# CMS ECAL monitoring and its upgrade for High-Luminosity LHC

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CMS

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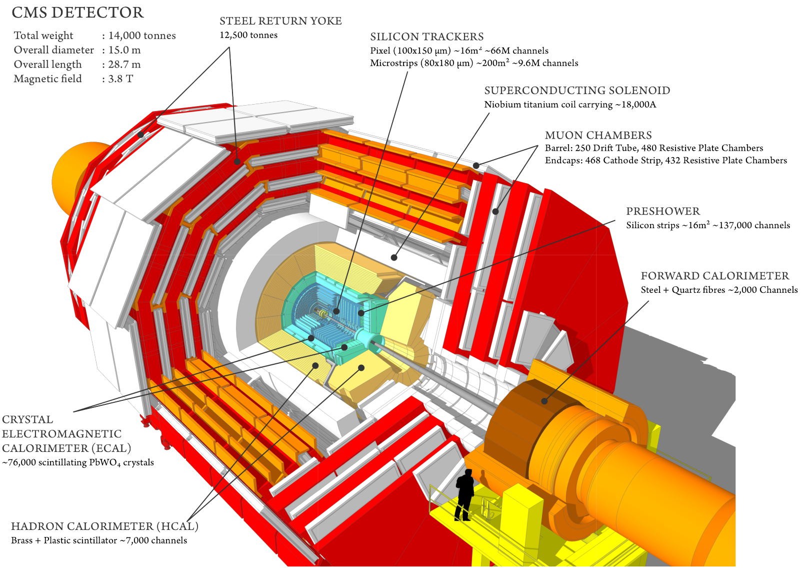
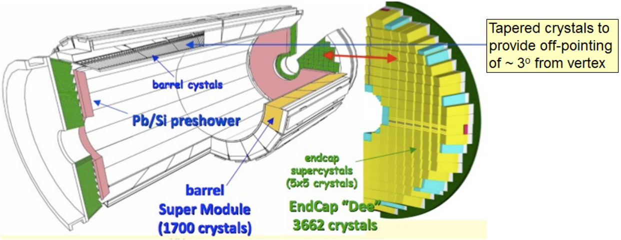
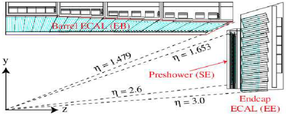
# The CMS Detector




ECAL: the main component of CMS to detect and precisely measure the energies of electrons and photons.
Goal: excellent diphoton mass resolution ($\sim$1%), needed for $H \rightarrow \gamma\gamma$ observation.

# CMS Electromagnetic calorimeter (ECAL)




Two crystal producers: BTCP (Russia) and SIC (China)

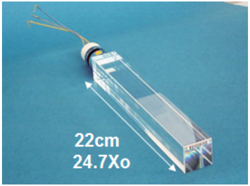
**Barrel:**
36 Supermodules
(18 per half barrel);
61200 crystals;
Total crystal mass 67.4t;
Avalanche PhotoDiode readout;
coverage: $|\eta| < 1.48$, $\sim 26X_0$.

**Endcaps:**
4 Dees (2 per endcap);
14648 crystals;
Total crystal mass 22.9t;
Vacuum PhotoTriode readout;
coverage: $1.48 < |\eta| < 3$, $\sim 25X_0$.

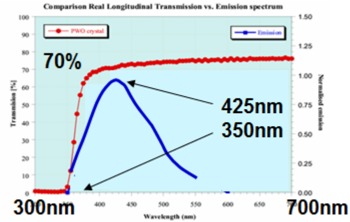
**Endcap Preshower:**
Pb ($2X_0$, $1X_0$)/Si;
4 Dees (2 per endcap);
4300 Si strips;
1.8 mm x 63 mm;
coverage: $1.65 < |\eta| < 2.6$.

# 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:

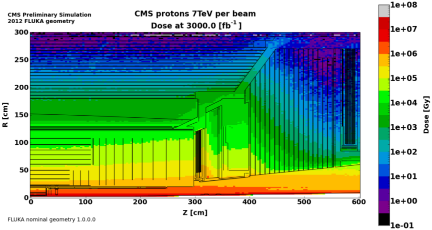
- Homogeneous medium;
- High density 8.28 g/$cm^3$;
- Short radiation length $X_0 = 0.89$ cm;
- Small Moliere radius $R_M = 2.19$ cm;
- Fast light emission ~80% in 25 ns;
- Emission peak 425 nm;
- Reasonable radiation resistance to very high doses.

