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Upgrade of the CMS Electromagnetic Calorimeter for the High-Luminosity LHC

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CMS

LHC High Luminosity Upgrade (Phase 2)

Phase 2 will deliver to the experiments a **much larger dataset** compared to Phase 1.

To achieve this, **unprecedented instantaneous luminosities** will be provided:
(currently $\mathscr{L} = \mathbf{2} \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ → $\mathscr{L} = \mathbf{7.5} \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)

This will pose **several challenges for the CMS subdetectors**:

- More collisions per Bunch Crossing
  (Pile Up 30-60 → 140-200)
- More radiation damage
- More stringent requirements
  - longer latencies (4.2 μs → 12 μs)
  - higher trigger rates (100 kHz → 750 kHz)

full renovation of many subdetectors (+ new timing layer)

The CMS subdetectors upgrade

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This will pose **several challenges for the CMS subdetectors:**

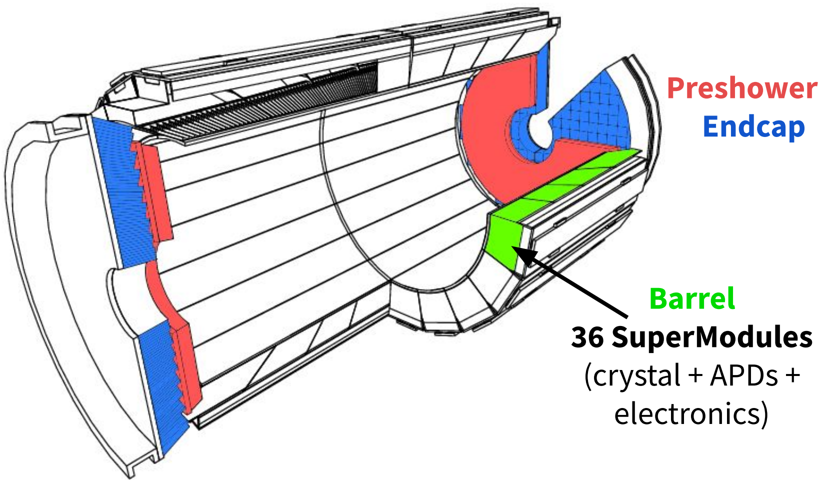
- More collisions per Bunch Crossing → **better discrimination of spurious events** (**Pile Up 30 → 200**)
- More **radiation damage** → **radiation tolerance**
- More stringent requirements
  - **longer latencies (3.5 μs → 12 μs)**
  - **higher trigger rates (100 kHz → 750 kHz)**

} **longer pipelines and faster readout**

The CMS Electromagnetic Calorimeter

key role in the **detection of electrons and photons** for the CMS experiment at LHC

- homogeneous, fine grained, high-resolution calorimeter
- $PbWO_4$ scintillating crystals
  - avalanche photodiodes (APD) in barrel
  - vacuum phototriodes in endcaps



Phase 2 Upgrade:

- endcaps and forward calorimeters will be replaced by HGCAL
- **barrel:**
  - **full refurbishment of electronics**
  - crystals + APDs will not change, but will be **operated at lower temperature**

Phase2 physics goal for ECAL barrel

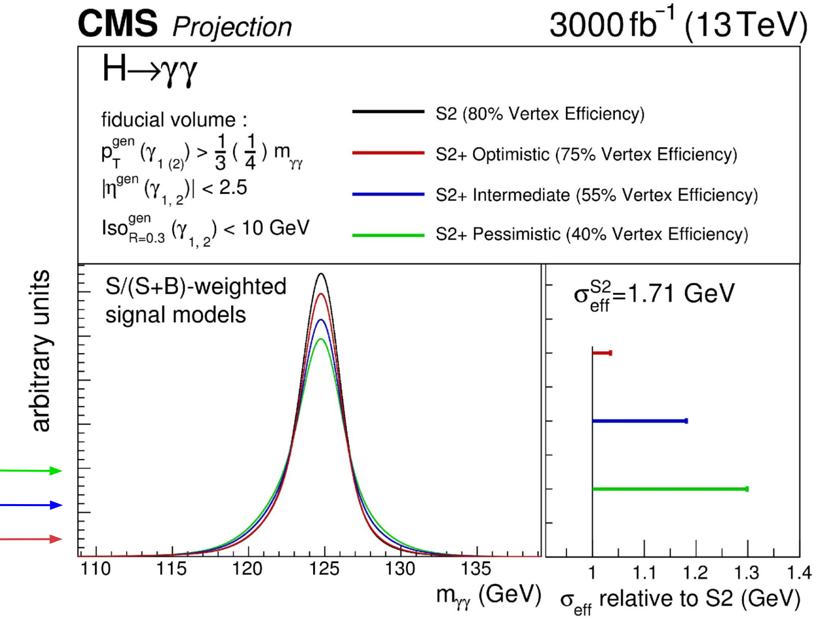
1. the goal is to **maintain the performance of Phase 1** despite the harsher datataking conditions: **target energy resolution same as Phase 1**

2. we aim at **precise time resolution** off-line **(σ_t = 30 ps)** for ***e* +/-** and **γ** with **E > 50 GeV** (unprecedented!)

