Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC

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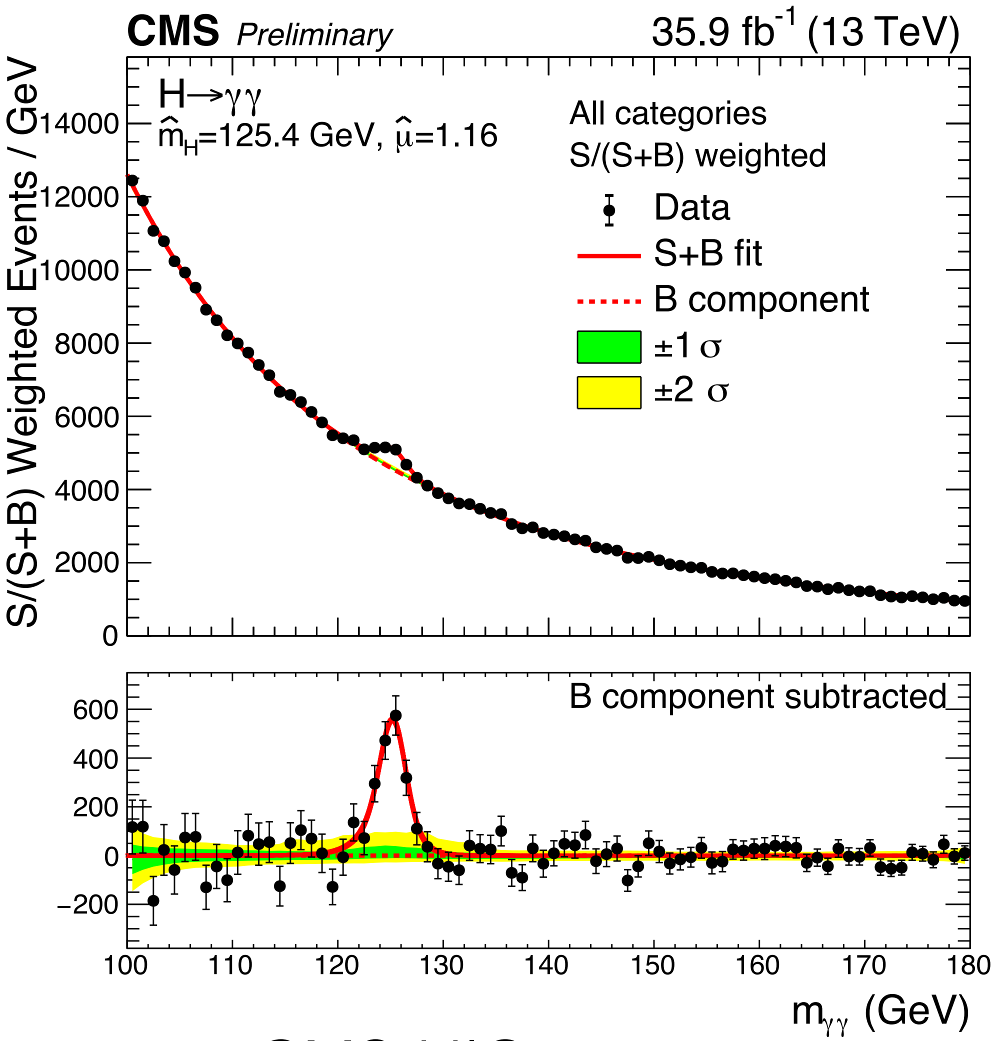
Caltech

on behalf of the CMS Collaboration

CHEF, October 2, 2017

ECAL is crucial in CMS physics analysis



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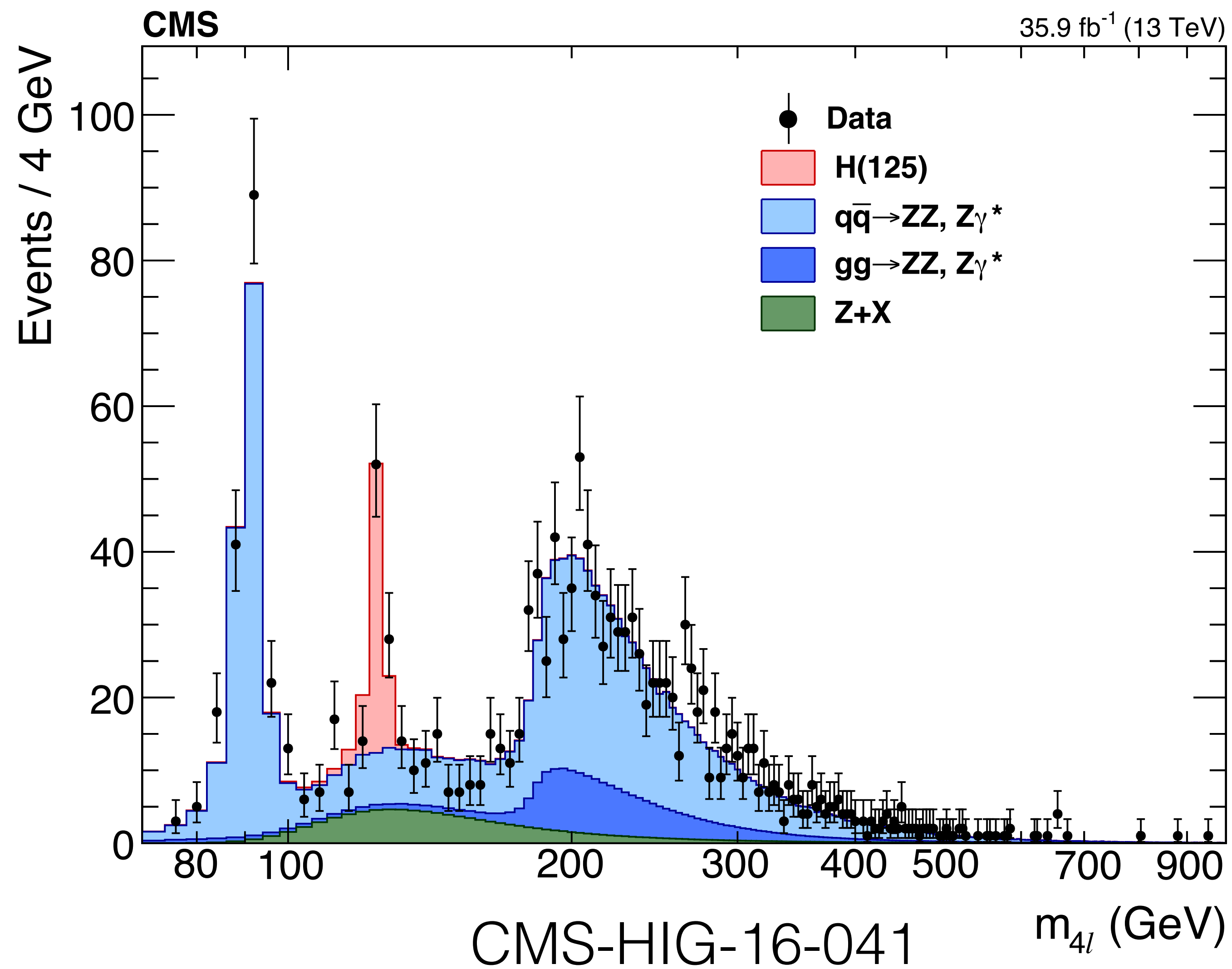

CMS-HIG-16-041

- Excellent e/ɣ energy resolution
- Position measurement

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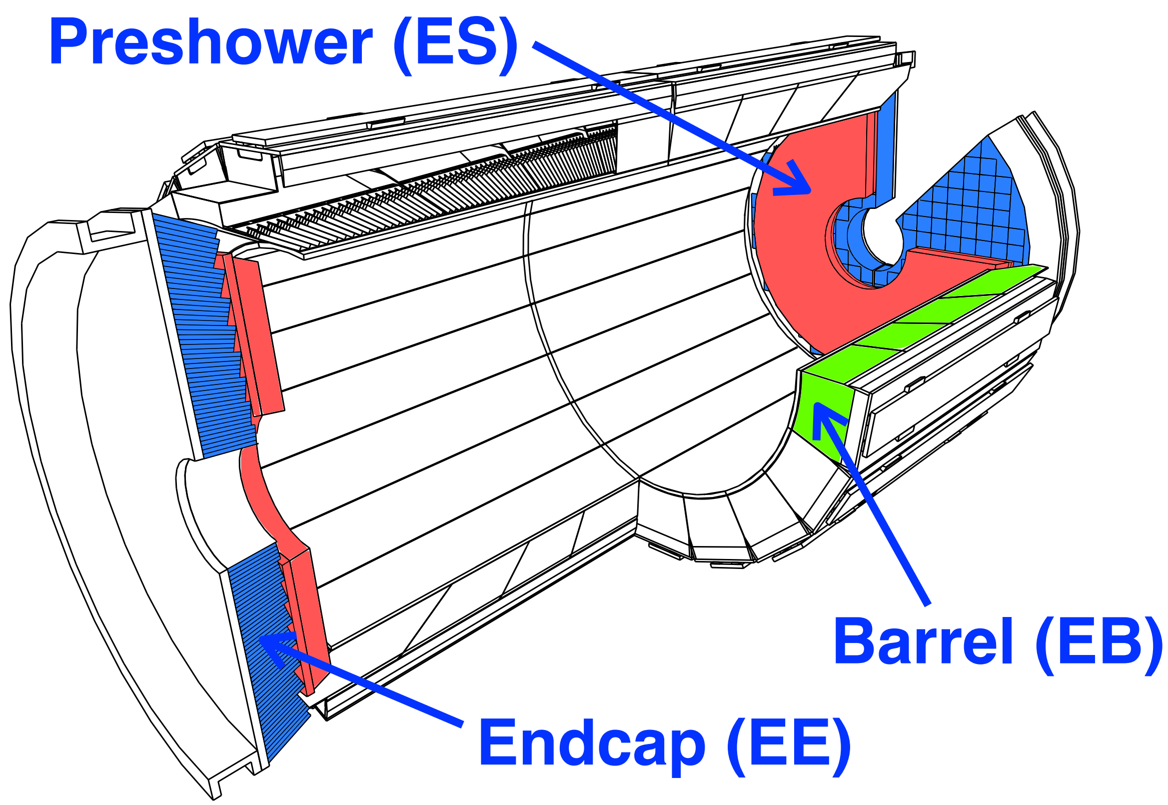
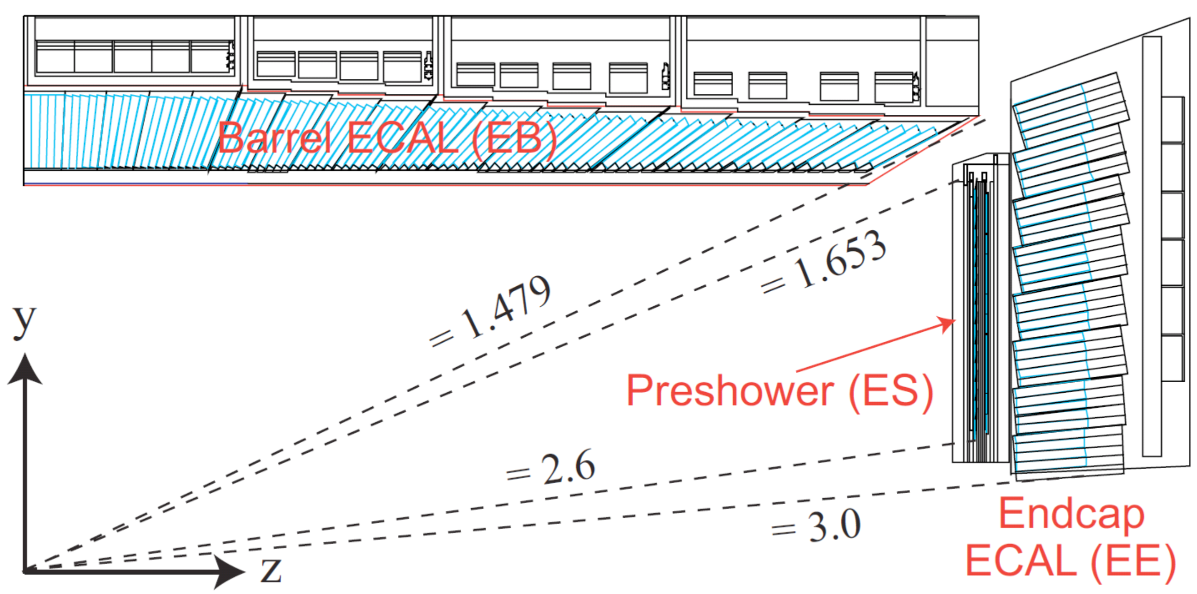
CMS electromagnetic calorimeter (ECAL)





