The CMS ECAL upgrade for precision timing measurements at the High-Luminosity LHC

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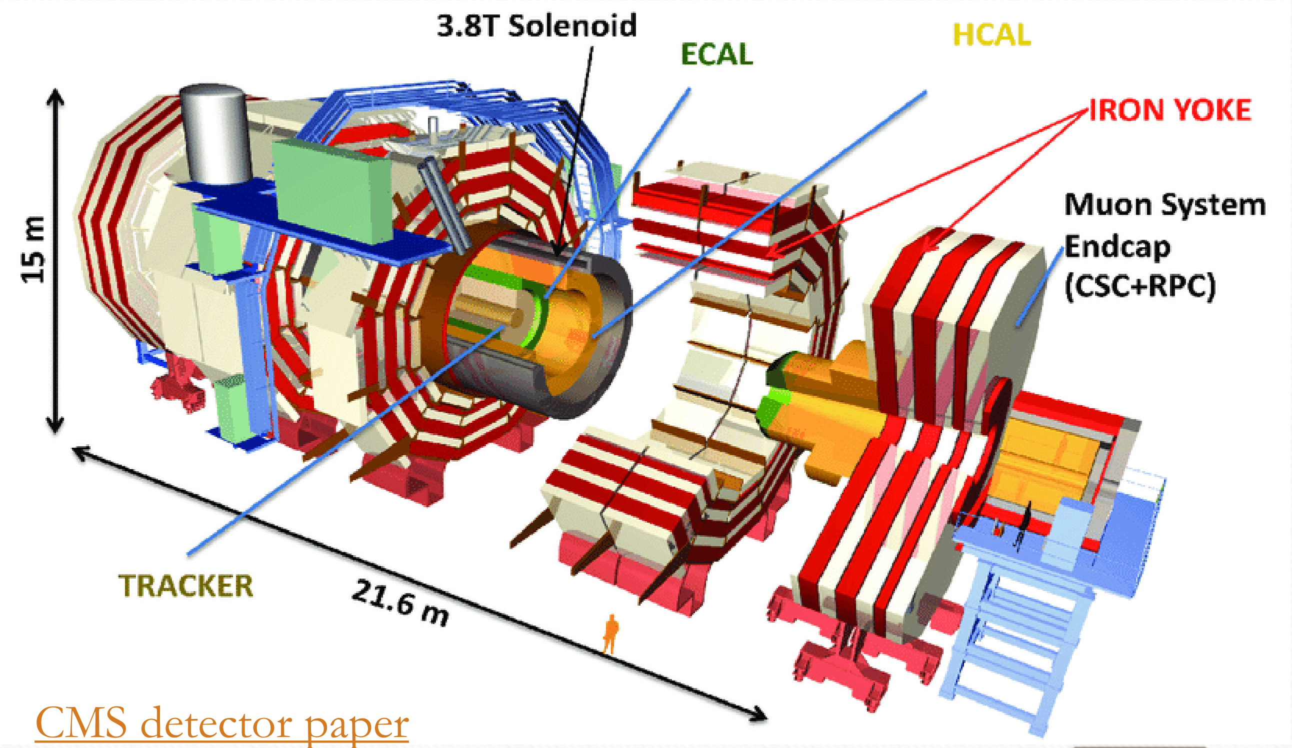
Compact Muon Solenoid

The CMS is a multi-purpose particle detector at the CERN Large Hadron Collider (LHC).
Central feature is a superconducting **solenoid** of 6m internal diameter, providing a magnetic field of 3.8 T.



CMS detector paper

Within the solenoid volume, there are:

- a silicon pixel and strip tracker
- a lead tungstate crystal electromagnetic calorimeter (**ECAL**)
- a brass and scintillator hadron calorimeter

Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

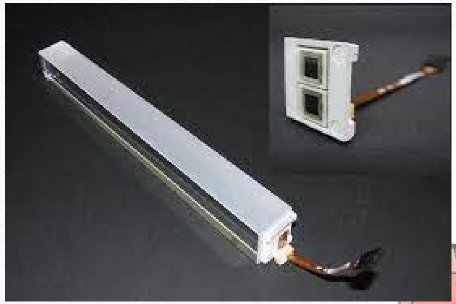
CMS has a two-tiered trigger system:
L1 trigger (40 MHz → around 100 kHz) and HLT (100 kHz → around 1 kHz)

Electromagnetic Calorimeter

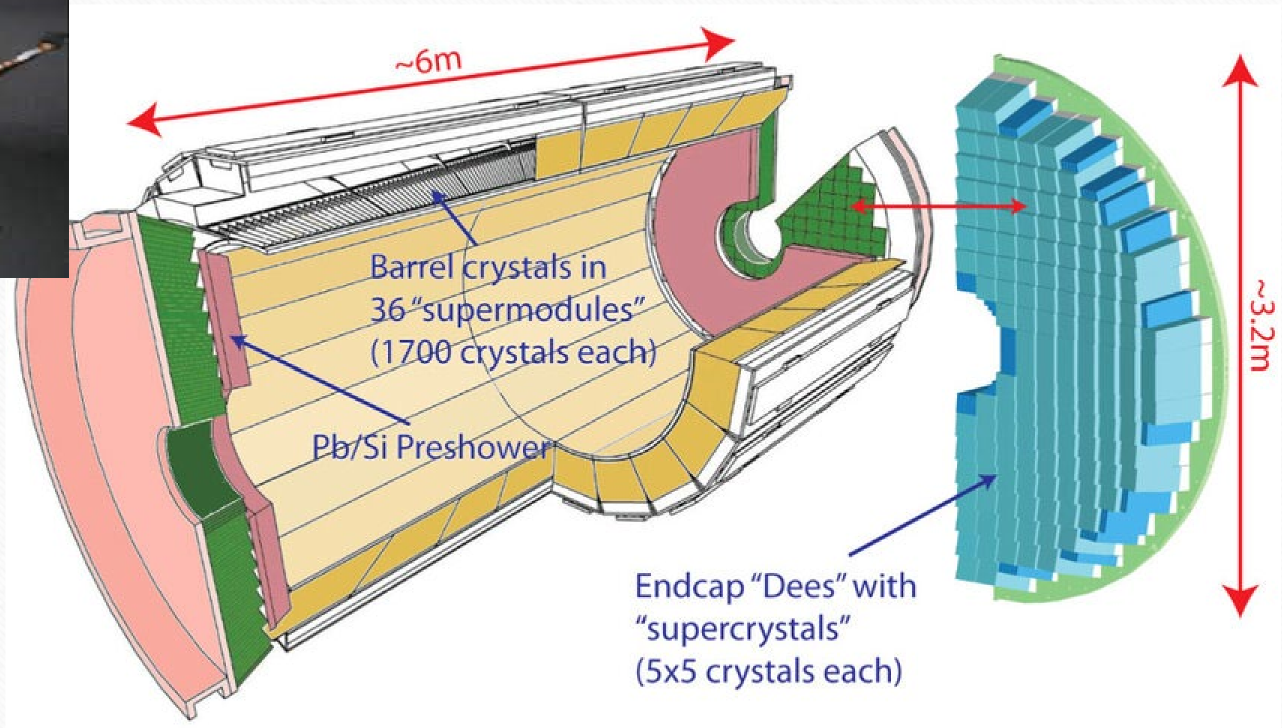
The CMS ECAL is a Lead Tungstate ($PbWO_4$) crystal hermetic homogenous calorimeter. This detector consists of a central part (**barrel**) and a forward part made of two endcaps with a Pb/Si Preshower in front.

