CHEF2013
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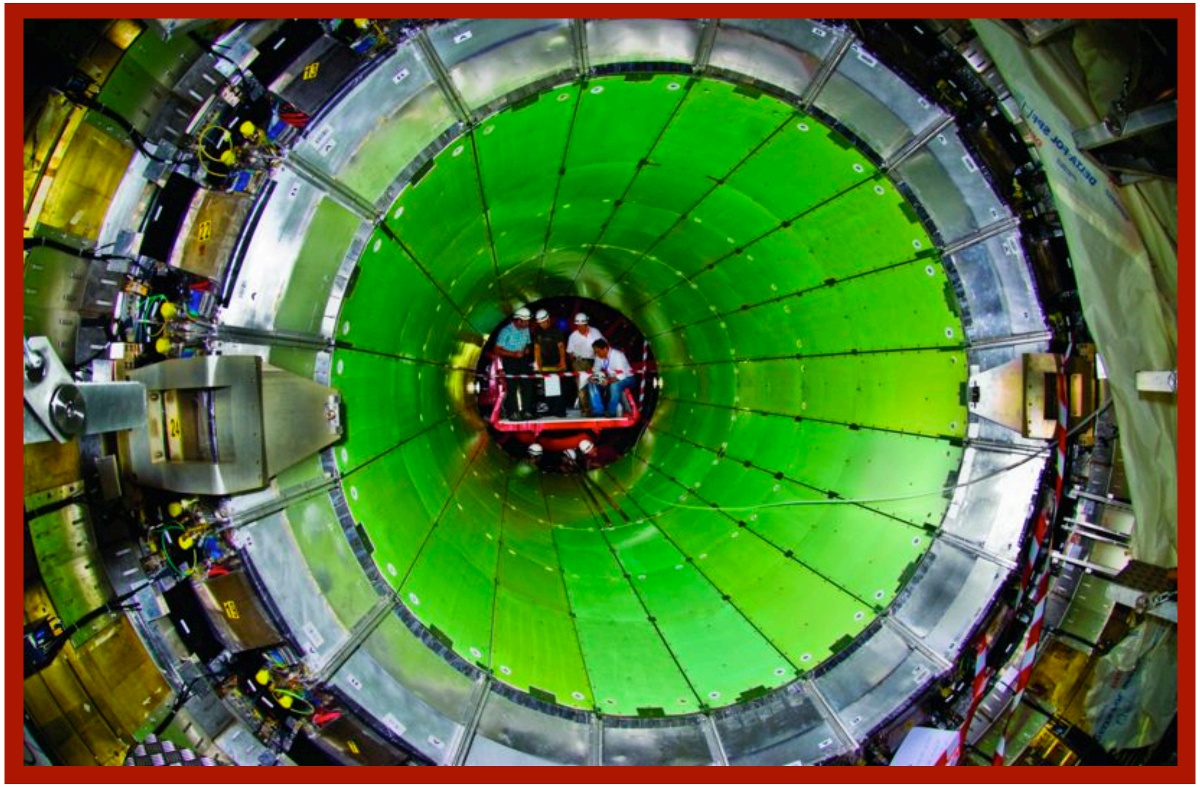

The challenges involving the calibration of the CMS Electromagnetic Calorimeter at the LHC

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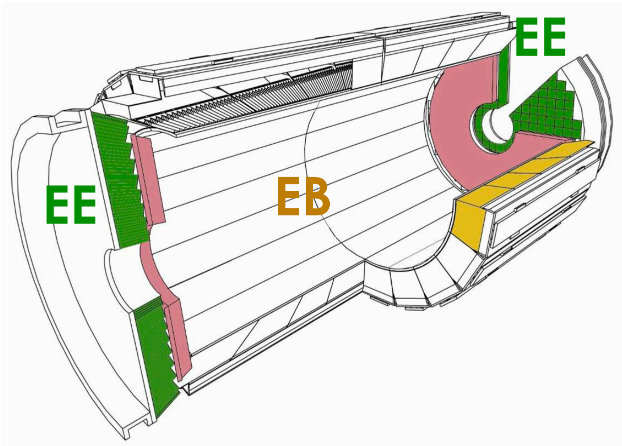
On behalf of the CMS Collaboration

ECAL

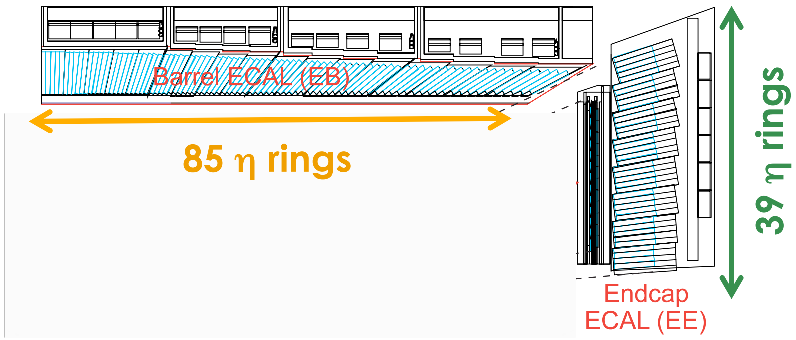
Hermetic homogeneous calorimeter made of $PbWO_4$ crystals



- Barrel (EB) [|η|<1.48]
  61200 crystals
  Photodetectors: Avalanche Photodiode (APD)
- Endcaps (EE) [1.48<|η|<3.0]
  14648 crystals
  Photodetectors: Vacuum Phototriodes (VPT)

η ring: *group of crystals located in the same pseudo-rapidity region*

- 85*2 η rings, 360 crystals/ring in EB
- 39*2 η rings with variable number of crystals in EE



ECAL is the first crystal calorimeter installed at a hadron collider

Excellent energy resolution but the harsh radiation environment makes it challenging maintain the high performance.

