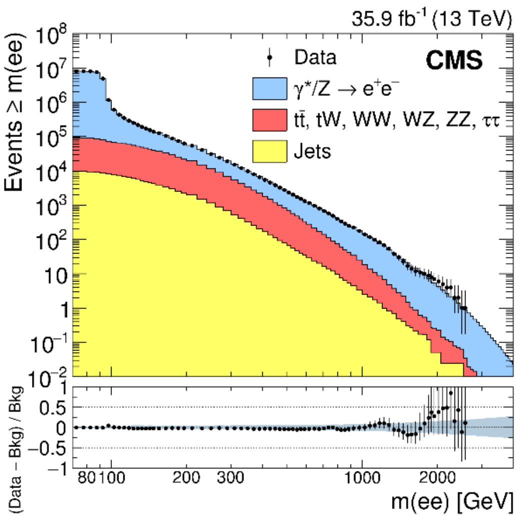
Calibration and performance of the CMS electromagnetic calorimeter during the LHC RunII

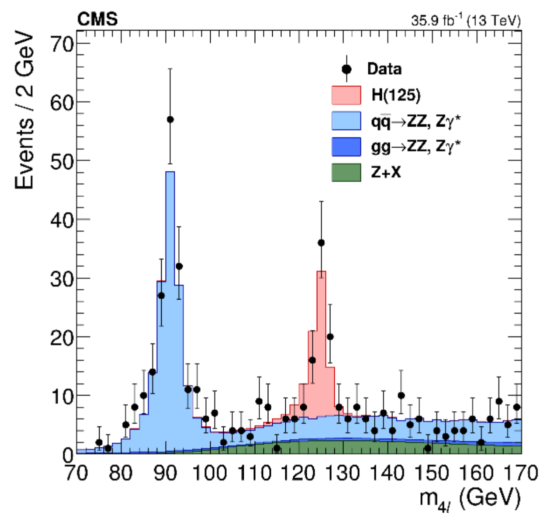
Tatyana Dimova
(Novosibirsk State University and Budker Institute of Nuclear Physics)
On behalf of the CMS Collaboration

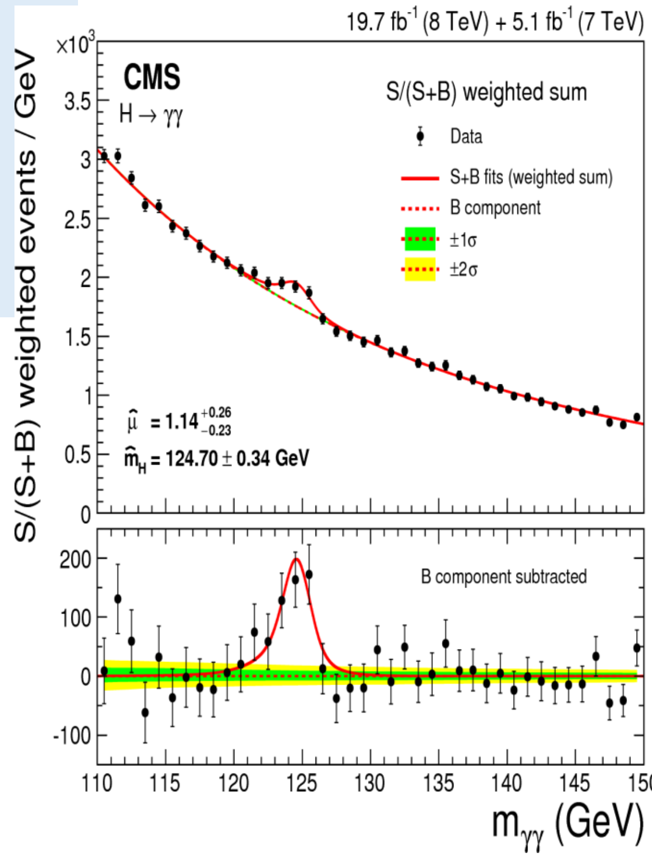
Introduction

Electrons and photons essential for CMS physics :

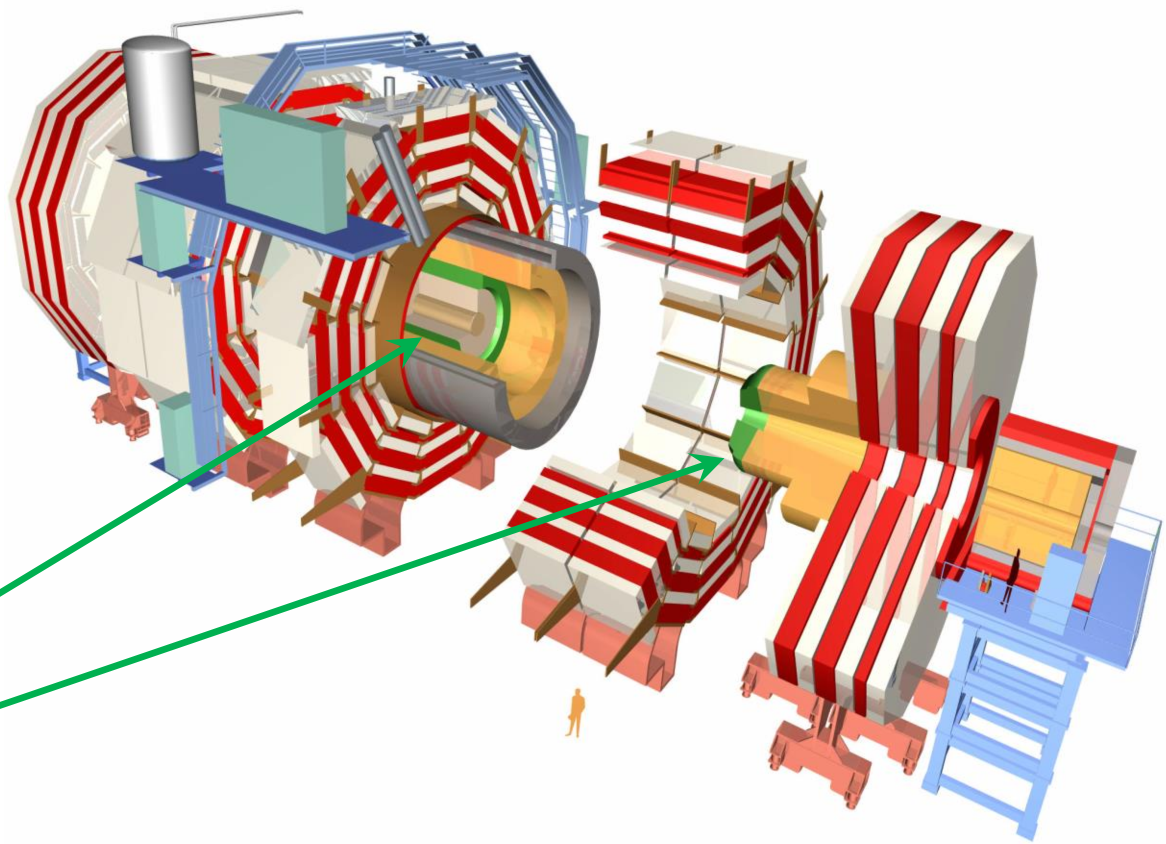
- Precise Higgs mass measurement in H→4*l* channel (*l* = $e^{\pm}$, $\mu^{\pm}$)
  - High energy resolution
  - Shower shape analysis due to the fine spatial granularity
- Measurement of σ(H) in the H→γγ final state
  - High photon energy resolution
  - Precise direction measurement
- BSM physics (heavy resonances, SUSY decays),
- SM measurements (top physics, multibosons,etc)







