



EPS Conference on High Energy Physics
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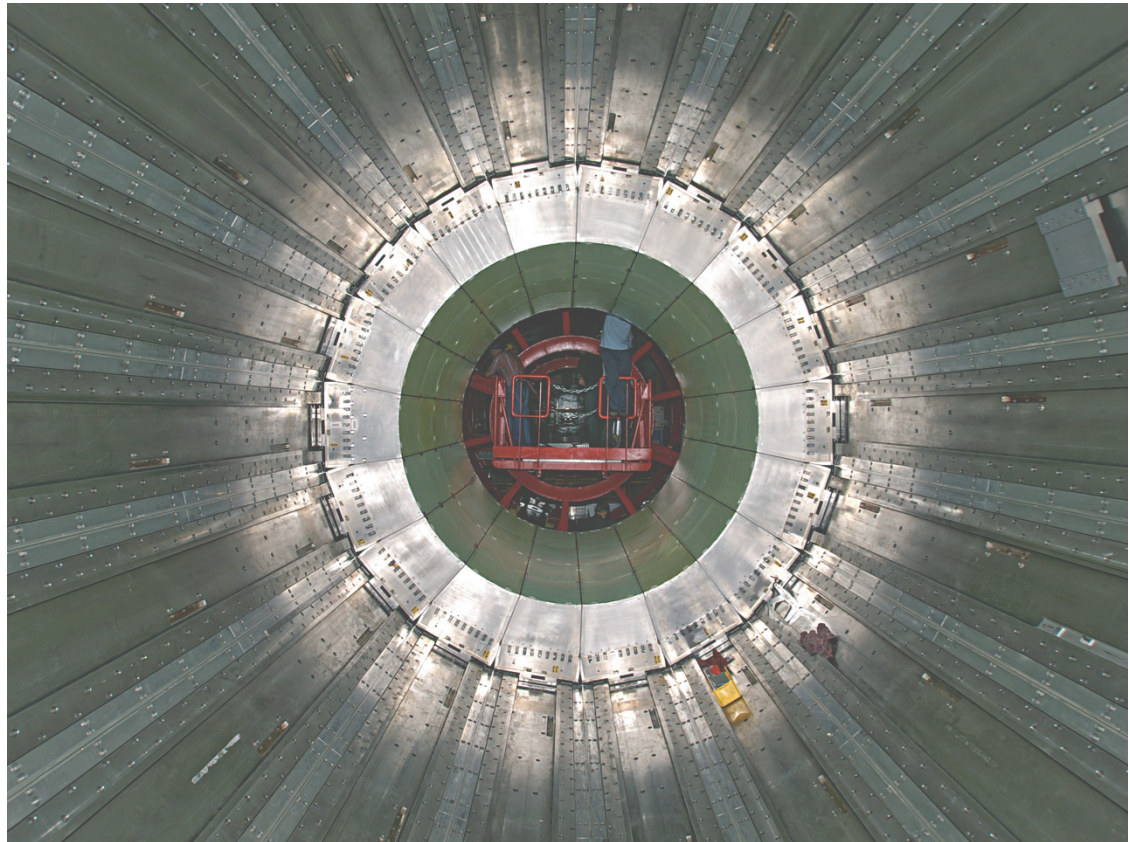


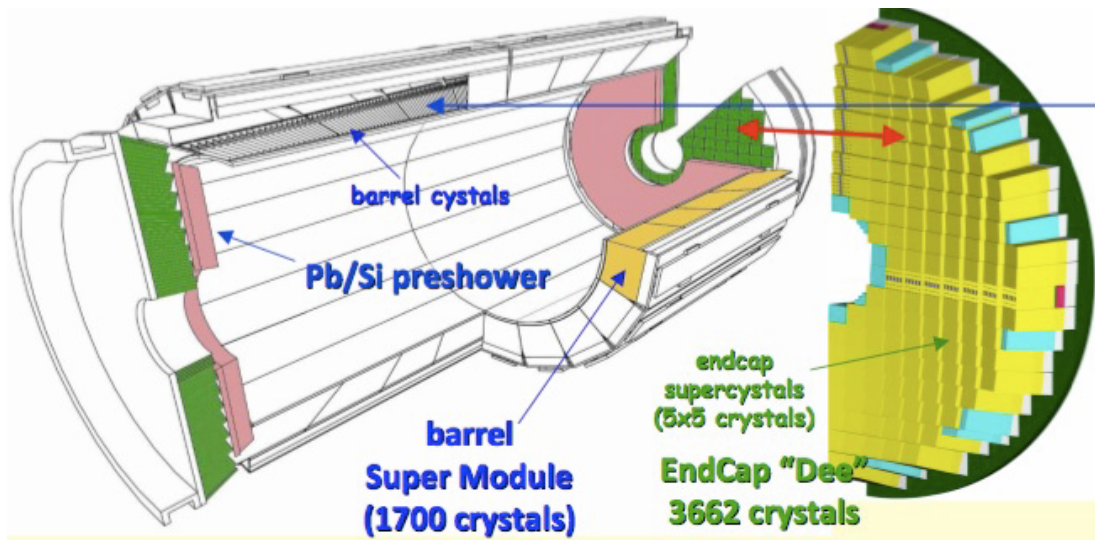
UNIVERSITY OF
NOTRE DAME

The CMS ECAL Upgrade for Precision Crystal Calorimetry at the HL-LHC

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On behalf of the CMS collaboration

