ICHEP 2024 - Prague, Czech Republic

The CMS ECAL upgrade for the High-Luminosity LHC

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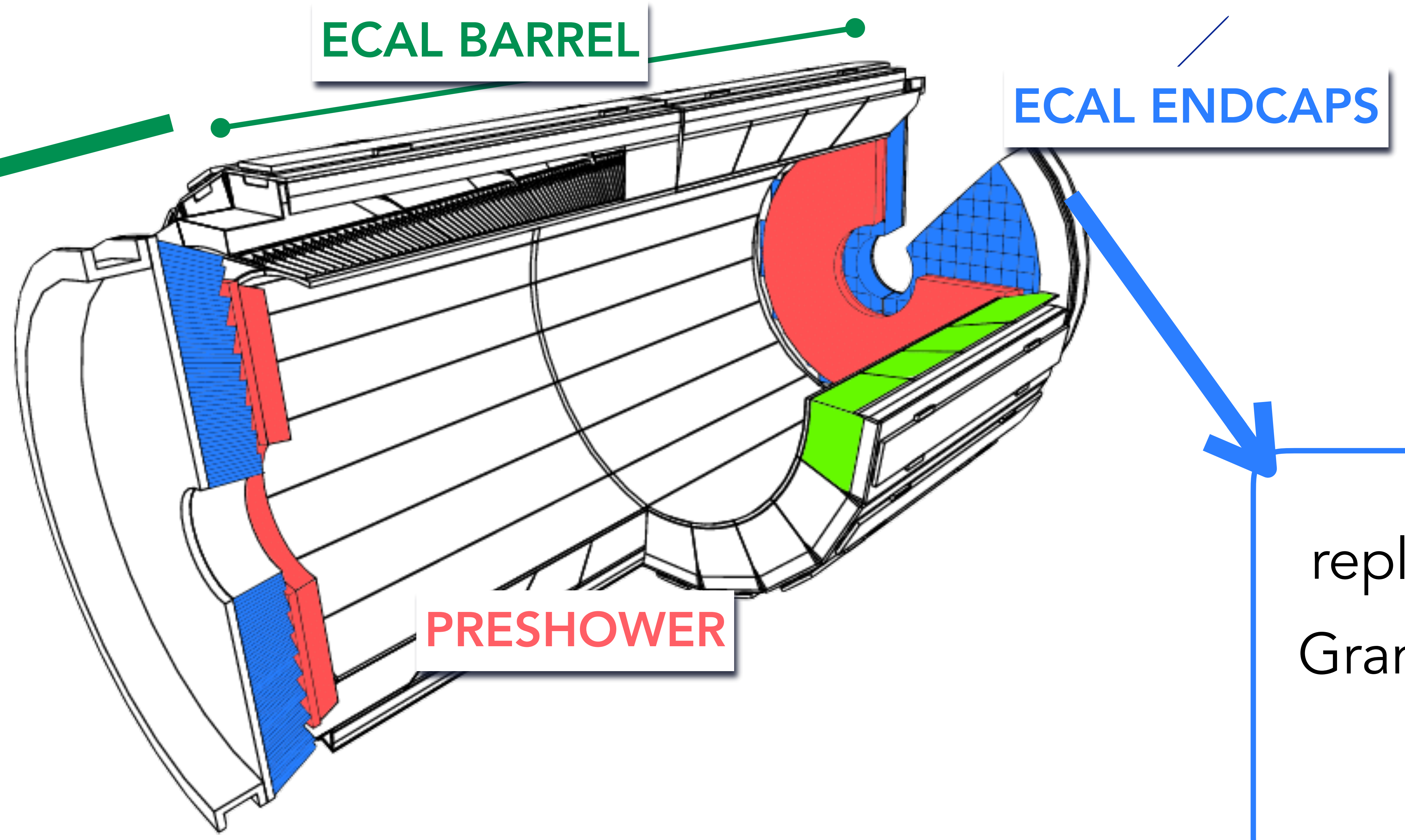
High Luminosity LHC and CMS ECAL

