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

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on behalf of the CMS Collaboration.

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HL-LHC and CMS upgrades

- **HL-LHC goal**: $\times 10$ **integrated luminosity** delivered to the experiments (ATLAS, CMS):

	LHC	HL-LHC baseline	HL-LHC ultimate*
$\mathcal{L}_{inst}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	2×10^{34}	5×10^{34}	7.5×10^{34}
PU (n_{vtxs})	40-60	140	200

*unexpected at the time of original ECAL TDR.

- **CMS upgrade**
  - ➔ Greater tracker ($|\eta| = 4$) and muon spectrometer ($|\eta| = 2.8$) acceptances.
  - ➔ Higher first level trigger (L1) rate: 100kHz ➔750kHz.
  - ➔ Tracking information at L1.
  - ➔ Detector upgrades to cope with larger radiation levels and higher pile-up.

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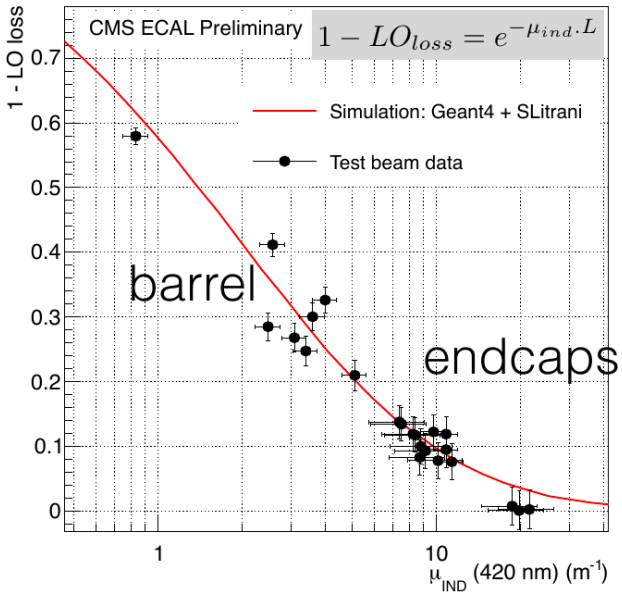
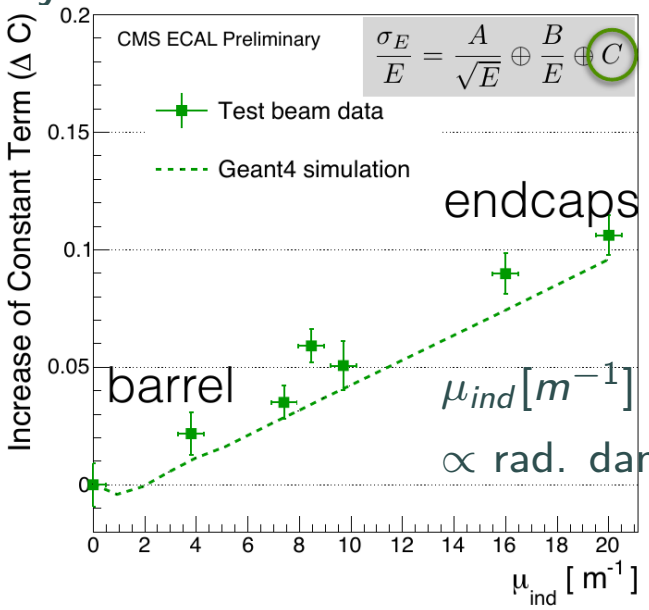
CMS calorimeters at HL-LHC

- **Endcaps**: complete replacement of current calorimeters to cope with expected radiation flux.
  - ➔ High granularity, silicon based, sampling calorimeter (HGCAL).
- **Barrel**:
  - ➔ **ECAL**: retain crystals+APD ➔upgraded readout electronics.
  - ➔ **HCAL**: Brass/plastic scintillator + SiPM.

Test with irradiated crystals in H4:



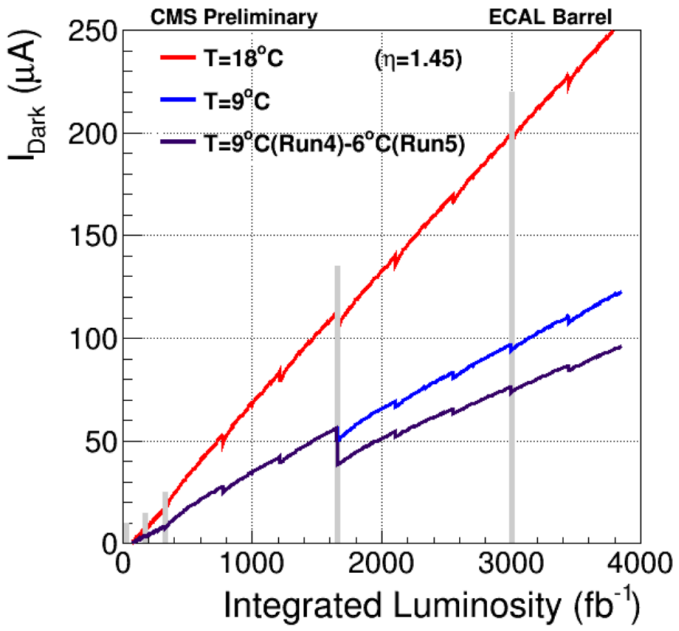


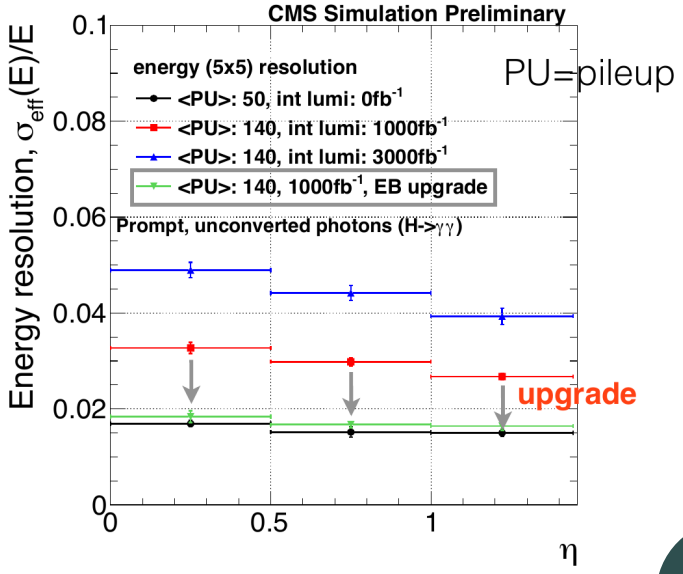
Barrel crystals will retain 30-50% of the light output after 3000 fb^{-1}.

Limited degradation of energy resolution.

ECAL APD performance

- ECAL barrel photo-sensors will continue to operate during HL-LHC:
  - ➔ Increase in APD leakage current due to radiation damage ➔**APD noise will dominate HL-LHC energy resolution**.
  - ➔ **Mitigation**:
    - ➔ **Lower ECAL operation temperature** $6 - 9^{\circ}C$ (now $18^{\circ}C$).
    - ➔ **Shorter pre-amplifier shaping time** (reduce PU impact, better S/N).

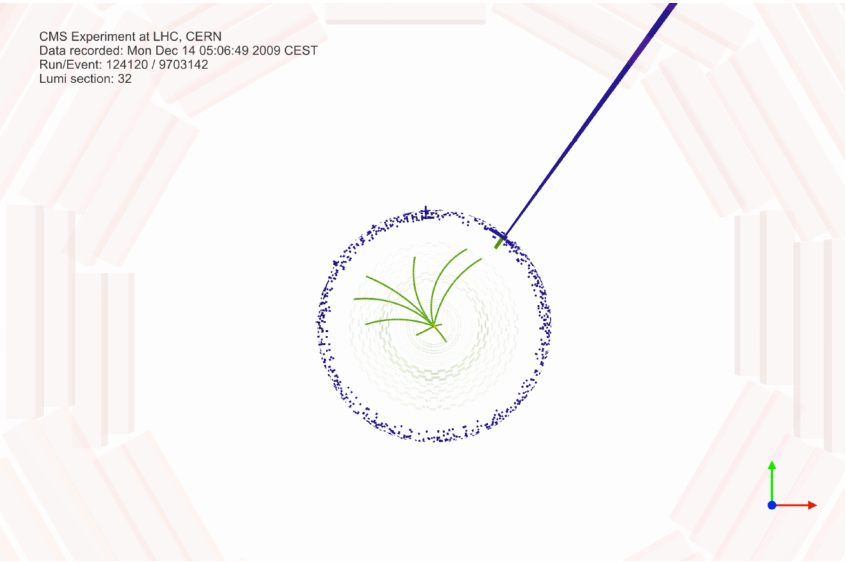




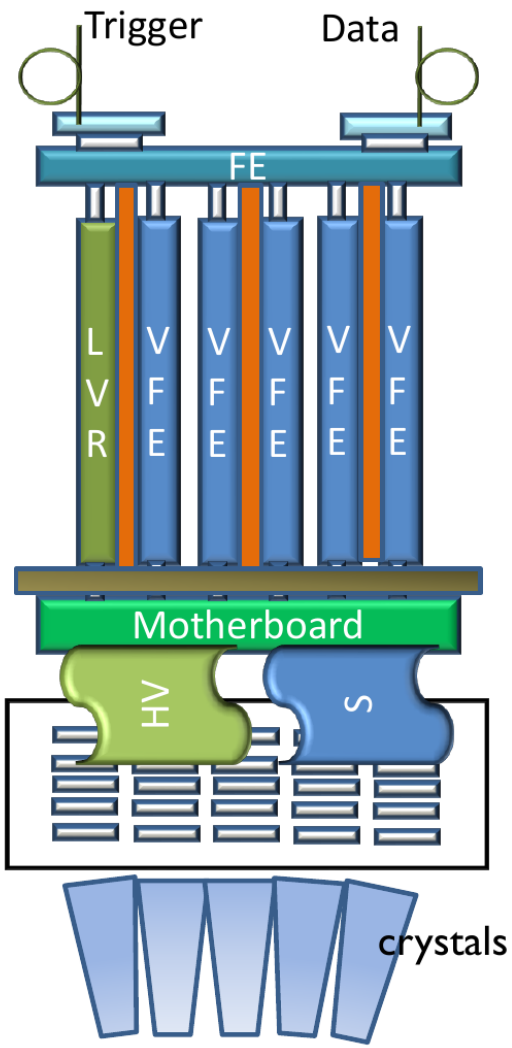
ECAL trigger

- **Improved Level-1 trigger capabilities needed at HL-LHC**:
  - ➔ **larger trigger rates (x 7.5)** and **trigger latency (12.5μs)** mandatory to exploit increased luminosity and implement Level-1 track-trigger.

