Precision timing with $PbWO_4$ crystals and prospects for a precision timing upgrade of the CMS electromagnetic calorimeter at HL-LHC

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CALOR 2016

Outline

- Precise time measurement of EM clusters as pileup mitigation techniques for HL-LHC.
- ECAL timing performance during LHC operation at $\sqrt{s} = 8$ TeV.
- Test of $PbWO_4$ crystals timing resolution with electron beam.

Timing at HL-LHC

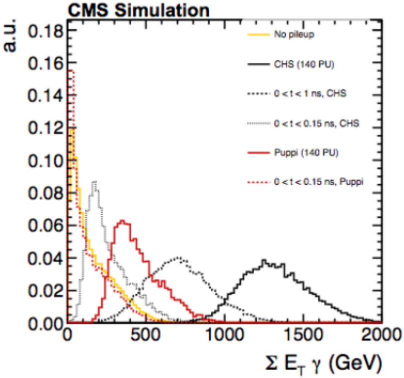
- High number of **concurrent interaction** (PU) expected for **HL-LHC** spoiling the event reconstruction.
- Precise time information of EM energy deposits provides a way to maintain the same performance of today.

QCD event, photons $\sum E_T$:

- No pileup interactions (solid yellow).
- 140 pileup interactions (solid black).

  CHS ➔track based charged hadrons cleaning.
- 140 PU + Puppi cleaning (solid red).

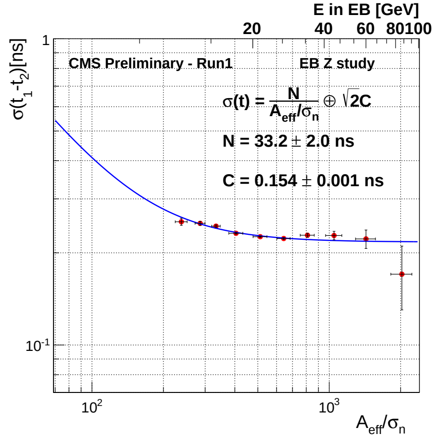
  Puppi ➔probability based charged and neutral hadrons cleaning.
- 140 PU + Puppi cleaning + **timing** (dashed red).



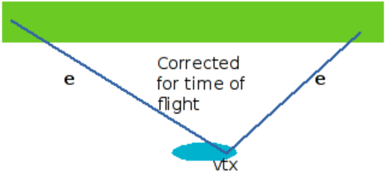
CMS ECAL current timing performance

- **Timing resolution of CMS ECAL better then 1 ns was not foreseen in the original design**, despite this:
  - → excellent timing resolution already achieved in 2012 (LHC collision @ 8 TeV).

***$Z \to ee$* events.**



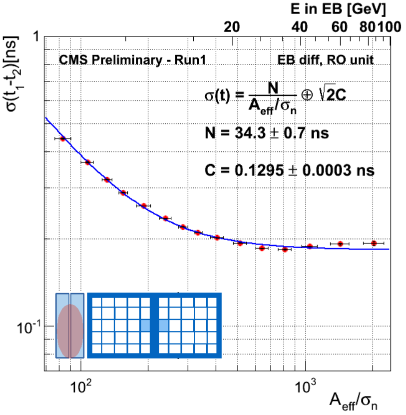
- Timing resolution estimated from fit to: $t_{channel\,1} - t_{channel\,2}$.
- Take the two most energetic channel for each electron cluster.



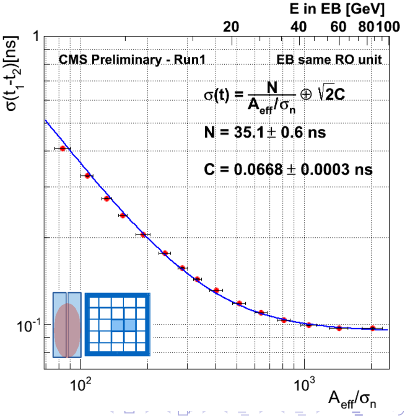
CMS ECAL current timing performance

- **Timing resolution improves for channels of the same cluster.**
- **Further gain when considering channels that belongs to the same readout unit.**

Channels in the **same shower** but **different readout units.**



Channels in the **same shower** and **same readout units.**

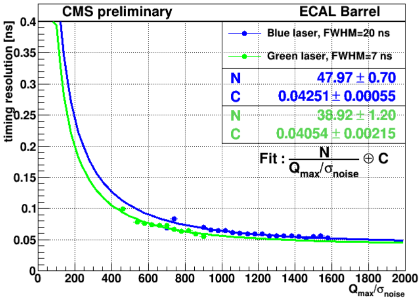


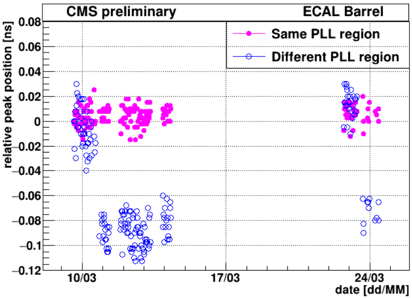
Timing resolution: effect of clock distribution stability

- Clock distribution checked using laser system.

- Many crystals illuminated at the same time, **across different readout units**.
- One crystal taken as reference (t_{ref}), timing resolution from fit to $\mathbf{t_{crystal} - t_{ref}}$.
- Timing resolution of ∼ **40 ps** measured, regardless of **same/different** readout units.

- Clock distribution **instabilities measured over time** (∼ 100 ps/days), between **different readout units**.
- Instabilities occur after system resets.
- Impact of instabilities measured as shift in signal peak position.