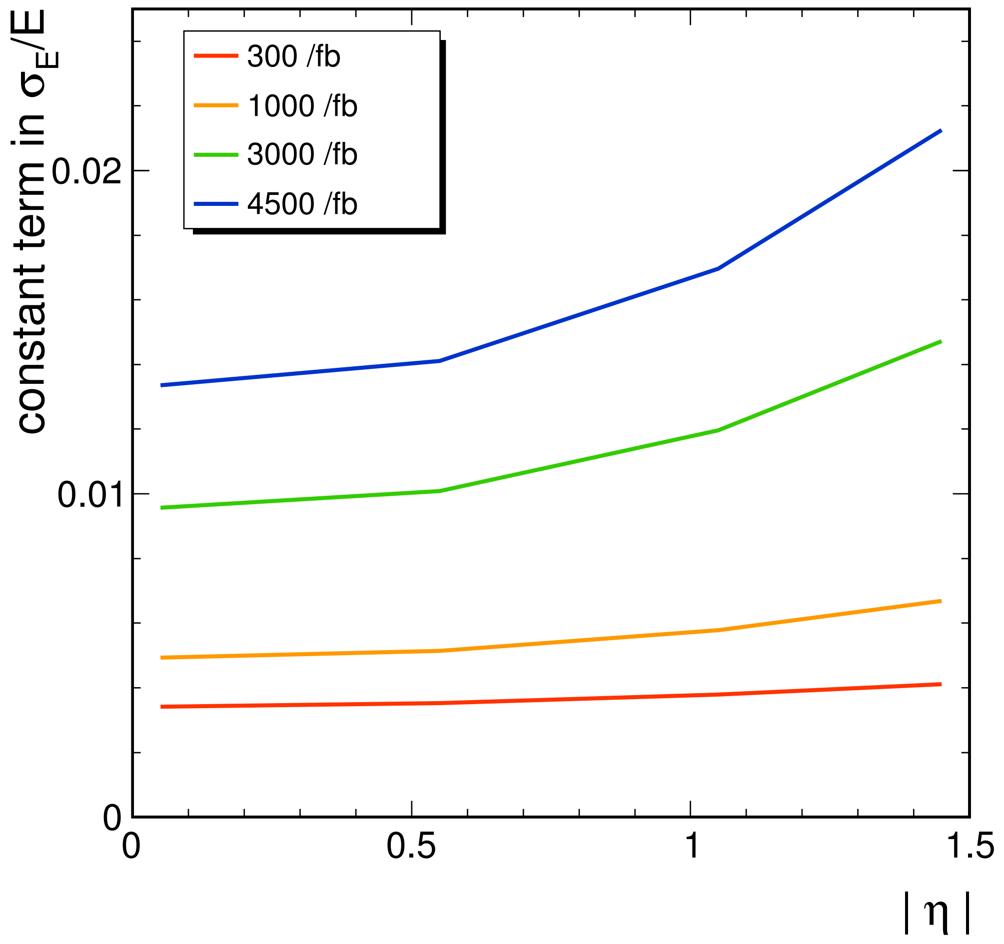
- High Luminosity Upgrade for LHC (HL-LHC) targets more than twice the current instantaneous luminosity and pile-up conditions → check Fabio's talk for more details!
  - New data-taking conditions demand for a full renovation of the **CMS** electromagnetic calorimeter **ECAL electronics**



electronics **fully renovated**
$PbWO_4$ crystals and Avalanche Phododiodes (APDs) remain operational

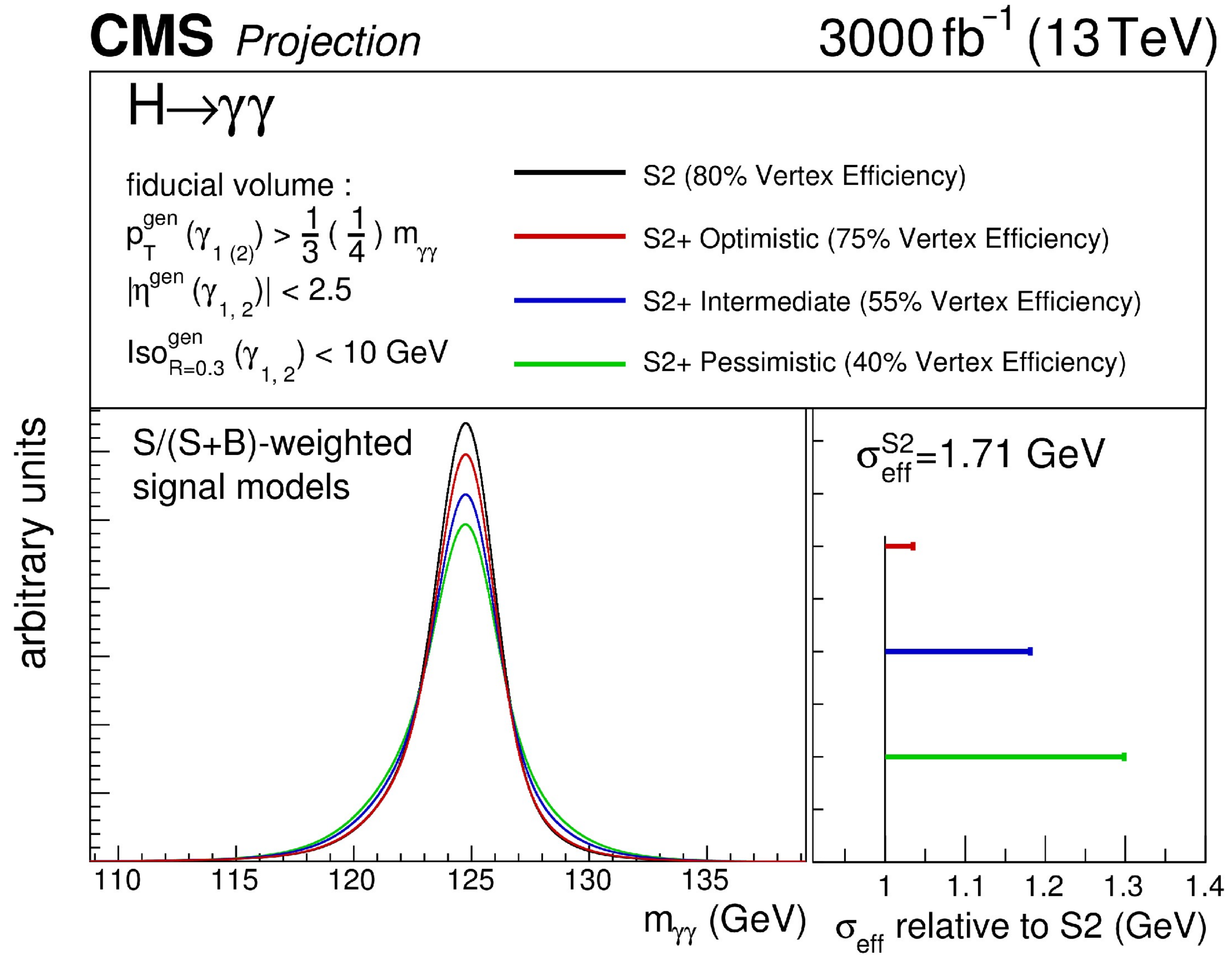
replaced by **new detector** High Granularity Calorimeter (**HGCAL**)
(check Arnaud's talk)