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

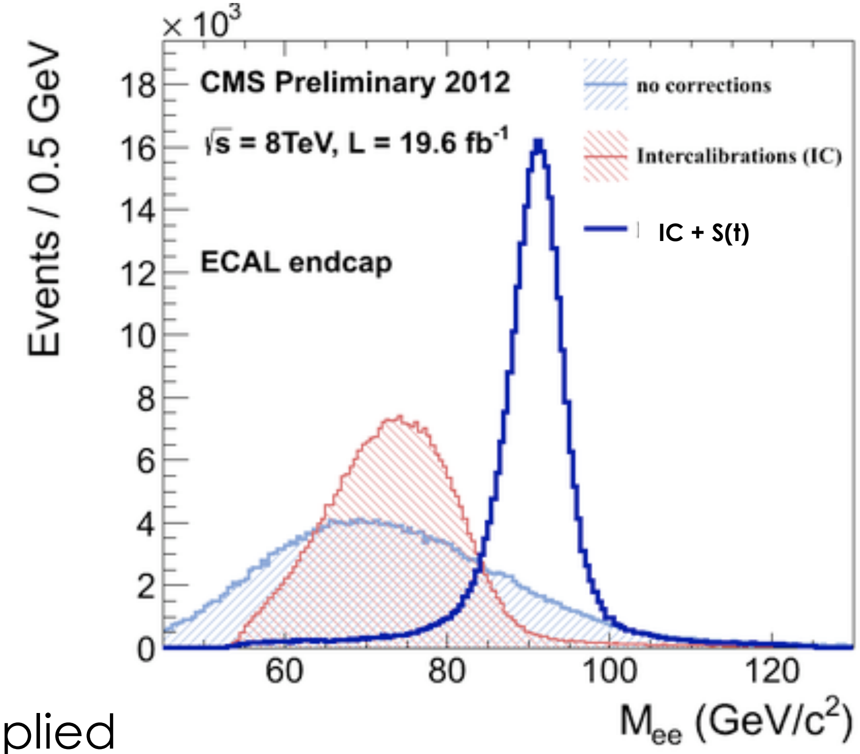
Very stable environmental conditions and appropriate calibration procedure required

e/γ energy measurement

Electron/photon energy measured from the energy deposited over several crystals

$$E_{e,\gamma} = F_{e,\gamma} \times G \cdot \sum_{xtal} \left[IC_{xtal} \cdot S(t)_{xtal} \cdot A_{xtal} \right]$$

- **A_{xtal}** : signal amplitude [ADC counts]
- **$S(t)_{xtal}$** : time-dependent corrections for radiation-induced response variations
- **IC_{xtal}** : inter-calibration factor, to equalize the response of all ECAL channels
- **G** : ECAL energy scale [GeV/ADC]
- **$F_{e,\gamma}$** : particle dependent corrections applied at the clustering level **[See M. Dejardin talk]**



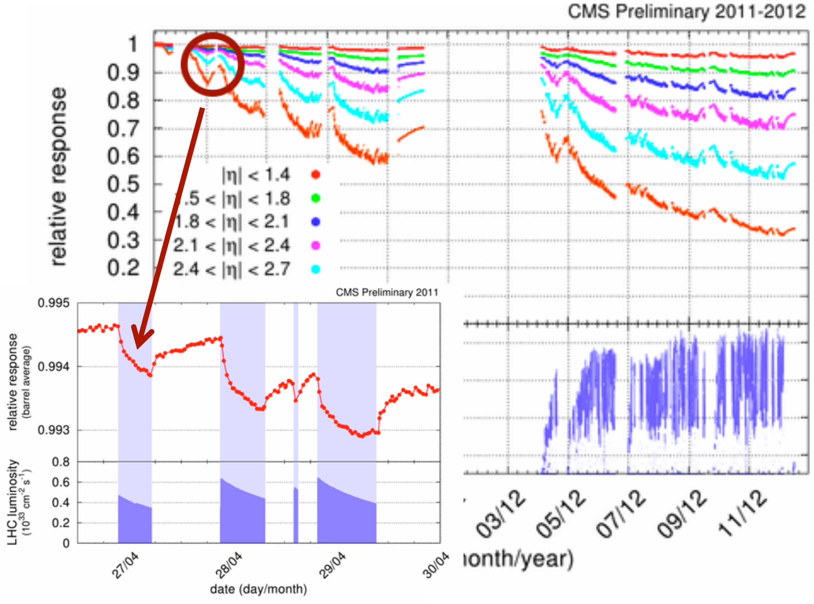
This talk: how the response of the 75848 ECAL channels is continuously corrected/equalized and the energy scale is estimated

$$E_{e,\gamma} = F_{e,\gamma} \times G \cdot \sum_{xtal} \left[IC_{xtal} \cdot S(t)_{xtal} \cdot A_{xtal} \right]$$

Time-dependent corrections for radiation-induced response variations

Time-dependent corrections $S(t)_{xtal}$

During LHC cycles the single channel response varies depending on the irradiation conditions.