Barrel: 61200 $PbWO_4$ scintillating crystals

- high density, small X_0 and R_M, fast decay time
- each crystal has two silicon avalanche photodiodes (APDs) at the rear face
- excellent energy resolution for electrons and photons.

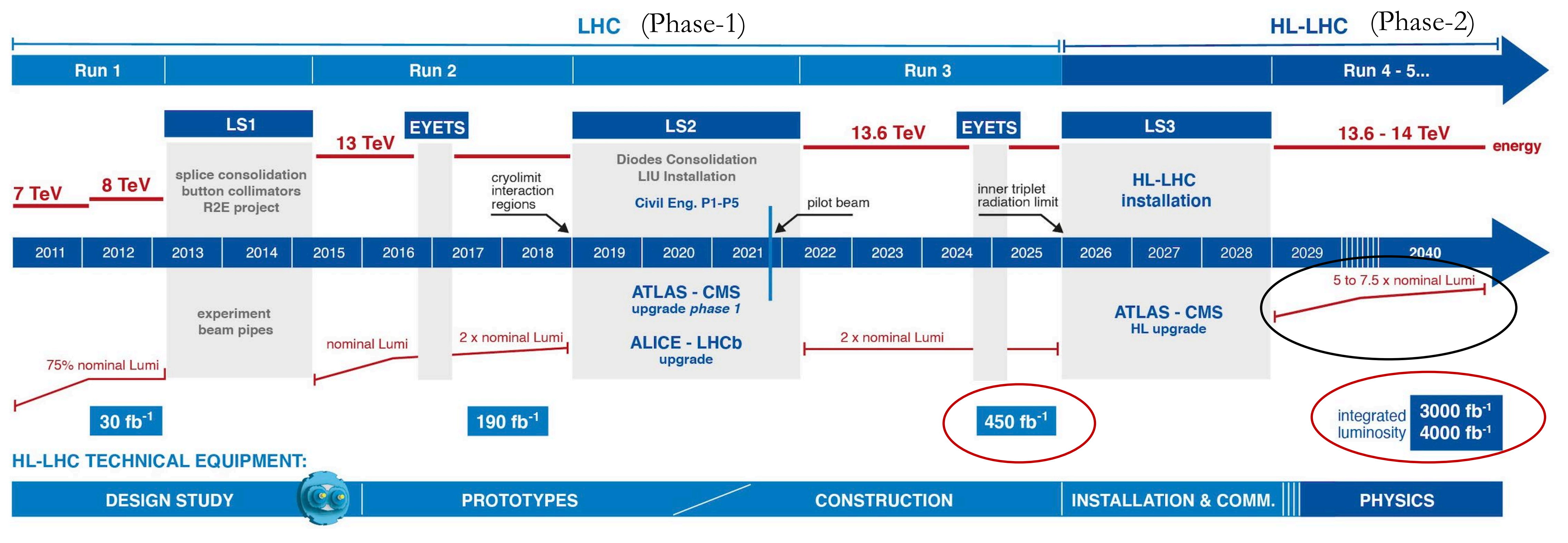


The forward part will be replaced by a new detector, the High Granularity Calorimeter (HGCAL) for the HL-LHC



ECAL Technical Design Report

High Luminosity LHC Plan



Nominal instantaneous luminosity: 10^{34} cm^{-2} s^{-1}

The integrated luminosity will be about ten times the expected luminosity of the Phase-1 (2011-2025).

HL-LHC Challenges

The current detectors were designed for 10 years running and L=500 fb^{-1}.

End of HL-LHC: 30 years of data-taking and 3000-4000 fb^{-1} → <u>ageing and irradiation</u>

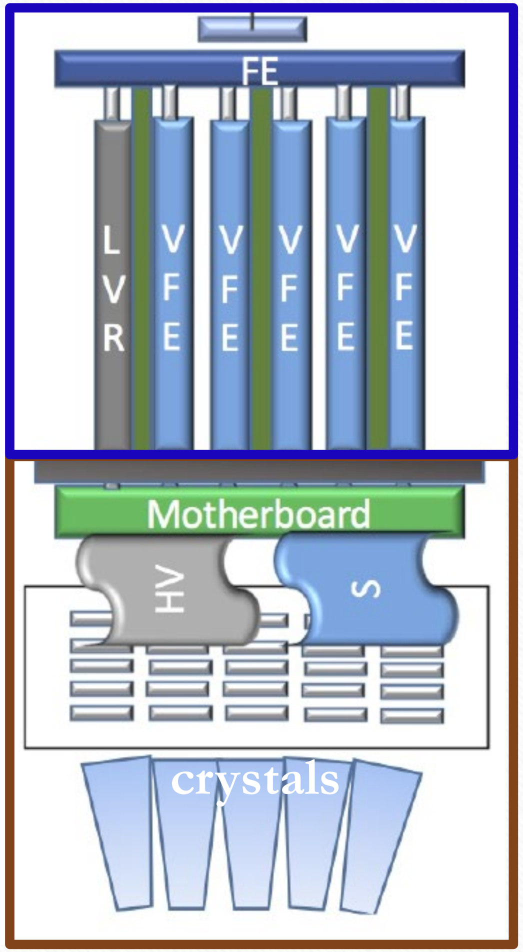
- The ECAL barrel on-detector electronics will undergo an accumulated irradiation of ~6 kGy at the end of the HL-LHC
- The average number of proton-proton interactions per bunch crossing (pileup) will increase up to 4 times w.r.t. phase1 (140-200): critical for vertex identification in $H\gamma\gamma$.
- The CMS L1 trigger rate will be increased up to ~750 kHz with the latency increased from 4 μs to 12.5 μs → **<u>ECAL electronics to be changed</u>**.

Moreover, on the electromagnetic calorimeter:

- With the legacy system the L1 trigger bandwidth would be saturated by the ECAL anomalous signals (spikes), the rate of which is proportional to the amount of pileup.
- APD dark current will critically increase the noise term of the ECAL energy resolution.