ECAL barrel upgrade physics goals



- **Goal:** restore ECAL performance to LHC Phase1
  - compensate for **energy resolution loss** from detector aging → impacting σ_E/E constant term

- **Detector performance target:** keeping $e^{\pm}$ and γ σ_E/E < 1% and improving timing resolution up to σ_t < 30 ps (at E ≥ 50 GeV)
  - precise γ **time of flight** measurement → efficient association reconstructed photon to vertex !
  - keep good resolution on $H \to \gamma\gamma$ → reduce γ **opening angle uncertainty** down to be negligible w.r.t. energy resolution

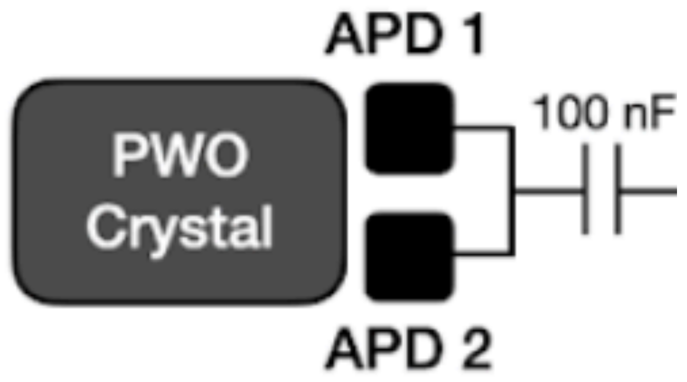


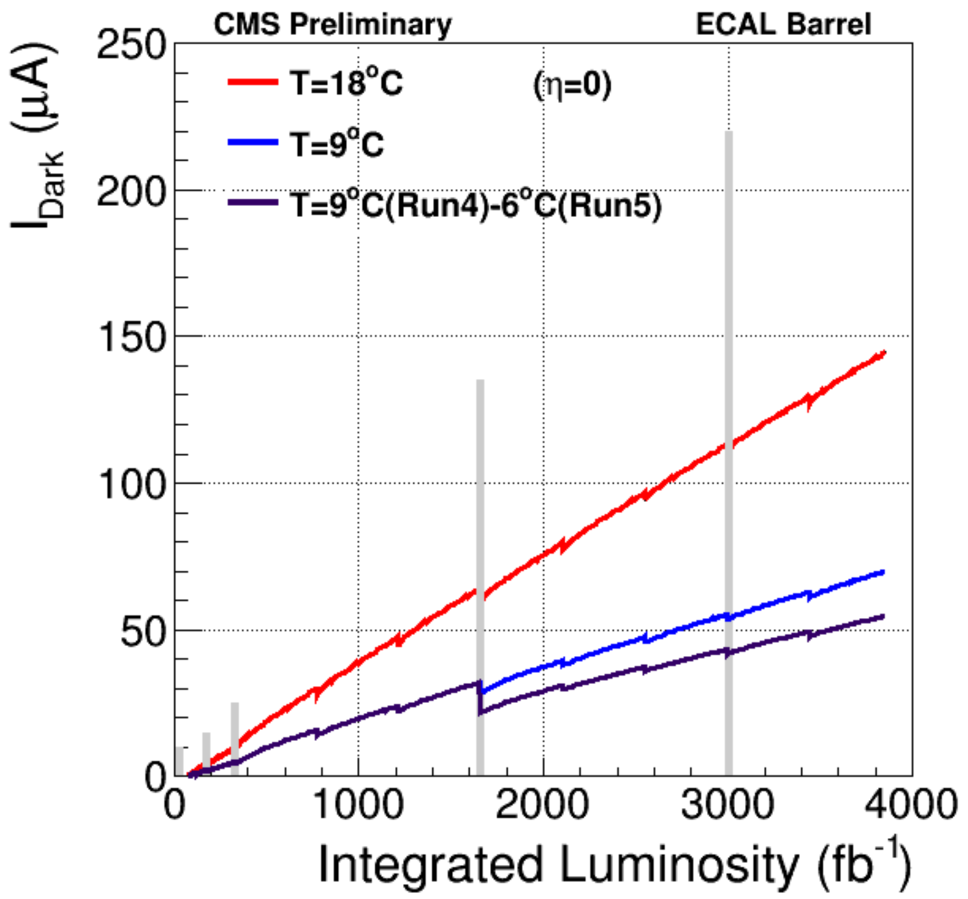
$H \to \gamma\gamma$ resolution at PU=140 with
no precise timing,
ECAL timing σ_t < 30 ps
precise timing in ECAL and MTD
compared to **Phase1**

