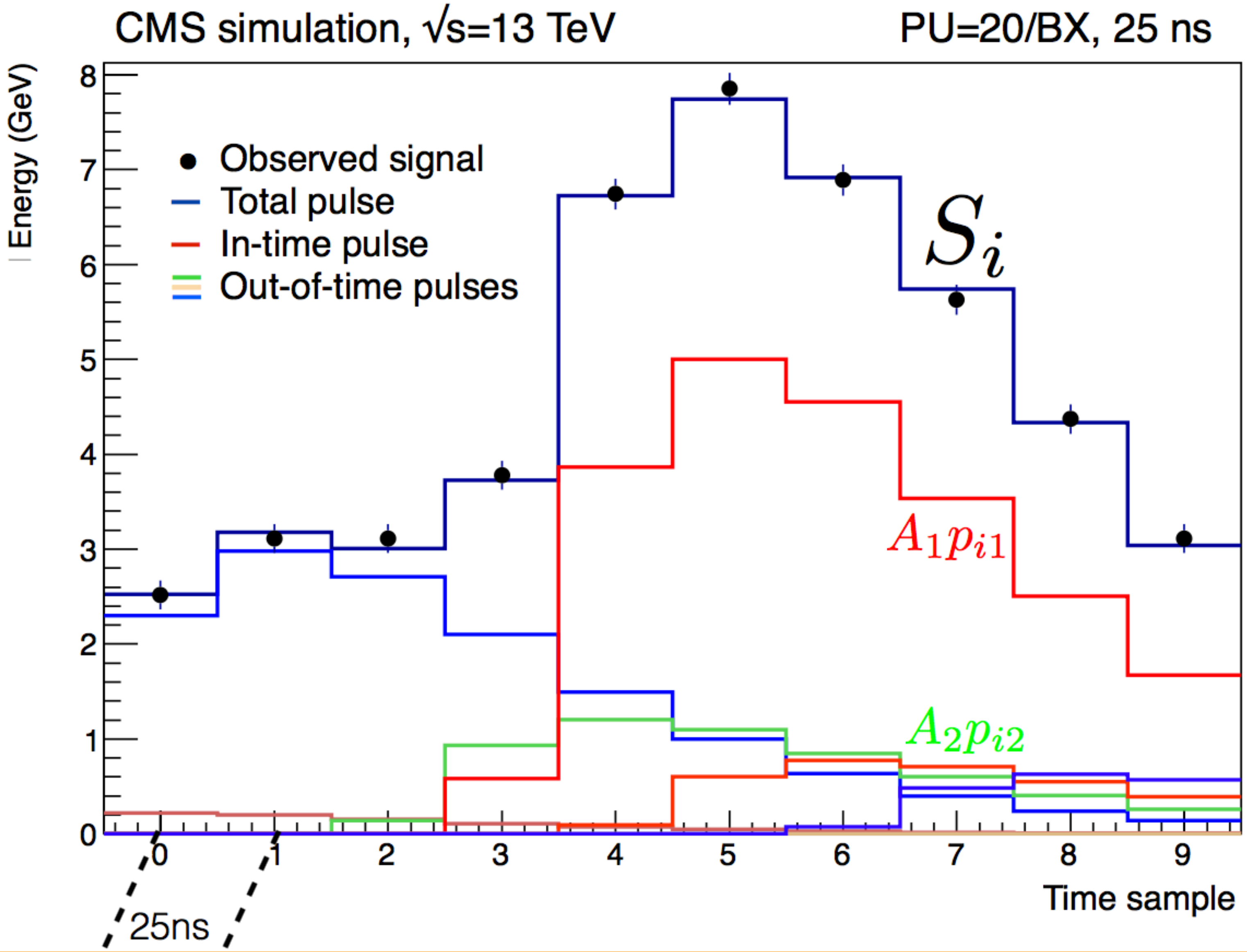
$$E_{e,\gamma} = F_{e,\gamma} \cdot G \cdot \sum_i S_i(t) \cdot C_i \cdot A_i(t)$$

cluster corrections

laser monitoring

pulse amplitude

Energy Reconstruction and Crystal Dependent Quantities: Pulse Amplitude/Pulse Shape(t)

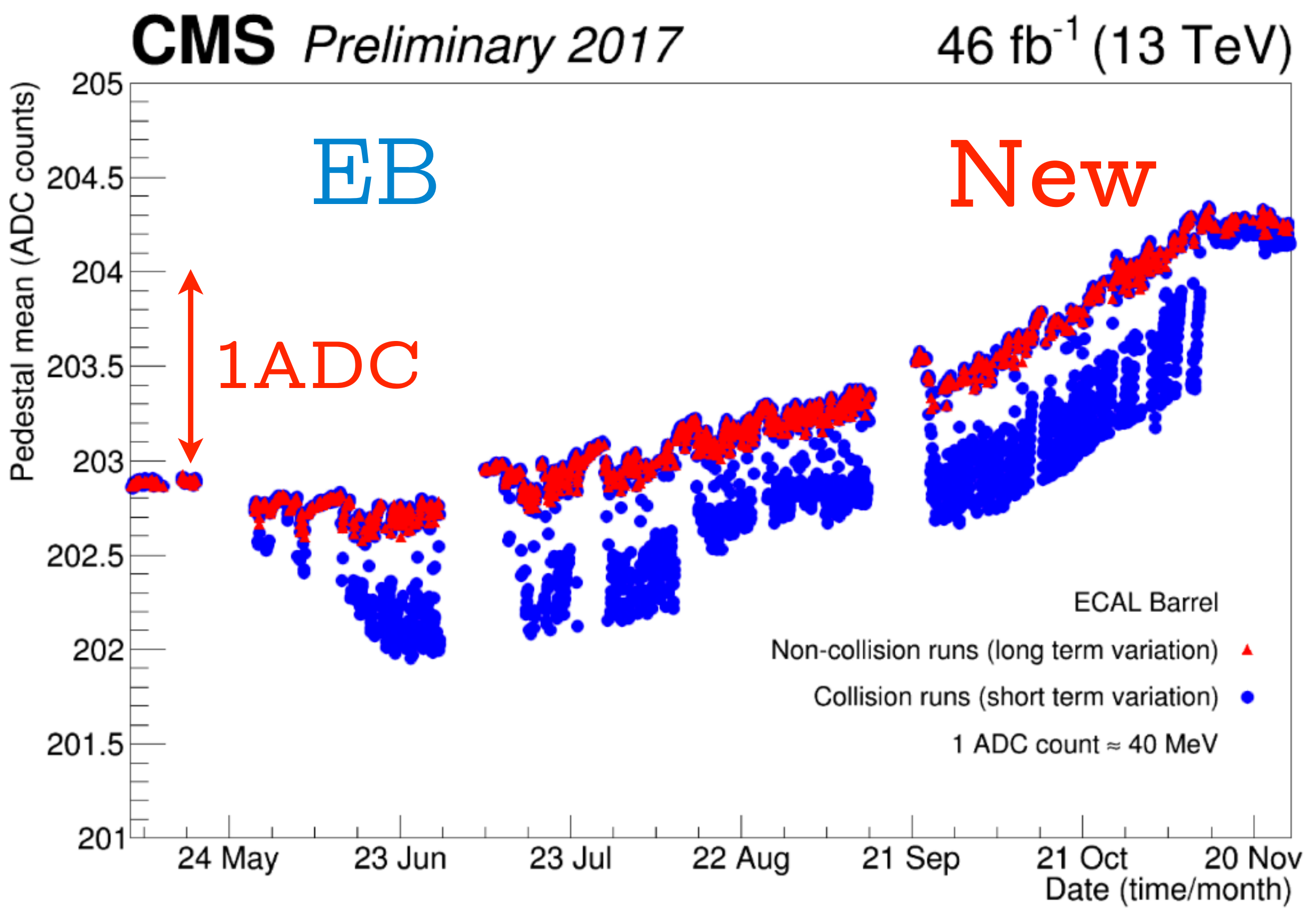


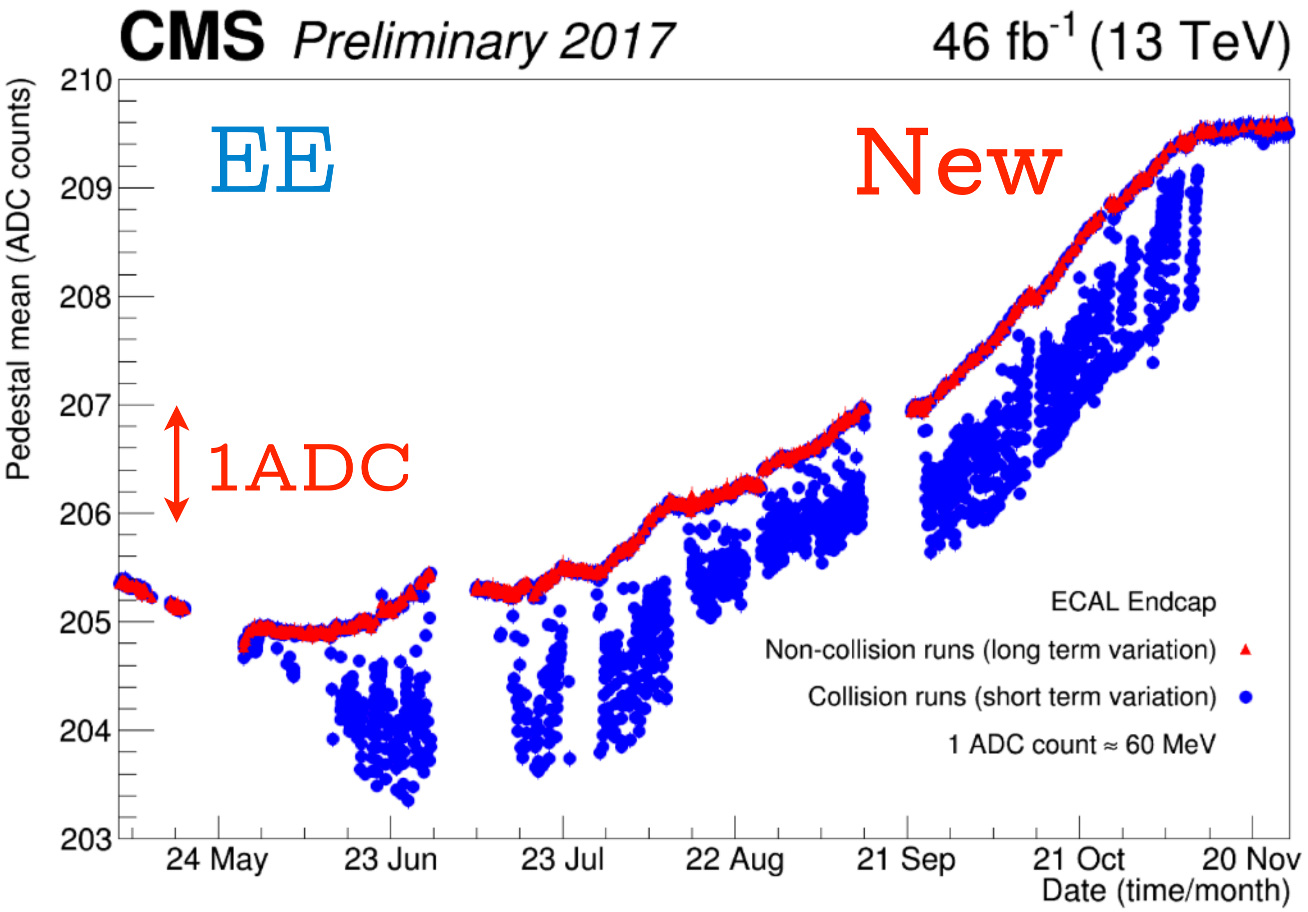
$$\chi^2 = \sum_{i=1}^{10} \frac{\left(\sum_{j=1}^{M} A_j \times p_{ij} - S_i\right)^2}{\sigma_{S_i}^2}$$

1. Multifit: pulse shape is modeled as in-time pulse plus several OOT pulses (up to 9)
2. Minimizing χ^2 to get best estimate of in-time pulse amplitude
3. Contamination from out-of-time (OOT) pulses effectively removed
4. Resolution improved w.r.t. Run I for e/γ reconstruction (substantial for low p_T)

1. Each pulse from APD/VPT is digitized in 10 samples
2. Run-I: Amplitude was a weighted sum of all 10 samples S_i
3. Run-II (higher pile-up): Multifit method and frequent measurement of the pulse shape templates
4. Because of the a template fit, pedestals must be also measured in order to be subtracted

Energy Reconstruction and Crystal Dependent Quantities: Amplitude/Pedestals(t)