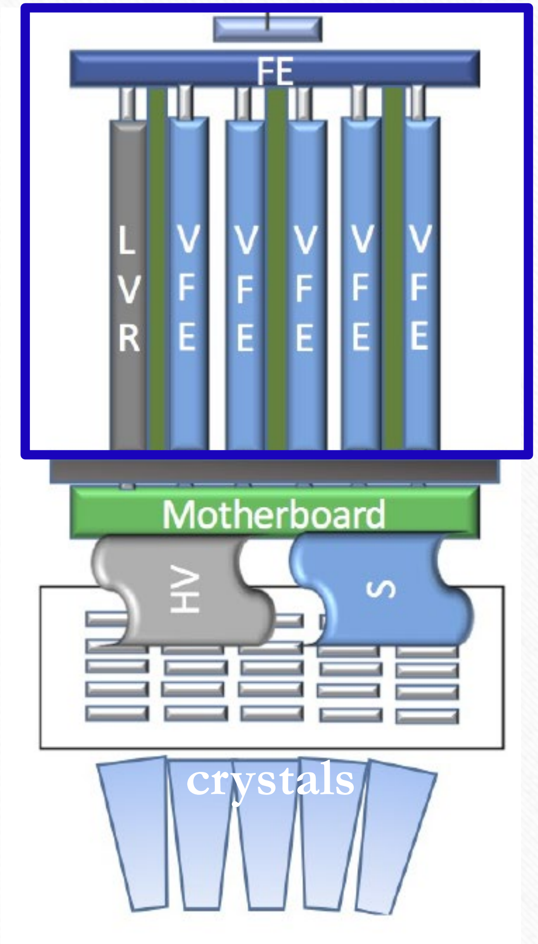
The ECAL Upgrade in two slides

- EB upgrade crucial to maintain the Phase-1 physics performance for photons and electrons also during HL-LHC.
- Goals of the EB upgrade: accommodate the Level-1 trigger requirements on latency and rate, provide more precise timing resolution, and help mitigate the increasing noise from the photodetectors.
- The lead tungstate crystals, the EB photodetectors and the Motherboards will be kept for the HL-LHC phase.
- The upgrade goals can be achieved through the replacement of the VFE+FE cards and back-end, together with the associated low-voltage distribution system and optical links.



The ECAL Upgrade in two slides

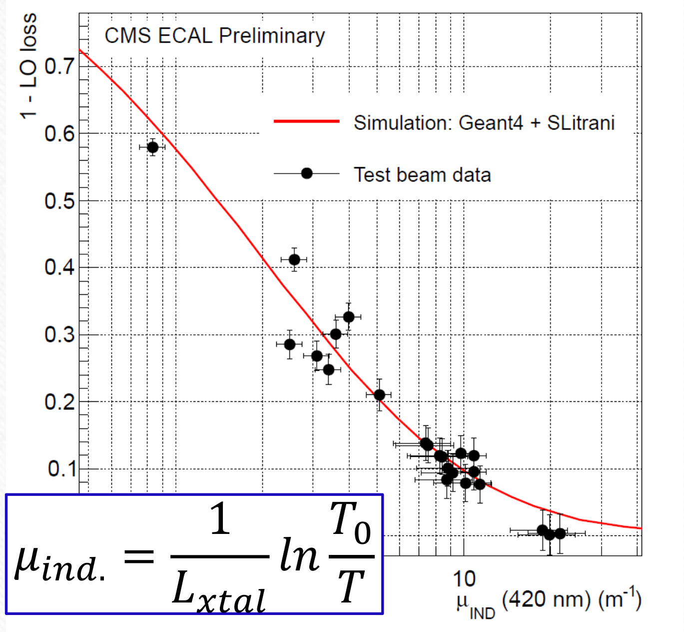
- New on-detector cards: more radiation resistance, narrower pulse shape and increased sampling rate (x4) → spike suppression at L1, improved timing resolution and APD noise mitigation.
- The operating temperature of EB will be decreased from 18 °C to 9 °C → APD dark current reduction.
- Single crystal information to the Level-1 calorimeter trigger (5x5 crystal tower in the legacy system) → better trigger performance and spike rejection.
- The Level-1 trigger pipeline and the trigger primitive generation will be off-detector (on-detector in the legacy system).

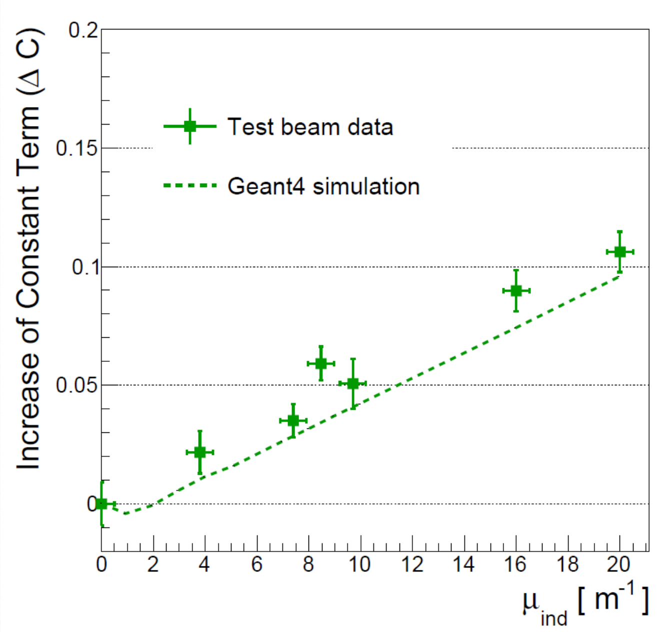


ECAL upgrade TDR

Longevity of $PbWO_4$ crystals

- The scintillation mechanism is not affected by radiation. Instead, the radiation creates crystal defects which reduce the crystal transparency and consequently the light output (LO).
- The hadron-induced component of the crystal radiation damage not recoverable: will be monitored with the ECAL laser system (as during LHC Phase-1).



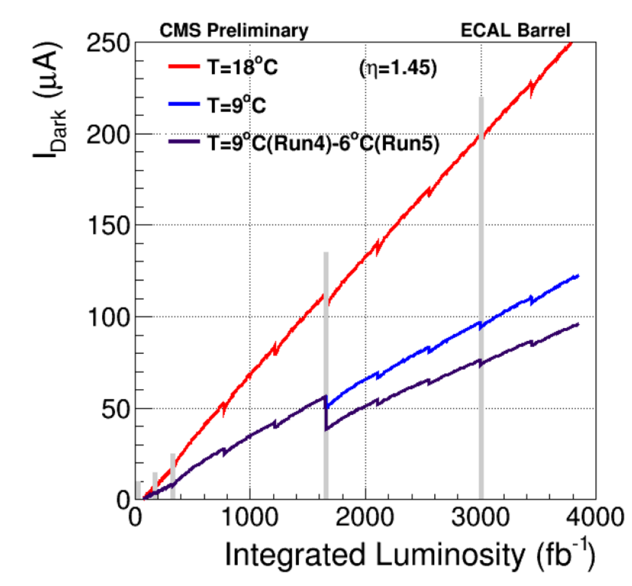


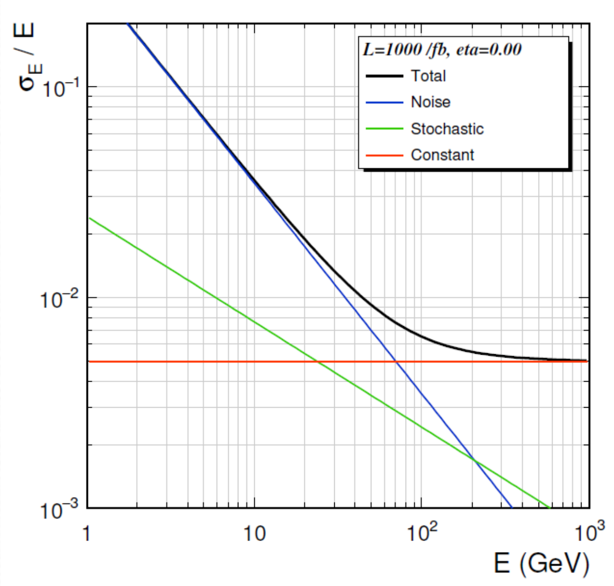
Energy response linearity (and therefore the constant term of the energy resolution) modified by the non-uniformity of light collection.