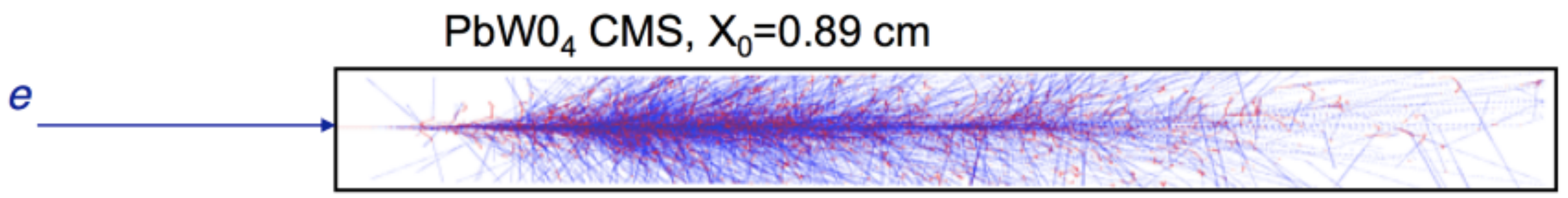
On detector readout electronics

CMS-TDR-015

- Operational temperature 18°C → 9°C
  - reduce **APDs dark current** and
  - +20% scintillation light yield

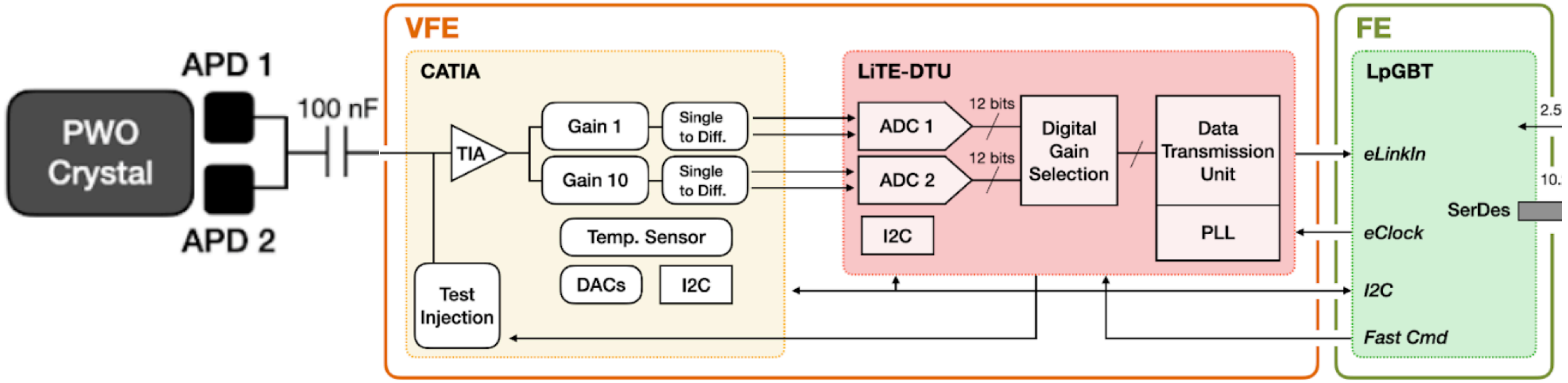






On detector readout electronics

[CMS-TDR-015](CMS-TDR-015)