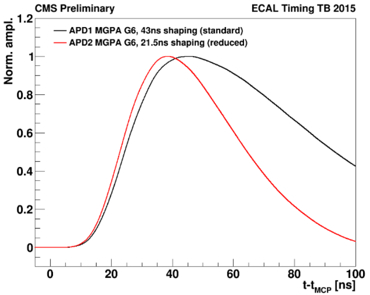


CMS ECAL electronics for HL-LHC

Improvements:

- Noise from APD leakage current.
  - ➔ increased by long exposure to radiation.
- Allow higher trigger rates.
- Mitigate pileup from previous and following bunch crossings.
- Mitigate signal contamination from concurrent interactions in the same bunch crossing (through timing).

Test beam: digitized APD signal



- Different solutions are under evaluation.
- Current ECAL electronics with faster shaping time could satisfy the requirements.
  - ➔ Shorter signal
  - ➔ Larger **Amplitude/noise**
  - ➔ **Better timing resolution.**

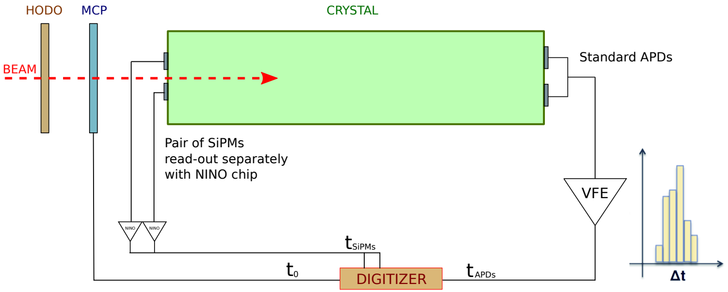
$PbWO_4$ intrinsic timing resolution: test beam

Test beam goals:

- Measure ultimate timing performance of **$PbWO_4$ crystal** in response to electrons.
- Timing resolution measured with external reference detector.
- Study impact on timing of **shower depth fluctuations**:
  - ➔ Standard CMS ECAL APD readout.
  - ➔ Additional SiPM light collection from the **front face** (opposite to the APD).
- Test different readout electronics configurations (different shaping times).

Test beam setup

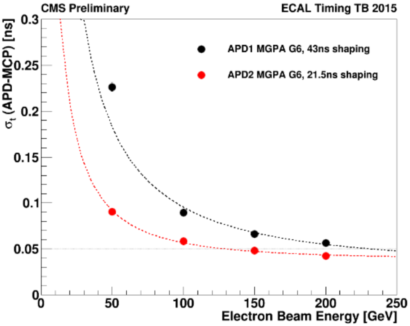
- Electron beam from CERN SPS, energies: 50, 100, 150, 200 GeV.
- Multi-channel-plate (MCP) detector used to measure electron time of arrival:
  ➔ **reference time**.
- CMS ECAL barrel configuration: 23 cm $PbWO_4$ crystal + APD.
- MCP, APD and SiPM signals sampled with a 5 GHz digitizer.



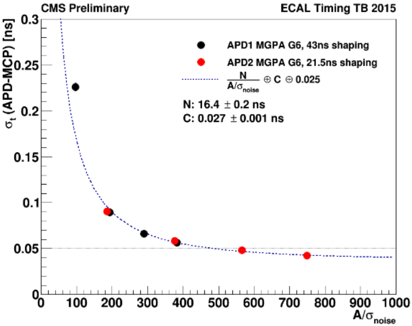
Test beam results: timing resolution with APD

- MCP resolution from independent measurement: **25 ps**.
- Faster shaping time readout has almost $\times 2 \frac{A}{\sigma_{noise}}$ (Signal amplitude/RMS_{noise}).
- **Test beam custom electronics source of additional noise:**
  - ➔ in CMS $A/\sigma_{noise} \sim 800$ for a 50 GeV shower.

Resolution vs Energy



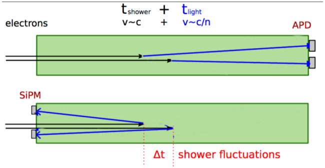
Resolution vs Amplitude/noise

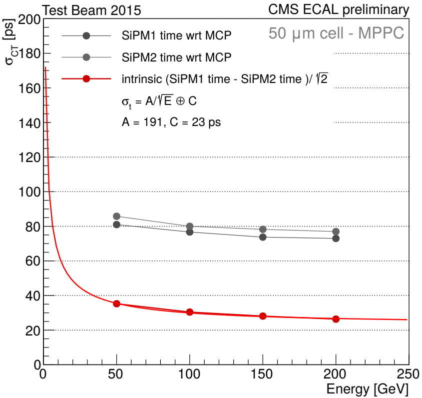


Test beam data: **Current ECAL (43 ns)** shaping time, **shorter (21.5 ns)** shaping time.

Impact of showers depth fluctuation on timing resolution

- Comparison with reference MCP time yields to a timing resolution **limited to 70-80 ps.**
- Coincidence between the two SiPM signals proves that SiPM has a $\sim$ **25 ps** resolution (constant term).
- Fluctuation in the light production depth affects timing from front face readout.
- **Back face readout (previous slide) not affected.**





Summary

- **Intrinsic timing resolution of $PbWO_4$ + APD system of the order of 50 ps can be achieved for shower above 25 GeV.**
- Clock stability needed to achieve excellent **detector wide** timing performance:
  - ➔ stability of $\sim$ **40** ps could be achieved with the current laser monitoring system.
- First test beam results on timing with front face light collection show poor performance compared to APD (back) readout:
  - ➔ **interpreted to be due to showers depth fluctuations.**
- Excellent ECAL timing resolution improves the event reconstruction at HL-LHC