- ❑ CMS Ecal
- ❑ HL-LHC Physics motivation
- ❑ HL-LHC
- ❑ ECAL @ the LH-LHC
- ❑ Ecal Barrel upgrade
 - ❑ Overview
 - ❑ APD noise
 - ❑ Anomalous signals
 - ❑ Precision timing
 - ❑ VFE design
 - ❑ FE & Off-detector
 - ❑ Prototypes
- ❑ Conclusions





| |
|--|
| Barrel (EB) $ \eta < 1.48$ 61200 crystals |
| Endcaps (EE) $1.48 < \eta < 3.0$ 14648 crystals |
| Pb/Si preshower $1.65 < \eta < 2.6$ |

Homogeneous PbWO_4 (PWO) scintillating crystals calorimeter

- Compact
- hermetic
- fine-grained
- high resolution

Design parameters:

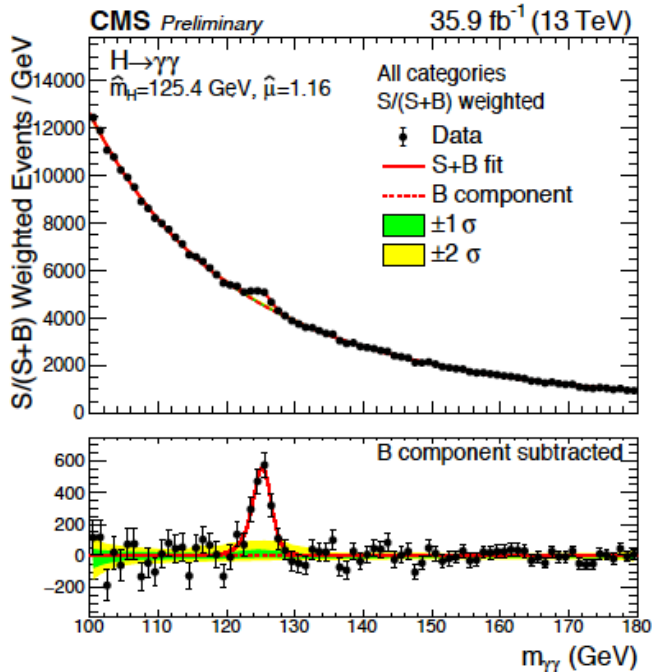
- Energy resolution: $\sigma E/E < 1\%$ above 100GeV
- Granularity: $\Delta\eta \times \Delta\phi \approx 0.0174 \times 0.0174$
- Noise: 50MeV in the barrel and 150MeV in the endcap region
- Appropriate radiation tolerance

EB crystals are arranged in 36 Super Modules
 Light is readout by Avalanche Photo Diodes

Electrons and photons are crucial for Higgs boson precision studies and BSM searches