1 measurement/channel/40min

A light monitoring system (LM) is used to track and correct for response changes

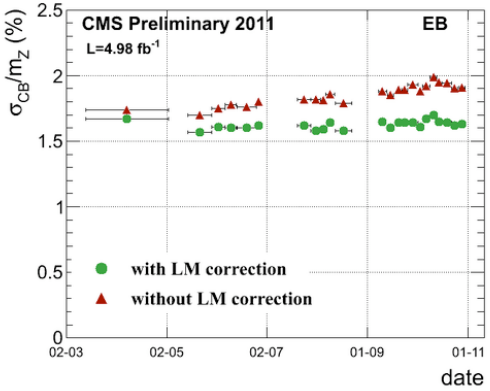
- LM system measures the response variation to the laser light (R/R_0)
- R/R_0 converted to response variation to the scintillation light: $$\frac{S}{S_0} = \left(\frac{R}{R_0}\right)^{\alpha_{EFF}}$$

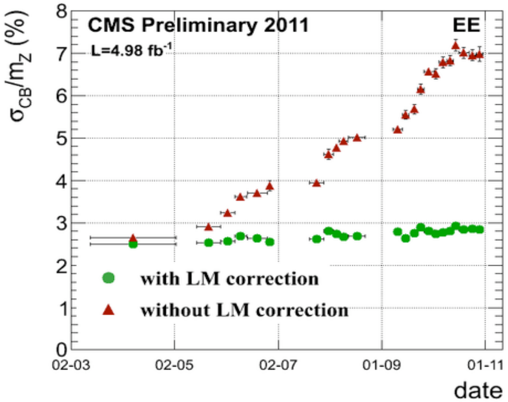
[Details in M.Dejardin's talk]

$\alpha_{EFF}(EB)=1.52$

$\alpha_{EFF}(EE)=1.16$

Z→e⁺e⁻ mass resolution stability





Same α used for all channels in EB (EE) even if **~10% spread** observed in beam test

→ **The spread on α limits the precision of the LM corrections**

$$E_{e,\gamma} = F_{e,\gamma} \times G \sum_{xtal} \left[IC_{xtal} \; S(t)_{xtal} \cdot A_{xtal} \right]$$

Inter-calibration and energy scale

ECAL calibration strategy

Sources of channel-to-channel response variation:

- spread in crystal light yield ~10% (main source in EB)
- spread in VPT gain ~25% (main source in EE)

Precalibration performed in 2000-2009 using test beams, cosmic rays, radiation source and "beam splashes" during the first LHC runs.

- 25% of EB and 500 crystals in EE calibrated in the test beams with a precision of 0.3%. Elsewhere: 0.3-2.2% in EB and 5% in EE
- Energy scale fixed by beam test data in EB and EE separately

In situ intercalibration performed combining different techniques

Intercalibration of crystals located within the same η ring:

- **ϕ-symmetry** of the energy flow through the ECAL crystals
- **π^0/η invariant mass peak**
- **Electron E(ECAL)/p(tracker)**

Intercalibration of the η rings (η scale):

- **Electron E/p (2011)**
- **Z invariant mass peak (2012)**

Energy scale and resolution:

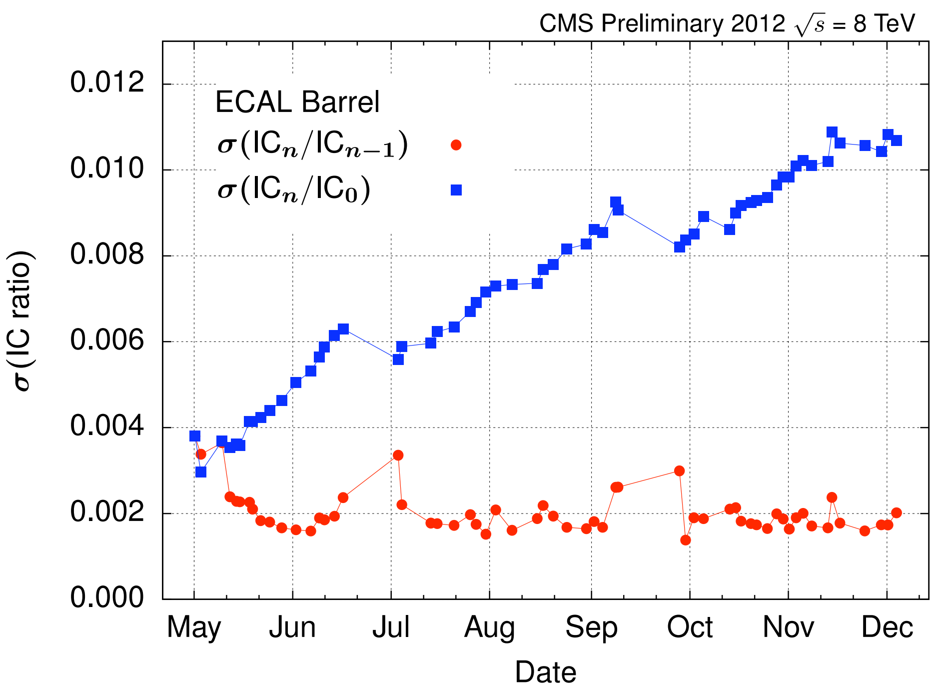
- **Z invariant mass peak**

ϕ-symmetry intercalibration

1 intercalibration / 3-4 days in 2012 [1 IC/10 days in 2011]

- Assumption: for a large number of zero-bias events the total transverse energy is the same in all crystals in a given η ring
- Precision limited by residual azimuthal inhomogeneities in the material in front of ECAL.
- Precision of ratio between two sets of intercalibration constants: ~0.2% in EB and ~0.4 % in EE (systematic uncertainties largely cancelled)

ϕ−symmetry used to monitor the stability of the intercalibration constants



The increasing value of $\sigma(IC_n/IC_0)$ indicates a drift of IC.

