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The CMS Electromagnetic Calorimeter: lessons learned during LHC run 1, overview and future projections

1. Introduction
2. The CMS ECAL
3. Energy measurement
   clustering, monitoring, calibration
4. Energy resolution
5. Photon ID
6. Application to H->γγ analysis
7. Perspectives for the future

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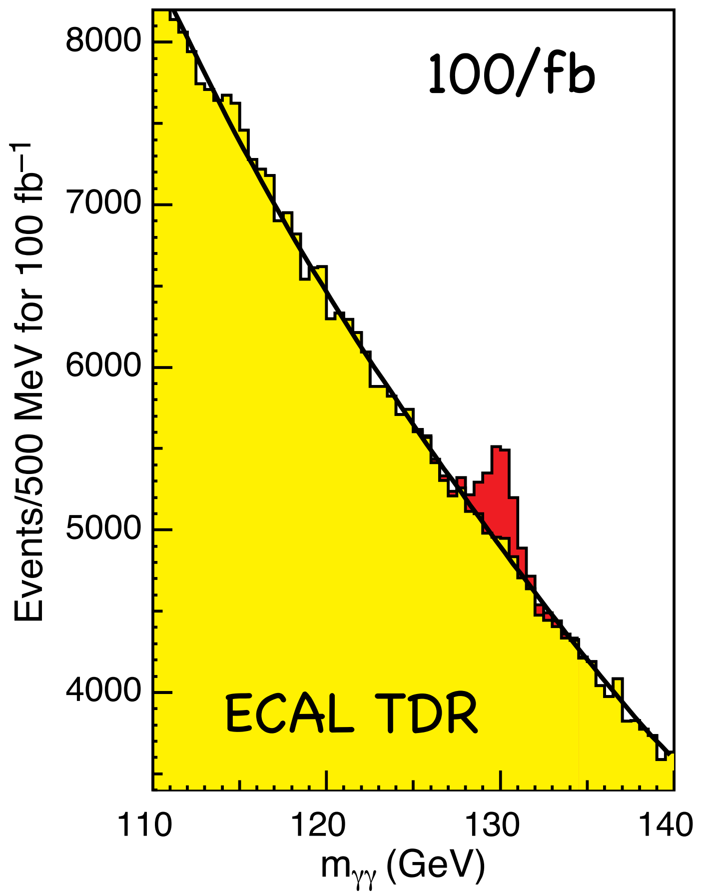
(for the CMS collaboration)

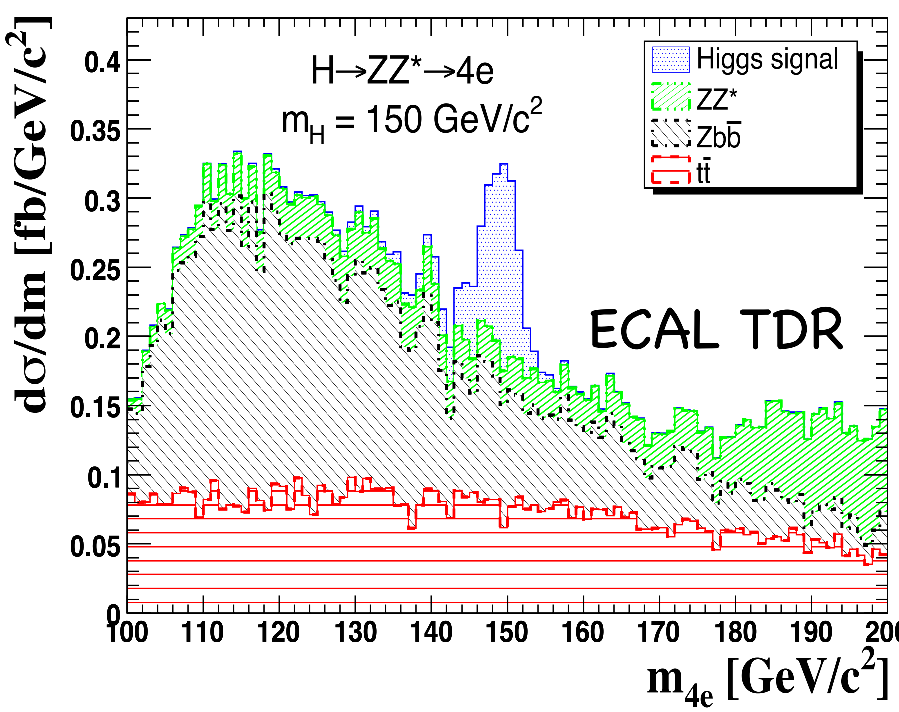
H->γγ - The ECAL benchmark design

- **H->γγ: most sensitive channel at mass lower than ~130 GeV**
  - **Small BR with very clean signature:**



- **Fundamental to control:**
  - Invariant mass resolution => Energy and position resolution
  - Background rejection => π^0/γ separation

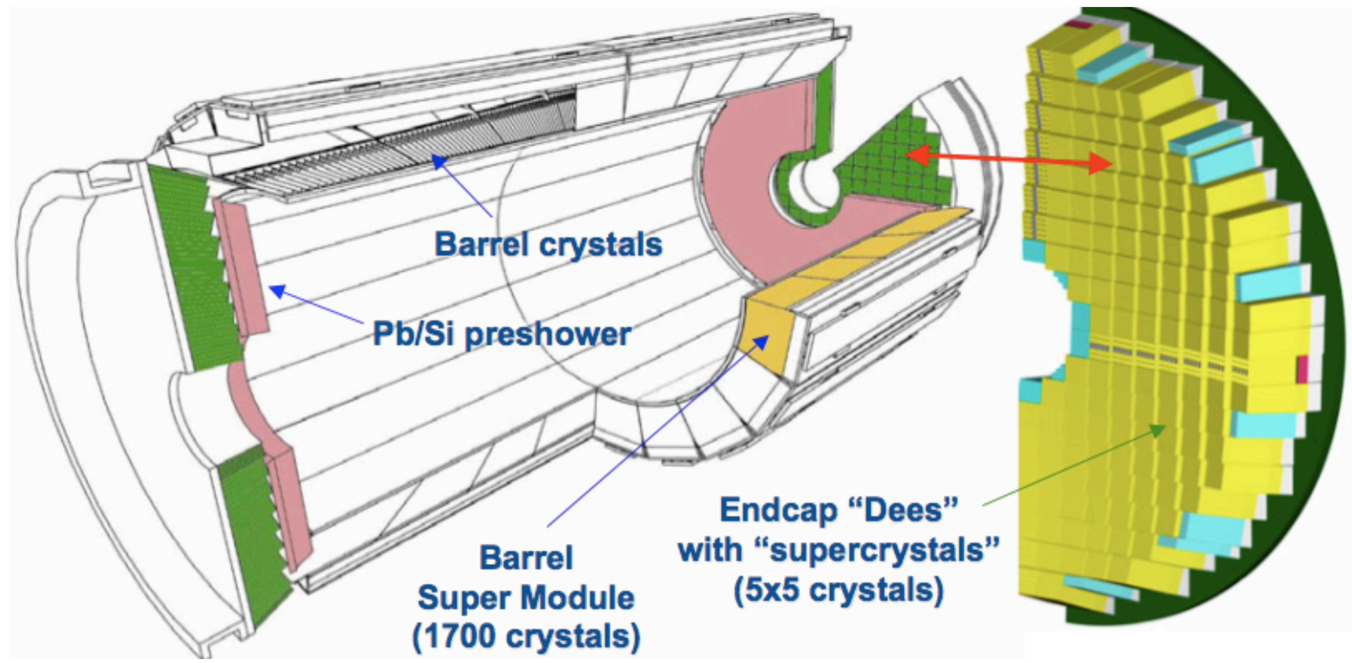
- H->ZZ: golden channel - 4e is most challenging final state
  - Electron resolution driven by ECAL for E > 20GeV
  - **Electron $|\eta_{max}|$ > 1.5 for half of Z->ee events**



- **ECAL REQUIREMENTS:**
  - Good resolution and efficiency up to |η|<2.5
  - granularity, trigger capability
  - linearity, hermeticity, compactness, speed and stability

The ECAL at the LHC

- **Homogeneous $PbWO_4$ crystals:**
  - Compact & high granularity (excellent energy containment)
  - Crystals light-yield spread (~10%)
  - Transparency variation with radiation



- **EB** (Barrel): $|\eta|<1.48$
  - ($2.2\times2.2\times23$ cm^3) $\sim26X_0$
  - **APD** photodetectors (gain 50)
- **EE** (Endcap): $1.48<|\eta|<3.$
  - ($2.9\times2.9\times22$ cm^3) $\sim25X_0$
  - **VPT** photodetectors (gain 10)
    - Gain spread between VPTs ~25%
- **ES** (Preshower): $1.65<|\eta|<2.6$
  - $3X_0$ Pb/Si strips
  - (1.90×61 mm^2) x-y plane

no longit. segmentation
(ES apart)

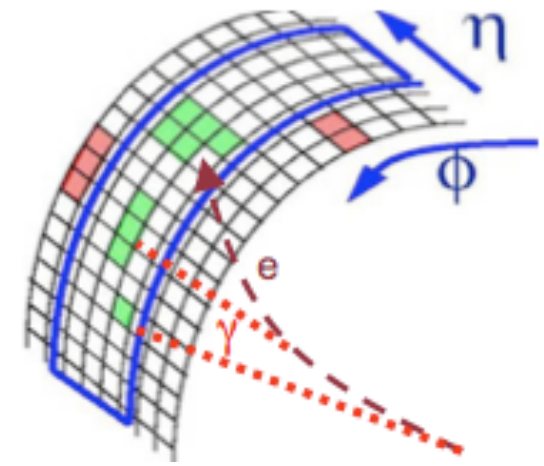
- **Required Intercalibration + Stabilisation and monitoring**
- **Energy resolution at test beams in EB**

