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

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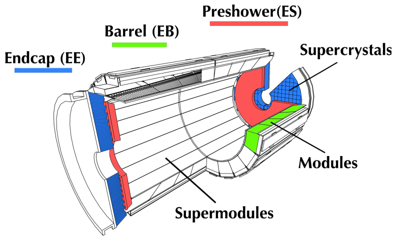
Outline

The CMS ECAL

The legacy ECAL

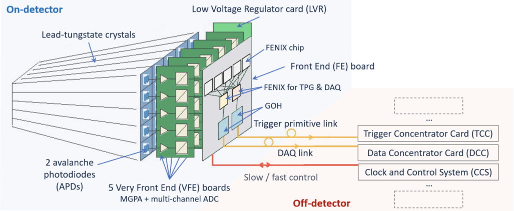
- Hermetic homogeneous PWO EM calorimeter
  - Fast decay scintillation light (25 ns), short radiation length (0.89 cm), small Molière radius (2.2 cm)
  - Precision measurement of e and γ energy ($\sigma_E/E < 1\%$ for $E > 50$ GeV)

See poster #234
(on ECAL Run3 performance)



The ECAL Barrel

- Arranged into **36 SMs in the barrel**
- Total of 61200 crystals, read by Avalanche Photo-Diodes (APDs)
- **Readout unit**: 5x5 matrix

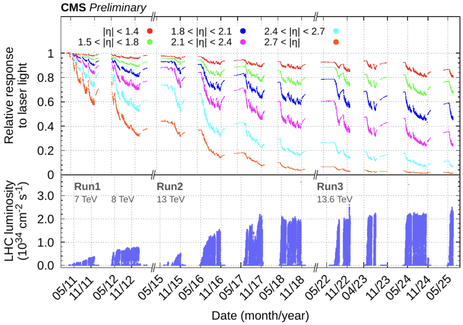


The HL-LHC Upgrade and the Challenges for ECAL

Main drivers for the ECAL Barrel Upgrade

- **Radiation damage** to the detector and sensors:
  - Increased leakage current in the APDs
  - PWOs lose transparency
- Increased **number of p-p interactions per bunch crossing** (pile-up)
  - Need precision timing to identify the primary vertex
- **New trigger requirements**
  - L1 rate: 100-115 kHz $\to$ 750 kHz
  - Latency: 4 μs $\to$ 12.5 μs

The **endcaps will not survive these radiation levels** → Replaced by the High-Granularity Calorimeter HGCAL: see parallel talk #270

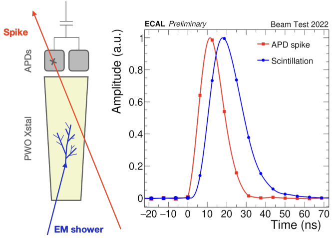


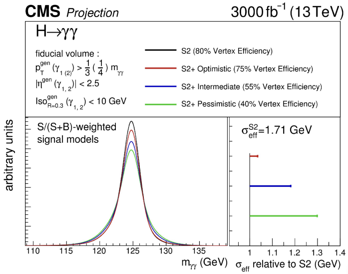
Parameter	Run3	HL-LHC
Inst. luminosity	$2 \cdot 10^{-34}$ cm^{-2}s^{-1}	5-7.5 $\cdot 10^{-34}$ cm^{-2}s^{-1}
Pile-up	up to 60	140–200
Integrated lum	$\sim$ 300 fb^{-1}	3000–4000 fb^{-1}
Fluence (EB)	$\sim 10^{12}$ n/cm^2	$\sim 10^{13}$ n/cm^2
TID (EB)	$<$ 1 kGy	5–7 kGy

Physics goals

- **Maintain the current energy resolution**: $\sigma_E/E < 1\%$ (for E>50 GeV)
- **Increase time resolution**: 30 ps (for E>50 GeV)
- Enable online **signal-spike*** **discrimination** (discrimination based on pulse shape)

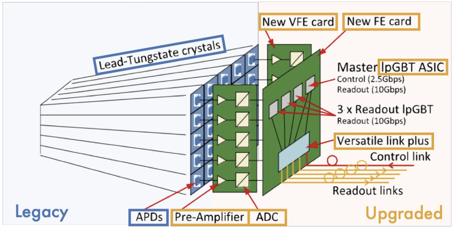
***spike**: direct ionisation of one ADP