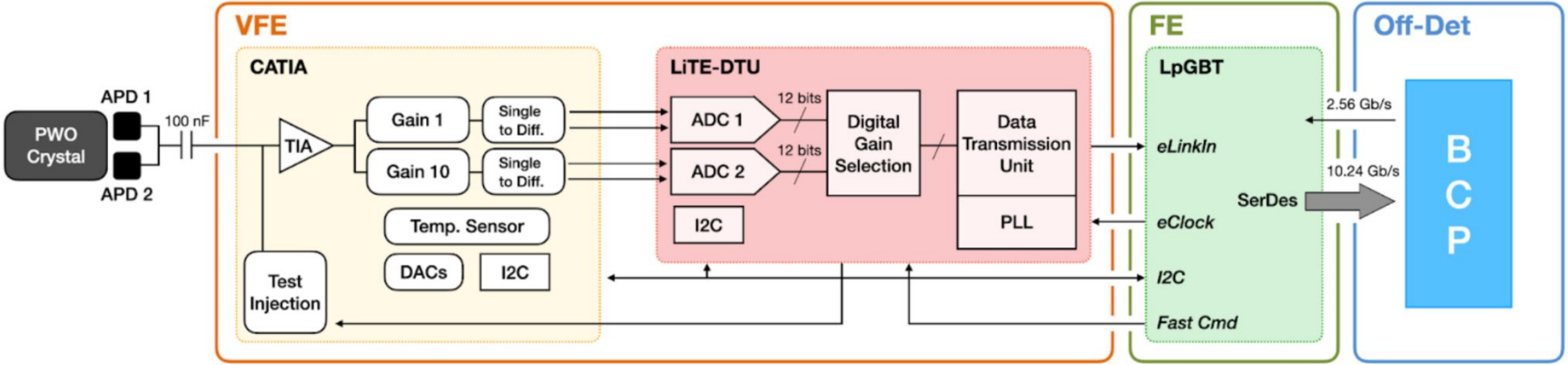
   motivation: improvement of **H→ γγ vertex identification** at high pile-up

+ benefit from CMS **MTD** (dedicated timing detector)
[CMS-TDR-020]

no ECAL timing
ECAL timing σ_t = 30 ps
ECAL + MTD

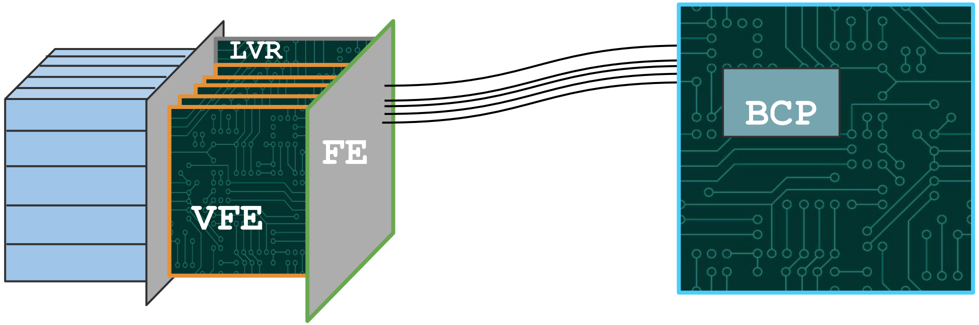


Electronics upgrade:

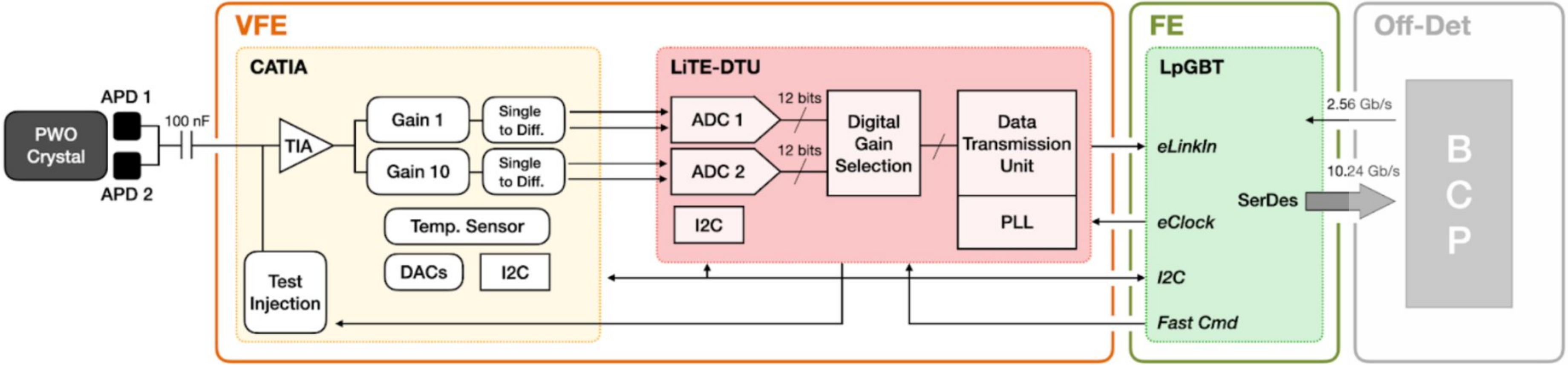


[CMS-TDR-015]()

5x5
crystals



Electronics upgrade: ON-DETECTOR



CATIA (analog ASIC)
2x transimpedance amplifier

LiTE-DTU (digital ASIC)
2x 12-bit ADCs sampling at 160 MHz
gain selection & data transmission unit
lossless data compression algorithm

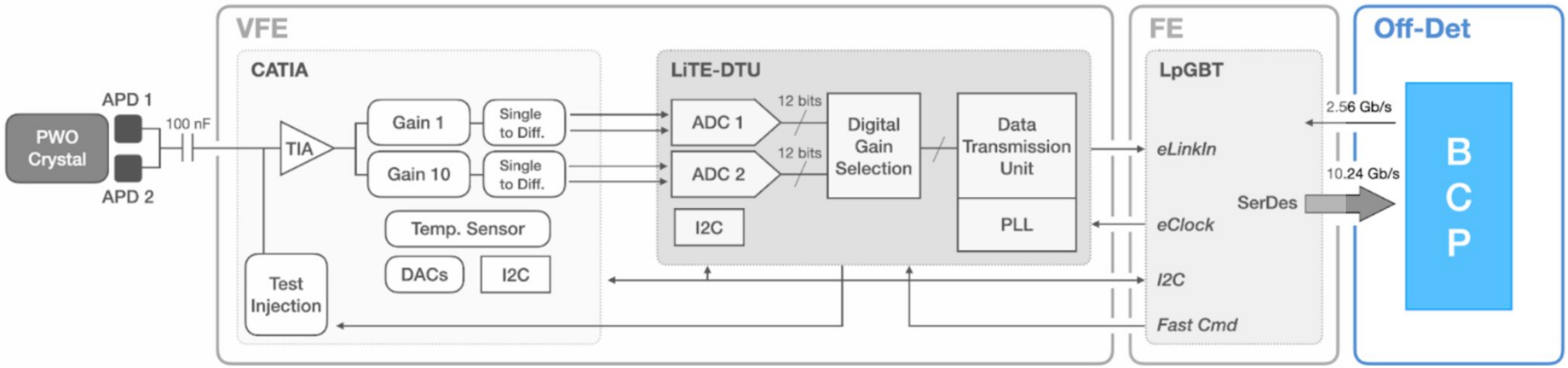
LpGBT
radiation tolerant optical transmission system

Faster analog electronics
(larger analog bandwidth, sampling rate from 40 to 160 MHz, with 12-bit resolution)

→ **better noise filtering and time measurements**

Fast optical links
for data transmission

Electronics upgrade: OFF-DETECTOR



Barrel Calorimeter Processor (BCP)

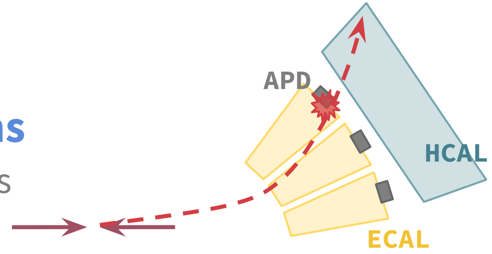
FPGA based data aggregator
+ decompression algorithm
+ trigger primitives construction
+ spike killing algos

Trigger objects reconstructed off-detector:

→ 25x more granular trigger primitives (single crystal granularity)