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

  - no B, no upstream material, fixed impact point
  - **Achieved 0.3% constant term for EB by careful design/construction**

Energy estimation

- **To obtain the most accurate estimate of e/γ energy in a supercluster of crystals**



- **Dynamic superclustering** of the deposits in ECAL
  to recover energy radiated due to bremsstrahlung/conversion

- $$E_{e/\gamma} = G F_{e/\gamma} \Sigma_i (S_i(t) c_i A_i)$$

A_i: single channel amplitude

Equalisation of channel response

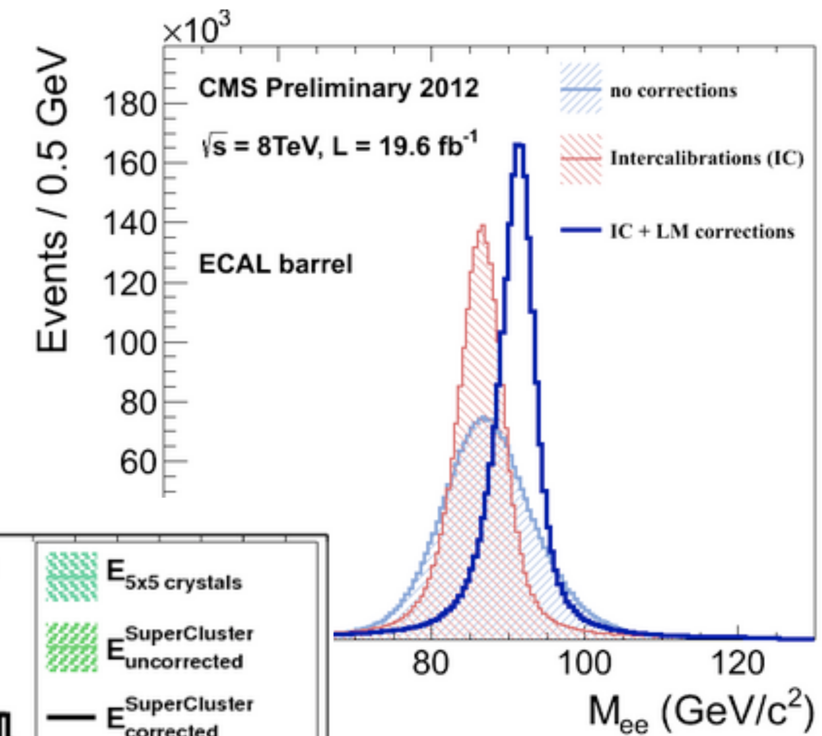
C_i: single channels inter-calibration coefficients

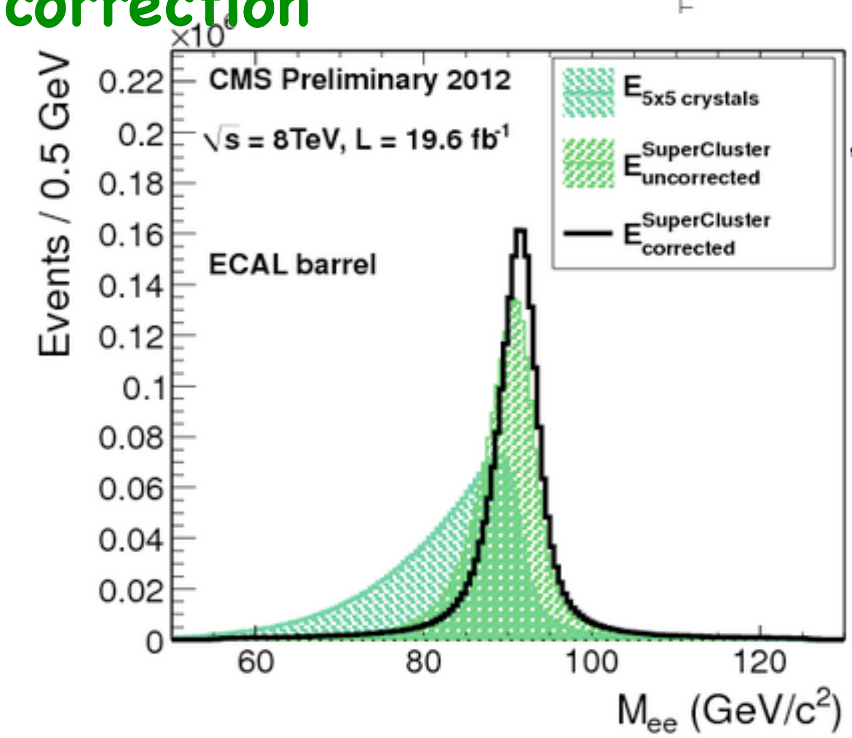
$S_i(t)$: time-dependent correction for response variations

Global scale calibration and cluster energy-correction

G: Global scale calibration

$F_{e/\gamma}$: Particle energy corrections
(geometry, clustering, upstream material, ...)

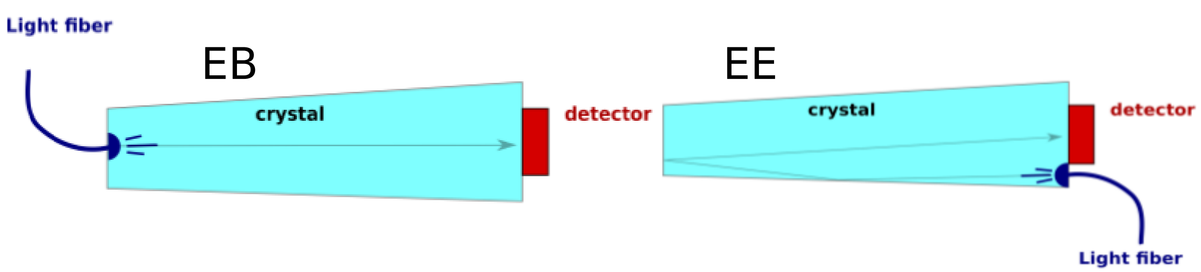




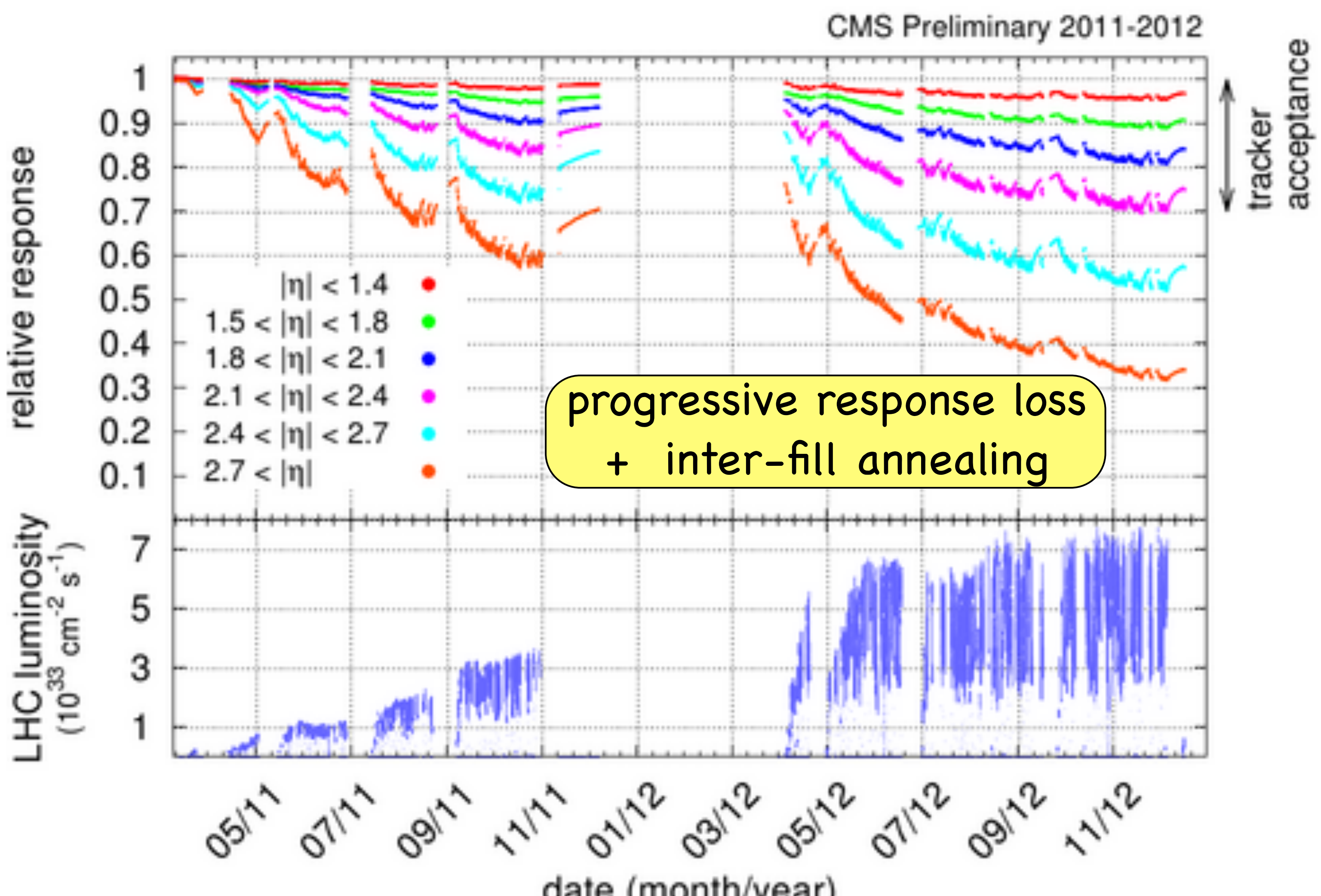
Time dependent response changes

- ECAL radiation-induced effects, heavily η dependent
  - Crystal transparency changes
  - VPT photocathode ageing with accumulated charge
  - APD I_{leak} increases