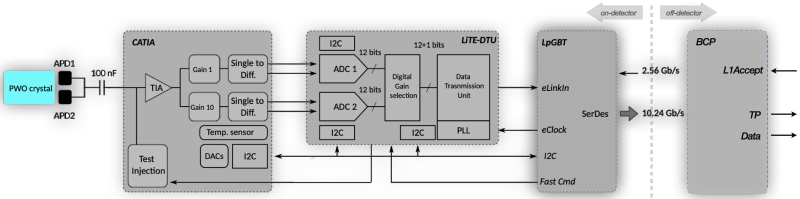


EB Readout Upgrade

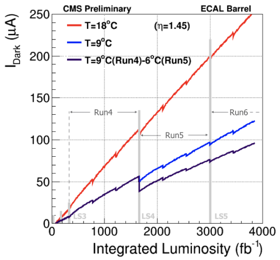
- **New faster front-end electronics** will enable signal-spike discrimination
  - Faster analogue shaping: 100 ns $\rightarrow$ 20 ns
  - Faster sampling rate: 40 MHz *to* 160 MHz
- **Trigger-less readout on the front-end**
- **New back-end card** will
  - Form trigger primitives (per crystal)
  - Cope with the new trigger requirements



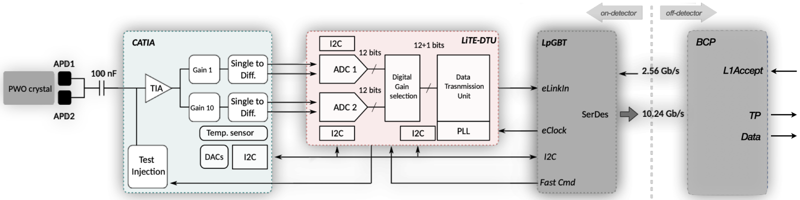
Upgraded channel - Crystal and APDs



- **Crystals and APDs are kept from Phase1**
- The APDs leakage current will increase for radiation damage
- **Decreasing the operational temperature 18→9 °C**
  - Mitigate the leakage current
  - Increase light yield by 20%



Upgraded channel - Amplifier + A/D Conversion



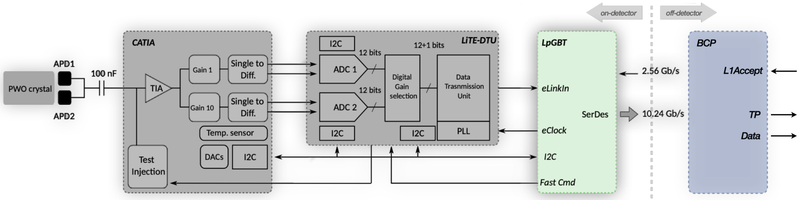
CALorimeter Trans-impedance Amplifier

- **Two gain stages** x1 and x10
- **G10: up to 200 GeV**
- **G1: up to 2 TeV**
- **Bandwidth 35 MHz** (tunable)

Lisbon-Turin ECAL Data Transmission Unit

- Two **12-bit 160 MS/s SAR ADCs**
- **Gain selection** mechanism
- **Loss-less data compression**
- **1.28 Gbps** serializer unit

Data Concentration, Transmission and Off-detector Electronics



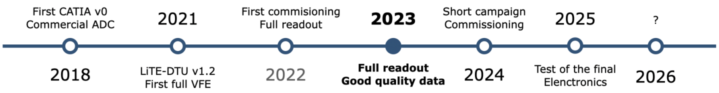
Front-End card

- CERN-developed radiation tolerant ASICs for HL-LHC
- **4 lpGBTs** (Low Power GigaBit Transceiver)
- **1 VTRx** (Versatile Link Plus optical Transceiver)
- **1 SCA-GBT** Slow Control ASIC

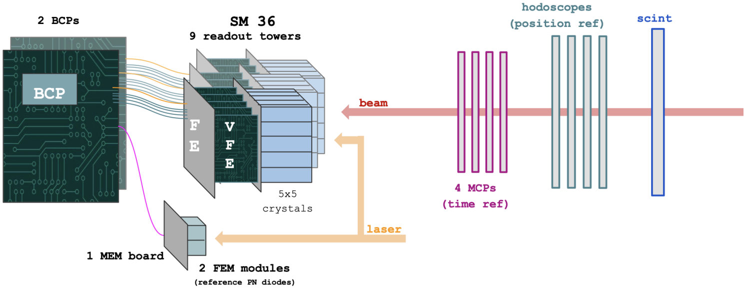
Barrel Calorimeter Processor

- **Clock, trigger and controls** distribution
- Data **decompression, alignment and transmission**
- **Trigger primitives** generation (Phase2: per crystal)
- Algorithms for online **spike-signal discrimination**