Pedestals drift in 2017

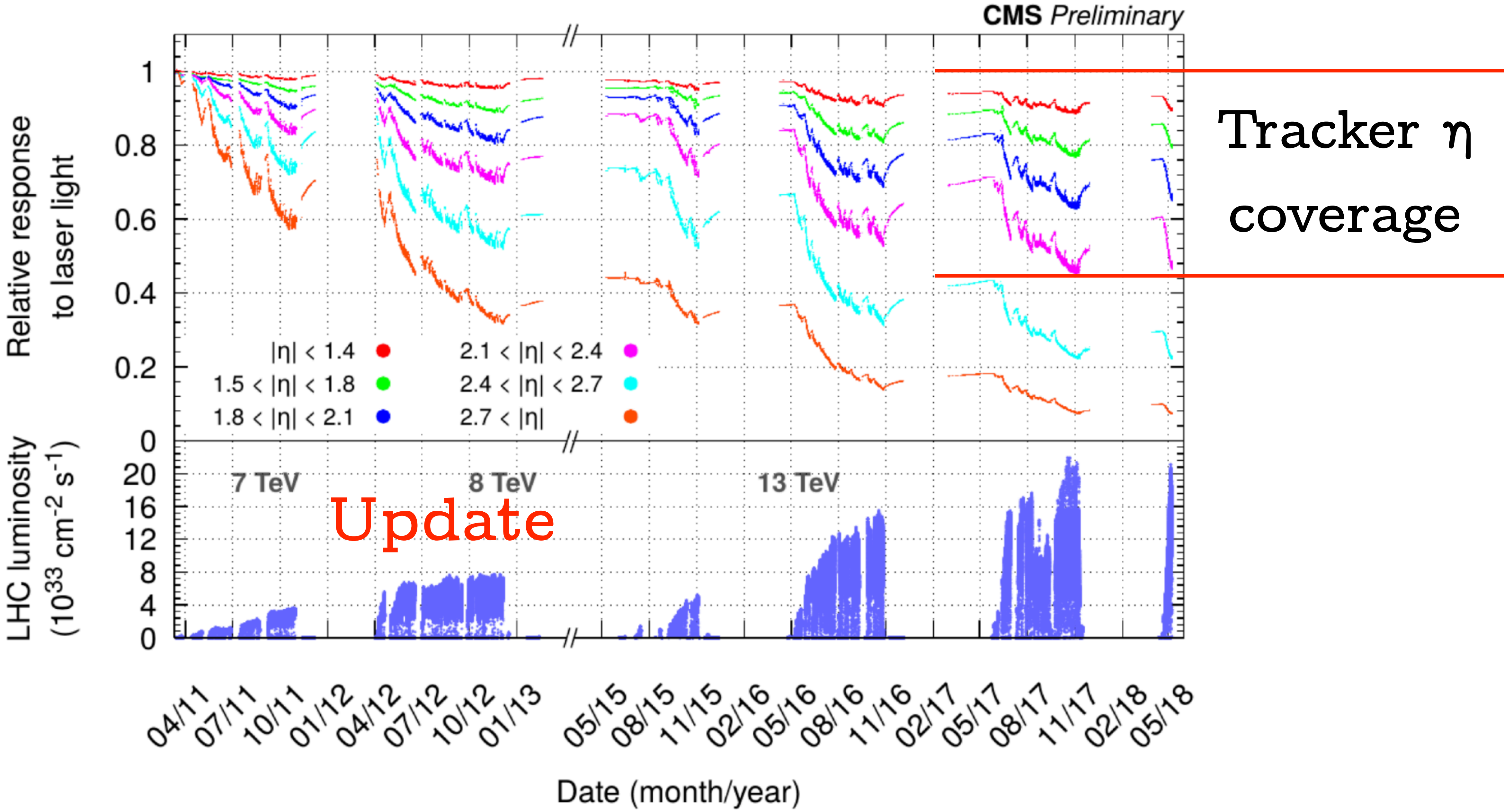
red = long term aging effects

blue = short term effects that depend on instantaneous luminosity

Pedestal measurements for each channel are directly used in the multifit.

Pedestal drifts observed during Run II - accounted for in the energy reconstruction with frequent pedestal updates

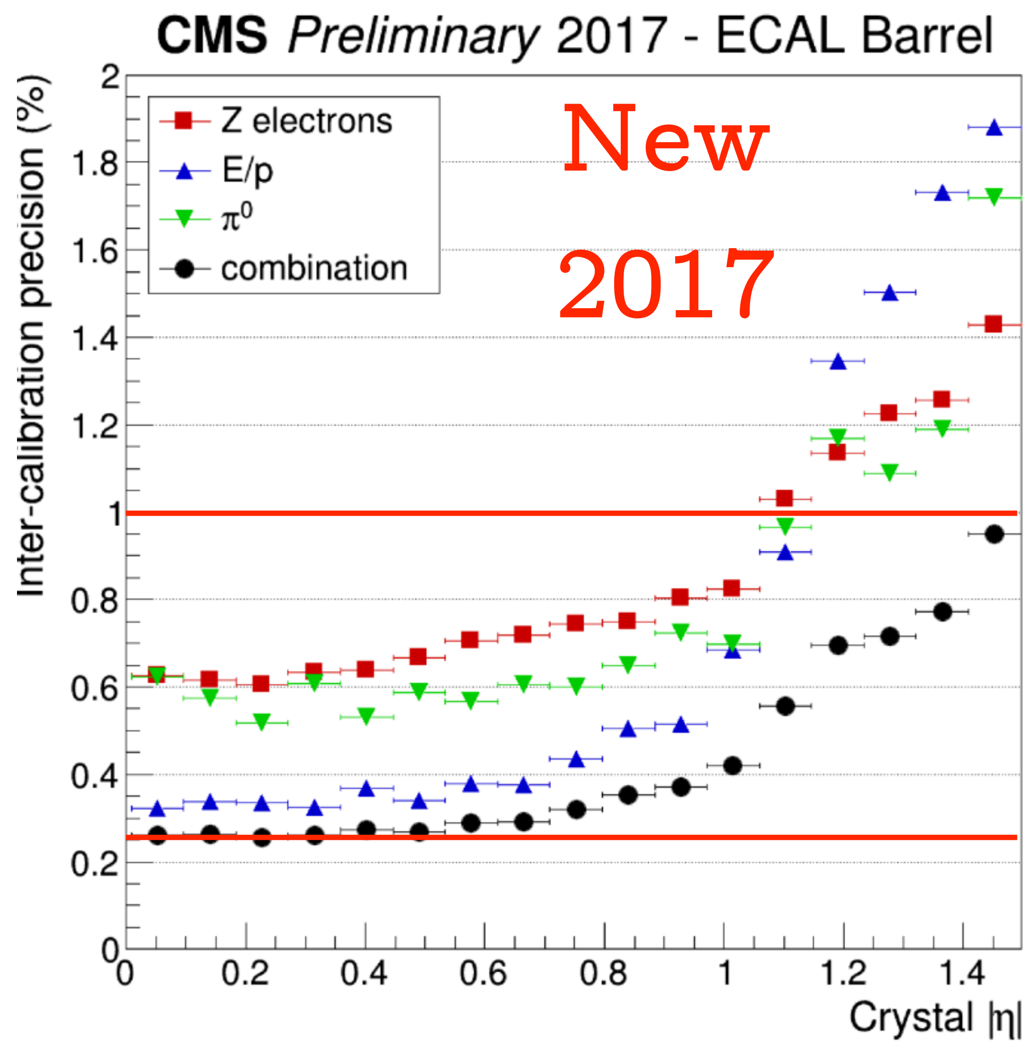
Energy Reconstruction and Crystal Dependent Quantities: $S_i(t)$, Response Correction



Response to laser light since 2011

Laser response measurements are recorded for each crystal every 40 minutes and the reconstructed energy is corrected accordingly

Energy Reconstruction and Crystal Dependent Quantities: C_i, single channel inter calibration