- Channel response is constantly monitored with λ = 447nm (peak emission) laser light



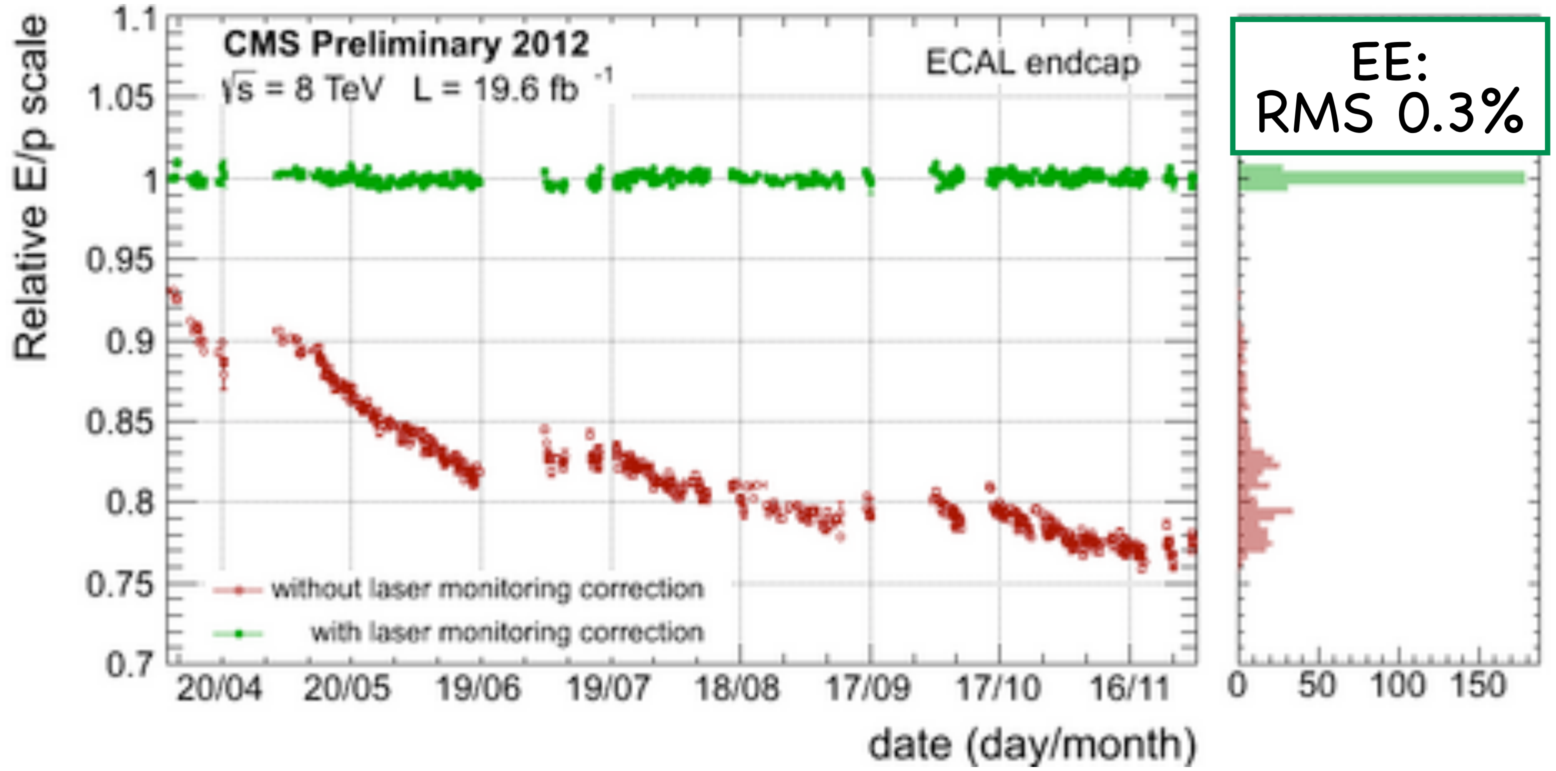
  - Averaged measurements every 40 minutes for all 75848 crystals
  - Corrections prepared and checked in less than 48 hours (using π^0/η) for prompt reconstruction



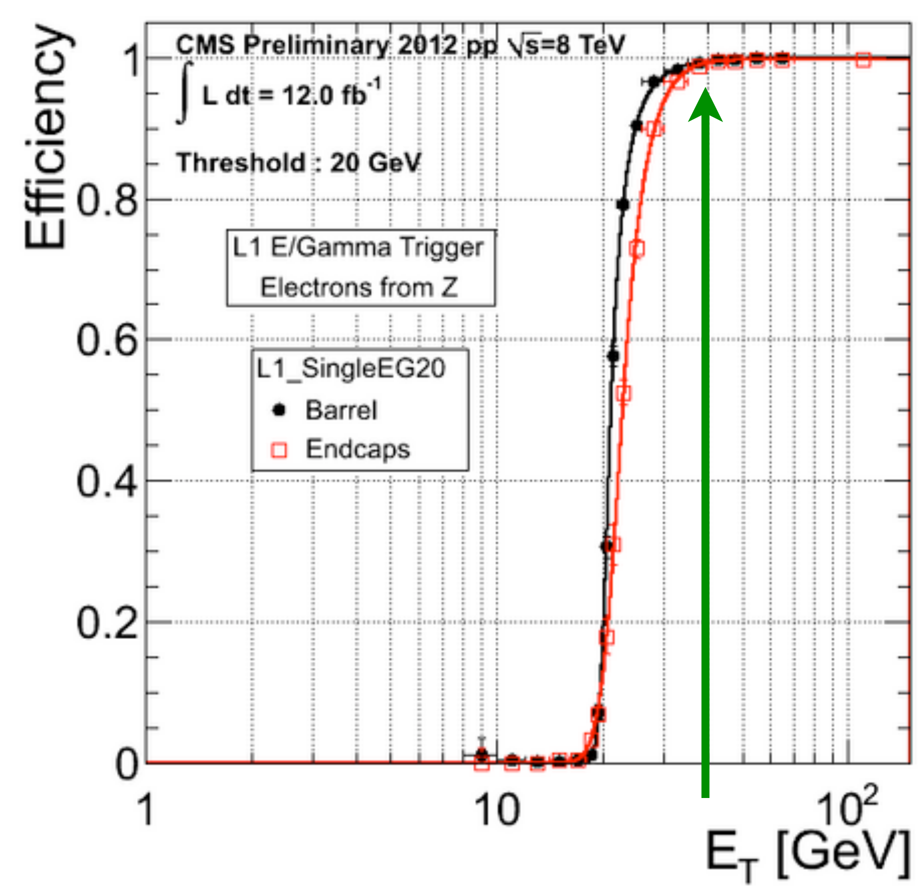
Loss of:
≤ 6% in EB
≤ 30% in EE up to |η|<2.5
~70% in EE for |η|>2.5

