Monitoring and Correcting for Response Changes in the CMS Lead-tungstate Electromagnetic Calorimeter in LHC Run2

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On behalf of the CMS Collaboration

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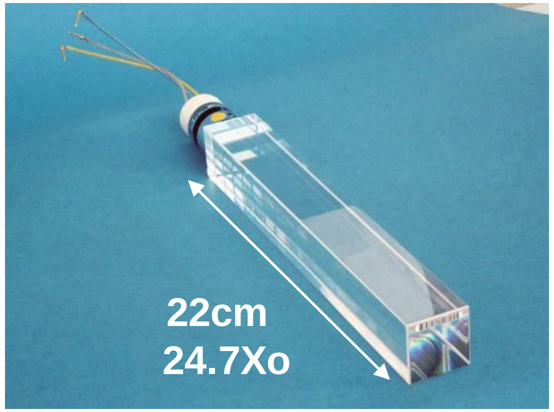
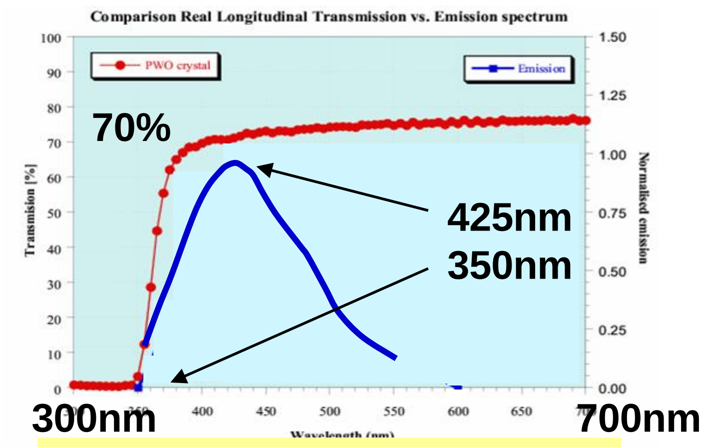
Lead tungstate crystals ($PbW0_4$)