The CMS Detector and the ECAL

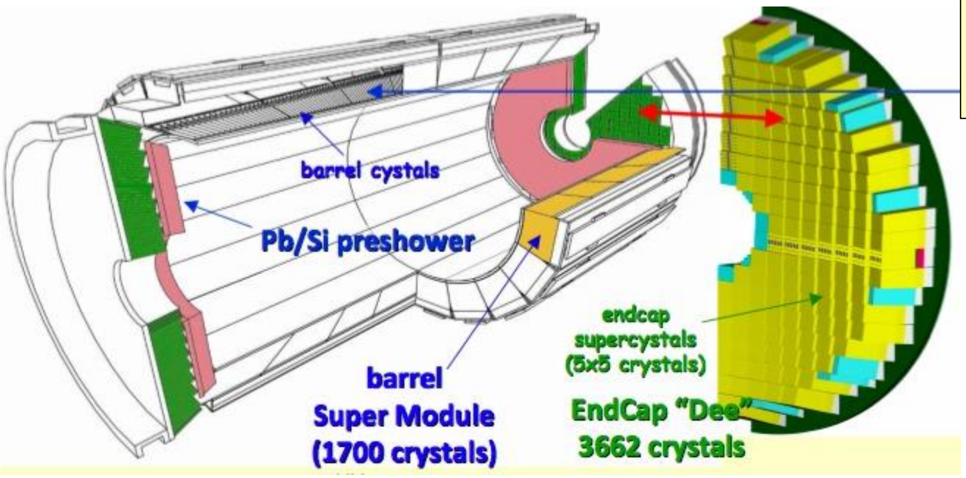


CMS

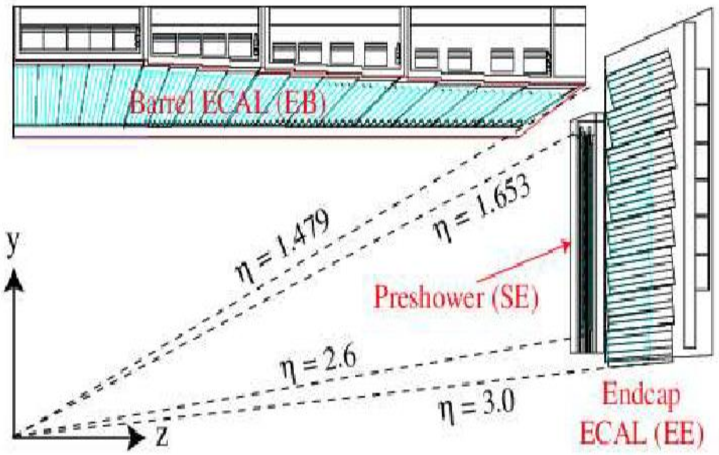
Length :21.5m
Diameter: 15m
Weight 14kT
Magnetic filed:3.8T

ECAL: the main goal is to detect and measure with high precision the energies of electrons and photons

The CMS Electromagnetic calorimeter



Tapered crystals to provide off-pointing of ~ 3° from vertex

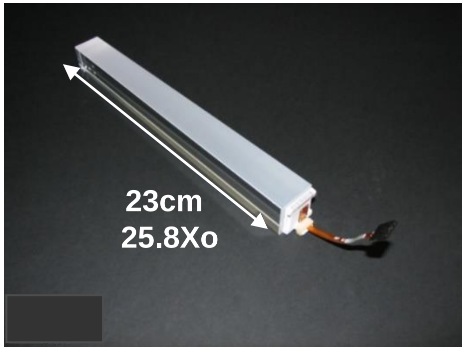


Barrel
36 Supermodules
(18 per half barrel)
61200 crystals
Total crystal mass 67.4t
$|\eta| < 1.48$, ~$26X_0$
$\Delta\eta \times \Delta\varphi = 0.0174 \times 0.0174$

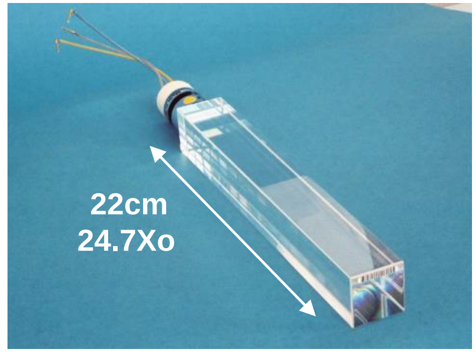
Endcaps
4 Dees (2 per endcap)
14648 crystals
Total crystal mass 22.9t
$1.48 < |\eta| < 3$, ~$25X_0$
$\Delta\eta \times \Delta\varphi = 0.0175^2 \leftrightarrow 0.05^2$

Endcap Preshower
Pb ($2X_o$,$1X_o$) / Si
4 Dees (2 per endcap)
4300 Si strips
1.8mm x 63mm
$1.65 < |\eta| < 2.6$

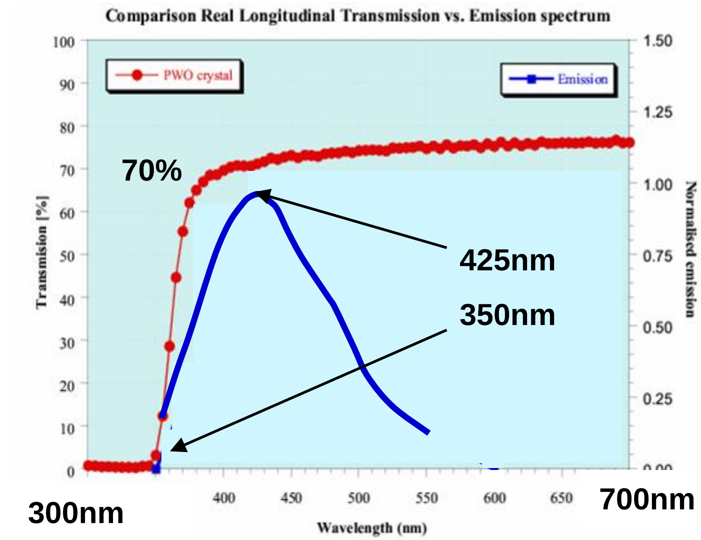
Lead tungstate crystals ($PbWO_4$)



Barrel crystal, tapered
34 types, ~2.6x2.6 cm^2 at rear



Endcap crystal, tapered
1 type, 3x3 cm^2 at rear



Emission spectrum (blue)
and transmission curve(red)