Challenges:

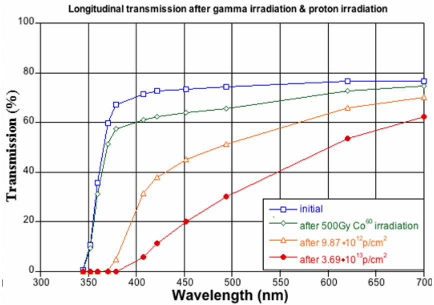
- LY temperature dependence -2.2%/$^o$C;
- Stabilise to $\leqslant 0.1^o$C;
- Irradiation affects crystal transparency;
- Need precise light monitoring system;
- Low light yield (1.3% NaI);
- Need photodetectors with gain in magnetic field.

# Radiation damage in $PbW0_4$

Absorbed dose after 10 years




Evolution of transmission due to irradiation




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

- 0.3 Gy/h in EB;
- 6.5 Gy/h at $\eta$=2.6.

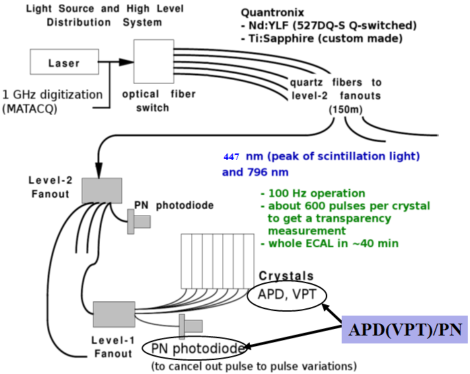
Ionizing radiation damage:

- It recovers at room temperature.

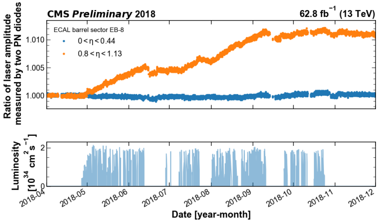
Hadron damage:

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

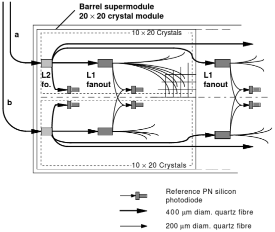
# Monitoring System




## History of PN Diodes laser amplitude measurement in 2018

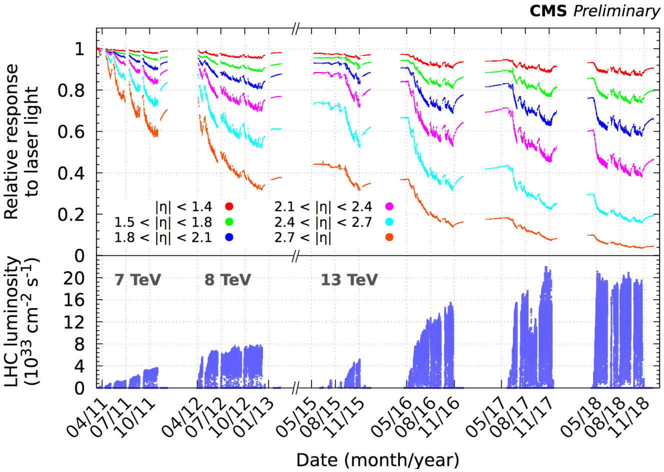



## Redundancy




- 2 lasers are used: 447 nm (main laser) and green;
- 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;
- Redundancy allows to detect faulty PNs (at least one working in each module).

# Evolution of crystal transparency (2011-2018)



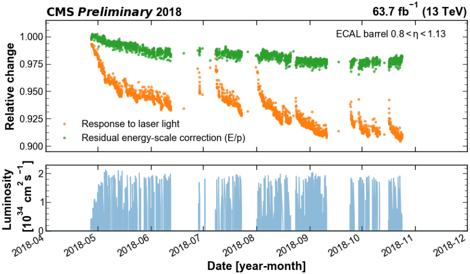

- The response change observed in the ECAL channels is up to 13% in the barrel and it reaches up to 62% at $\eta \sim 2.5$;
- The response change is up to 96% in the region closest to the beam pipe;
- The recovery of the crystal response during the periods without collisions is visible;
- Corrections obtained and applied promptly ($\sim$48 h). Expected precision is 0.2%;
- These measurements are used to correct the physics data.