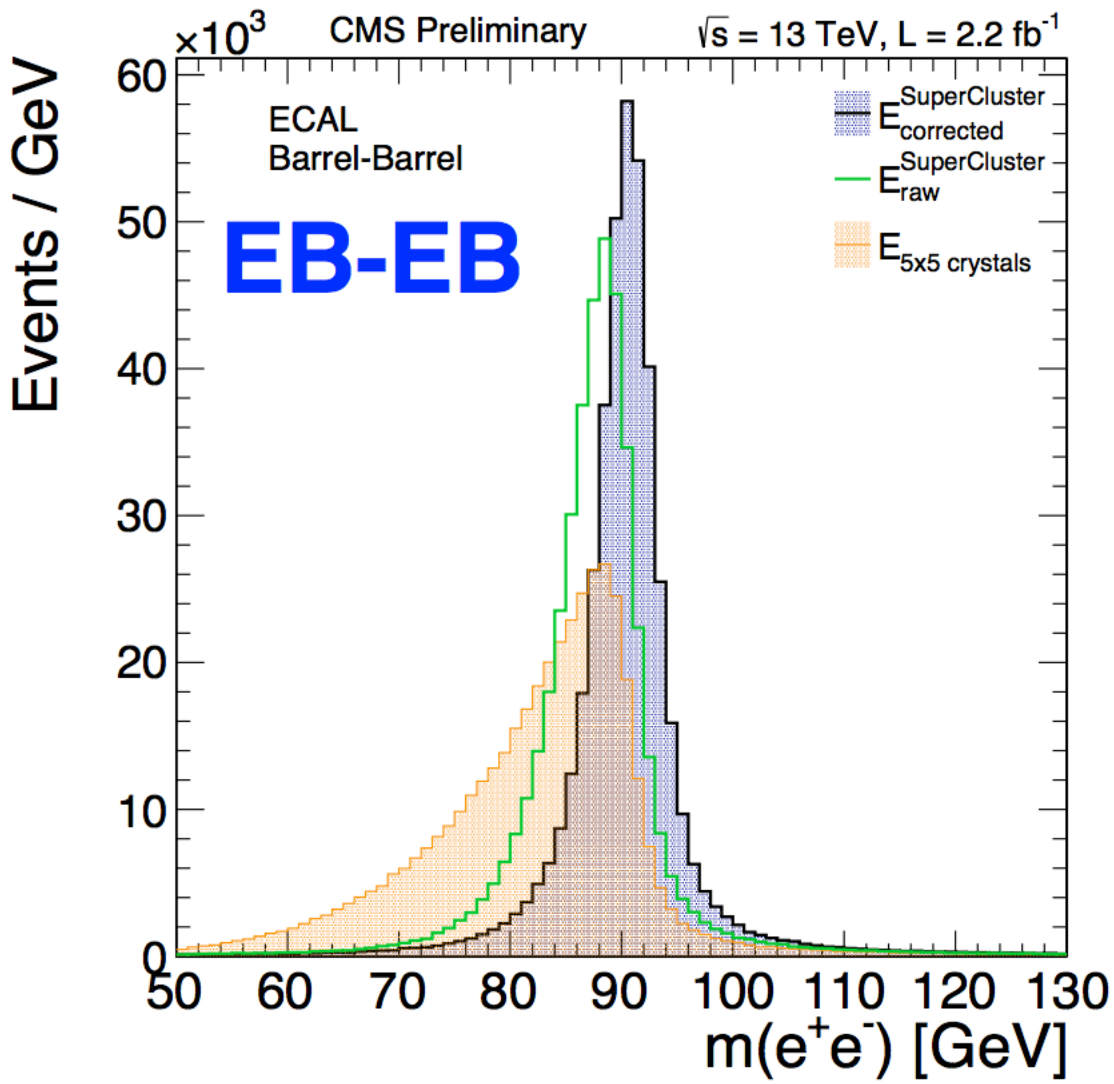
Run II: 0.25-1% in EB

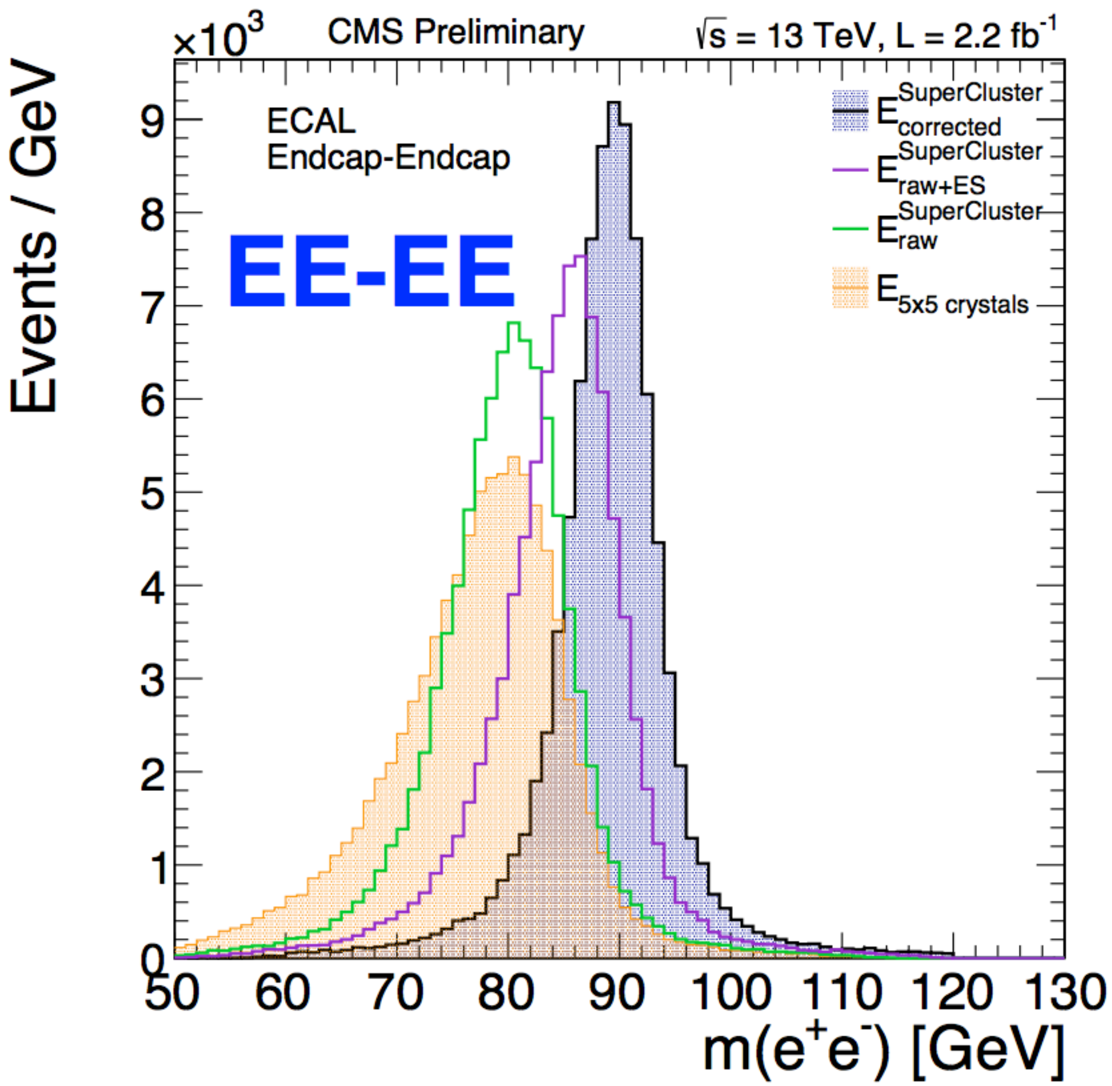
3 methods: π^0/η invariant mass, single electrons from W/Z (E/p), Z→ee mass (see T. Mudholkar's talk for more details)

The black points represent the precision of the combination of three methods (weighted average)

The IC precision contributes to the constant term of the final energy resolution

Energy Reconstruction and Global normalization: Supercluster (SC) energy correction $F_{e,\gamma}$





MVA training with MC simulation:

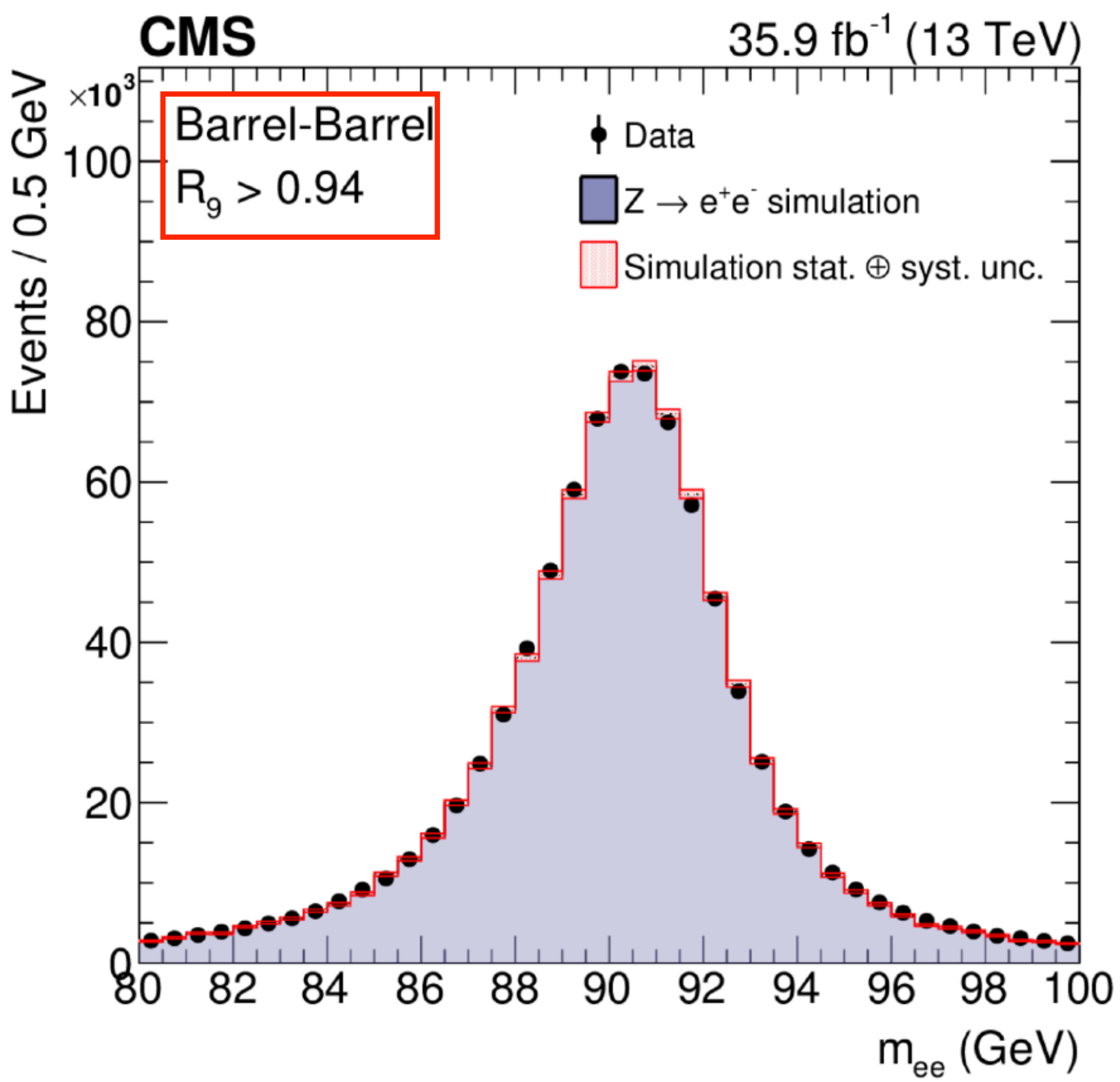
Crystal coordinates and shower shapes as input

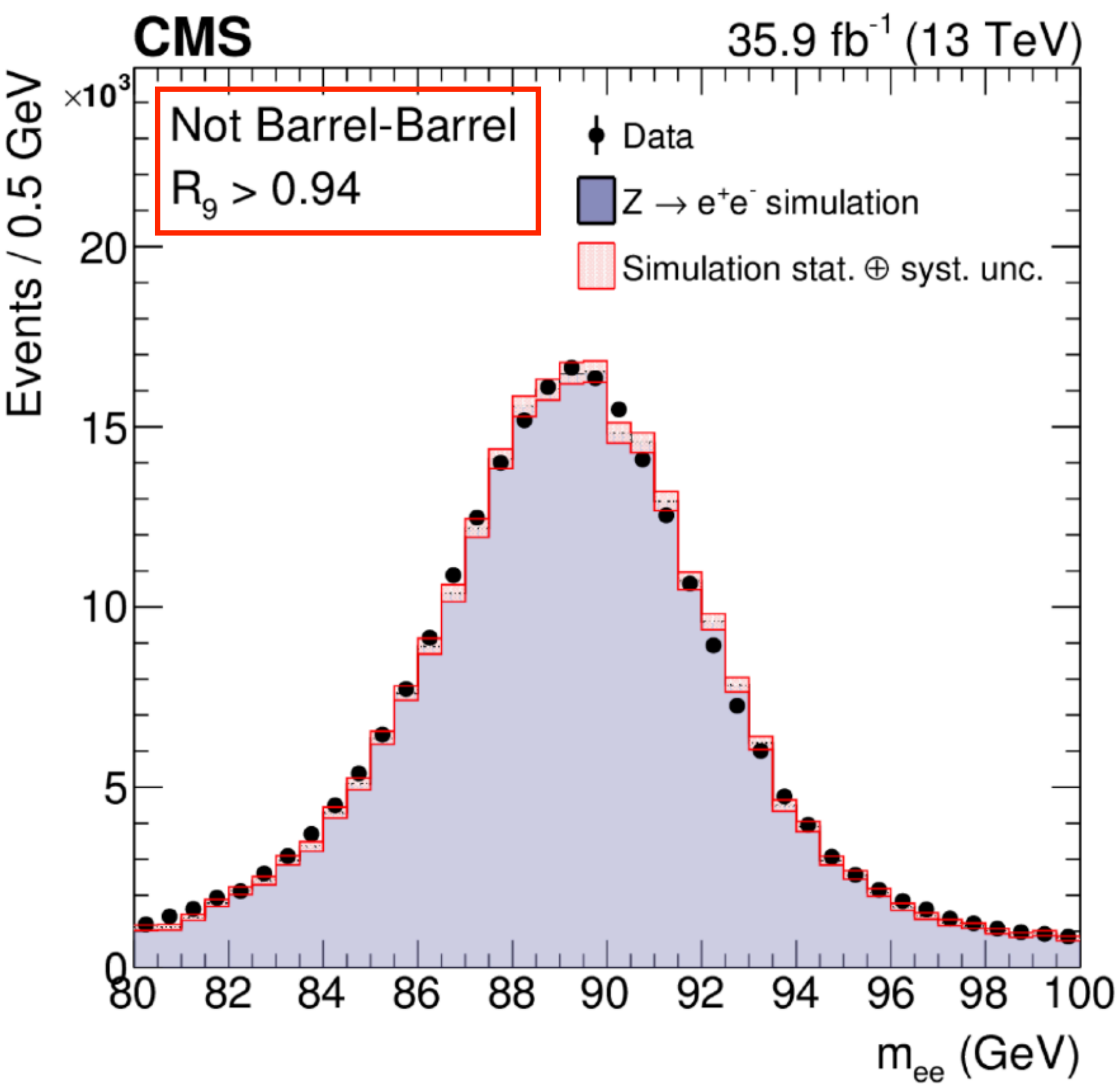
Electrons and photons MVA are tuned separately to take into account their different behaviors (conversion, bremsstrahlung)

Improvement on Z mass is demonstrated by using SC (vs. 5 x 5 cluster) and the MVA correction (vs. raw SC energy)