Reasons for choice

Homogeneous medium

High density 8.28 g/cm^3

Short radiation length $X_0 = 0.89$ cm

Small Molière radius $R_M = 2.19$ cm

Fast light emission ~80% in 25 ns

Emission peak 425nm

Reasonable radiation resistance to very high doses

Challenges

LY temperature dependence -2.2%/^{O}C

Stabilise to ≤ 0.1^{O}C

Irradiation affects crystal transparency

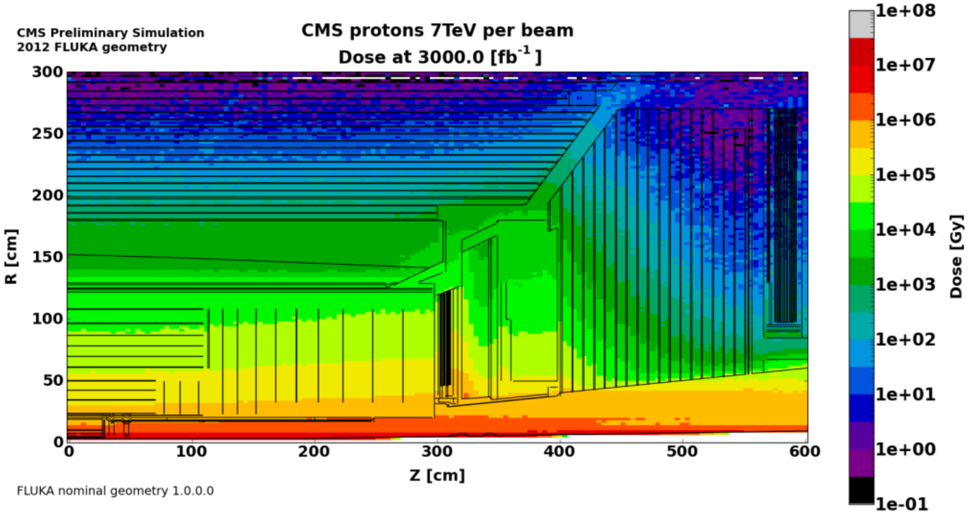
Need precise light monitoring system

Low light yield (1.3% NaI)

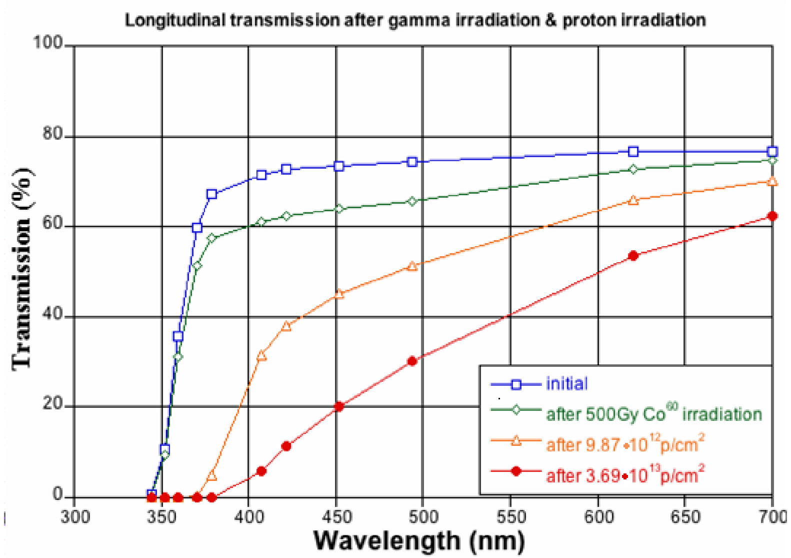
Need photodetectors with gain in magnetic field

Radiation damage in $PbWO_4$

Absorbed dose after 10 years



Evolution of transmission due to irradiation



Radiation dose at the EM shower max for $L=10^{34}cm^{-2}s^{-1}$:

- 0.3Gy/h in EB
- 6.5 Gy/h at η=2.6

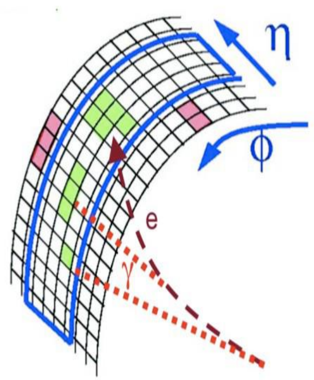
Ionizing radiation damage:

- It recovers at room temperature

Hadron damage:

- No recovery at room temperature
- Shift of transmission band edge
- Will dominate at HL-LHC

Energy reconstruction



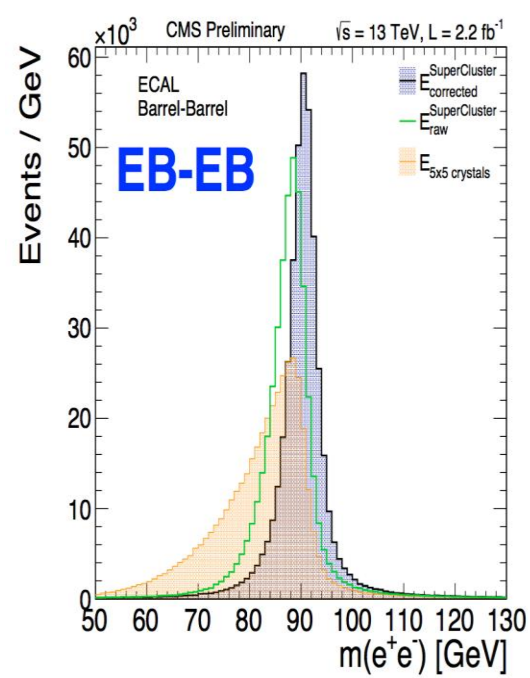
Clusterization

- Crystal transverse size is ~ R_M so EM shower spread over several crystals
- Clusters are extended in φ direction to form “superclusters” to recover energy radiated via bremsstrahlung or conversion

$$E_{e,\gamma} = F_{e,\gamma} \times \left[E_{ES} + G \times \sum_i C_i \times S_i(t) \times A_i(t) \right]$$