At the end of HL-LHC barrel crystals will retain 30-50% of the light output, sufficient to be kept for Phase-II.

Longevity of APDs

- The APD leakage current grows due to the radiation damage (bulk damage of the silicon).
- The electronic noise contribution in the energy resolution increases as the square root of the current.
- To mitigate the increase in APD dark current:
  - baseline EB operating temperature for LHC Phase-2 will be reduced from 18 °C to 9 °C (6 °C).
  - narrower pulse provided by the new VFE card.





Noise term in the energy resolution down to a level comparable with the constant term, for the range of Hgg photon energies.

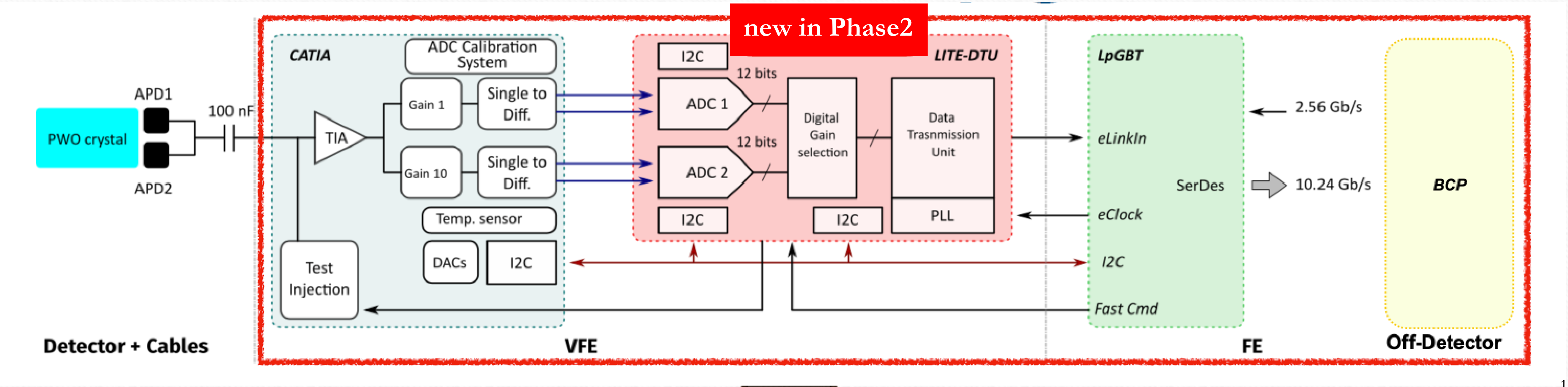
New on-detector electronics

Very Front End (VFE) card:

- Calorimeter Transimpedance Amplifier (CATIA) ASIC
- Lisboa-Torino ECAL Data Transmission Unit (LiTE-DTU) ASIC

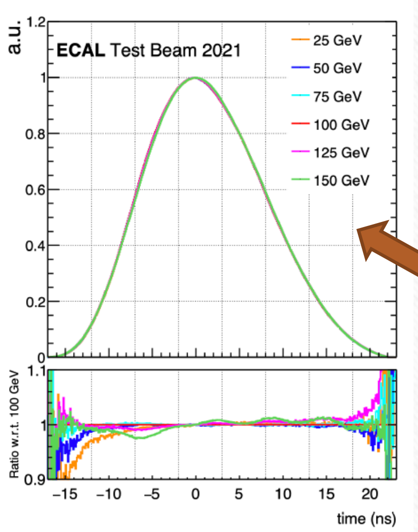
Front End (FE) card:

- low power Gigabit Transmission (lpGBT)



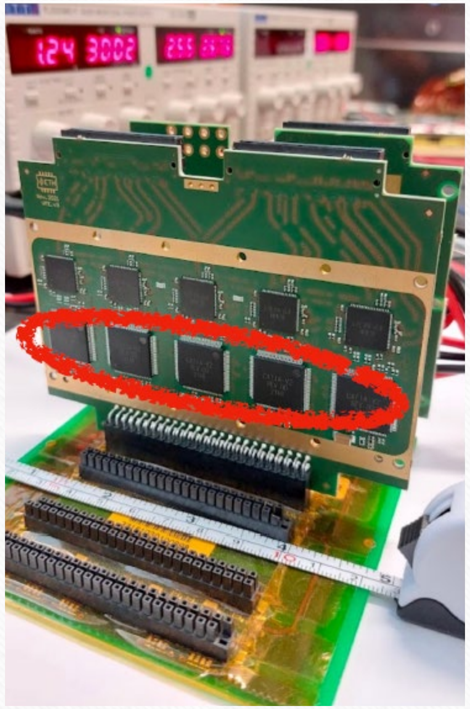
CATIA

- The ASIC Trans-Impedance Amplifier outputs a voltage image of the photocurrent generated by the APD.
- Two output gains are used to cover the full dynamic range of the signals: gain 10 for low energy (50 MeV – 200 GeV) with 50 MeV resolution, gain 1 for high energy (up to 2 TeV) with 500 MeV resolution



- **Use of TIA allows for narrower pulse**
- Internal non-linearity (ILN) of ±1/1000

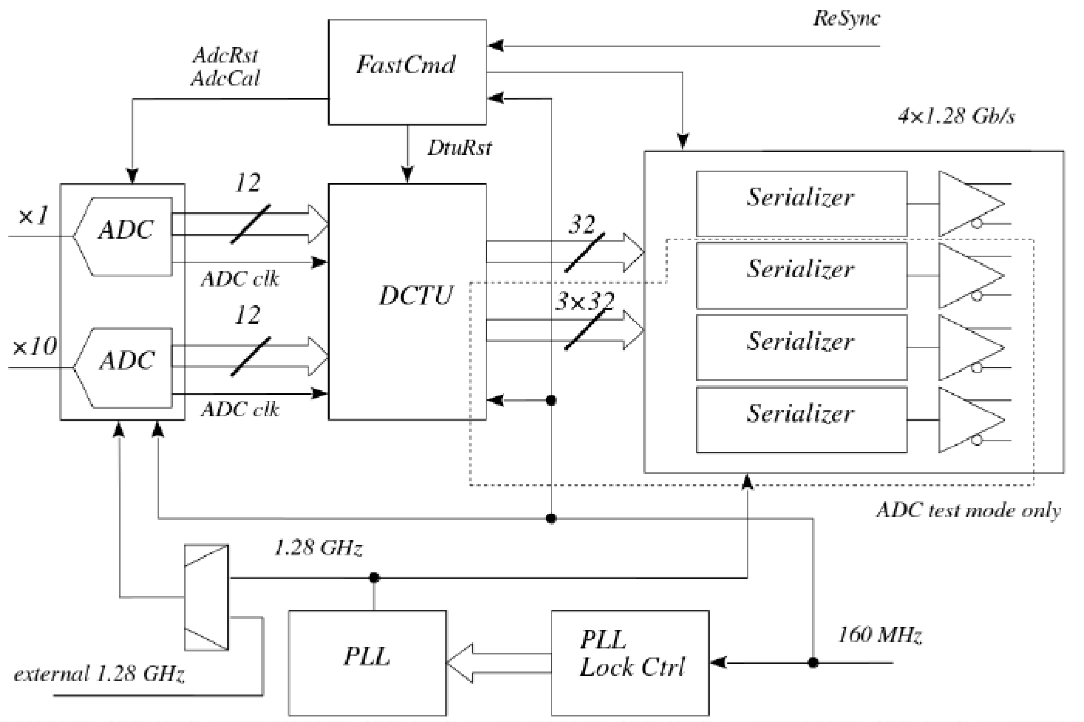
Very uniform single crystal pulse shape across a wide range of energy observed in Test Beam with new VFE.



