Prospects for a precision timing upgrade of the CMS $PbWO_4$ crystal electromagnetic calorimeter for the HL-LHC

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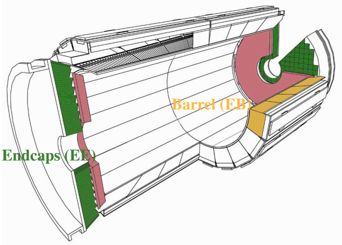
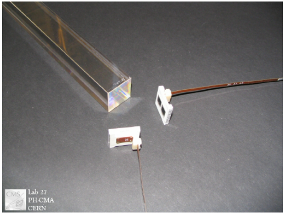
CMS ECAL detector





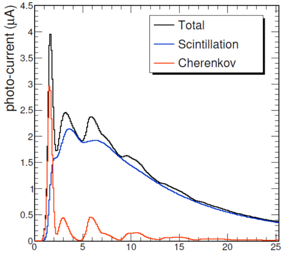
- **Compact, homogeneous, hermetic and fine grain** calorimeter made of:
  - **75848 lead-tungstate** ($PbWO_4$) **scintillating crystals** ($X_0 = 0.89$ cm, $r_M = 21.9$ mm, 25 ns scintillating time, radiation resilience)
  - Embedded in **4 T magnetic field**
  - **Scintillating light read by** avalanche photodiodes **(APDs) in EB** and vacuum phototriodes **(VPTs) in EE**
  - **Intrinsic light yield 100 γ/MeV** $\rightarrow$ 4 p.e./MeV on the APD pair
  - Detector designed for **excellent energy resolution for photons with 0.1 MeV-1.5 TeV**

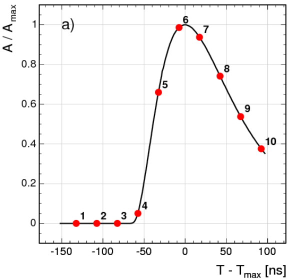
APDs (Hamamatsu S8148)

- Operated at a gain of 50
- High voltage bias of 380 V

Timing performance of ECAL

- **Exploit the timing resolution of the crystal+APD pulse shape**
- Scintillation light takes time to propagate and reach the photodetector → **90% of light yield collected within 25 ns**
- **Precise understanding of the pulse shape (Monte Carlo simulation)** → optimize readout electronics
- **Current pulse shapes:**
  - **Shaping optimized PhaseI conditions** (noise and <PU>)
  - **Electronics:** 43 ns shaping time and sampling ADC at 40 MHz
  - **Storing 10 samples:** 3 for pedestal, 3 for the rising and 4 for the tail
- **Initial ECAL requirement of timing stability within 1 ns** to ensure good energy resolution
- **Timing information extracted from the shaping time of signal** → timing resolution amelioration with faster shaping time

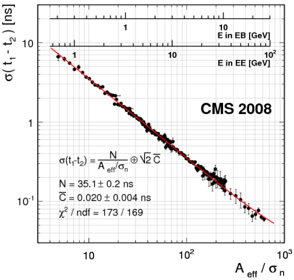




Current timing performance of ECAL

1. **Test beam: two neighbour crystals sharing the same e.m. shower energy** → constant term of 20 ps
2. **In situ neighbour crystals from the same e.m. shower and read out unit:** constant term of ∼67 ps → degradation wrt test beam due to timing calibration
3. **In situ electron showers from Z→ee decay:** resolution of ∼270 ps → additional degradation due to clock distribution

1)



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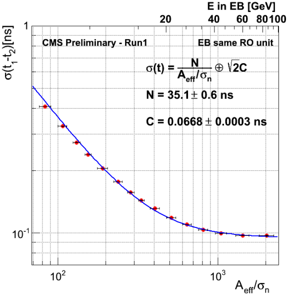

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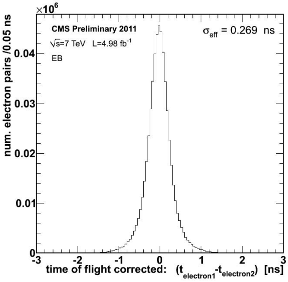
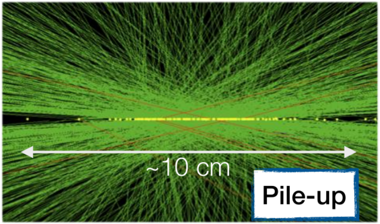


High Luminosity LHC

HL-LHC

- **L = 5x10^{34} cm^{-2}s^{-1}** (current L = 10^{34} cm^{-2}s^{-1})
- **L$_{int}$ $\sim$ 3000 fb^{-1}** (current L$_{int}$ $\sim$ 300-500 fb^{-1})
- **<PU>$\sim$140-200** (current <PU>$\sim$40-60)
- **Hadron fluence 10^{12} cm^{-2}** in EB (current 10^{11} cm^{-2})