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

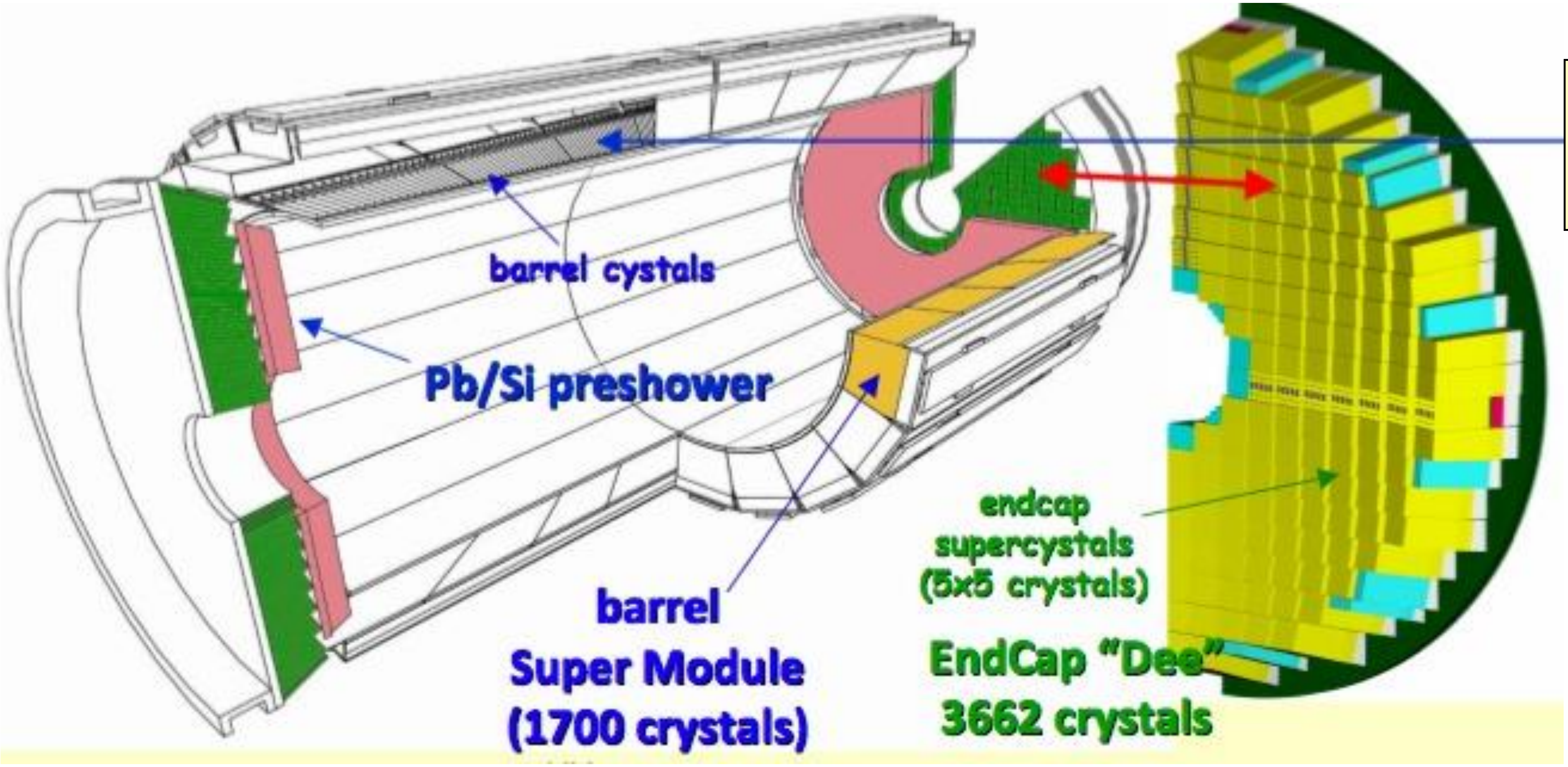
Challenges

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

Electromagnetic calorimeter



Tapered crystals to provide off-pointing of ~ 3^{o} from vertex

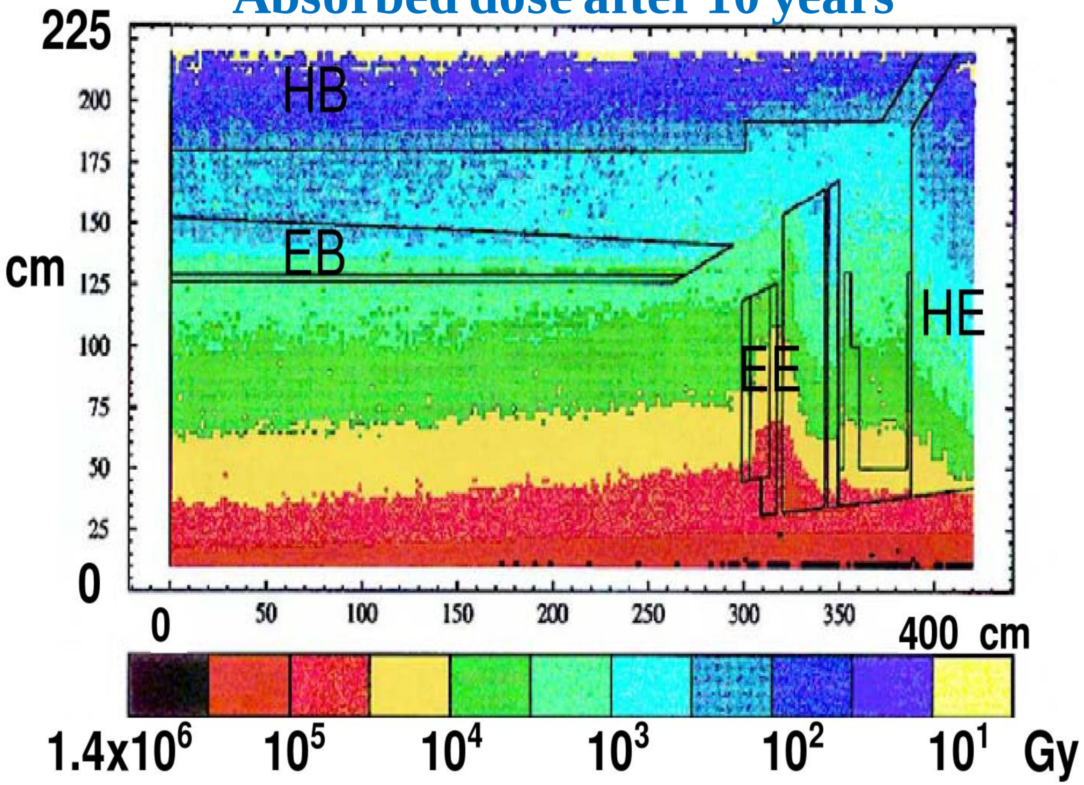
Barrel
36 Supermodules (18 per half barrel)
61200 crystals
Total crystal mass 67.4t
$|\eta| < 1.48$, ~26X_0
$\Delta\eta \times \Delta\varphi = 0.0174 \times 0.0174$