# Performance of LM system

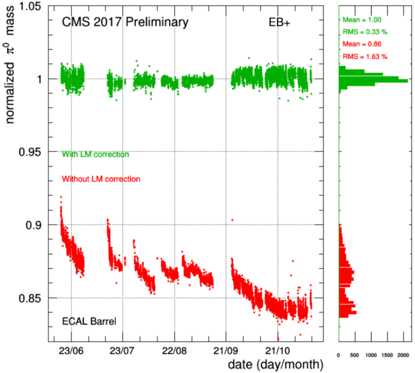
Energy-scale corrections and checks using physics (E/p for W,Z; $\pi^0$ mass)

- Residual corrections after laser ~ few % for a whole year
- No dependence on instantaneous luminosity

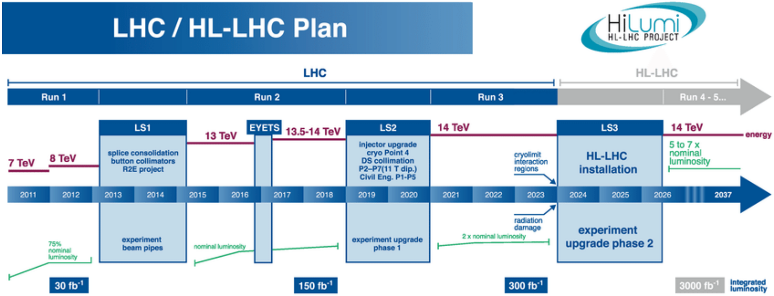
**E/p (2018)**




**Laser corrections in $\pi^0$ invariant mass (2017)**



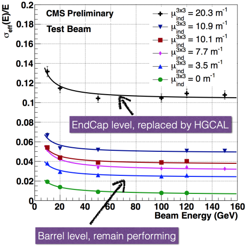
# High-luminosity LHC




- Accelerator upgrade in LS3 to provide **10× larger dataset** for physics focus on new physics searches, Higgs coupling and precision SM measurements:
  - Luminosity – $7.5\times10^{34}$ cm$^{-2}$s$^{-1}$;
  - Peak pileup – 200;
  - Delivered luminosity – 320 fb$^{-1}$ per year;
  - Total integrated luminosity – 3000-4000 fb$^{-1}$ in 2026-2038.
- Luminosity and radiation well beyond detector design

**Phase II upgrade will allow us to maintain energy resolution for measuring electrons and photons at the similar level of current RunII**

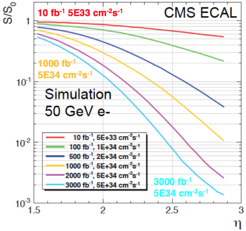
# Planned upgrade of ECAL




**Main effect at HL-LHC due to hadron irradiation**

$$\frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

- Radiation damage affects all three terms:
  - Stochastic: crystal light yielding components
  - Noise: amplified by the light output loss
  - Constant: non-uniformity of the light collection
- ECAL barrel crystals expected to loose $< 50\%$ of transparency
  - APDs continue to perform well but will have increased noise
  - Upgrade of electronics for the trigger and precise e/$\gamma$
- Endcap calorimeters replaced by HGCal (mostly Si)




**Phase-II Upgrade:**
**EB upgrade + EE complete replacement**

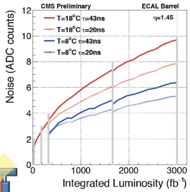
**Known and possible problems of ECAL LM system:**

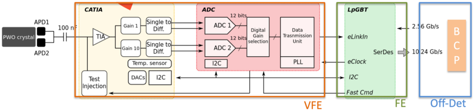
- PN diodes tested at $5\times10^{13}$ n/cm$^2$, 2 kGy ($\sim$ 500 fb$^{-1}$)
  - Only 0.7% Q.E. loss but few already show strange behaviour
    - Increase redundancy of PN diodes ($\times$2)
- Fibers darkening with radiation
  - Essential to keep the injected light measurement inside the detector (PN diodes)
- Electronics not compatible with readout scheme for HL-LHC

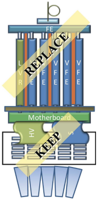
# ECAL Electronics Upgrade

Everything before motherboard remain unchanged

- **APD:** colder operation (from 18$^o$C to 8$^o$C)
- **VFE:** optimize shaping and sampling, improve timing
  - reduce impact of noise, PU, spikes
- **FE:** read data from all crystals
  - increase trigger latency and reject spikes
  - ECAL granularity available at L1 trigger (improved by x25)