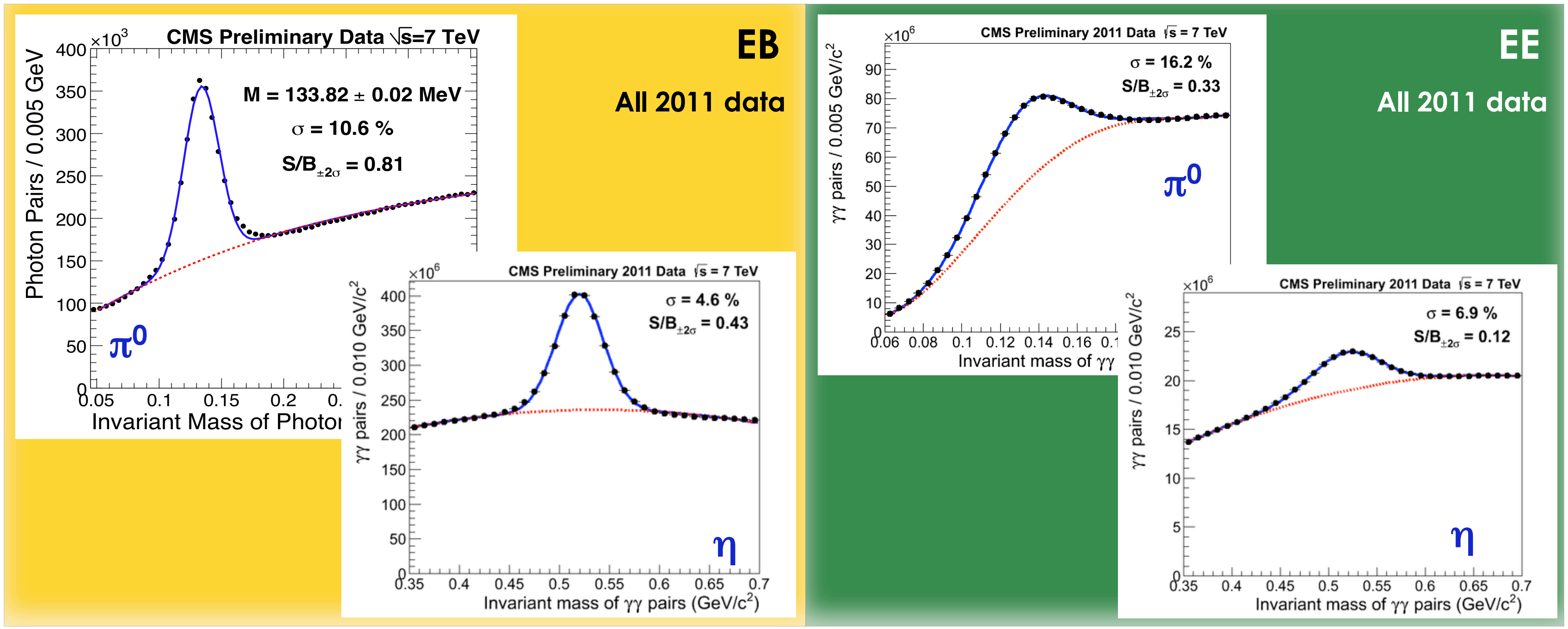
ICs compensate for imperfection in LM corrections mainly ascribable to the uncertain knowledge of α

A frequent recalibration crucial

π^0/η intercalibration

1 intercalibration / 1.5 month [1 IC/3 month in 2011]

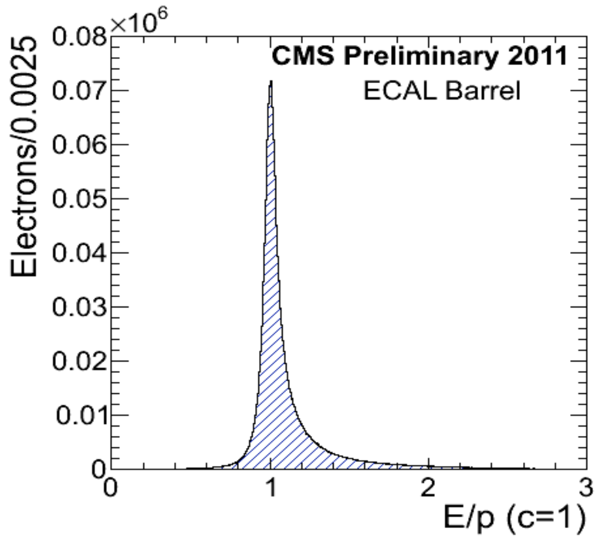
- The decay of π^0 and η to two photons exploited to inter-calibrate the ECAL crystals by using peak of $\gamma\gamma$ invariant mass distribution
- Only unconverted γ's reconstructed in matrices of 3x3 crystals used
- In EB ~3000 π^0/crystal necessary to reach statistical precision of 0.5%
- Reconstruction of π^0 peak more challenging in 2012 due to high PU; not exploitable for $|\eta|>2$

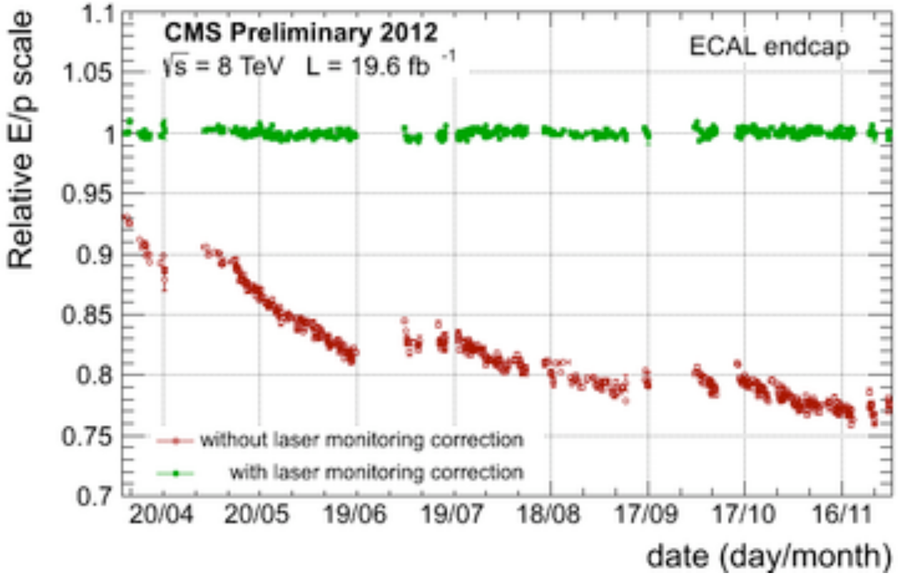


Electron intercalibration (E/p)