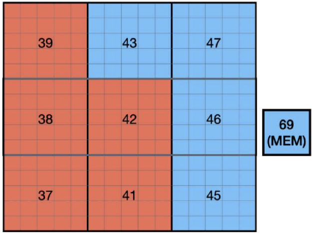
Beam Test Campaigns

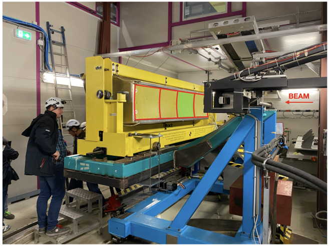


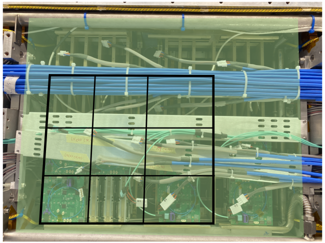
2023 beam test campaign setup



2023 Test Beam Setup



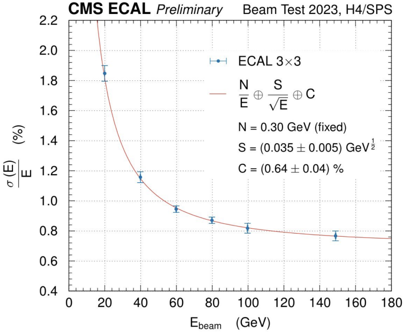




9 RU equipped

- Very fruitful campaign with a lot of **good quality data acquired**
- BCP0 reads 5 RU
- BCP1 reads 4 RU + MEM box
- Auxiliary boards: MCP for time reference, hodoscopes for beam position monitoring

ECAL Performance at 2023 Beam Test: Energy Resolution



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

- N: **noise term** (fixed after noise studies per channel)
- S: **stochastic term** (statistical component of the shower)
- C: **constant term** (intrinsic imperfections)

✔ **Performance compatible with Phase1:** $\sigma_E/E < 1\,\%$ ($E > 50$ GeV)

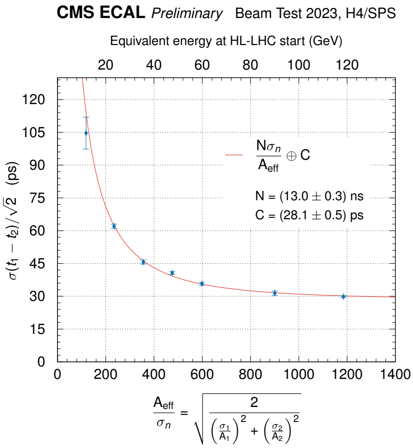
ECAL Performance at 2023 Beam Test: Time Resolution

- Beam **centred on the edge of neighbouring crystals**
- Relative time resolution: **spread between arrival times**

$$\sigma_t = \frac{N\sigma_n}{A_{\text{eff}}} \oplus C$$

- N: **noise term**
- $\frac{A_{\text{eff}}}{\sigma_n}$: **signal-to-noise ratio**
- C: **constant term** (intrinsic jitter and limits to time resolution)

✔ **Constant term < 30 ps**
$\sigma_t \sim 40$ ps @50 GeV



Summary, Status and Plans

- The ECAL barrel upgrade is designed to **maintain excellent energy resolution and deliver 30 ps time resolution**, ensuring optimal performance in the HL-LHC environment

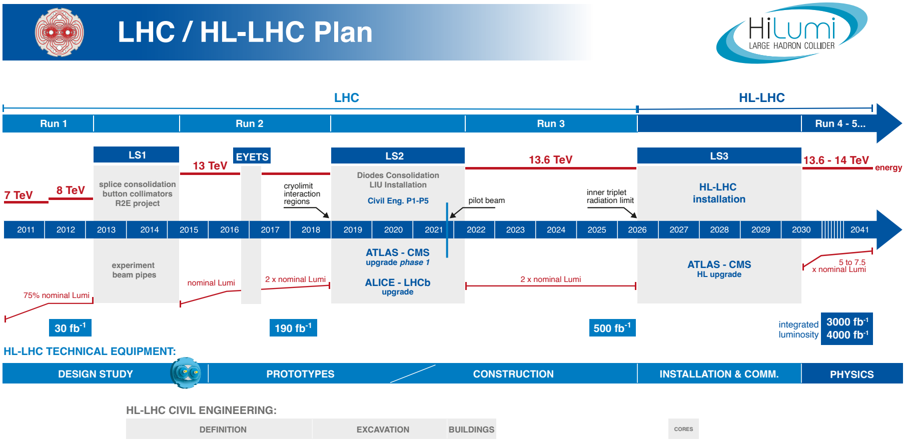
- **All the components of the new CMS ECAL readout are well into production**:
  - The ASICs are produced: a pre-sample was received and we expect the full production by the end of Q3 2025
  - Card preproduction sample already received and it is available for tests