Energy Reconstruction and Global normalization: Absolute Energy Scale G

CMS-HIG-16-040

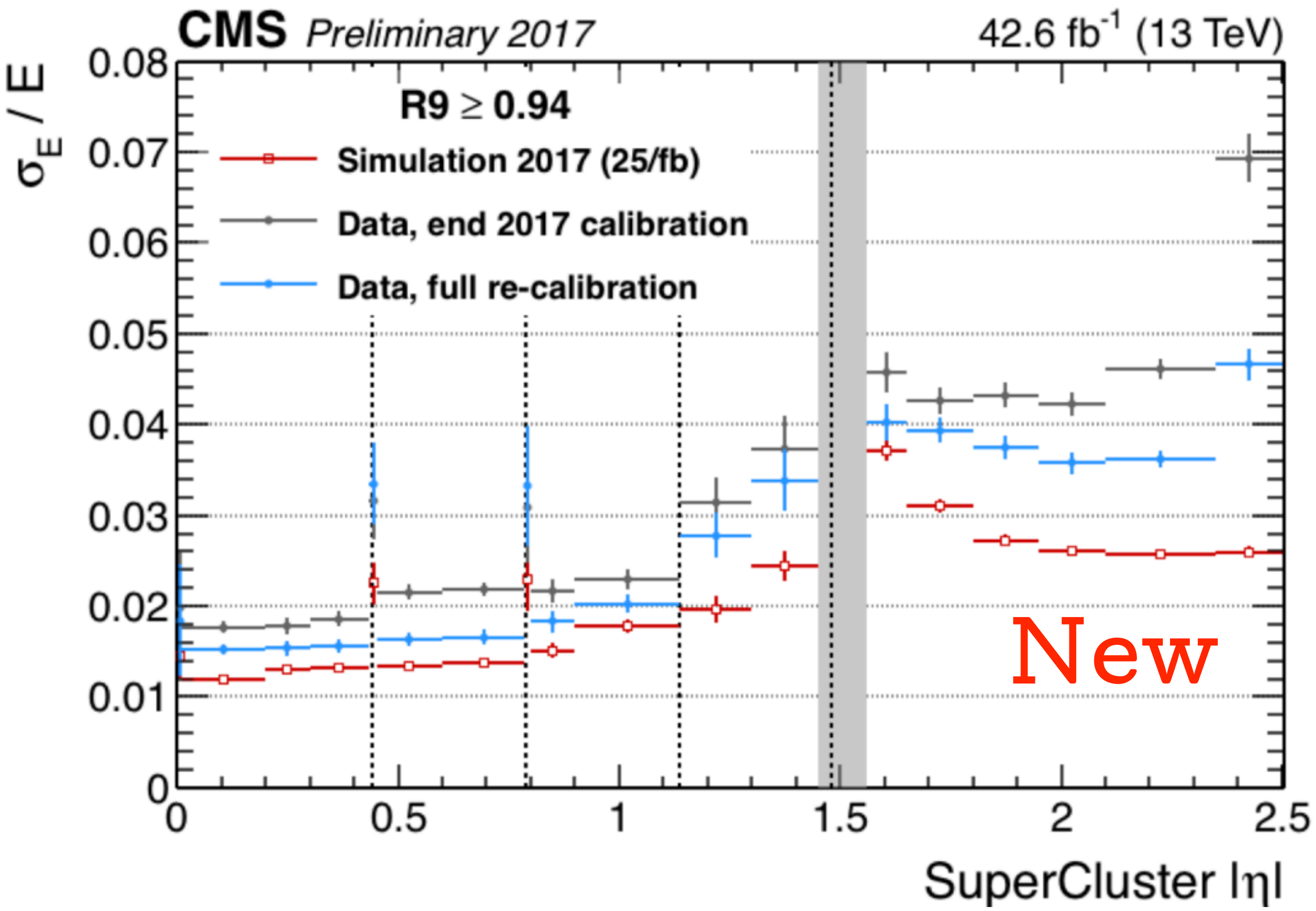


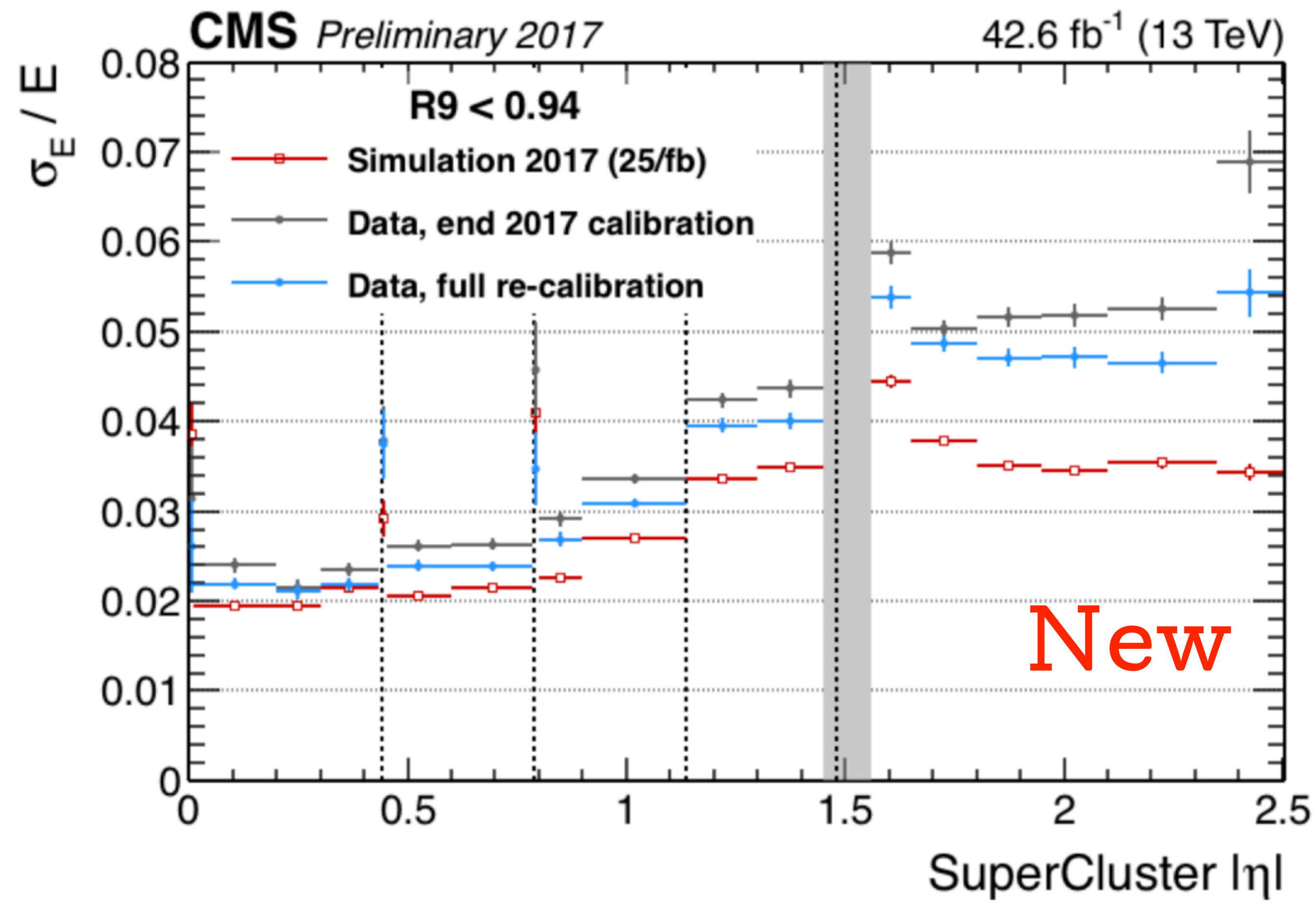


- The absolute energy scale calibration G is adjusted such that the fitted data Z→ee peak agrees with MC (see J. Rembser talk for more details)
- The η-dependance of the energy reconstruction is also taken into account using Z→ee events

CMS ECAL Performance

Offline Performance: Electron Energy Resolution





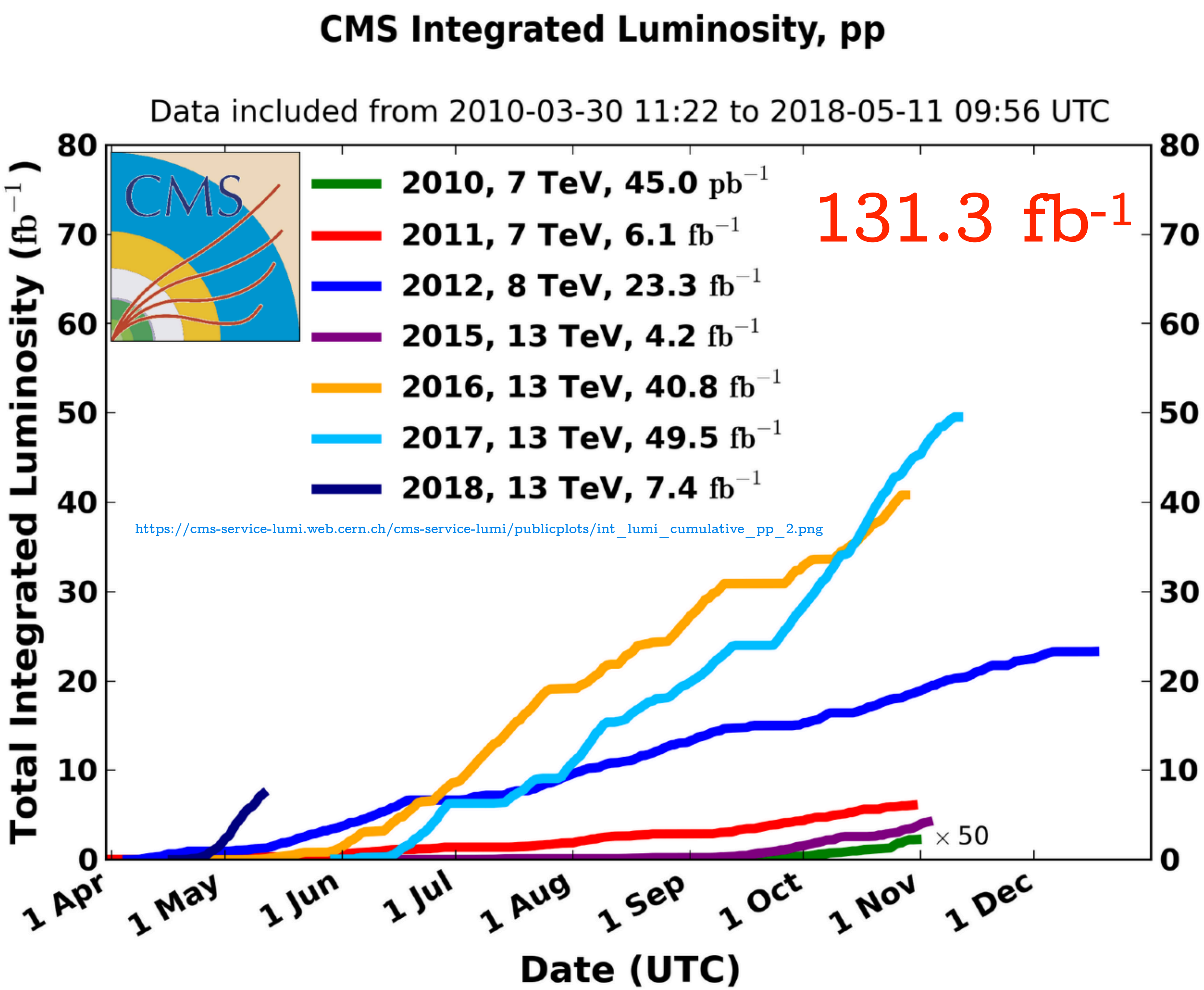
The resolution improves significantly after a dedicated calibration using the full 2017 dataset (blue points) with respect to the end-of-year-2017 calibration (gray points) for which only time dependent effects were corrected

Summary and prospects

1. ECAL has operated smoothly and with excellent performance during Run II
    1. ECAL online and offline reconstruction has been adapted to meet the challenges of higher LHC luminosity and detector aging
    2. Regular monitoring and updates of crystal response, pedestals, noise, and pulse shape and timing are performed to maintain stability of triggering and energy resolution
    3. Effective suppression of out-of-time PU using the multifit algorithm
2. With these updates, the excellent energy resolution and stability achieved during Run I has been maintained in Run II
3. Special care is given to the high η region of EE, where the crystal+photodetector response losses are greatest
4. Lessons learned here will be invaluable for Run III and for the performance of the ECAL Barrel in Phase II

Spares

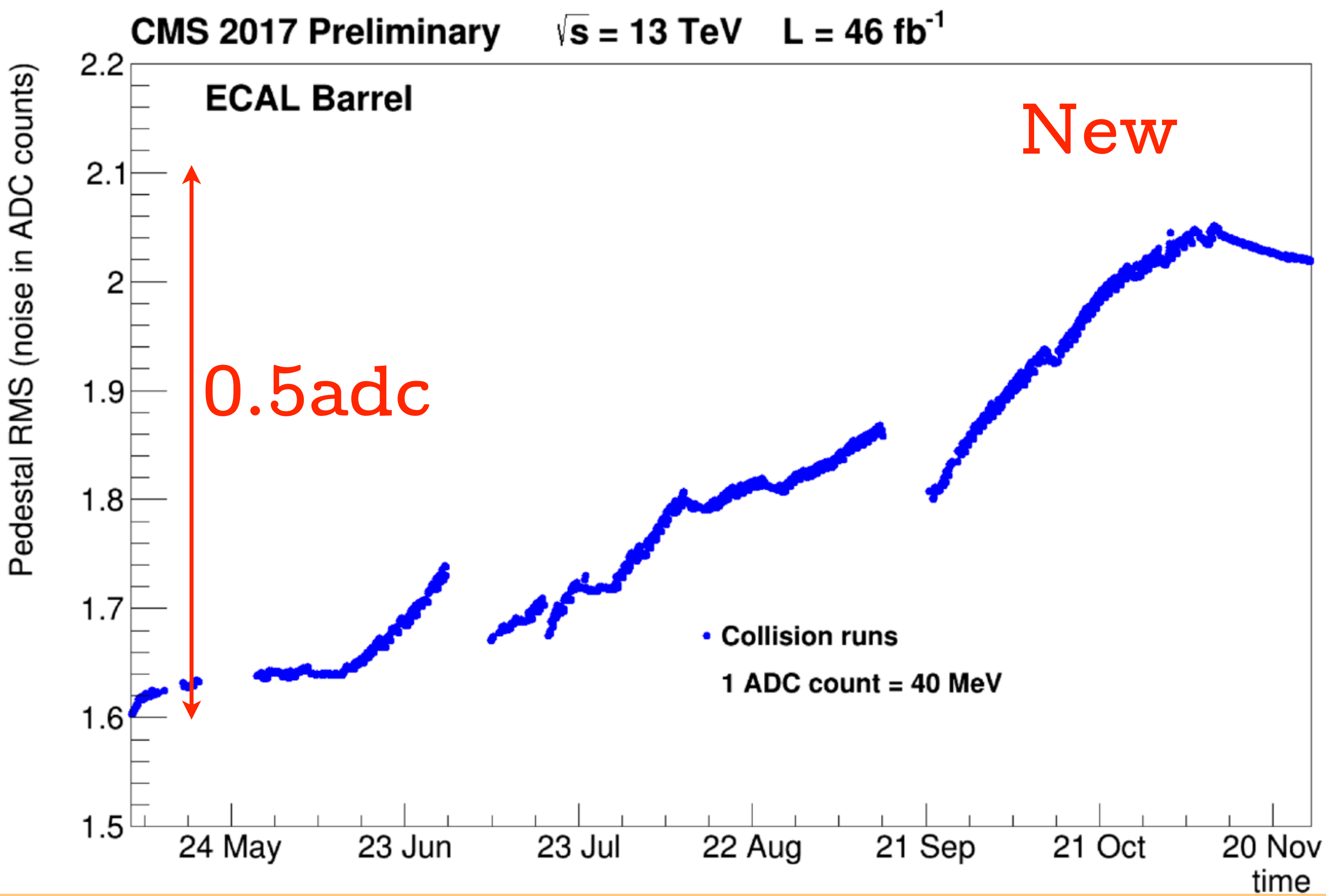
LHC Integrated Luminosity



LHC has delivered over 130 fb^{-1} since 2010 → detector aging needs to be taken into account

