The Phase II upgrade of the CMS Barrel Electromagnetic Calorimeter

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On behalf of the CMS Collaboration

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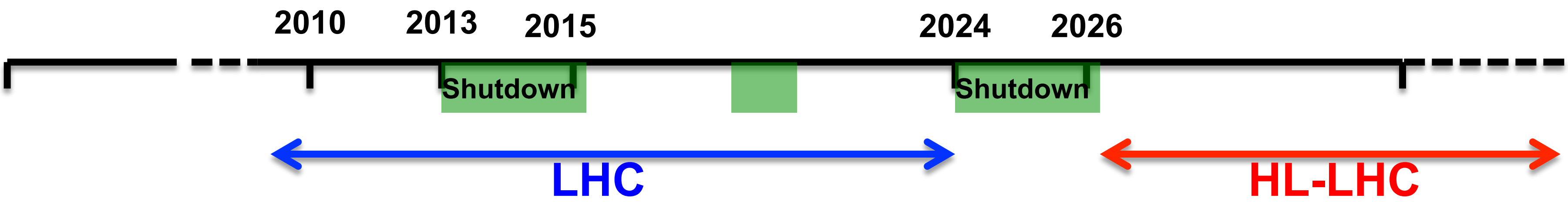
Outline

CMS ECAL Phase II Upgrade:

- Upgrade motivation
  - LHC Phase II
- ECAL detector
  - Actual state
  - Expected Phase II performance
- ECAL Phase II electronics

LHC: from design to HL upgrade



	Design	Current (2016) state	Upgraded
E_{beam} TeV	7	6.5	7
L_{inst} $cm^{-2}s^{-1}$	10^{34}	$(1.0\text{-}1.4)\times10^{34}$	5×10^{34}
L_{int} fb^{-1}, 10 years operation	300	40 per year	3000
β^* cm	50	40	15
Pileup	20	37	120-200

CMS ECAL specification

Goal (CMS-ECAL TDR, Dec1997):

- "Search for Higgs ··· will strongly rely on information from ECAL"
- "Objective is to construct a very high performance electromagnetic calorimeter"

Design parameters:

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

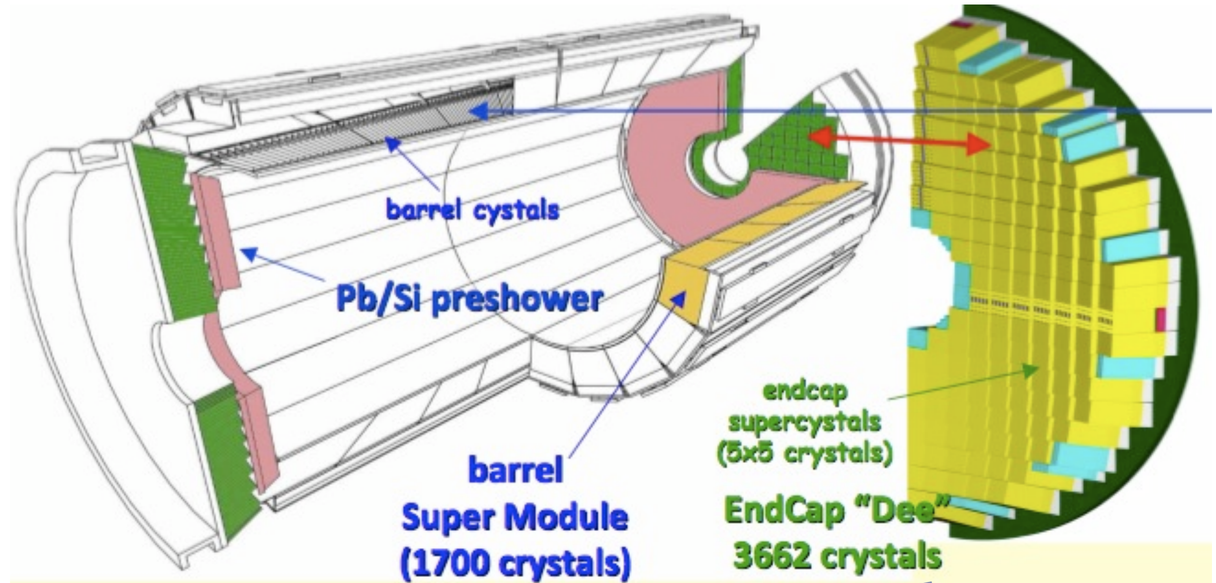
CMS ECAL design

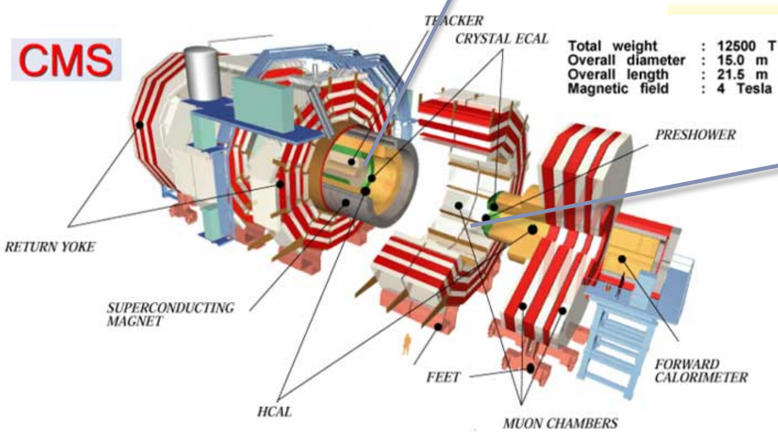
- Homogeneous $PbWO_4$ (PWO) scintillating crystals calorimeter
- Compact, hermetic, fine-grained, high resolution

Barrel (EB)
$\eta < 1.48$
61200 crystals

EndCap (EE)
$1.48 < \eta < 3.00$
14648 crystals

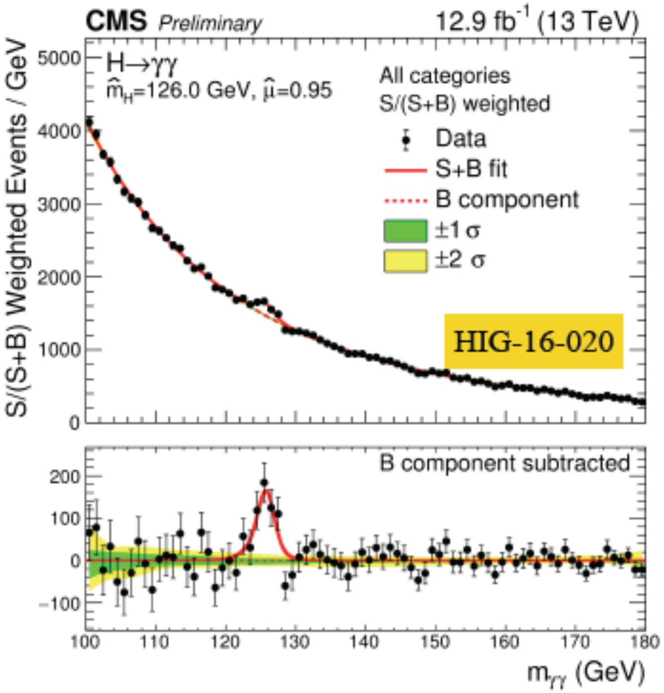
Pb/Si preshower
$1.65 < \eta < 2.6$

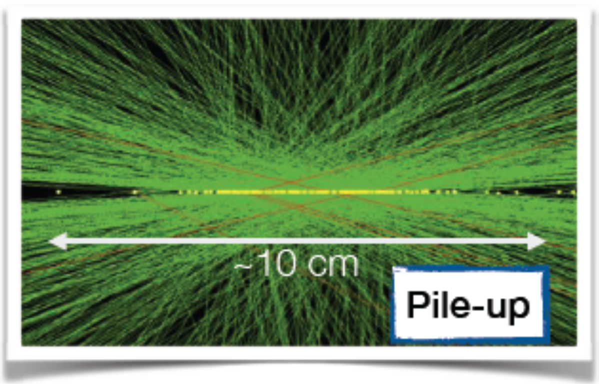




EB is divided to 36 Super Modules
Light readout by Avalanche Photo Diodes

CMS ECAL current performance





- ECAL energy resolution **crucial** for **Higgs boson** and many CMS analysis:
  - **H→γγ:** Resolution on $m_{\gamma\gamma}$ ~ 1%
- Performance affected by **Pile Up (PU)** = Overlapping interactions for single bunch crossing
- Improved techniques for **LHC Run II** (2015-2018) to cope with higher PU (x2 wrt Run I)

