Role of the CMS electromagnetic calorimeter in the measurement of Higgs boson properties at LHC Run 2 and projections for the HL-LHC with the CMS Phase-2 detector

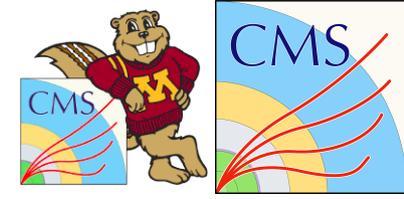## Neil Schroeder
University of Minnesota

On behalf of the CMS collaboration

DPF 2019:
2019 Meeting of the Division of Particles & Fields of the American Physical Society
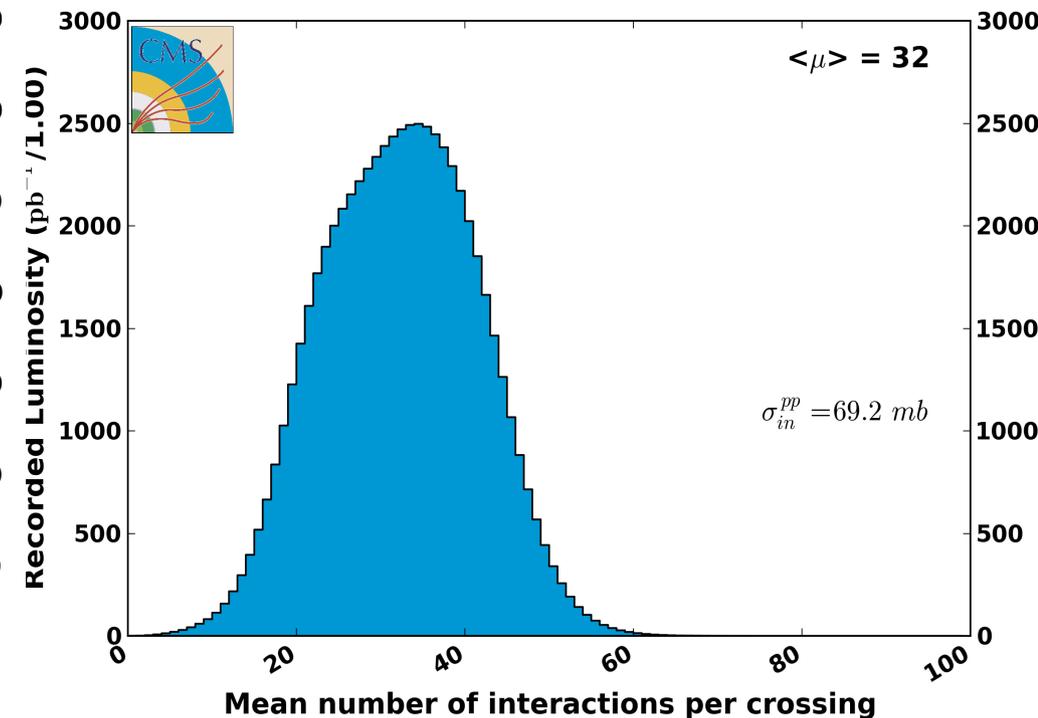
29 July – 02 August, 2019

Introduction to CMS

- **General Purpose Experiment at the LHC**
  - **40 MHz bunch crossings (BX) rate (1 per 25 ns)**
- **Many interactions per BX (10^{11} protons per bunch) called pileup (PU)**
  - Average PU in Run 2 ≈ 30
  - There is some overlap of PU between BXs (out-of-time PU)

CMS Integrated Luminosity, pp, 2018, $\sqrt{s} = 13$ TeV

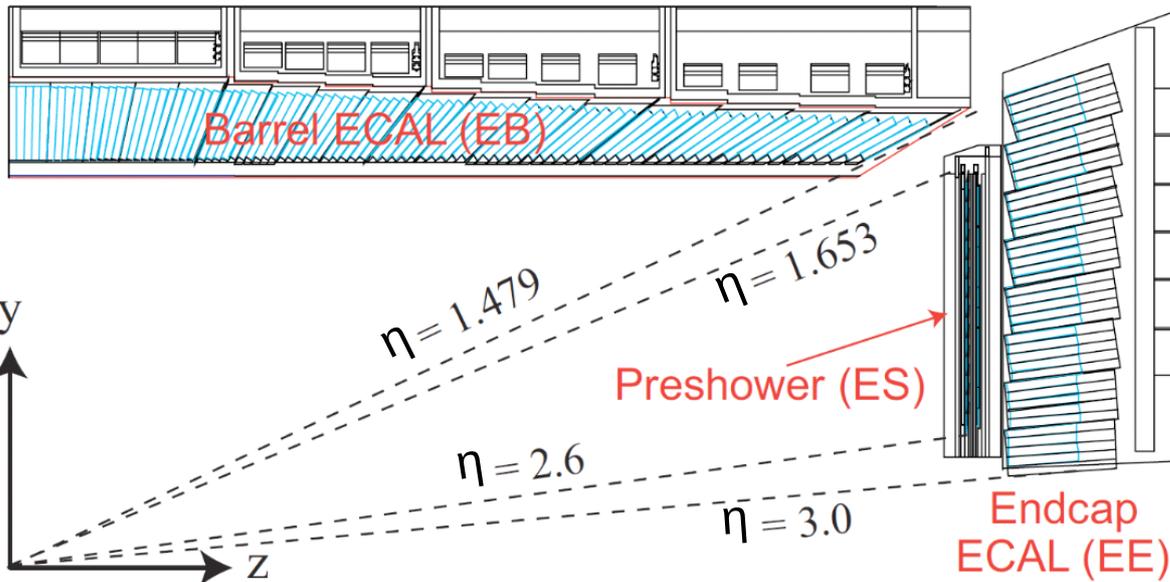Data included from 2018-04-17 10:54 to 2018-10-26 08:23 UTC

LHC Delivered: 67.86 fb^{-1}
CMS Recorded: 63.67 fb^{-1}

CMS Preliminary
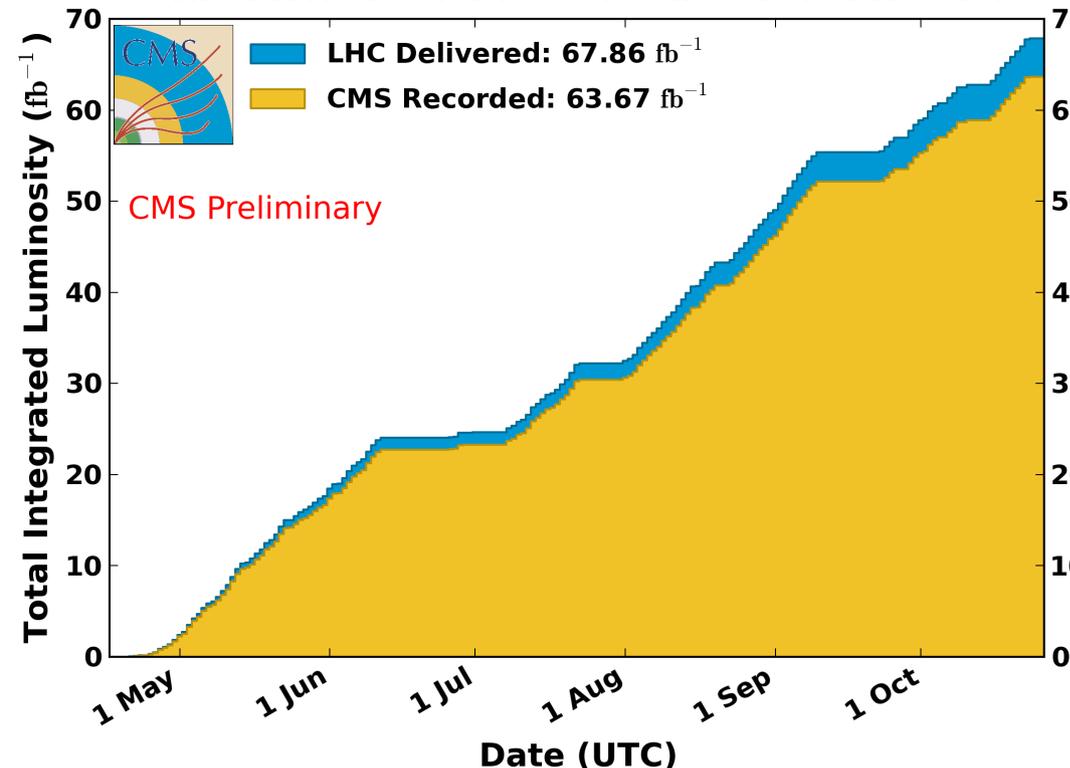
CMS Average Pileup, pp, 2018, $\sqrt{s} = 13$ TeV