Powerful spikes suppression algorithms

Spikes are particle ionizing in the APDs



Laser monitoring upgrade

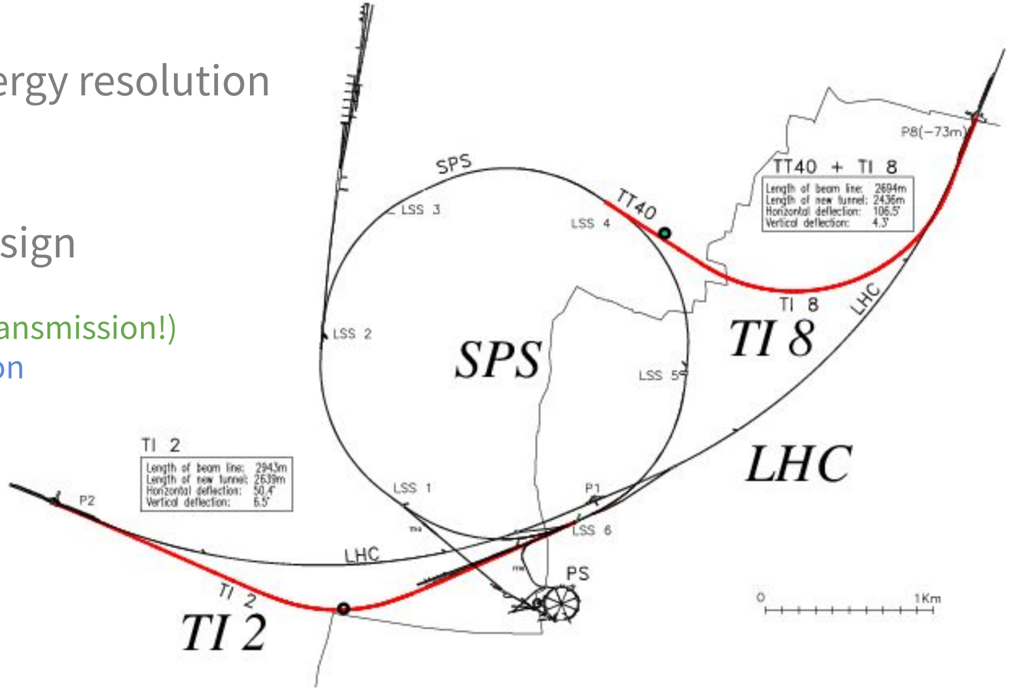
The Laser monitoring system **continuously monitors crystal transparency changes** using **PN diodes as a reference.**

- **HL-FEM (Front End Module):**
  - hosts the **PN diodes, 2x** wrt Phase 1
  - hosts the new charge pre-amplifier MONACAL ASIC
- **HL-MEM (Monitoring Electronics read-out Module)**
  - LiTE-DTU for signal digitization
- Data are sent to the backend electronics through **standard FE boards**
- **Interface with trigger and DAQ through commercial FPGAs**

Test Beams

H4 test beam line at the North Area of the **CERN SPS: e^+/e^- (20 - 300 GeV**, $\Delta p/p < 0.5\%$)

- **Physics performance:** timing and energy resolution
- **System stability tests**
- **Test of prototypes** up to their final design
  - VFE v3.0 currently in pre-production
  - FE v3.3 ready for production (stable data transmission!)
  - BCP v2 firmware and layout near completion



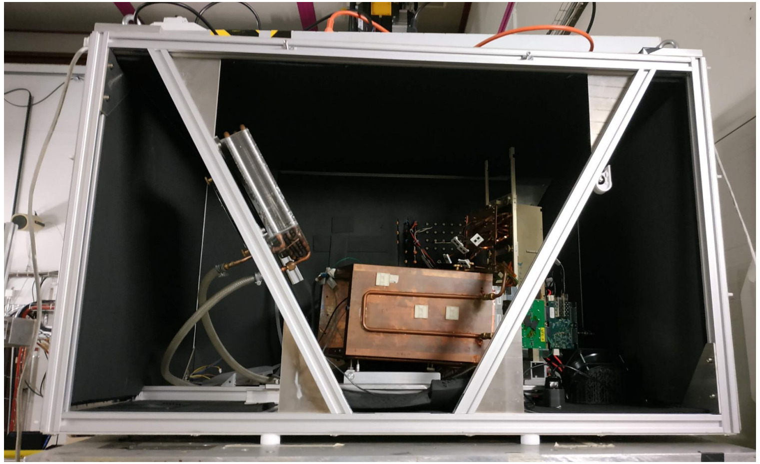
Recent Test Beam campaigns (1/2)