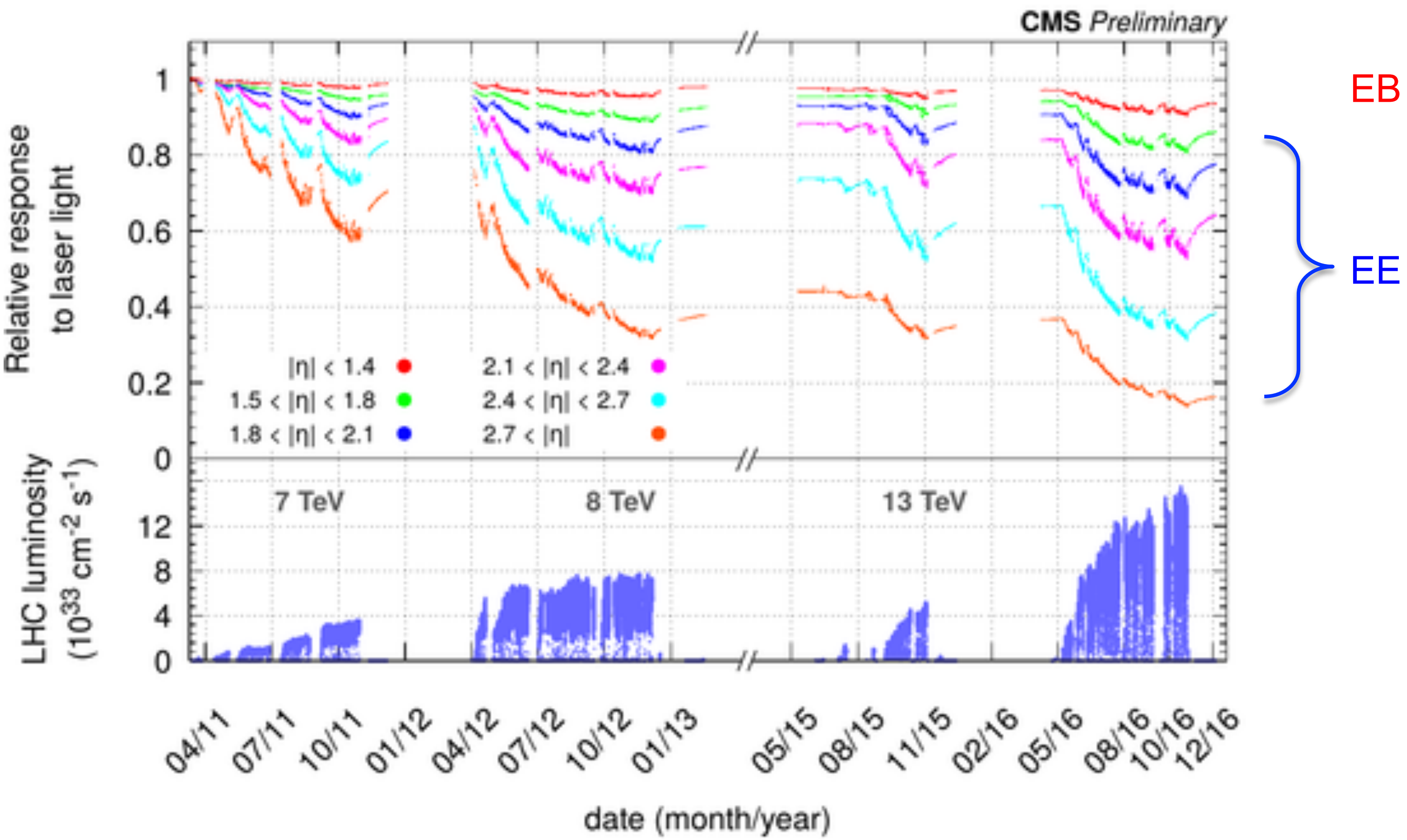
Excellent performance of ECAL at 13 TeV:
Photon Energy resolution: **1-3%** in **EB**, **2.5-4.5%** in **EE**

CMS ECAL limits

Several time- and accumulated dose – related factors which can lead to the ECAL performance degradation

1. Loss of the crystals optical transmission due to the radiation damage
2. Increase of the electronic noise due to the APD dark current
3. Abnormal signals in APD (spikes)

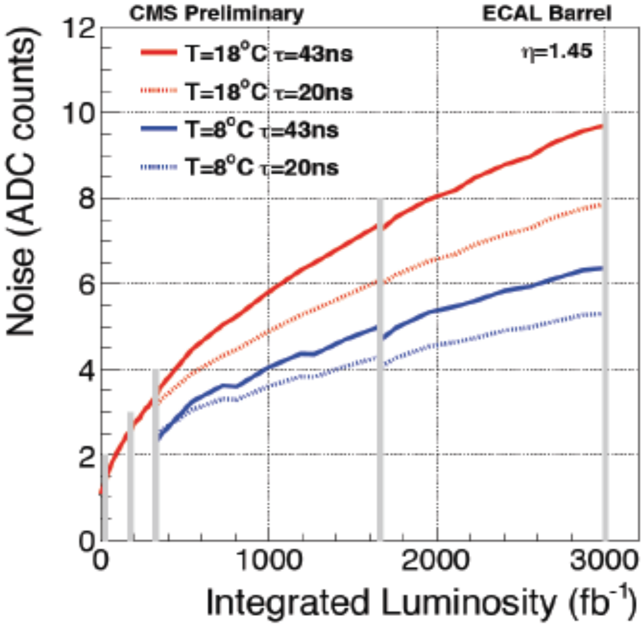
PWO crystals transmission



- Radiation damage leads to response degradation of crystals
  - Light monitoring system: laser light injected into each crystal to derive corrections
- Stability monitored with several methods (π^0 mass, E/p)
  - After correction stability of 0.15% (2015 data)