- **Improved rejection of ECAL APD anomalous signals required**.
  - ➔ "Spike" from direct hadron ionization in APD volume.
    - ➔ Large isolated signals.
    - ➔ Faster signal than scintillation.
  - ➔ **Will dominate L1 trigger at HL-LHC if unsuppressed.**



ECAL upgrade key aspects

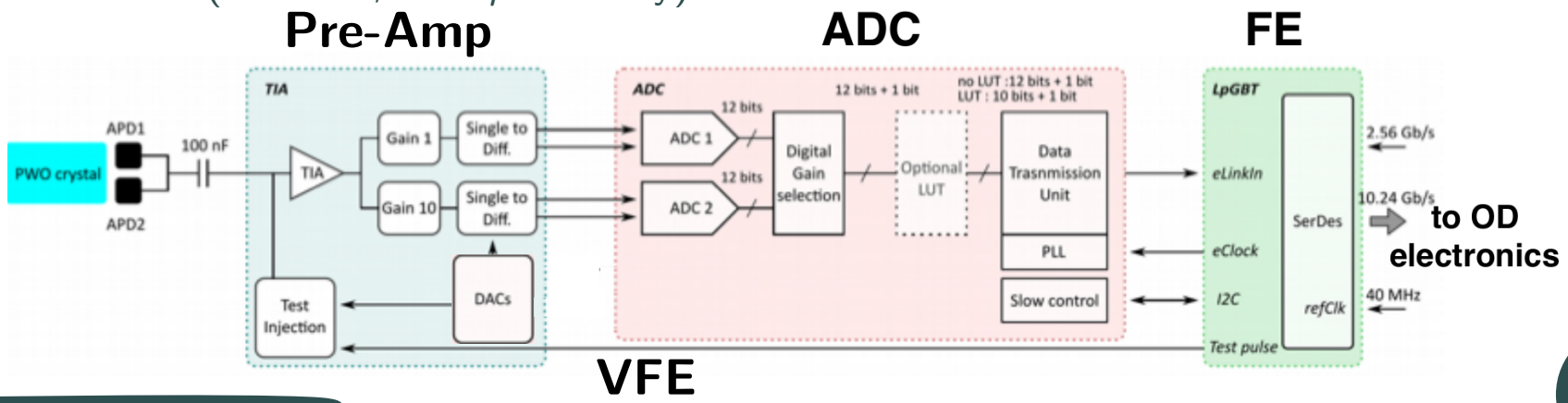


- **Replace off-detector electronics:**
  - ➔ To cope with higher output bandwidth from FE and upgraded CMS L1 trigger.
- **Replace on-detector electronics** (VFE and FE):
  - ➔ New amplifier + ADC running at 160MHz.
    - ➔ Spike rejection, pileup and noise mitigation.
    - ➔ Precise time measurement.
- **Run Colder:**
  - ➔ mitigate increase in radiation induced APD noise.

The upgrade will allow to exploit the full potential of the CMS ECAL during HL-LHC.

TDR design choices

- **Pre-amplifier:** Trans Impedance Amplifier (TIA) architecture:
  - ➔ matches the requirements for noise, pileup mitigation and CMS-wide effort for hermetic precision timing.
- **ADC designed chosen**: 12 bit, 160MHz sampling frequency.
  - ➔ Custom chip designed by external company + data compression system.
  - ➔ 2 TeV dynamic range, two gain ranges (G1, G10) with 50, 500 MeV LSB.
- **FE card design**:
  - ➔ Fast optical links to stream crystal data off-detector through CERN lpGBT/VL+ chip.
- **Off-detector electronics (OD)**:
  - ➔ FPGA based. Will provide single crystal information to L1 trigger (750 kHz, 12.5 μs latency).

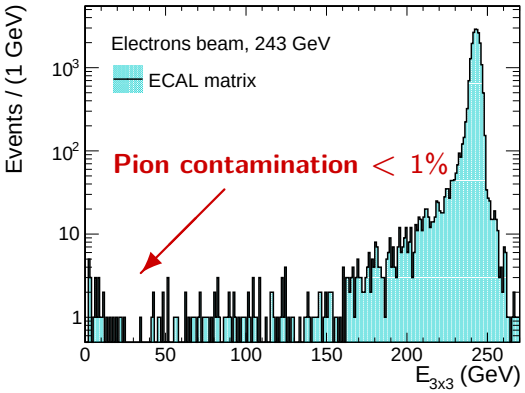


Beam configuration at the CERN SPS North Area

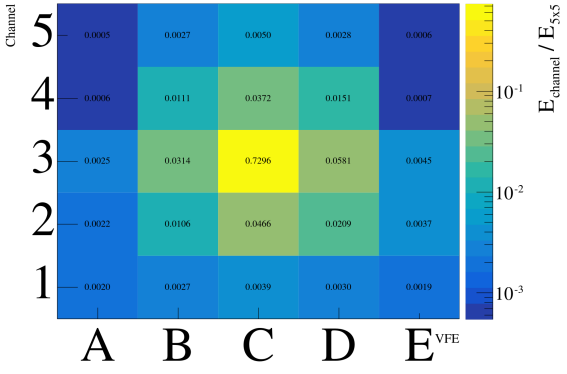
- Series of tests performed at the H4/H2 beam lines:
  - ➔ **H4: very pure electron beam** $\Delta p/p = 0.5\%$ with $20 < p < 250$ GeV.
  - ➔ Beam time in H2 exploited to collect sample of APD direct hadronic ionization signals using pion beam.