Much of the luminosity has been delivered in Run II → intensity related effects are increasingly important

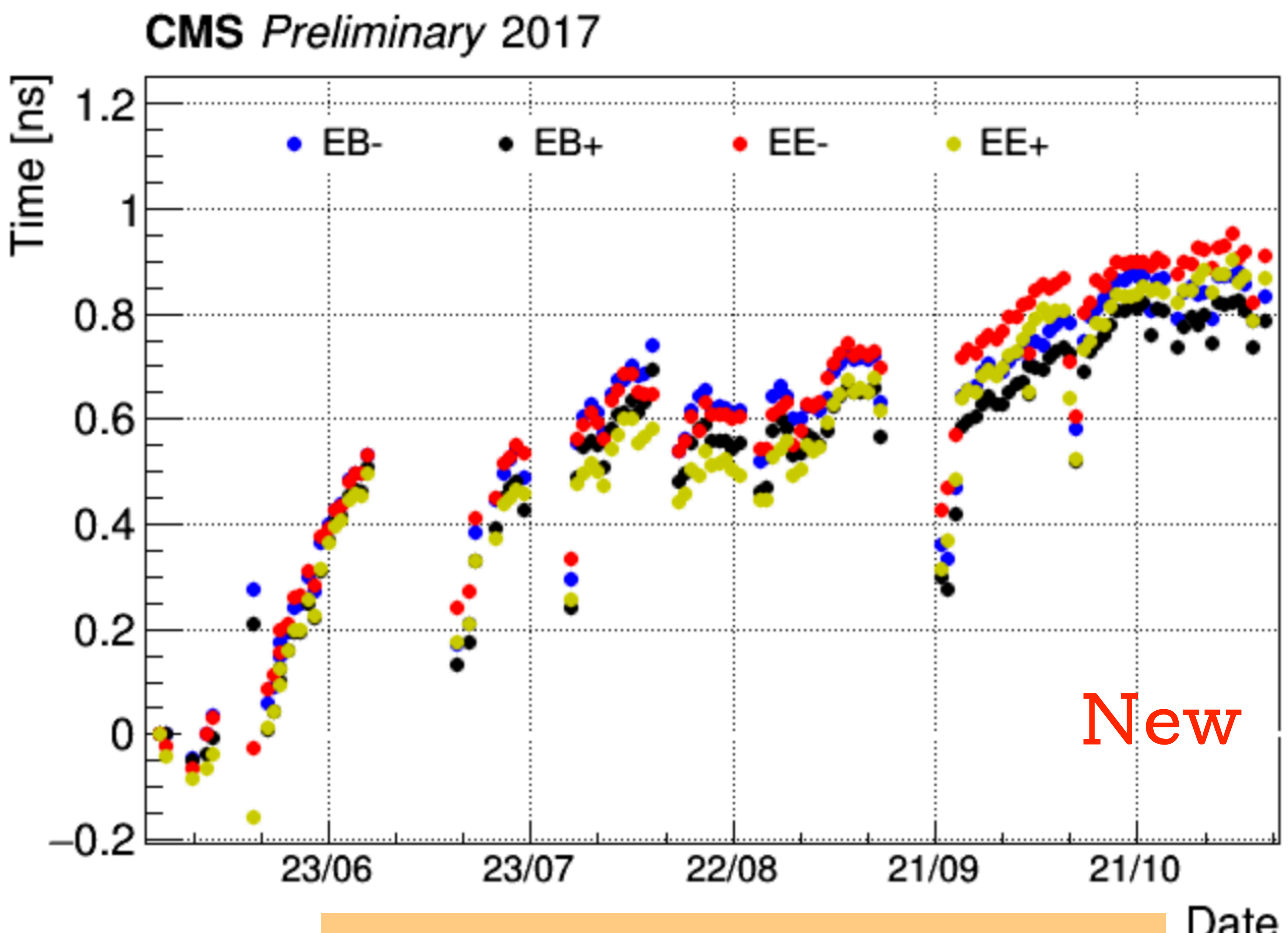
Energy Reconstruction and Crystal Dependent Quantities: Noise(t)



Noise increase in EB due to APD irradiation.

Minor impact on resolution for electrons/photons from Z, W, H, but can impact shower shape variables and lepton isolation.

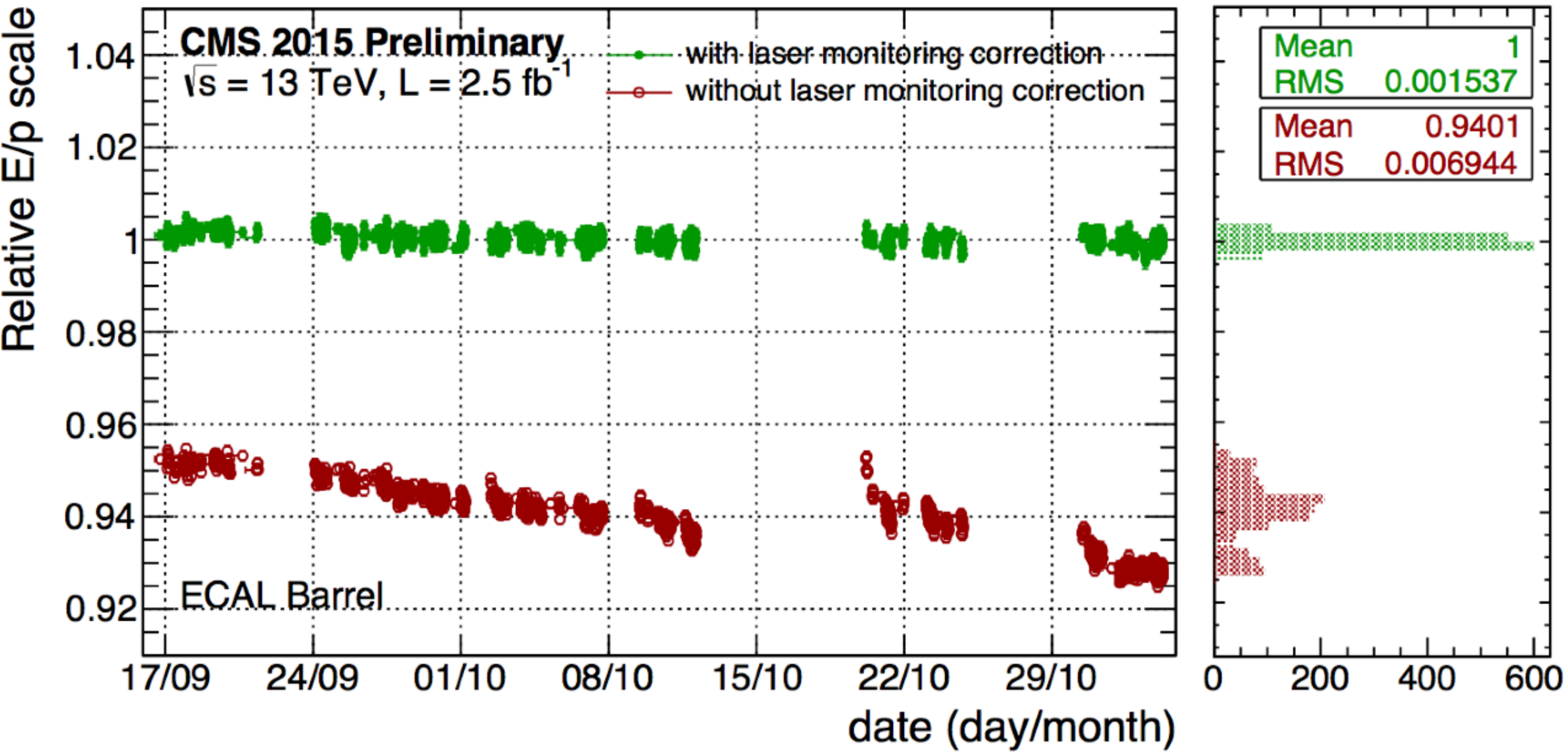
Energy Reconstruction and Crystal Dependent Quantities: Amplitude/Timing(t)

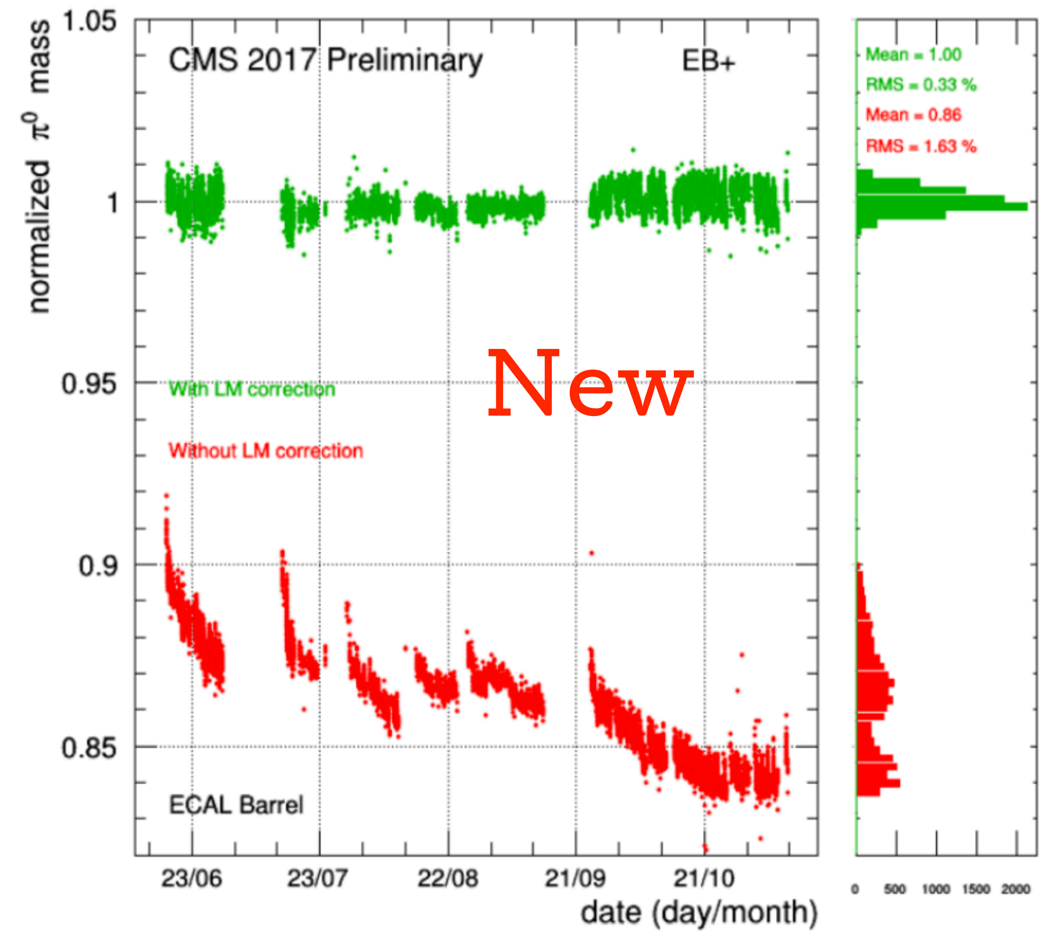


Timing drift during 2017

Update timing calibration and pulse shape templates (used in the multifit) when the drift exceeds 200ps

Energy Reconstruction and Crystal Dependent Quantities: $S_i(t)$, Response Monitoring validation