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
$1.65 < |\eta| < 2.6$

Study of radiation damage in $PbW0_4$

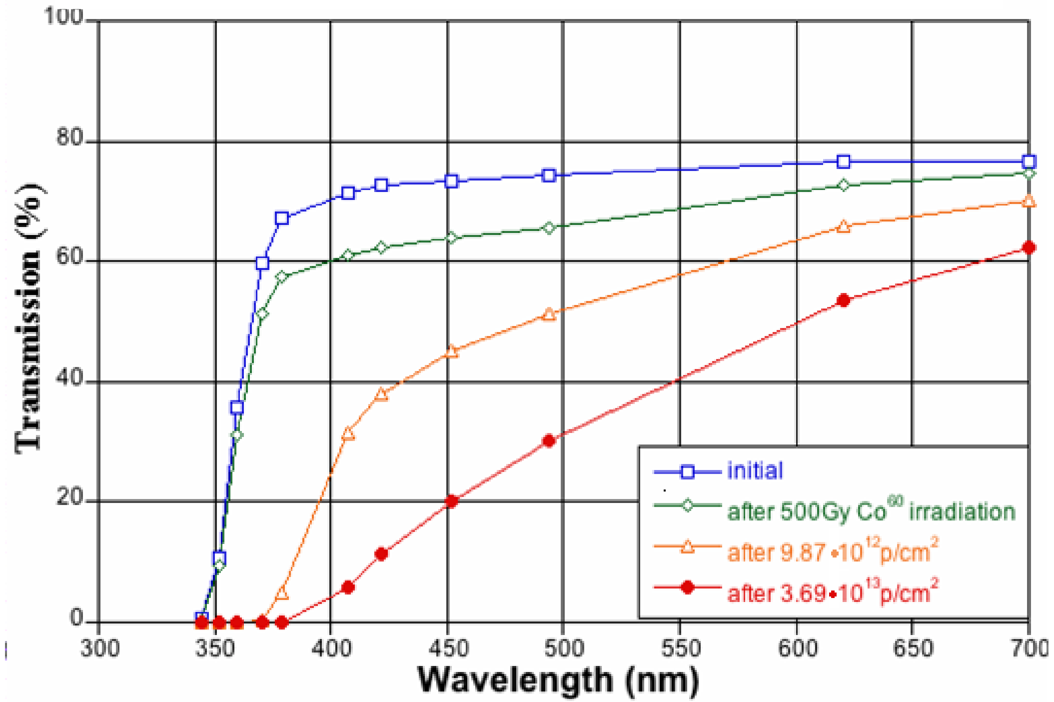
Absorbed dose after 10 years



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

Evolution of transmission due to irradiation



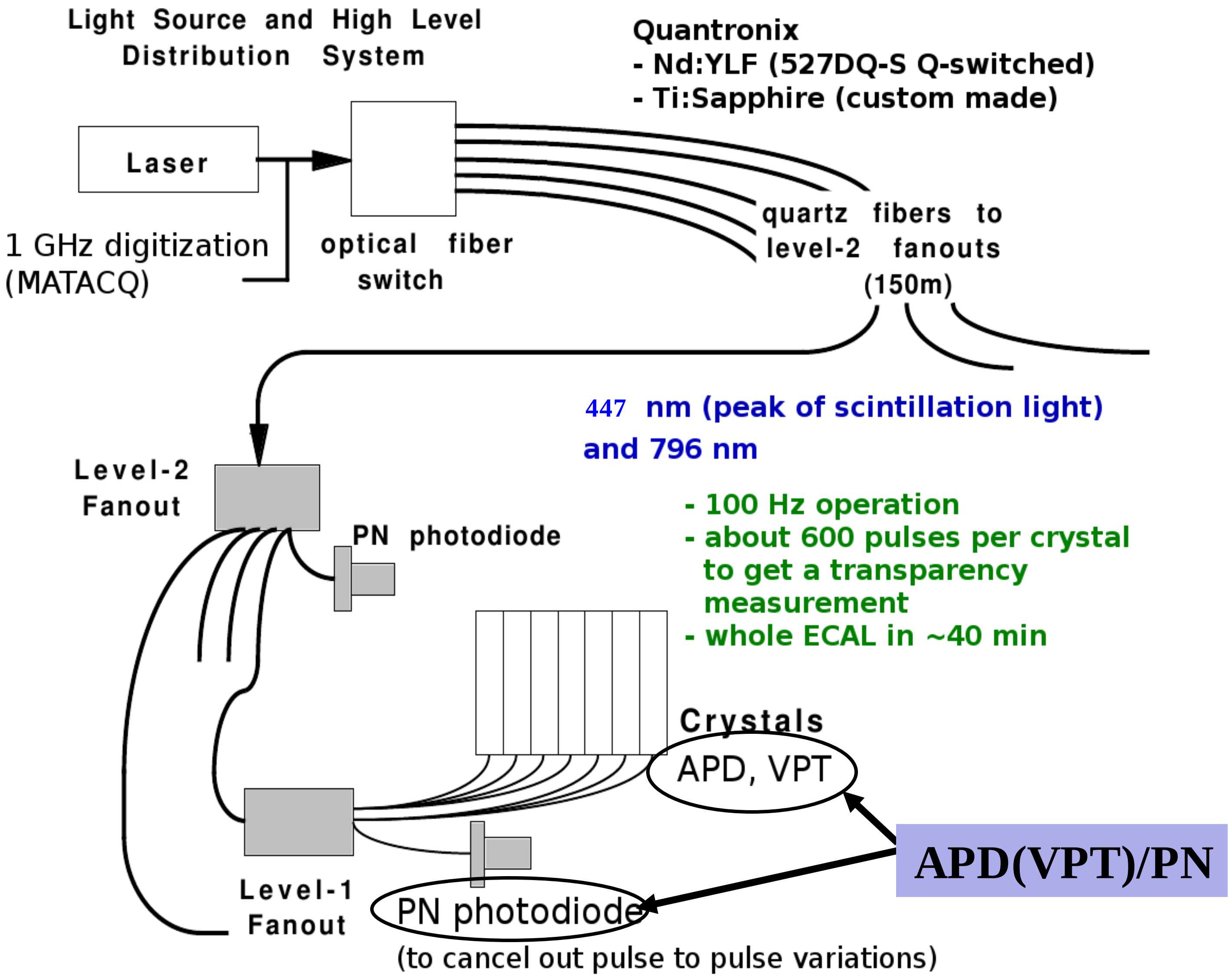
Ionizing radiation damage:

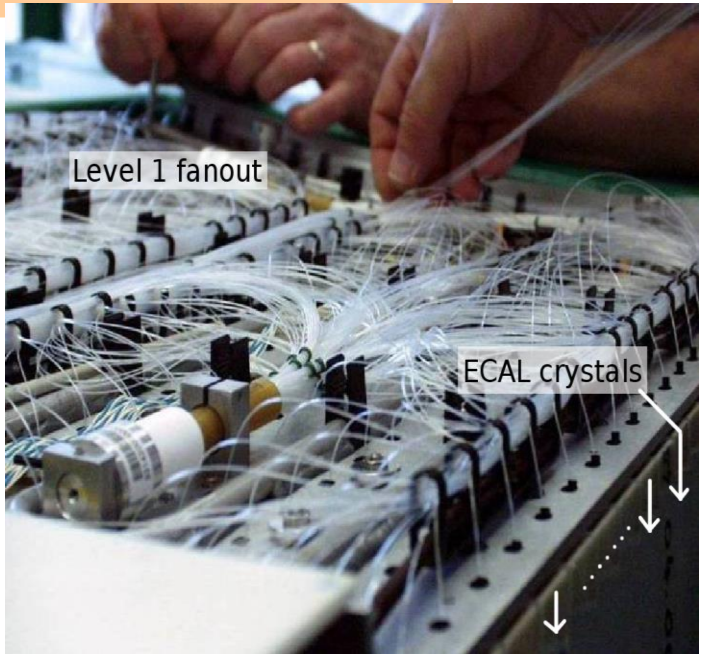
- It recovers at room temperature

Hadron damage:

