Role of the CMS electromagnetic calorimeter in the measurement of the Higgs boson properties

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on behalf of CMS Collaboration

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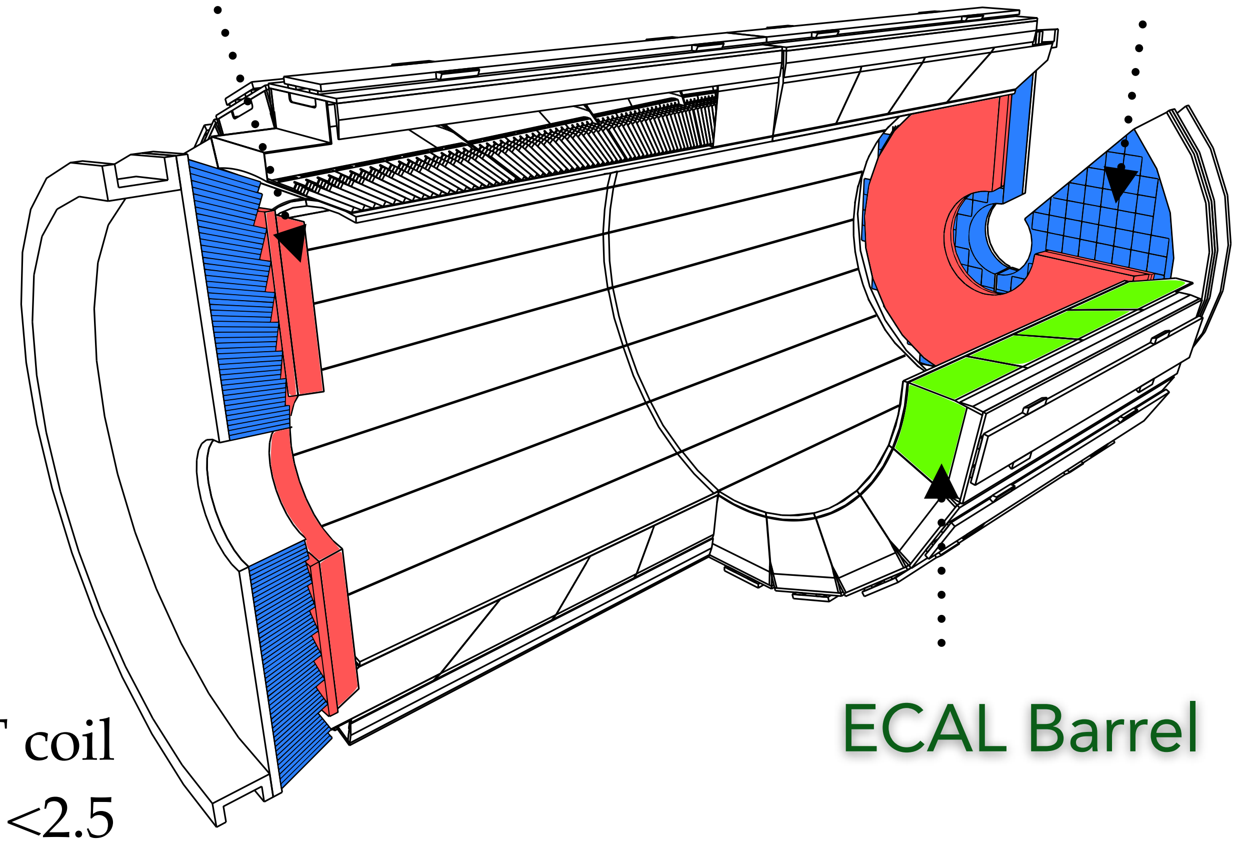
CMS Electromagnetic Calorimeter

ECAL: a homogeneous, hermetic, high granularity PWO_4 crystal calorimeter

- density of 8.3 g/cm^3, radiation length 0.89 cm, Molière radius 2.2 cm
- ≈ 80% of scintillating light in ≈ 25 ns
- refractive index = 2.2
- light yield spread among crystals ≈ 10% (RMS)



ECAL fully contained in the 3.8T coil
Tracker acceptance: $|\eta|<2.5$

Barrel (EB)	$|\eta|<1.48$	61200 $PbWO_4$ Crystals	25.8 X_0	APDs
Endcap (EE)	$1.48<|\eta|<3.0$	14648 $PbWO_4$ Crystals	24.7 X_0	VPTs
Preshower (ES)	$1.65<|\eta|<2.6$	137200 Pb/Si	3 X_0	strips

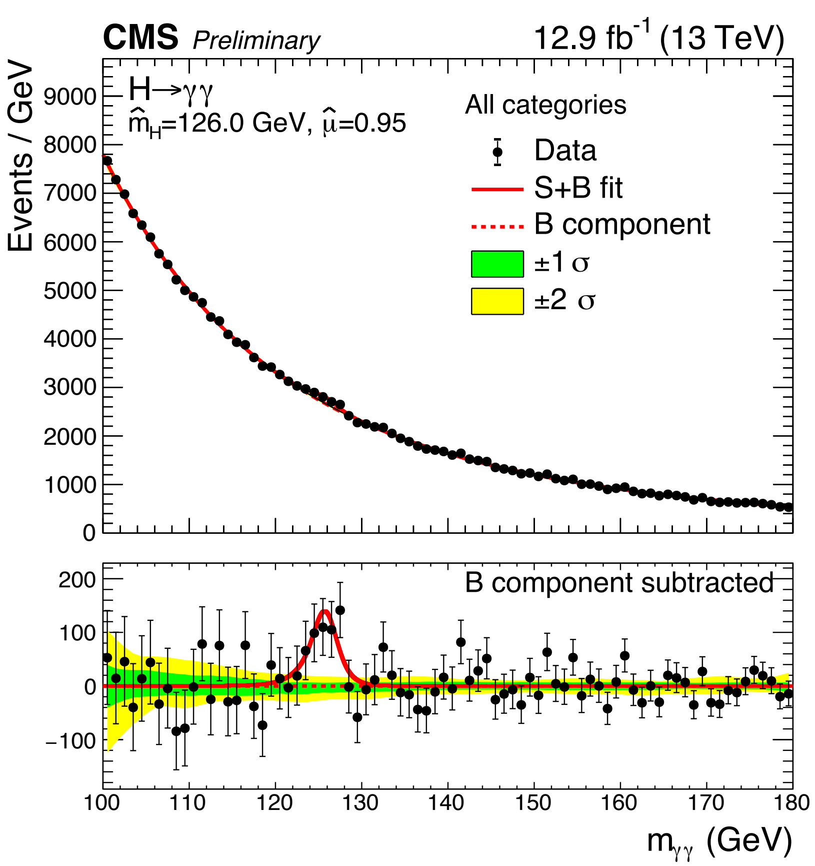
ECAL targets:

- precise e/γ energy and position measurements
- good timing resolution
- fast response for trigger and DAQ

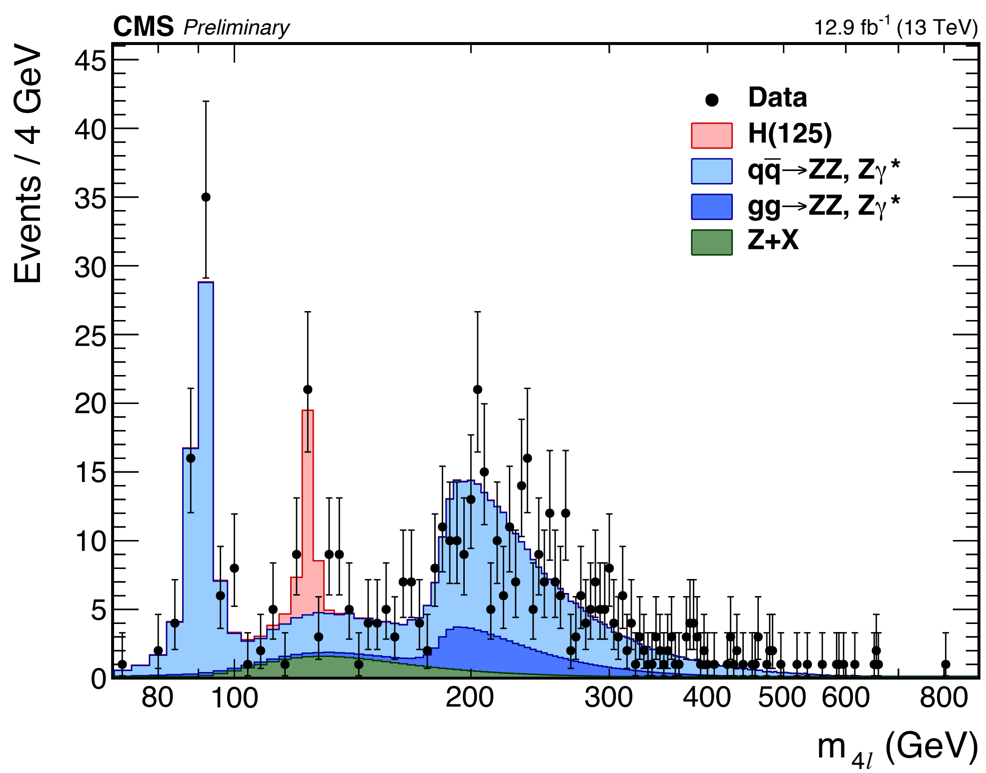
ECAL role in physics analysis

Search and measurements of narrow resonances with photons and electrons:

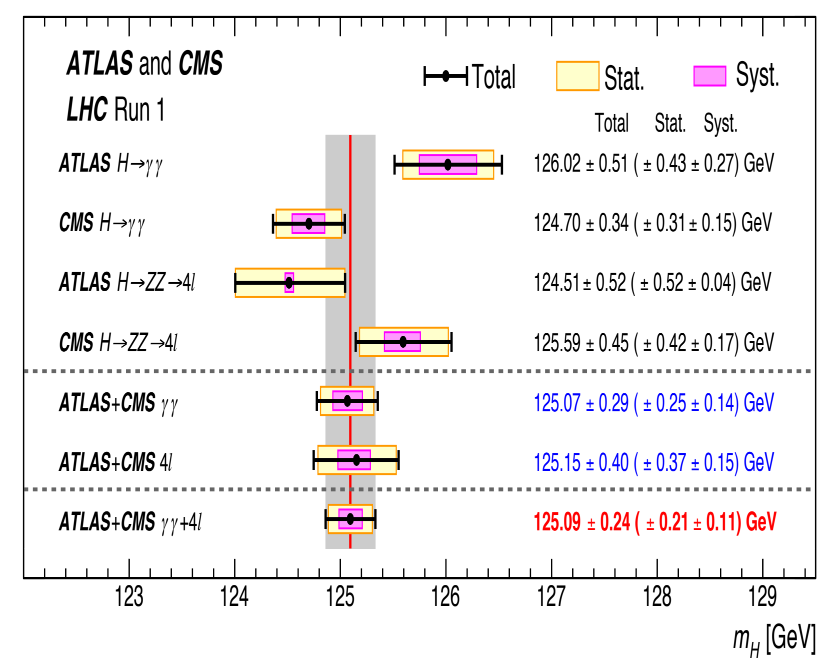
- H→$\gamma\gamma$: high energy resolution, position measurement to achieve high S/B
- H→ZZ→2e2μ,4e: energy reconstruction for a wide range of E_T for electron identification
  - and precise measurement of the Higgs boson properties: e.g. ***mass***, couplings, J^{CP}…
- high mass X→$\gamma\gamma$ (EXO-16-027), Z′→ee (EXO-16-031): high resolution and energy linearity



H→$\gamma\gamma$
(HIG-16-020)



H→ZZ→4 leptons
(HIG-16-033)



Run I ATLAS+CMS:
m_H=125.09 ± 0.24 GeV
(PRL 114 (2015) 191803)

Energy reconstruction

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

$$E_{e,\gamma} = \sum_i [A_i \times S_i(t) \times c_i] \times G(\eta) \times F_{e,\gamma}$$

- Pulse Amplitude: A_i
- time-dependent response corrections: laser monitoring system: $S_i(t)$
- intercalibration: c_i
- Global scale: $G(\eta)$
- cluster corrections: $F_{e,\gamma}$

Test Beam: Perfect calibration, no B field, no material upstream, no irradiation

- energy resolution on 3x3 EB crystals:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