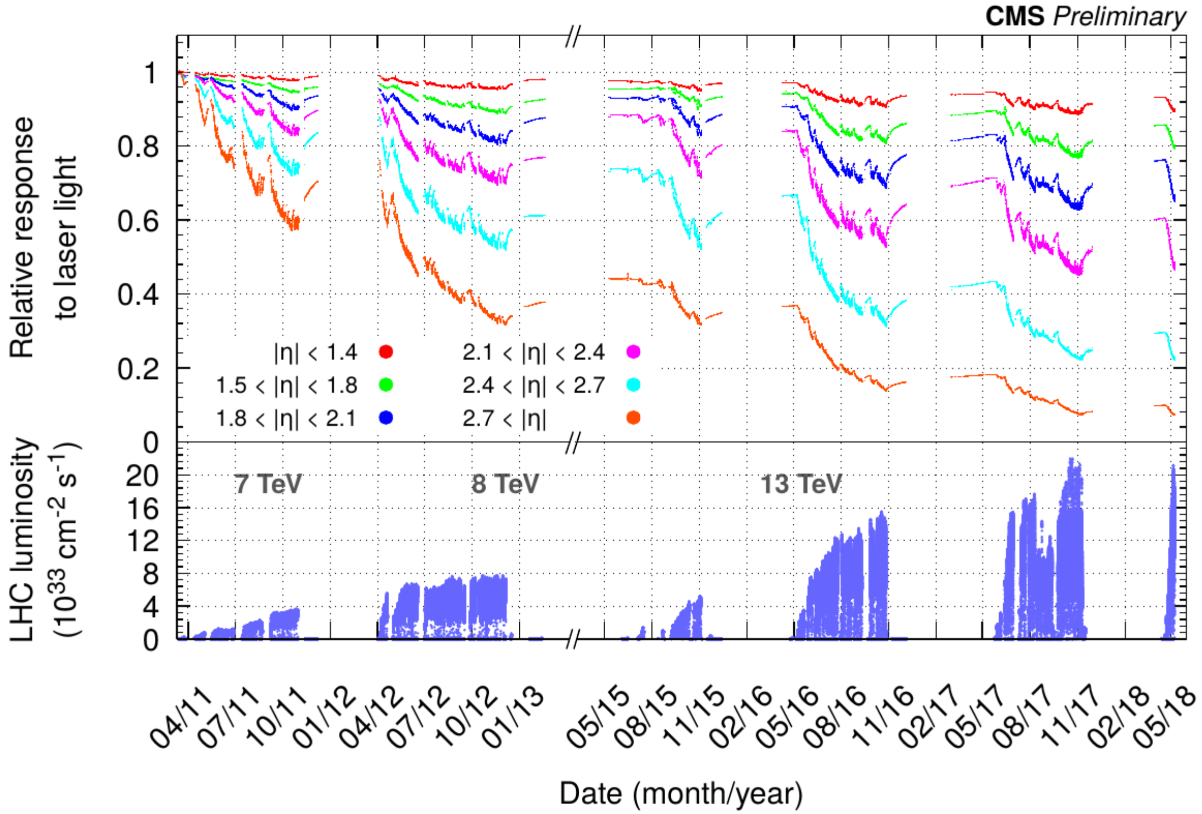
Energy of electrons/photons $\mathbf{E_{e,\gamma}}$:

- **C_i** – inter-calibration among crystals
- **$S_i(t)$** – corrections for response time variations
- **$A_i(t)$** – signal amplitude
- **G** – ADC to GeV global scale
- **$F_{e/\gamma}$** – cluster corrections
- E_{ES} – preshower energy

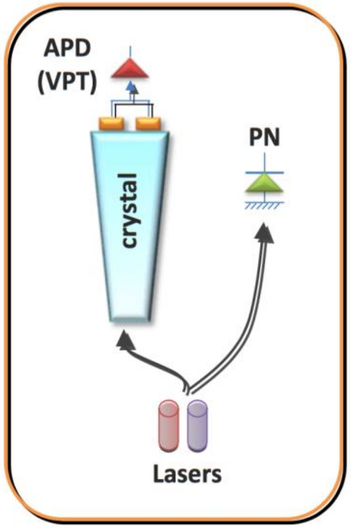


Response monitoring

- Barrel: the response change is **up to 10%** . Endcaps: reaches **up to 50% at η ~ 2.5** and **up to 90%** in the region closest to the beam pipe.
- The recovery of the crystal response during the period without collisions is visible. In the regions close to beam pipe, not fully recovered



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



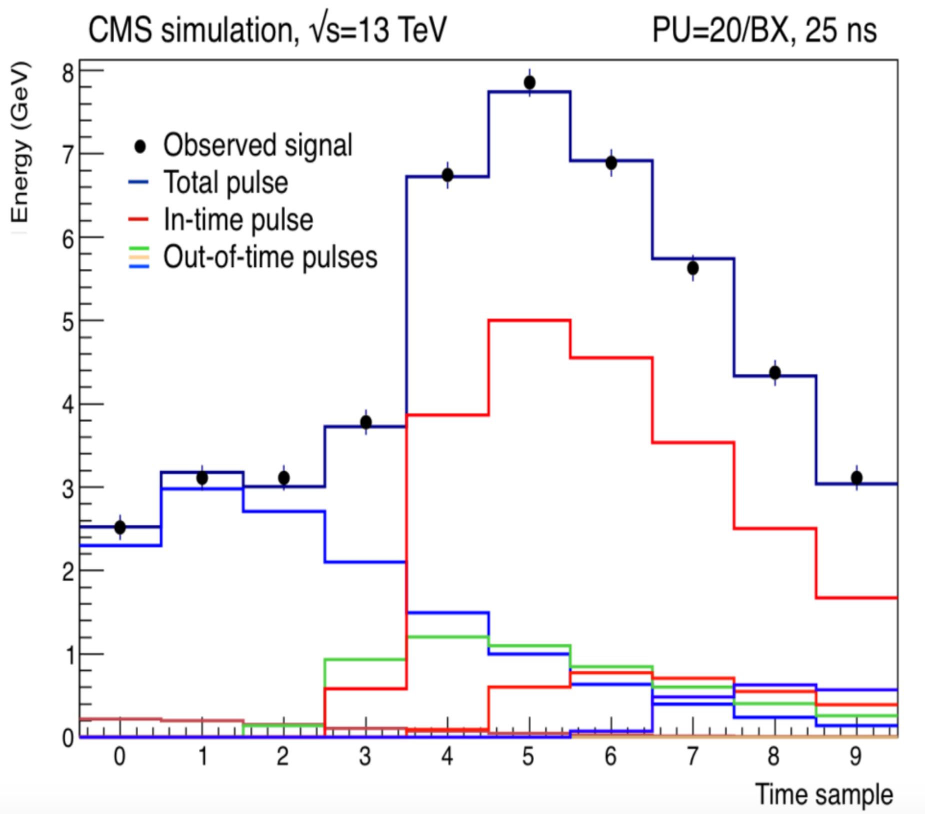
APD: Avalanche Photodiode (EB)
VPT: Vacuum Phototriode (EE)
PN: Reference diode

Pulse shape reconstruction

New method –"multifit":

estimate the in-time signal amplitude and up to 9 out-of-time amplitudes by means of χ^2 minimization

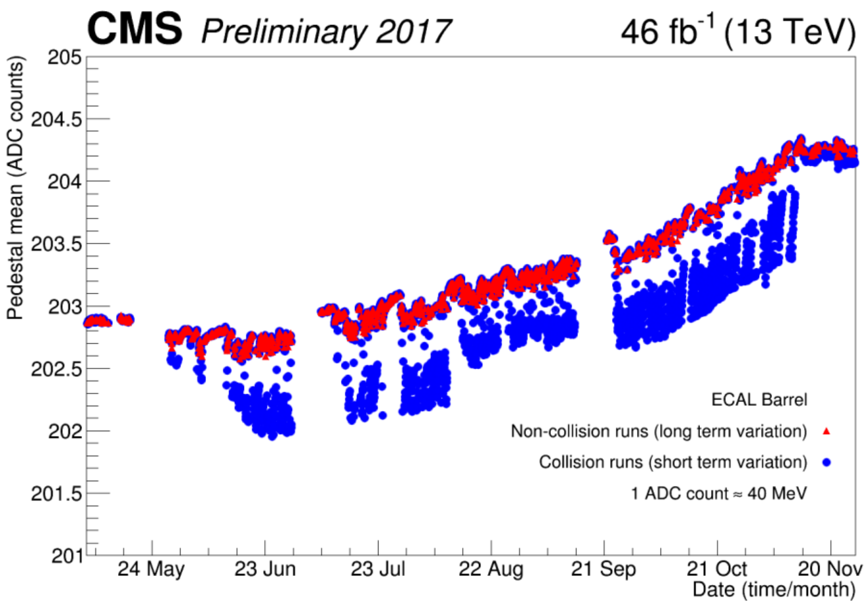
$$\chi^2 = \sum_{i=1}^{10} \frac{\left(\sum_{j=1}^{M} A_j \times p_{ij} - S_i\right)^2}{\sigma_{S_i}^2}$$