$<\mu> = 32$

$\sigma_{in}^{pp} = 69.2\ mb$

CMS ECAL Overview

Homogeneous, highly granular, hermetic PbWO$_4$ crystal calorimeter

- Short radiation length (0.89 cm)
- Small Moliere radius (2.2cm)
- Fast decay time (25 ns)

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

Barrel (EB):
- **|η| < 1.48**
- 61,200 crystals
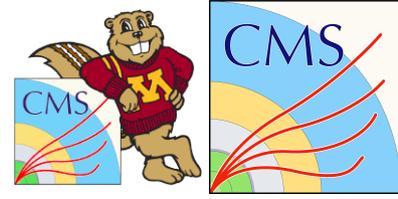- 26 radiation lengths
- Avalanche photodiode (APD) readout

Endcap (EE):
- **1.48 < |η| < 3.0**
- 14,684 crystals
- 25 radiation lengths
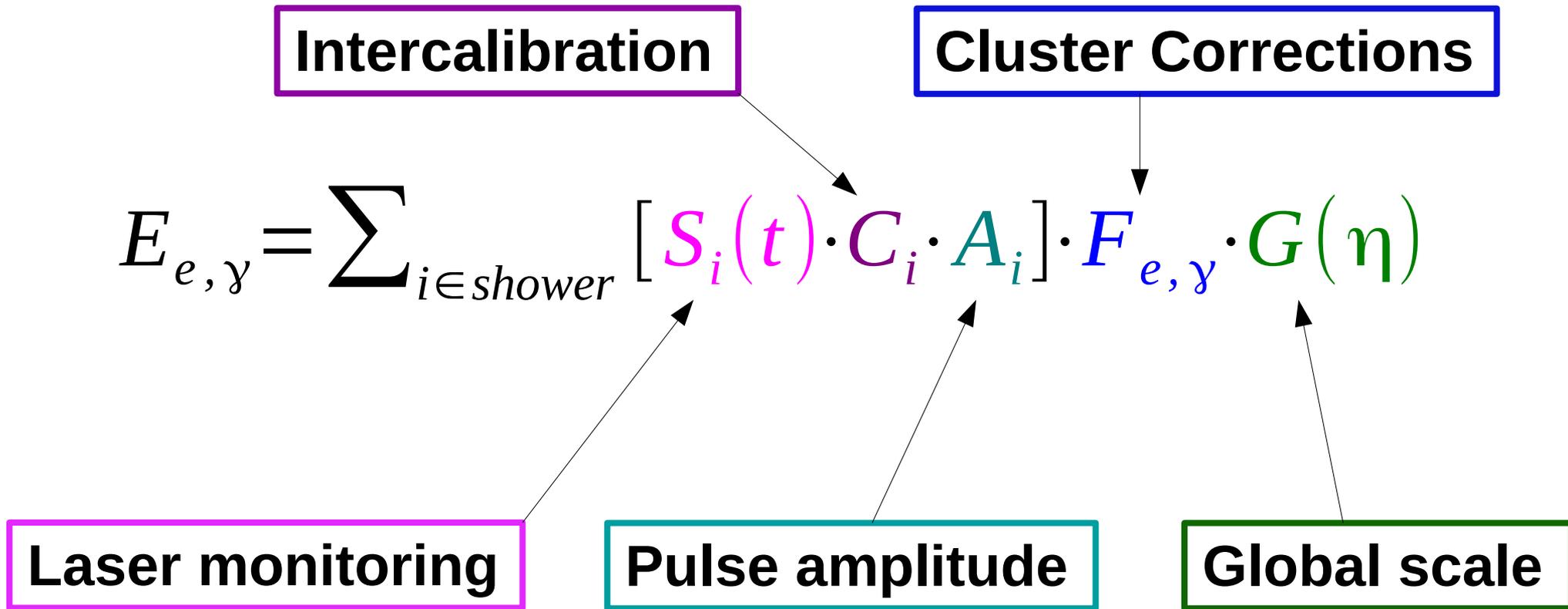- Vacuum photo-triode (VPT) readout

Preshower (ES):
- **1.65 < |η| < 2.6**
- 4 Dees of 2 Pb/Si planes

e/γ Energy Reconstruction

Energy is measured using all crystals in a shower
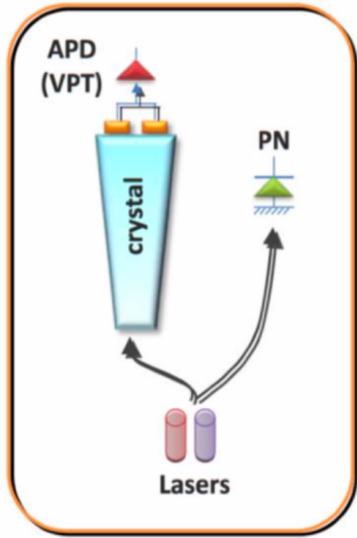
Intercalibration

Cluster Corrections

$$E_{e,\gamma} = \sum_{i\in shower} [S_i(t) \cdot C_i \cdot A_i] \cdot F_{e,\gamma} \cdot G(\eta)$$