☞ uniformity and stability required *in situ* **< 0.5%**

Run I: **in barrel, 1% energy resolution** achieved for unconverted photons

Pulse reconstruction

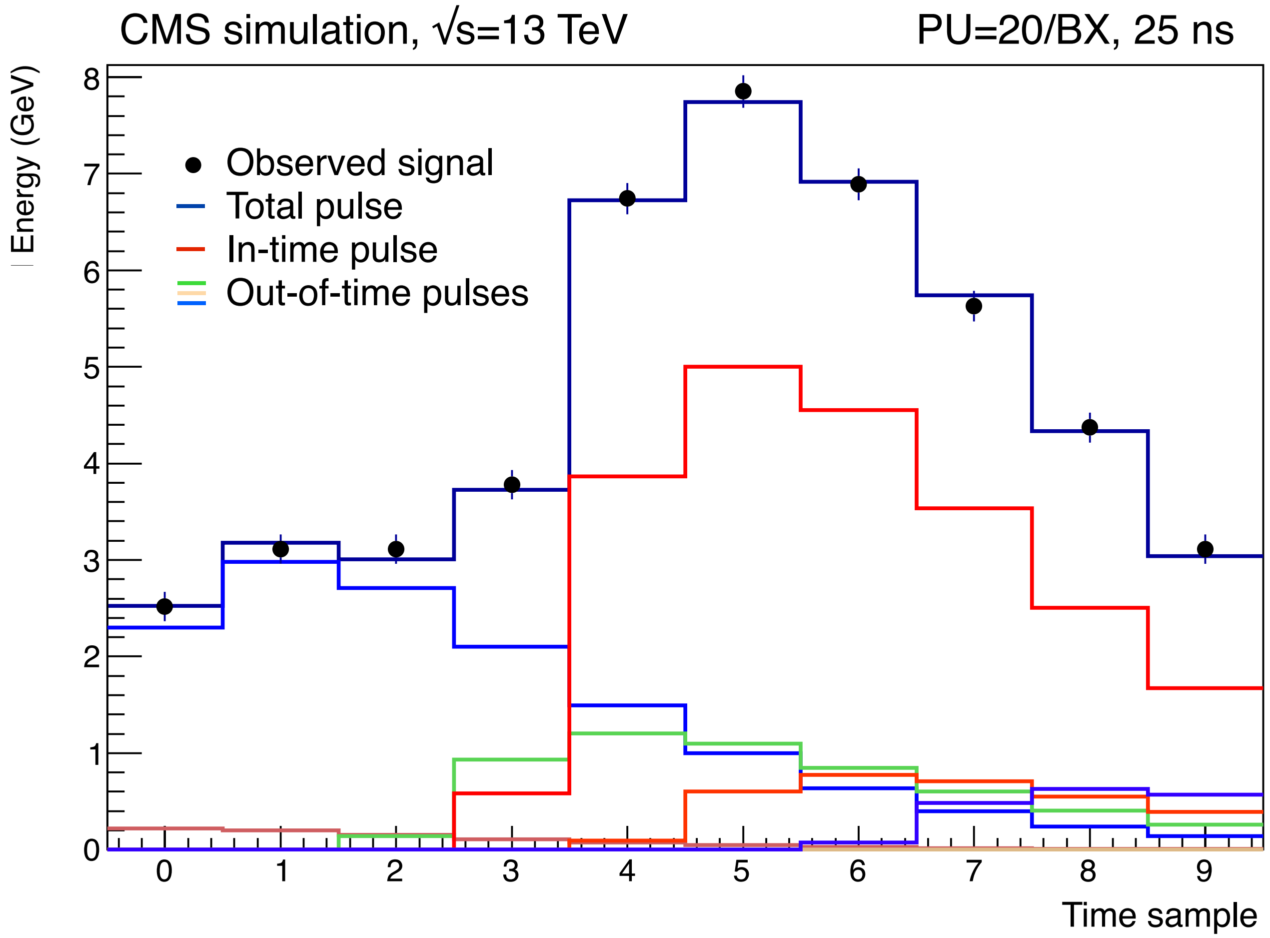
With RunII LHC running with 25ns bunch-spacing, need a pulse reconstruction resistant to out-of-time (OOT) pile-up: **multifit algorithm**:

Pulse shape is modeled as a sum of one in-time pulse plus OOT pulses

Time samples — Max 10 pulses

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

- Up to 9 OOT pulses (one per time sample)
- Minimize $\chi 2$ distribution for best description of the in-time amplitude
- Pulse shapes (binned templates) extracted periodically from LHC isolated bunches



- Baseline and electronic noise periodically measured from dedicated runs and used in the covariance matrix
- Minimisation using non-negative least-squares: fast enough to be used both offline and in the high-level trigger

Response monitoring

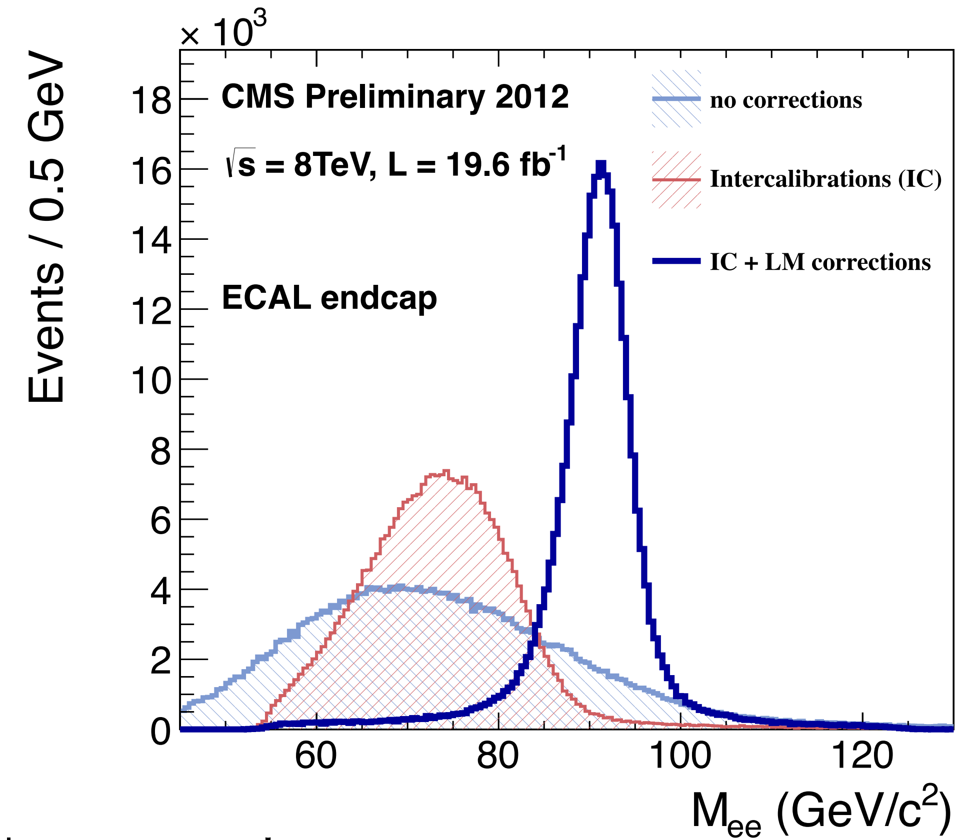
Sources of response variations under irradiation:

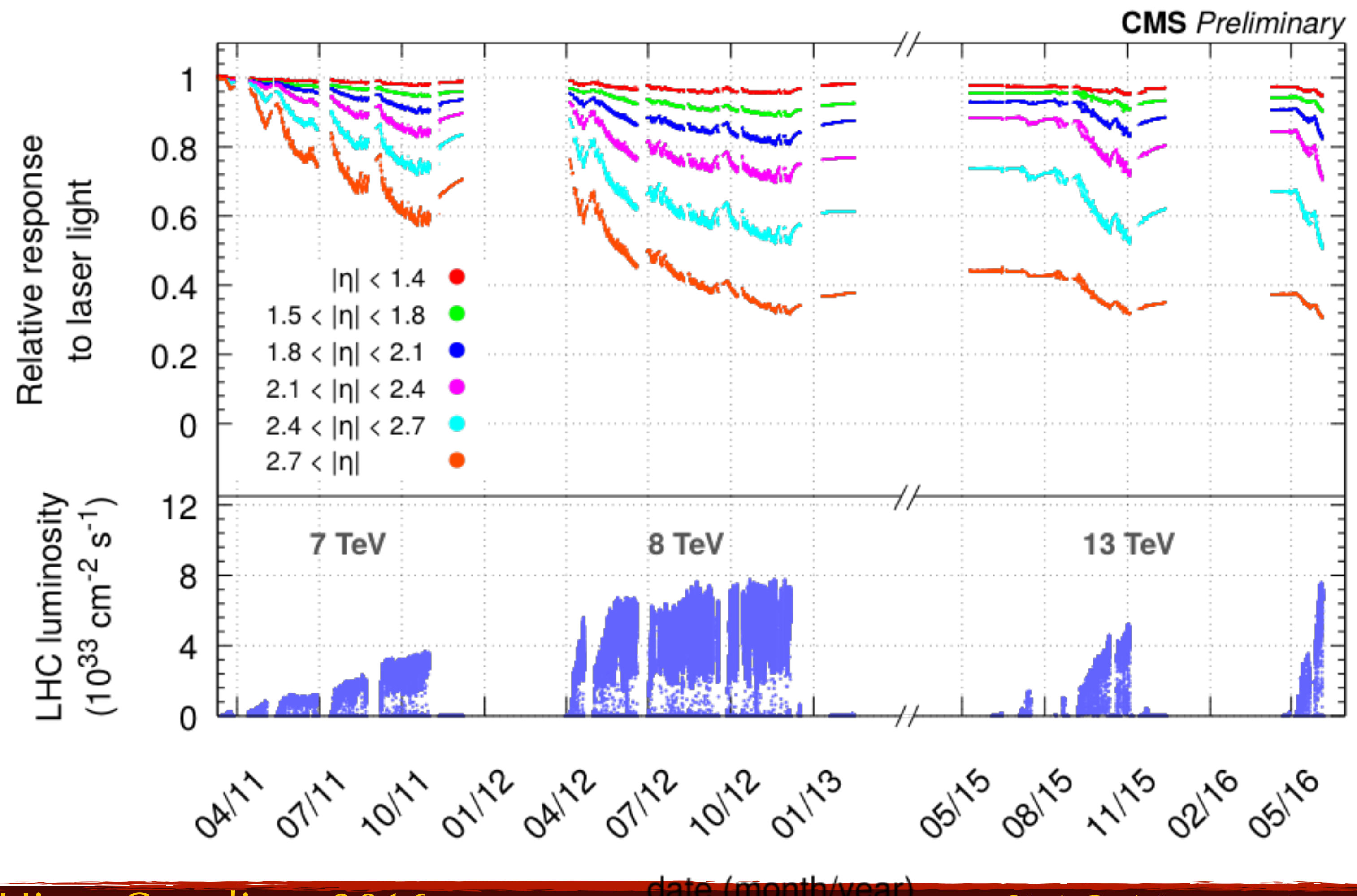
- **crystal transparency** (time dependent)
- VPT conditioning in the endcaps