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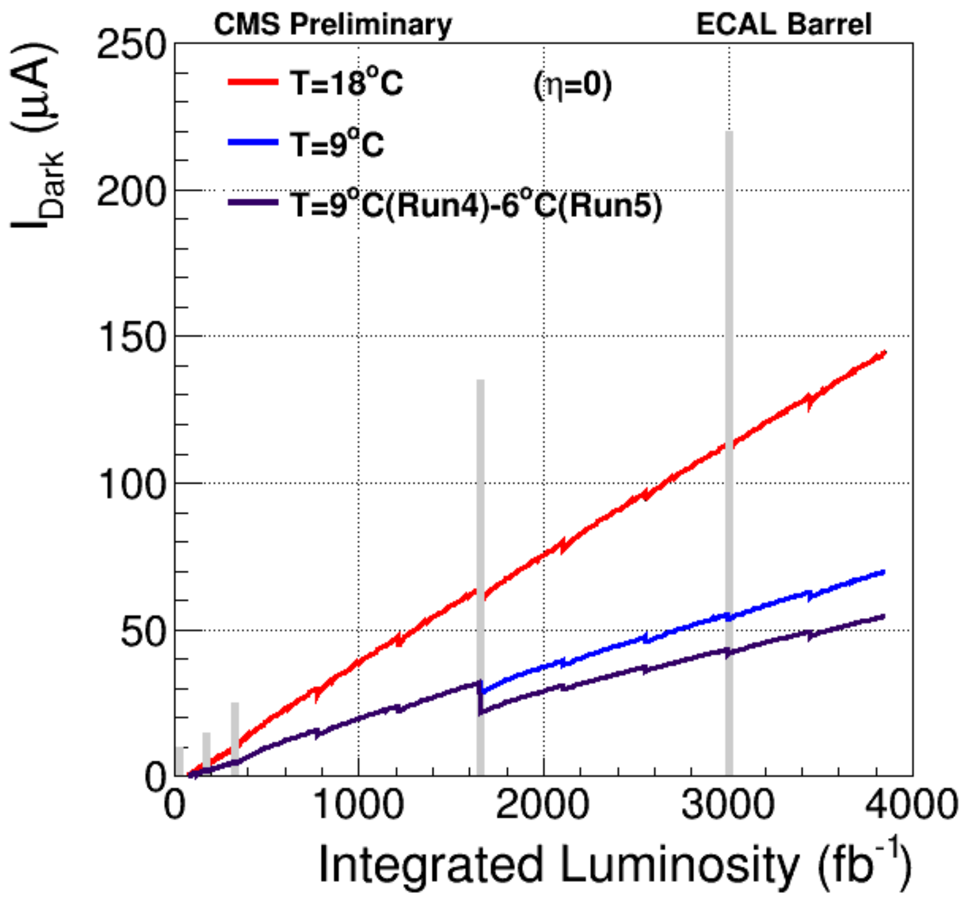
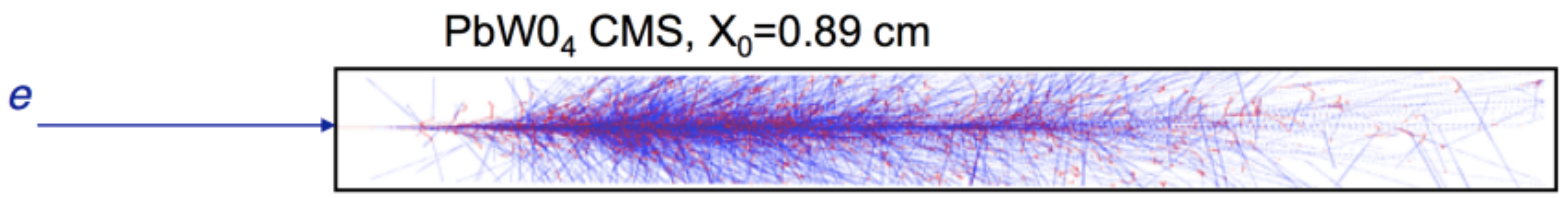




Very Front End (VFE) cards

- **ASICs** : preamplifier → ADC + gain selection + data compression
  - 2x transimpedance amplifiers (gain=1 or gain=10)
  - 2x ADCs sampling frequency 160 MS/s &12bit resolution (40 MS/s legacy)

Front End (FE) cards

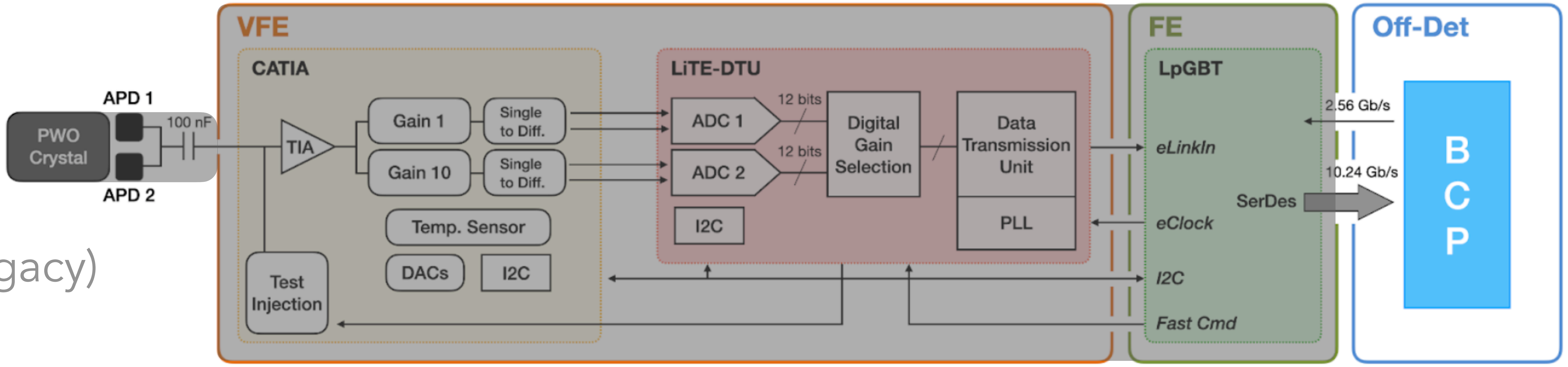
- Radiation tolerant **optical transmission system**
  - single crystal granularity data stream to off-detector boards (x25 granularity w.r.t. legacy)