Laser monitoring

Pulse amplitude

Global scale
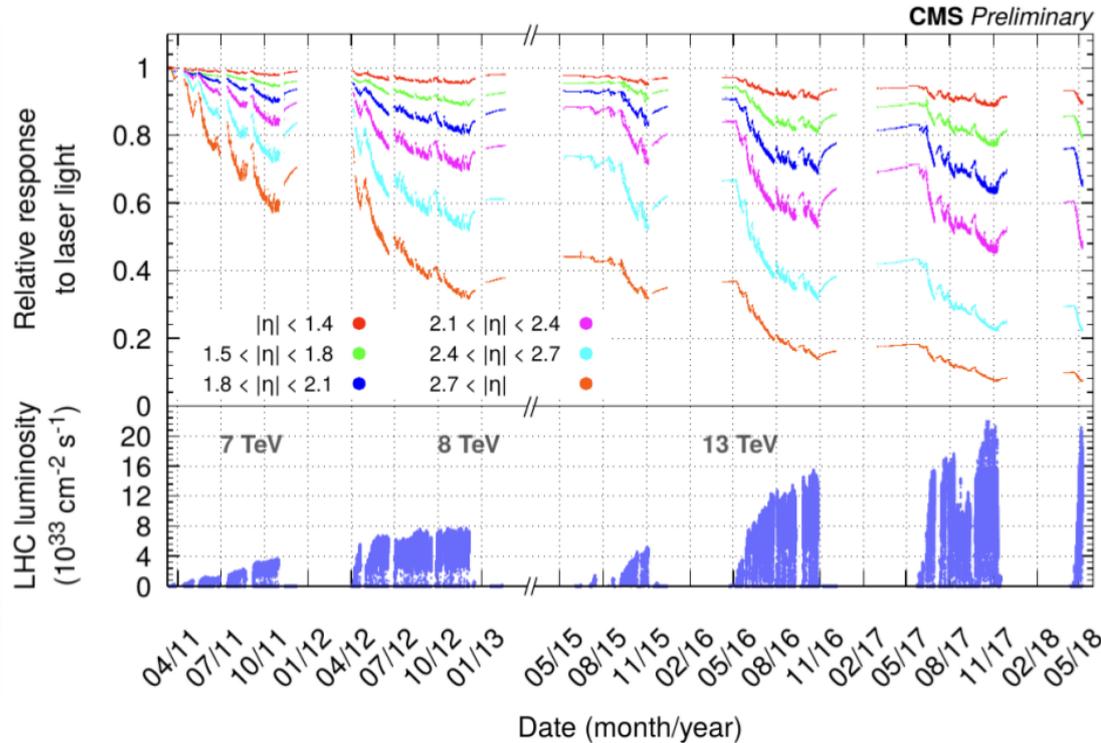
Laser Corrections

$$\frac{S(t)}{S_0} = \left(\frac{R(t)}{R_0} \right)^{\alpha}$$

- **Irradiated PbWO$_4$ crystals lose transparency**

  – Recoverable loss (EM)

  – Non-recoverable (Hadronic)

- The transparency of the crystals is monitored with a dedicated laser based monitoring system

- S(t)/S$_0$ = correction for e/γ scintillation

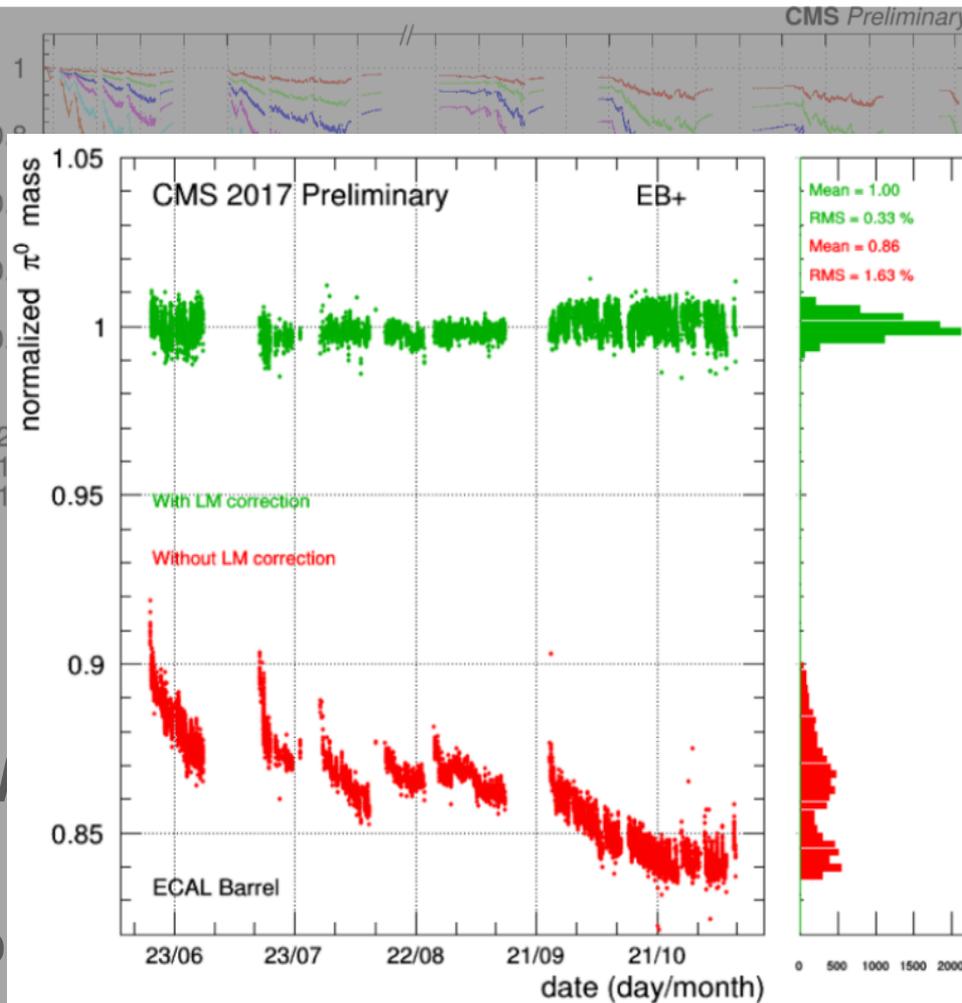- R(t)/R$_0$ = response to injected laser

- α = power law factor ~0.6 - ~1.2

Laser Corrections
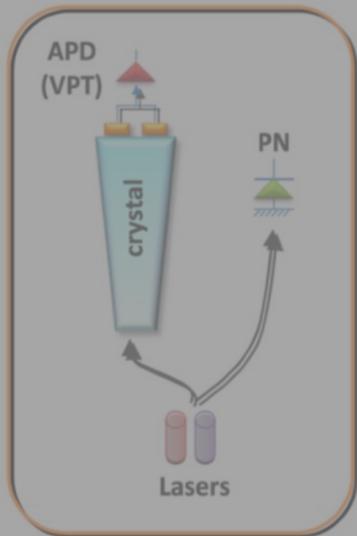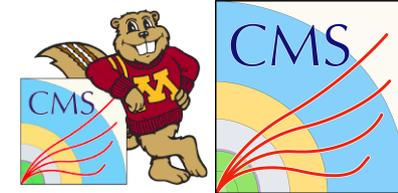
Mass stability of π^0 vs time during 2017 after applying the laser monitoring corrections
Peak RMS ~ 0.3%

$$\frac{S(t)}{S_0} = \left(\frac{R(t)}{R_0} \right)^{\alpha}$$

- **Irradiated PbW** ... **transparency** ... rection for e/γ
  - Recoverable lo ... sponse to injected
  - Non-recoverable