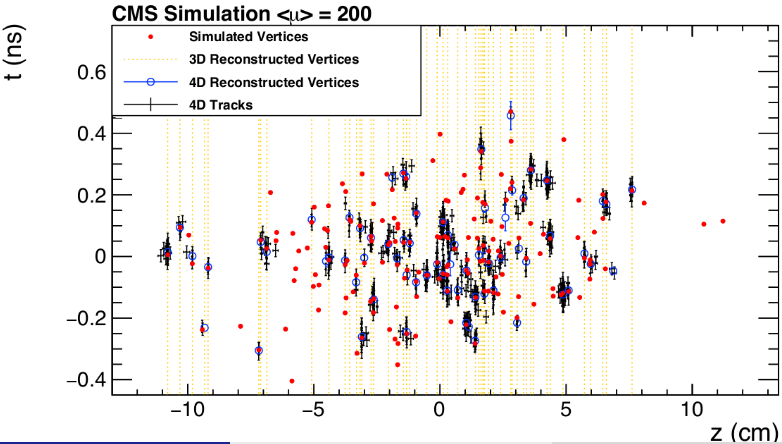
- **HL-LHC is a harsh environment**
  Increase of Trigger rate to retain comparable performance
- For **ECAL different strategy for EB and EE** (radiation dose 100 times bigger in EE)
  - **EE fully replaced:** high-granularity Silicon calorimeter (HGCAL)
  - **EB maintained:** upgrade of electronics

Additional improvement

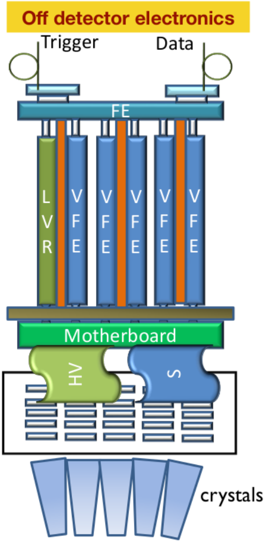
- **Precise measurement of the time of the energy deposits** ($\sim$ 20 ps) to separate events in time reducing the in-time pile-up contribution
- **Physics cases:**
  Vertex identification of the H$\rightarrow \gamma\gamma$ production (impact the diphoton mass resolution) $\rightarrow$ aiming 30 ps time resolution to retain current performance

Vertex Identification in HL-LHC

- **Timing information can be exploited in the vertex identification and reconstruction** $\rightarrow$ 4D vertex reconstruction simulated inefficiency $< 2\%$, assuming time resolution of 20 ps

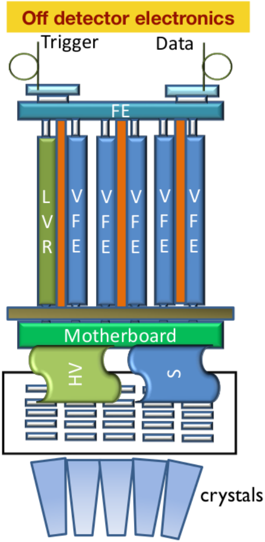


Current EB electronics



- **Basic read out unit:** 5x5 crystal matrix
- **Passive motherboard (25 crystals = 1 Motherboard):** HV to APD and signals to Very Front-End (VFE)
- **Very Front-End card:**
  - Each VFE accept has **5 channels** (1 Motherboard = 5 VFE)
  - **Preamplifier** (MGPA) with **43 ns shaping time + ADC** (12 bit)
- **Front-End card:**
  - Generates **trigger data** summing 5x5 signals
  - Separate readout from **data & trigger**
- **40 MHz readout of 5x5 matrix**
- **100 kHz readout of single crystals** for triggered events