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

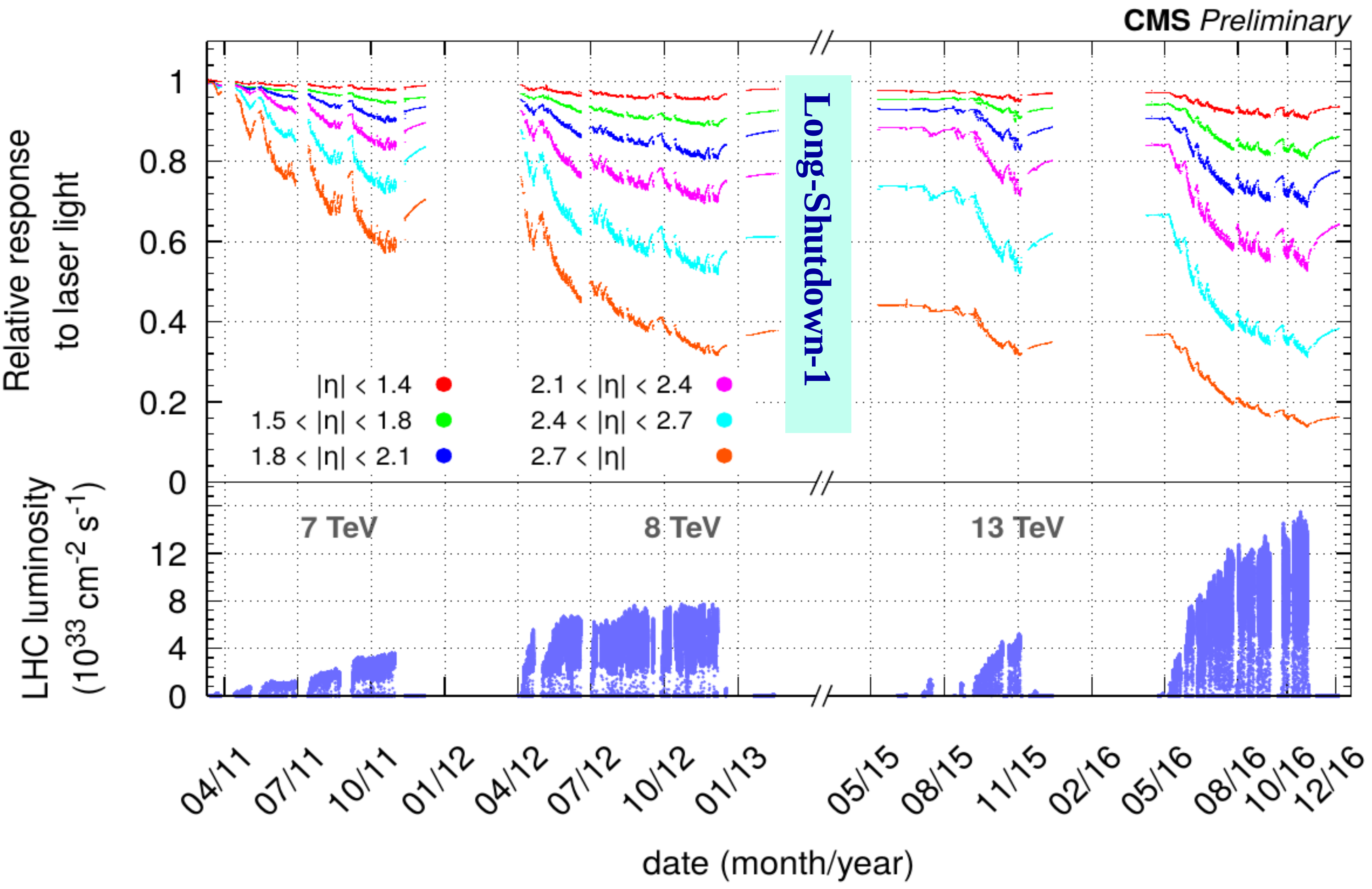
On-Detector Monitoring System





- 3 lasers are used: 447 nm (main laser), green and infra-red:
  - Laser light injection in each crystal every ~ 40 minutes
  - Very stable PN-diodes used as reference system
- ECAL signals compared event by event to PN reference

Evolution of laser data (2011-2016)



Relative response to laser light averaged over all crystals in bins of pseudorapidity (η), for the 2011, 2012, 2015 and 2016 data taking periods, with magnetic field at 3.8 T:

- The response change is **up to 10%** in the barrel and it reaches **up to 50% at η ~ 2.5**. The response change is **up to 90%** in the region closest to the beam pipe.
- The recovery of the crystal response during the Long-Shutdown-1 period is visible, where the response was not fully recovered, particularly in the region closest to the beam pipe.
- These measurements are used to correct the physics data.

Laser Monitoring Dataflow and L1&HLT

Data Flow:

- Laser monitoring data is taken during the LHC “gap” events, 3μs every 90μs
- Gap events are arriving at the Filter Farm, and then analyzed in a PC farm to extract APD/PN values
- The laser APD/PN ratios and other necessary information stored in the offline database

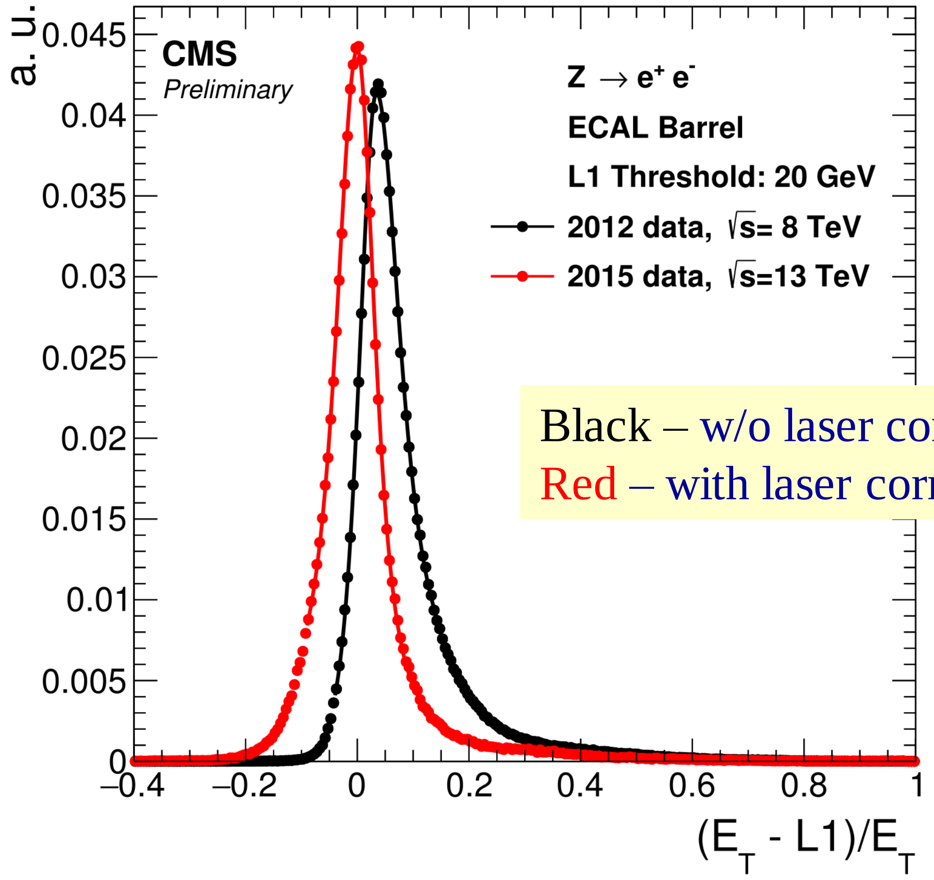
Corrections ready for reconstruction in less than 48 h!

Using transparencies for L1 & HLT:

- Once the data of previous week is in database
  - Averaging over week of transparencies
  - Producing of trigger parameters for L1 and HLT
  - Validation with trigger primitives and energy reconstruction
  - Uploading of L1&HLT trigger parameters
- This procedure is performing once a week
- Because of relatively quick changes of transparencies in Endcap it will be replaced by a quicker and more frequent procedure.

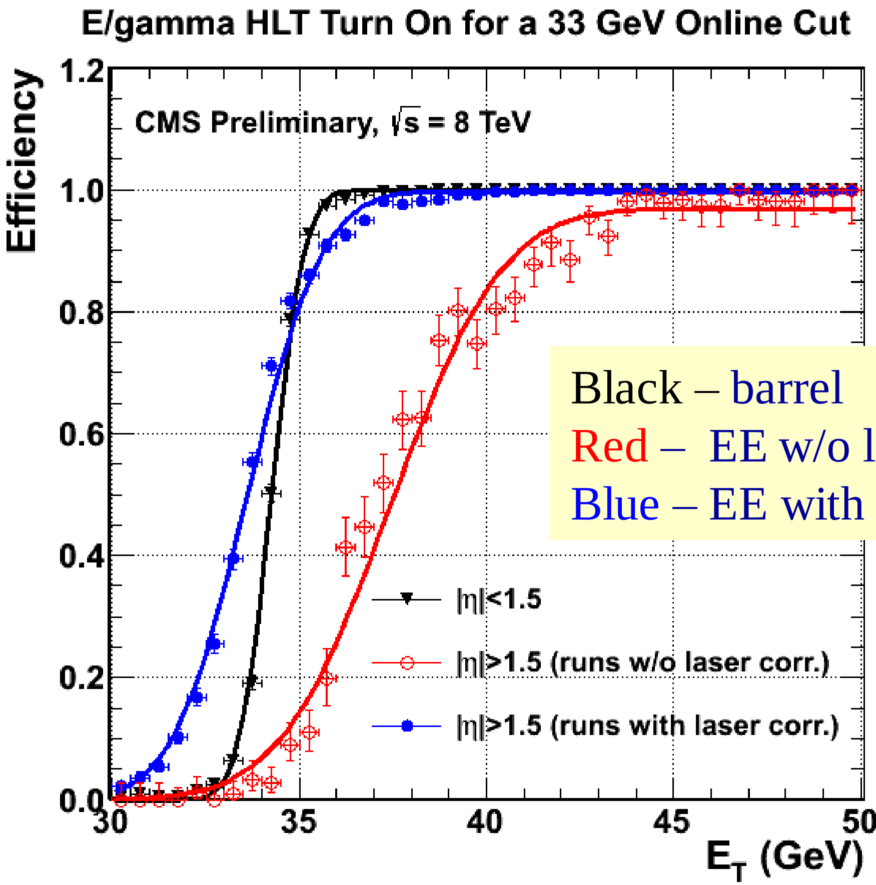
Using Laser Data for L1&HLT

Fractional difference in transverse energy between offline electron and corresponding online L1 candidate