- The transparency ... er law factor ~0.6 - monitored with a ... based monitoring system
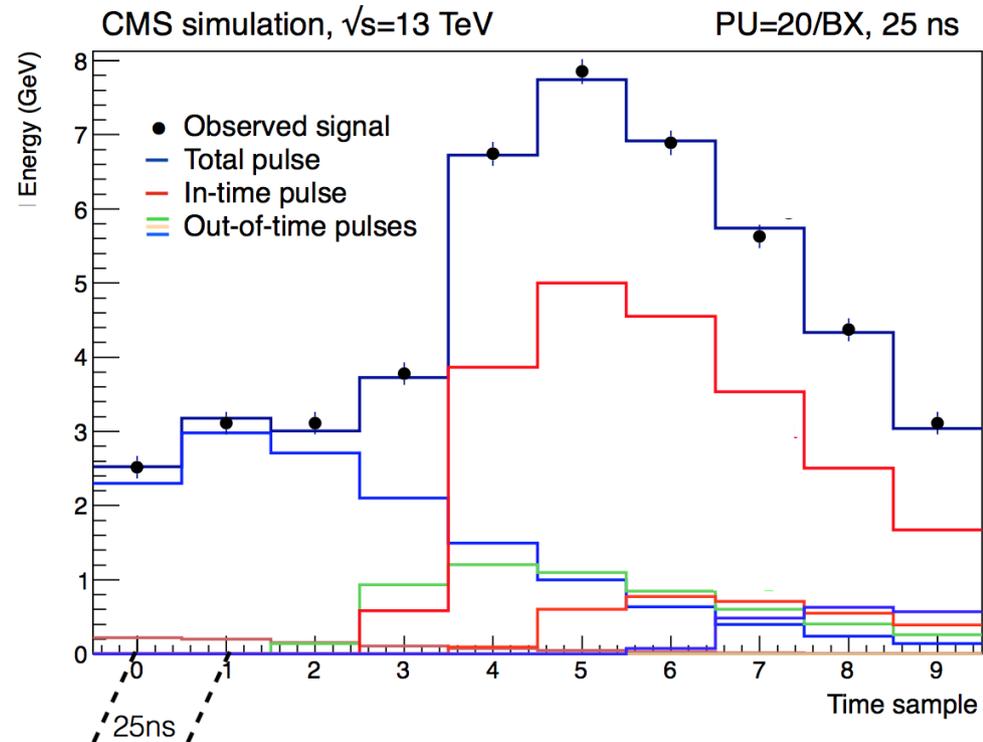
Inter-calibration (IC)

- Equalizes channel-to-channel responses using:

  - **Φ-symmetry**: for a large sample of events, the total deposited transverse energy in a given η-ring should be the same in every crystal

  - **π⁰→γγ peak**: reconstructed peak in this decay is used to iteratively correct the IC for each channel

  - **Z→ee peak**: Z peak is reconstructed from electron pairs by fitting to a Breit-Wigner and Gaussian. A maximum likelihood algorithm calculates the ICs.

  - E_{ECAL}/p_{Tkr} : the ratio of ECAL energy and tracker momentum for high energy electrons from Z and W decays is required to fit a data-based template (1 on average)
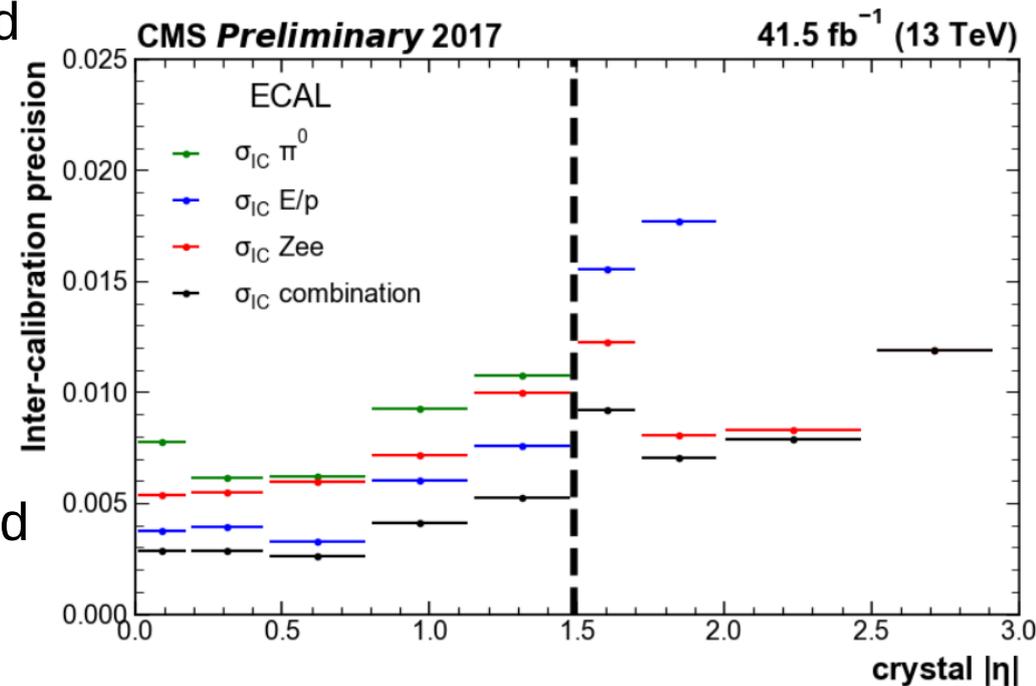
Signal Extraction + Pulse Reconstruction

- **Signal from APDs is digitized in 10 samples of 25 ns**

- **Parameterized pulse templates are used to extract the in-time signal**

  - Reject Out-of-time pile-up (OOT PU)

- **Most parameters used in signal extraction are time dependent**

  - ECAL Pulse Shape

  - Crystals transparency (laser monitoring system)

  - Baseline for signal (pedestal monitoring)

CMS simulation, √s=13 TeV   PU=20/BX, 25 ns

- Observed signal
- Total pulse
- In-time pulse
- Out-of-time pulses

Energy (GeV)