1 intercalibration / year

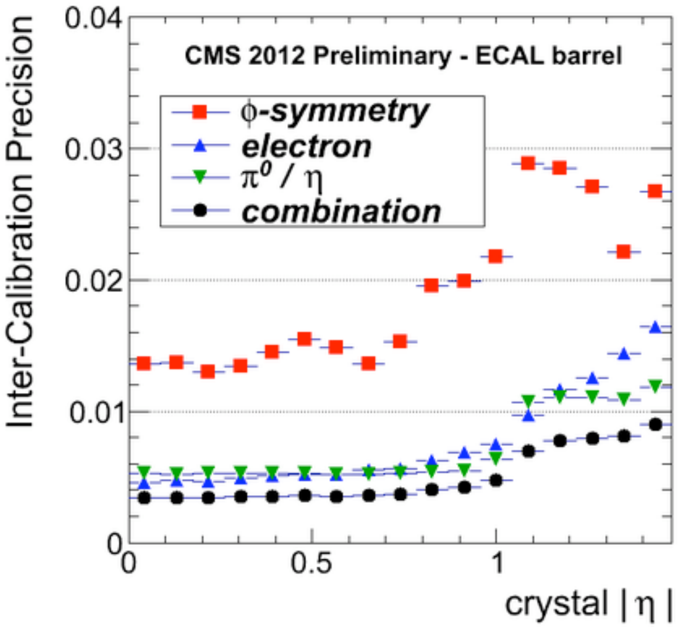
- High energy electrons from W→eν and Z→ee decays
- Calibration performed with an iterative procedure by fitting E(ECAL)/p(tracker) distribution for each crystal
- In the central part of EB ~120 (~500) e/crystal in 2011 (2012)

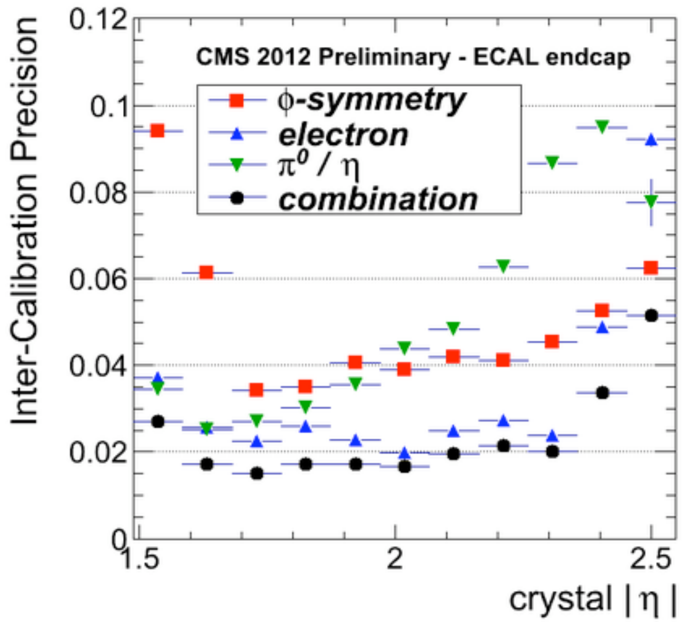




- E/p method can be also used to check the stability of the ECAL response for groups of 100 crystals
- Time-dependent corrections of intercalibration constants derived with this method for each group of 100 crystals

Intercalibration precision

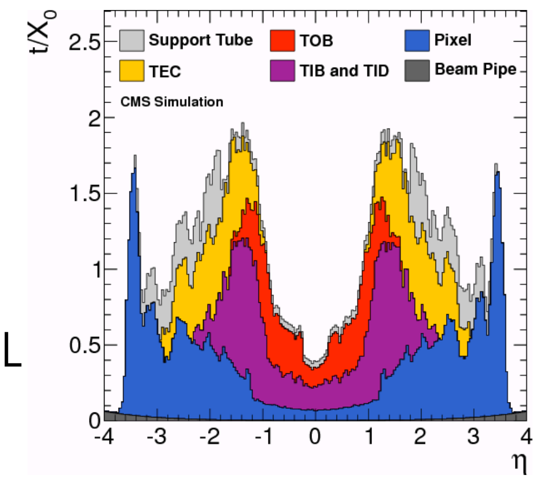




Combination precision similar in 2011

- ϕ–symmetry and π^0/η calibration precision at the level of systematic errors
- E/p calibration precision still dominated by statistical errors for $\eta > 1$

The variation of the precision with pseudo-rapidity arises from the amount of material in front of ECAL

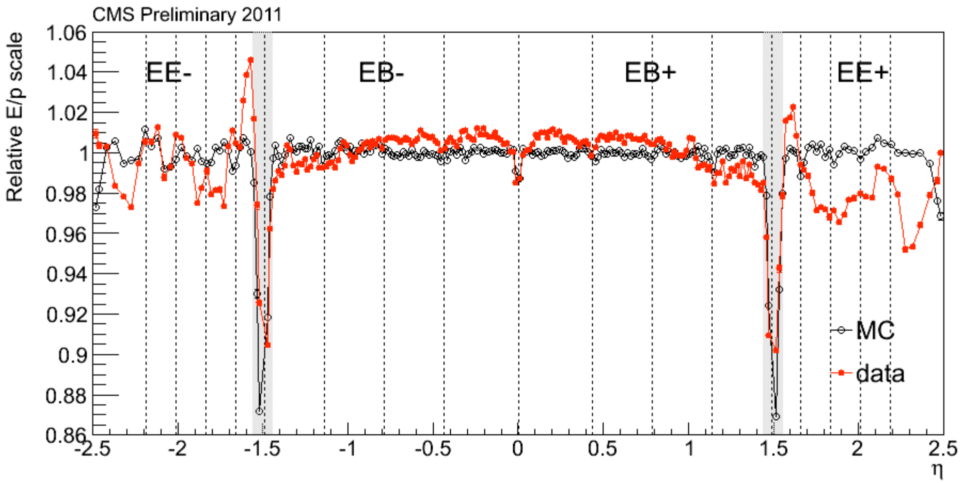


Final intercalibration: weighted average of the three methods (combination)