Five CATIAs (one per crystal) on the new VFE card

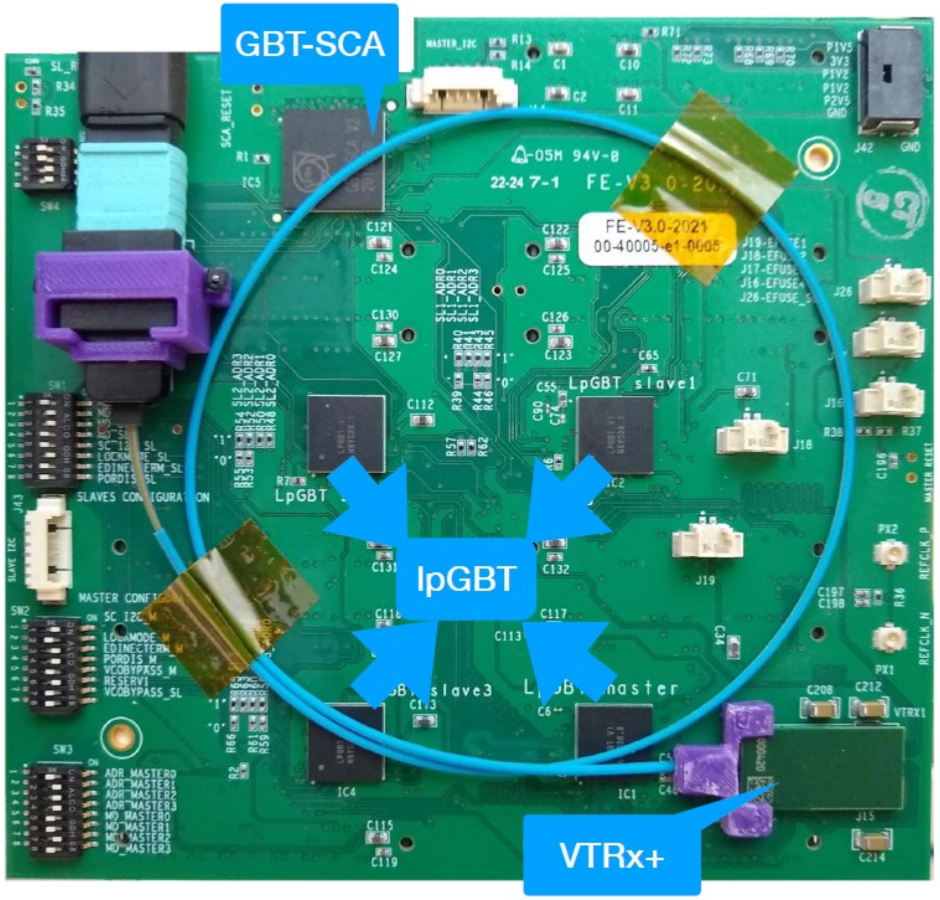
LiTE-DTU

- The ASIC Data Transmission Unit digitizes (2 ADCs) the two CATIA outputs (12+1 bit, 160 MHz) and performs gain selection and data compression.
- The single crystal energy spectrum is almost entirely made of noise and very low-energy signal (E>2.5 GeV in <0.01% of events).
  If E < 2.5 GeV → 6 bit sample
  If E > 2.5 GeV → 13 bit sample
- Lossless simplified Huffman compression algorithm to reduce data output bandwidth (one single 1.28 Gb/s serial link).

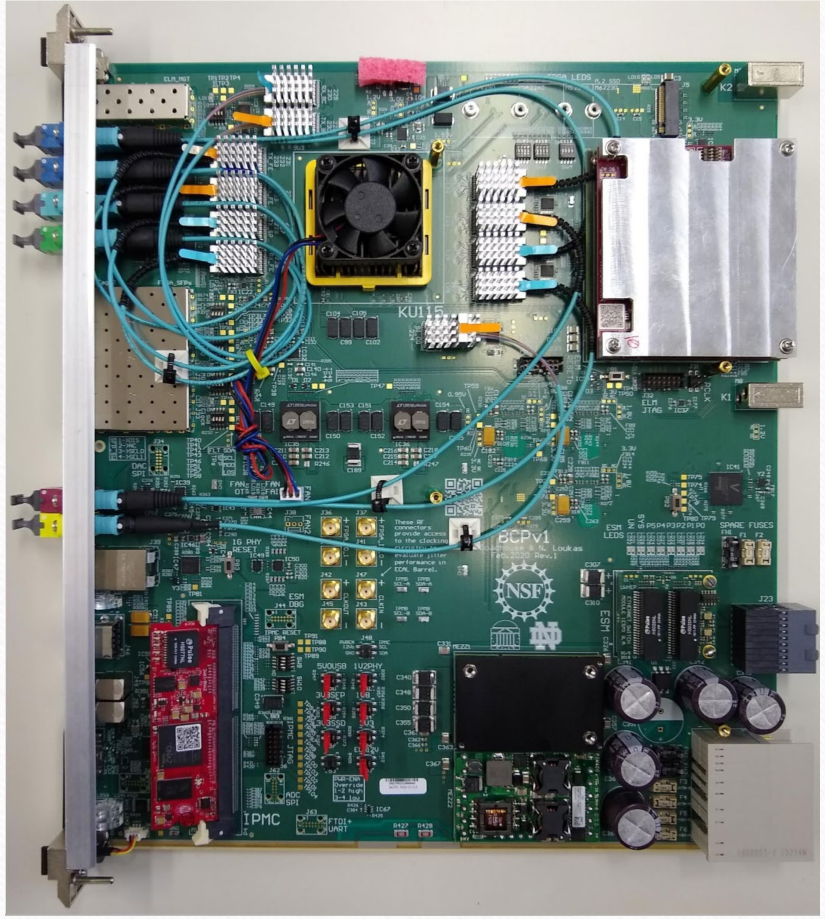


Front End Card

- The new Front End card is the interface between the VFE cards and the off-detector electronics and will send single crystal data sampled at 160 MHz for processing.
- The required rate for data readout from VFEs and the receiving of LHC clock and control signals from the back-end is achieved using respectively four low-power Gigabit Transceiver (lpGBT) chips (10.24 Gb/s) and one Versatile Link plus (VL+) optical link (2.56 Gb/s).
- The Card include also one Slow Control Adapter (GBT-SCA).