Discovery of SM di-Higgs (HH) production is one of the main goals of the HL-LHC

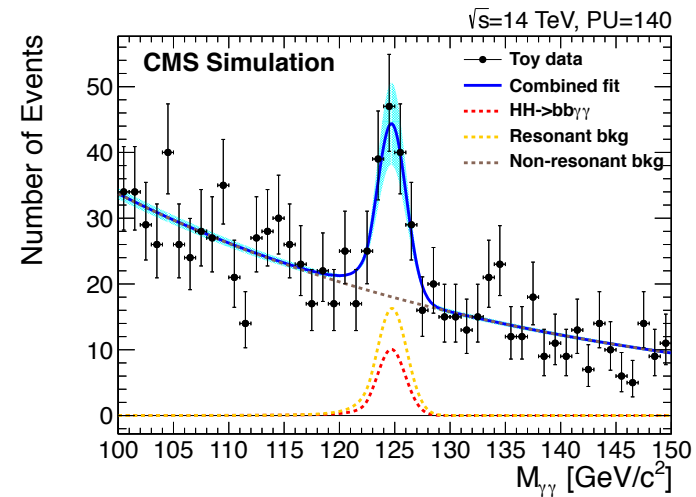
TODAY



$H \rightarrow \gamma\gamma$: Resolution on $m_{\gamma\gamma} \sim 1\%$

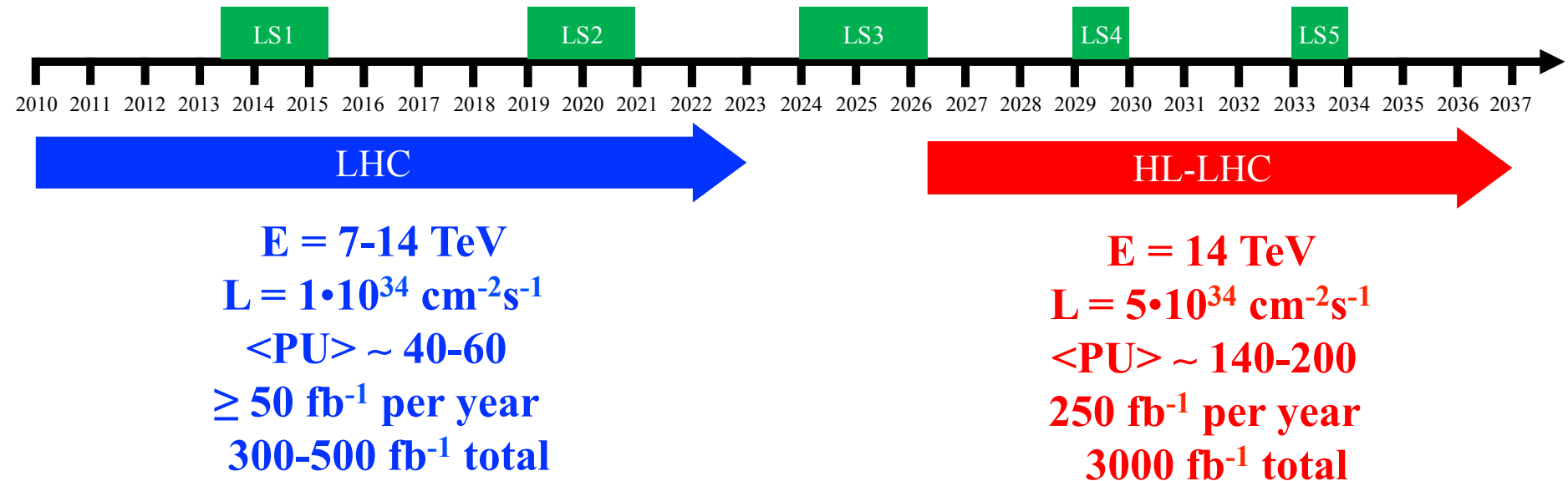


TOMORROW



HH production will help us measure the Higgs Boson self coupling, which determines the shape of the Higgs potential and helps us understand the vacuum stability of the universe

HL-LHC will provide unprecedented instantaneous & integrated luminosity in a highly challenging environment



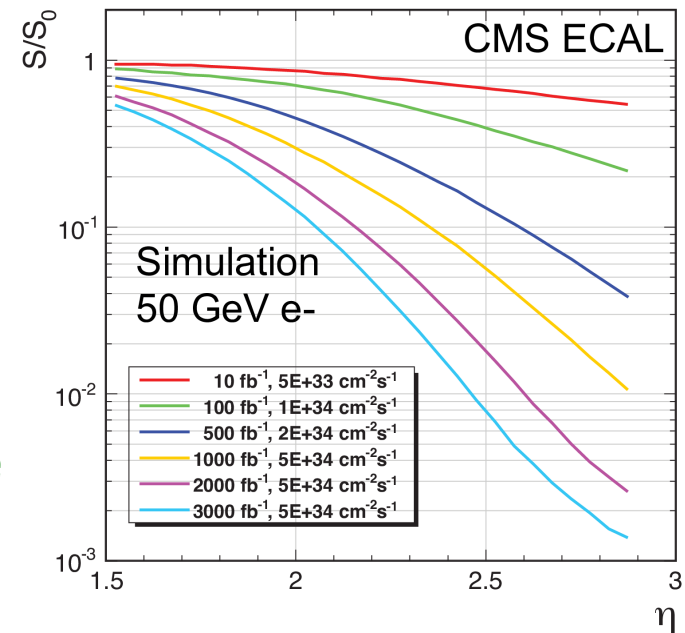
- Higher instantaneous and annual integrated luminosity
- Much higher levels of overlapping events: pile-up (PU)
- Radiation levels will be 6x higher than for LHC

While EE crystals are expected to suffer large transparency losses due to the high radiation level
 → Replace in LS3 (previous talk)

EB crystals are expected to survive well during HL-LHC
 -- Transparency loss < 50% --

However life will be made difficult by

- increased dark current in the APD → increased noise
- high Pileup



Motivations for EB upgrade

Make FE and Off-detector electronics adequate to Phase II L1 requirements

→ Replace VFE/FE and off-detector electronics

Insure same performance (resolution) as at LHC

Improve mitigation of anomalous signals (spikes)

| | L1 rate | L1 latency |
|----------|---------|------------|
| Phase I | 150 KHz | 6.4 μs |
| Phase II | 750 KHz | 12.5 μs |

5x5 crystals arrangement, APDs, mother boards and mechanical structure will not change