η scale and absolute scale

η scale:

2011: E/p of electrons from W→νe and Z→ee decays



- Ratio between data and MC used to derive the η scale
- Precision: 0.3% in EB
  0.7% in EE

2012: Z→ee invariant mass peak

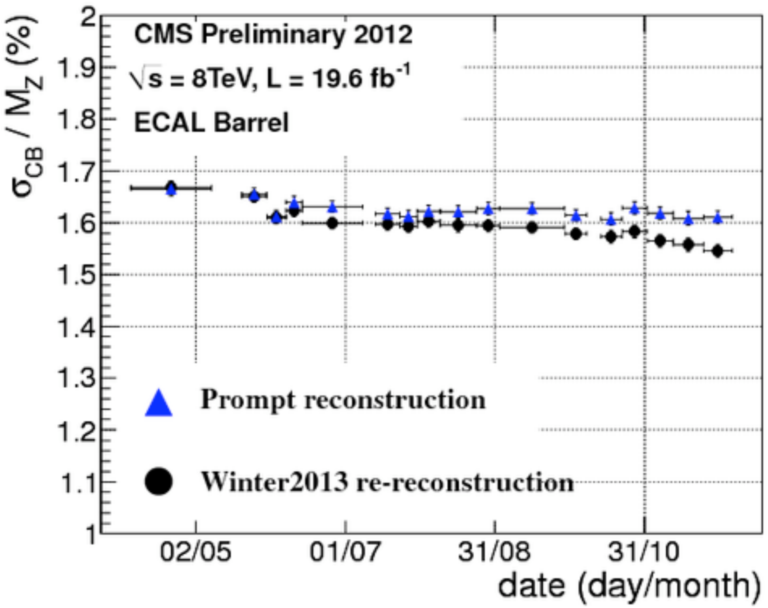
- Low bremsstrahlung electrons from Z decay used
- Statistical uncertainty: 0.2% if calibration done with 1fb^{-1}(scales with $\sqrt{L_{INT}}$)

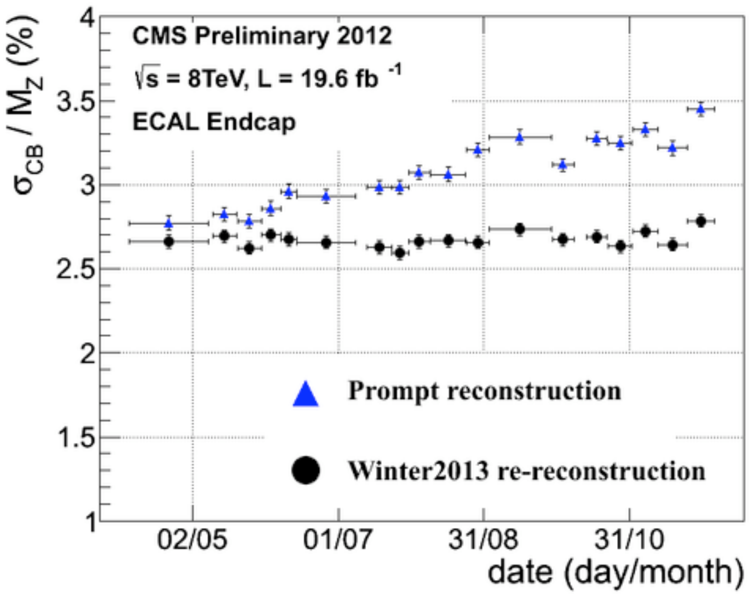
Energy scale: Z→ee invariant mass peak

- Defined such that Z→ee peak agrees between data and MC
- Derived separately for EB and EE
- Systematic uncertainty: 0.6% in EB and 1.5% in EE

Validation of final calibration

Z→ee mass resolution versus time





- Prompt: 1 IC set derived on data collected in the first 3 months of 2012
- Winter2013: 21 sets of IC delivered for 2012 data reprocessing
  - ✓ Very good stability already in prompt in EB
  - ✓ A clear improvement in the value and stability of the Z mass resolution, especially in the EE

Summary

- ✓ Light monitoring system used to track and correct for radiation-induced response variations
- ✓ Different methods developed to calibrate ECAL crystals in situ
  Each method play an important role.
- ✓ **Remarkable energy response and resolution stability achieved by the applying LM corrections and time-dependent intercalibration constants**
- ✓ Combined intercalibration precision achieved in both 2011 and 2012:
  - 0.4% in central EB ($|\eta|<1$)
  - 0.7-0.8% in the rest of EB ($1|\eta|<1.48$)
  - 1.5-2% in central part of EE ($1.6|\eta|<2.3$)
- ✓ **Contribution to the constant term of the energy resolution within requirements**:
  - 0.3% in central EB ($|\eta|<1$)
  - 0.5% in the rest of EB ($1|\eta|<1.48$)
  - 1-1.5% in EE