Shorter pulse shaping + higher sampling rate

→ noise reduction, pile up mitigation

Off detector back-end

CMS-TDR-015

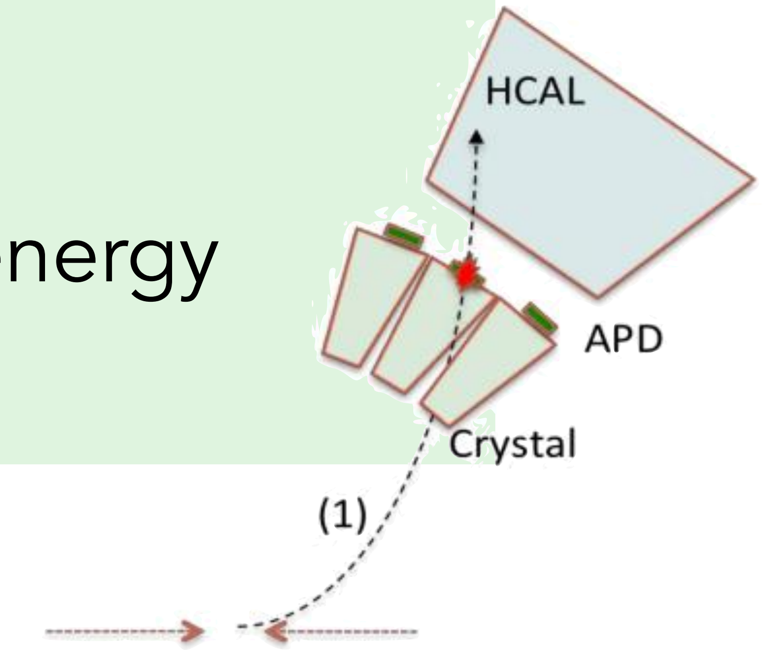


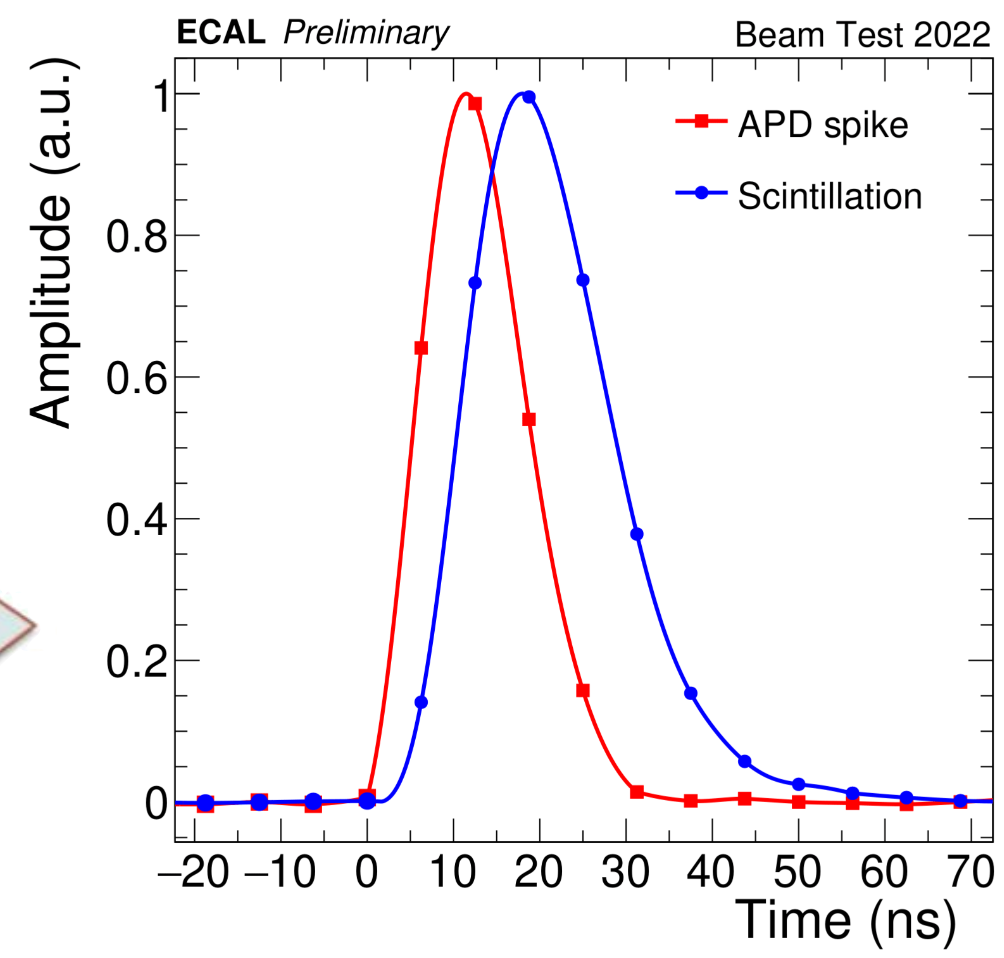
Barrel Calorimeter Processor (BCP)