- Homogeneous and hermetic calorimeter
- Lead tungstate ($PbWO_4$) as scintillating crystals (61200 in EB, 7324 x 2 in EE)
  - Density: 8.28 g/cm^3
  - X_0 = 0.89 cm
  - Molière radius (R_M) = 2.2 cm
  - Size: 2.2 x 2.2 x 23 cm (EB), 2.86 x 2.86 x 22 cm (EE)
  - Granularity (EB): 360 in ϕ and 2 x 85 in η (0.0174 x 0.0174)
- APDs/VPTs as photodetector
- 1% - 5% energy resolution for e/ɣ from Z/H boson

e/ɣ energy reconstruction

- e/ɣ energy is reconstructed by the sum over all crystals in the supercluster (SC)

global scale

inter calibration

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

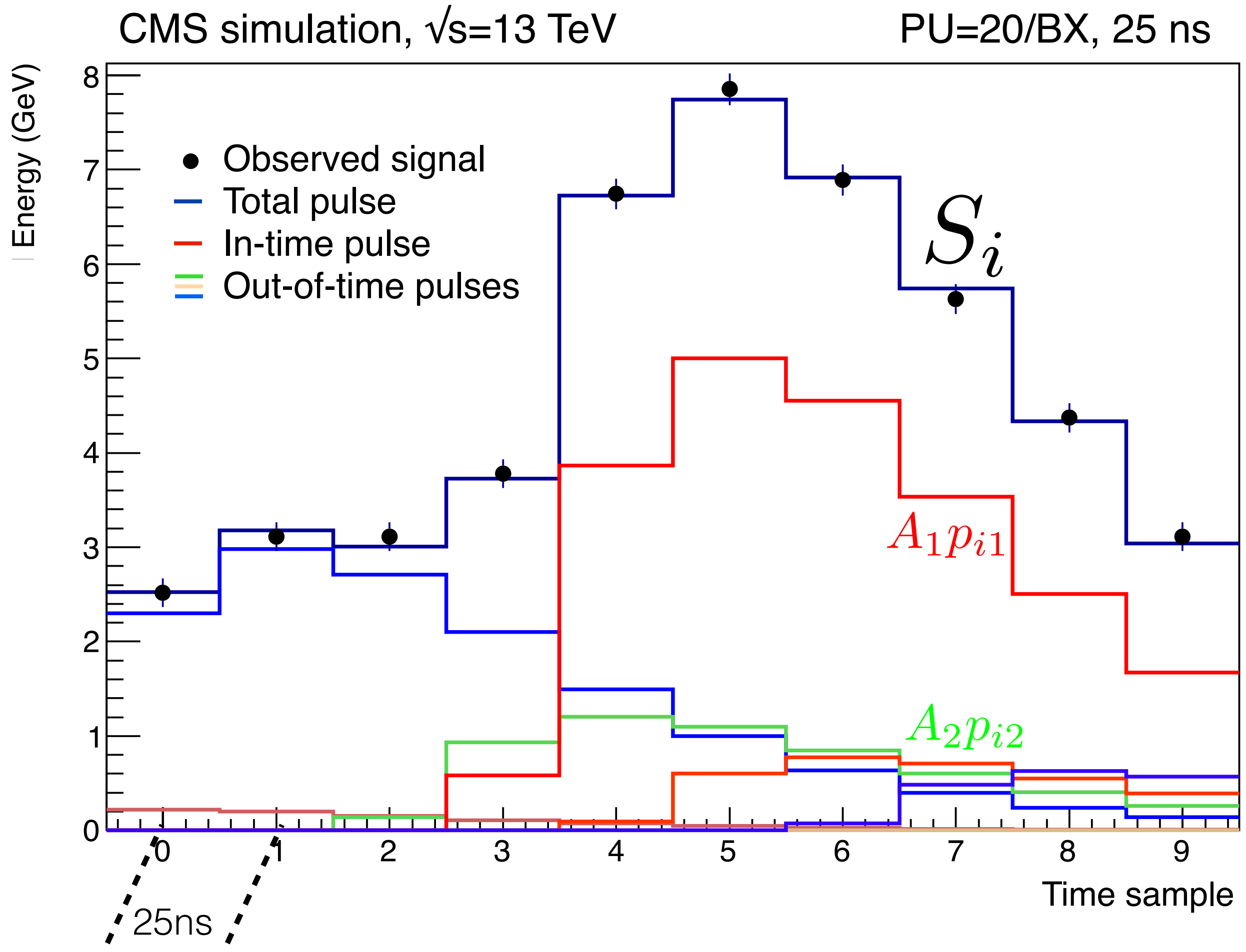
cluster corrections

laser monitoring

pulse amplitude

- Dynamic clustering algorithm:
  - Crystal size ~ R_M => EM showers spread in several crystals
  - Basic clusters are extended in ϕ direction to form supercluster to recover further energy spread due to magnetic field + conversion of photons / bremsstrahlung from electrons

pulse amplitude - A_i



Each pulse from APD/VPT is digitized into 10 samples

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

Weight method (Run I)

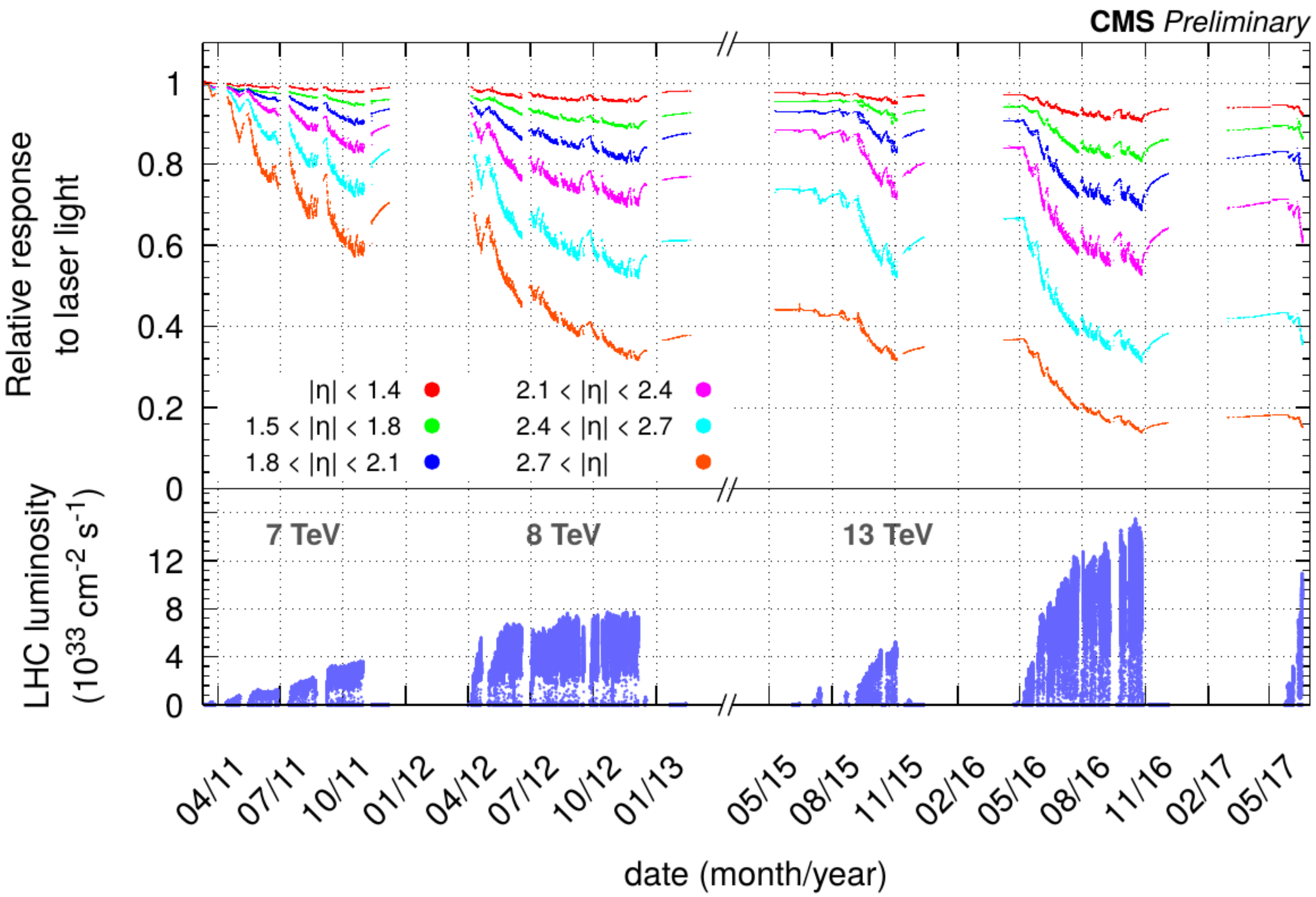
- Amplitude is a weighted sum of all 10 samples