Very good starting point to face even more challenging conditions in 2015 …

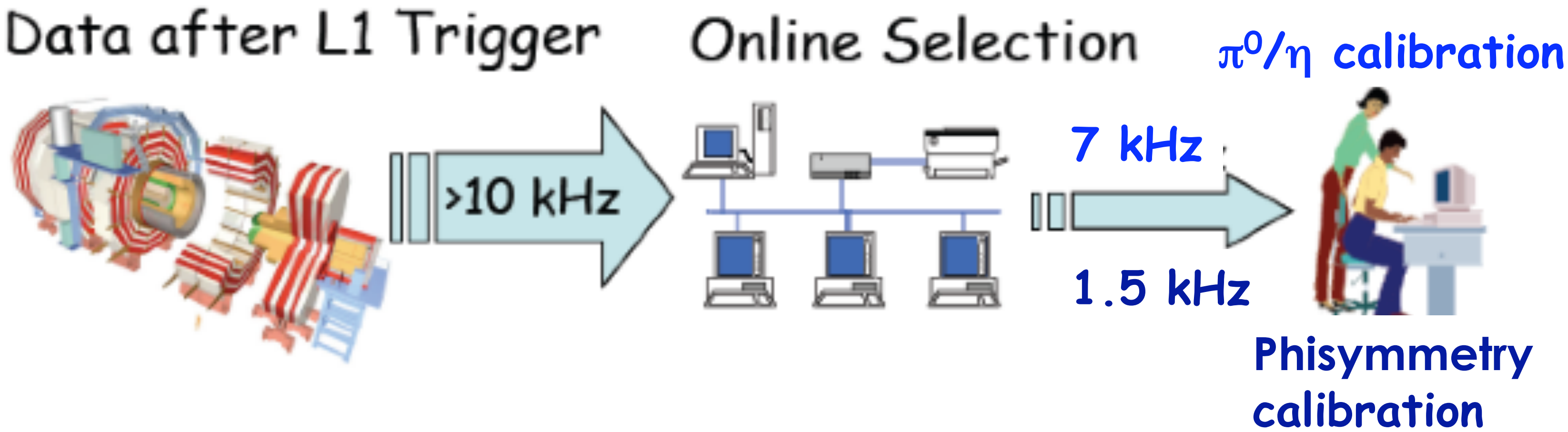
2015 LHC parameters

CM ENERGY	~13 TeV
Peak Luminosity	2-3 10^{34} cm^{-2} s^{-1}
Bunch spacing	25 ns

BACKUP

Phisymmetry and π^0/η DATA STREAM

Dedicated paths of data acquisition (streams) implemented for phisymmetry and π^0/η methods



Event size reduced (only few tens of "useful"(*)crystal hits are stored for each accepted event) → **high rate with little impact on CMS bandwidth**

Trigger rate increased at the end of 2011 to allow more frequent calibration

Method	Systematic limit 2011	reached after … 2012
Phisymmetry	1 week	2-3 days
π^0/η	3 months	1.5 months

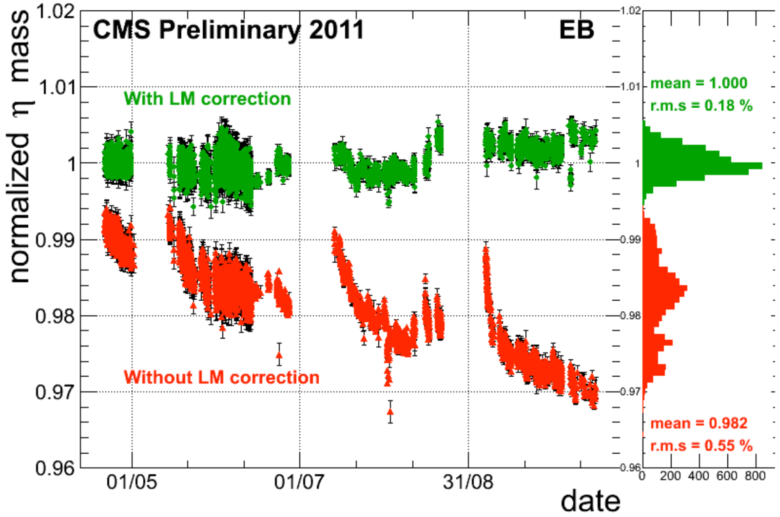
(*) in restricted region of ECAL around specific L1 triggers

Monitoring the monitoring

Several physics channels used to check the monitoring corrections

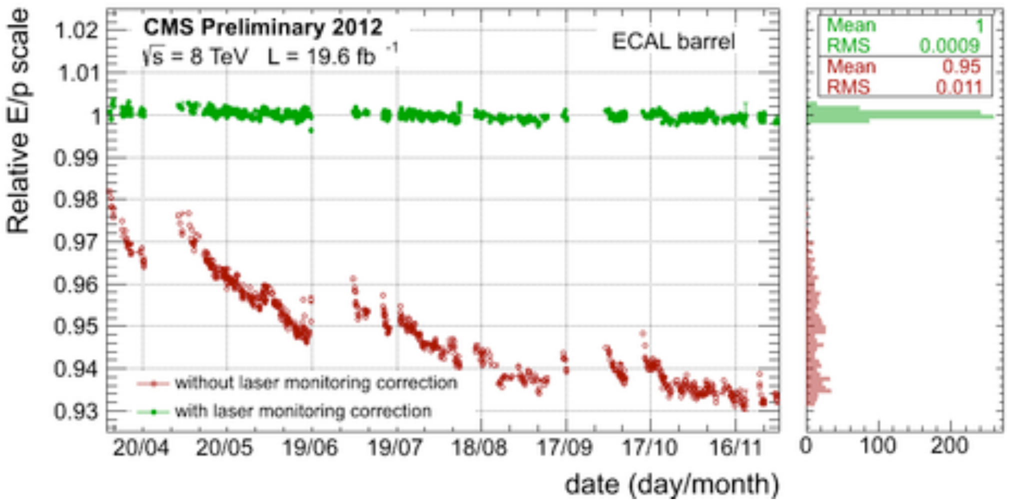
$\pi^0/\eta \rightarrow \gamma\gamma$ decay: invariant mass peak stability