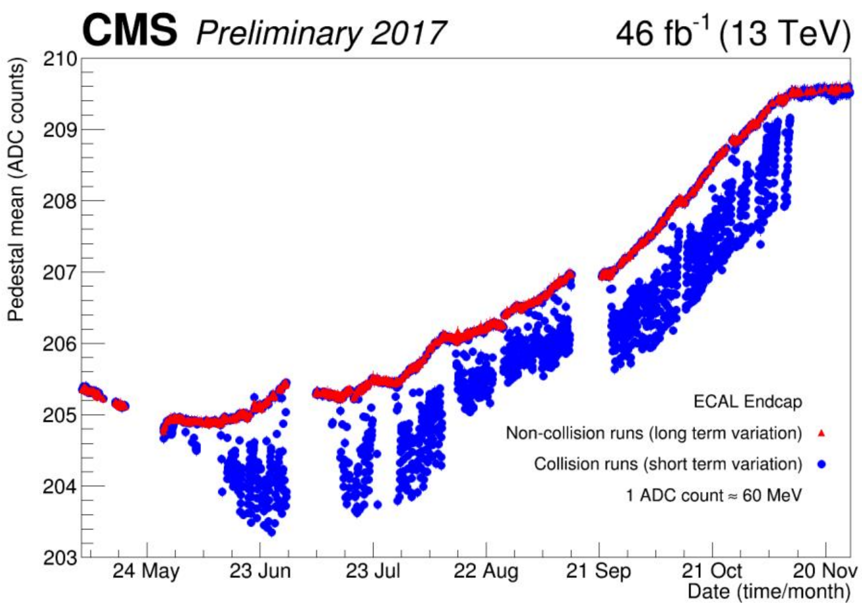


- S_i : digitized amplitudes
- $A_j(\geq 0)$: amplitudes from pulse at bunch crossing *j*
- p_{ij}: the template pulses , all identical and shifted by jx25ns
- σ_{Si}: noise covariance matrix

Pedestal measurement

Pedestals drift in 2017: red – long term aging effects,
blue – short term effects that depend on instantaneous luminosity



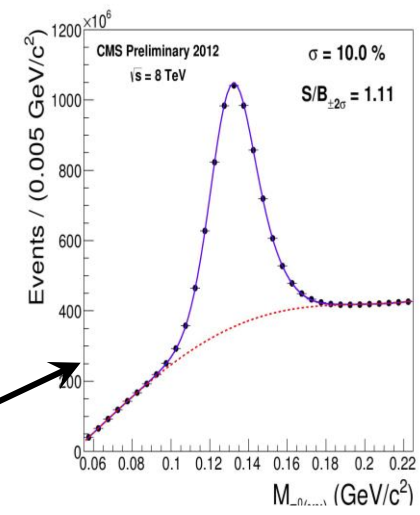


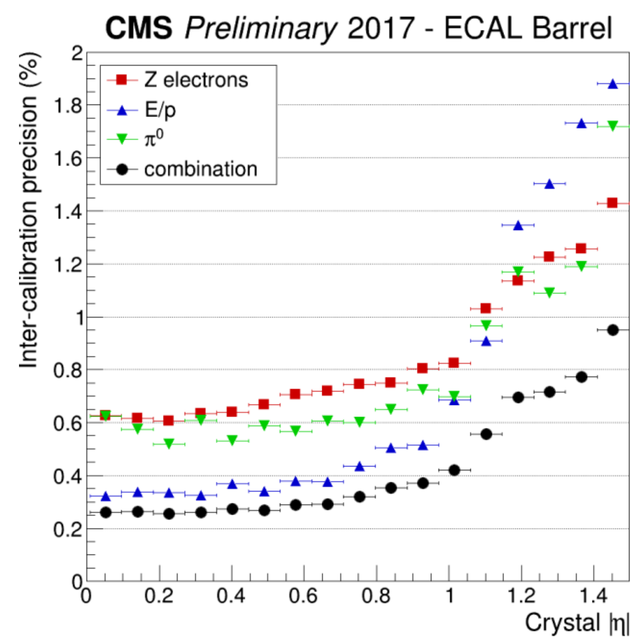
Pedestal measurements for each channel are directly used in the multifit.

ECAL intercalibration

Crystal by crystal **inter-calibration** due to different light-yield and photodetector response to equalize the response among different crystals:

- **ϕ-symmetry:** balance average energy response in channels at constant η
- **π^0/η mass:** iterative method based on invariant mass reconstructed from unconverted photons
- **E/p method:** iterative method based on ECAL energy and tracker momentum for isolated electrons, E/p ~ 1
- **Z → ee mass (in Run II):** exploiting the invariant mass constraint of di-electron system