Response stability and trigger

- Stability checked using electrons from W decays

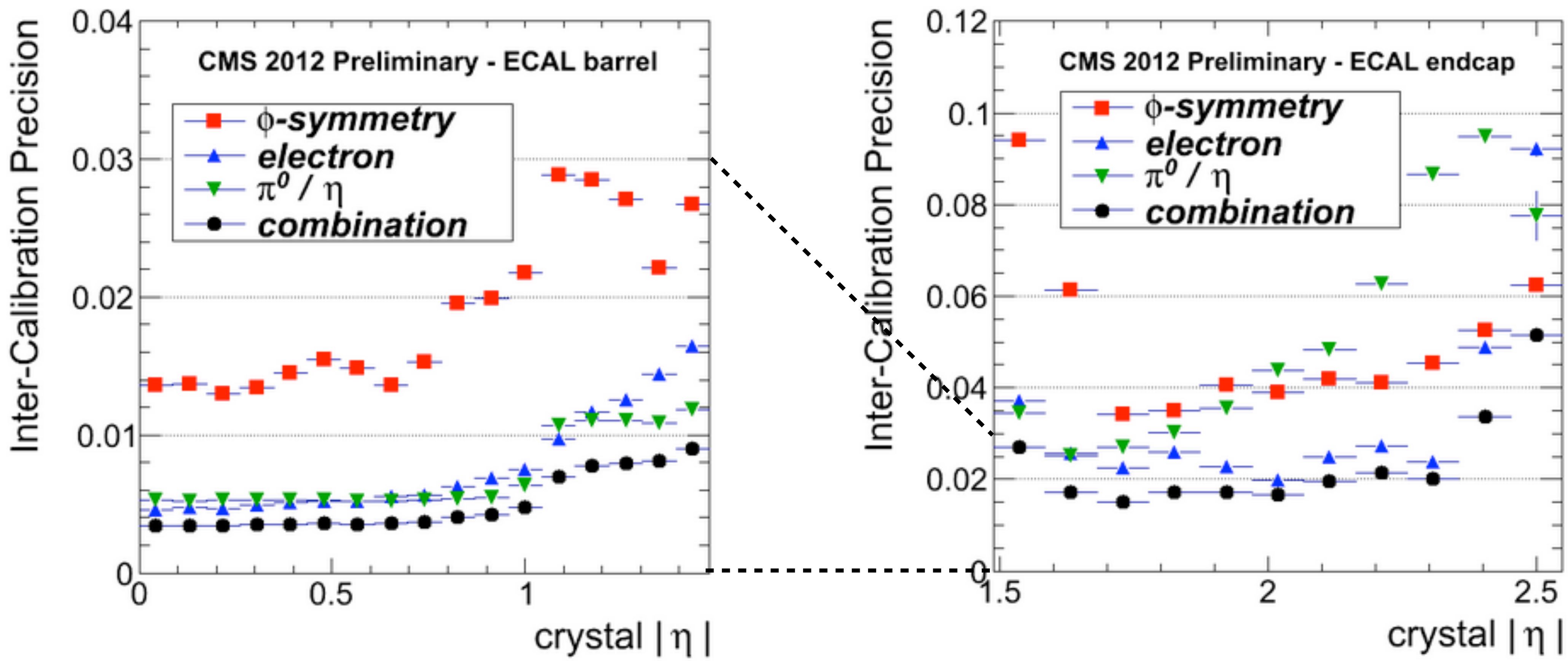


- **Weekly corrections for optimising the L1 e/γ trigger**
  - **currently for EE, foreseen for EB in Run2**
- **Efficient and stable e/γ trigger**
  - Level-1 (40 MHz) trigger primitives (E_T sum of energies in 5x5 crystals)
- E.g. EG20 (E_T>20 GeV)
  - Lowest un-prescaled e/γ trigger in 2012
  - **Fully efficient for Hγγ with mH>100 GeV**
    Leading γ E_T>40 GeV



Inter-calibration

- Cross-comparison and combination of methods



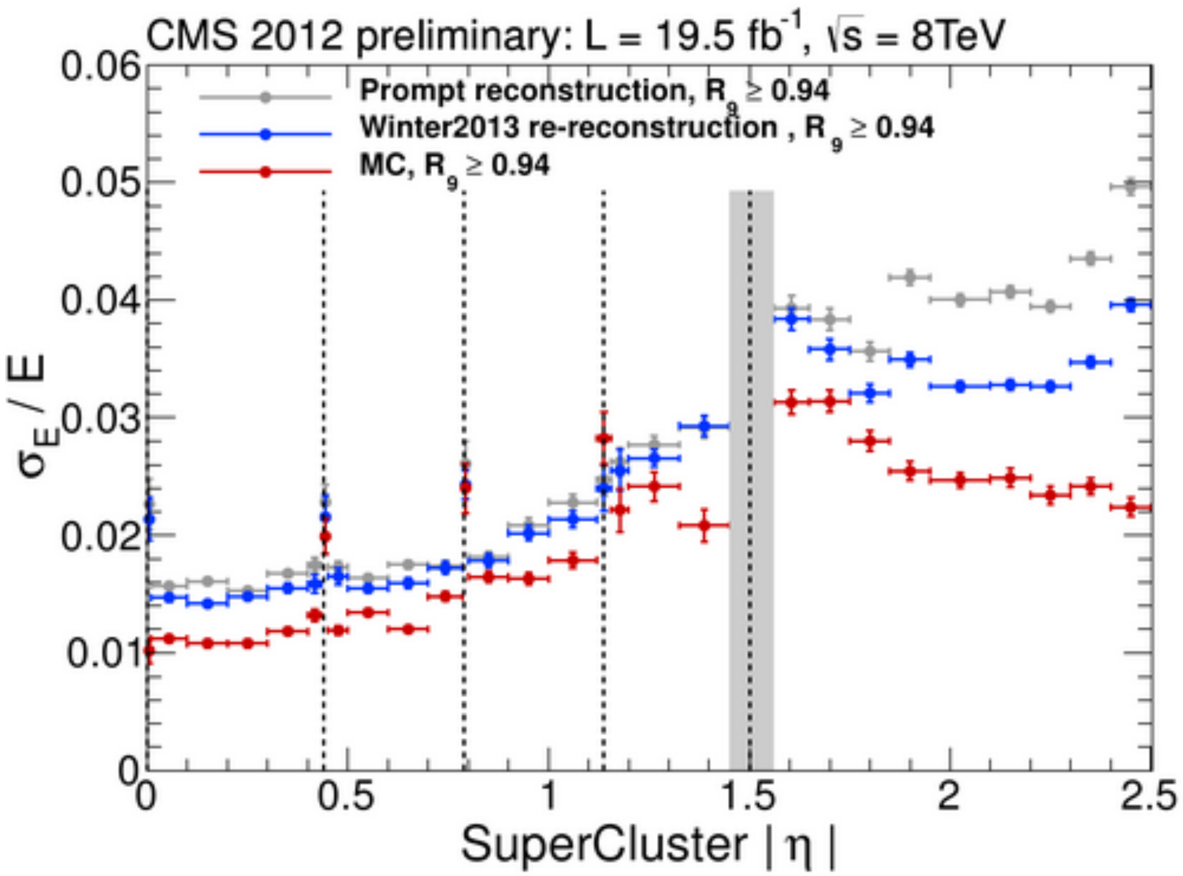
- Calibration
  - φ-symmetry, π^0/η: limited by systematic uncertainties
  - E/p: limited by statistical uncertainty (dominant for |η|>1)

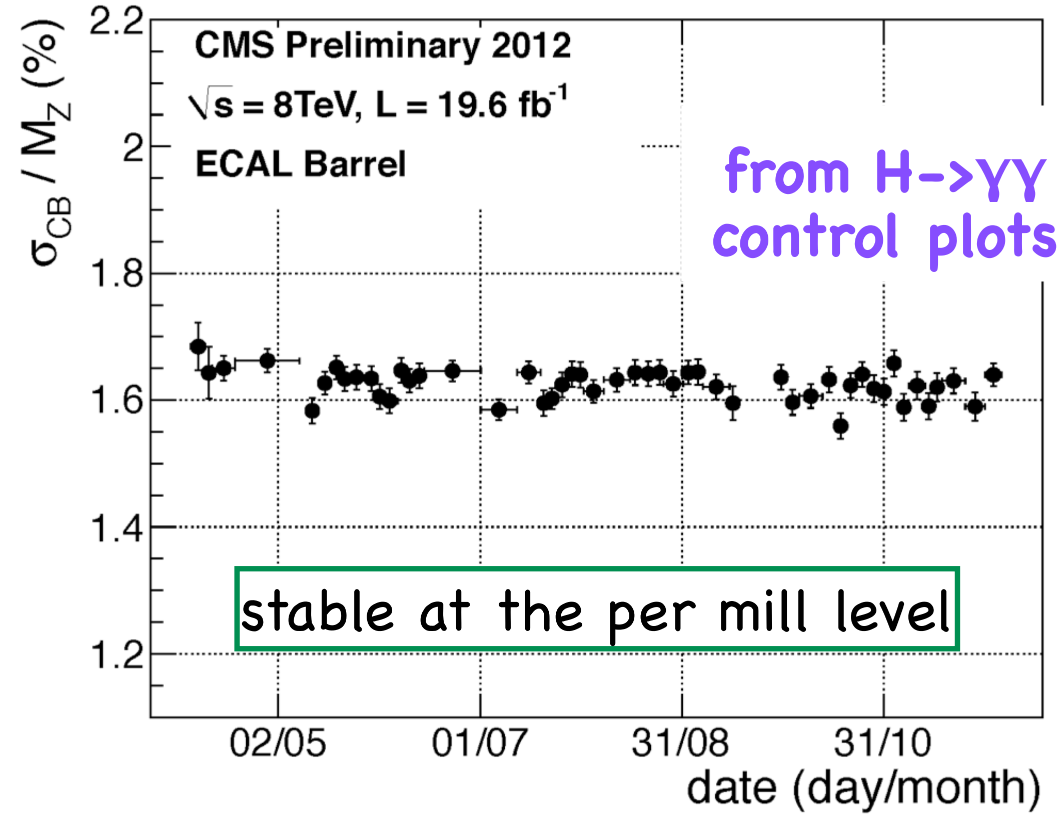
- **COMBINED**:
  Barrel: <1% (~0.4% for |η|<1)
  Endcaps: ~2% (almost everywhere)

- Precise calibration of the detector plays a key role in the energy resolution.