See talk of Tatyana Dimova for more details

APD ageing / noise



1 ADC count = 40 MeV

- **Ageing**
  - **APD dark current increases with integrated lumi → more noise**
  - Extrapolation: noise increase x10 (~400 MeV/channel) after 3000 fb^{-1}
- Mitigation
  - Operating EB colder: 18°C → 8°C, reduce noise by 35%, prevent APD self heating
  - Shortening the signal shaping time in VFE will also reduce noise which goes like $\sqrt{t}$

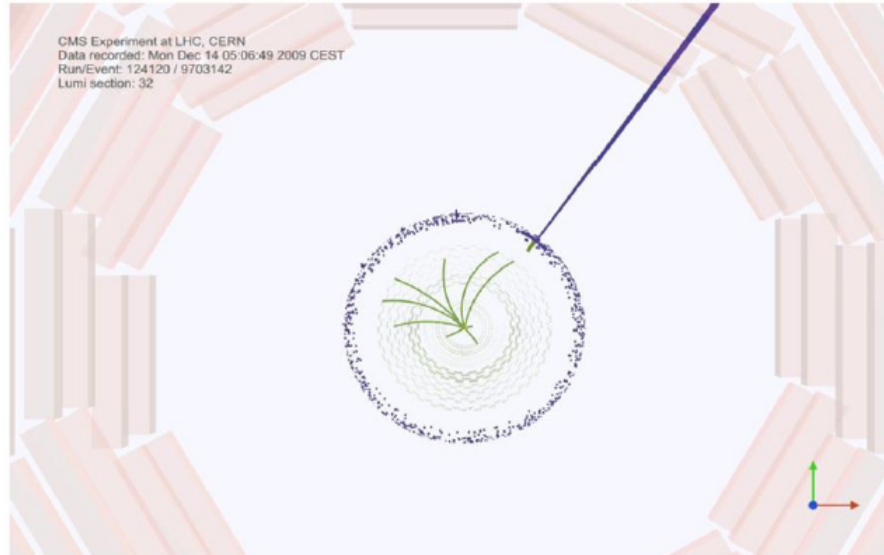
Electronic noise contribution to the energy resolution

	σ_E/E(%)
Now	1.2
3000 fb^{-1} no cooling no VFE upgrade	4.0
3000 fb^{-1} cooled	2.8
3000 fb^{-1} cooled and VFE upgraded	2.5

Spikes

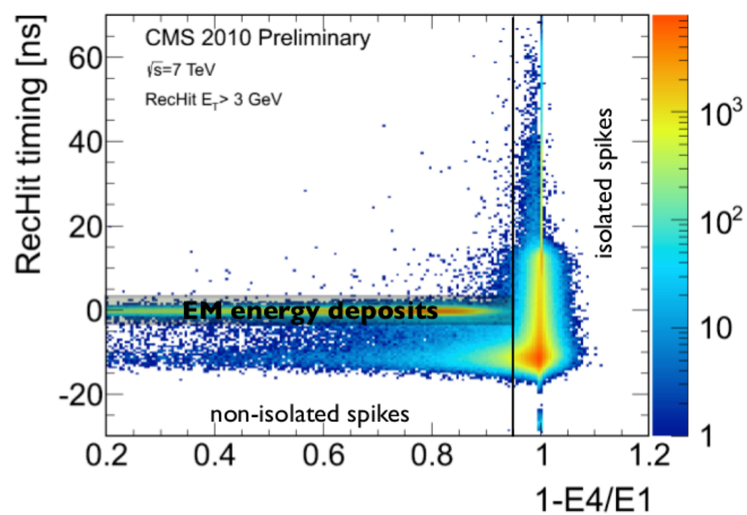
Energy deposited directly in the bulk of APD produce a signal

- Equivalent to multi-GeV photon shower
- Faster than e.m. shower signal
- Isolated channel
- Rate proportional to instantaneous luminosity



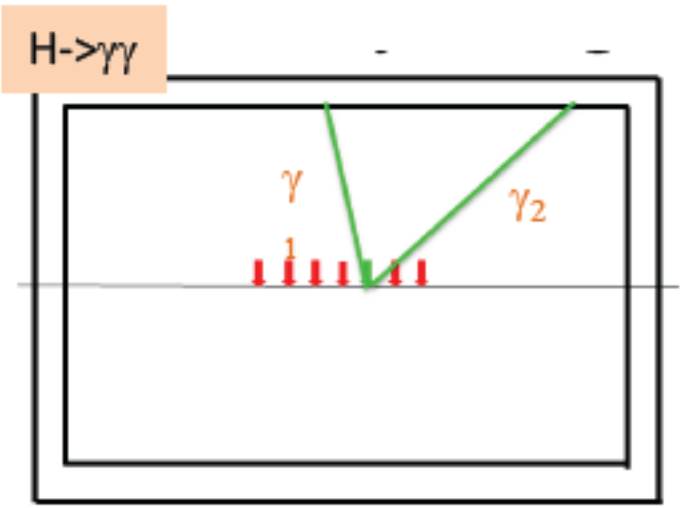
Spike rejection

- Currently rejected at L1 via coarse topological algorithm
- Rejection efficiency will degrade to unacceptable levels at HL-LHC due to higher noise and Pile-Up