Multifit (Run II)

- Contamination from out-of-time (OOT) pulses becomes more severe
- **Multifit**: pulse shape is modeled as in time pulse plus several OOT pulses (up to 9)
- Minimizing χ^2 to get best in-time pulse amplitude
- Resolution improved w.r.t. Run I for e/ɣ reconstruction (substantial for low p_T ones)

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

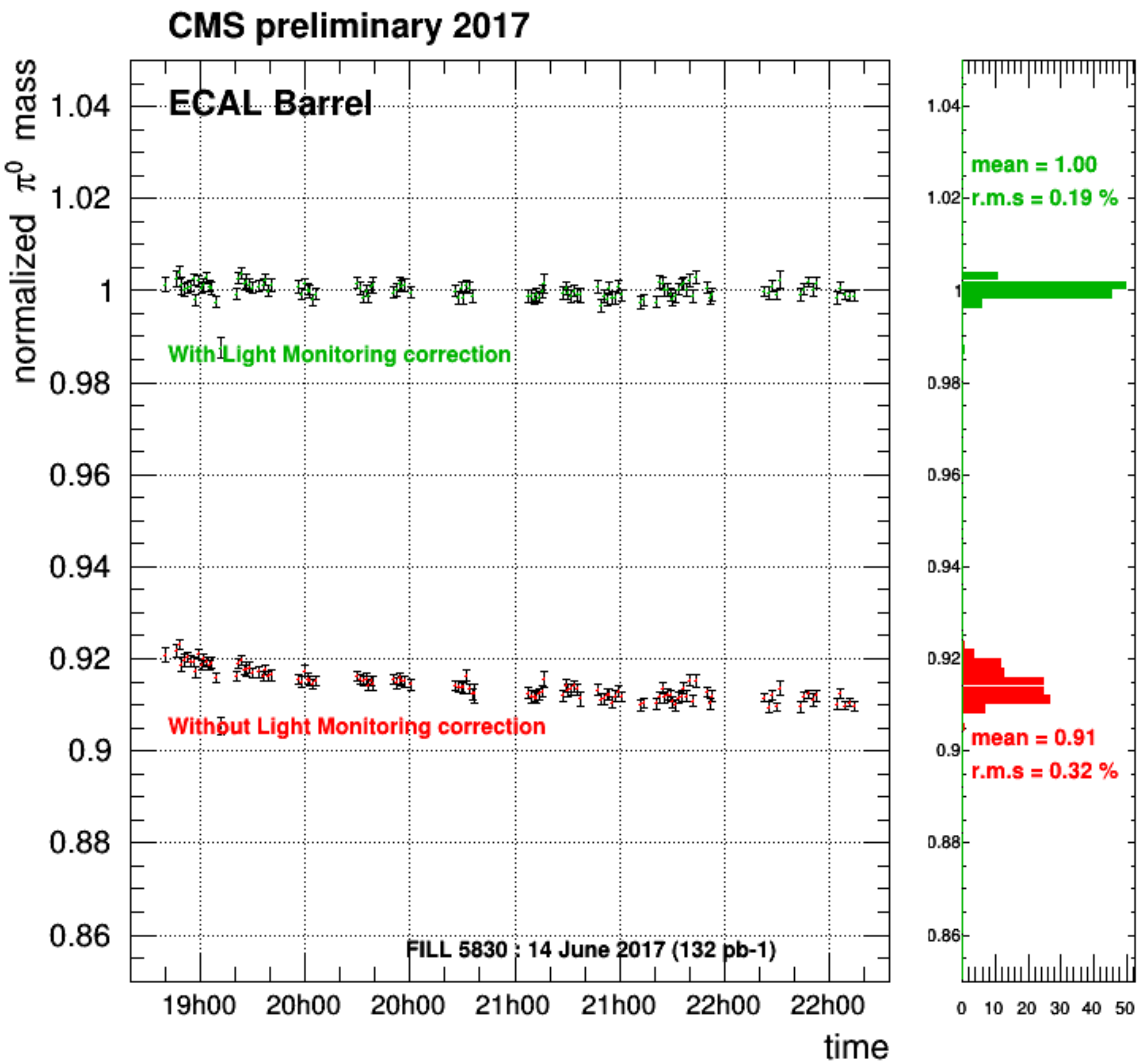
response changes - $S_i(t)$



- Crystal transparency changes under radiation damage, and recovers through self-annealing during shutdowns
- A laser monitoring (LM) system is used to measure such response change
- Scan over all crystals in about 40 mins, and then the corrections are delivered in less than 48h for prompt reconstruction

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

laser monitoring validation - *$S_i(t)$*

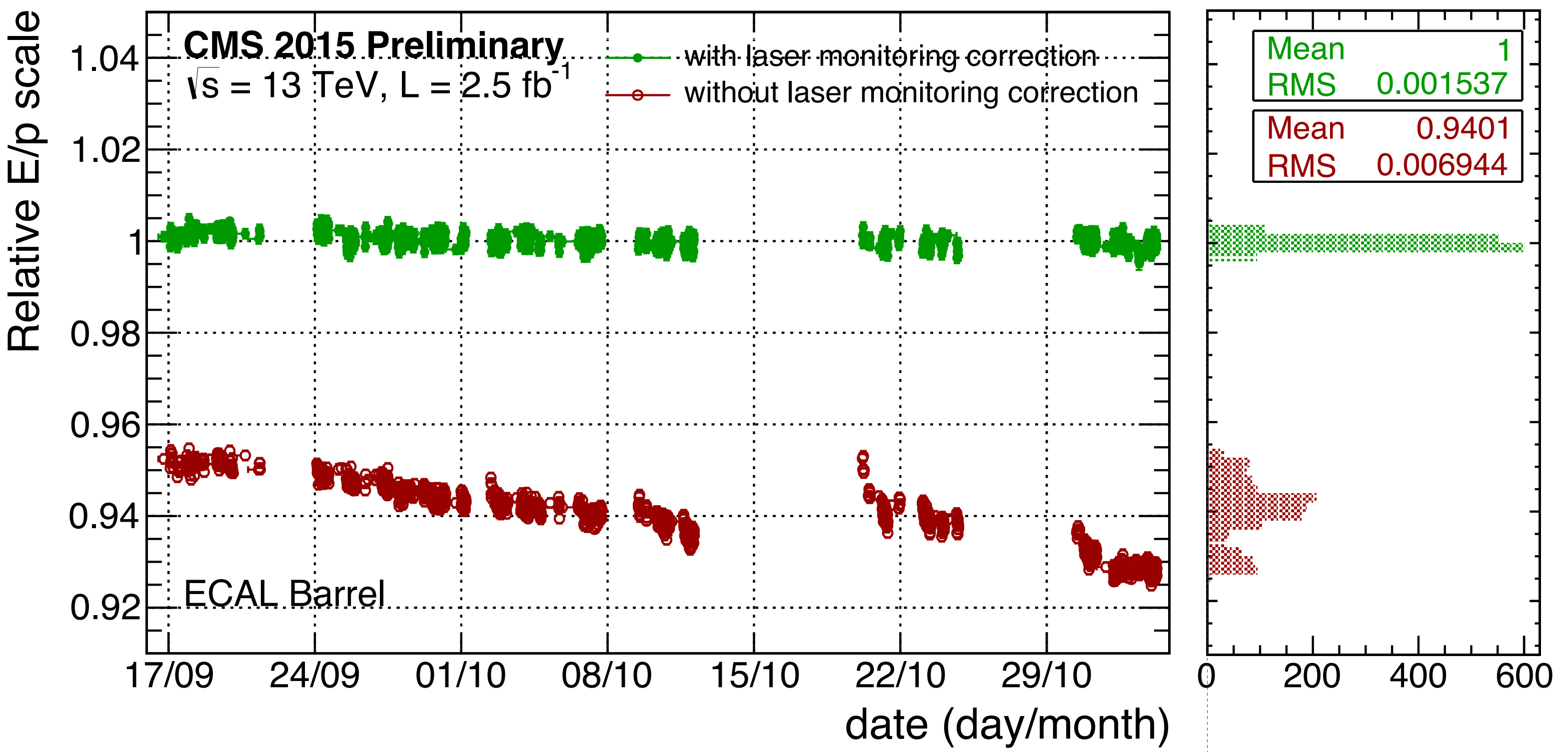


π^0 mass

- Huge amount of data for fast feedback (every few mins)
  - A dedicated trigger with high rate (~ 10 kHz) and small data size
- RMS after LM correction (in 2017): 0.19% (EB)