Time sample

25ns

Pulse Shape and Pedestal Monitoring

- **Time dependence of average pulse time during 2017 data taking**

  – Drift of ~ 0.8 ns due to ageing

- **Pulse shape templates are measured frequently to monitor their time dependence**
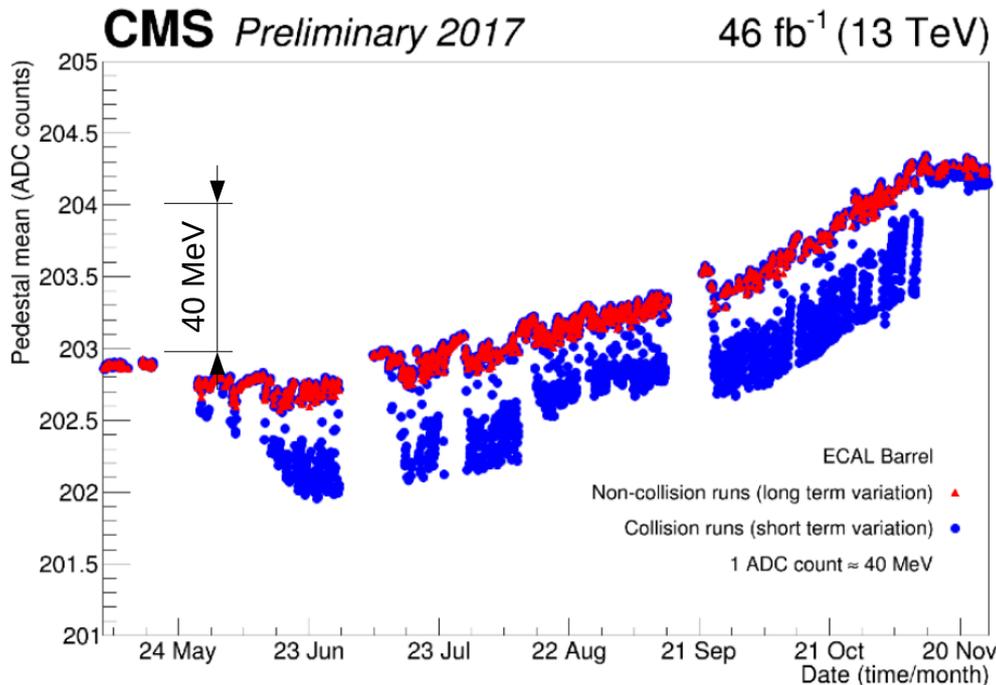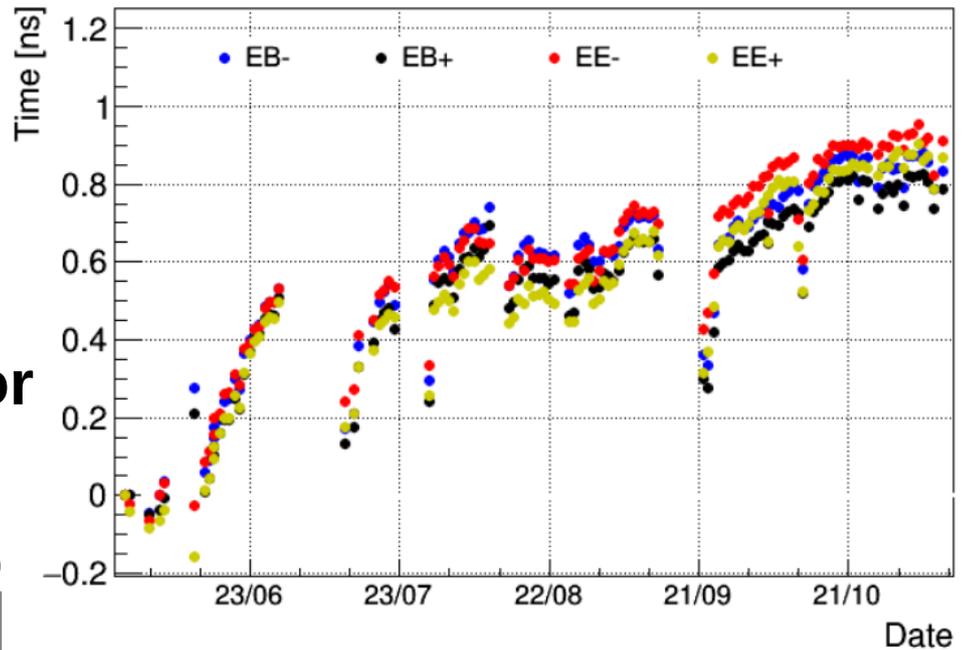

- **Pedestals measured during data-taking drift over time**

  – **Long term drift:** aging effects

 – **Short term drift:** effects from instantaneous luminosity

e/γ Clustering

EM showers in the ECAL are spread over many crystals

- This spread can be further separated by bremsstrahlung, and photon pair conversions

- **e/γ clustered using the same algorithm**

  - Basic clusters merged into "superclusters"

  - Accounts for electron B-field in η and φ (necessary for low energy clusters)

- Dedicated Gaussian-Sum Filter (GSF) tracking algorithm for electrons

- SC's are refined by merging clusters compatible with bremsstrahlung photons
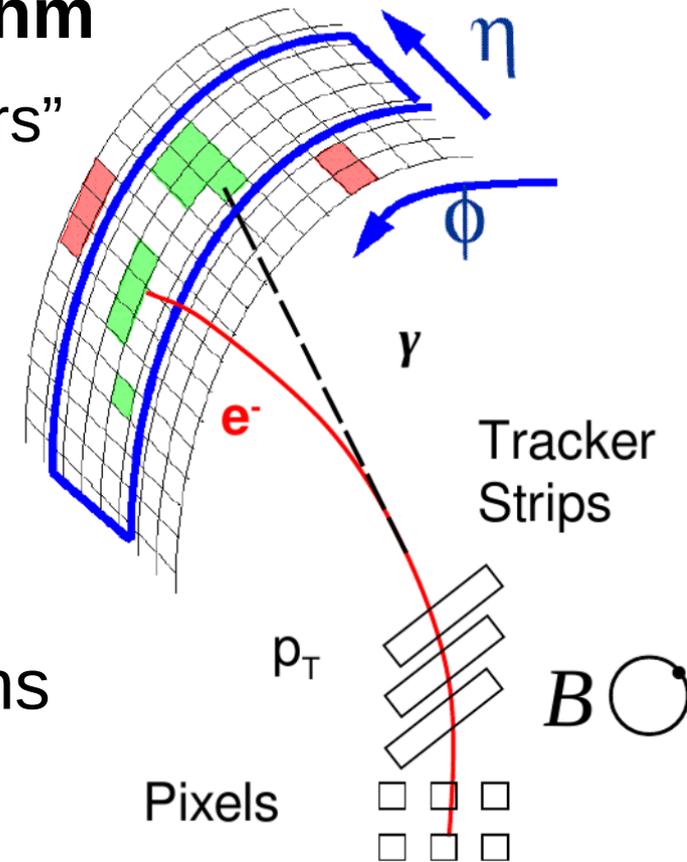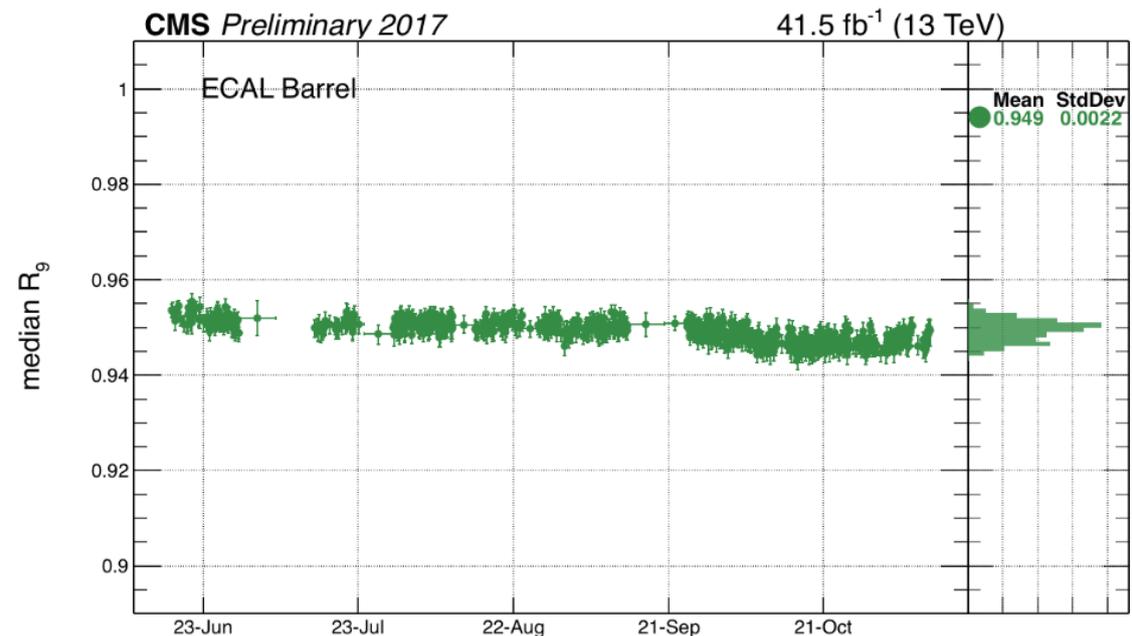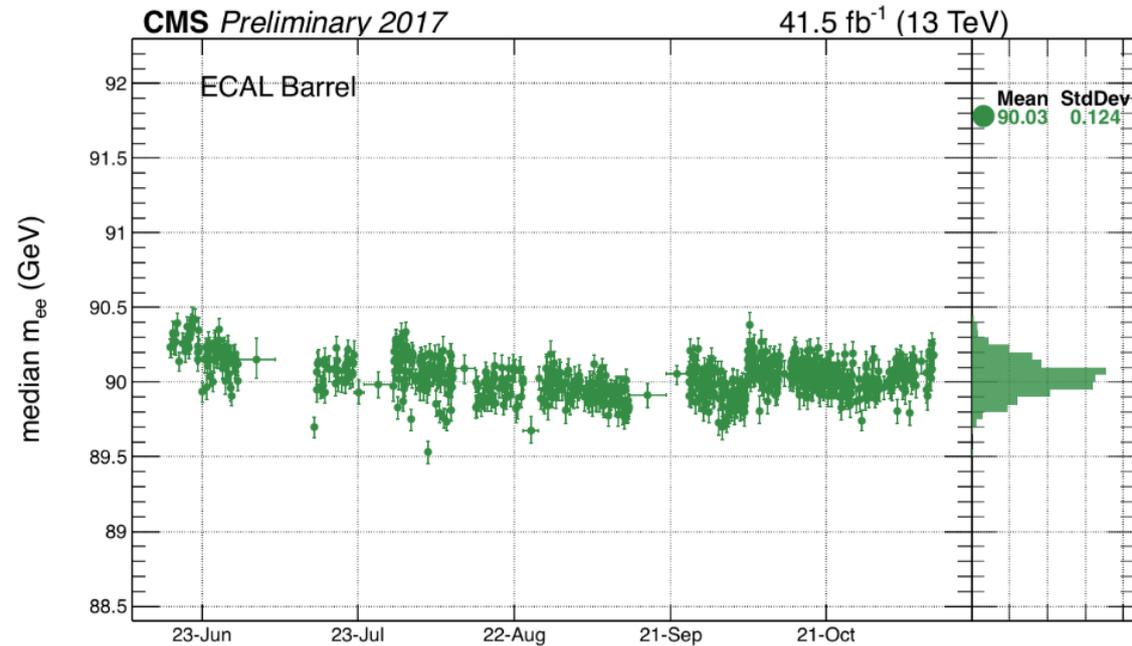
ECAL Performance in Run 2, 2017
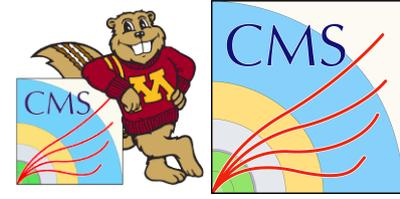
The ECAL response is found to be stable over the 2017 data taking period after the latest calibration campaign