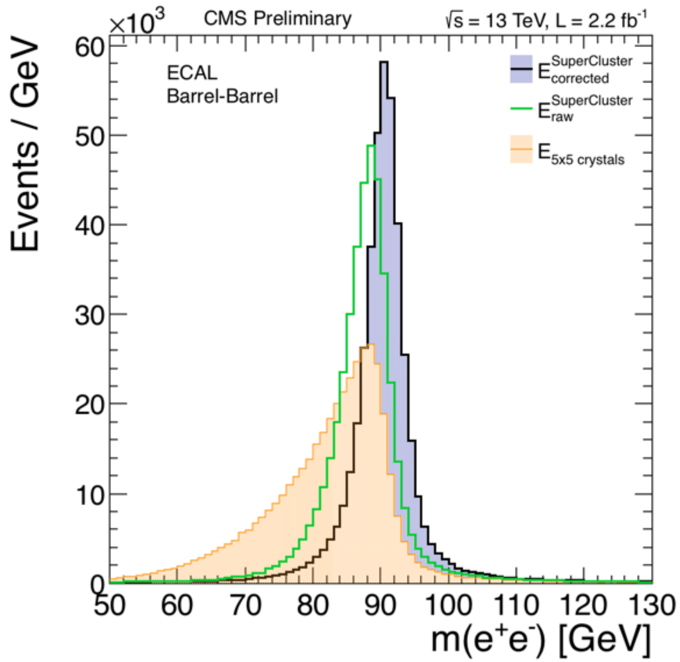


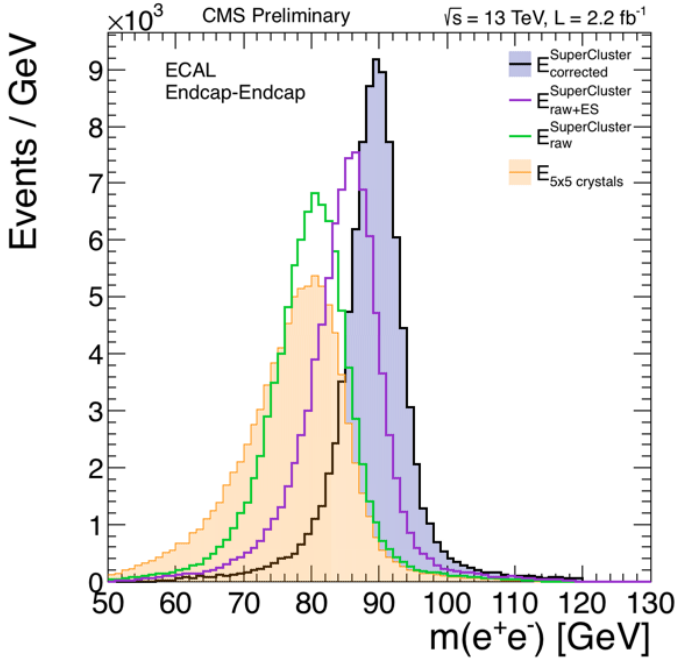
Supercluser energy correction

energy sum over the seed 5x5 crystal matrix → bremsstrahlung recovery using supercluster → energy correction using a multivariate algorithm

Improvement of the resolution by using the supercluster algorithm, that dynamically includes cluster spread, especially in the ϕ-direction, for showering electrons

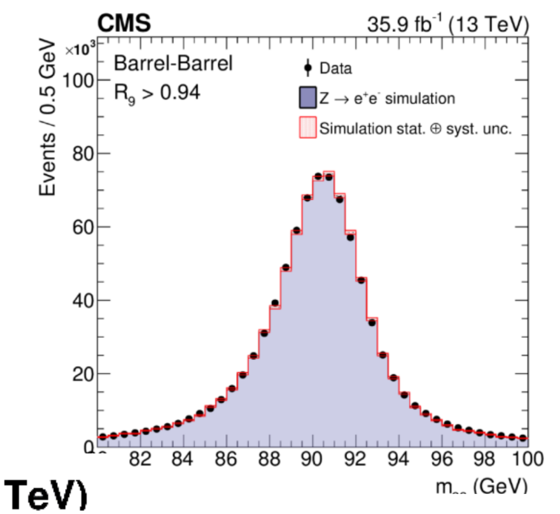
Multivariate algorithm uses the ECAL variables as input data and is training with MC simulation separately for electrons and photons.

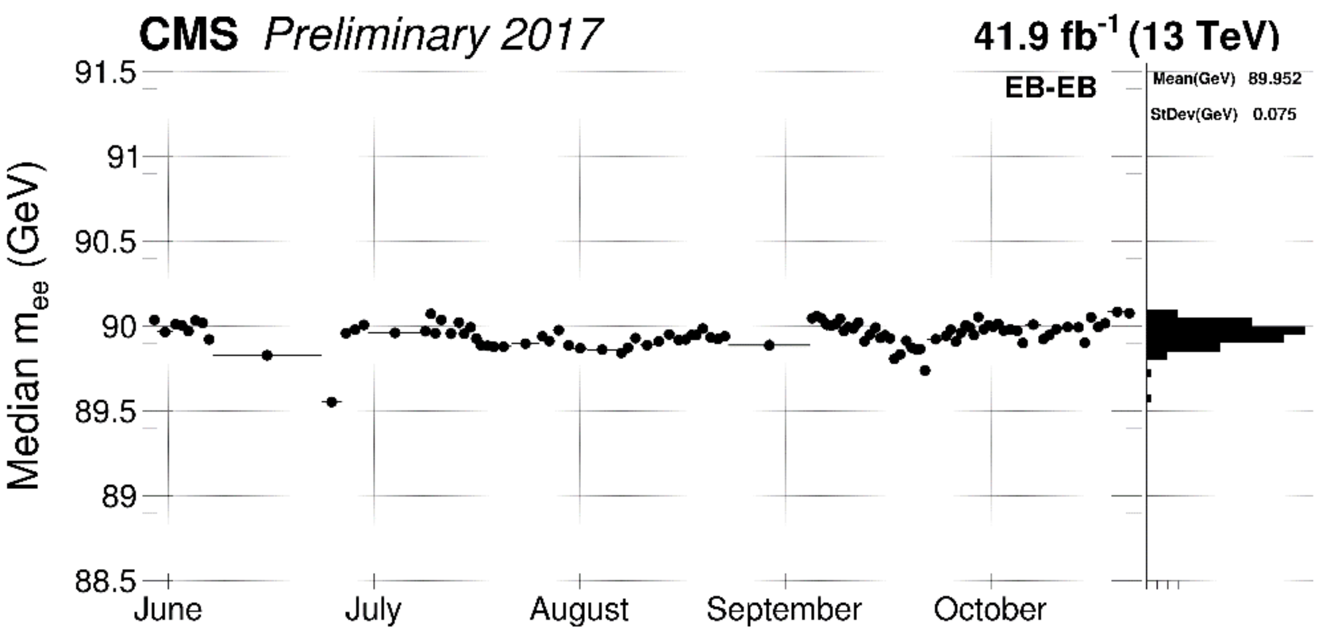




Energy global scale

Global energy scale is adjusted thus the data $Z \rightarrow e^+e^-$ peak agrees with MC simulation.