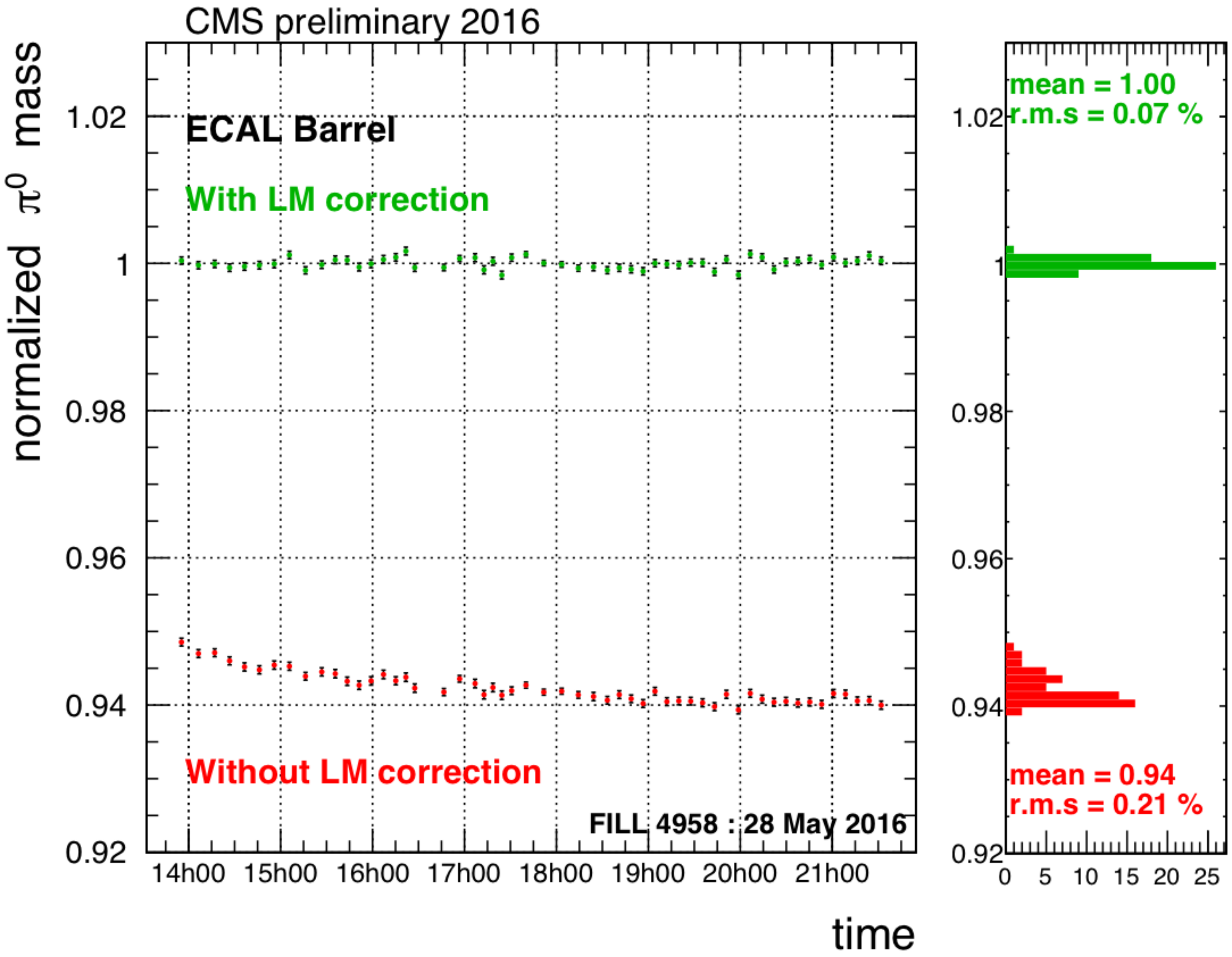
Black – w/o laser corr.
Red – with laser corr.

Trigger efficiency versus electron transverse energy for HLT candidate



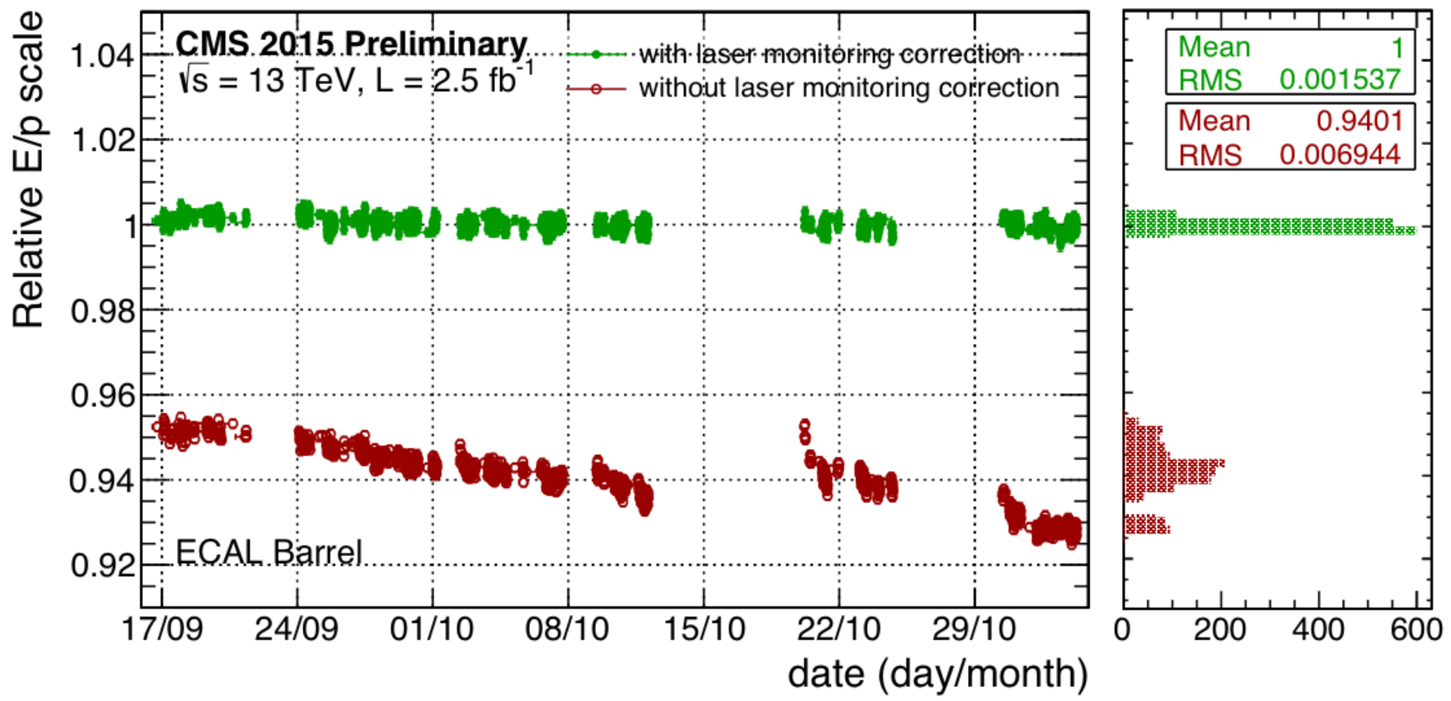
Black – barrel
Red – EE w/o laser corr.
Blue – EE with laser corr.