New off-detector electronics



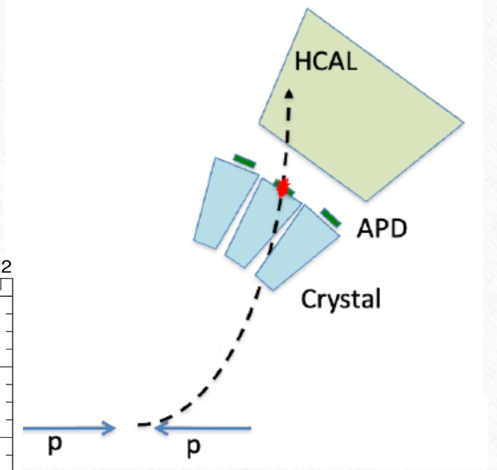
Barrel Calorimeter Processor (BCP)

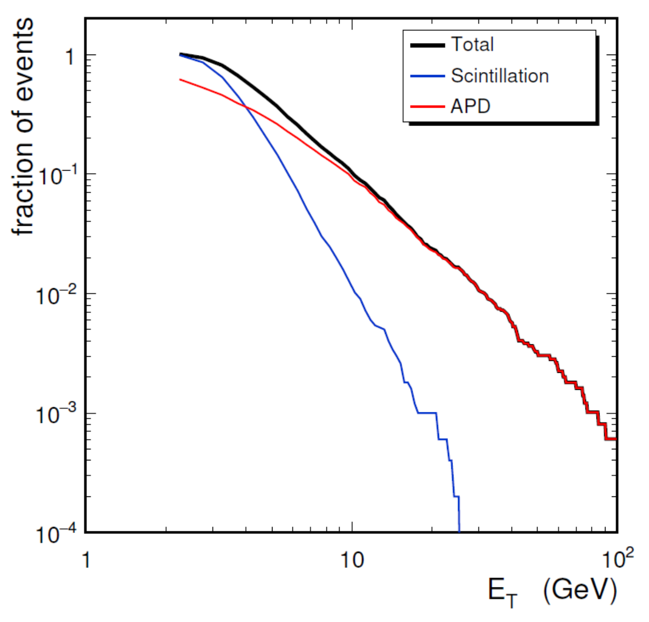
- Located outside the CMS cavern.
- Based on FPGAs
- Handling the clock distribution to the FEs.
- Data decompression (single crystal information), trigger primitive generation, spike flagging and data transmission to L1 trigger and to the DAQ thanks to two 16.3 Gb/s links.
- First version of BCP, used in the Test Beam
- BCP version 2, with more powerful FPGA and faster optical links, being designed for production.

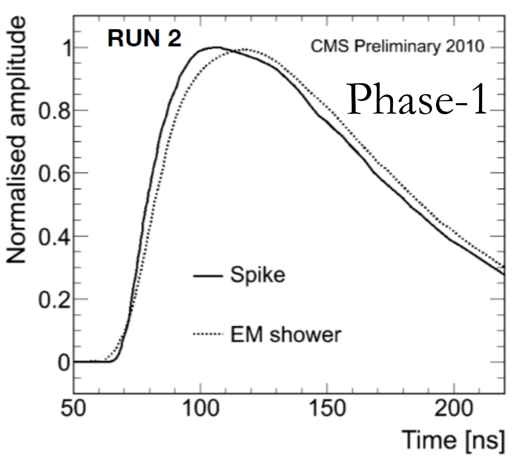
Spike suppression at L1

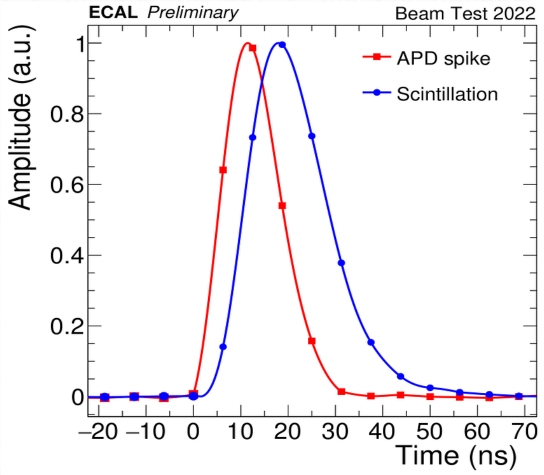
Spikes are anomalous signals in ECAL, generated by direct ionization with energy deposition in the depleted silicon bulk of the APDs from ionizing particles:

- fast rising time and highly localized energy deposit compared to scintillation
- rate proportional to the amount of pileup → would saturate the L1 bandwidth









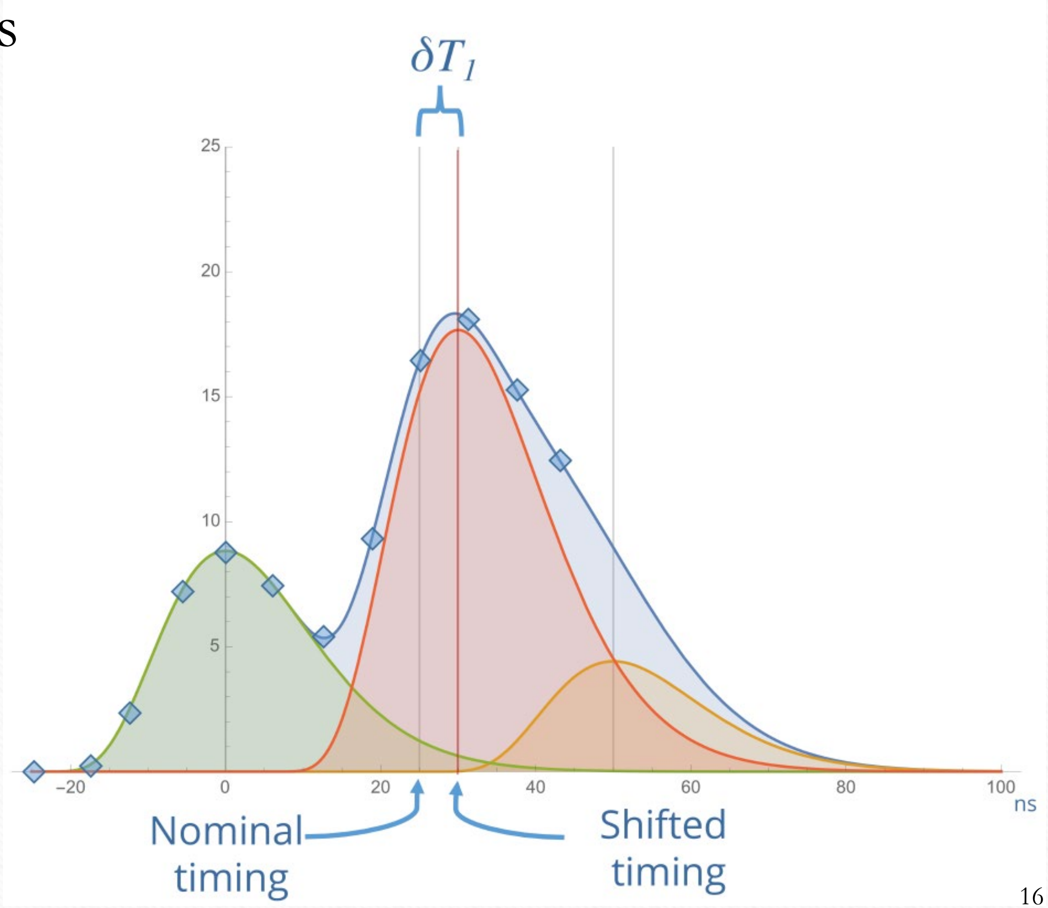
The narrower pulse shape and the single crystal info @ L1 will provide a much better spike rejection than in Phase-1

Trigger Primitive

Trigger Primitive Generation (TPG) algorithms on the BCP will perform amplitude, timing reconstruction and spike flagging:

- samples multiplied by the proper gain and subtracted by the baseline pedestals;
- transverse energy signal amplitude and time of the pulse extracted with a linear least square method considering -1, 0, +1 bunch crossing overlapping.