Reduce operating temperature: from 18°C to 8°C

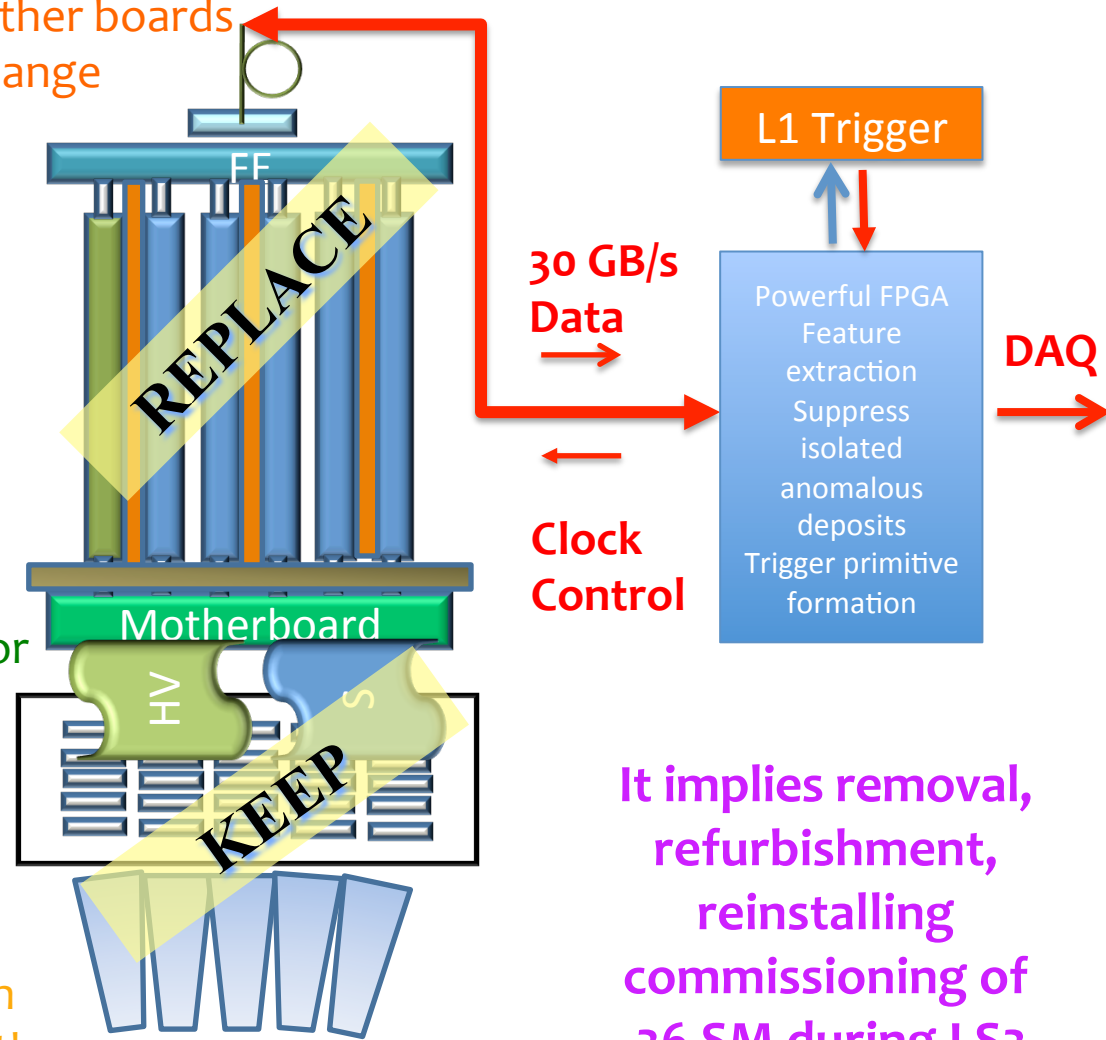
VFE: shorter shaping time + optimized sampling + new ADC

FE: single channel readout at 160MHz, 30Gb/s Latency buffer and all processing are moved off-detector

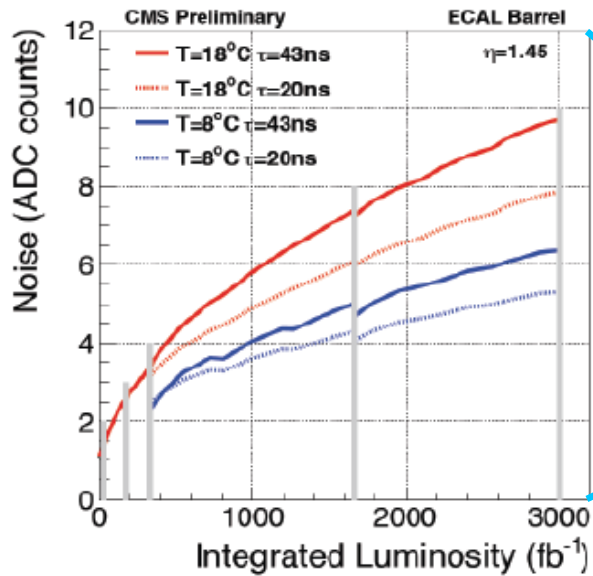
Upgraded high-speed links

Unified path for data and trigger

New Off-detector electronics will run trigger primitive generation + algorithm for timing and spike removal → Max flexibility