2018: first CATIAv0 prototype

- Single readout unit + custom readout electronics

2021: full VFE design

- **5 VFE cards tested**, 25 crystals
- custom readout electronic
- data for physics performance evaluation



2022: full readout chain

- **Commissioning of the readout chain**
- few data taken for physics → mainly system commissioning and stability tests

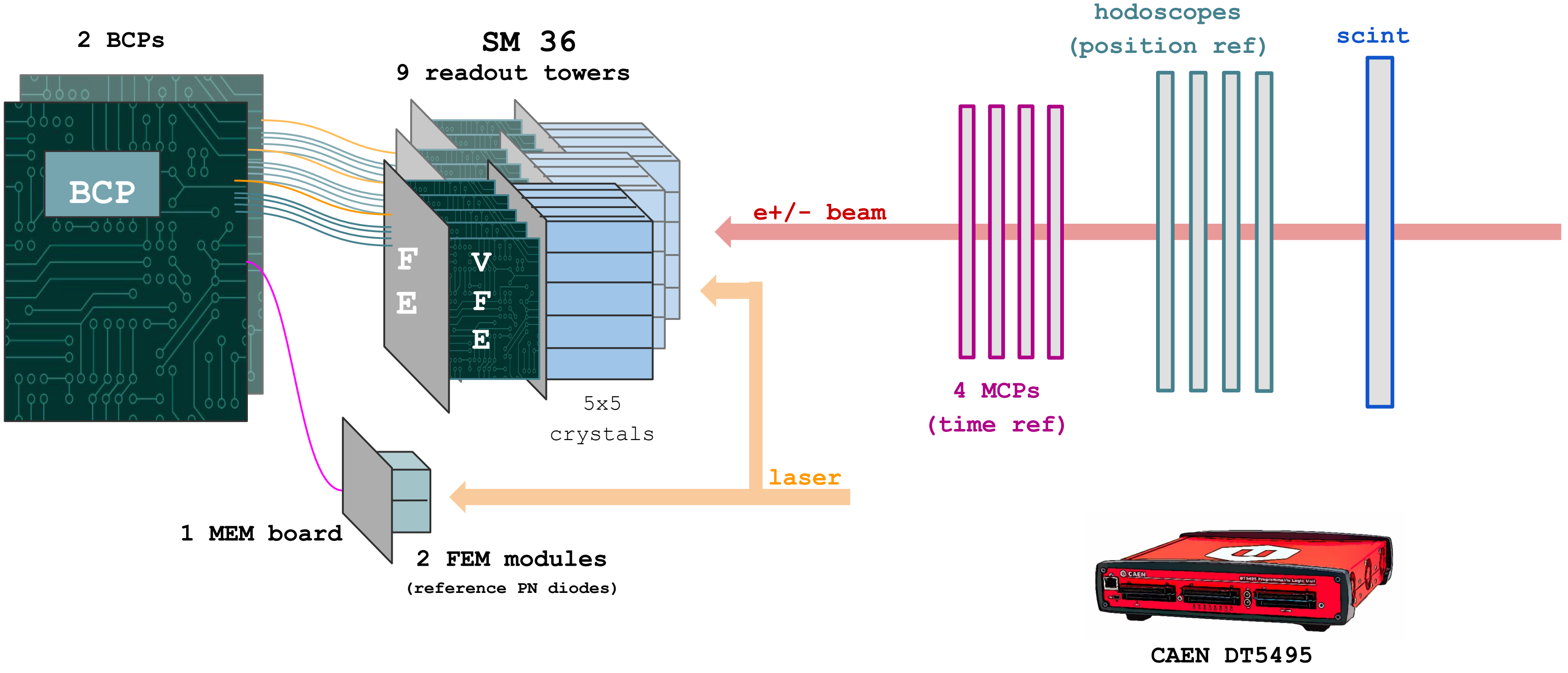
Recent Test Beam campaigns (2/2)

2023:

- **The whole electronic chain** is mounted on a **spare SuperModule** (SM36), **identical to the ones in ECAL**
  - 25 crystals x 9 readout units
  - full-setup test, very close to real detector conditions!
  - **first time taking physics data with BCPs (v1)**
- **Upgrade laser monitoring**, between e^+/e^- fills
  - laser is used in ECAL to monitor crystal transparency

NEXT: Oct 2024

Test Beam setup (2023)