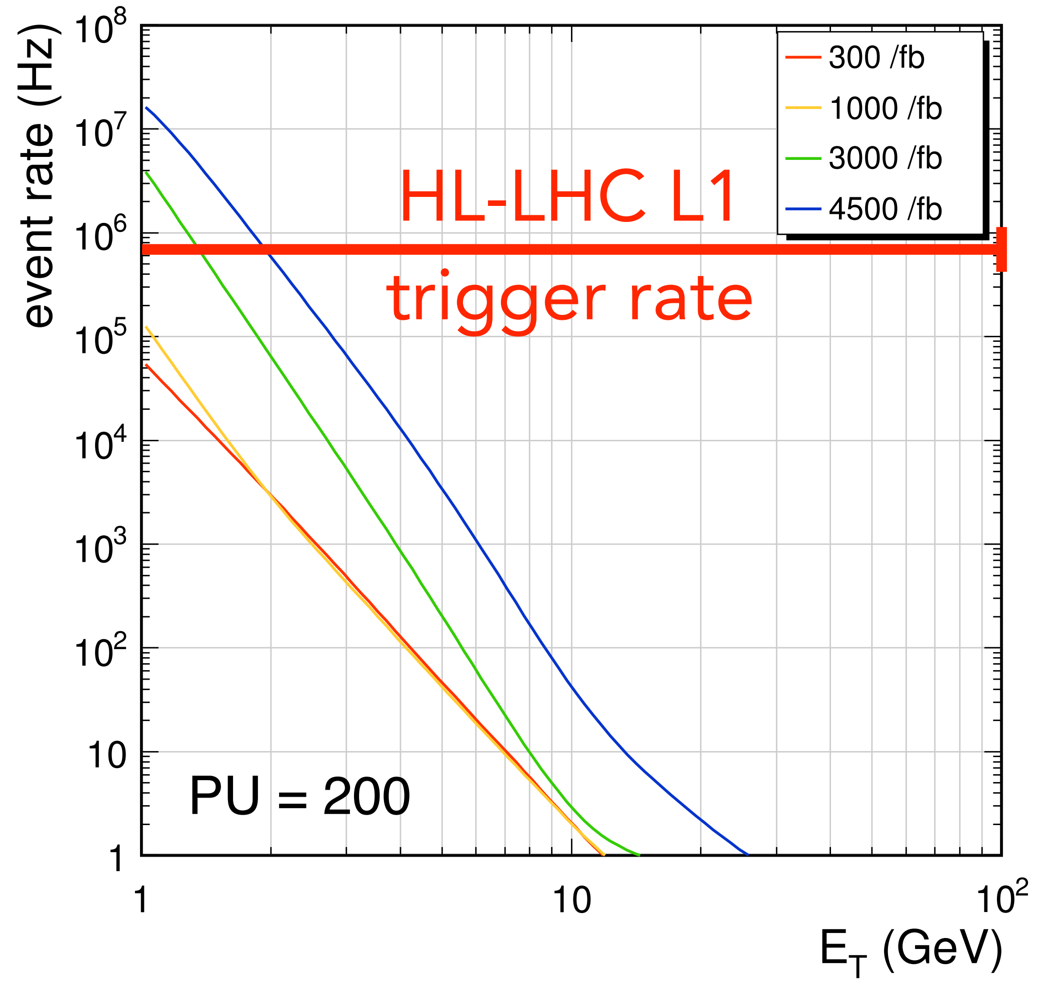
- **FPGA** based data aggregator :
  - back-end **off-detector** → latency 12.5 μs (4μs legacy)
  - digitized pulses → transverse energy conversion
    - * single crystal granularity to CMS L1 trigger cards
    - * basic clustering for prompt time/energy reconstruction → **spike rejection**

Spikes = particles directly ionizing in APD bulk

- **Single channel large** energy deposit
- HL-LHC : spike events would **saturate L1 trigger** bandwidth
  - ➔ faster pulse shape w.r.t. scintillation → discrimination enabled by ECAL upgraded FE
  - ➔ BCP **spikes suppression** → keep L1 transverse energy threshold E_T~10 GeV