Improved time resolution

- Current ECAL provide (70-140)ps time resolution but was not optimized for timing resolution in design
- ~30ps is measured limit from shower fluctuation and APD jitter established in test beam measurements in 2015/2016
- Precision timing ~30ps @ 30GeV is an upscope from the Upgrade technical proposal requirements
- Recent studies from the Higgs diphoton group and timing group provide important argument for 30ps photons timing in EB



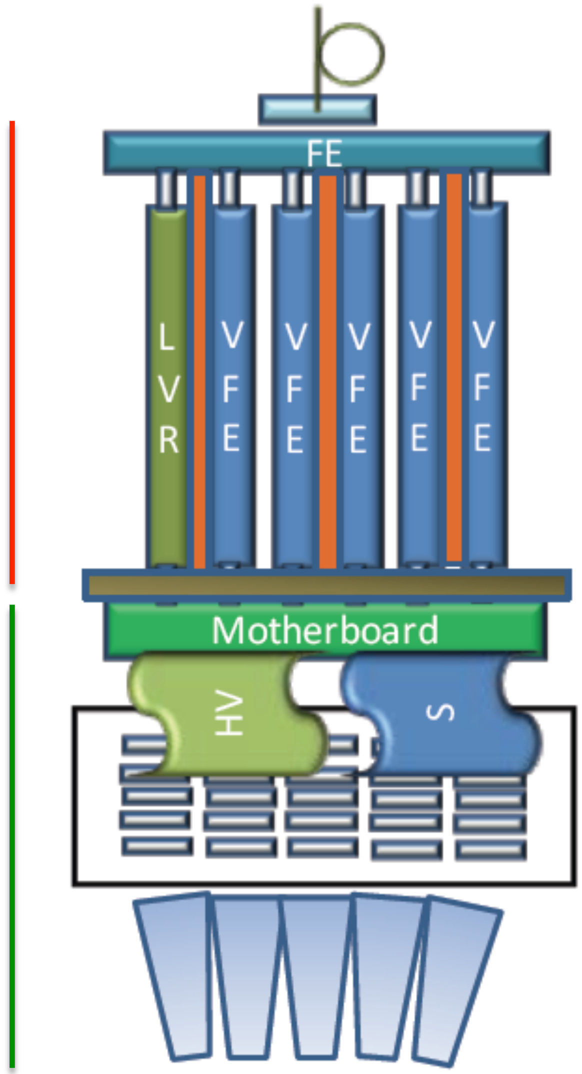
- Mass resolution of H→ϒϒ determined by energy resolution and vertex resolution (provides the origin of four ϒ vectors)
- 30ps timing allows better determination of H→ϒϒ photon vertex in high pileup
- Better resolution means more significant signal which is same as luminosity gain
- 30ps timing gives effective luminosity gain of 10% for H→ϒϒ cross-section measurement

CMS ECAL Phase-II

- Maintain (or improve) the energy resolution
- Readout
  - Consistent with the extended data rate and tracker-in-trigger conditions
  - 750kHz L1 accept rate and 12.5 μ s latency (currently 100kHz and 5 μ s)
- Mitigate spikes
- Good time resolution: 30ps

- Detector: ageing / rad. damage
  - OK in the barrel region → keep EB (crystals & APDs)
  - Too much damage in the endcap region → replace EE
- On-detector electronics
  - Does not fit to the new requirements → replace
- Off-detector electronics
  - Does not fit to the new requirements → replace

ECAL on-detector electronics



- Trigger Tower (TT)
  - 5x5 array of crystals, building block of the on-detector electronics
- Very-Front-End (VFE)
  - Each VFE card has 5 identical readout channels with pre-amplifiers (MGPA): 3 gains, 43ns shaping time, and 12bit ADC sampling at 40MHz
- Front-End (FE)
  - Data pipeline and transmission
  - Receive L1 trigger
  - Generate trigger primitives with TT granularity
  - Separate optical transmitters for data and trigger information
- Bandwidth
  - 40MHz readout of 2448 TT (5x5 array)
  - 100kHz readout for 61200 channels for L1 triggered events

Since the detector remains unchanged, the TT-based on-detector electronics structure will be maintained

PhaseII EB on-detector electronics

- Dynamic range: maintain the current one
  - 50 MeV to 2 TeV
- Spike rejection
  - 99.9% above 5 GeV at L1 trigger
- Electronics noise contribution to the energy resolution
  - 50 – 250 MeV for 0 to 100μA APD leakage current
- Out-of-time pileup mitigation
  - Reduce signal tails
- Time resolution
  - 30 ps for high energy photons (mitigate in-time pileup)