- The **Z → ee invariant mass has a relative spread < 0.2%** over this period

- The shower shape variable **R_9 (E_{3x3}/E_{SC}) has a relative spread < 0.25% over Run2, 2017**
  - This is a variable crucial to photon and electron identification

Performance in Run 2

- The resolution of data in the CMS ECAL before after corrections

- Much improvement is shown in the endcaps (η > 1.57).

- **The entire Run 2 dataset (2016-2018) is being reprocessed to optimize the resolution and stability of the ECAL energy reconstruction**
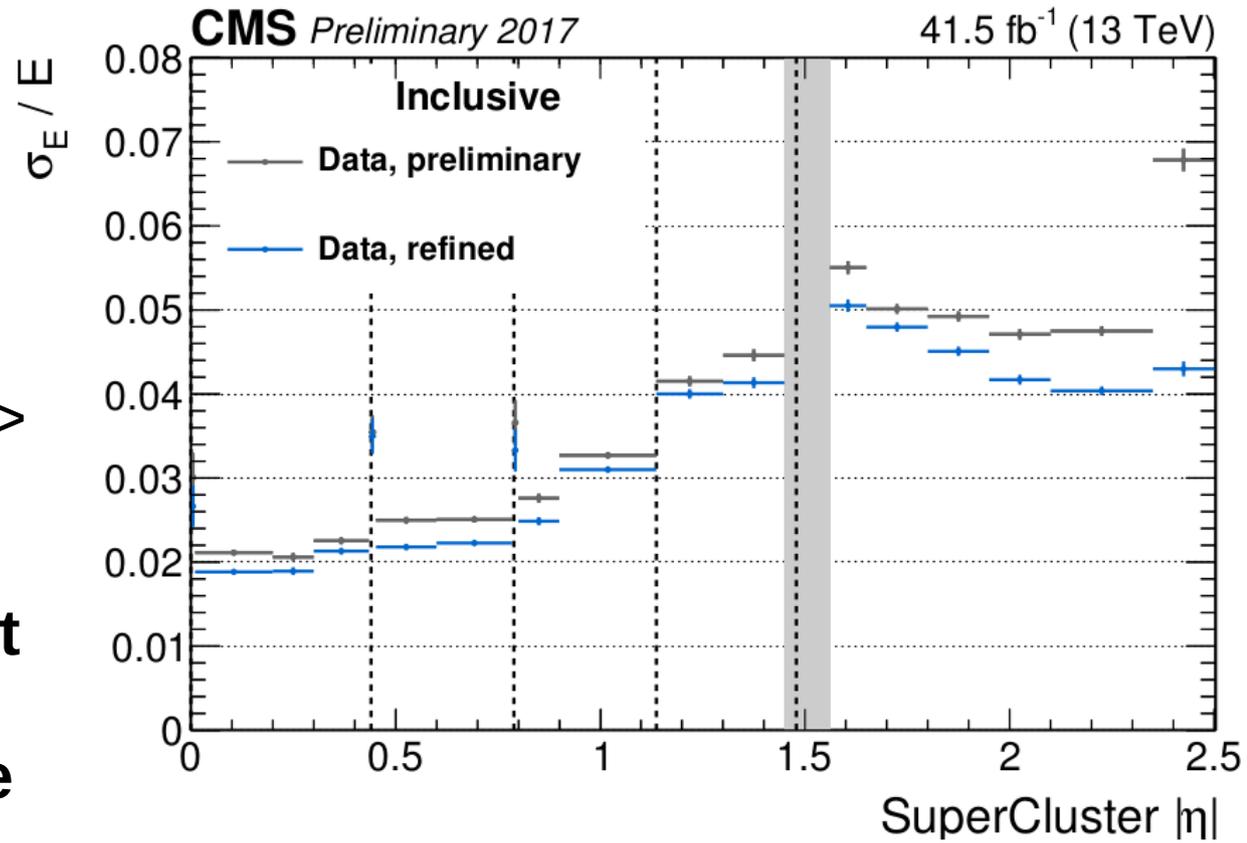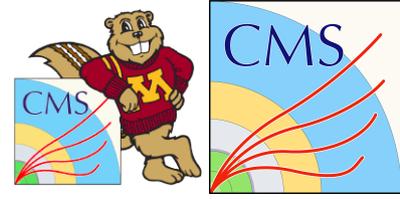
Higgs Mass Measurement

Run 2, 2016 Dataset

$m(H \rightarrow ZZ^* \rightarrow 4l) = 125.26 \pm 0.21$ (total) ± 0.19 (stat.) GeV