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

laser monitoring validation - $S_i(t)$

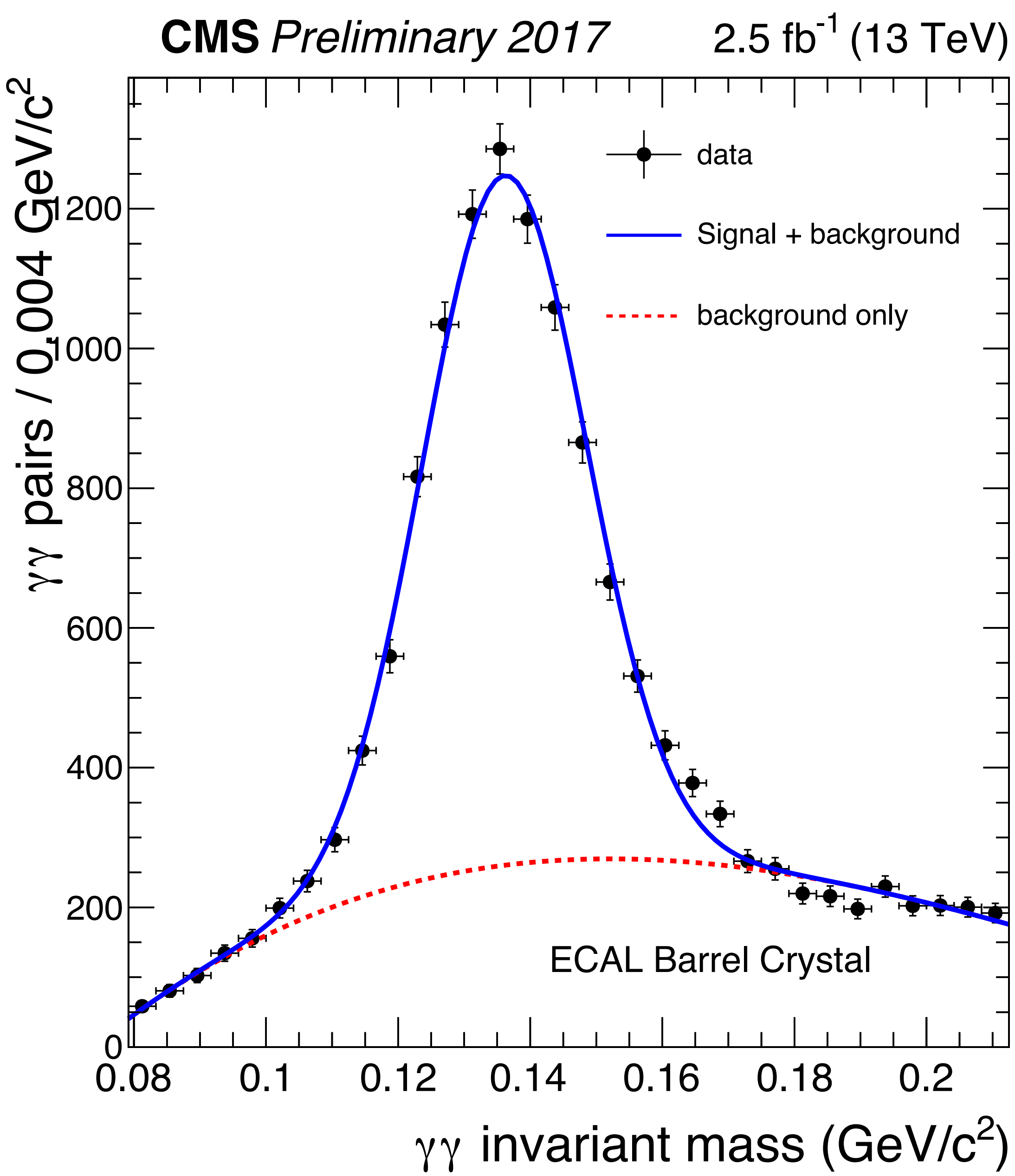


electrons from W/Z bosons

- Ratio of energy E (measure by ECAL) to the momentum p (measured by tracker) to provide energy scale
- RMS after LM correction (in 2015): 0.15% (EB)

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

single channel intercalibration - C_i



Intercalibration

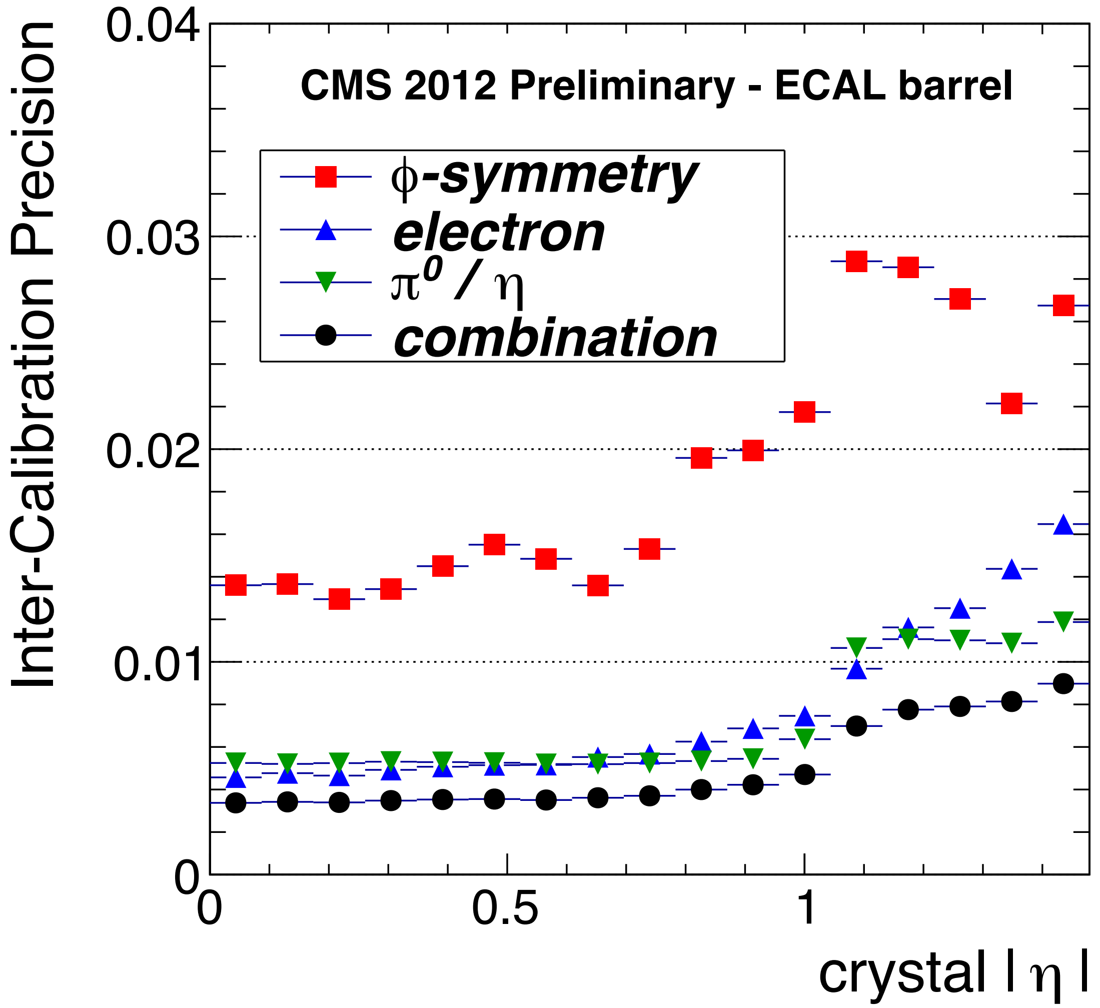
- Relative calibration between channels; equalize their crystal+APD/VPT responses

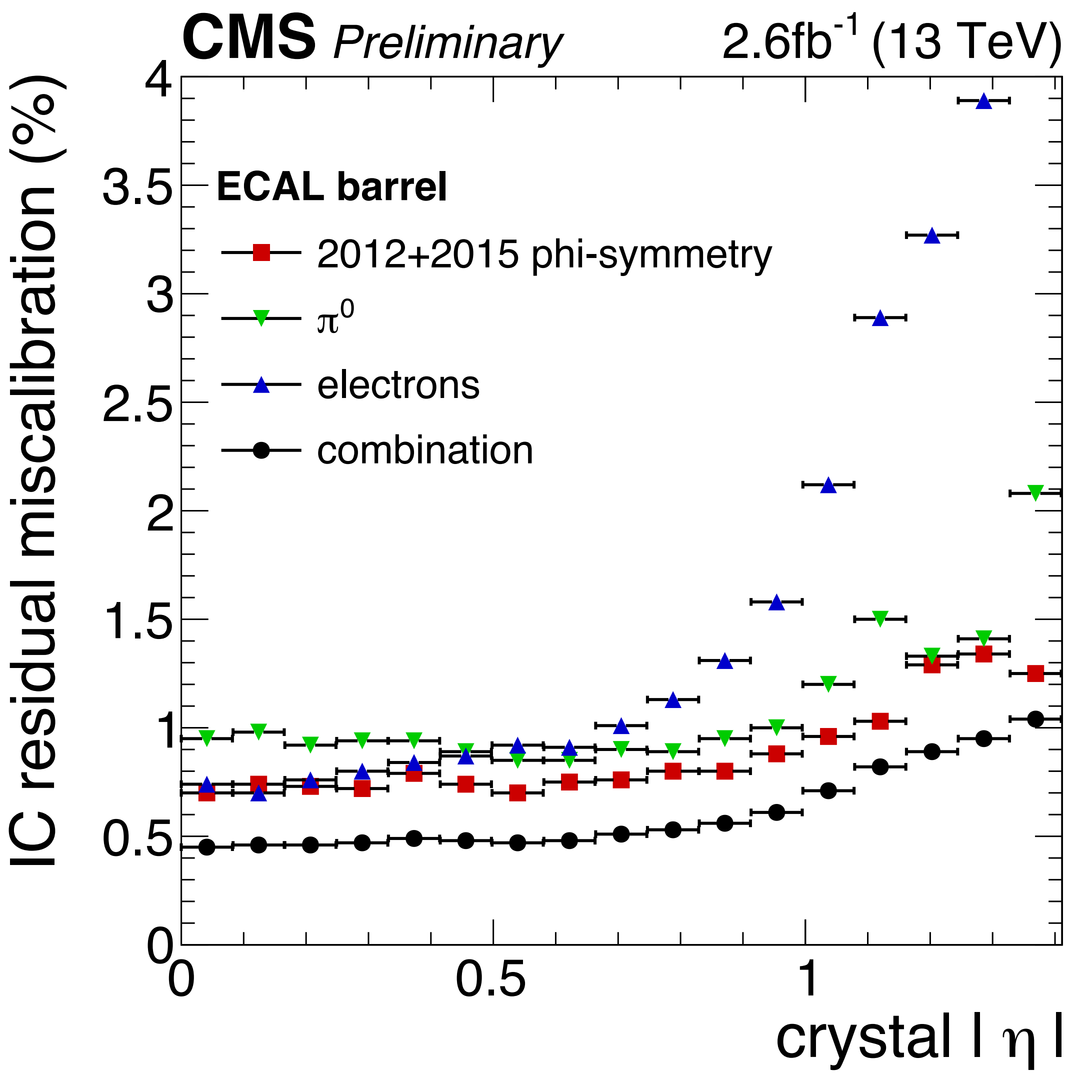
Methods

- **ϕ-symmetry**: equalize the average transverse energy in crystals at constant η
- π^0/η **mass**: iterative procedure to update the C_i which corrects the diphoton mass (one photon centered on crystal i)
- **E/p**: iterative method based on ECAL energy and tracker momentum for isolated electrons from Z/W decays