- 1point/20 min



$W \rightarrow e\nu$: Relative E(ECAL)/p(tracker) scale stability

- ~12000 $W \rightarrow \nu e$ events/point



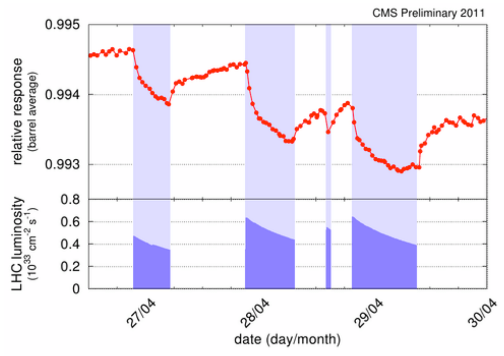
A stable E/p scale achieved in after applying LM corrections

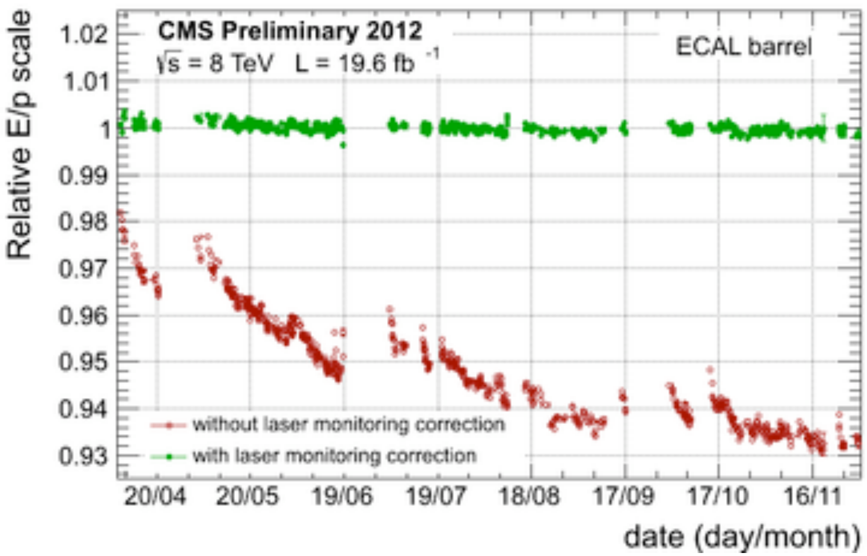
- **EB**: average signal loss ~5%, RMS after corrections 0.09%
- **EE**: average signal loss ~18%, RMS after corrections 0.28%.

Similar results in 2011

E/p time dependent corrections

Laser monitoring corrects for short term changes in response due to LHC irradiation





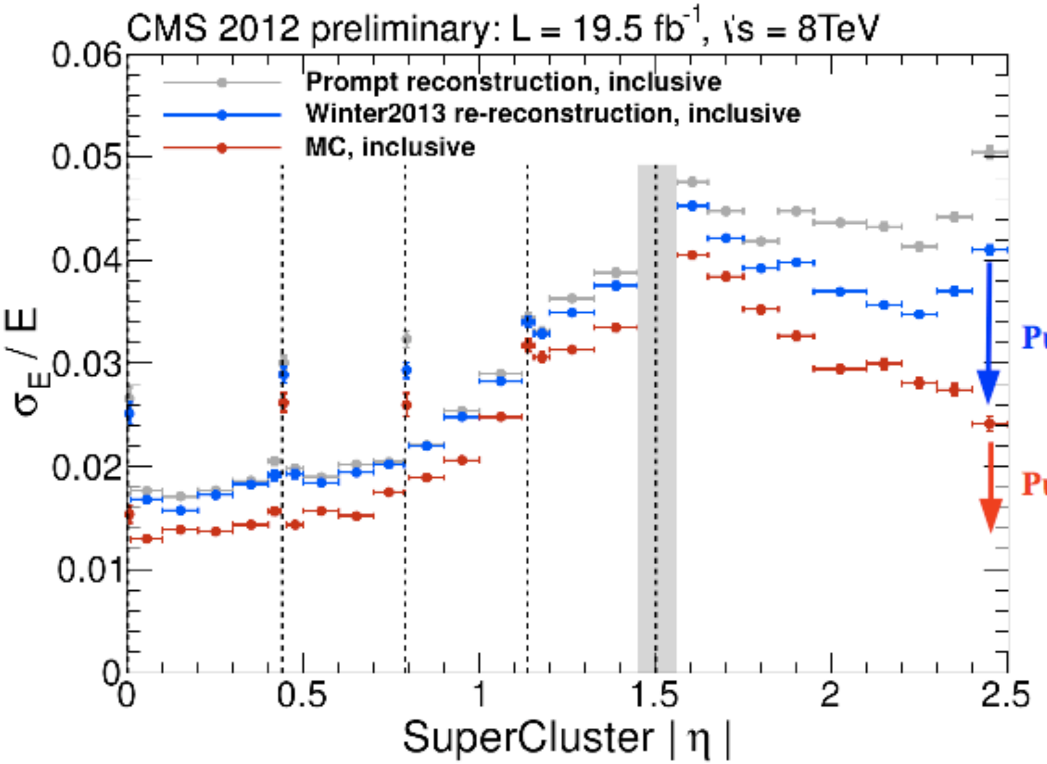
When examining history plots of energy scale vs time with physics data, slow drifts in the overall response versus time observed.

These drifts vary by region, and are likely related to crystal properties and the assumed value of α

Effective time-dependent corrections per monitoring region applied on top of existing inter-calibrations, to make E/p histories flat.

ECAL performance in 2011-2012

- Resolution of the energy measurement
  - Electrons from $Z^0 \rightarrow e^+e^-$



2013-2014 goals:

Put blue points over red points

Put red points lower

- **Optimizing the ECAL response is critical for the next LHC runs !**
  - ▶ Refine scintillation/laser relationship
  - ▶ Improve reconstruction tools
  - ▶ Include aging effects in simulation
  - ▶ Optimize tools for high pileup: in- and out-of-time