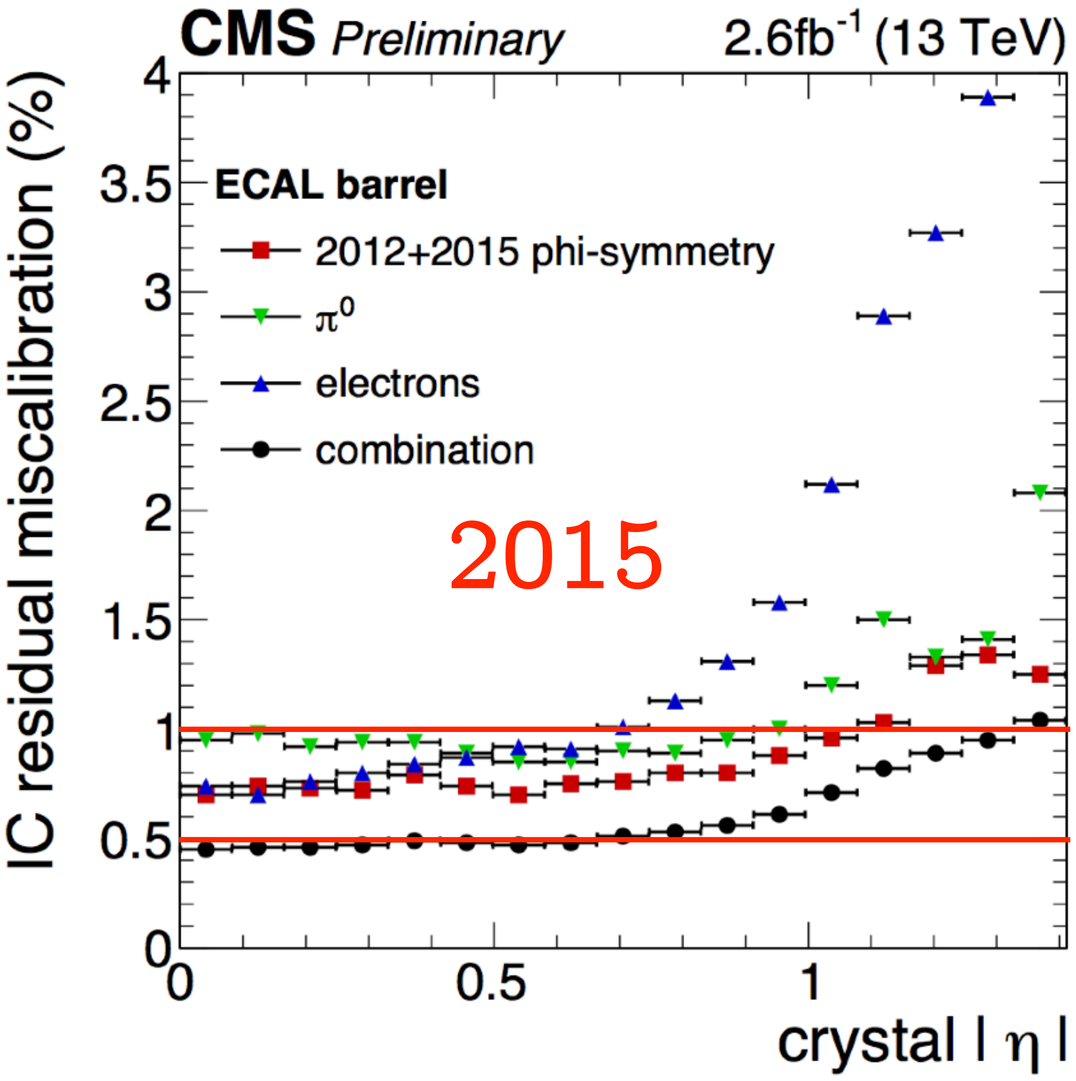


history plots of the prompt validation of the laser monitoring system with E(isolated electron from Z/W)/p(Tracker)

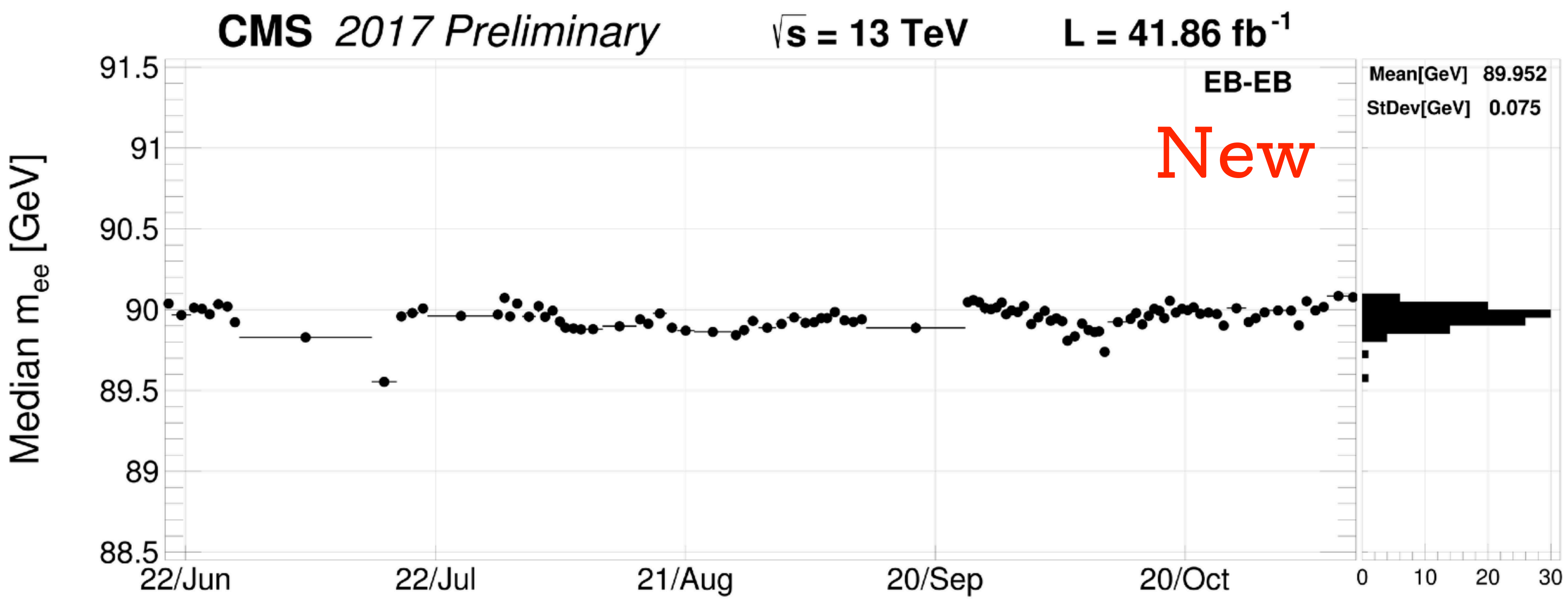
and: π^0 mass

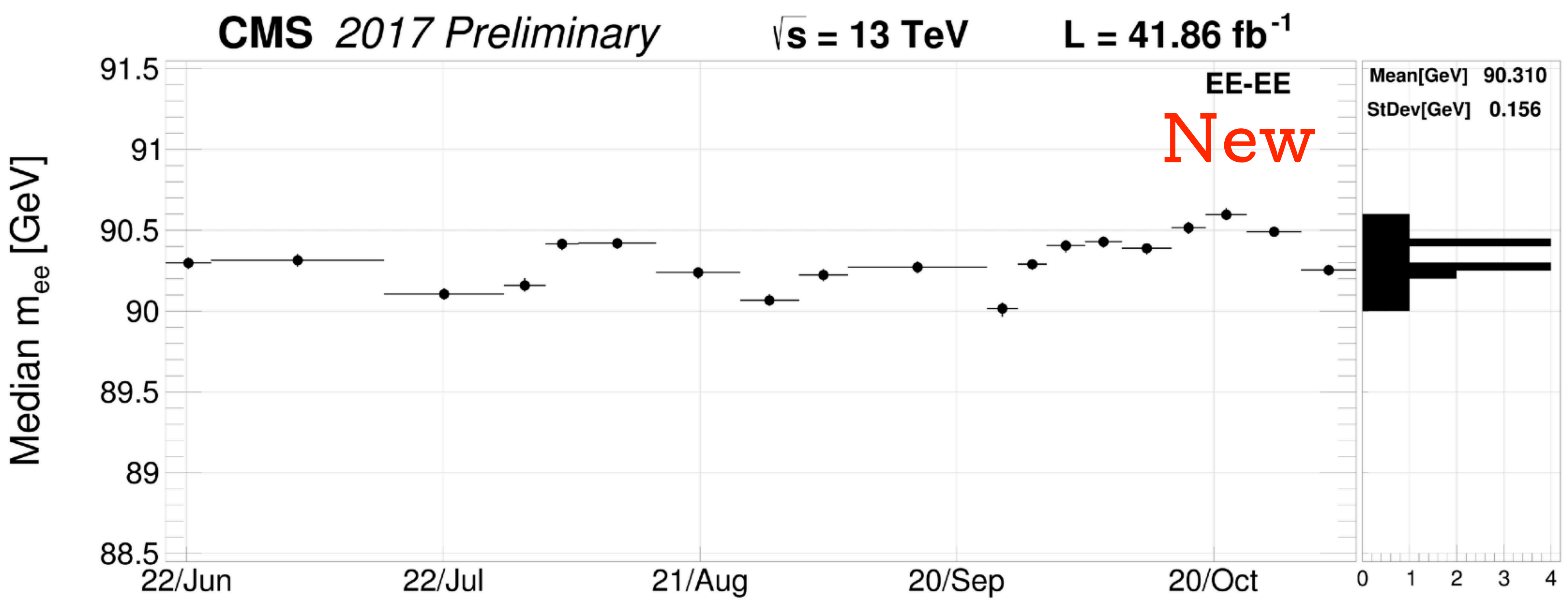
After transparency corrections, the stability of the relative energy scale is demonstrated

Energy Reconstruction and Crystal Dependent Quantities: C_i, single channel inter calibration



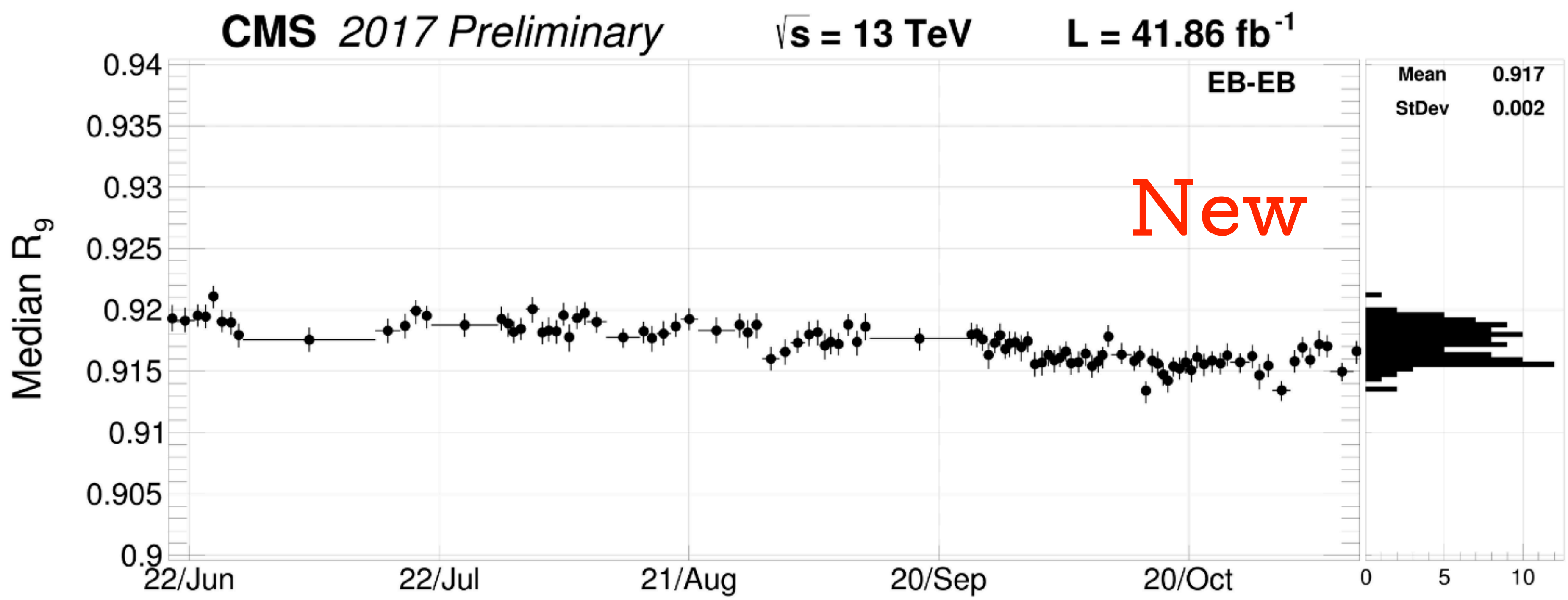
Offline Performance : Z→ee mass stability