Response **monitored with a laser system** injecting light in every ECAL crystal

$PbWO_4$ crystals partially recover during periods with no exposure

- 1 calibration point / channel / 40min
- corrections injected in (prompt) reconstruction (~48h latency)





|η|<2.5: tracker coverage ⇒ precision physics

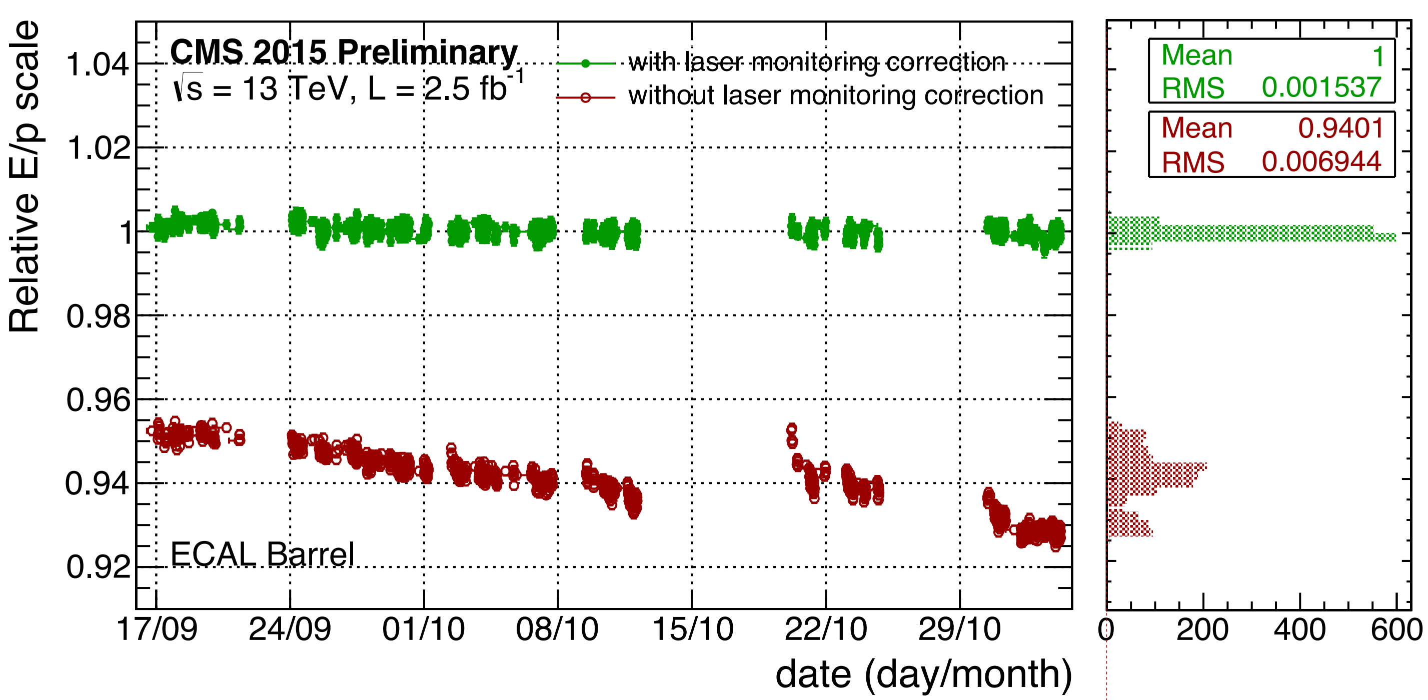
Outer endcap: jet physics

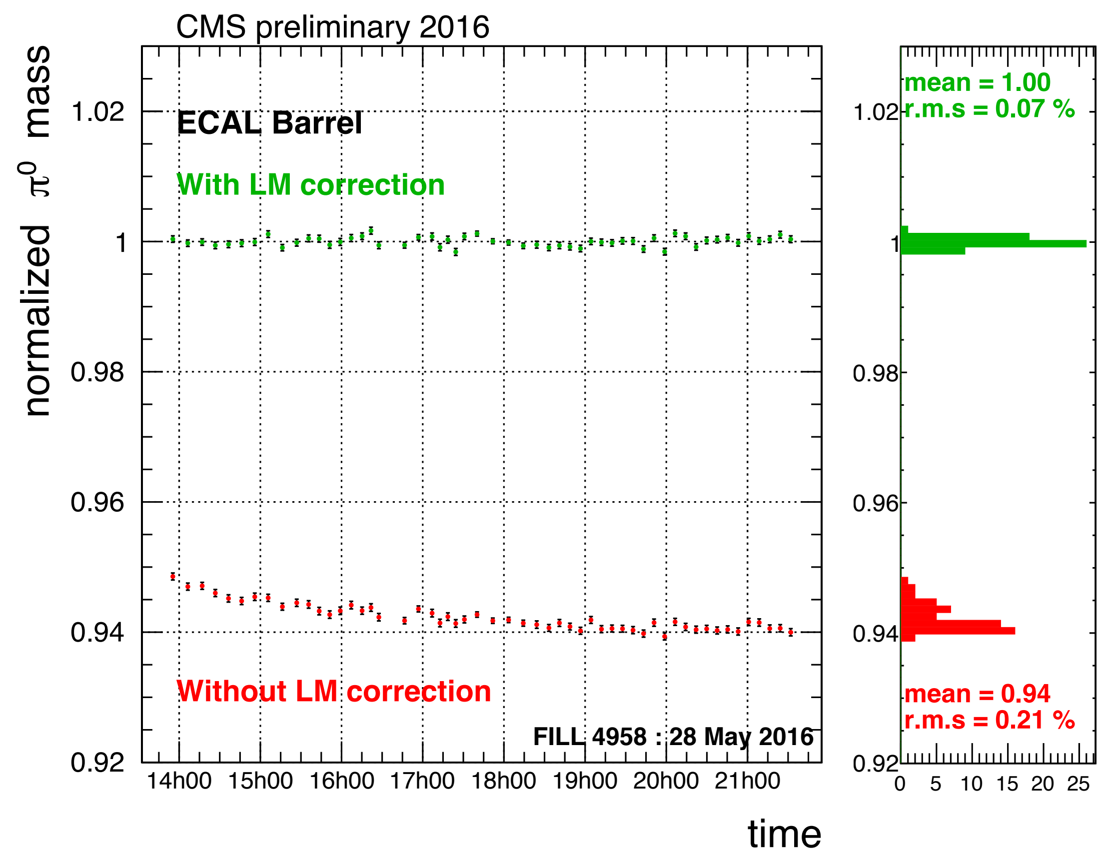
- Steady recovery during shutdowns and inter-fills
- In the regions close to beam pipe, not fully recovered

Validation of monitoring

Response stability after corrections validated with physics signals:

- π^0 invariant mass
- E/p relative scale of W and Z electrons





Electrons E/p history in barrel in 2015

- <signal loss> ~ 6%
- RMS after corrections: ~0.14%
- similar to RunI

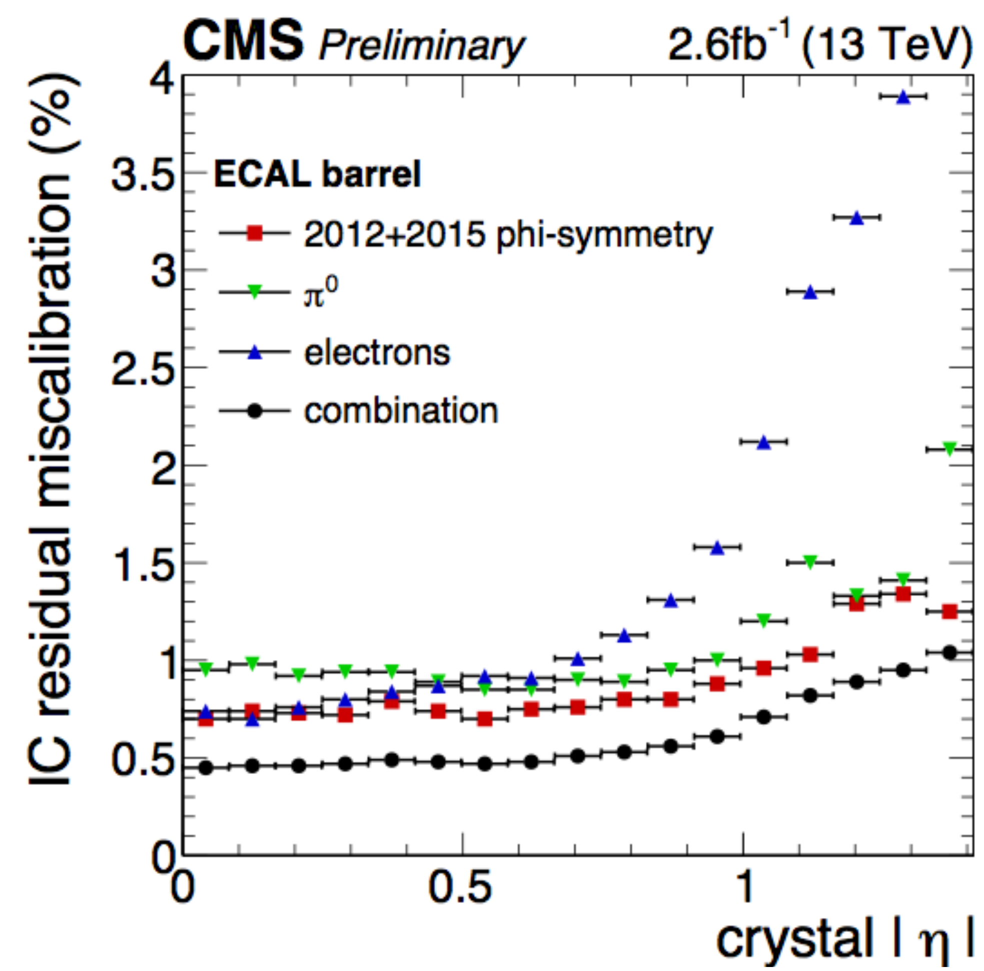
π^0 mass history in barrel in 1 fill

- <signal loss> ~ 1%
- RMS after corrections: ~0.07%
- very fast monitoring: 1 point / 8 minutes

Energy intercalibration (IC)

Several methods used to equalize the response of each single crystal to the deposited energy. Same methods used as in Run I

method	time needed	Run I precision
ϕ-symmetry	few days	1-3% in EB 3-5% in EE
$\pi^0/\eta \to \gamma\gamma$	1 month	0.5% in EB 3% in EE (|η|<2)
electron E/p	20 fb^{-1}	0.5% in EB 2% in EE
Z→ee mass	20 fb^{-1}	equalise the scale vs η in EE



ϕ-symmetry:

- In 2015 used to transfer 2012 calibrations
- in 2016 being used for time evolution of IC as in Run I
- systematically limited

E/p precision:

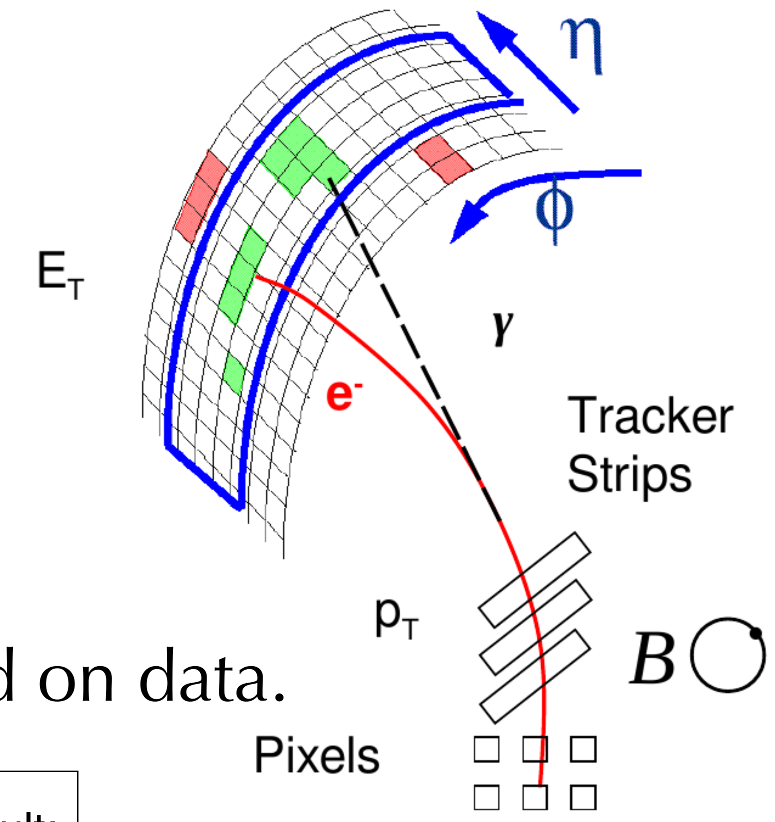
- was limited by W/Z statistics in 2015, especially for |η|>1
- combination then still dominated by Run I