Energy and mass resolution

- Derive electron energy resolution from Z->ee peak width (Breit-Wigner ⊗ Crystal-Ball)

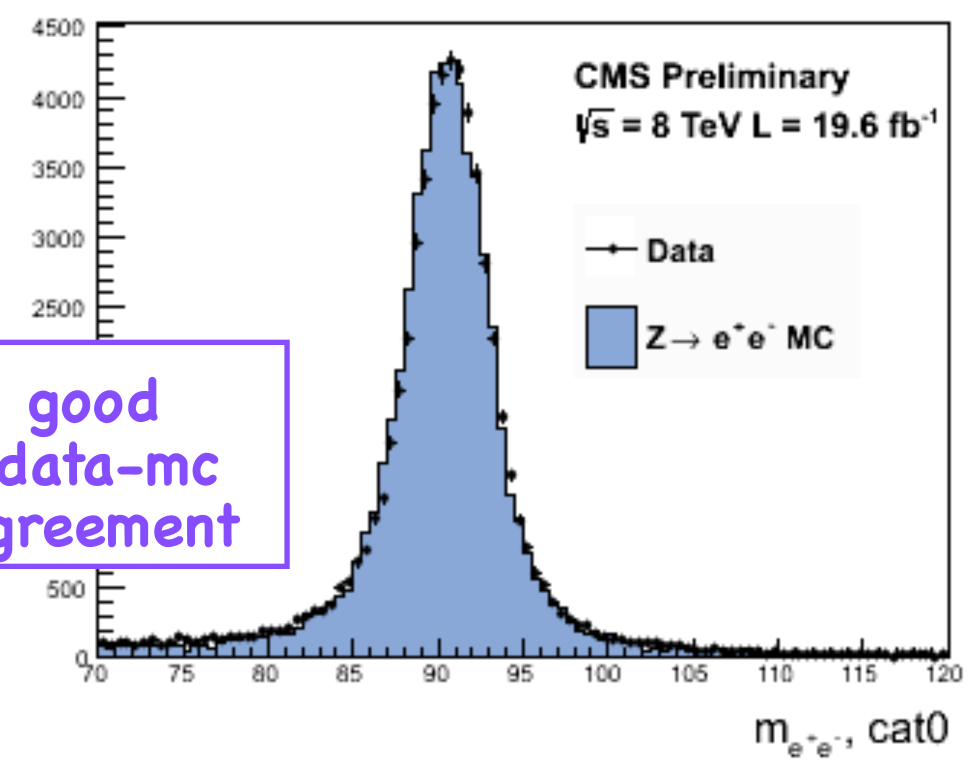




- Improvement from prompt to refined conditions
  - Evident in EE where irradiation effects are important
- Some data-mc discrepancy:
  - Upstream material effect
  - Evolution in 2012 conditions

- **Detailed MC simulation**
- **MC tuning** through extra smearing

good data-mc agreement



└→ Result in improved cluster energy corrections

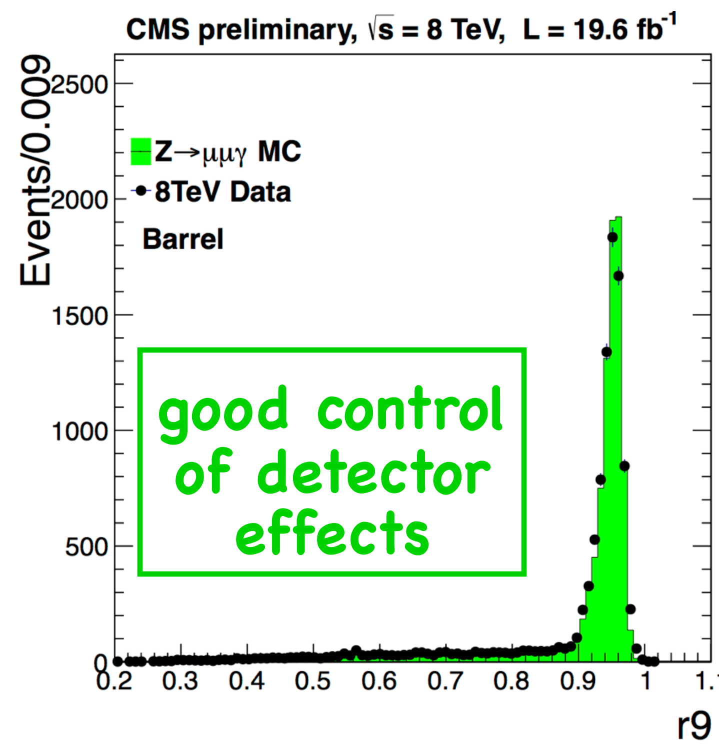
H->γγ analysis

- Narrow resonance of two high E_T photons over a falling background: prompt (70%) + fake di-photon (30%) events

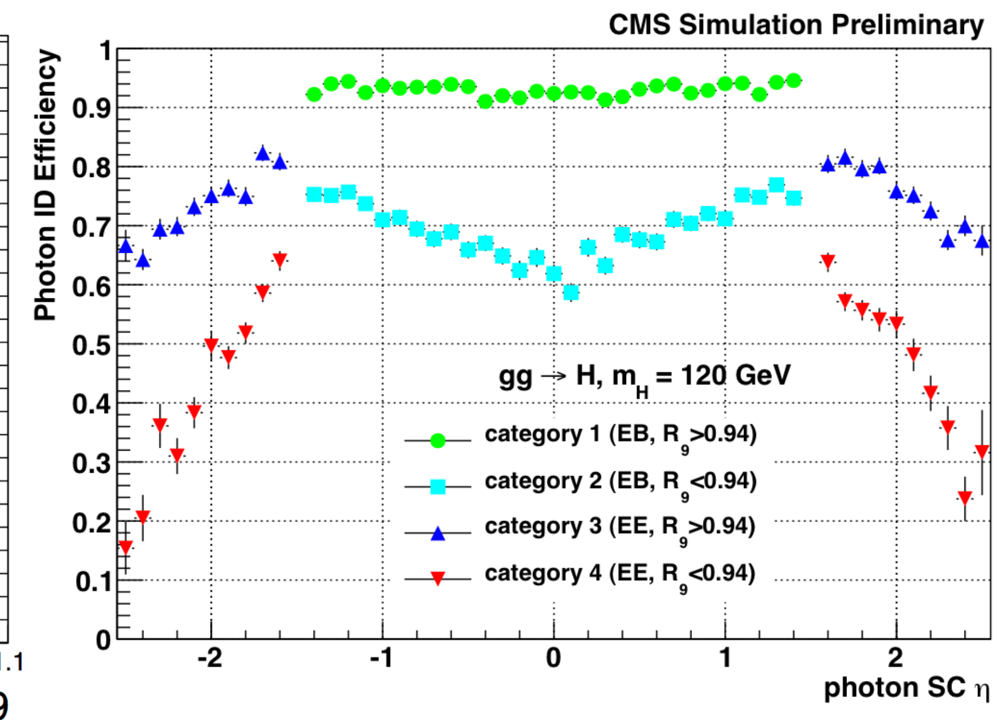
Key requirements:

- **Excellent γ energy resolution**
  - see previous slides

from H->γγ control plots

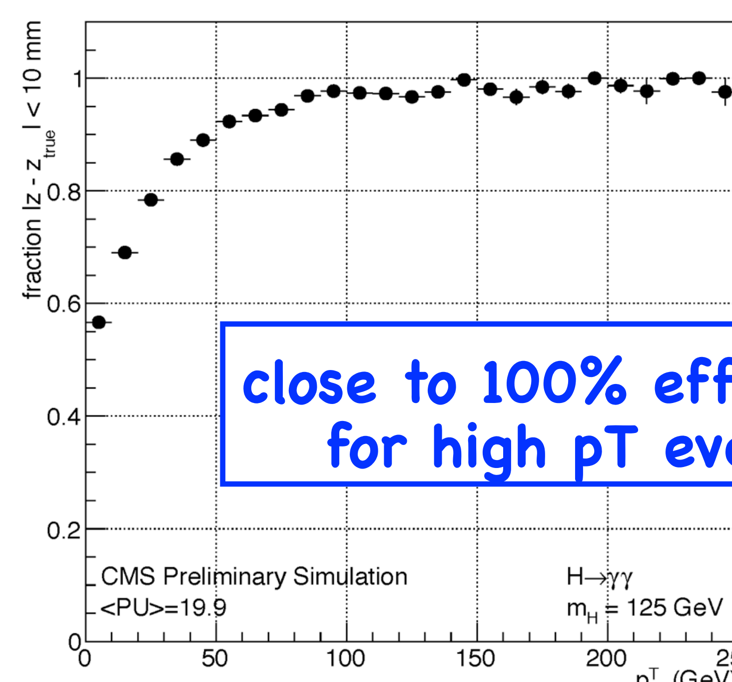


good control of detector effects



- **Highly efficient γ ID**
  - Shower spread vs η
  - R9 ≈ $E_{3x3}/E_{cluster}$
  - Isolation, H/E...