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

single channel intercalibration - C_i

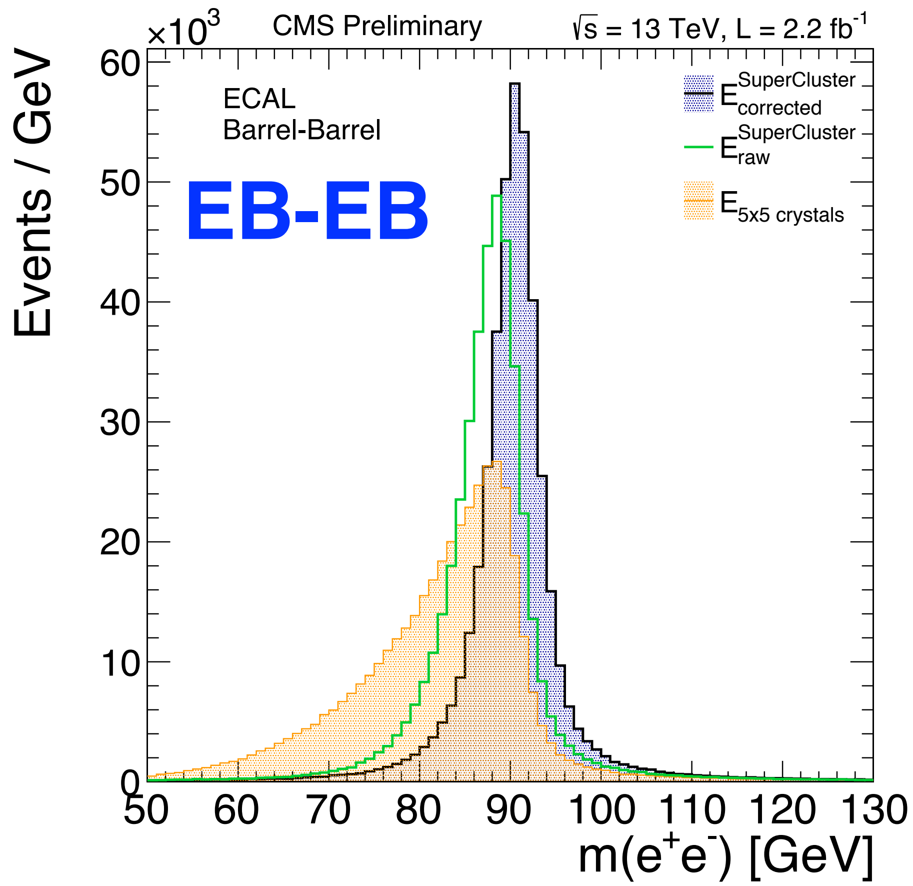


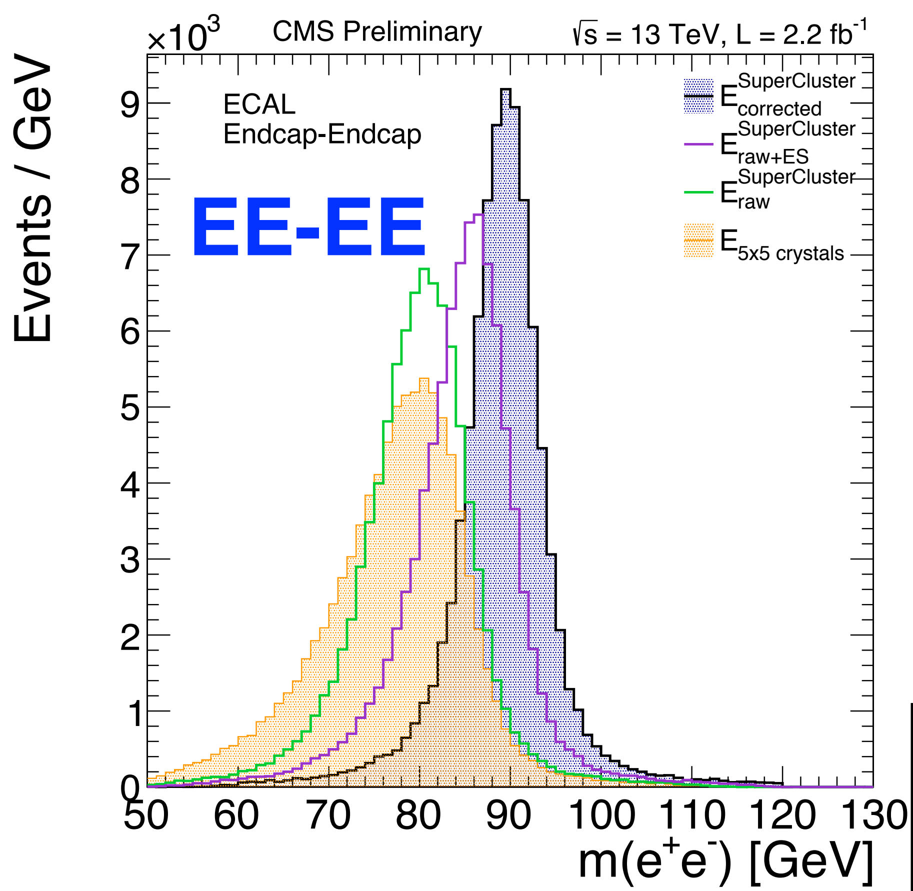


- Combination is weighted (by precision) mean of each method
- Precision (contributes to the constant term of final resolution):
  - Run I: 0.3-0.5% in EB
  - Run II: 0.5-1% in EB

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

supercluster energy correction - $F_{e,\gamma}$





MVA technique

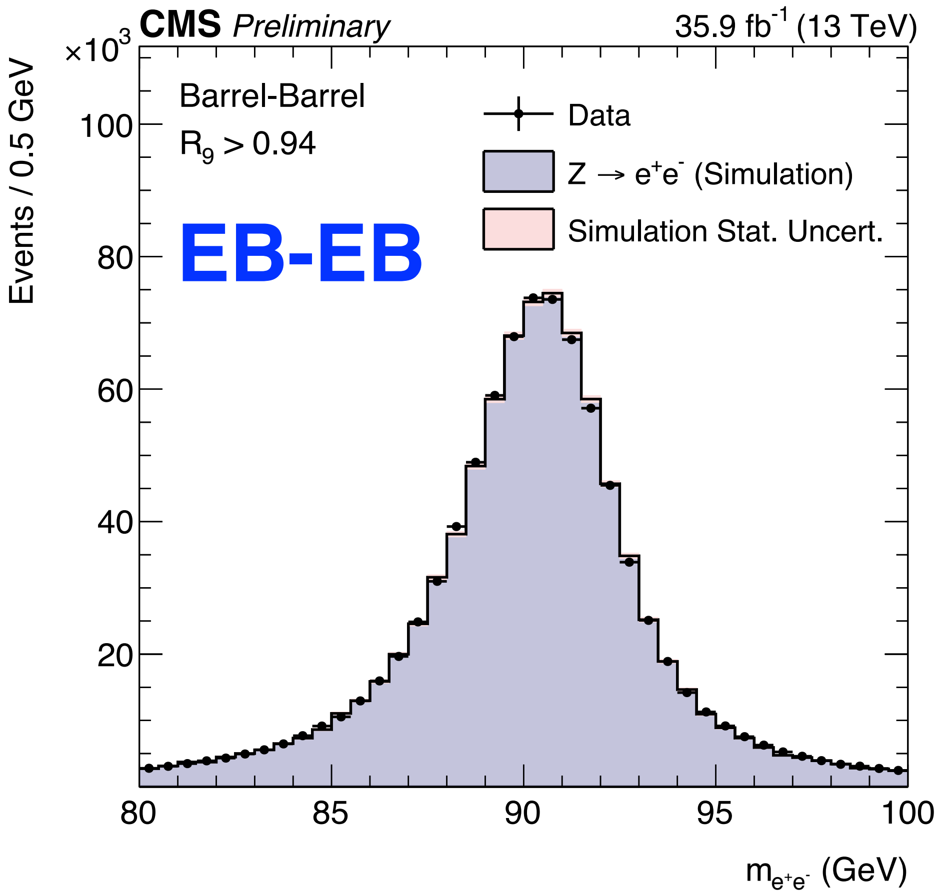
- Supercluster energy containment:
  - Material budget before ECAL
  - Shower containment in supercluster: gaps, cracks between crystals …
- MVA training with MC simulation
  - Gen level energy known
  - Crystal coordinates and shower shapes as input
  - Electrons and photons are tuned separately due to their different behaviors (conversion, bremsstrahlung)

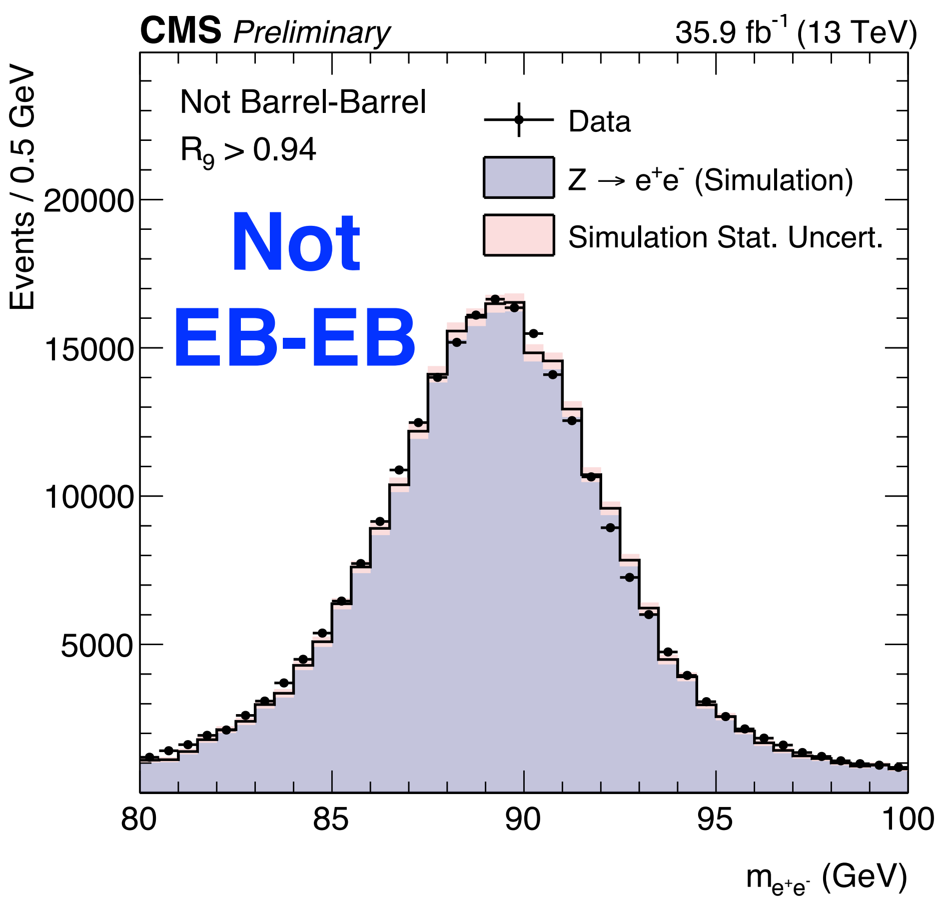
validation with Z->ee

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

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

absolute energy calibration - *G*





- The absolute energy scale calibration ***G*** is adjusted such that the fitted Z->ee peak in data agrees with that of the MC simulation