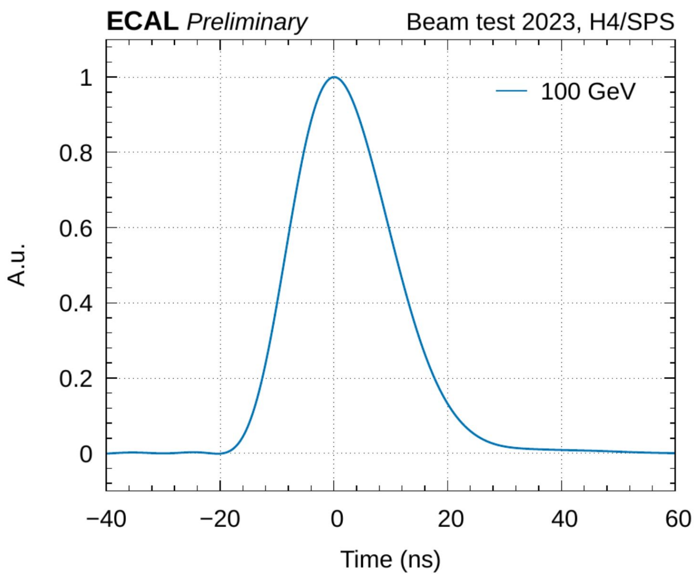


2023 TB results: general considerations

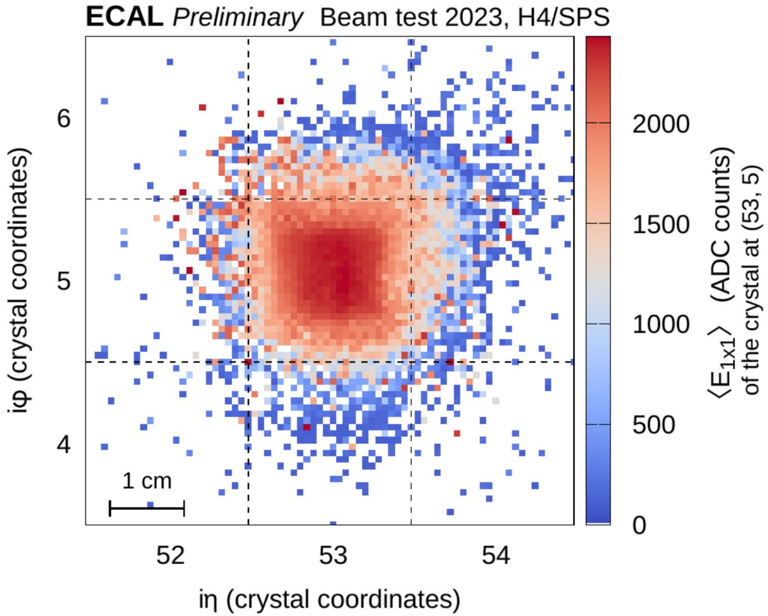
Electron signal amplitude A **and time** t_0 are reconstructed with a **template fit**:

$$f(x) = A \cdot template(t - t_0)$$

templates via software oversampling in frequency domain



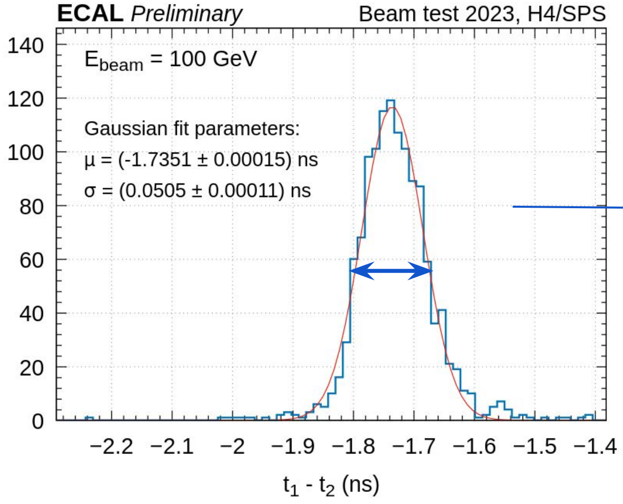
Electron impact position in a matrix of n crystals is reconstructed based on the energy deposits in each crystals:

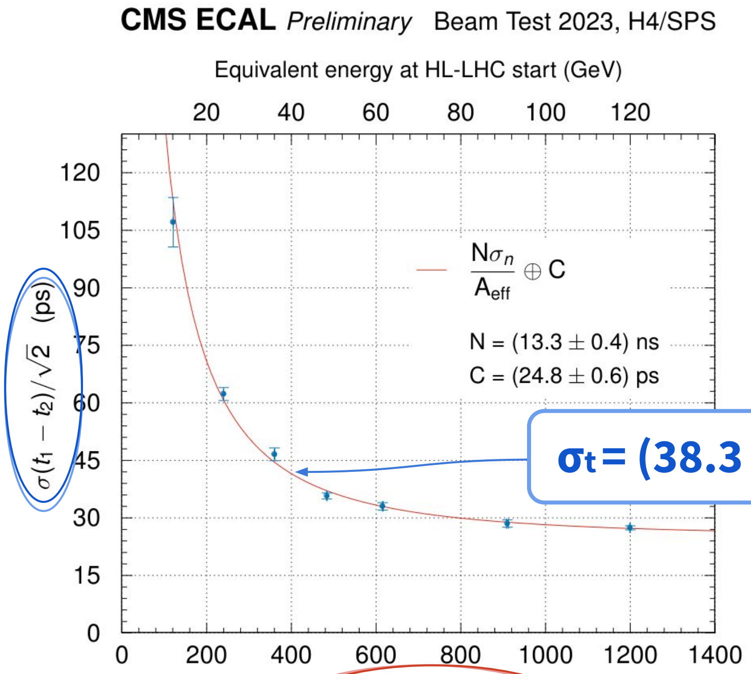


Timing resolution

Obtained using data collected with **e+/- beam firing between two crystals**

timing resolution → **width of the distribution of** the difference **Δt** of the signal arrival times





σn = 100 MeV

Aeff = 50 GeV

σt = (38.3 ± 0.5) ps

studied as a function of the "effective amplitude"

$$\frac{A_{eff}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$$

Energy resolution

Monochromatic e+/- beam firing at the center of a single crystal

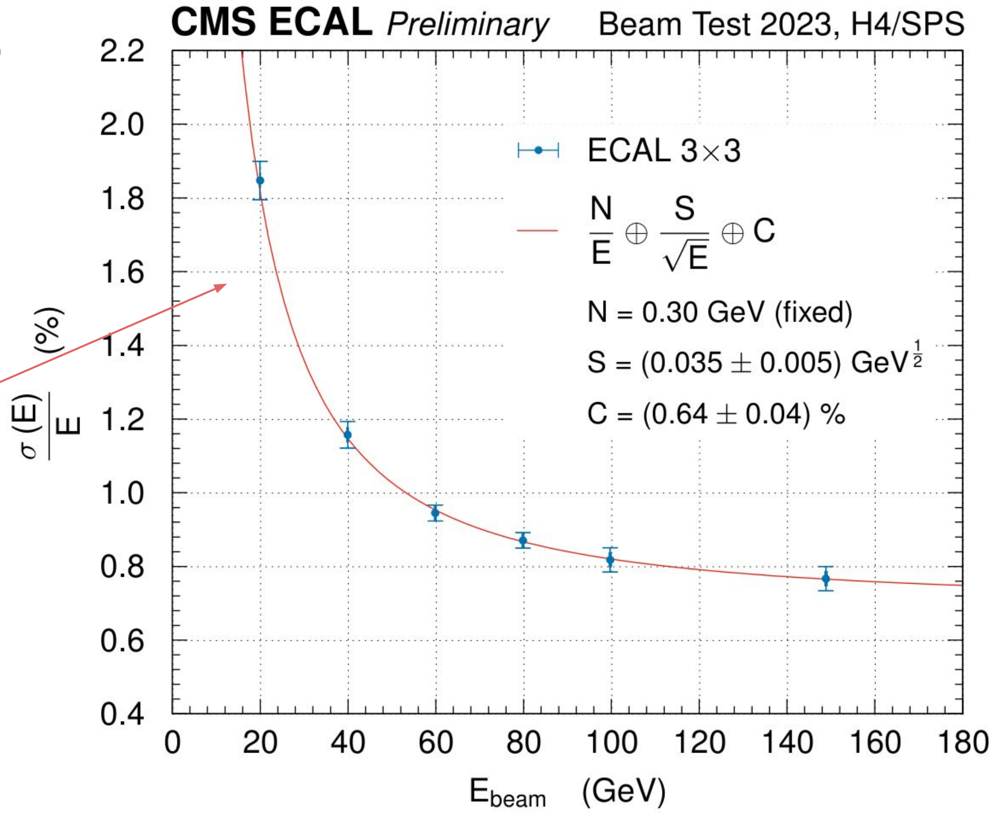
- σ_E/E retrieved from fit of signal amplitude distribution
- Computed using a **3x3** crystal matrix

$$\frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C$$

noise term

stochastic term

constant term



Conclusions

→ The upgrade of ECAL for Phase 2 consists in a **full refurbishment of the electronics (on-detector** and **off-detector):**

- need to comply with more stringent trigger and DAQ requirements
- need to mitigate the increased radiation-induced noise
- target 30ps timing precision and 1% energy resolution (> 50 GeV)

✓ **Performance tests ongoing** at several Test Beams (2018 - ongoing)

- Test of prototypes and commissioning of full readout chain
- Collected large dataset for physics performance evaluation
  - so far, in line with targeted specifications!