PhaseII EB electronics: VFE options

Fast shaping

- Decrease parallel noise (APD leakage current mitigation)
- Mitigate Out-of-time pileup

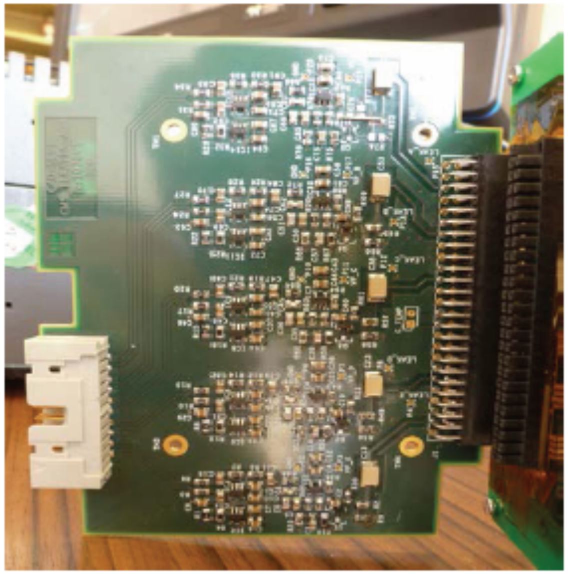
Options under study:

- Trans-impedance Amplifier(TIA) & Oversampling
  - Shaping defined by TIA bandwidth
  - Spike discrimination by shape analysis
  - Good timing resolution
  - Best performance at 160mHz sampling
- MGPA++ Transition of the existing MGPA to new technology (backup)
  - CR-RC shaper. Shaping reduced to 20ns & 80Ms/s ADC (currently 43ns and 40Ms/s)
  - Implementation of peak hold / pulse stretching to use multiple samples for spike reconstruction (amplitude and timing). Flag spike at the VFE level.

PhaseII EB electronics: prototypes

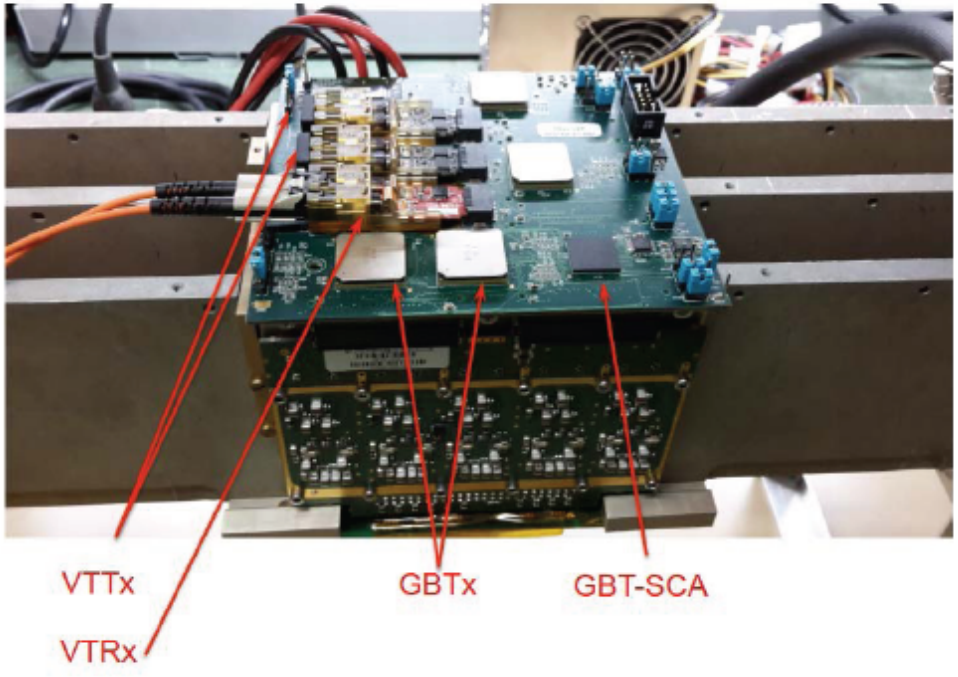
- **Prototype boards undergoing lab & test beam measurement**

VFE with TIA with discrete components (op-amps)