It implies removal, refurbishment, reinstalling commissioning of 36 SM during LS3



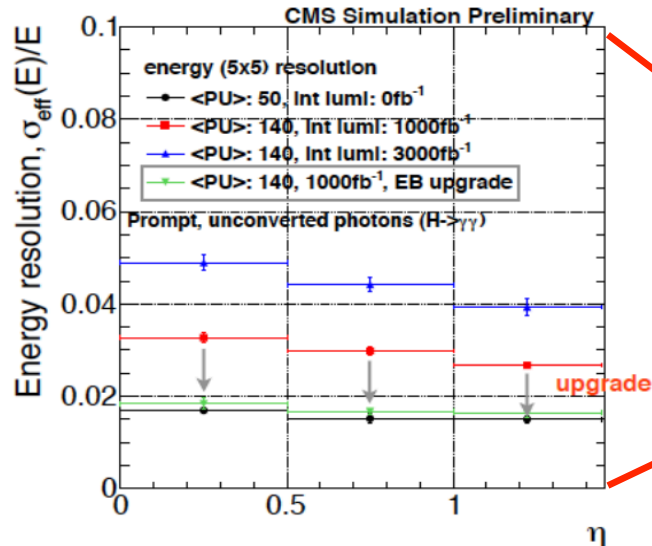
APD dark current increases with integrated luminosity

→ x10 more noise after 3000 fb^{-1}

Dark current strongly depends on temperature

→ mitigate negative effects by cooling down (more)

→ Going from 18°C to 8°C reduces noise by 35%

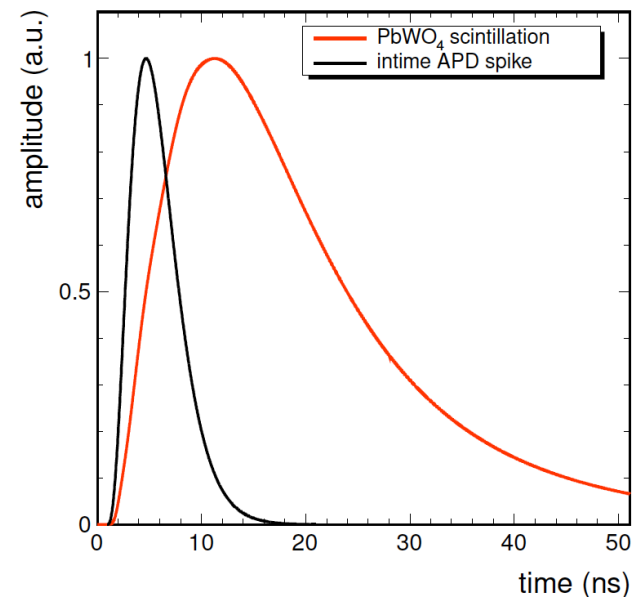


New VFE with shorter signal shaping time helps reducing the \sqrt{t} noise component

Recover resolution of today

Hadrons, occasionally, hit the APDs, releasing energy directly in the bulk (spikes)

- ◆ Large signals, can exceed 100 GeV
- ◆ They are isolated signals unlike genuine e/ γ which spread over many crystals
- ◆ The signal in the APD is faster and narrower
- ◆ Rate is proportional to the LHC collision rate
→ if not suppressed they lead to unsustainable L1 EG rate

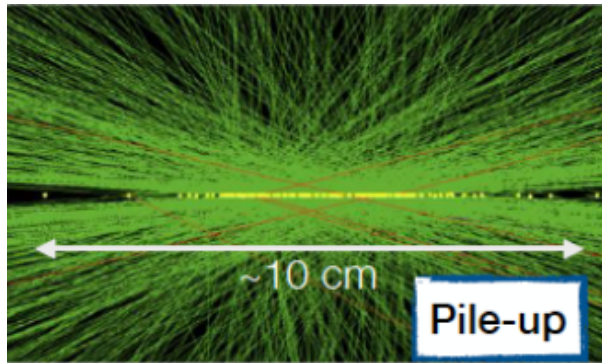


Spike rejection

- Currently rejected at L1 with coarse topological algorithm very sensitive to PU level
→ Rejection efficiency expected to drop to un-acceptable levels

Upgrade will include high granularity readout and VFE/FE design to cope with increased spike rates

For the $H \rightarrow \gamma\gamma$ analysis the right primary vertex assignment within 1 cm is vital to the $M(\gamma\gamma)$ resolution