    Slot originally assigned to CMS-HCAL. Shared with CMS-iTK
  - ➔ **Excellent support from SPS team** (in particular **N. Charitonidis** and **B. Rae**) **allowed us to take high quality data efficiently**.

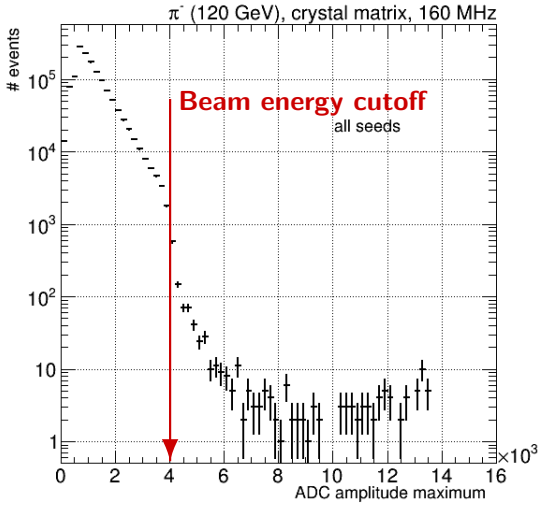
Trigger only selection. e^- beam in H4.



EM-shower shape with e^- beam in H4.



Pion beam in H2

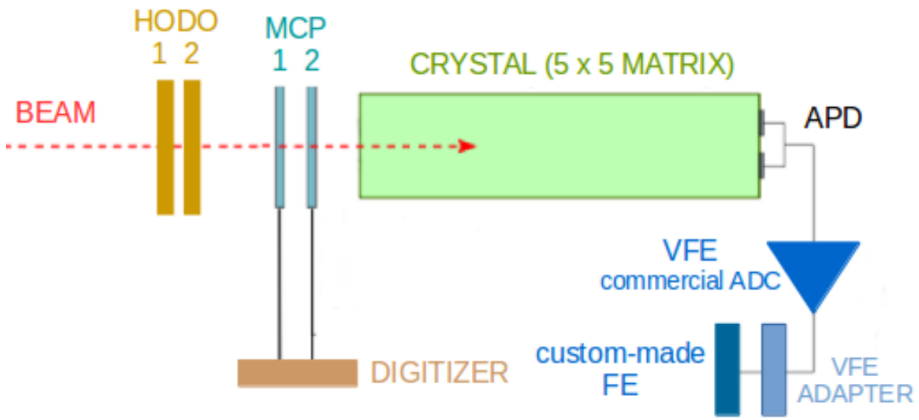


Test beam setup infrastructure

- On the H4 line setup hosted in the CMS-ECAL air-conditioned experimental area (18 °C).
- **Remote controlled cooling unit and movable table easily operated through DAQ GUI** (also for different setups: CMS-MTD, AIDA2020, ...).
- **Trigger counters and reference detectors installed just upstream of R&D setup.**

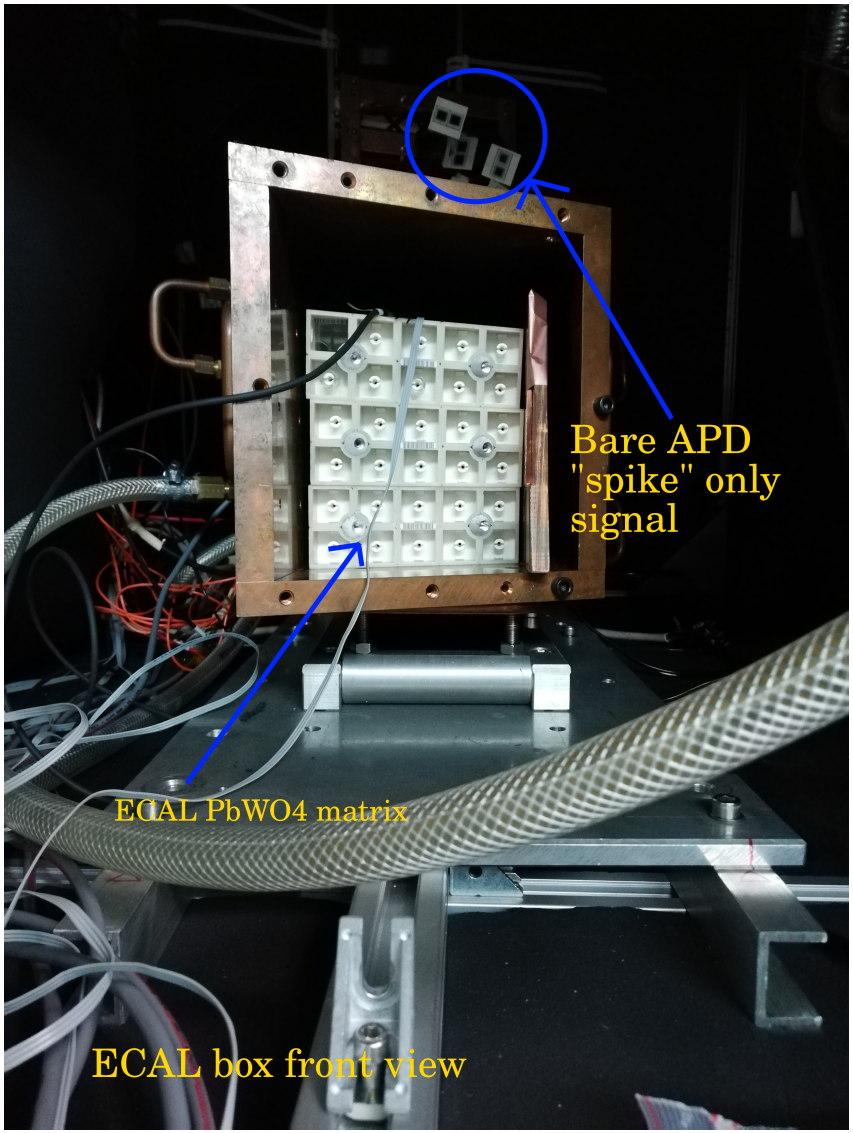
➔ Plastic fiber hodoscopes for position measurement.