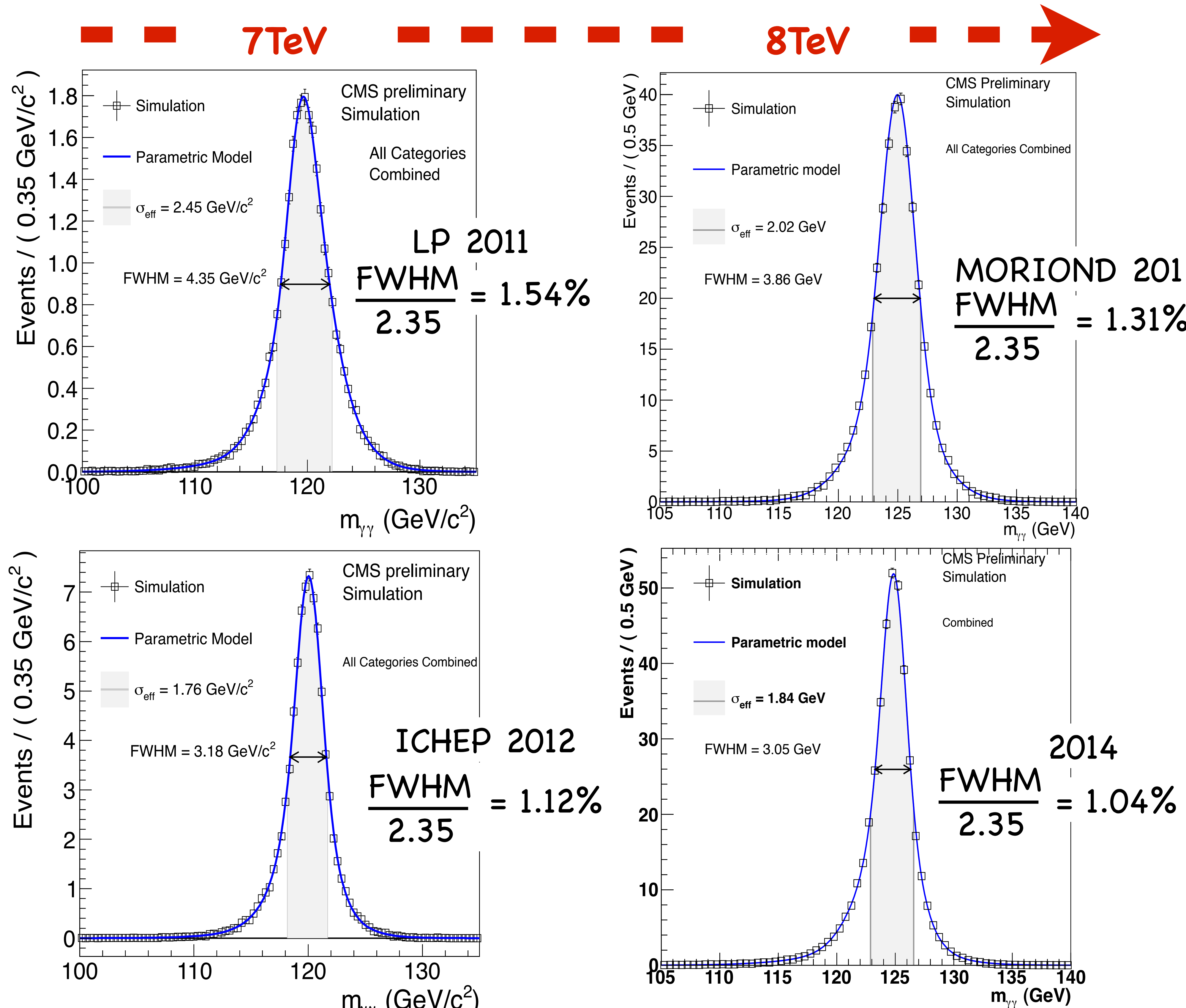
- **γγ vertex-finding**
  - No longitudinal segmentation of ECAL
  - Photon direction from shower position and interaction vertex identification
  - Vertex assignment based on tracks and di-photon system kinematics
  - If incorrect assignment, dominant contribution to γγ mass resolution



close to 100% efficiency for high pT events

Evolution of ECAL understanding…

- Expected H->γγ signal modelled with energy resolution measured from data (Z->ee)



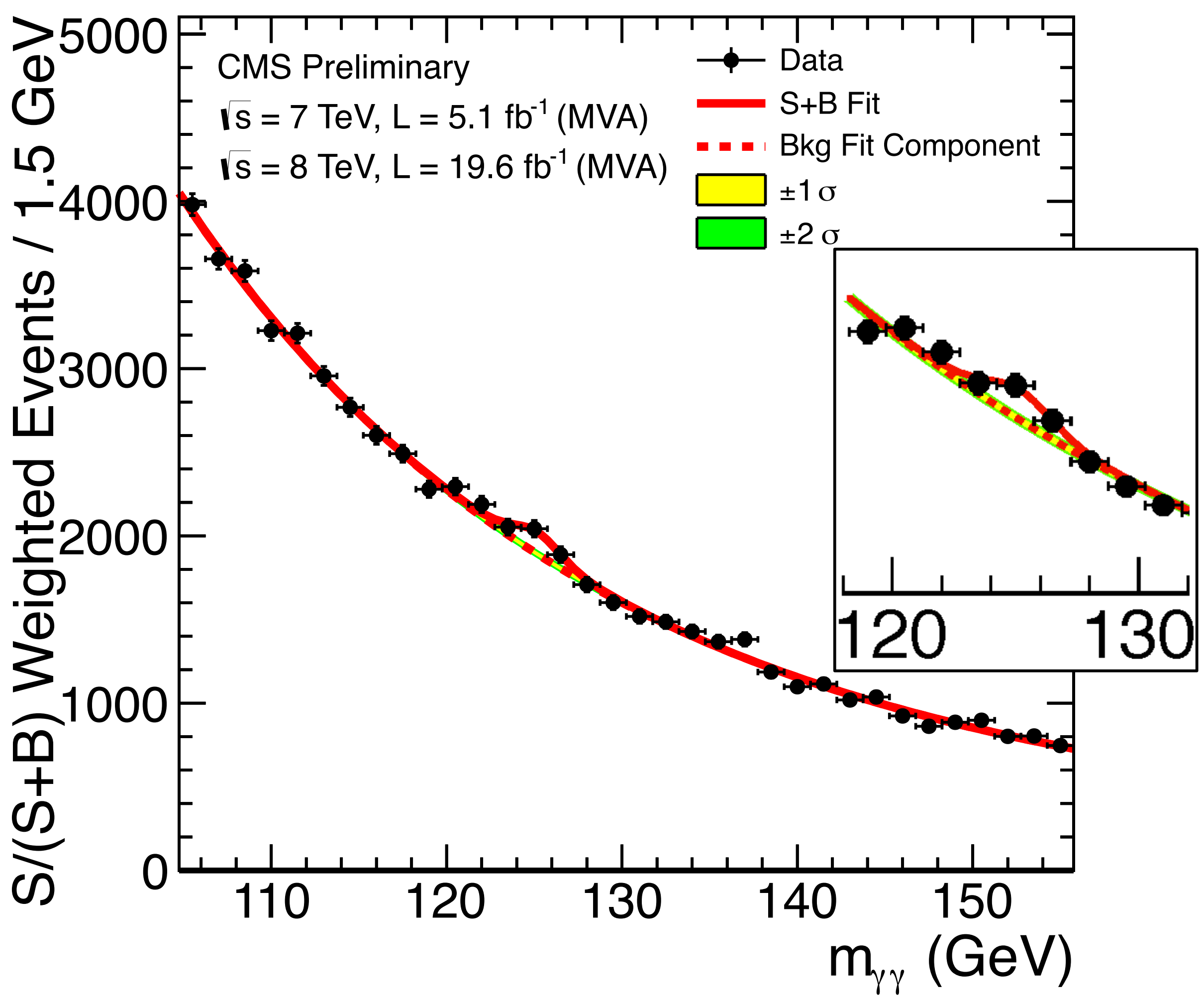
- **PROMPT** reconstruction within 48h from data taking

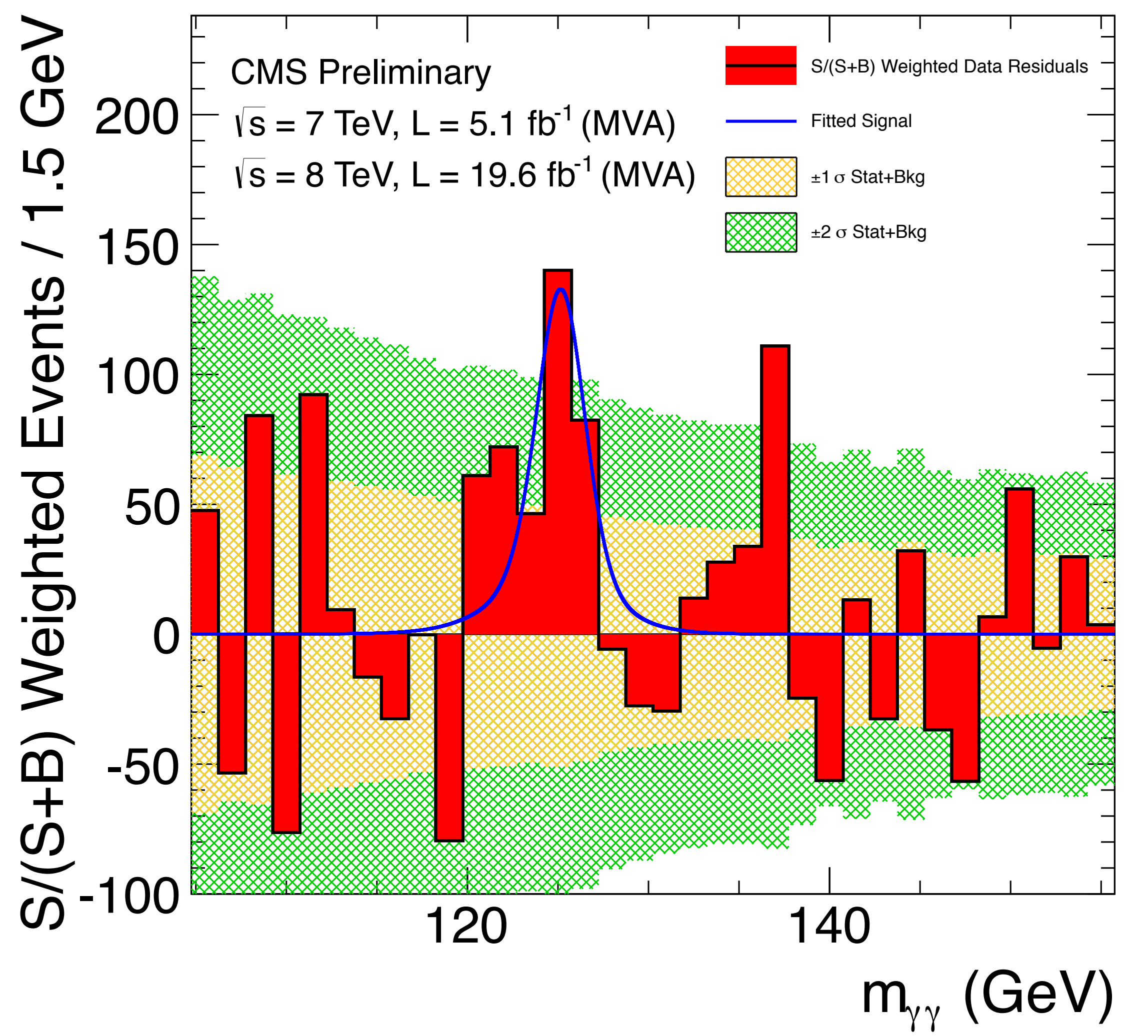
- **RECONSTRUCTION** with improved conditions