With full Run II sample, expected similar precision as in Run I

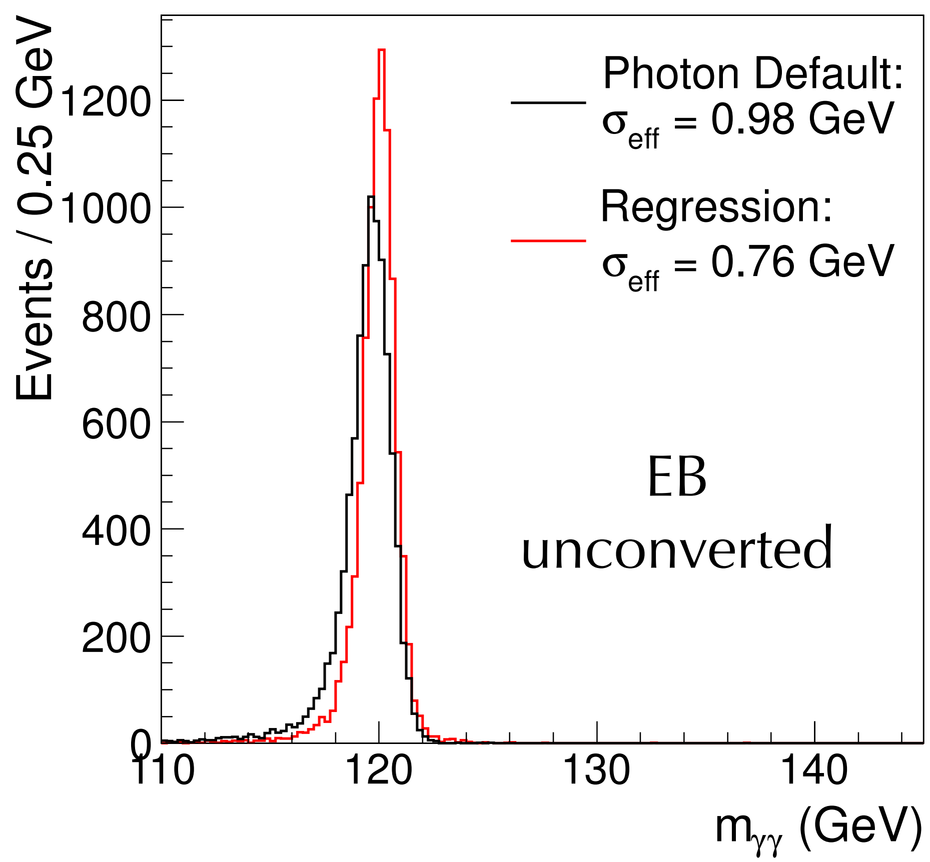
Clustering and corrections

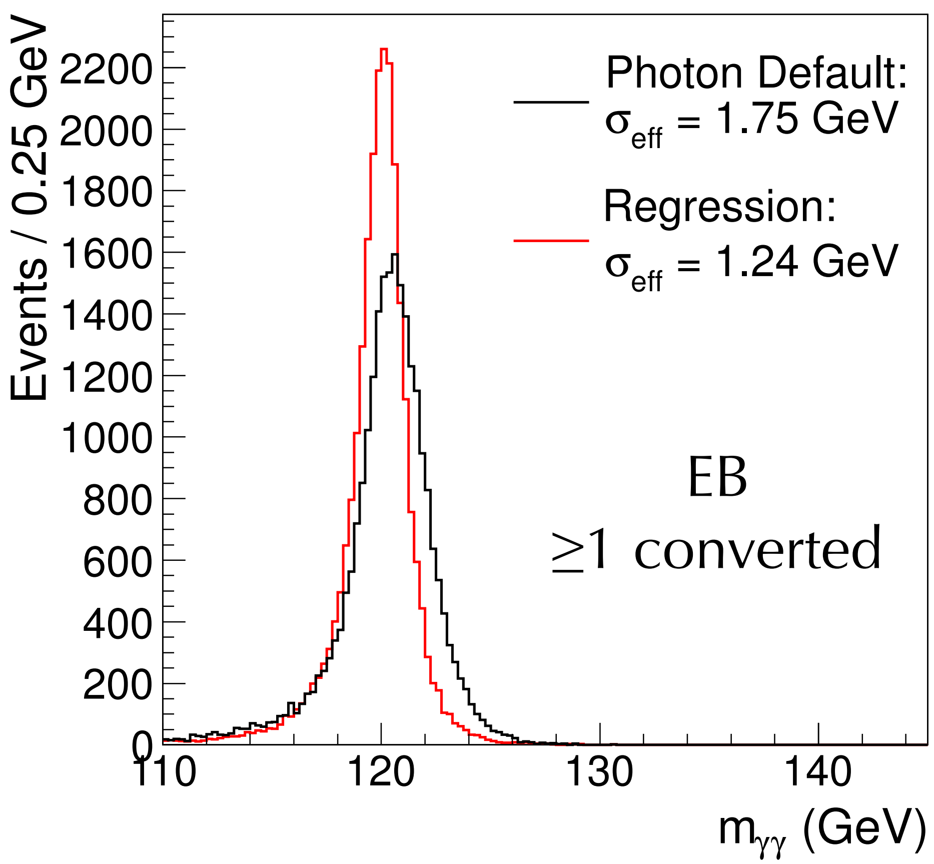
Dynamic clustering to recover energy radiated upstream of ECAL via bremsstrahlung or conversions

- Super-clusters of clusters along ϕ (bending direction)
- soft conversion legs / brem may be not included in super-clusters
- In the endcaps, add also preshower energy
- additional energy from pileup contaminates the shower



☞ Algorithmic multivariate corrections used to maximally exploit the information of the event. Tuned on MC, validated on data.





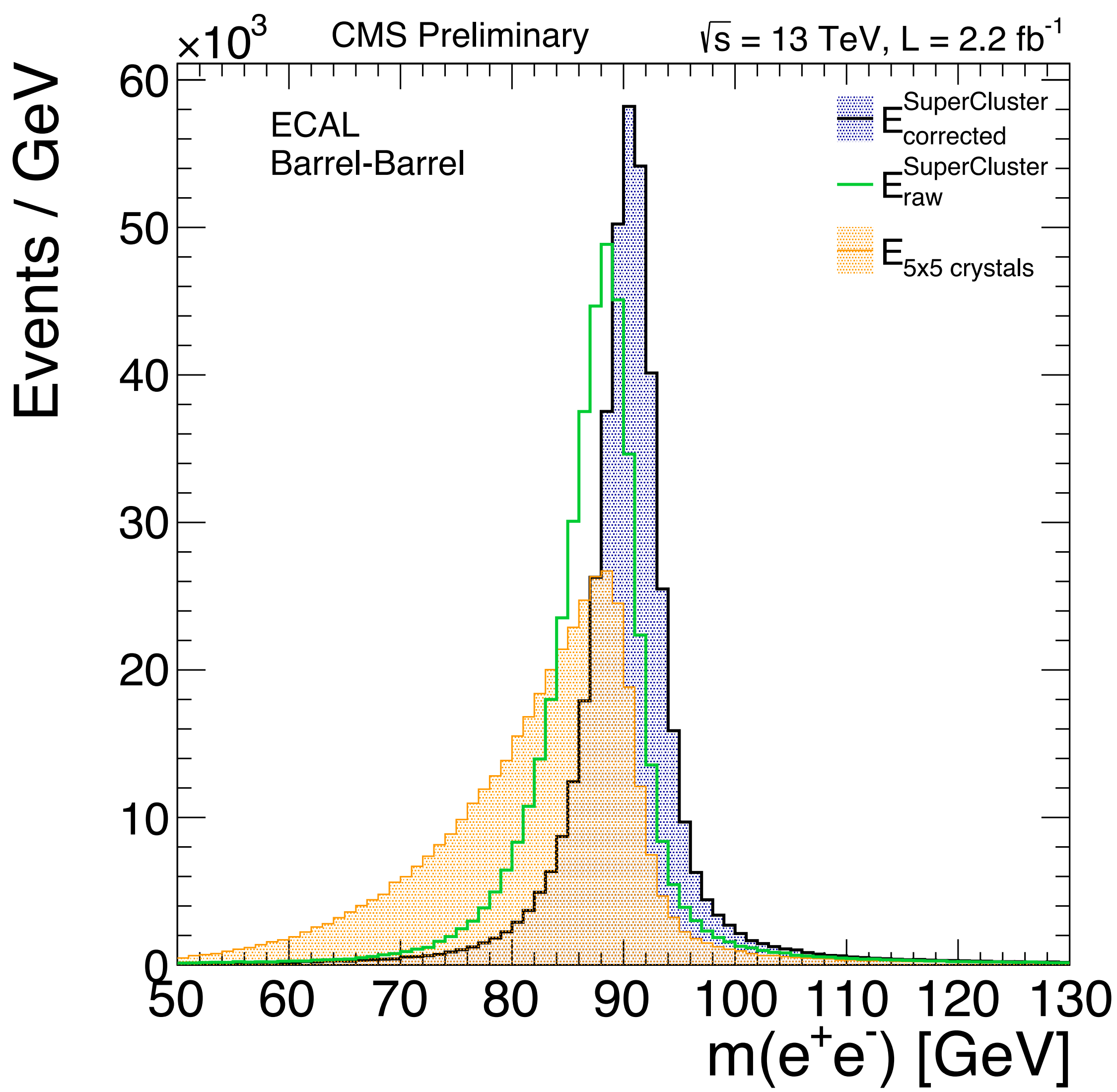
Visible improvement wrt Run I parametric corrections

Cluster energy in data

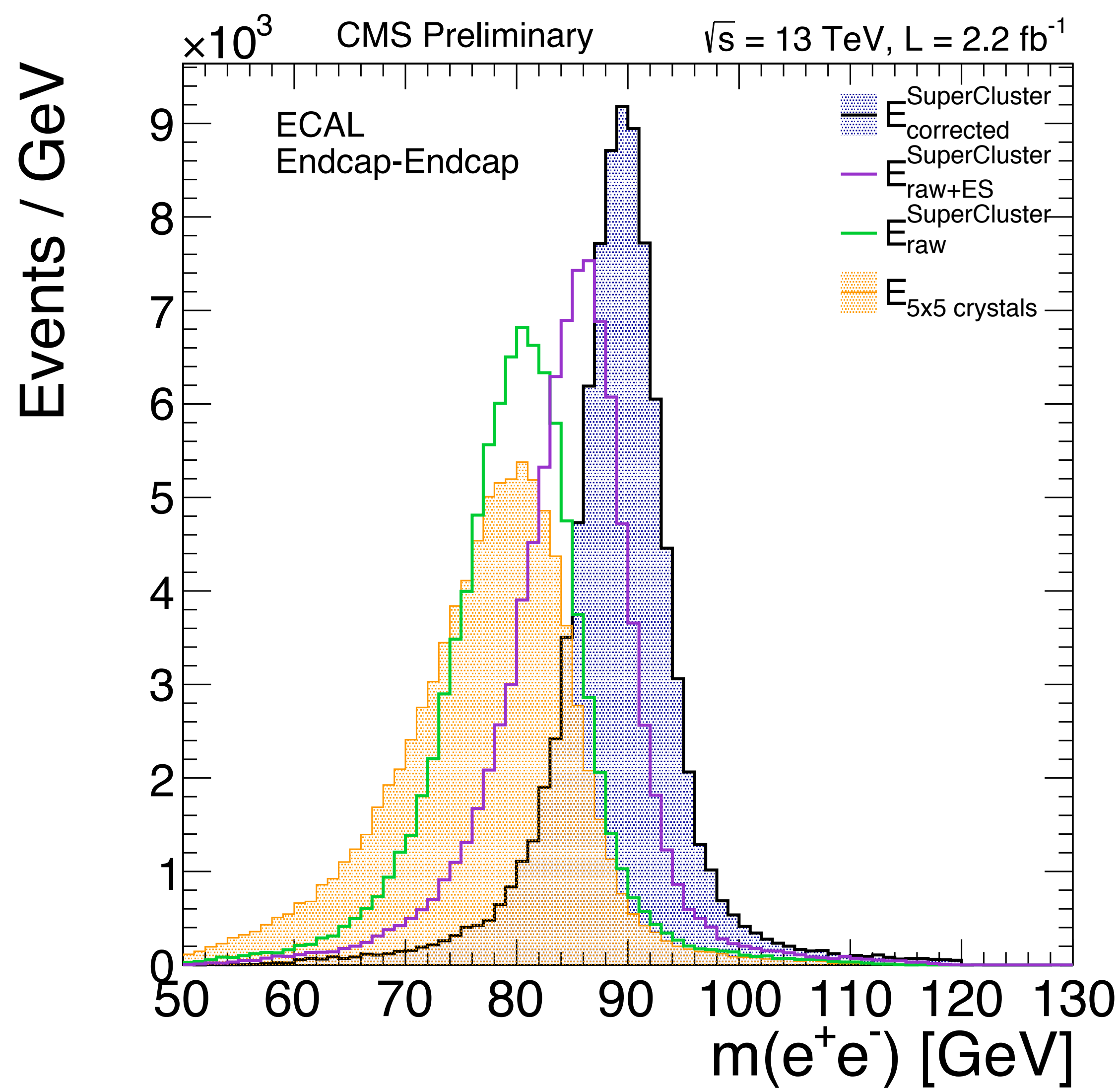
Reconstructed Z mass in data with different levels of energy reconstruction and corrections