- Z->ee events are also used to calibrate the η ring dependence of the energy reconstruction

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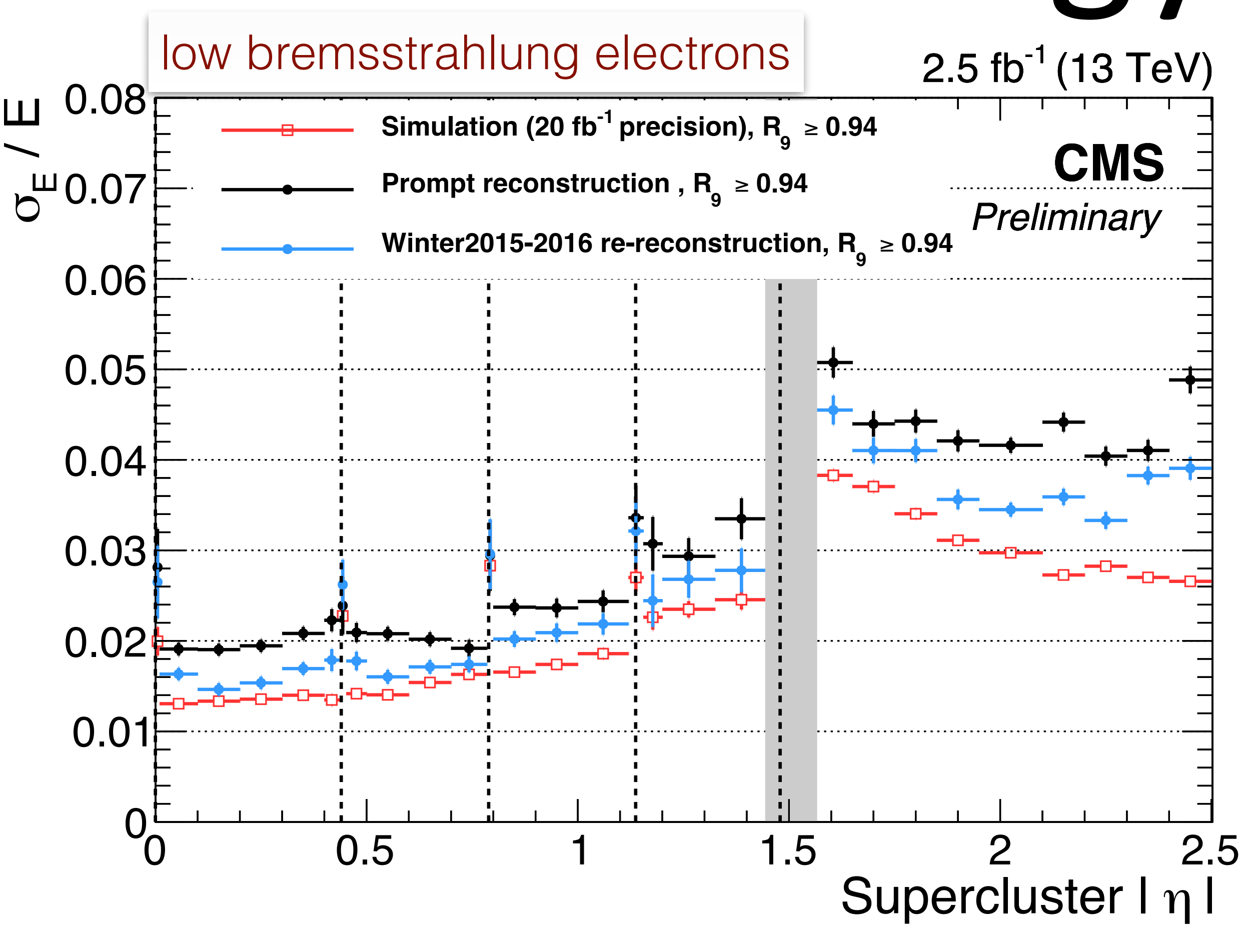
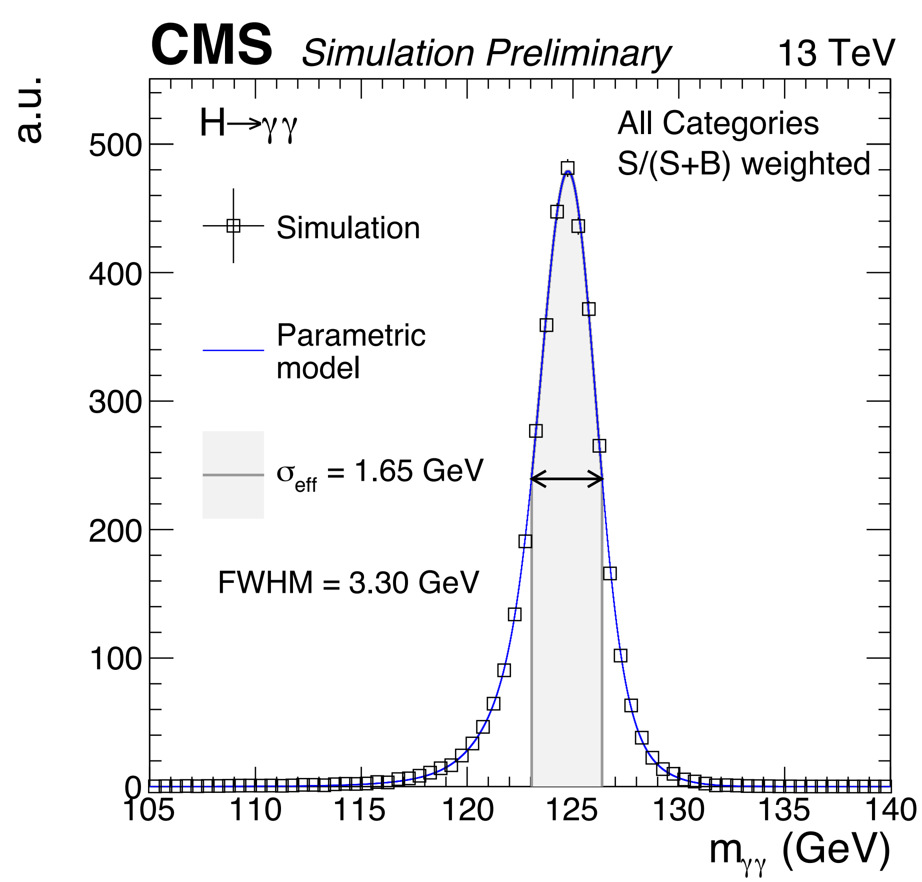
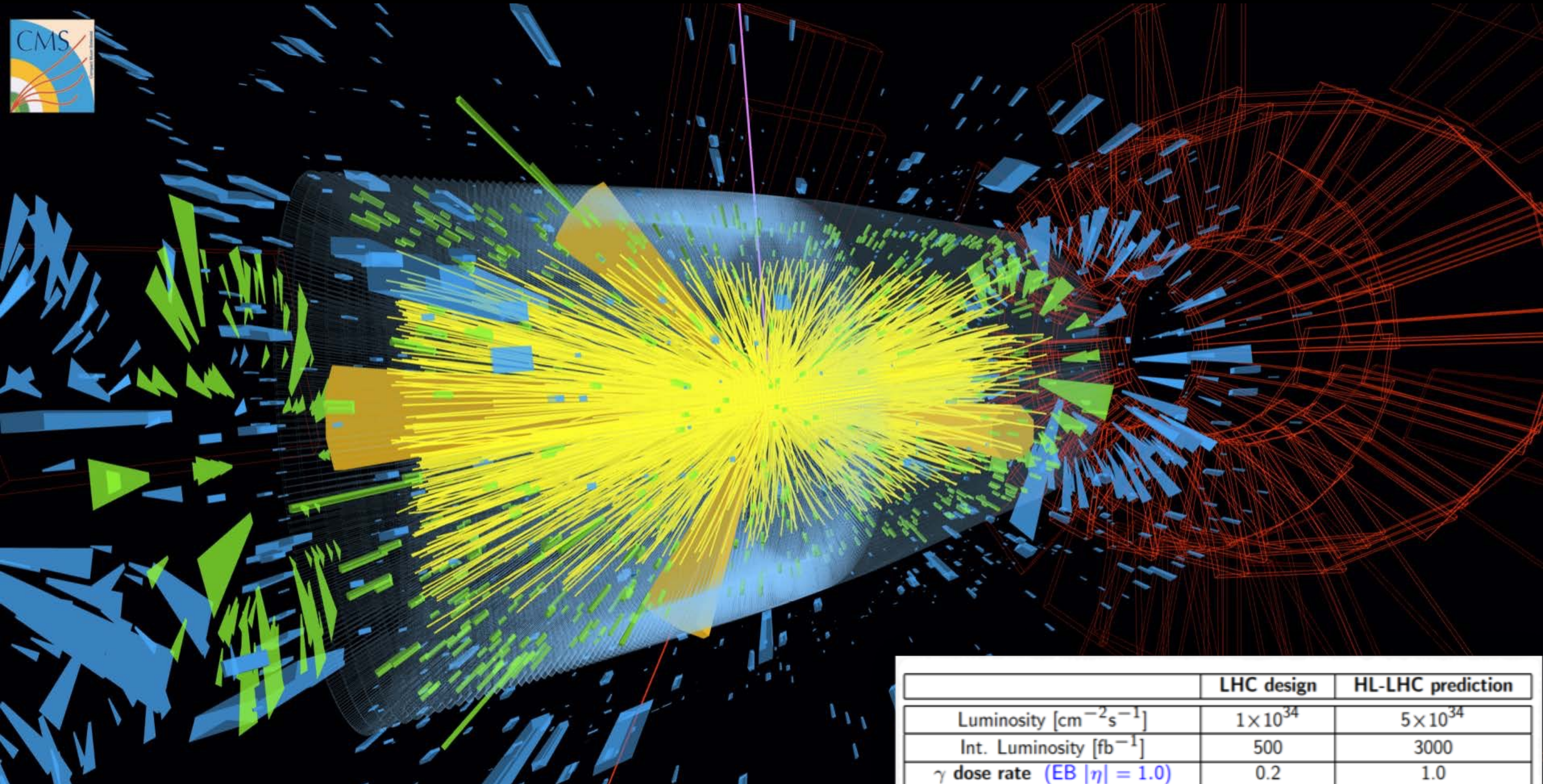
energy resolution