**New VFE is designed with 30 ps precision for high energy signals**

VFE serves 5 crystals

- Analog ASIC: CATIA
  - 35 MHz trans-impedance amplifier
- Digital ASIC: LiTE-DTU
  - 12-bit, 160 MHz ADC, Data Transmission Unit

FE serves 5 VFEs

- fast optical links using lpGBT
- clock distribution

Low Voltage Regulator (LVR)

- rad-hard cards based on the FEAST DC-DC converter

Barrel Calorimeter Processor (BCP)

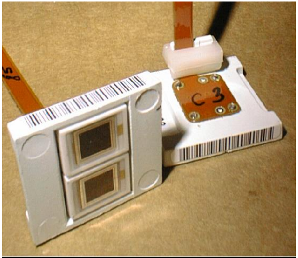
- FPGA-based
- L1 primitive formation and readout cards
- pulse reconstruction
- spike rejection
- receive and distribute LHC clock to FE

# Summary

- The CMS electromagnetic calorimeter has efficiently operated during LHC Run I and Run II;
- 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;
- Planned upgrade for high-luminosity LHC to ensure good performance for another 10-15 years.

BACKUP

# ECAL photodetectors




Hamamatsu S1848 APDs

**Barrel: Avalanche PhotoDiodes (APD)**

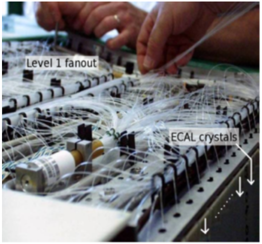
Two $5\times5$ mm 2 APDs/crystal, $\sim$4.5 p.e./MeV
Gain 50
QE $\sim$75% at 420 nm
Temperature dependence $1/G\ \triangle G/\triangle T$ = -2.4%/C
High-Voltage dependence $1/G\ \triangle G/\triangle V$ = 3.1%/V
Need to stabilize HV at 30 mV
Measured HV fluctuation: $\sim$30 mV

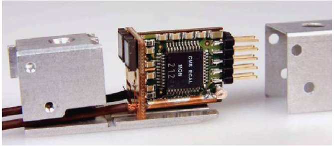
NRIE (St. Petersburg) PMT188 VPT

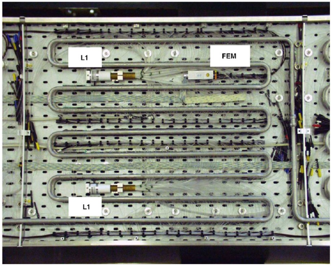
**Endcaps: Vacuum photo-triodes (VPT, Research Institute "Electron Russia)**

More radiation resistant than Si diodes
UV glass window
Active area $\sim$280 mm$^2$/crystal, $\sim$4.5 p.e./MeV
Gain 8-10 (B=4 T)
Q.E. $\sim$20% at 420 nm
Gain spread among VPTs $\sim$25%
Need intercalibration

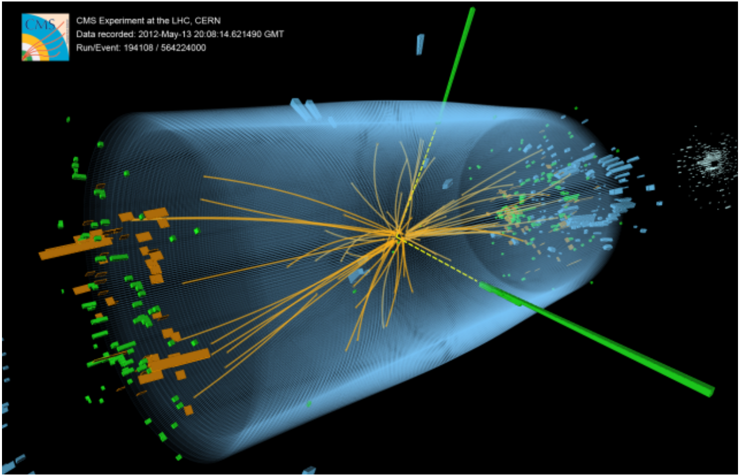
# Monitoring System



# Measuring deposited energy




Candidate $H \to \gamma\gamma$ event