- In EB, long tail to lower values of the E_{5x5} due to the high fraction of showering electrons in the high-material region at $|\eta|>1$
- in EE, the energy scale is improved by adding the preshower energy to the crystals energy

barrel

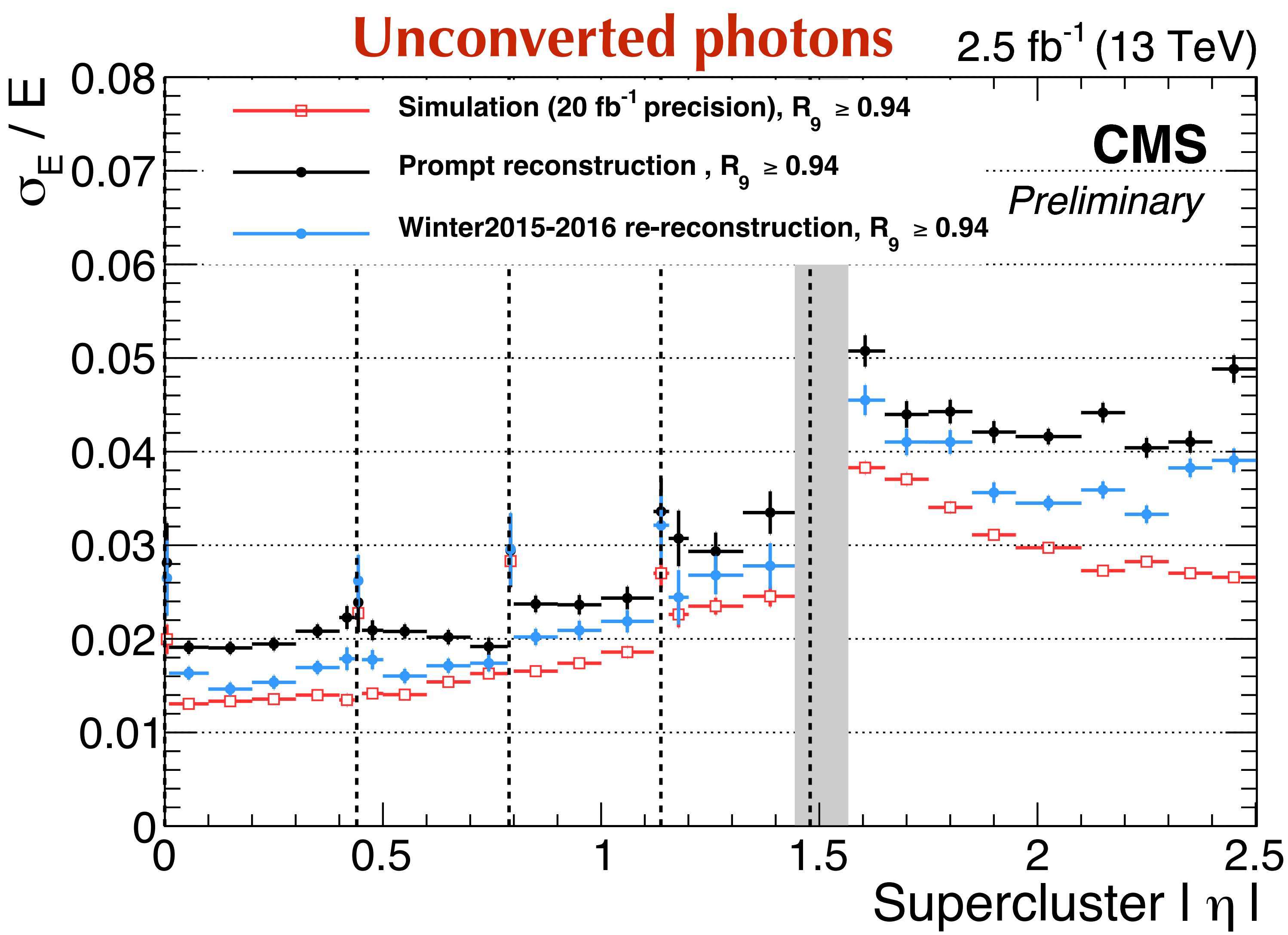


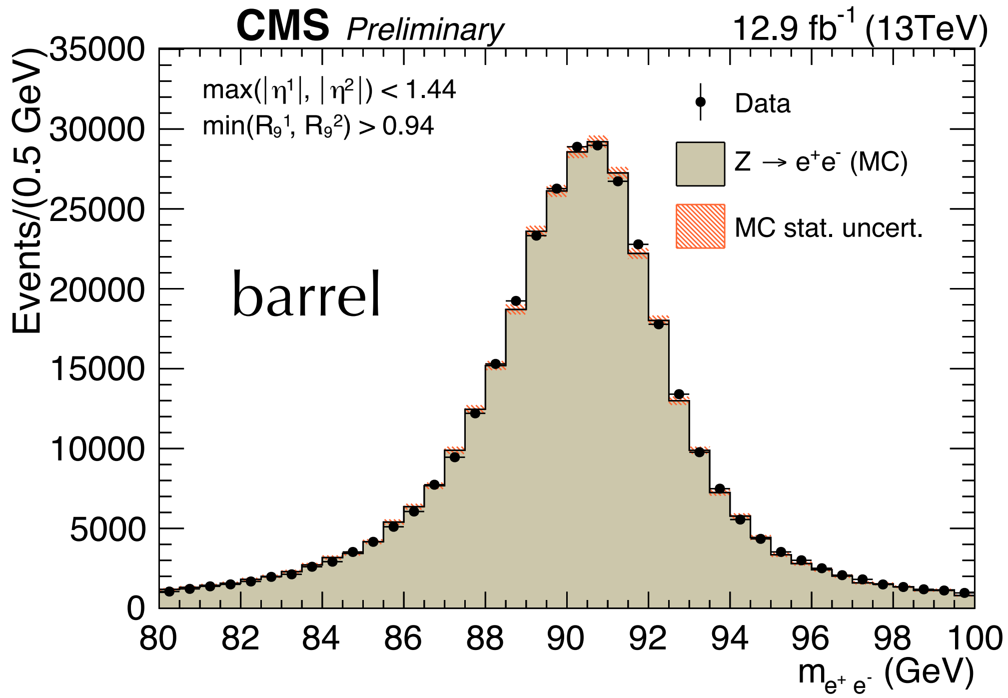
endcap

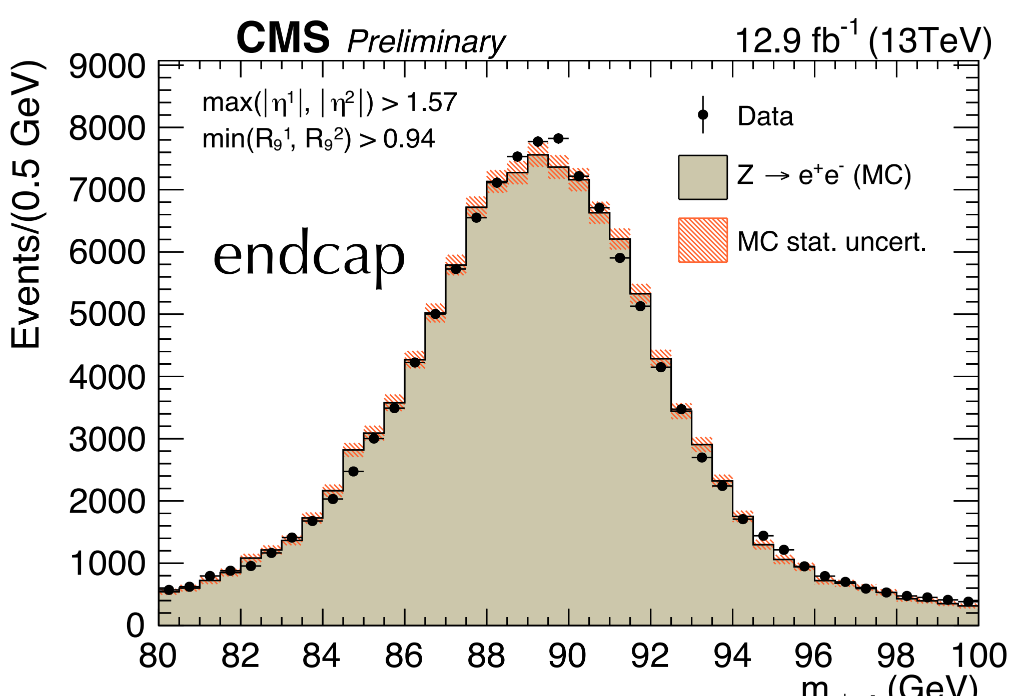


Energy resolution

$R_9 = E_{3x3}/E_{SC}$ is an effective conversion tagging variable (R>0.94 used to classify majority of unconverted photons / low-brem electrons)







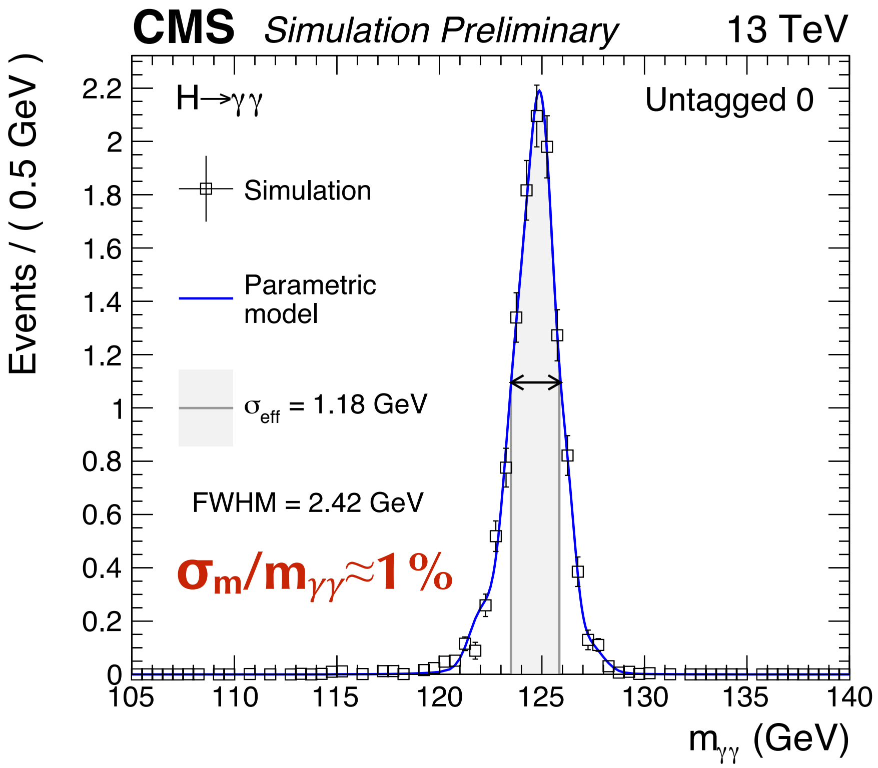
Resolution improves after 2015 calibration:

- **For |η|<1, precision at the level of Run I**
- elsewhere, limited by electron-sample statistics
- estimated with fit to Z→ee with BW convolved with a Crystal-ball