➔ A pair of **Micro channel plates devices** (1.2 cm diameter, thickness $< 1X_0$) provide a **precise reference time**. MCP signals sampled by a DRS4 chip (CAEN V1742 board, 5 GS/s) [1].

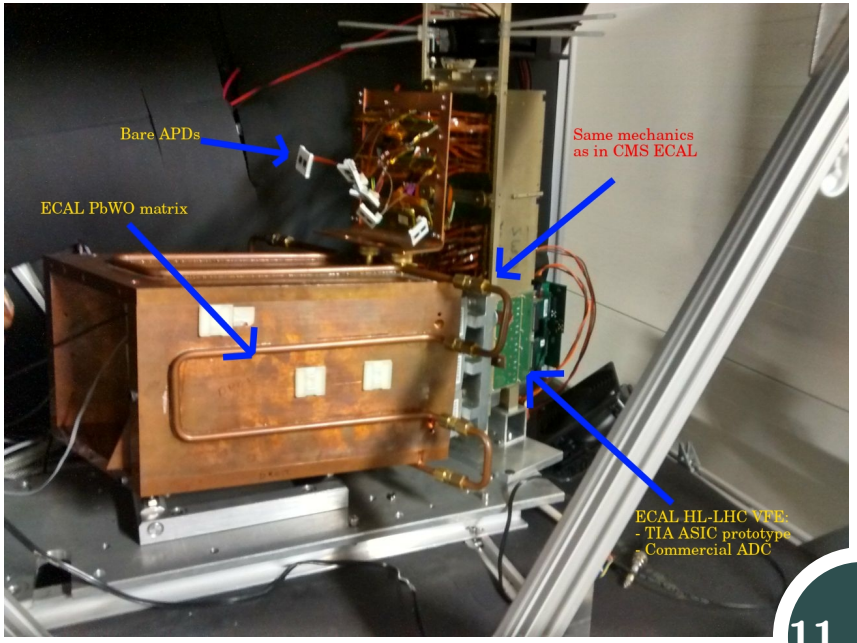


Custom DAQ, see Giacomo's talk

ECAL HL-LHC R&D setup



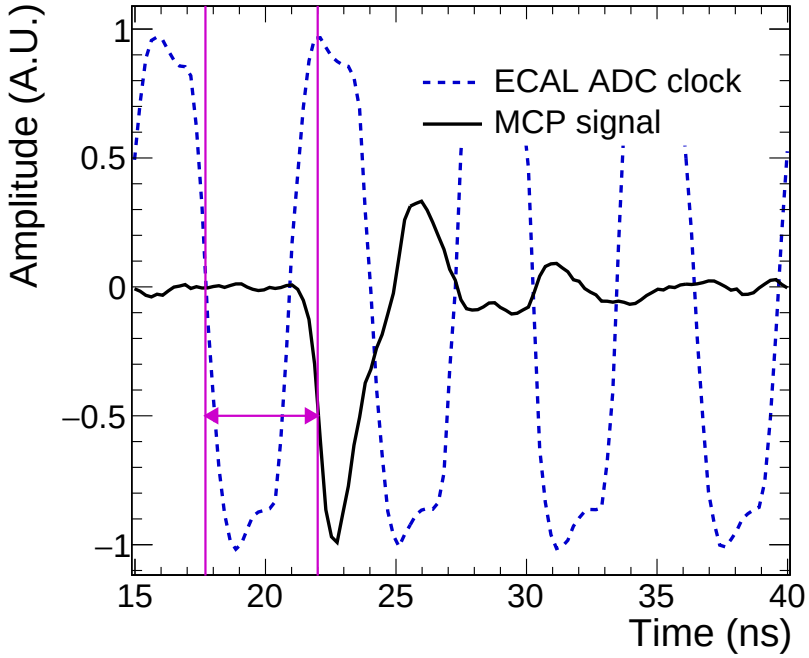
- **One ECAL tower reproduced in R&D box:**
  - ➔ Same noise condition of CMS can be achieved with HL-LHC prototypes.
  - ➔ Cooling available: 9 - 18 °C.
  - ➔ Bare APDs also installed to study direct ionization signals.