H->γγ result

MORIOND 2013

- Excess of events above background at a mass close to 125 GeV
  All measurements are compatible with a Higgs boson with a mass of 125.4 GeV



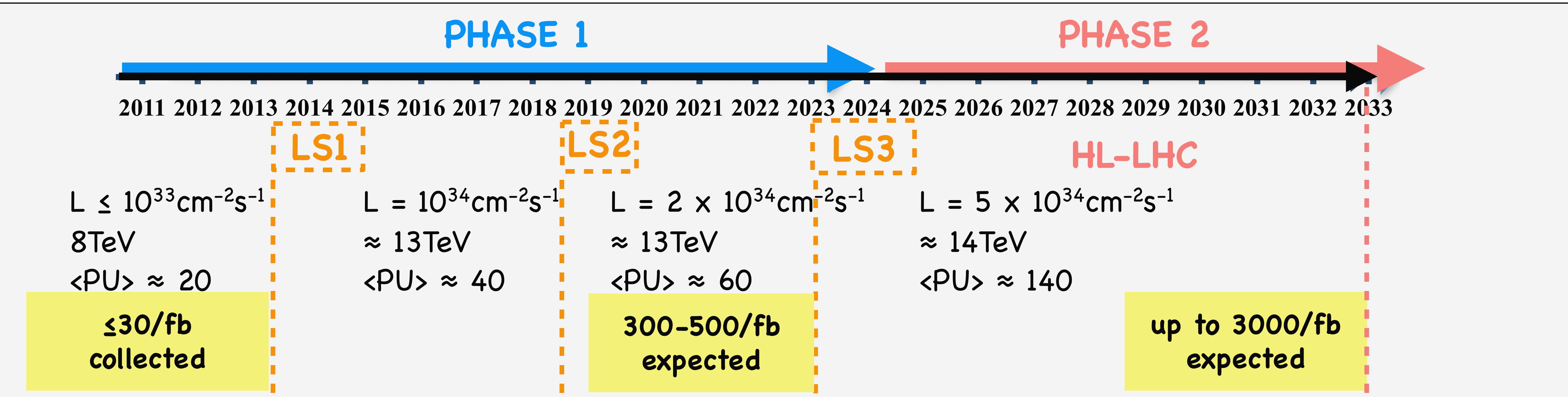


- Clean signal
- High precision mass measurement

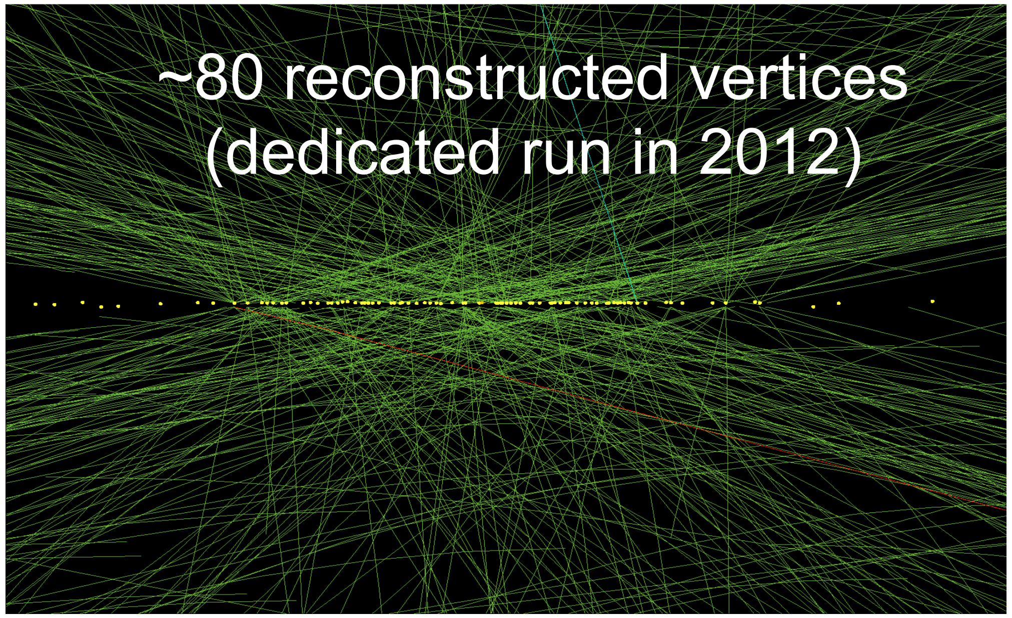
VERY GOOD CONTROL OF DETECTOR EFFECTS

Perspectives for the future...

- ECAL is designed to operate up to 500/fb at 10^{34} $cm^{-2}s^{-1}$
  - Phase 1: **will be operated at 2X design lumi**



- **Increasing challenges: for next runs and HL-LHC**
  - harsh environment => evolution of conditions and ageing
  - high stat => trigger rate
  - PU mitigation



towards the next runs...

- **ECAL will continue to have excellent performance**

- Provided some revised strategies and tunings:

- **Calorimeter trigger update**
  in view of 13 TeV and increased instantaneous lumi

  poster by A. Zabi

- **ECAL timing performance**:
  - expected to be crucial for PU-mitigation and particle ID at HL-LHC
  - could be important to improve performance with current/run 2 conditions

  talk by A. Bornheim

- Further improvements from:
  - **fine tune of calibration** and **time-dependent corrections**
  - **local containment** and **upstream material corrections**
  - possible **enhanced reconstruction algorithms**

and the HL-LHC

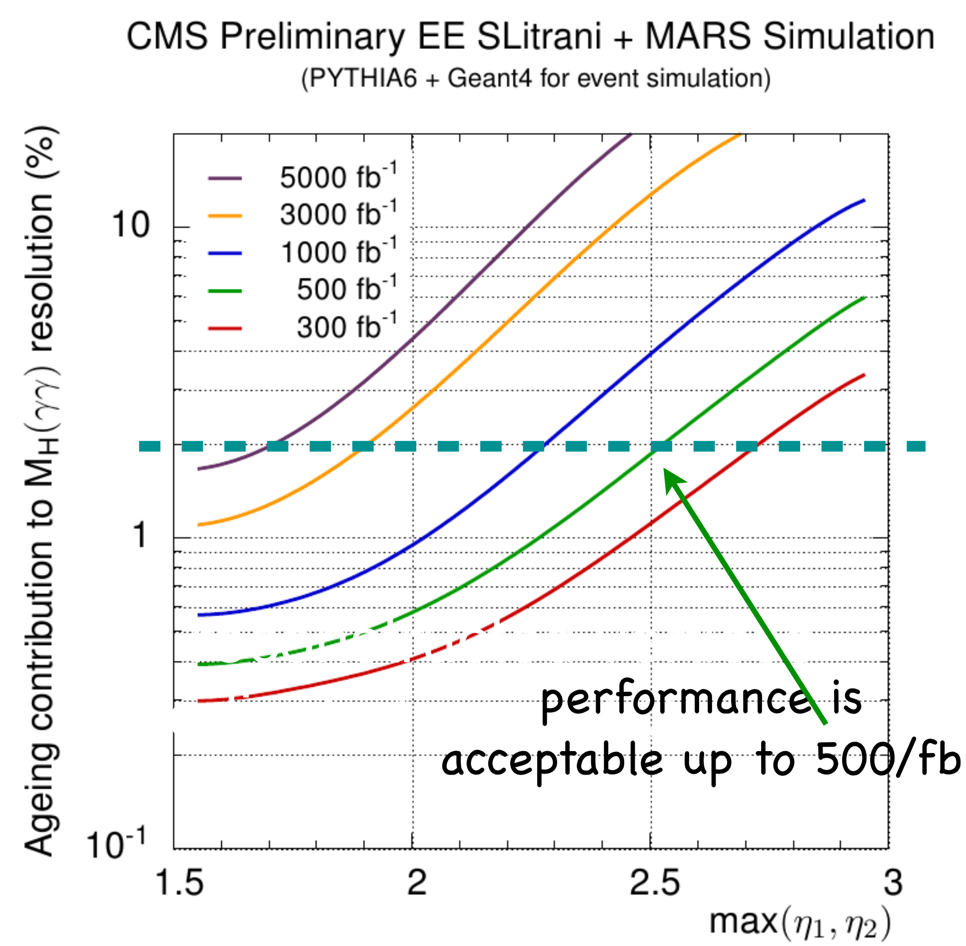
- Detector upgrades will be needed during LS3 to deal with the HL-LHC conditions
- Requirements from the **ageing of the detector**