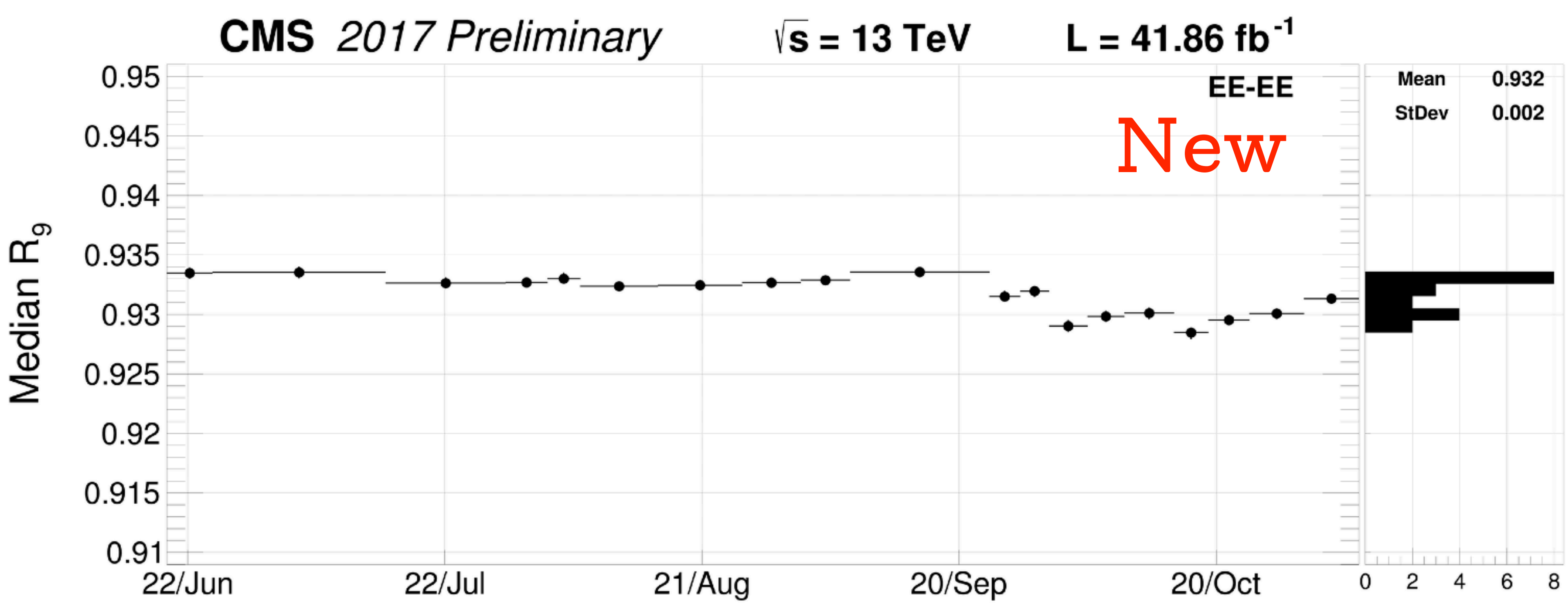




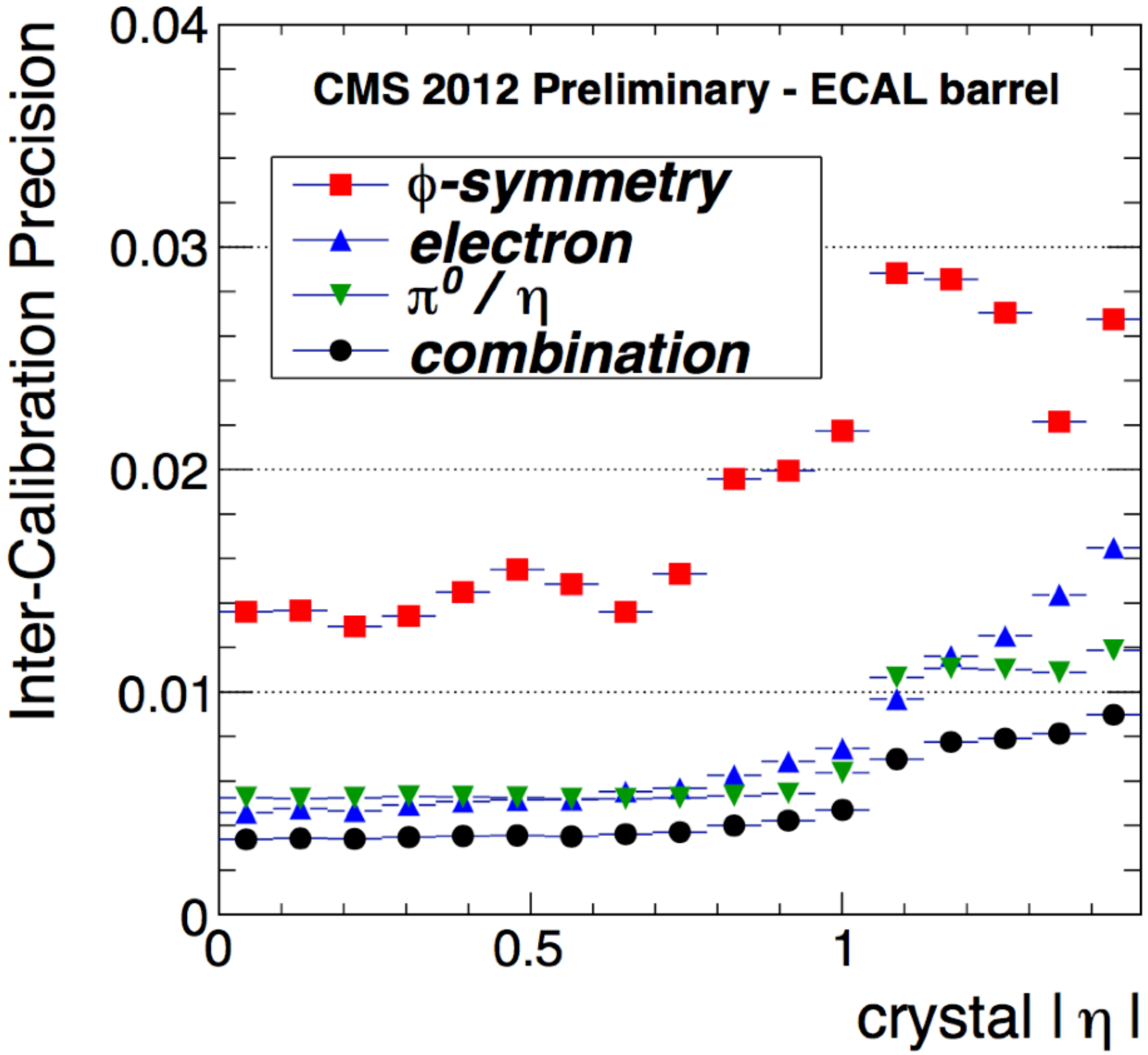
See T. Mudholkar for more

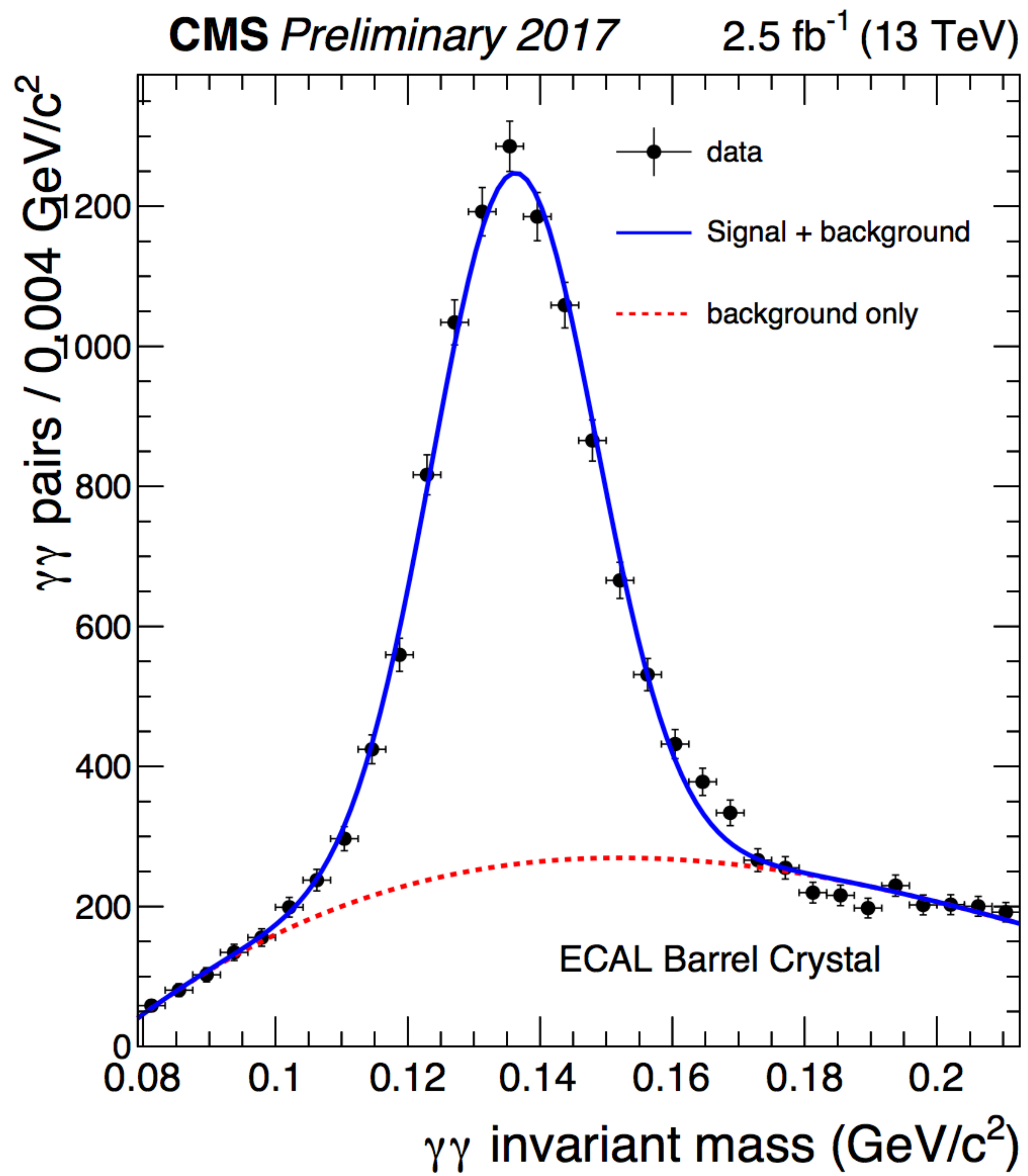
R9 Stability





Single channel IC





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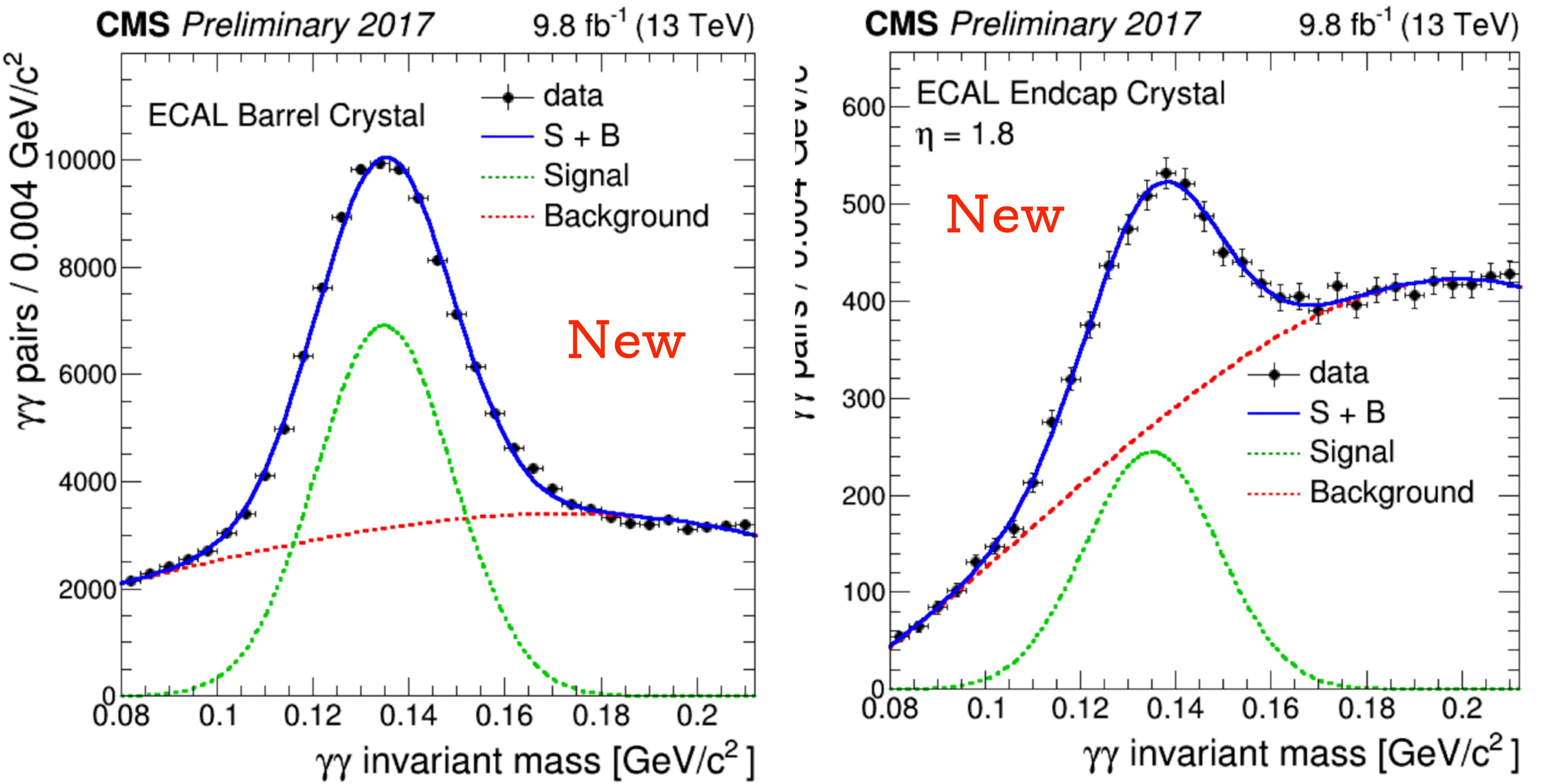
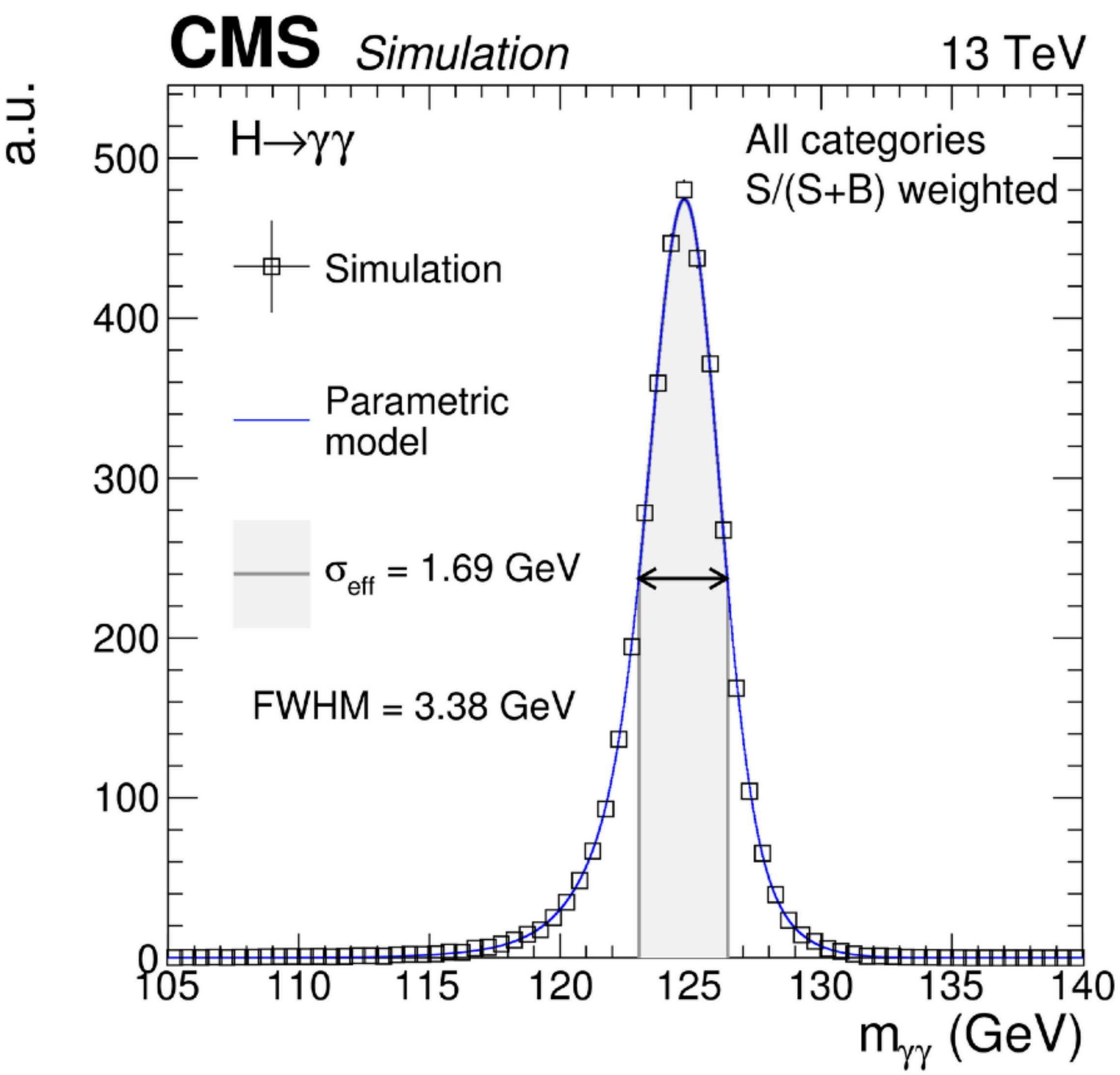