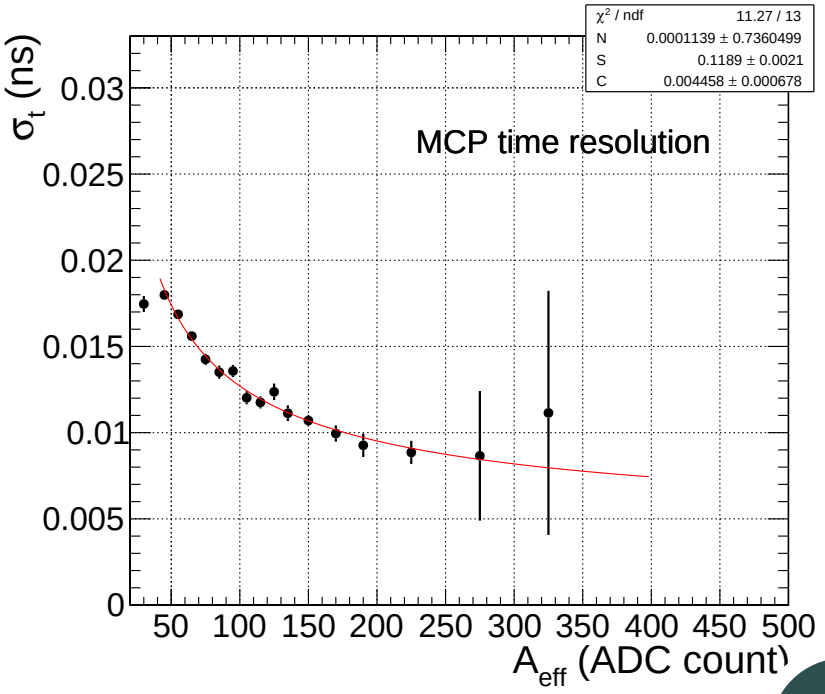
Reference time reconstruction

- DRS4 ([2]) and ECAL readout synchronized by reading out the ECAL clock with the same DRS4 chip used for the MCPs.
- Dedicated DRS4 calibration to achieve best time resolution with the MCPs:
  - ➔ ADC calibration.
  - ➔ Cell-to-cell time delay calibration.

MCP and ECAL sync

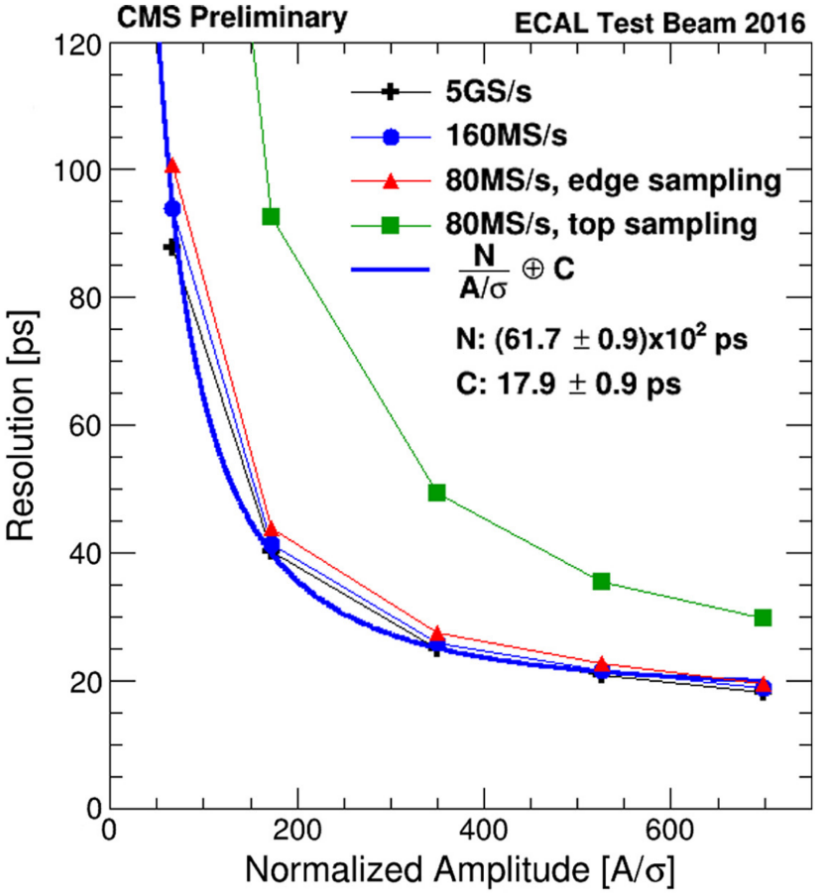


MCP time performance



Impact of ADC sampling frequency

- Setup: $PbWO_4$ + APD + discrete component TIA + DRS4 readout. **Noise different from real detector.**
- Different ADC sampling frequency emulated offline by sampling the 5 GS/s signal from the DRS4:
  - ➔ **Results prove that 160 MHz sampling is optimal to achieve the best time resolution.**
  - ➔ **Lower sampling frequencies performance depends on relative phase between APD signal and ADC clock.**