- Very promising results forthcoming for a mass measurement in the γγ channel

- Run 2 is the best opportunity for a mass measurement

  – Crystals will continue to lose transparency

  – Systematic uncertainties will dominate analyses in Run 3 and in the High Luminosity LHC

https://arxiv.org/abs/1706.09936
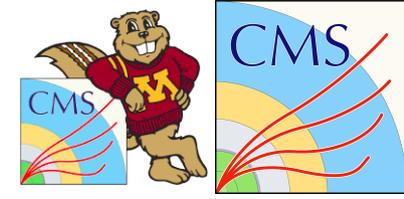
High-Luminosity (HL) LHC
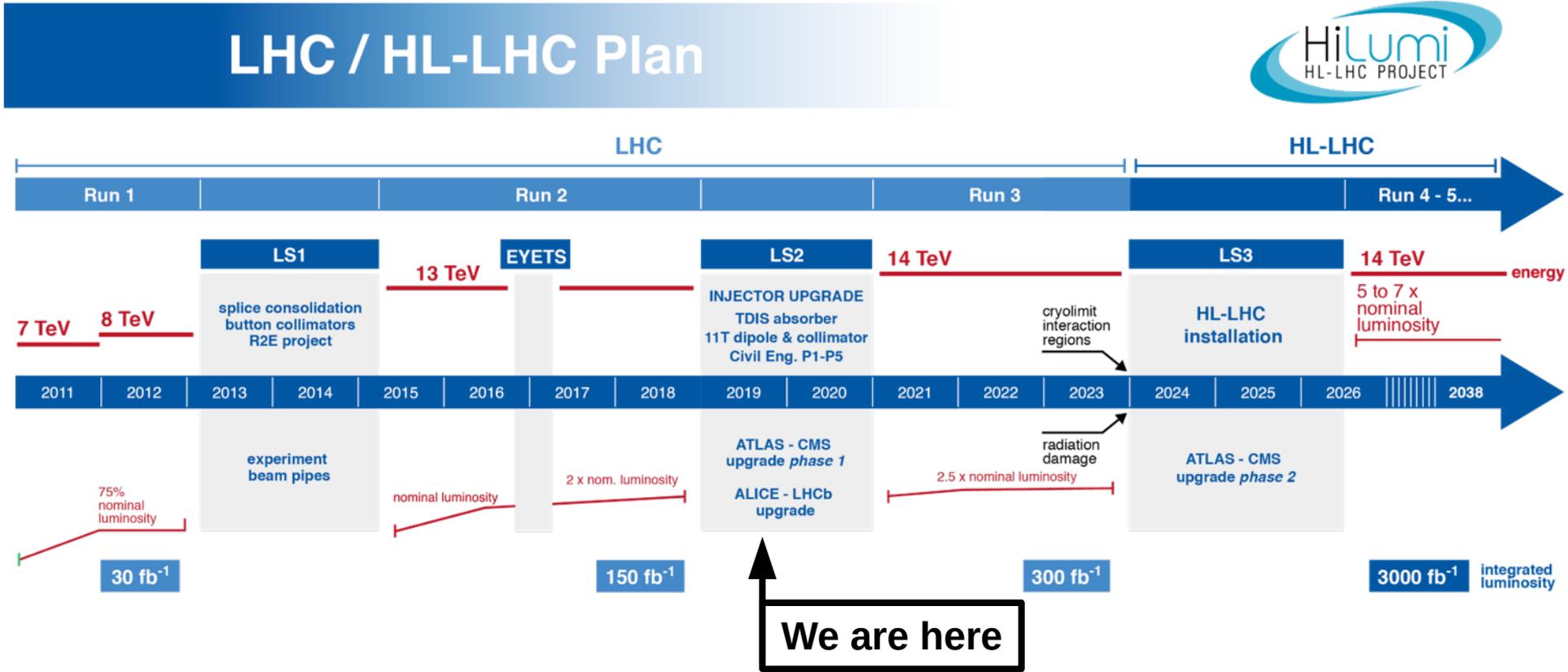
**HL-LHC will be a dramatic increase in luminosity**

- PU will jump from ~ 40 to ~ 200

- Particle reconstruction and primary vertex assignment will become main challenges for detectors

  - An upgrade to CMS is necessary in order to maintain current performance

ECAL Upgrades

- HL-LHC will have ~200 PU, and APD spikes in ECAL will have a rate of ~40 kHz

  - Upgrades are necessary to combat these challenges

- **Upgrades to the ECAL are specifically targeting**

  - **PU and OOT PU mitigation**

  - **spike rejection**

  - **signal arrival time and resolution**

  - **noise rejection in APDs and improved light yield is ECAL crystals.**
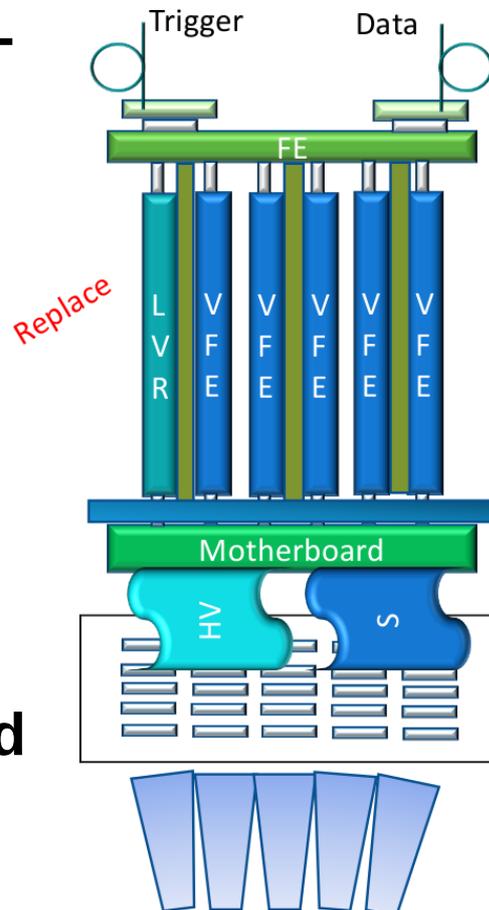
FE = Front End passes single crystal information to the back end. No latency buffer in front end

VFE = Very Front End. Preamp, Shaping and ADC

Motherboard is passive – basically just a connector HV and LV to APD and signals to VFE

Crystals with two Avalanche Photodiodes (Connected so I channel per 2 APD's)

ECAL Before and After
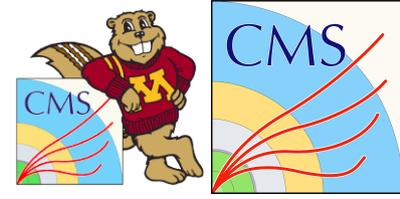
Before   **After**