Current EB electronics

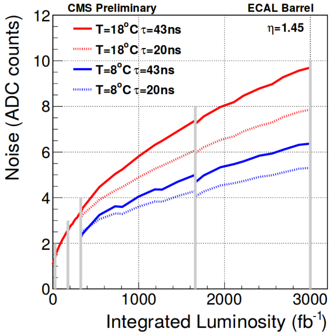


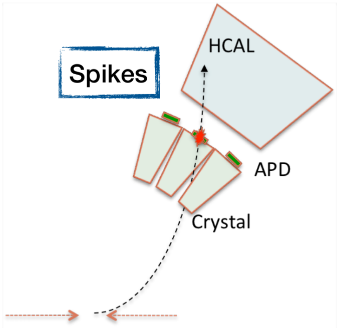
→ **REPLACE**

→ **KEEP**

EB Upgrade

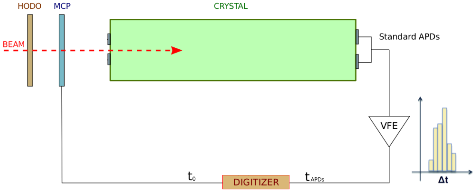
- **Increase trigger rate** to retain performance comparable to Run II → replace FE, VFE and off-detector electronics: main motivation for upgrade is matching 750 kHz accept rate and 12.5 μs latency
- **Mitigation of APD Noise** (dark current increase due to higher neutron fluence) → upgrade of cooling system: cooling temperature reduced to 10 or 8°C (now 18°C)
- **Improved spike** (hadron direct ionization signal in the APD) **rejection** → single crystal information in trigger + VFE fast shaping
- **Precision timing for e.m. signal is desirable** → new design for VFE electronics

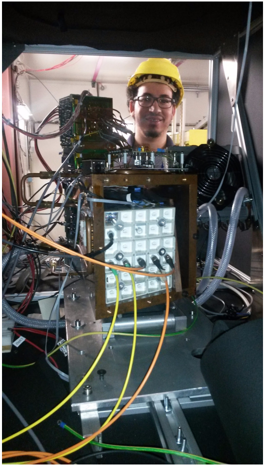




Test Beam Measurements

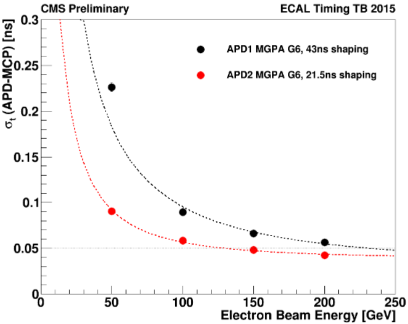
- Electron beam from CERN SPS, energies: 50, 100, 150, 200 GeV
- **CMS ECAL barrel configuration:** 23 cm $PbWO_4$ crystal+APD, signals sampled with a 5 GHz digitizer
- Measure **timing performance of $PbWO_4$ crystal** in response to electrons, **with different electronics configurations** (current and upgrade VFE), **different energy and different temperatures**
- Timing extracted from fit to the pulse shape
- Micro-channel-plate **(MCP) detector used as time reference** ($\sigma_t \sim 20$ ps)





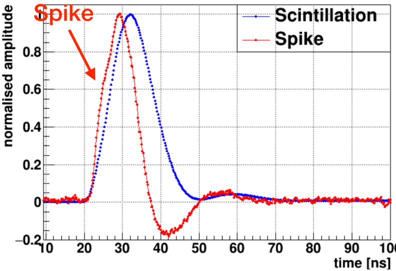
Test Beam Results: Shaping Times

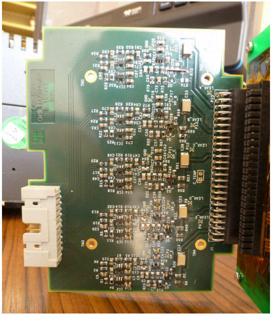
- Measure time resolution with **different shaping time** on current electronics
- The faster shaping time readout has **almost** twice $\frac{A}{\sigma_{noise}}$ (Signal amplitude/RMS noise)
- Test beam custom electronics with quite high noise → still **timing resolution below 50 ps for the faster shaping time at high energy**



EB Upgrade electronics

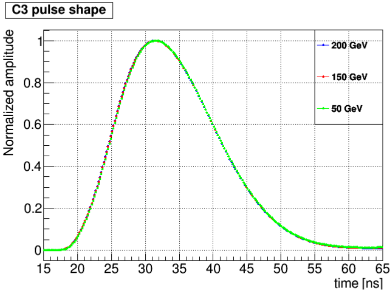
- Exploit the fast scintillation signal → **reduce the shaping time**
- **Cope with increased APD dark current**, better identification of the higher APD noise and higher data rates, induced by HL-LHC conditions
- **TIA (Trans-impedance Amplifier):** Design with dual gain trans-impedance amplifier, **focused on achieving optimal time resolution, very fast preserving the pulse shape**. **Discrete components of the TIA have been tested**.
- **ADC:** ADC with 12 bit resolution at 160 MHz sampling including data compression
- **Trigger-less streaming front end system** with precision sampling clock distribution and high speed data transmission towards the off-detector