Laser corrections in π^0 invariant mass



- The plot shows the data with (**green points**) and without (**red points**) light monitoring (LM) corrections applied.
- The energy scale is measured by fitting the invariant mass distribution of two photons in the mass range of the π^0 meson. .
- The right-hand panel shows the projected relative energy scales

Laser corrections and E/p ratio for electrons



The ratio of electron energy E, measured in the ECAL Barrel, to the electron momentum p, measured in the tracker:

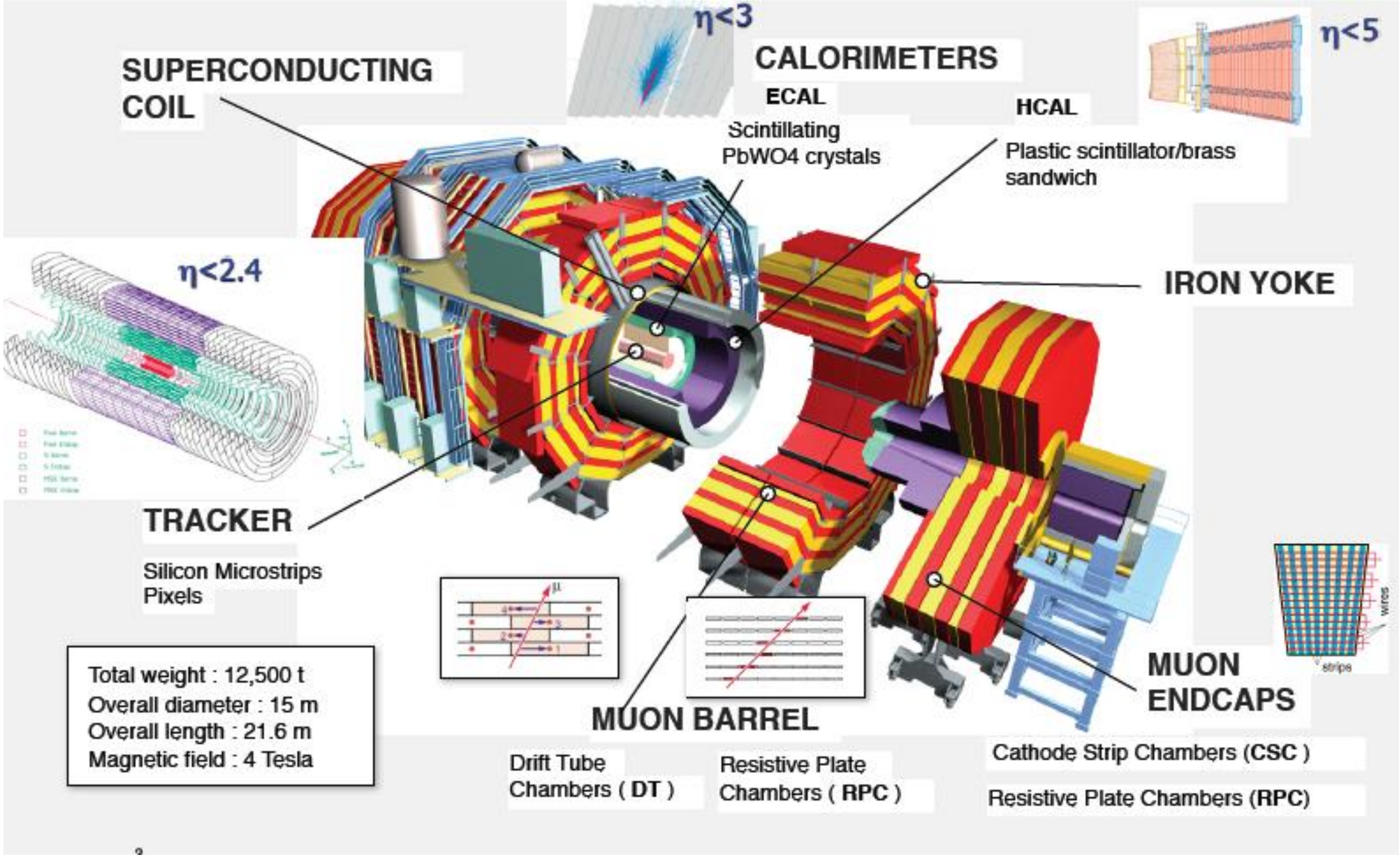
- the history plots are shown before (**red points**) and after (**green points**) corrections to ECAL crystal response variations due to transparency loss are applied;
- the E/p distribution for each point is fitted to a template E/p distribution measured from data
- A stable energy scale is achieved throughout 2015 run after applying laser corrections: ECAL Barrel: average signal loss **~6%**, RMS stability after corrections **0.15%**