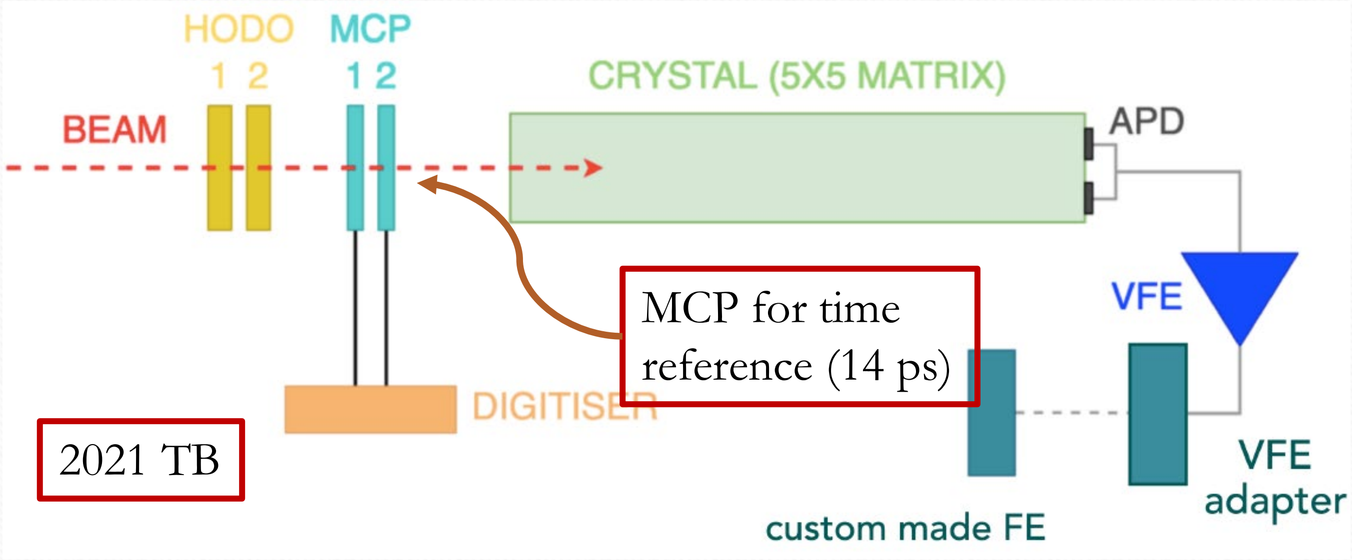
18 bits per crystal consisting of the transverse energy (12), time information (5), and one APD spike flag bit.

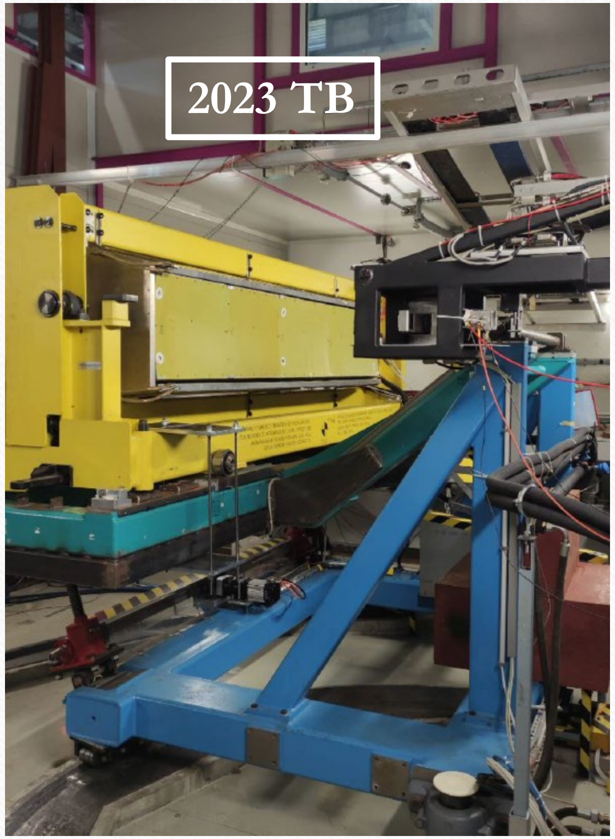


Test beam @ CERN

Test beam campaigns at the CERN Prevessin H4 facility (electron beam 20-250 GeV)

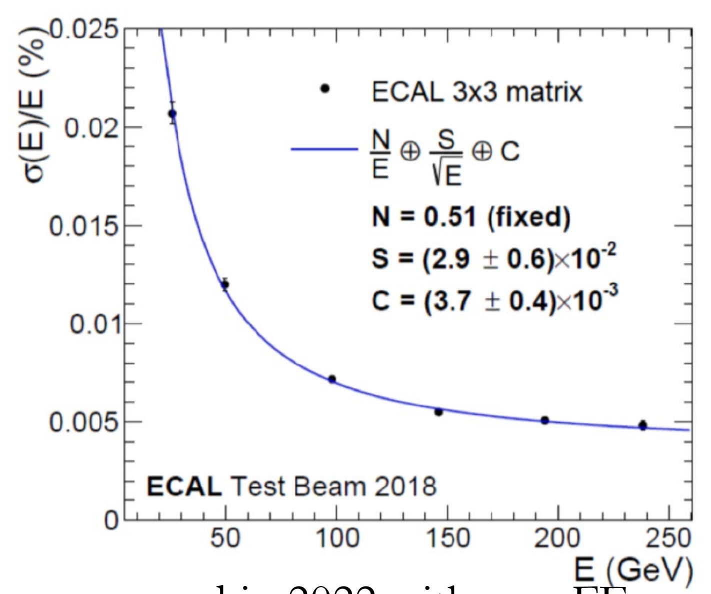
- 2018 CATIA ASIC + commercial ADC at 160 MHz
- 2021 25 crystals with new VFE (CATIA + LiTE-DTU)
- 2023 9x25 crystals with new VFE and FE + BCP V1