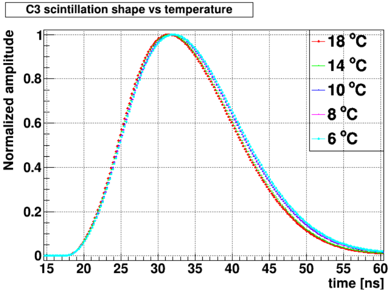




Test Beam Results: Pulse Shapes

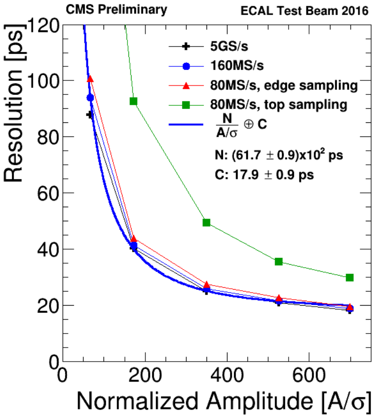
- Preamp output sampled at **High frequency (5GHz)**
- Different energies and temperature to check **electronics response:**
    - **Energy Scan:** Good stability with amplitude
    - **Temperature Scan:** 18-6°C, PWO_4 decay time depends on temperature, but the rise timing is almost unaffected





Test Beam Results: VFE with TIA

- **Offline reduction of sampling rate** to explore minimal digitization rate:
  - 160 MHz (baseline design) behaves as 5 GHz (intrinsic resolution)
  - 80 MHz are not enough for optimal timing resolution at all phases
- **Initial results on this prototype meet design specifics** → 30 ps resolution at $A/\sigma_{noise} = 250$
  - Equivalent to 25 GeV photons (at 100 MeV noise or HL-LHC start)
  - Equivalent to 60 GeV photons (at 240 MeV noise, HL-LHC end)

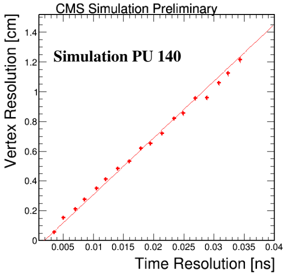


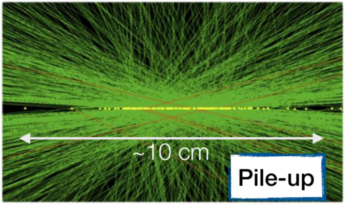
Summary

- CMS ECAL **Phase II upgrade is designed to cope with the HL-LHC extreme conditions**, providing also a global photon timing performance of 30 ps for photons from Higgs decays
- **Prototypes of readout tested in high energy beams meet the design goals**
  - Energy and temperature stability of the pulse shapes
  - Time resolution improvement with faster signal
  - 30 ps resolution for equivalent 25 (60) GeV photons at 100 (240) MeV noise
  - At test beam discrete components of the TIA have been tested. First chip will come towards the end of the year
  - Preliminary one crystal time resolution $\rightarrow$ evaluate many crystals time distribution in the future
- Additional upgrade precision timing capability **being investigated at test beam**

BACKUP

Photon Timing in H$\rightarrow \gamma\gamma$





Physics motivation

- **Clean and sharp signal,and low intrinsic background** $\rightarrow$ important for precision Higgs physics
- Standard candle for **Higgs self-coupling measurement**

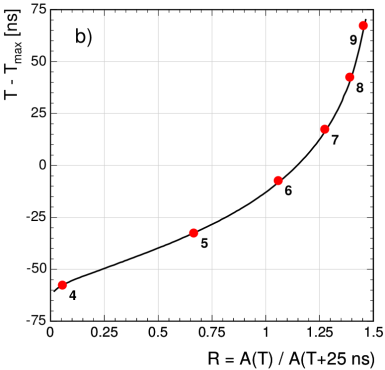
Vertex identification

- **Diphoton mass resolution depends on the vertex identification**
- Negligible energy resolution degradation if $\Delta z \lesssim 1\text{cm} \rightarrow$ **aiming to 30 ps time resolution after the upgrade**
- **Timing helps reducing the effective pile-up**

ECAL Timing Reconstruction

- **From pulse shape template fit**
  extract $T_{max,i}$ for each sample:
  $$T_{max} = \frac{\sum_i T_{max,i}/\sigma_i^2}{\sum_i 1/\sigma_i^2}, \frac{1}{\sigma^2} = \sum_i \frac{1}{\sigma_i^2}$$
- **Uncertainties coming from:**
  - Noise fluctuations in each sample
  - Uncertainty on the estimation of the pedestal value subtracted from the measured amplitudes
  - Truncation during 12 bit digitization
- Reference:

[1] The CMS Collaboration, "Time Reconstruction and Performance of the CMS Electromagnetic Calorimeter", JINST 5:T03011,2010, DOI:10.1088/1748-0221/5/03/T03011



Spike Rejection

- **Improved spike rejection at trigger level needed otherwise unacceptable rate:** spike rate increasing linearly with the PU
- Currently a **topological variable "swiss-cross" is used for rejection**
- **Pulse reconstruction with fast VFE electronics** can flag trigger information
- **TB results:**
  - Spikes produced in dedicated runs with hadron beam
  - **Test beam results show promising separation:** spikes have faster signal