✓ **Components design almost finalized and production started!**

BACKUP

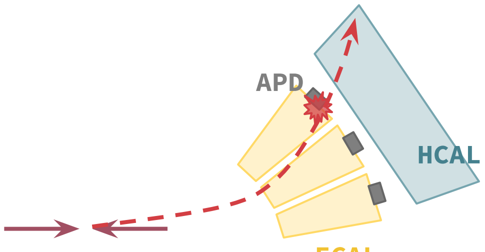
Lossless compression algorithm

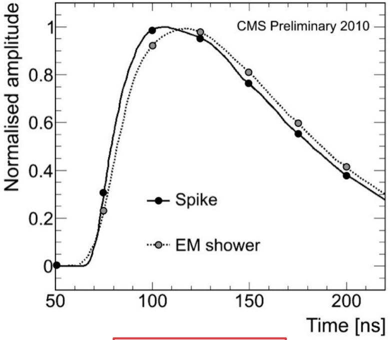
"Baseline" data format	01	6 bits sample	6 bits sample	6 bits sample	6 bits sample	6 bits sample
"Baseline" data format 1	10	sample map	6 bits sample/00	6 bits sample/00	6 bits sample/00	6 bits sample
"Signal" data format	001010	13 bits sample	13 bits sample			
"Signal" data format 1	001011	0101010101010	13 bits sample			
Frame delimiter	1101	8 bits #samples	CRC12	8 bits frame #		
Idle pattern	1110	101010101010				

implementation of lossless data compression algorithm
CMS-TDR-015

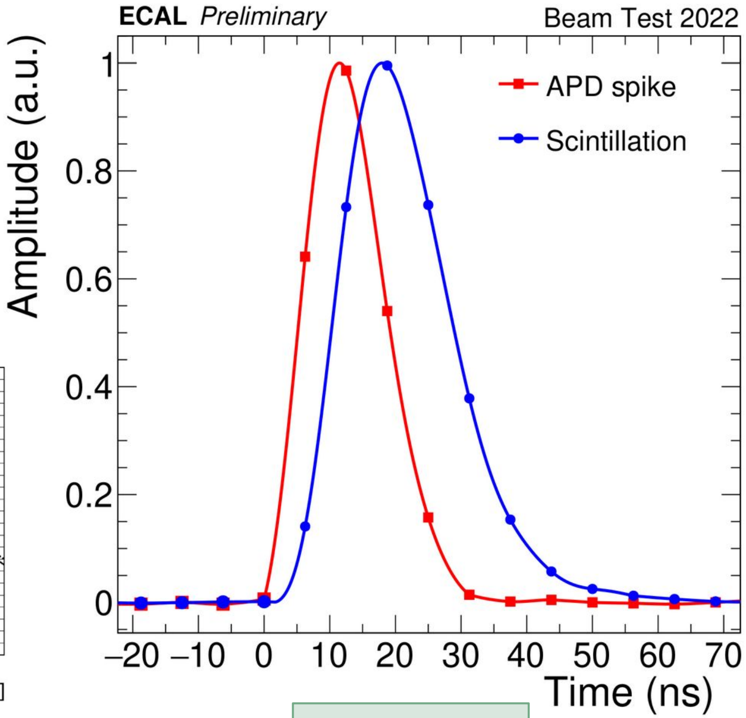
Pulse shape vs APD spike

Comparison of the pulse shape from a scintillation event and a signal induced by a direct hit in the avalanche photodiode. The latter was identified using topological constraints. Pulses are re-aligned in time to the first sample of the rising edge. The solid line are the templates of the two signals.





current



upgrade (TB)

Barrel Calorimeter Processor

→ Back-end off-detector electronics both for ECAL and HCAL (barrel)

- One BCP for **up to 24 TTs** (600 crystals)
- Control and clock distribution
- Single crystal trigger primitives generation (currently done by the FE)
- Data acquisition from detector and transmission to central DAQ

v1 → KU115

✓ already operational and tested, employed in TBs

v2 → VU13P

More memory and logic cells, more digital signal processing power

↝ Design and fw close to completion

Linearity in single crystal response (TB 2021)

Single crystal response in terms of average amplitude of the signal (in ADC counts) w.r.t. the energy of the incident electron-beam. In the lower panel we report the deviation of the reconstructed energy (in ADC count) with respect to the linear fit. Maximum deviation from linearity is < 0.3%.