Conclusions

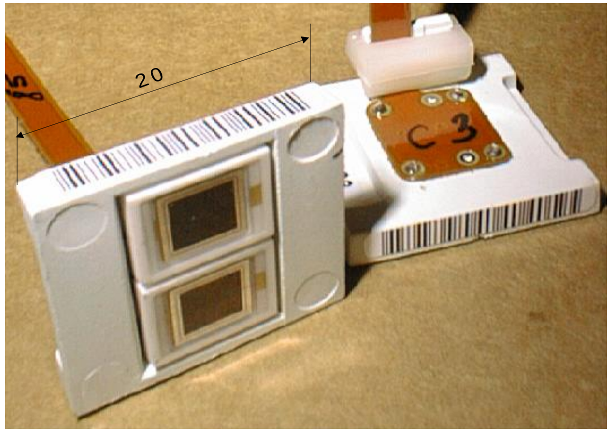
- The CMS electromagnetic calorimeter has efficiently operated during LHC Run I and Run II.
- A multiple wavelength laser monitoring system was used to control the changes in transparency of each crystal with high precision
- This system permitted to have stable calorimeter parameters under LHC radiation conditions
- 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

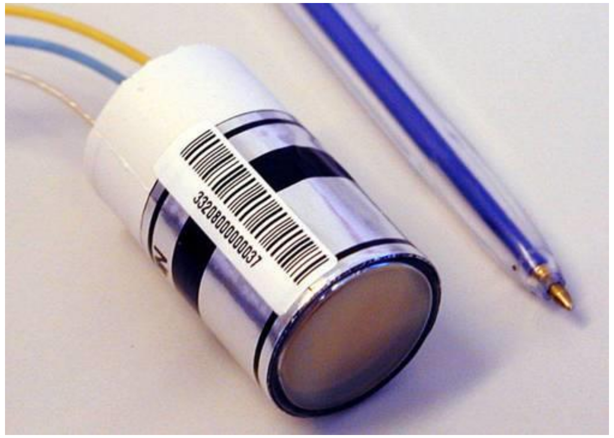
Detector layout



Photodetectors



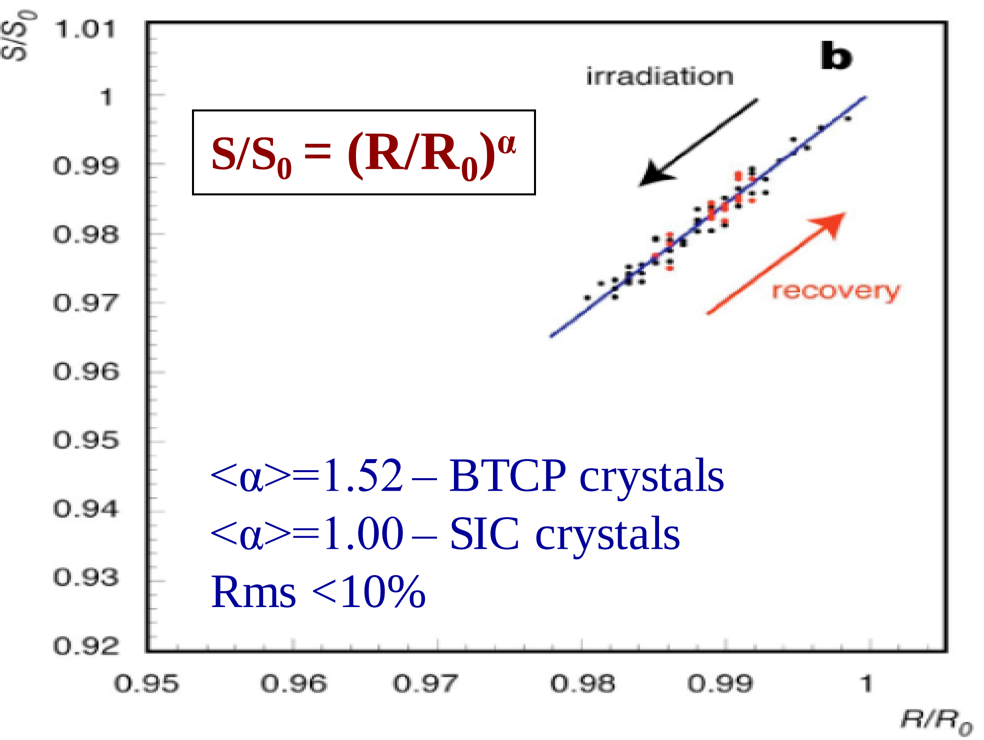
Barrel: Avalanche photo-diodes (APD, Hamamatsu)
Two 5x5 mm^2 APDs/crystal, ~ 4.5 p.e./MeV
Gain 50
QE ~ 75% at 420 nm
Temperature dependence $1/G\ \Delta G/\Delta T = -2.4\%/C$
High-Voltage dependence $1/G\ \Delta G/\Delta V = 3.1\%/V$
Need to stabilize HV at 30 mV
Measured HV fluctuation: ~30 mV