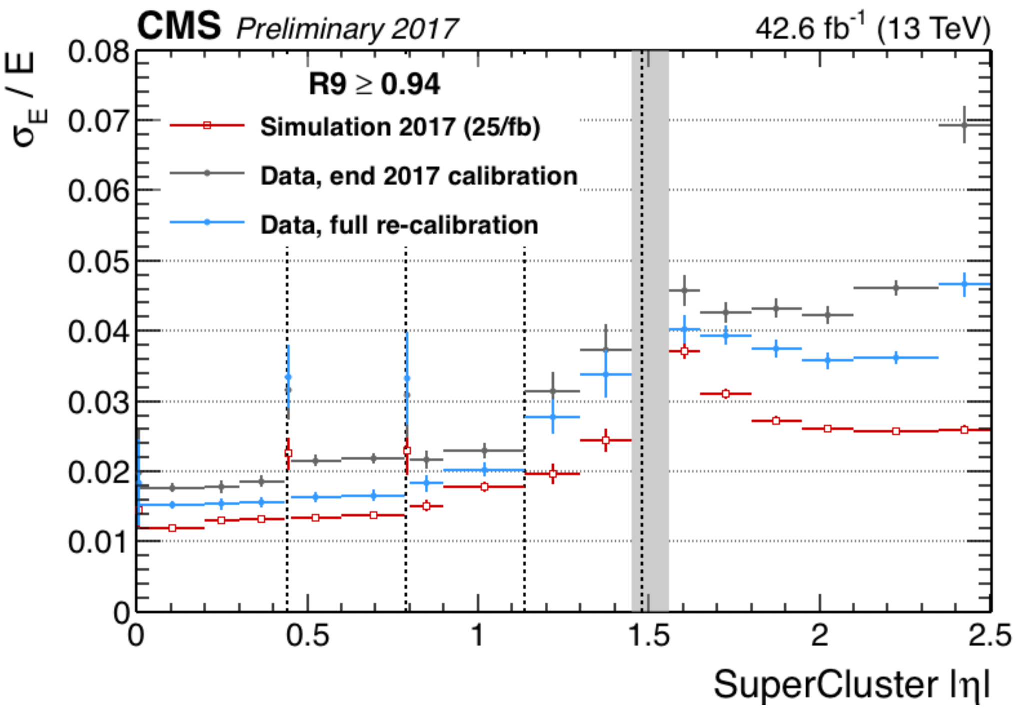




Long term stability of energy scale

ECAL performance

Relative electron resolution for barrel and endcaps



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

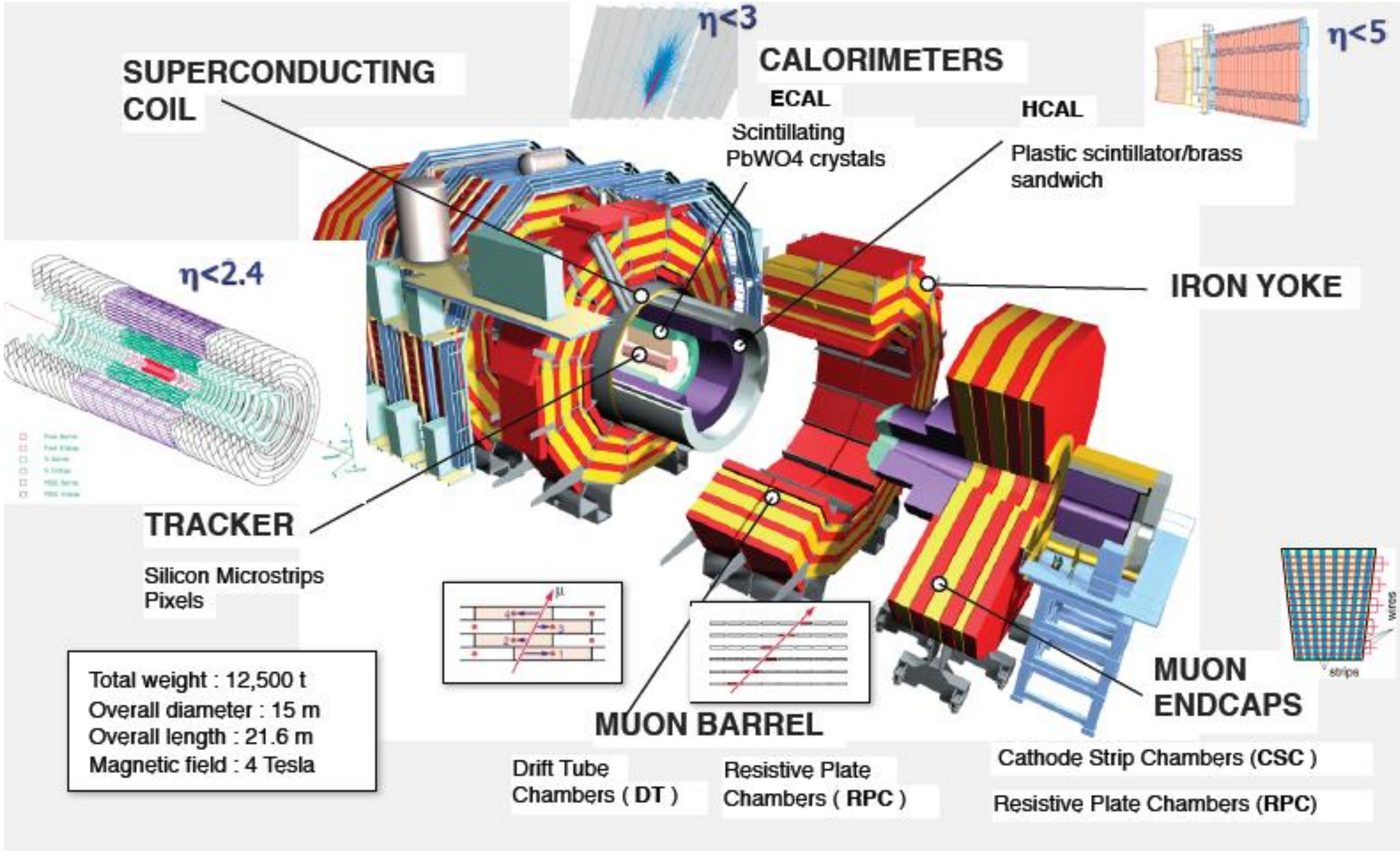
Conclusions

- ✓ **ECAL has operated smoothly and with excellent performance during Run II due to**
    - ECAL online and offline reconstruction has been adapted to meet the challenges of higher LHC luminosity and detector aging
    - Regular monitoring and updates of crystal response, pedestals, pulse shape are performed to maintain energy resolution
    - Effective suppression of out-of-time PU using the multifit algorithm
    - With these updates, the excellent energy resolution and stability achieved during Run I has been maintained in Run II

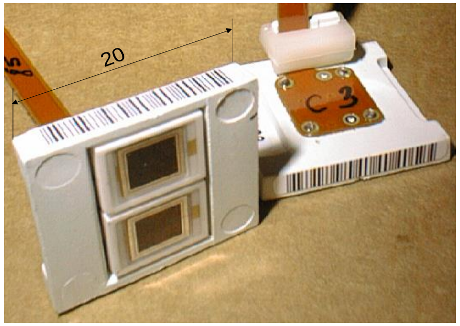
- ✓ **The excellent ECAL performance was crucial for the Higgs boson discovery made by CMS and remains very important for precision measurements and for searches of new physics, as well**

Backup slides

Detector layout

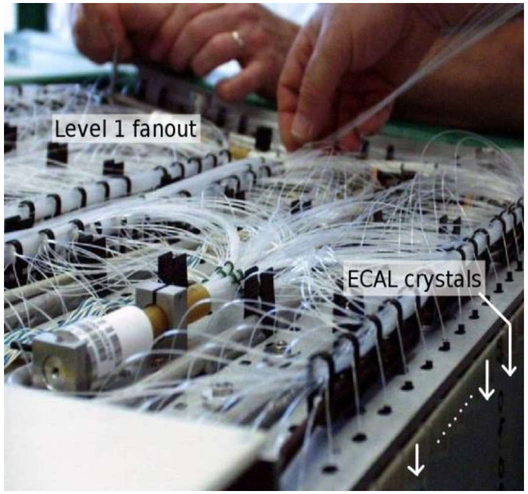


Photodetectors

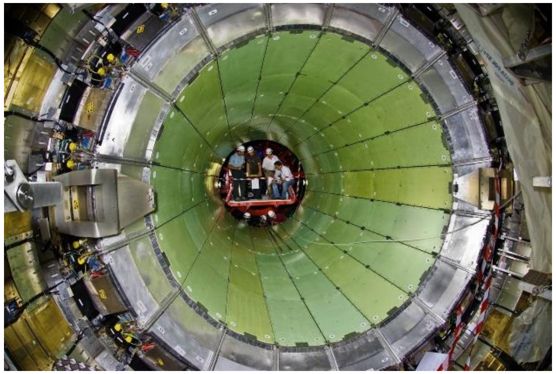


Barrel: Avalanche photo-diodes (APD, Hamamatsu)
Two 5x5 mm^2 APDs/crystal, ~ 4.5 p.e./MeV
Gain 50
QE ~ 75% at 420 nm
Temperature dependence $1/G\ \Delta G/\Delta T = -2.4\%/C$
High-Voltage dependence $1/G\ \Delta G/\Delta V = 3.1\%/V$
Need to stabilize HV at 30 mV
Measured HV fluctuation: ~30 mV