VFE demonstrator w/ TIA

FE with GBT

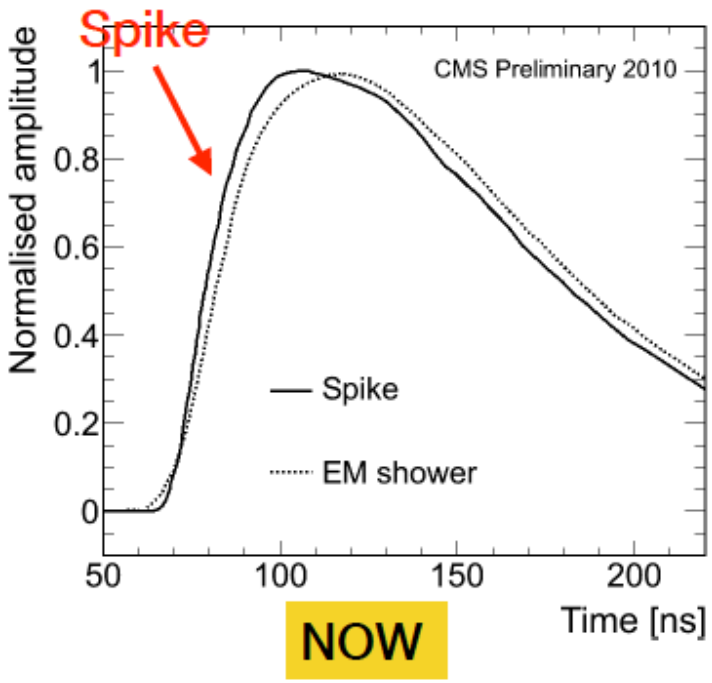


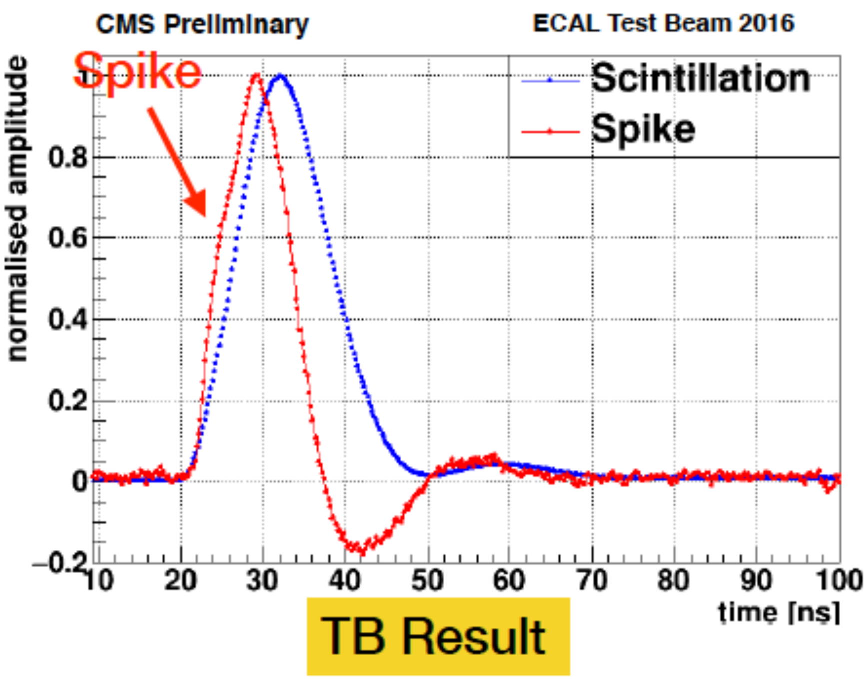
Simulation studies ongoing to optimize shaping time & sampling rate data flow

PhaseII VFE: spike rejection

→ **Pulse reconstruction** with **fast** VFE electronics can flag trigger information

- Spikes produced in **dedicated runs with hadron beam**
- Test beam results show **promising separation**:
  - Spike pulse shape is faster and can be rejected