Photodetectors

- Operating Temperature: **18° C**
- Operating Temperature: **9° C**

Very Front End Electronics

- Sampling Rate: **40 MHz**
- Sampling Rate: **160 MHz**

- Number of Samples: **10 Samples**
- Number of Samples: **20 Samples**
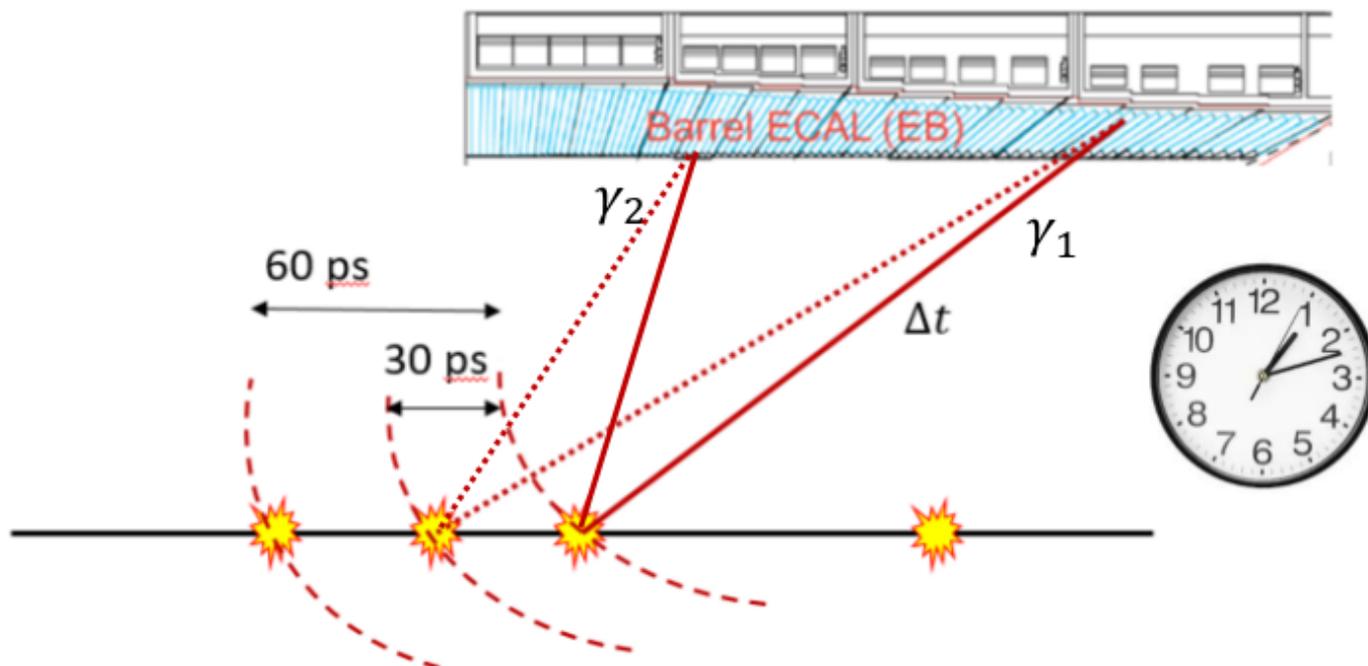
Front End Electronics

- Crystal Info: **5x5**
- Crystal Info: **1x1**

L1 Trigger

- Acceptance Rate: **100 kHz**
- Acceptance Rate: **750 kHz**

- Max Latency: **6.4 µs**
- Max Latency: **12.5 µs**

ECAL Timing Resolution

- The VFE upgrade will also change the signal shape allowing the ECAL to make timing measurements of showers

- Time Resolution < **30 ps per shower**
  - By triangulation ~200 PU becomes ~40 PU

Exploring Rare Processes

- ## Many milestones in Higgs physics during Run 2

  - Observation of ttH production

- ## 3000 fb^{-1} expected at HL-LHC

  - Perform differential measurements

  - Enhanced sensitivity to rare processes:
   - **Higgs Pair Production**
    - **Higgs Self-coupling**
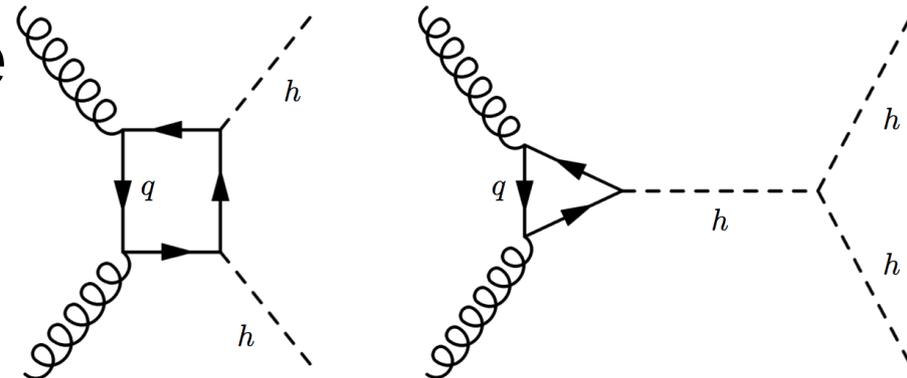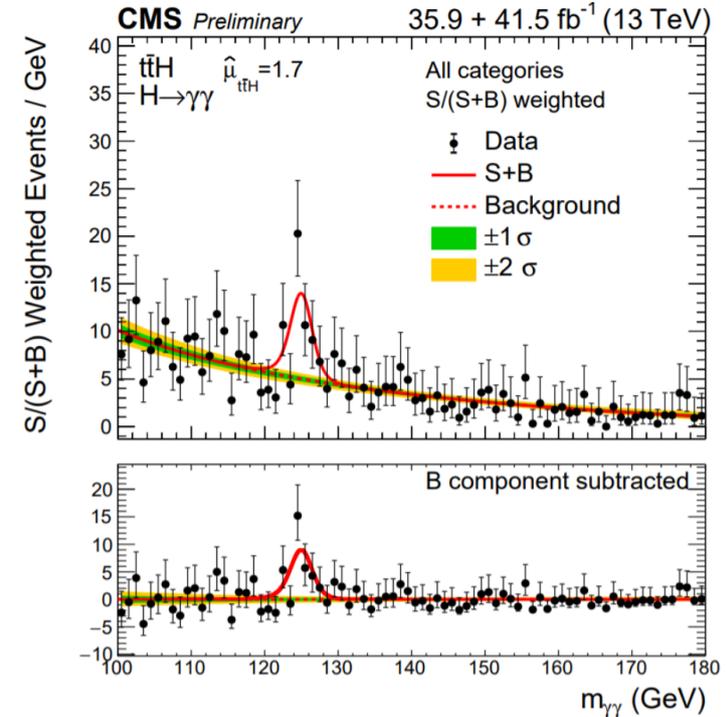
Summary

- **ECAL has shown excellent performance in photon reconstruction during Run 2**
  - Recalibration of Run 2 data ongoing
  - **Very promising results from 2016 data alone, many more to come with full Run 2 dataset**

- **HL-LHC is on its way**
  - Will provide unprecedented luminosity
  - Such a harsh environment will give rise to some experimental challenges
  - **ECAL upgrade plans are well underway**

- **3000 fb^{-1} of data will be collected at HL-LHC**
  - Target rare processes: HH production and self-coupling
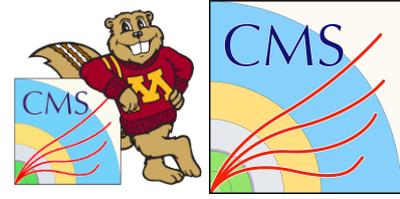
References:

- CMS Experiment
  - CMS Collaboration, "The CMS experiment at the CERN LHC", JINST 3, S08004 (2008)

- CMS ECAL
  - CMS Collaboration, "CMS: The electromagnetic calorimeter. Techical design report", CERN-LHCC-97-33, CMS-TDR-4

- ECAL Detector Performance Plots
  - CMS twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/EcalDPGResults

- Phase 2 Upgrade of the CMS Barrel Calorimeters
  - https://cds.cern.ch/record/2283187/files/CMS-TDR-015.pdf

- Higgs physics public results from CMS
  - preliminary http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG/index.html
  - pulic http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html