- Single electron energy resolutions are measured by relating them to di-electron mass resolution of Z->ee events
  - Recalibration gives us significant improvement
  - Precision at the level of Run I in low η region
- Higgs mass resolution is a combination of the resolutions of photon energies and the opening angle

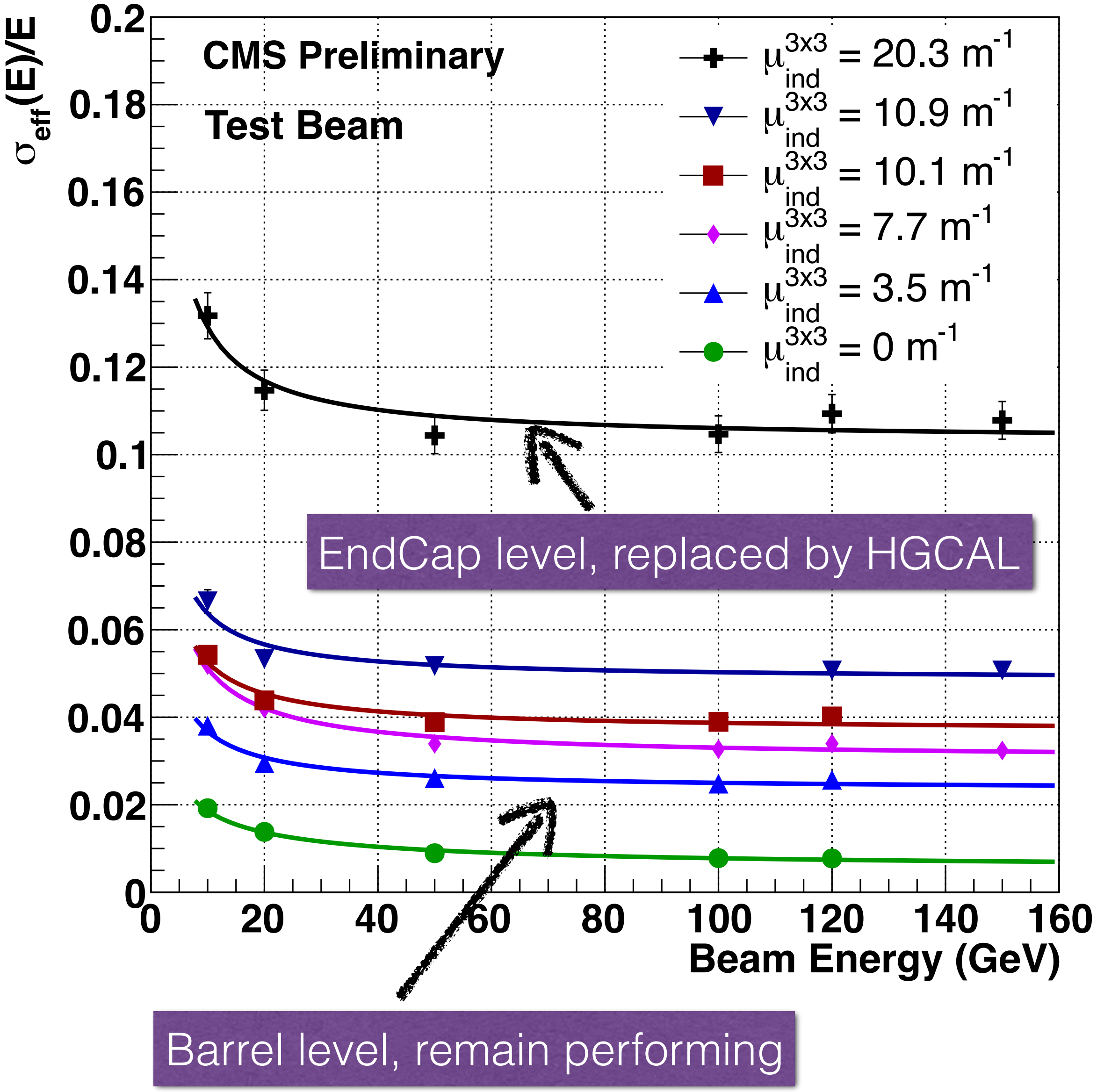
challenges for HL-LHC



VBF H→γγ with 200 PU

	LHC design	HL-LHC prediction
Luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	5×10^{34}
Int. Luminosity [fb^{-1}]	500	3000
γ **dose rate** (EB $\lvert\eta\rvert = 1.0$)	0.2	1.0
[Gy/h] (EE $\lvert\eta\rvert = 2.6$)	6	30
hadron fluence (EB $\lvert\eta\rvert = 1.0$)	12×10^{11}	7.6×10^{12}
[cm^{-2}] (EE $\lvert\eta\rvert = 2.6$)	3×10^{13}	2.0×10^{14}

energy resolution of irradiated crystals

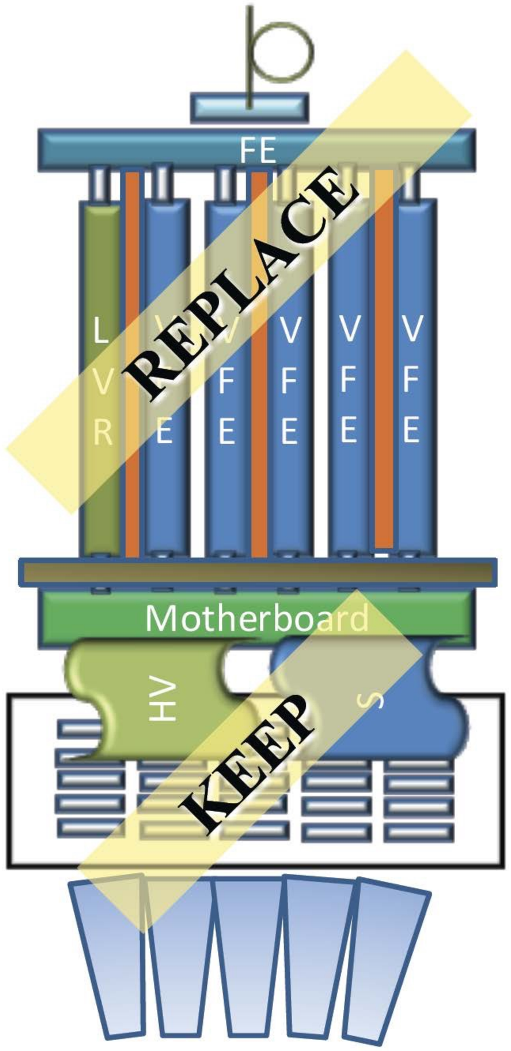


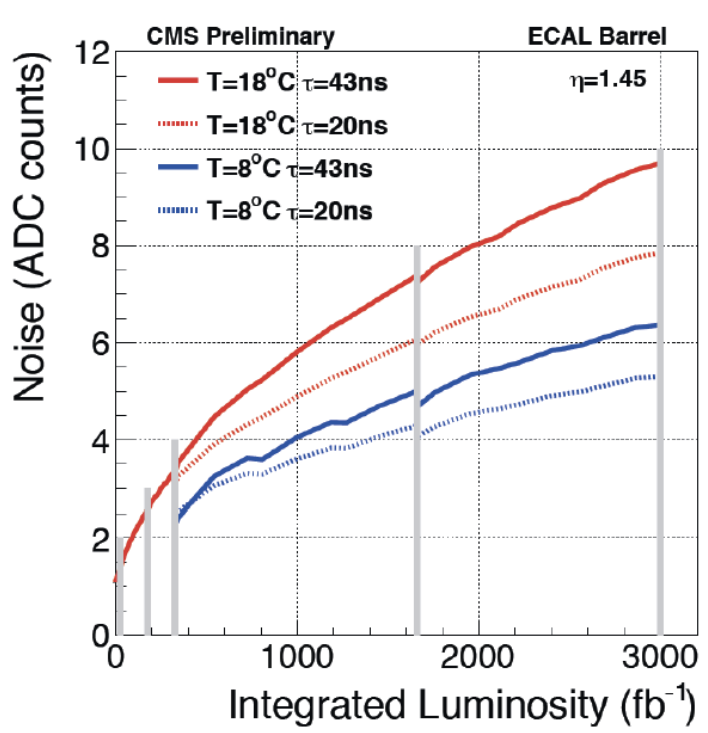
$$\mu_{IND}(\lambda) = \frac{1}{\ell} \times \ln \frac{LT_0(\lambda)}{LT(\lambda)}$$

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

- Energy resolution of irradiated $PbWO_4$ crystals have been measured in test beam data with high energy electrons (10-150 GeV)
- Radiation damage affects all three terms:
  - **Stochastic**: crystal light yield
  - **Noise**: the noise term is amplified by the light output loss
  - **Constant**: non-uniformity of the light collection