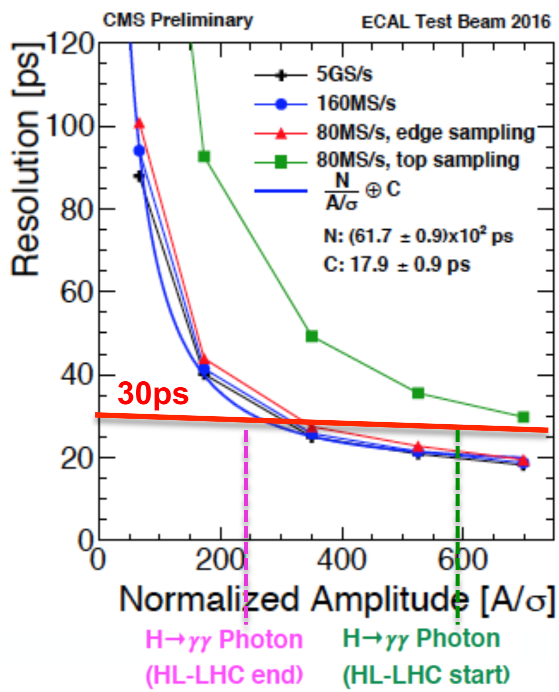




PhaseII VFE: time resolution

Test beam - 2016 results

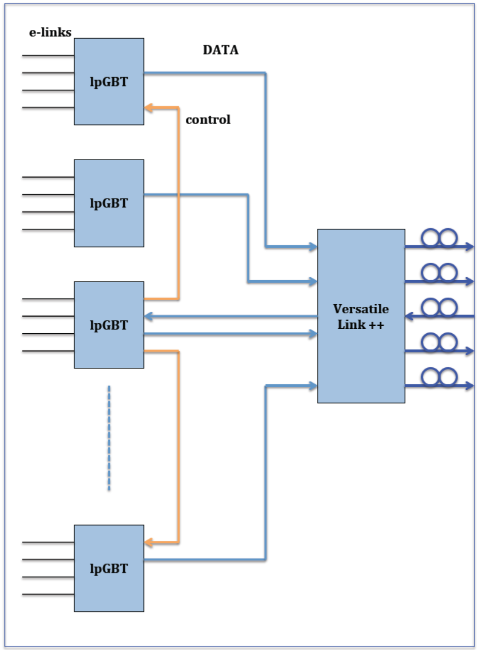
- Pulse shape **sampled at high frequency** (5 GHz):
  - Different sampling frequency can be emulated (baseline for TIA design is 160 MHz)
- APD timing extracted through **template fit to pulse shape**:
  - Comparing with time of entrance of electrons (**Micro-Channel Plate sensors** in front of the matrix) we can extract **timing resolution**



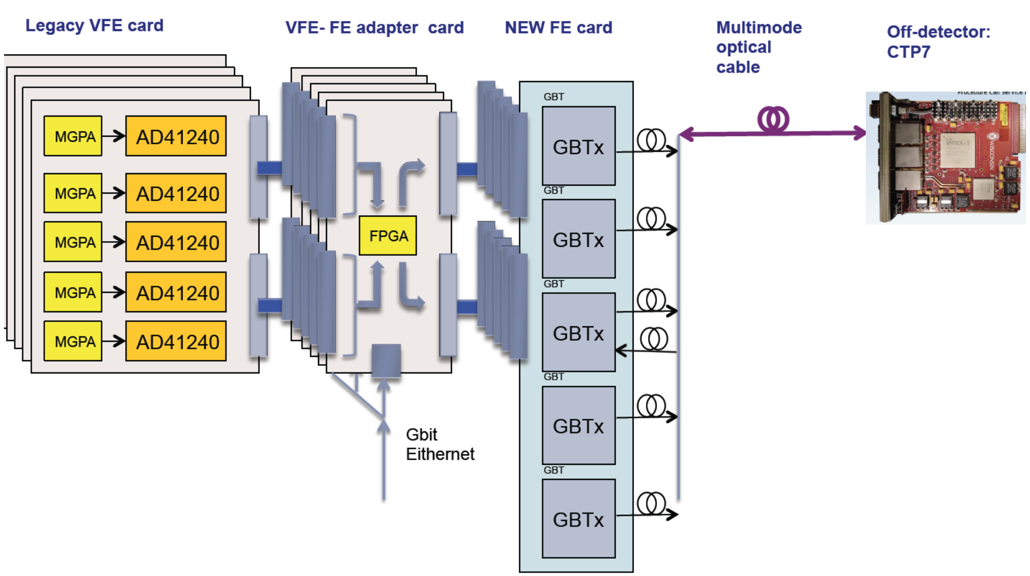
- Encouraging preliminary performance for **single undamaged crystal** (to be confirmed on additional crystals, further investigations ongoing):
- At 160 MHz σ~30 ps reached @ A/σ=250:
  - **25 GeV** with 100 MeV noise (**HL-LHC start**)
  - **60 GeV** with 240 MeV noise (**HL-LHC end**)

PhaseII EB electronics: FE

- FE card should provide:
  - Full readout of the data, generated by 5 x VFE cards: 5 x 5 x 14bit @ (40 – 160) MHz ➔ (20 – 80) Gbit/s data transmission rate (per TT)
  - High quality clock to VFE for good (~30ps) time resolution
  - VFE components control
- Will be based on the CERN GBT, lpGBT, and Versatile_Link_+ products
  - lpGBT: up to ~10Gb/s data bandwidth
  - up to 8 optical links per FE (in case of 160MHz sampling without compression)



Test in 2016: FE deminstrator



Conclusions

- CMS ECAL crystal calorimeter show excellent performance (although suffering from ageing and radiation damage effects)
  - Fit to the new requirements in the barrel region (EB) $0 < \eta < 1.48$ and will remain operational
  - Too much damaged expected in the endcap region (EE) $1.48 < \eta < 3.0$ and will be replaced
- Upgraded EB on-detector electronics should:
  - Maintain high dynamic range and precision
  - Provide extended data bandwidth, longer pipeline
  - Allow spike filtering at the detector level, mitigation of the increased APD noise
  - Provide precision timing, sufficient for the vertex determination
- Require full refurbishment of EB on-detector electronics during LS3
  - Operation at 8°C to mitigate increase of the APD dark current
- After this upgrade ECAL Barrel calorimeter will maintain (or even improve) performance after more than 10 years of running and will be ready for another decade of operation