- The system has been **tested extensively** in the lab and in beam test settings
- The close-to-final components, tested in 2021 and 2023 beam tests, showed that **the physics requirements for HL-LHC are met** in terms of energy and time resolution

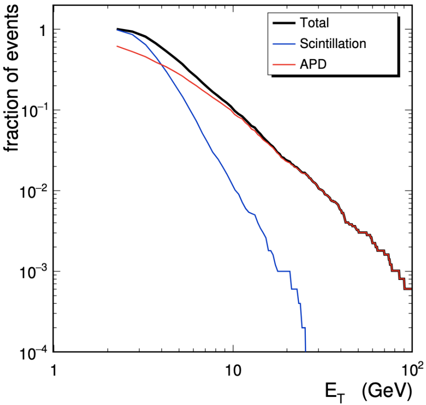
- The **next beam test planned for October 2025** will extensively **test the final components with 18 readout units equipped** in different modules

BACKUP

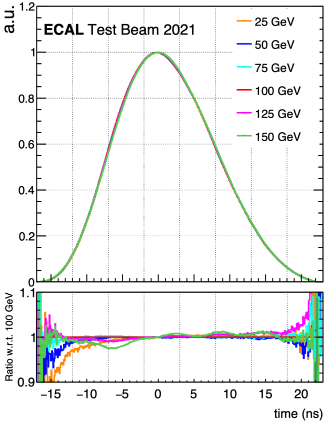
The Updated HL-LHC Timeline (January 2025)



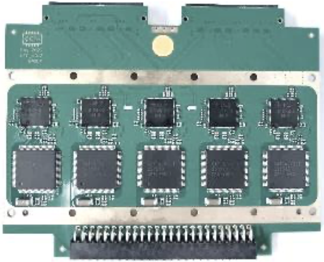
Spikes-signal spectrum

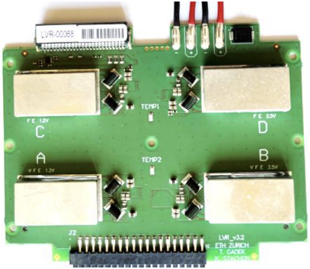


Pulse shapes at different energies



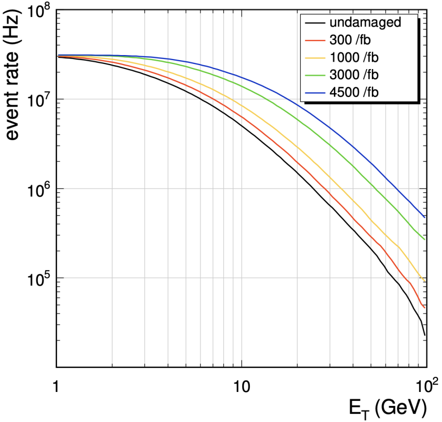
On-detector electronics status

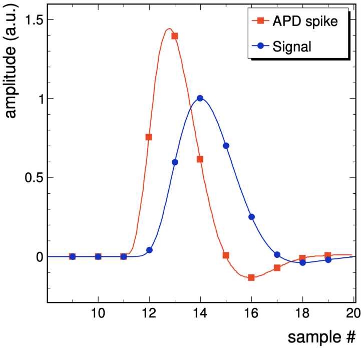


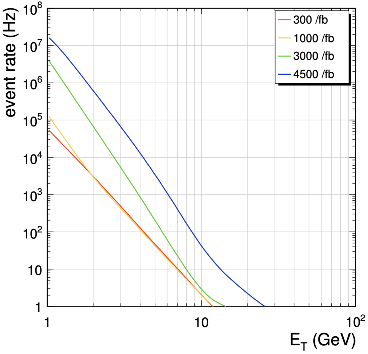


- **CATIA v2.1**:
  - Testing of the production is ongoing, 3k pcs already delivered
  - Hicups in the mass test system slowed down the mass testing but ()
- **LiTE-DTU v3.0b**:
  - Testing of the production is ongoing, 10k pcs already delivered
  - Yield at 94% (with tighter acceptance limits proposed)
- **VFE v5**:
  - First production sample (6 cards) arrived an already tested successfully, second batch just delivered
- **LVR 3.3**:
  - Preproduction sample of 12 pieces: quality porblems identified and solved
- Multiple test setups for both VFE and LVR are ready
- **FE v4**
  - Successful 100 card preproduction (beginning 2025)
  - Mass production starting end 2025

Expected rate at pu=200




APD spike
Signal
amplitude (a.u.)
1.5
1
0.5
0
10
12
14
16
18
20
sample #


300 /fb
1000 /fb
3000 /fb
4500 /fb
event rate (Hz)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
1
10
10^2
E_T (GeV)