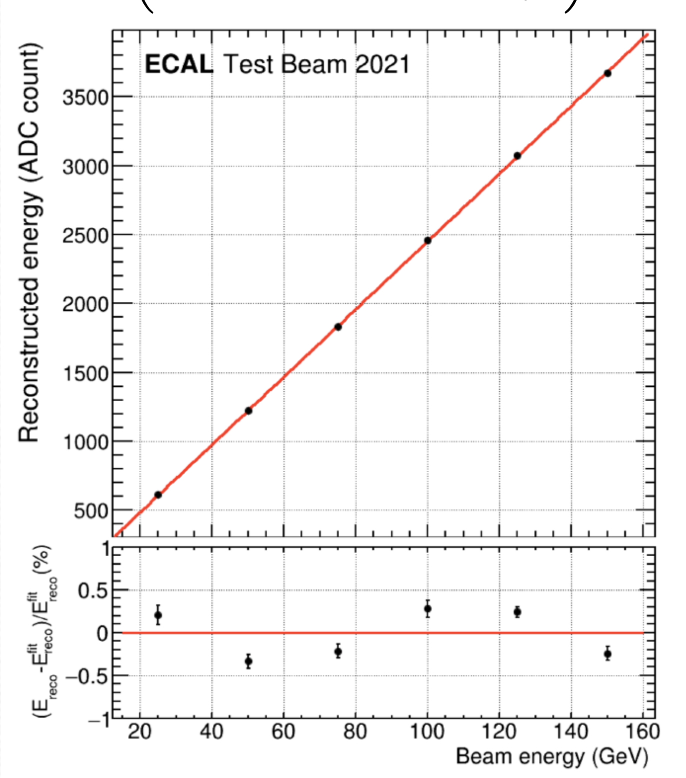
Test beam @ CERN

Energy resolution
(~1% @ Hγγ photon energy, matching current resolution)

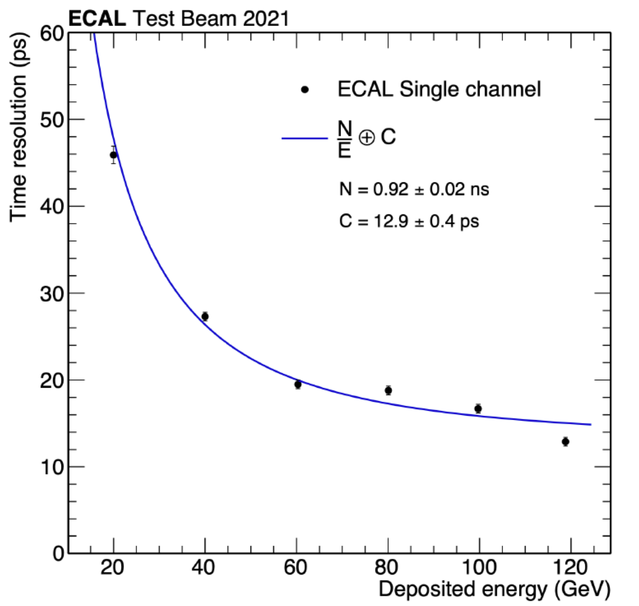


re-measured in 2022 with new FE

Energy linearity
(deviation <0.3%)

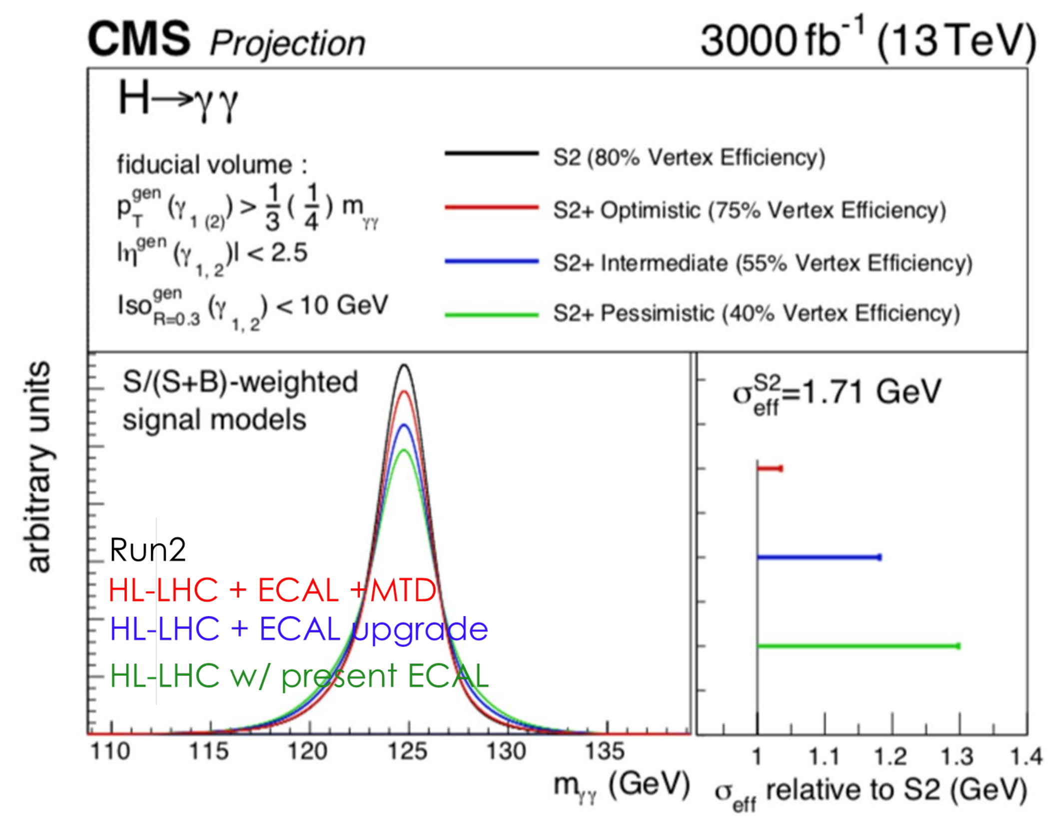


Time resolution
(matching design expectation of 30 ps for energy > 50 GeV)



CMS Timing @ HL-LHC

- The upgraded ECAL will greatly improve on the time resolution for photons and electrons. The target is 30 ps with E>50 GeV.
- With such a precision on the arrival time of photons, a constraint of **1 cm** can be placed on the **H$\gamma\gamma$ vertex** position along the longitudinal axis.
- Together with the introduction of a new timing detector (**MTD**) designed to perform measurements with a resolution of a few tens of picoseconds for minimum ionizing particles, the CMS detector will be able to precisely reconstruct the primary interaction vertex even with 140-200 pileup interactions per event.



Conclusions

- The full ECAL barrel readout electronics at the CMS experiment is being redesigned (in an advanced state) to face the HL-LHC challenges and to maintain the current physics performance for electrons and photons.
- A VFE card with two custom ASICs (CATIA and LiTEDTU), a FE card, and a new off-detector readout (BCP) will allow to:
  - accommodate the CMS Level-1 trigger requirements on latency and rate;
  - improve the timing resolution: ~30 ps for e/γ with energy above 50 GeV;
  - mitigate the photodetector leakage current and the consequent electronic noise;
  - make available single crystal information at the L1 Trigger;
  - drastically improve the spikes rejection at L1 trigger.
- Very good pulse shape uniformity, energy linearity and timing resolution have been observed in test beam with the new VFE electronics (more results available soon).