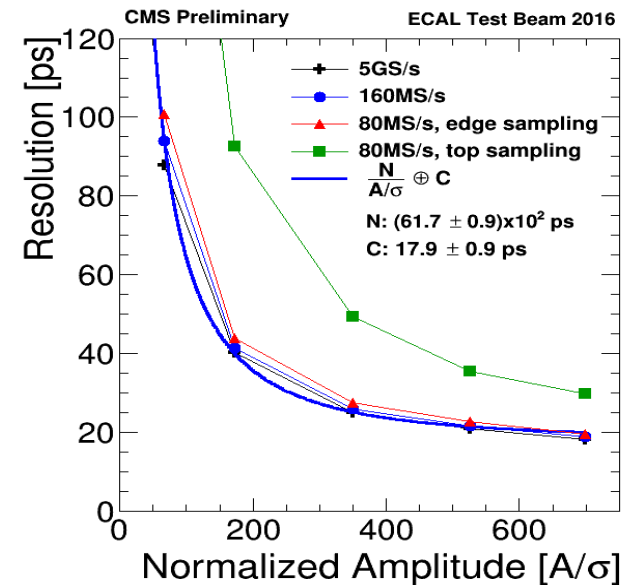
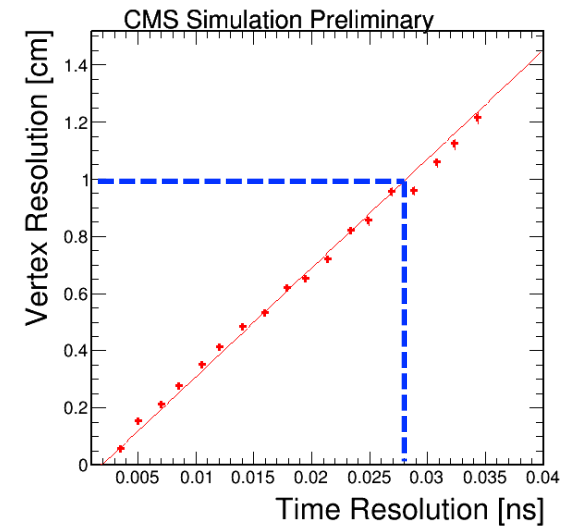


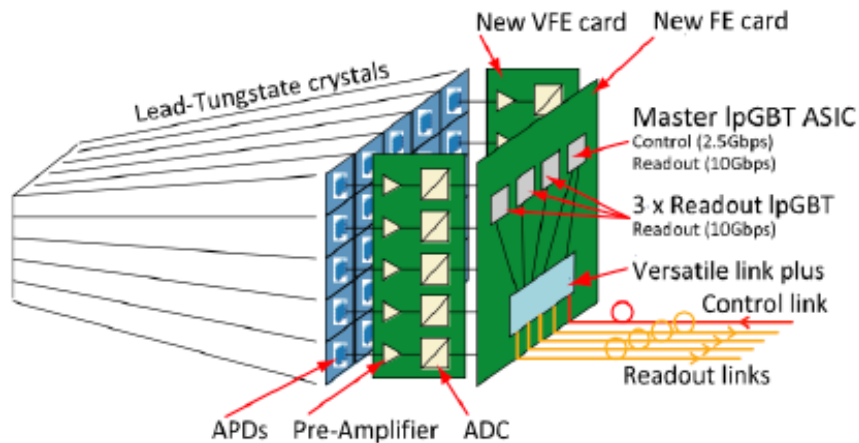
Precision timing would help with:

- Keeping the vertex assignment efficiency close to the Run 1 level ($\sim 80\%$)
- Subtracting the in-time pileup neutral energy from EM clusters as well as identifying jets from pileup

The intrinsic timing resolution of $\text{PbWO}_4 + \text{APD}$ is < 30 ps

VFE designed with short shaping time and sampling at 160MHz will bring us close to the intrinsic resolution, i.e. ~ 30 ps at 50 GeV

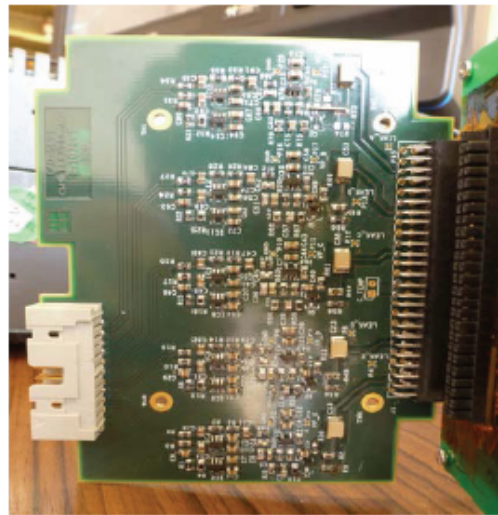
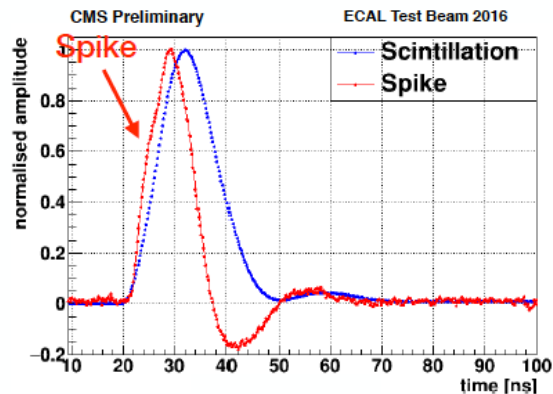