EB upgrade strategies for HL-LHC





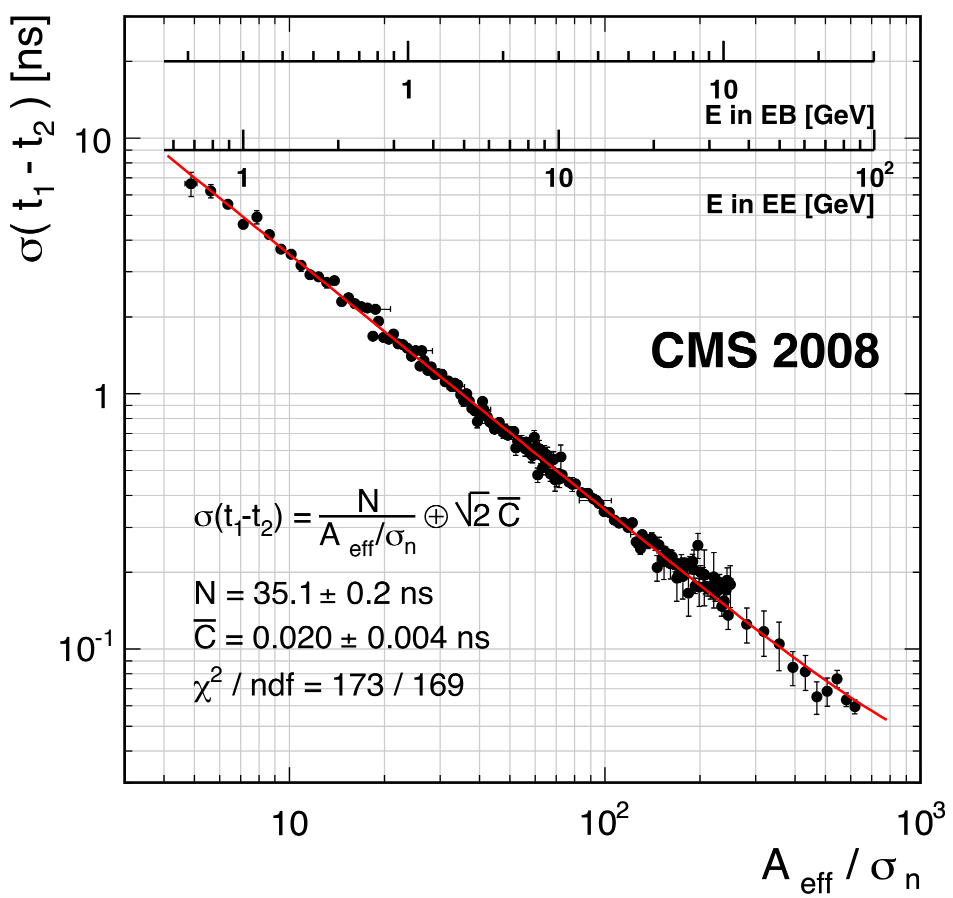
- Everything before motherboard remain unchanged
  - APD colder (from 18°C to 8°C) to mitigate radiation induced noise
- VFE: similar, optimize shaping time & sampling, to reduce OOT pile-up, spikes, noise and improve timing
- FE card becomes streaming readout, most processing off-detector
- Trigger: single crystal trigger primitive vs current 5x5 for spike rejection and improved trigger performance

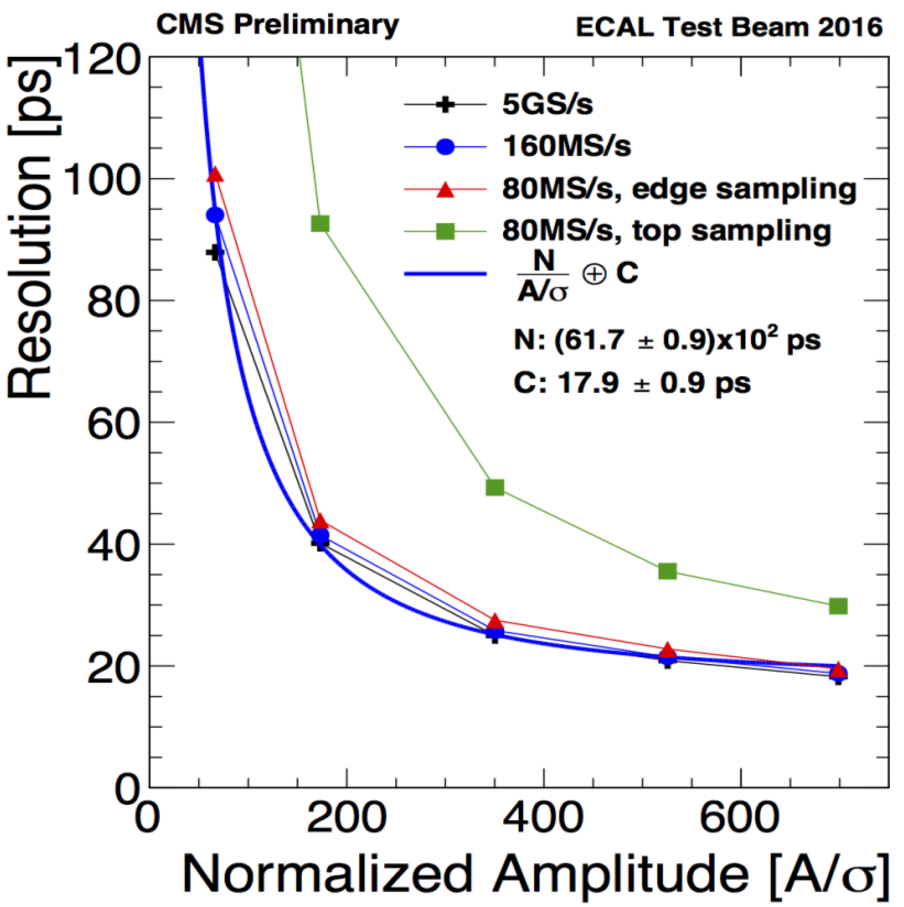
See talks from Gianni Mazza, Alexander Ledovskoy

timing performance: Run I vs. HL-LHC

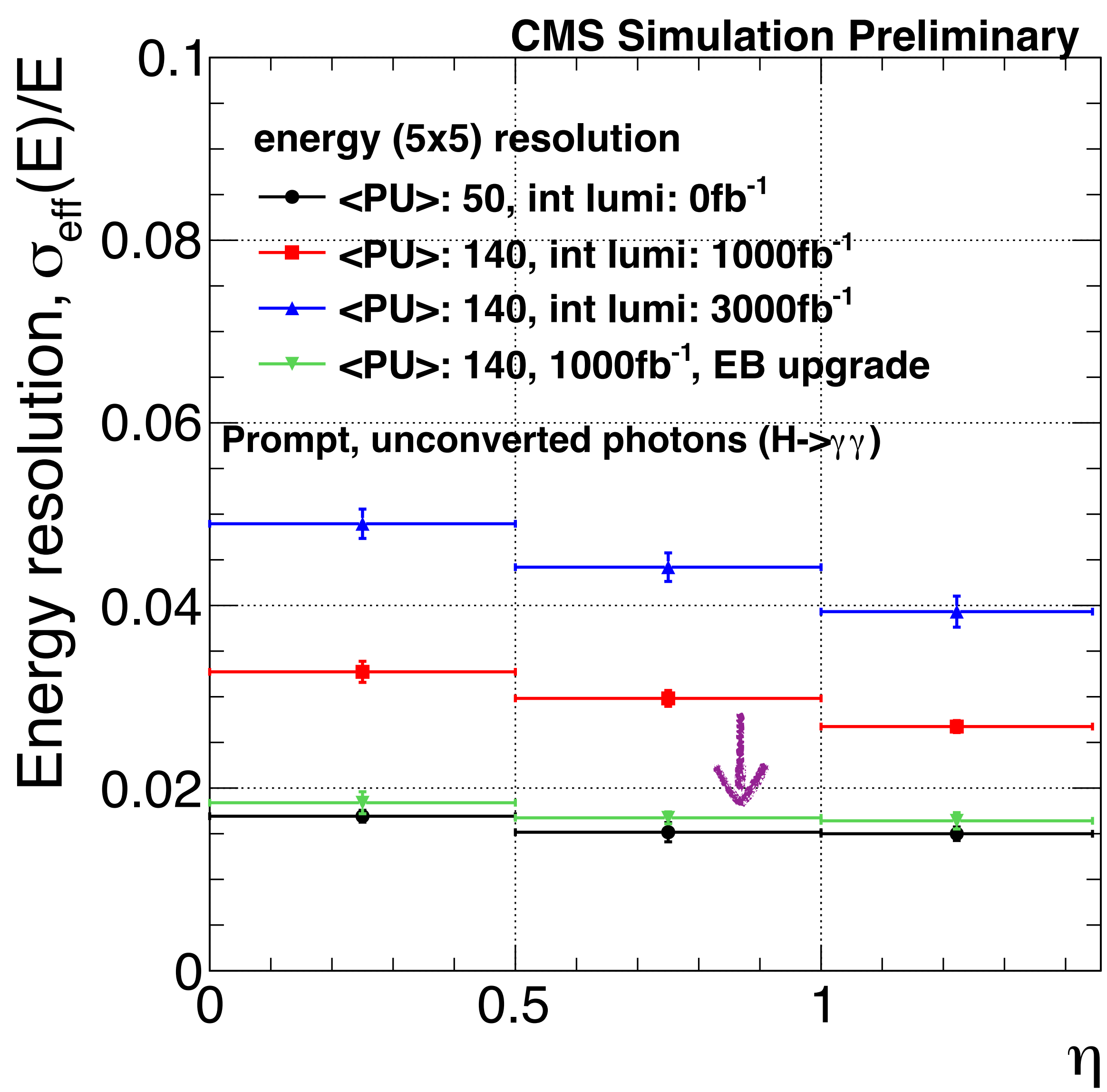
- Upgrades for timing improvement
  - VFE with Trans-impedance Amplifier (TIA)
  - Faster ADC sampling rates: 40MHZ to 160MHZ
- Promising intrinsic timing performance measured in test beam: 30ps resolution at $A/\sigma = 250$
  - HL-LHC start: $\sigma \sim 100$ MeV => 25 GeV photon
  - HL-LHC end: $\sigma \sim 240$ MeV => 60 GeV photon

See talk from Andrea Massironi





energy resolution w/ vs. w/o upgrades



- With the proposed upgrades, the energy resolution during HL-LHC will be maintained at the similar level of current Run II

Summary

- Excellent ECAL performance is achieved in Run II in a similar level as in Run I

- Upgrades are needed to maintain the performance in HL-LHC

BACKUP