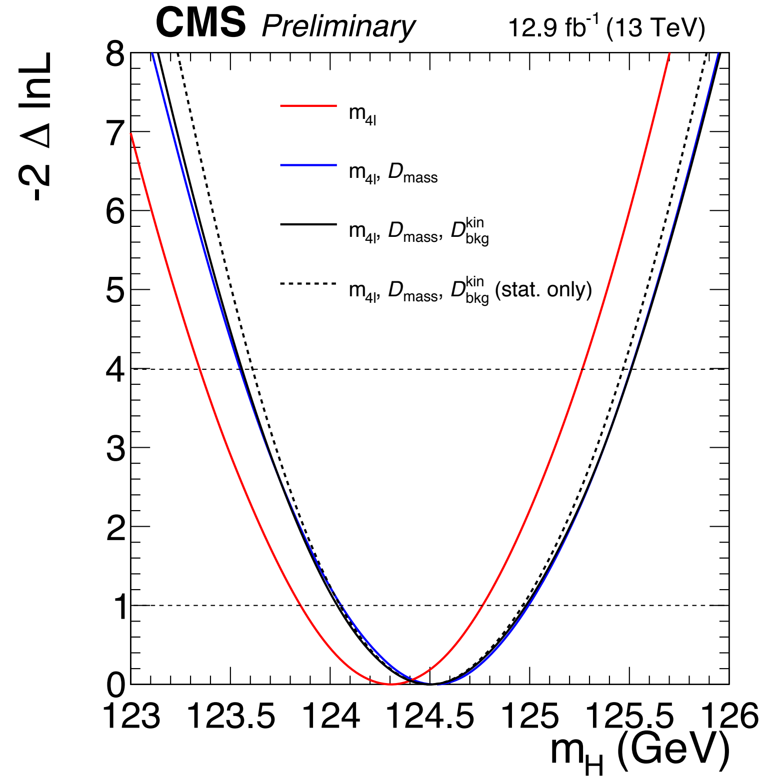
simulation tuned
to match resolution observed in data

single e/γ resolution estimate

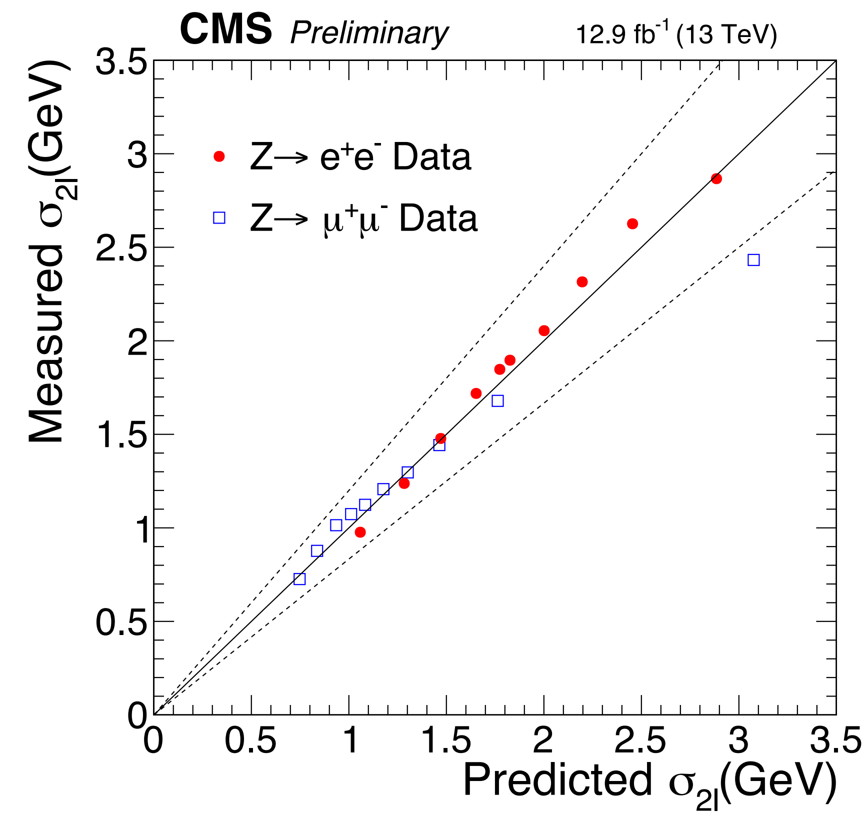
H→γγ best category



H→4l mass likelihood



observed vs predicted σ_m



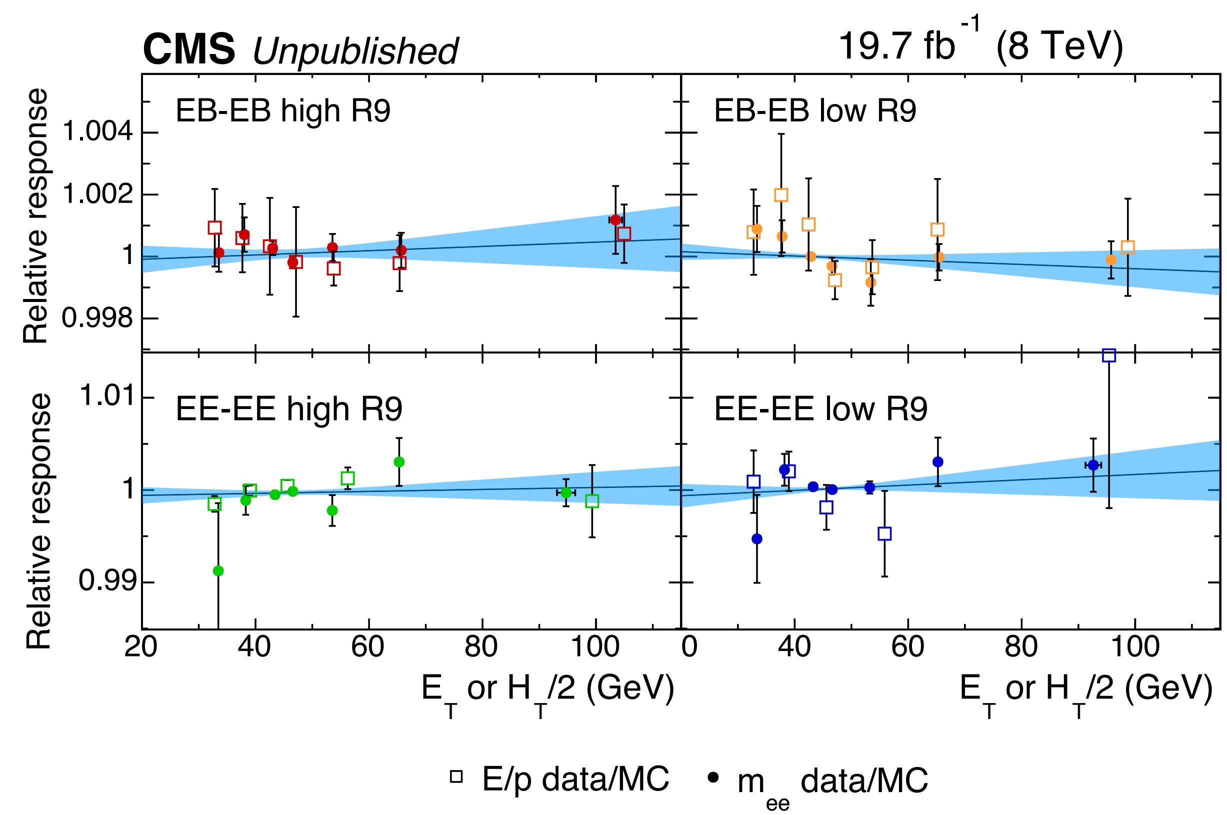
Per-electron or per-photon resolution used to build a per-event mass resolution (σ_m/m), utilised to make optimal use of the highest resolution events:

- H→$\gamma\gamma$: used to classify events in several "untagged" categories for $m_{\gamma\gamma}$ fit
- H→4l: per-event mass resolution used as a third variable in the fit for mass measurement
  - Validated in data with fits to Z→ee by comparing the predicted σ_{m2l} / m_{2l}

ECAL systematics on SM Higgs

Possible sources of non perfect knowledge of the energy scale and resolution (after Run I, *re-estimated for ICHEP 2016*):

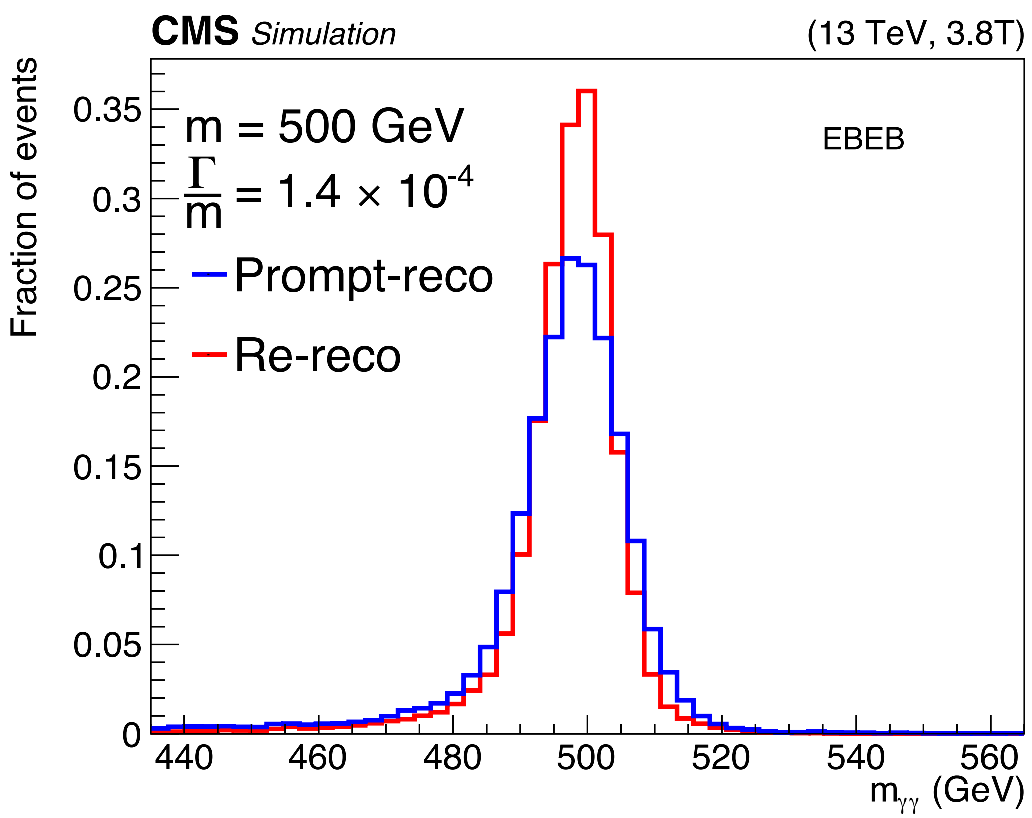
- Residual non-linearity in scale (mostly for $H\to\gamma\gamma$; in $H\to 4l$ mitigated by E-track momentum combination for the electron energy): **[0.1 - 0.2]%**
  - extrapolation from E measured at Z peak (90 GeV) to m_H (125 GeV)
- Electron/photon differences in the simulation (residual data wrt MC): **[0.15 - 0.5]%**
- material distribution upstream ECAL: **0.17%**
  - improved description at beginning of Run II
- *longitudinal light-yield non-uniformity*: **0.07%**
- Geant4 (shower simulation): **0.05%**
- Shower shape modelling: **0.06%**

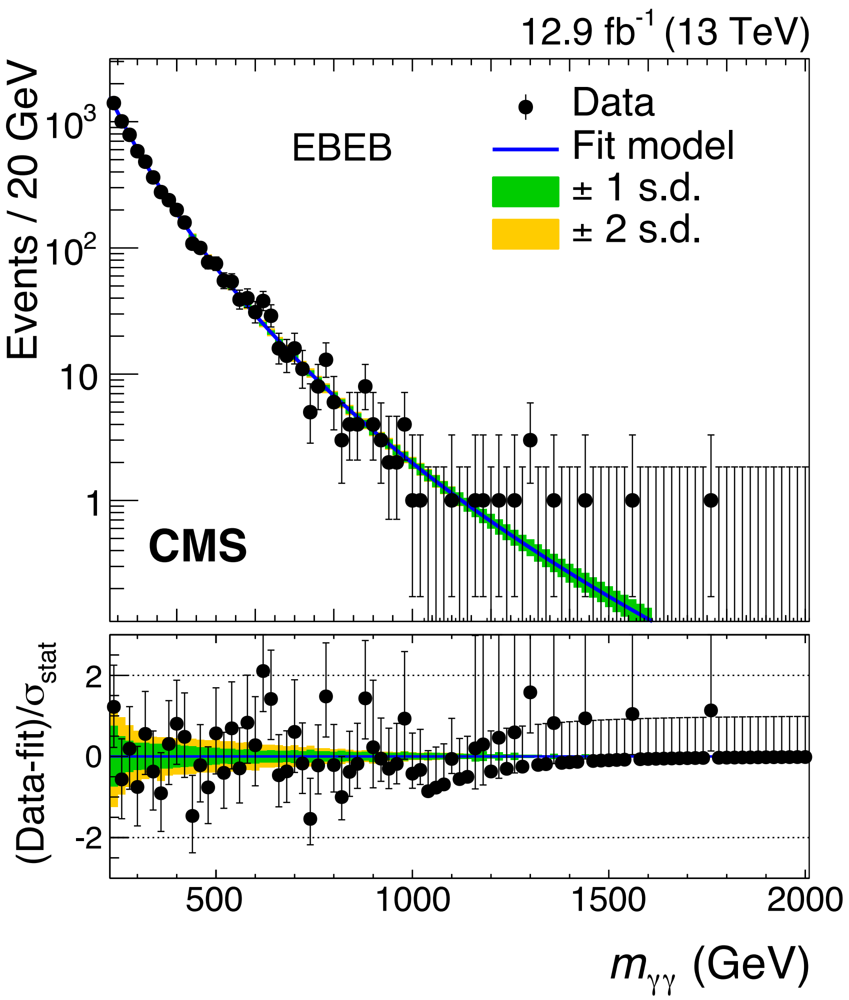


Measurement of high energy e/γ

Search of $X \rightarrow \gamma\gamma$ resonances: target RS gravitons, excluded $m_G \approx$[2-4] TeV