UNCHANGED

- ❑ 5x5 channel modularity
- ❑ Lead-tungstate crystals with two APDs connected in parallel
- ❑ Motherboard
- ❑ Dual-Gain Trans Impedance Amplifier with dynamic range 50MeV-2GTeV
 - ❖ precision timing
 - ❖ minimise APD noise, OOT PU
 - ❖ maximises spike rejection

Measured spike and scintillation pulse shapes



VFE demonstrator w/ TIA

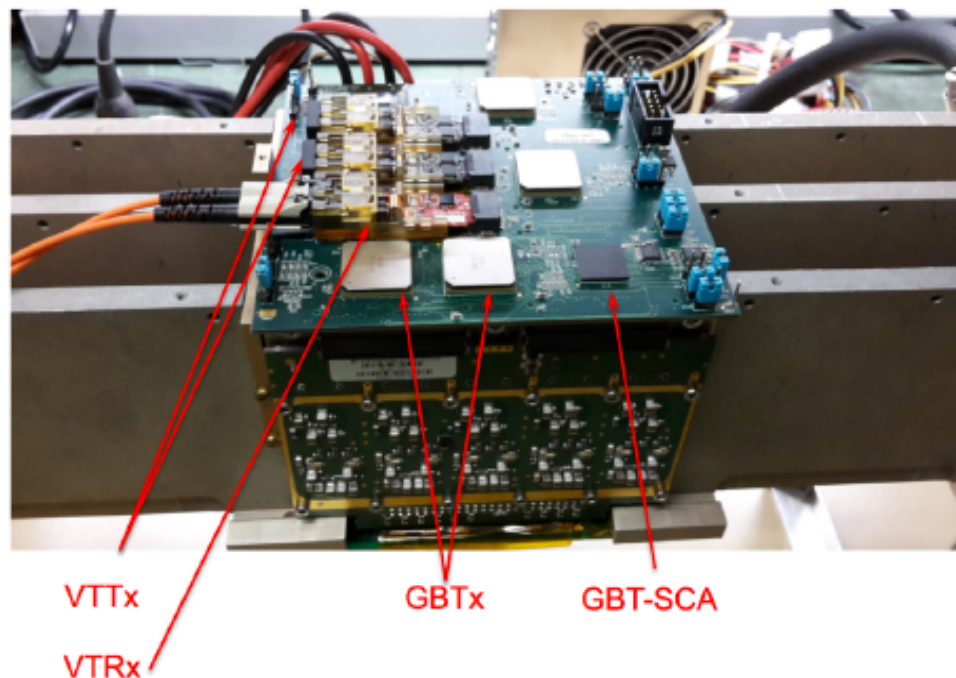
Dual ADC

- ❑ 12 bit @ 160 MHz
- ❑ Loss-less data compression

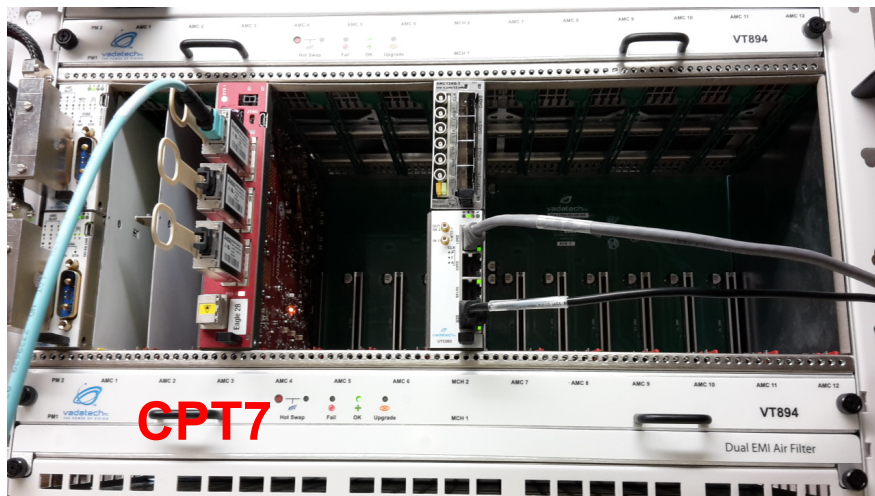
Front End:

- ✧ Full readout of 5 VFE cards:
5x5x13bits @ 160 MHz
- ✧ Move L1A pipeline off-detector to accommodate 12.5 μ s CMS latency
- ✧ Move trigger primitive generation off-detector
- ✧ Data links from FE to off-detector readout cards based on CERN GBT, IpGBT and Versatile links
- ✧ IpGBT allows up to ~10Gb/s bandwidth on the common data-trigger path

FE demonstrator



OFF-DETECTOR demonstrator



Off-detector

Powerful processing boards needed to deal with large amount of EB data


- ✧ Amplitude extraction and BX identification
- ✧ Signal shape analysis for spike rejection
- ✧ Channel calibration
- ✧ Timing
- ✧ Clustering
- ✧ Fine-grained trigger primitive generation

The challenging conditions of the HL-LHC will require:

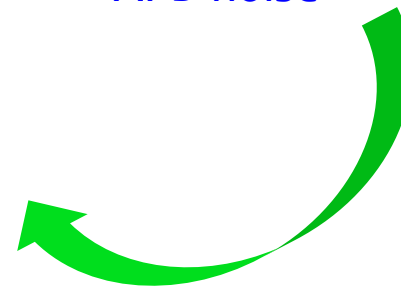
- ❑ Longer data pipeline, more bandwidth
- ❑ Improved spike filter at trigger level
- ❑ Mitigation of increased APD noise
- ❑ Precision timing for vertex determination & PU mitigation

Requires full refurbishment of ECAL barrel on-detector electronics during LS3

- ❑ Replace/optimize FE & VFE to cope with increased noise, pileup, spikes
- ❑ New off-detector readout cards to process higher granularity/bandwidth data from FE → Move all algorithms off-detector allows for tuning when necessary
- ❑ Lower by 10°C the operating temperature to mitigate increase of APD noise



The upgrade will rejuvenate the ECAL barrel making it ready for a new successful decade of operation





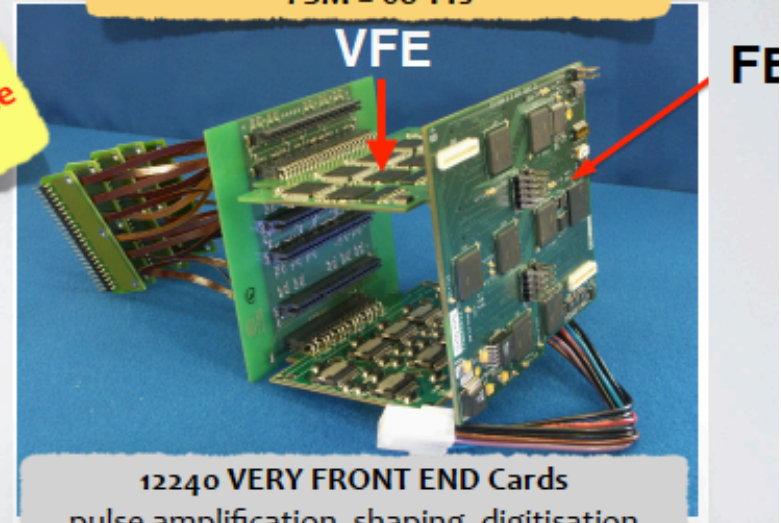
Backup

36 SUPERMODULES (SM)



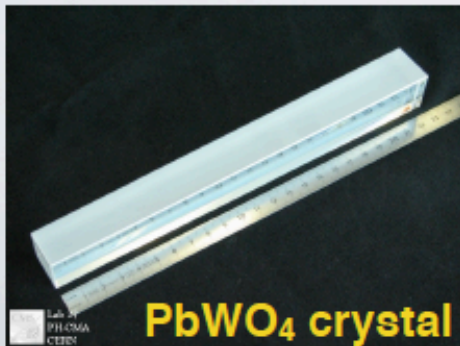
All the SMs will be removed for the electronics upgrade
MAJOR EFFORT

2448 TRIGGER TOWERS (TT)
basic readout unit 5x5 crystals matrix
1 SM = 68 TTs



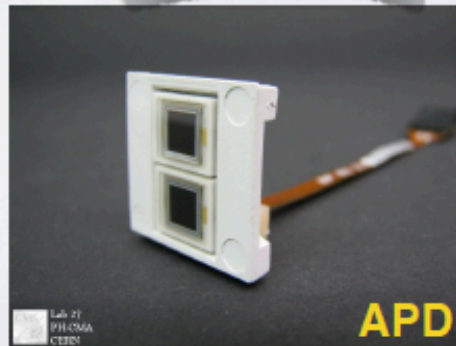
12240 VERY FRONT END Cards
pulse amplification, shaping, digitisation

61200 PbWO₄ CRYSTALS



PbWO₄ crystal

61200 APD pairs



APD

2448 FRONT END Cards
data pipeline and transmission, TP formation, clock/control



VFE



FE