Endcaps: Vacuum photo-triodes (VPT, Research Institute "Electron", Russia)
More radiation resistant than Si diodes
UV glass window
Active area ~ 280 mm^2/crystal, ~ 4.5 p.e./MeV
Gain 8 -10 (B=4T)
Q.E. ~ 20% at 420 nm
Gain spread among VPTs ~ 25%
Need intercalibration



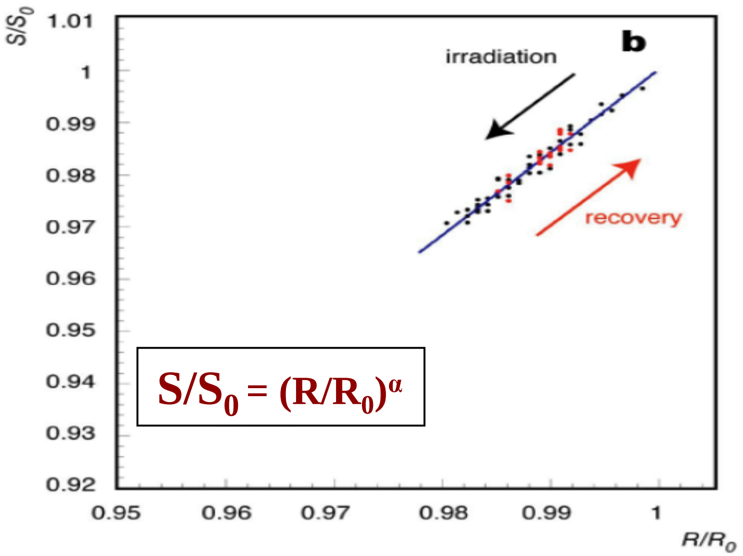
Level 1 fanout
ECAL crystals



CMS
Lab 27
PH CMA
CERN

Radiation damage in $PbWO_4$

Scintillation (S/S_0) vs laser light (R/R_0)

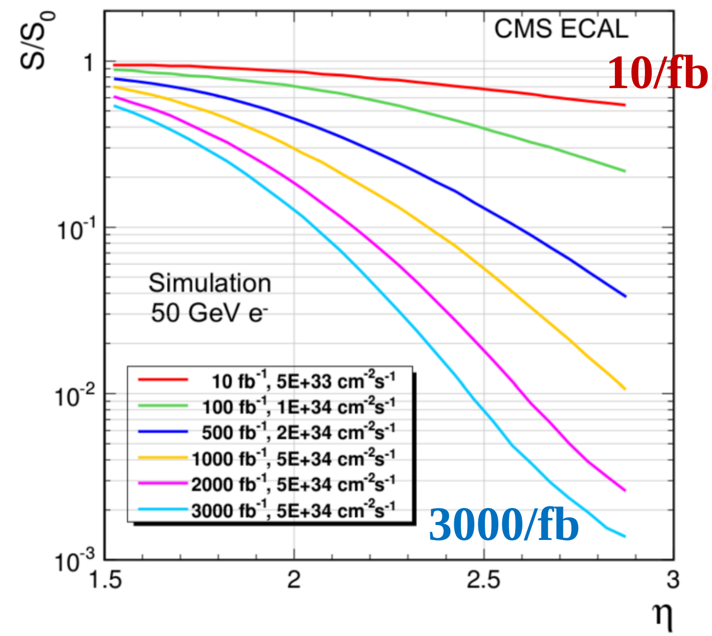


$<\alpha>=1.52$ – BTCP crystals

$<\alpha>=1.00$ – SIC crystals

Rms <10%

Simulation of changes in EE crystal response

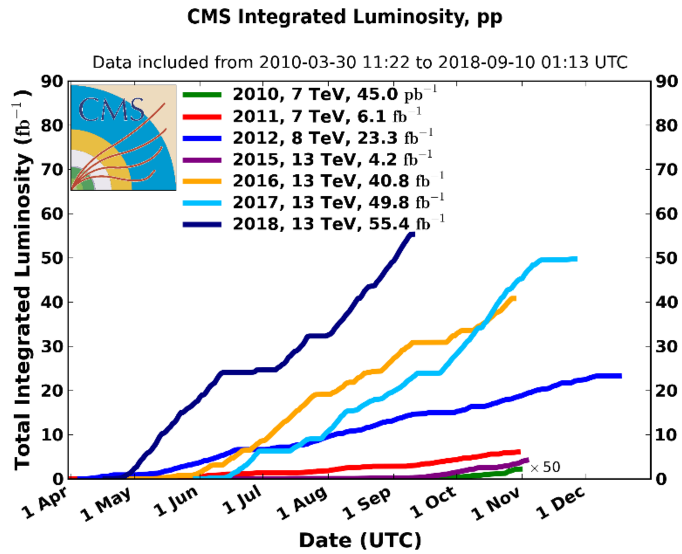


The changes in the crystal transparency due to irradiation impact on the signals from an electromagnetic shower in different way than from laser pulse.

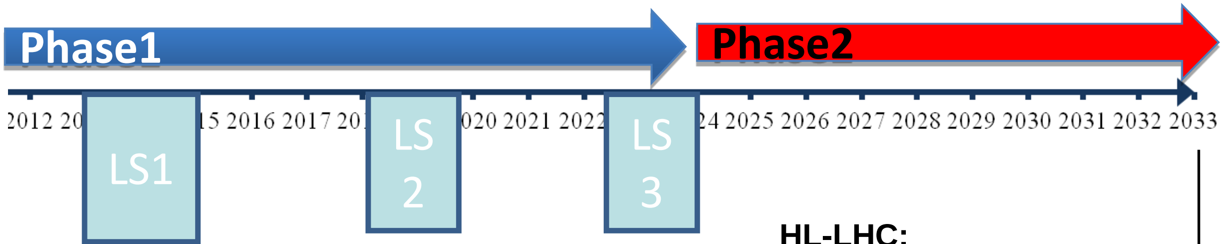
With large transparency losses, energy resolution will degrade :

- photo statistics reduced
- relative noise increased
- crystal non-uniformity

Integrated luminosity (2010-2018)



LHC schedule



ECM=13 TeV
L=1 $\cdot 10^{34}$ $cm^{-2}s^{-1}$
50 fb^{-1} per year
3 years

L=2 $\cdot 10^{34}$ $cm^{-2}s^{-1}$
≥50 fb^{-1} per year
3 years

HL-LHC:

L=5 $\cdot 10^{34}$ $cm^{-2}s^{-1}$
250 fb^{-1} per year
~140 events per bunch-crossing

~ 300 fb^{-1}

~ 3000 fb^{-1}

A new machine, for high luminosity, to measure the H couplings, H rare decays, HH, Vector boson scattering, other searches and difficult SUSY benchmarks, measure properties of other particles eventually discovered in Phase1.