- improved calibrations significant also for high-energy photons
- electronics saturation accounted by the multivariate cluster corrections
  - single channel saturation in barrel: E~1.6 TeV
  - impact on energy scale **< 2%**
- residual non-linearity checked with boosted $Z \rightarrow ee$: **< 0.5% (0.7%)** for photons up to 150 GeV in the barrel (endcap)





Conclusions

- Continuous developments and understandings of the detector details:
    - New amplitude reconstruction algorithm in place to cope with $\approx$ 40 pileup interaction
    - ready for even higher values expected in 2017
    - energy measurement, calibrated with the 2.5 fb^{-1} of 2015 data, is as good as in Run I in the most precise region
- The CMS ECAL has played a crucial role in the re-assessment of the Higgs boson and its measurements with Run II data
    - $> 5\sigma$ signal in each of the two high-resolution channels, $H\rightarrow\gamma\gamma$ and $H\rightarrow 4l$
    - re-calibration with 2016 data ongoing. Target is m_H measurement with full Run II dataset
- It has been the leading ingredient of the searches of high-mass resonances in the di-photon and di-electron resonances
- Looking forward for physics beyond SM searches and / or precise SM measurements, including the Higgs boson ones

backup

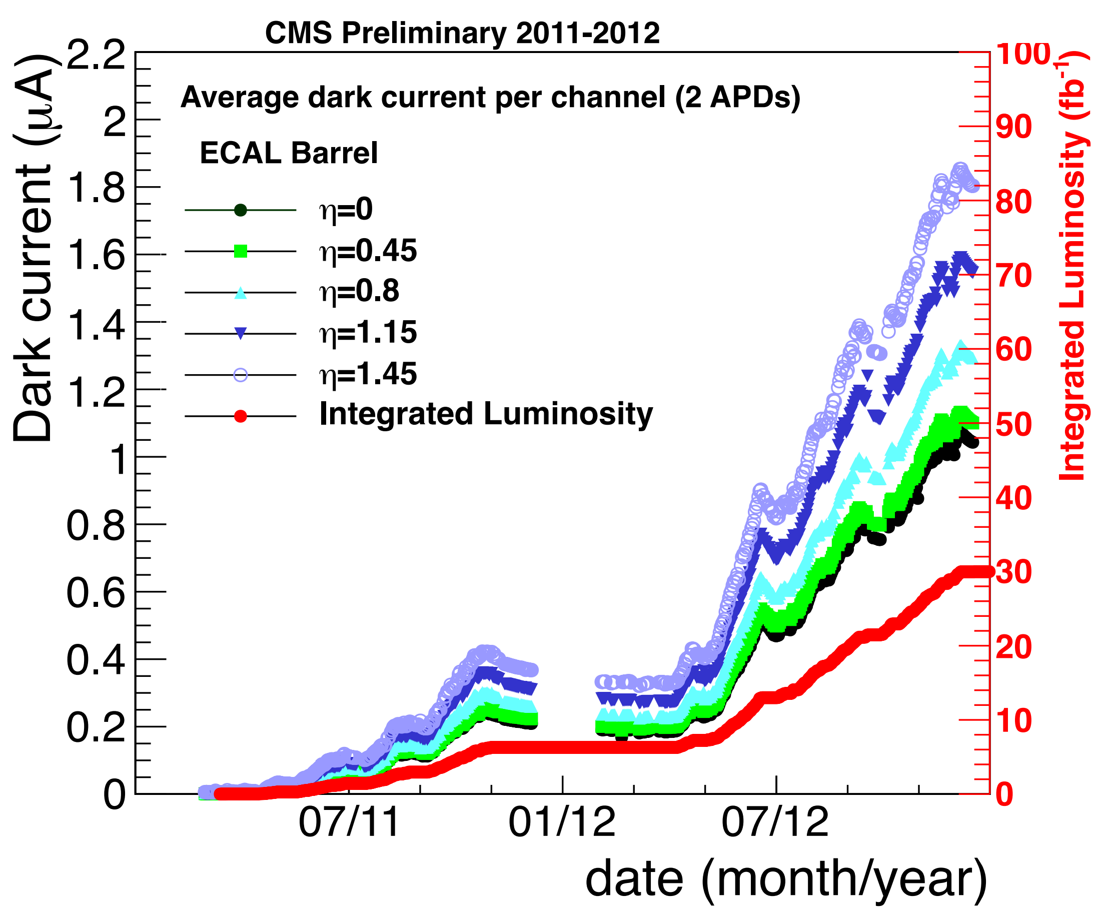
Simulation

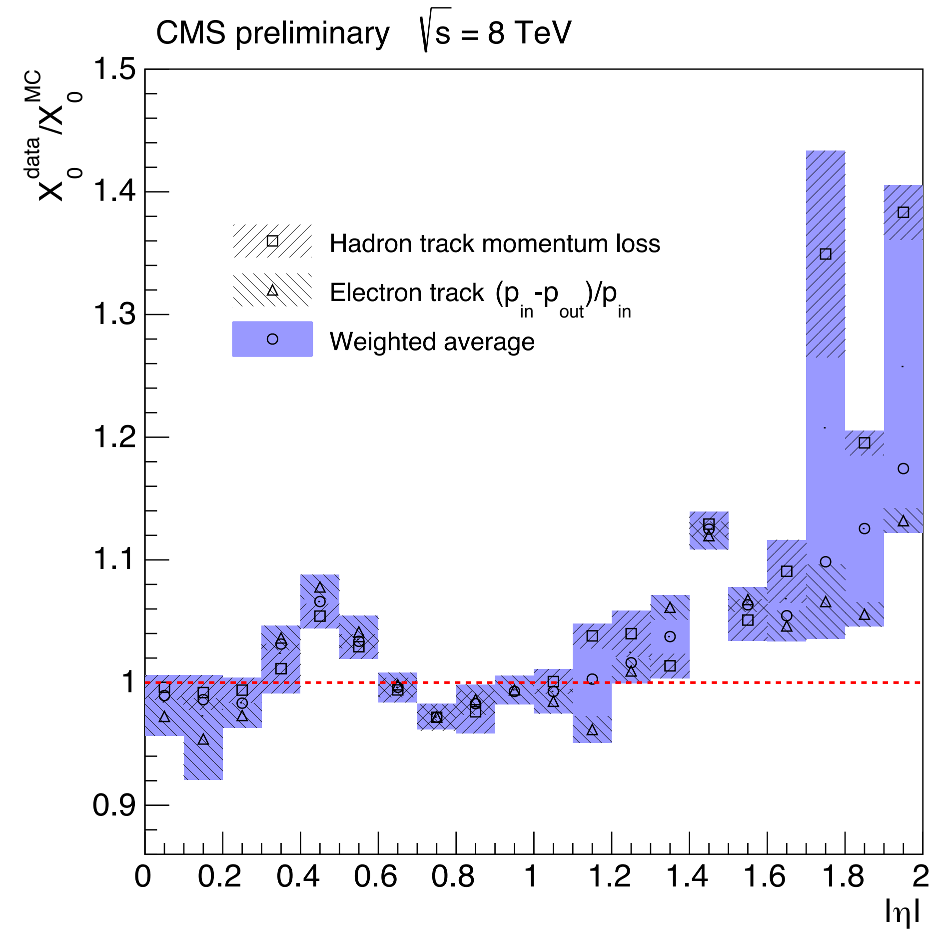
Noise model:

- realistic noise with sample-correlations and channel-to-channel variations
- increase of the **APD dark current** (expected with irradiation)
- transparency variations for realistic light-yield

Material budget in front of ECAL:

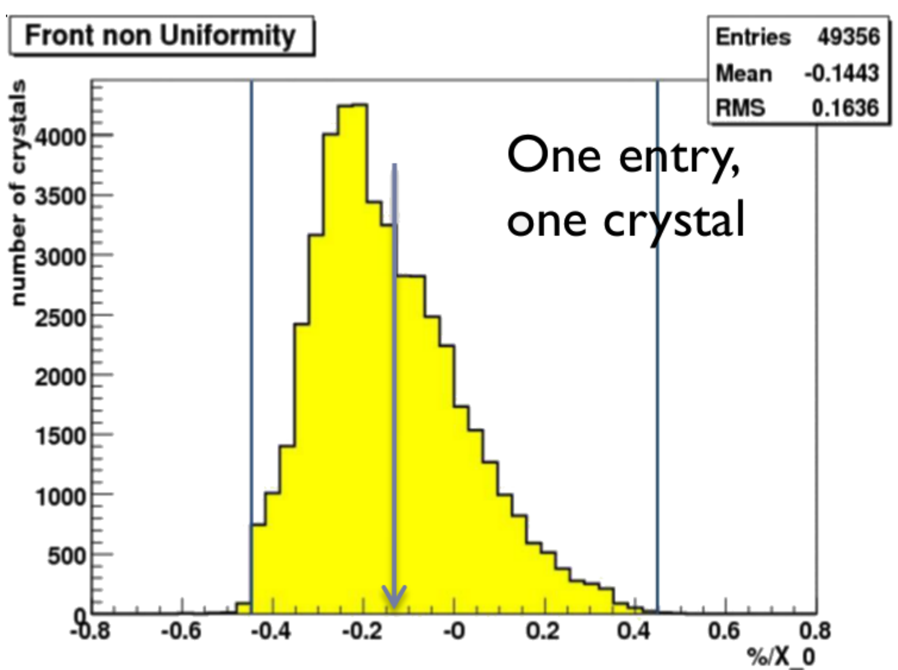
- **tracker material description**, including in-homogeneities in φ of services in front of the endcaps implemented in simulation in Run 2

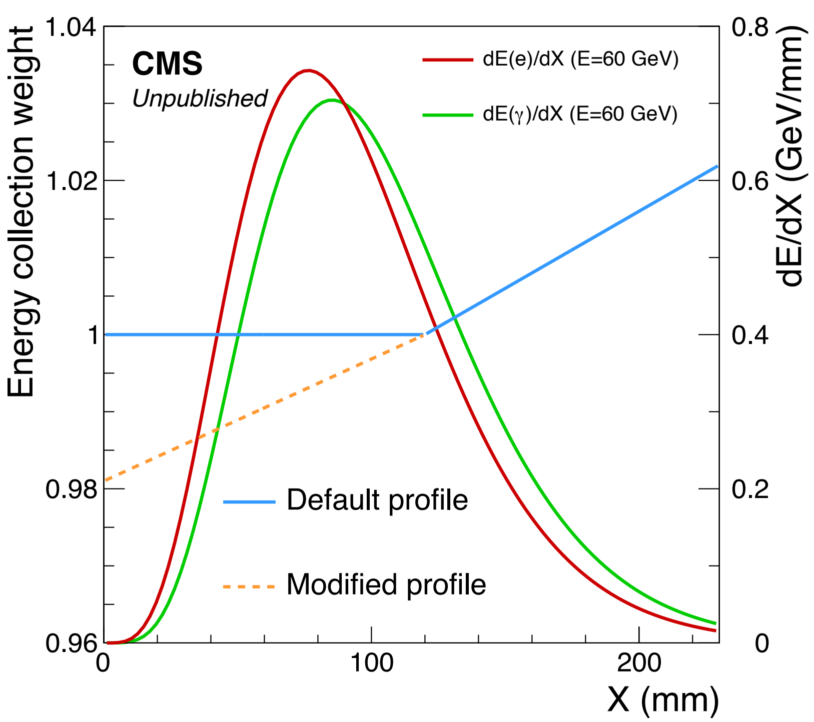




Longitudinal non-uniformity

- Target: adequate uniformity of longitudinal light yield
  - one face of each barrel crystal depolished
  - Simulation: rear non-uniformity of 0.15%, front part assumed uniform
  - Ionizing radiation found to induce additional NUF of 30% of its initial value (worst case scenario) at the end of Run1
    - ➡ simulation modified to account for these effects





- **Result: 0.07% effect on the energy scale**, anti-correlated between converted and un-converted photons

ECAL @ 0T

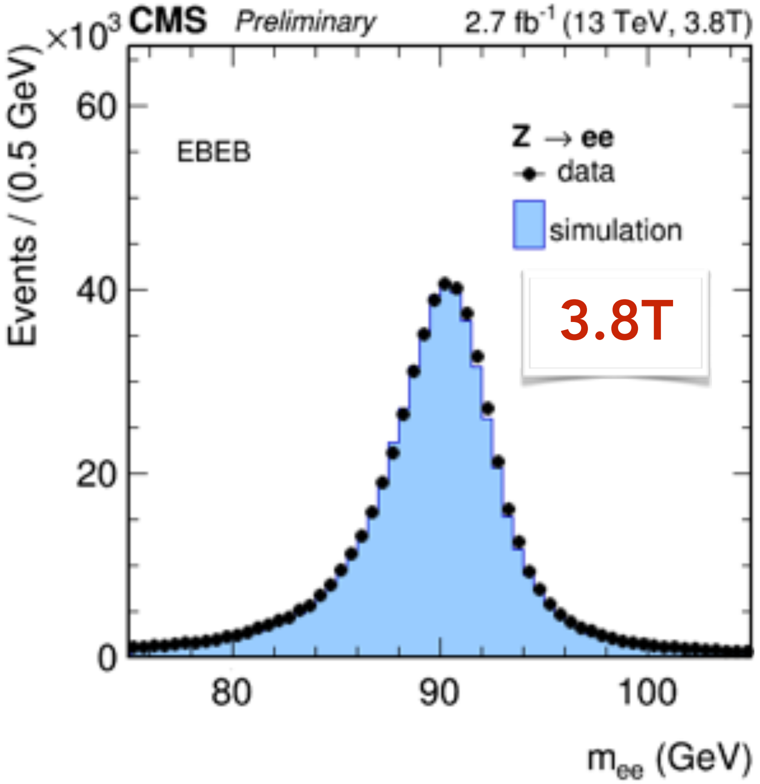
Di-Photon analyses are possible with data at B=0T (0.6 fb-1 of 2015 data).