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

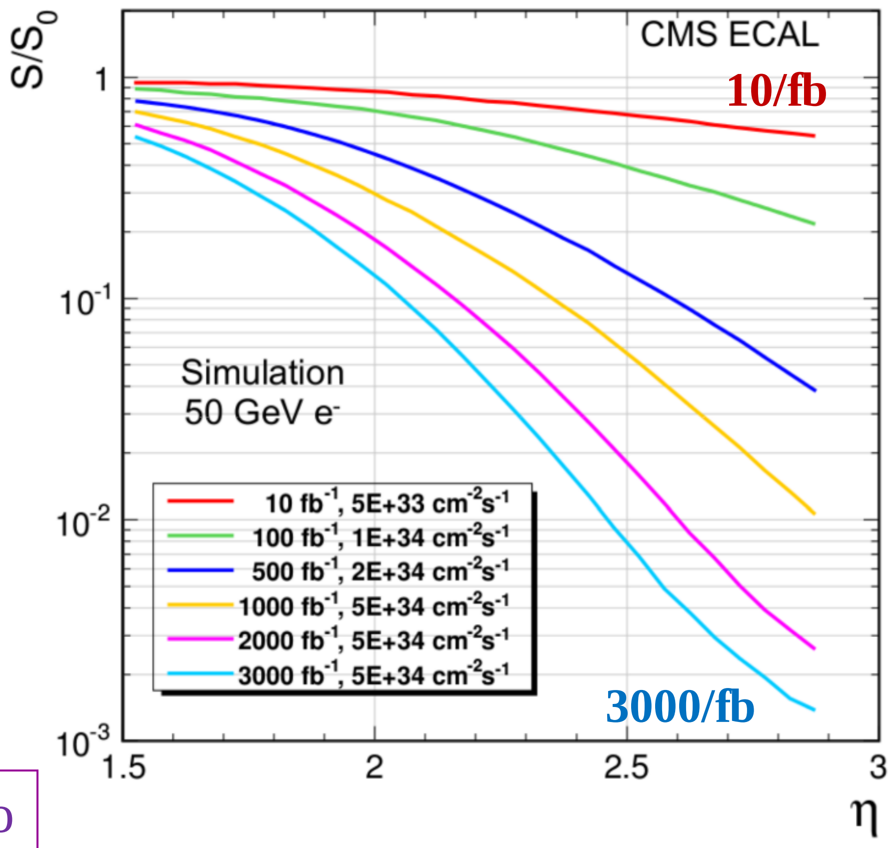
Radiation damage in $PbW0_4$

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



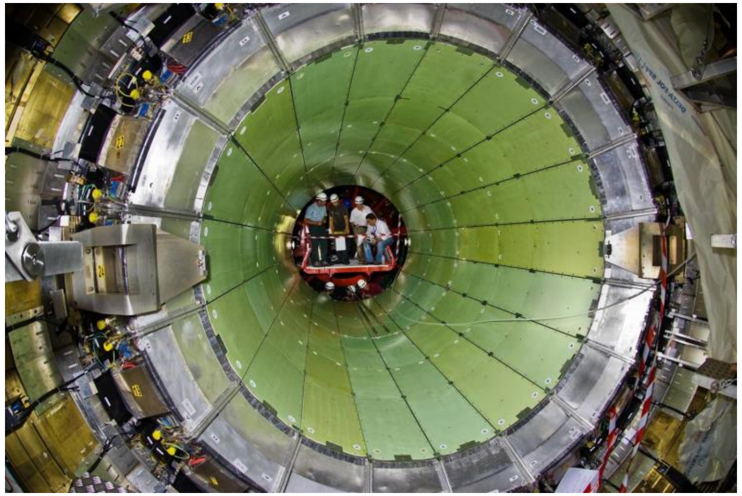
The changes in the crystal transparency due to irradiation impact on the signals from an electromagnetic shower in different way than from laser pulse.

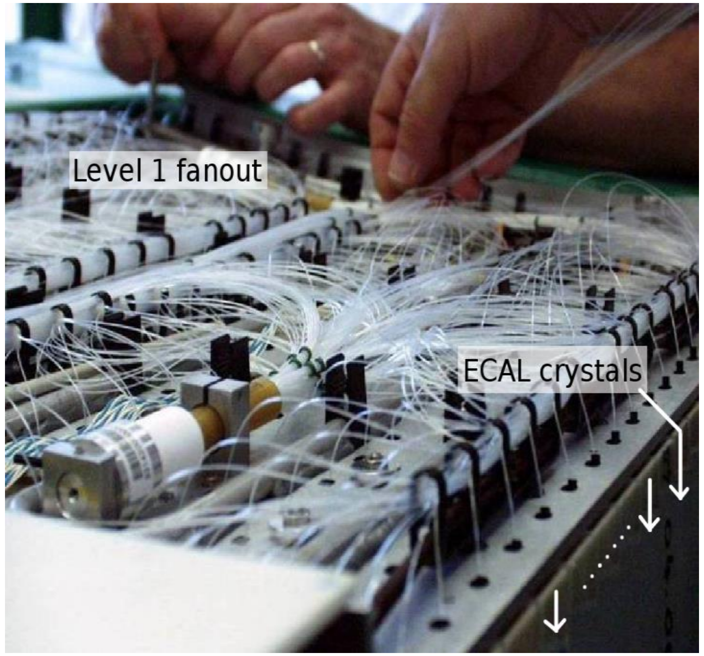
Simulation of changes in EE crystal response



With large transparency losses, energy resolution will degrade :

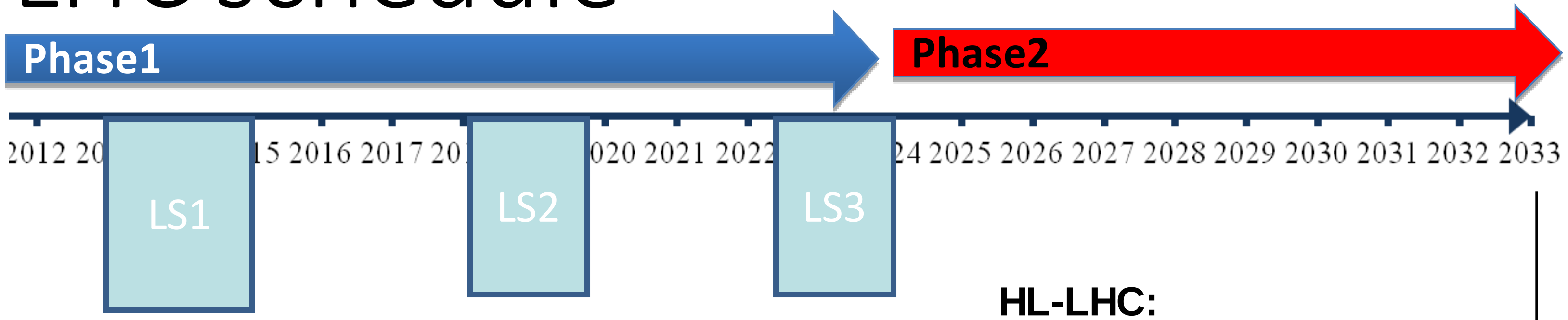
- **photo statistics reduced**
- **relative noise increased**
- **crystal non-uniformity**



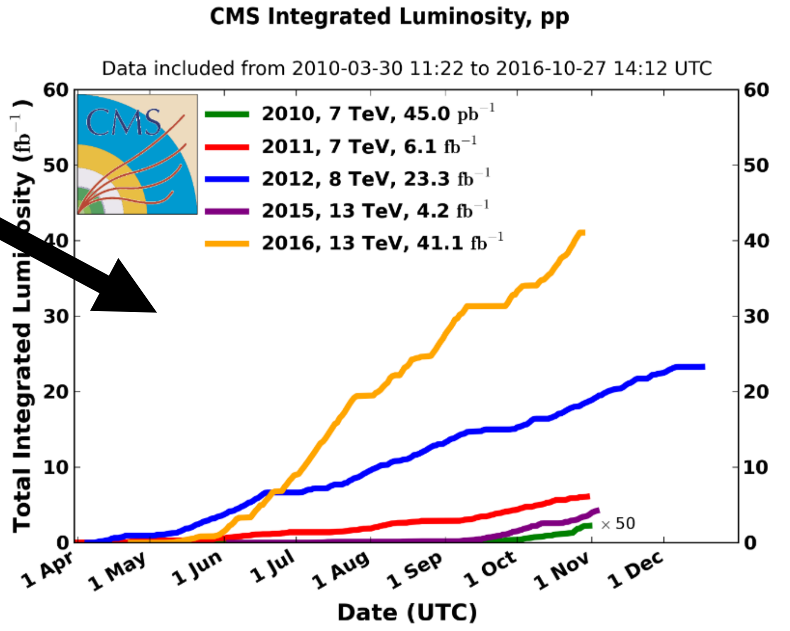

Level 1 fanout
ECAL crystals


CMS
Lab 27
PH-CMA
CERN

LHC schedule



Integrated luminosity (2010-2016)



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

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

~ 300 fb^{-1}

HL-LHC:

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

~ 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.