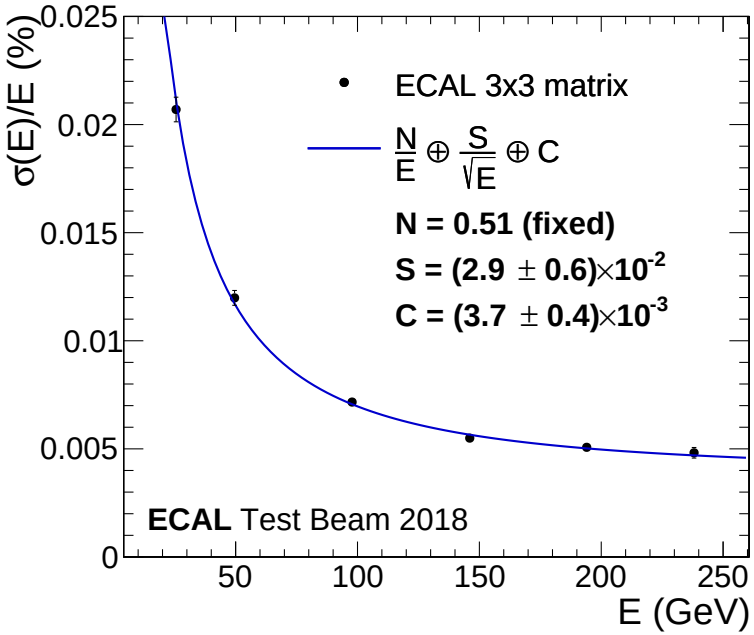


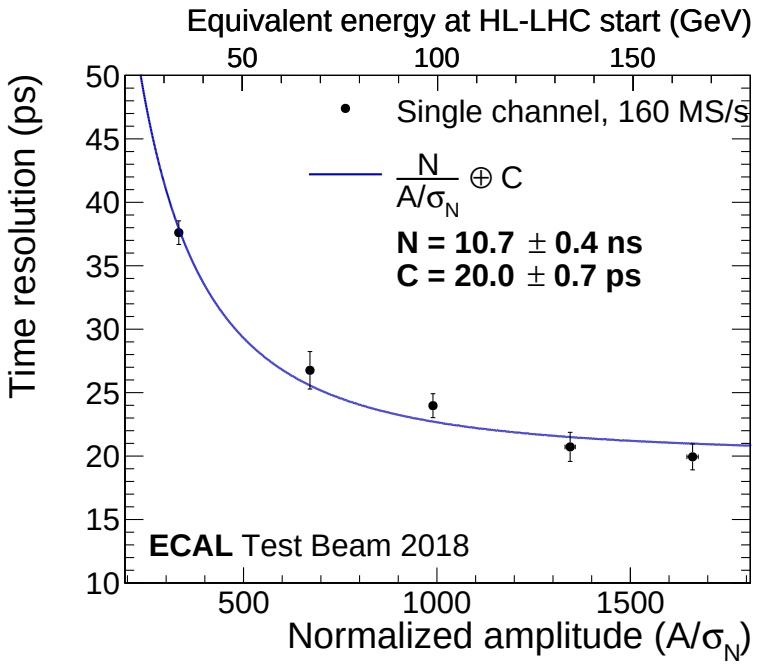
First results with ASIC prototype

- One ECAL tower (25 channels) equipped with first prototype of HL-LHC ASIC amplification chip and 160 MHz commercial ADC.
- Electron beam, 25-250 GeV energy range. Setup kept at 18 °C.
- **Preliminary results:**
  - ➔ **Energy resolution performance matches LHC legacy electronics.**
  - ➔ **Excellent time resolution, $\sigma_t < 40$ ps:**

    $E_{EM-shower} > 30$ GeV (HL-LHC start).

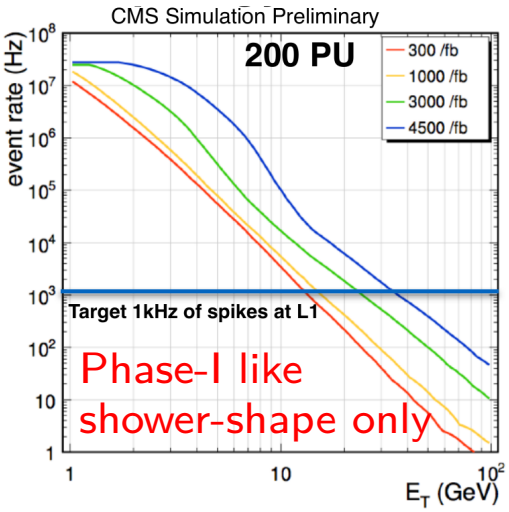
    $E_{EM-shower} > 75$ GeV (HL-LHC end).