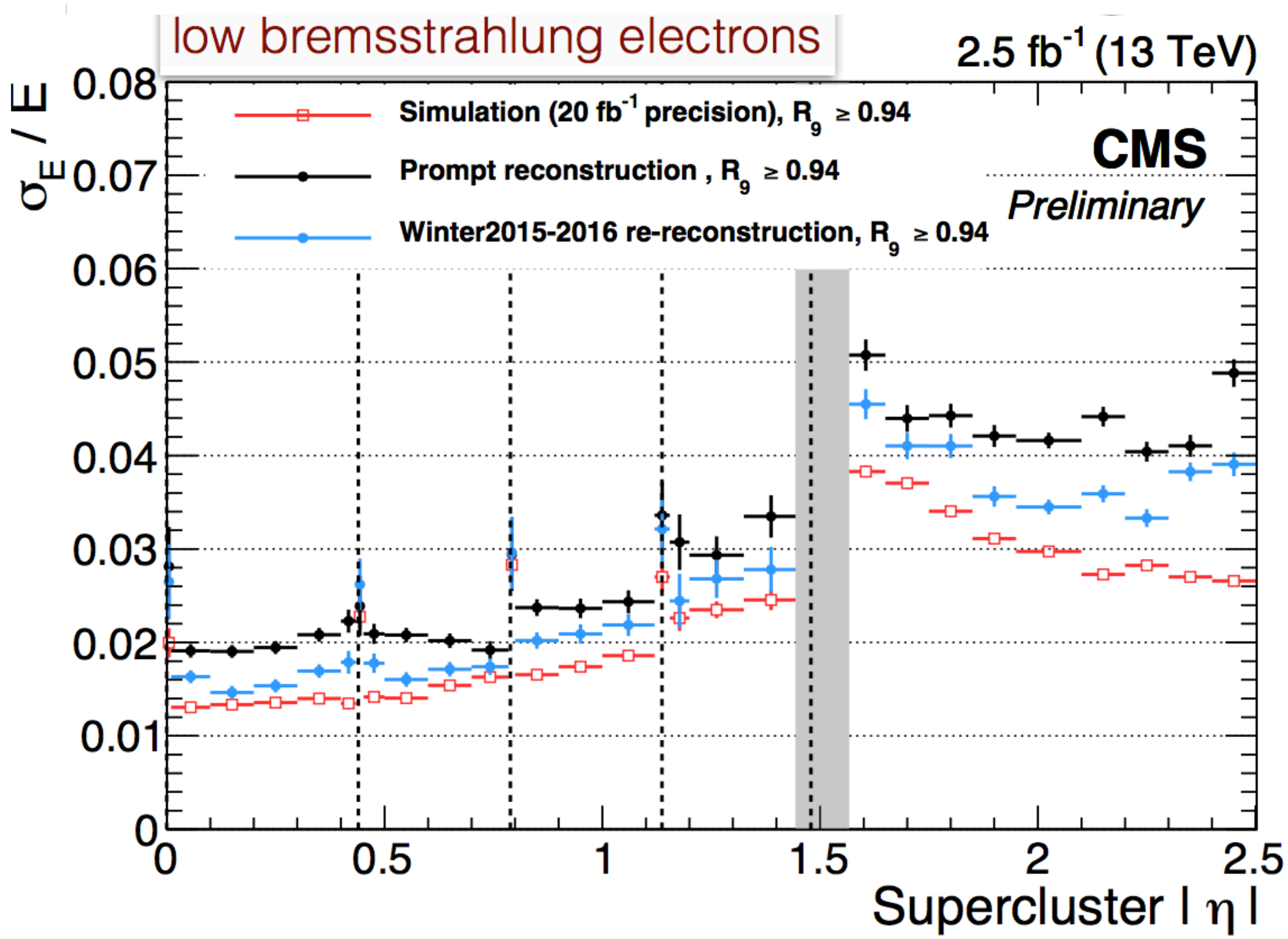


ECAL resolution: MC/2015 data





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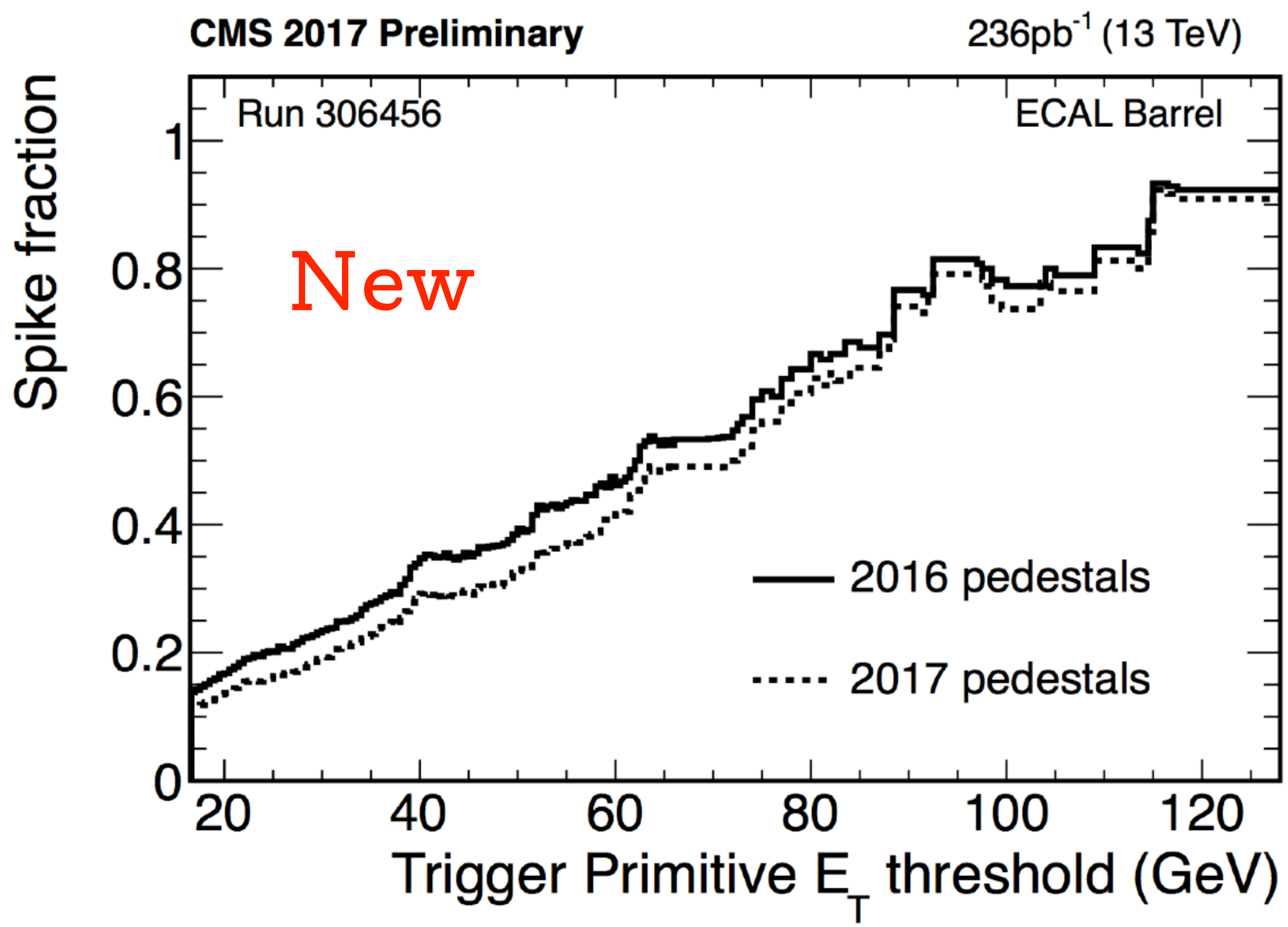
Performance: Direct APD Signal Rejection



E_T threshold	Old pedestals	New pedestals
20 GeV	16.7%	**13.7%**
30 GeV	23.5%	**19.3%**
40 GeV	34.8%	**29.2%**
50 GeV	39.4%	**33.0%**