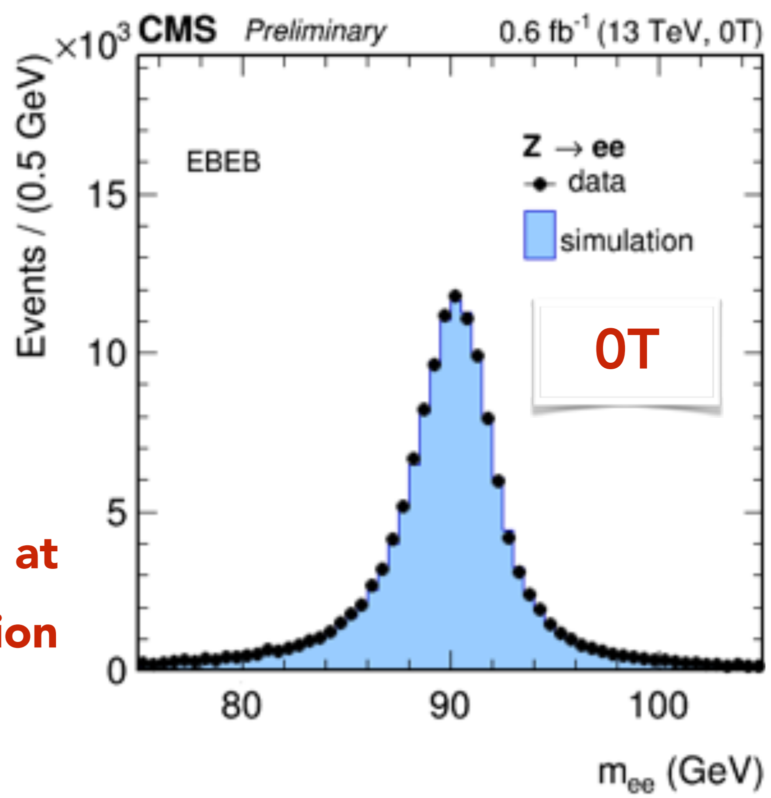
No information on track momenta:

- weakens isolation power
- more difficult to identify correct vertex

But energy spread for conversions / brem reduced

- better energy resolution, easier e/ɣ extrapolation
- shower shape discrimination more powerful
- need dedicated channel IC, need absolute scale re-calibration
  - especially in EE, where VPT gain changes wrt 3.8T value as a function of η

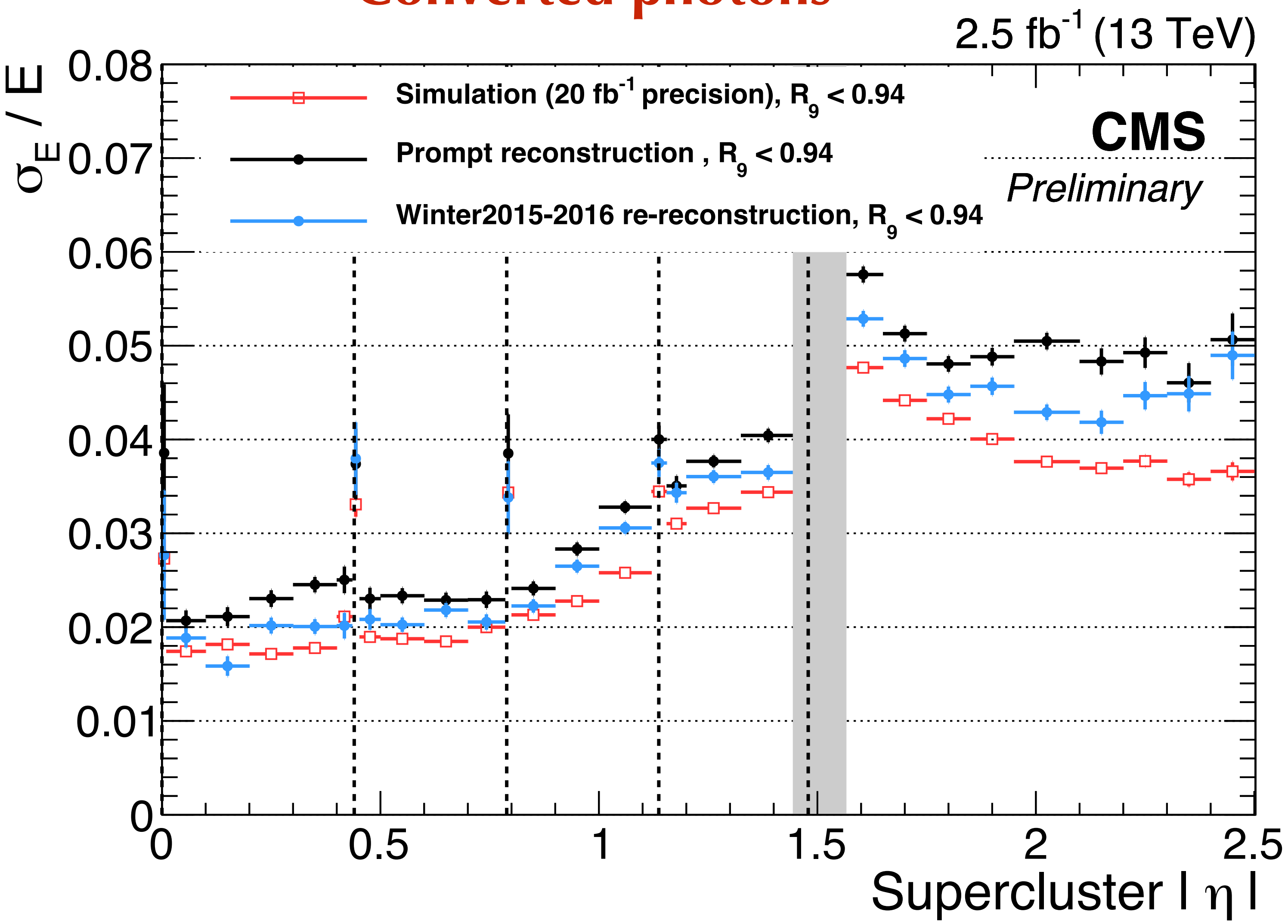


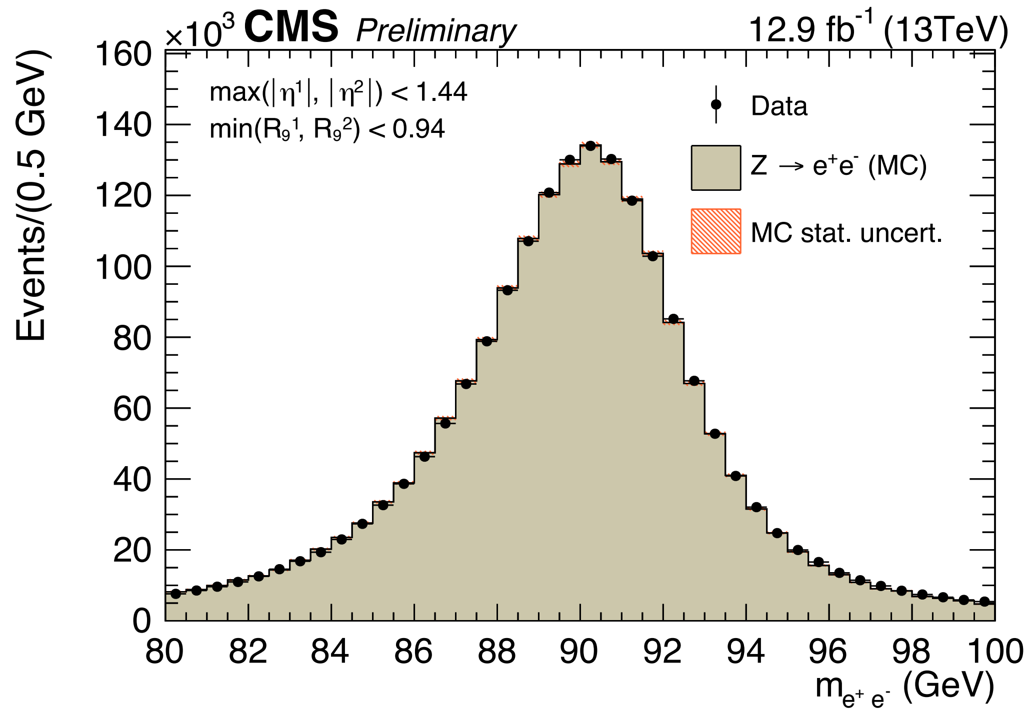


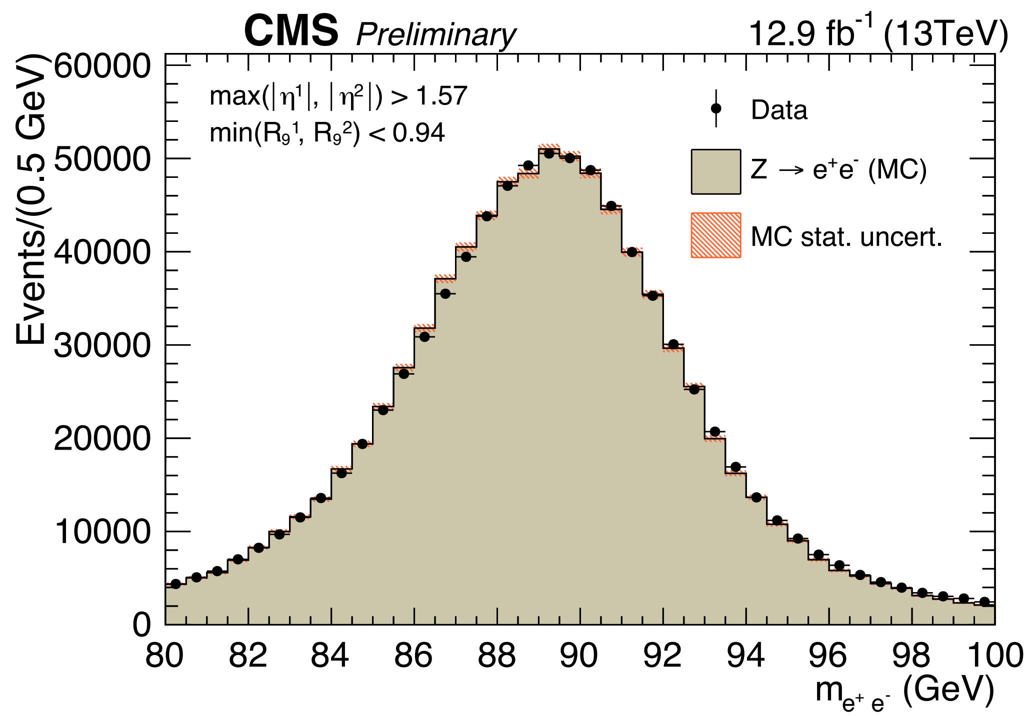
0T: no energy loss in reconstruction due to bremsstrahlung (e.g. in barrel at |η|>1 where material upstream ECAL is higher) → better resolution

Energy resolution

Converted photons







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