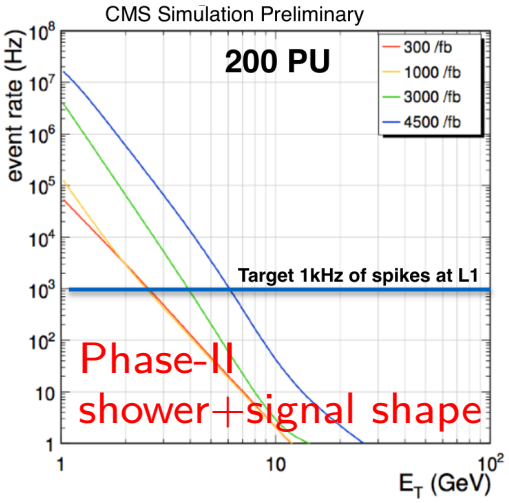




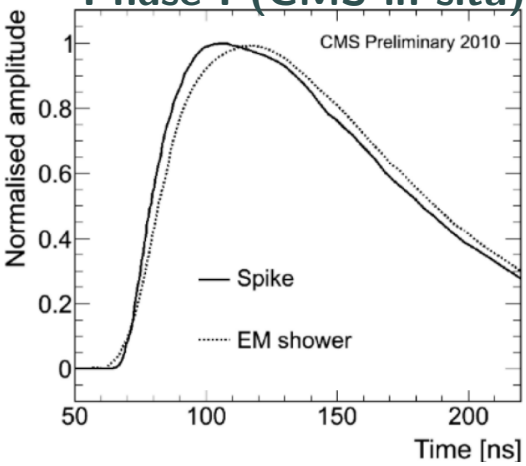
ECAL upgrade impact on trigger

- **Spike suppression target: 1kHz @ L1 trigger** ($E_T > 5$ GeV).

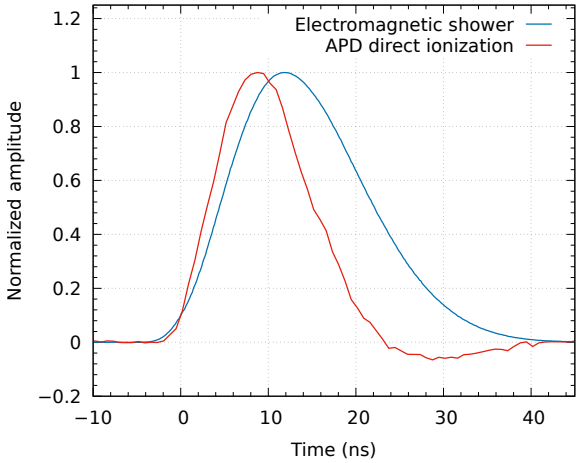




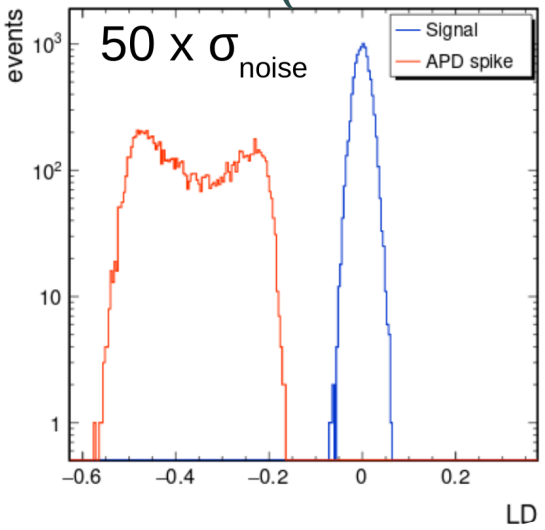
Phase-I (CMS in-situ)



Phase-II (π/e TBs)

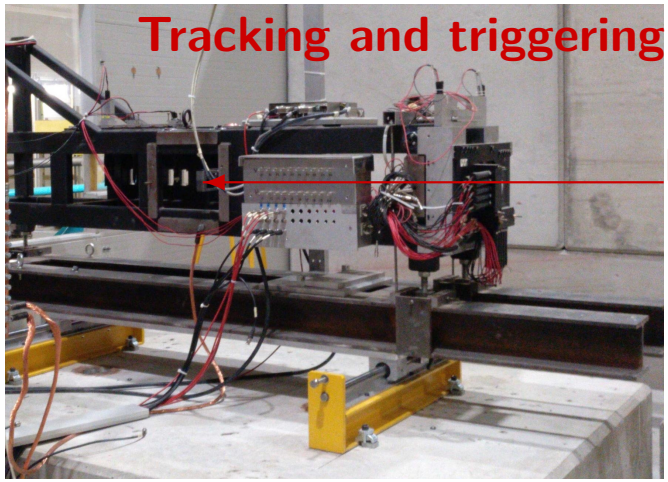


Example of signal shape discriminant (TDR simulation)



Plans for test beams in Run 3

- **Test with spare supermodule:**
  - ➔ Test full HL-LHC electronics chain: VFE + FE + DAQ.
- **CMS-ECAL area in H4 upgrade LS2:**
  - ➔ Supermodule support table refurbishment.
  - ➔ Room and SM cooling upgrade to run at 9 °C.
  - ➔ Tracking telescope and reference detectors upgrade.



Spare SM (1700 channels)

Summary

- **HL-LHC demands a general upgrade of the CMS detector in order to provide required performance:**

- The CMS ECAL barrel electronics will be upgraded:
  - ➔ Mitigate noise and pile-up impact.
  - ➔ Improve trigger capabilities.
  - ➔ Add precise time information to the event reconstruction.

- Series of **test with electron and pions beams** performed during Run 2:
  - ➔ **TBs have been crucial to test new electronics design.**

- New electronics **maintains excellent energy resolution** and provides **signal shape analysis and precise time reconstruction** capabilities.