- EB performance will be excellent up to 3000/fb (with modifications)

poster by M. Planer

- EE will be ok until 500/fb and then gradually lose acceptance
  they need to be replaced for the HL-LHC

talk by B. Bilki



Lessons learned and projections

- **ECAL performed excellently throughout LHC Run 1**

- **Good understanding and control of detector => H->γγ discovery with high sensitivity**
- **ECAL barrel** drives the sensitivity to the H->γγ search
  with close-to-excellent resolution and photon ID capabilities
  - Limitation due to material budget at |η|>1 => tunings and corrections ongoing

- **ECAL endcaps** currently less optimal to the H->γγ sensitivity
  object of optimisation for next operation to further exploit LHC potential
  - Increased material budget in front of the calorimeter => tunings and corrections ongoing
  - Less precise single channel calibrations => tunings and corrections ongoing

- ECAL collected 1% of total expected luminosity
  - **ECAL** performance **OK up to 500/fb** (end of Phase 1)
  - **BARREL** performance **OK up to 3000/fb** and upgrade required for ENDCAPS (Phase 2)

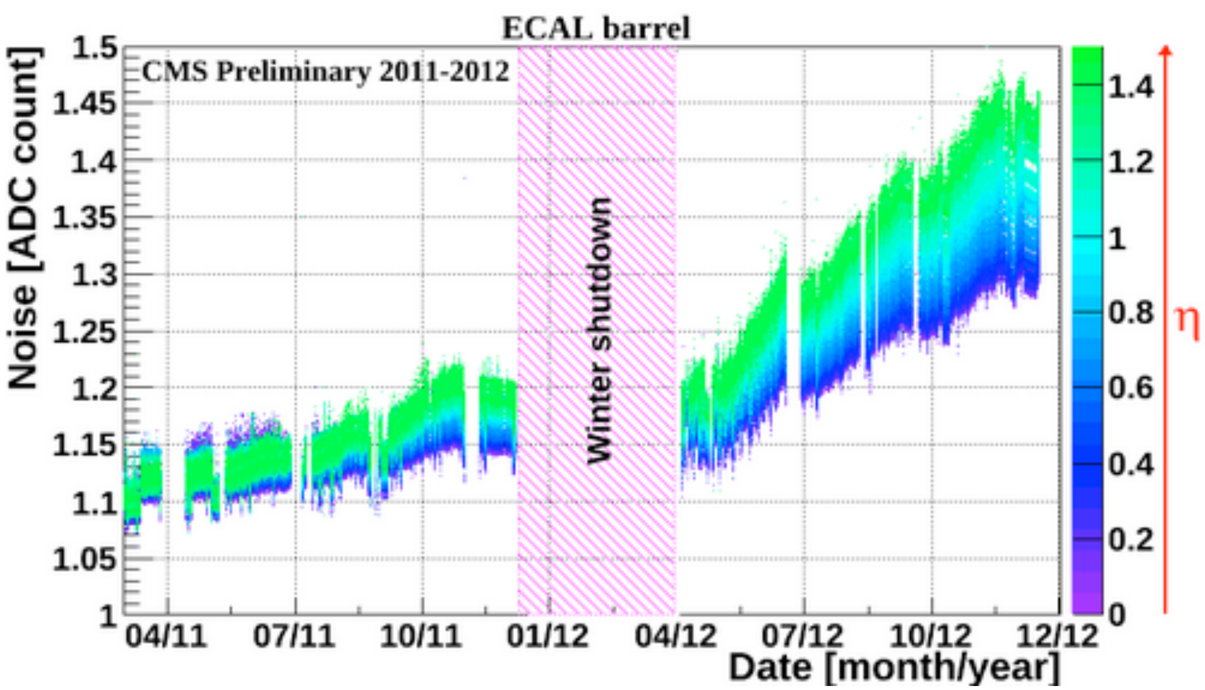
- … and now wait for LHC Run2 lesson

BACKUP

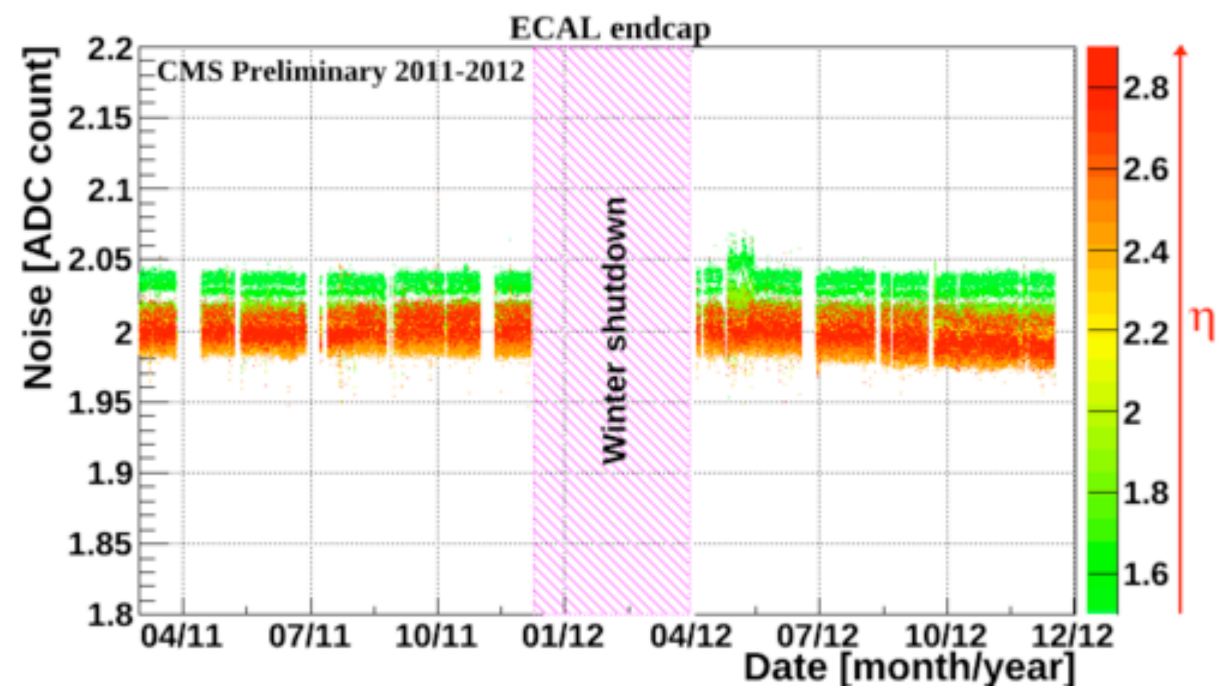
Noise evolution in run 1

- Electronic noise in ADC counts:

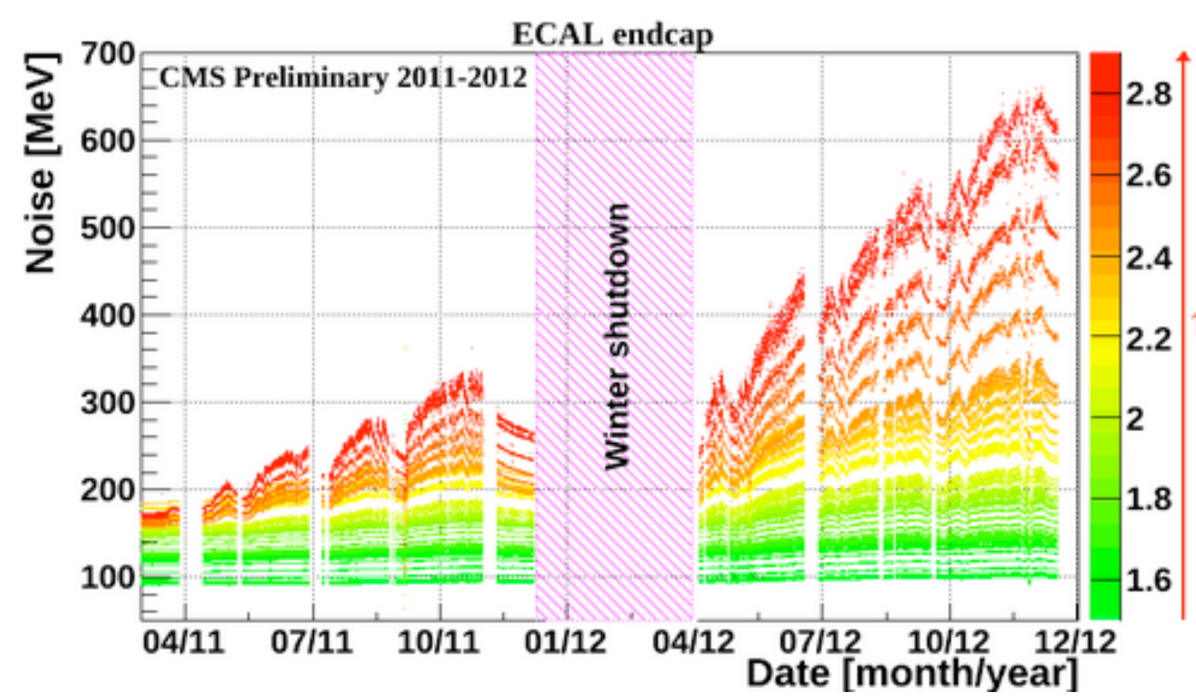
increase of the APDs dark current in EB



constant in EE (VPTs)



- Energy equivalent noise (in MeV): noise in ADC is scaled by the laser corrections and IC



Energy corrections along η