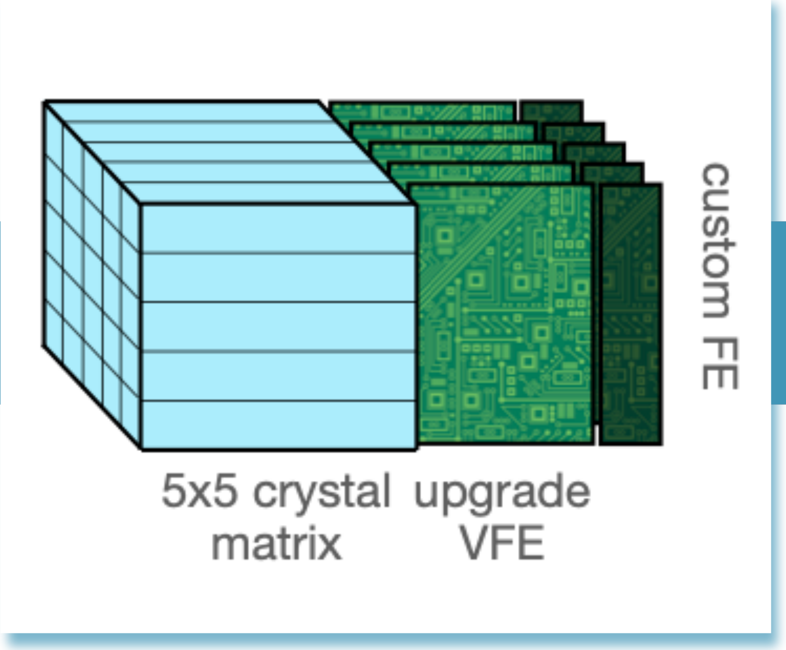


Test beam campaigns

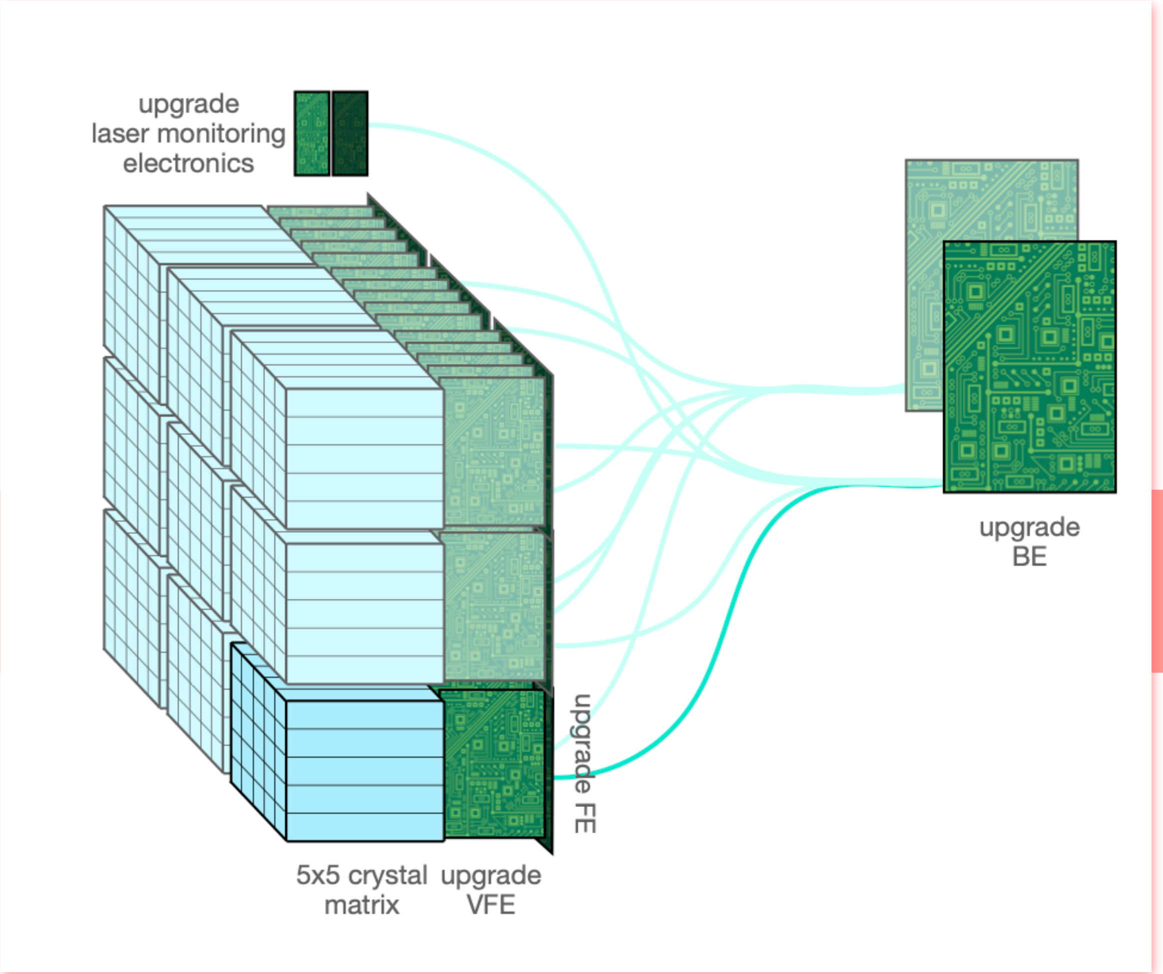
- Test beam campaign at CERN, SPS/H4 beamline : very pure $e^{\pm}$ beam $\Delta p/p = 0.5\,\%$ in [25 , 300] GeV
- Test beams have driven prototypes improvements up to their **final design**
  - **VFE v3.0** reduces jitter w.r.t. input clock → pre-production is happening now
  - **FE v3.3** boards reached stable data transmission architecture → ready for production
  - **BCPv2** firmware and layout near completion
- **Next** tests beam → test final prototypes & optimize data stream synchronization

2018
first CATIAv0
prototype

testing 1 readout unit



2021
complete VFE design
energy / timing performances



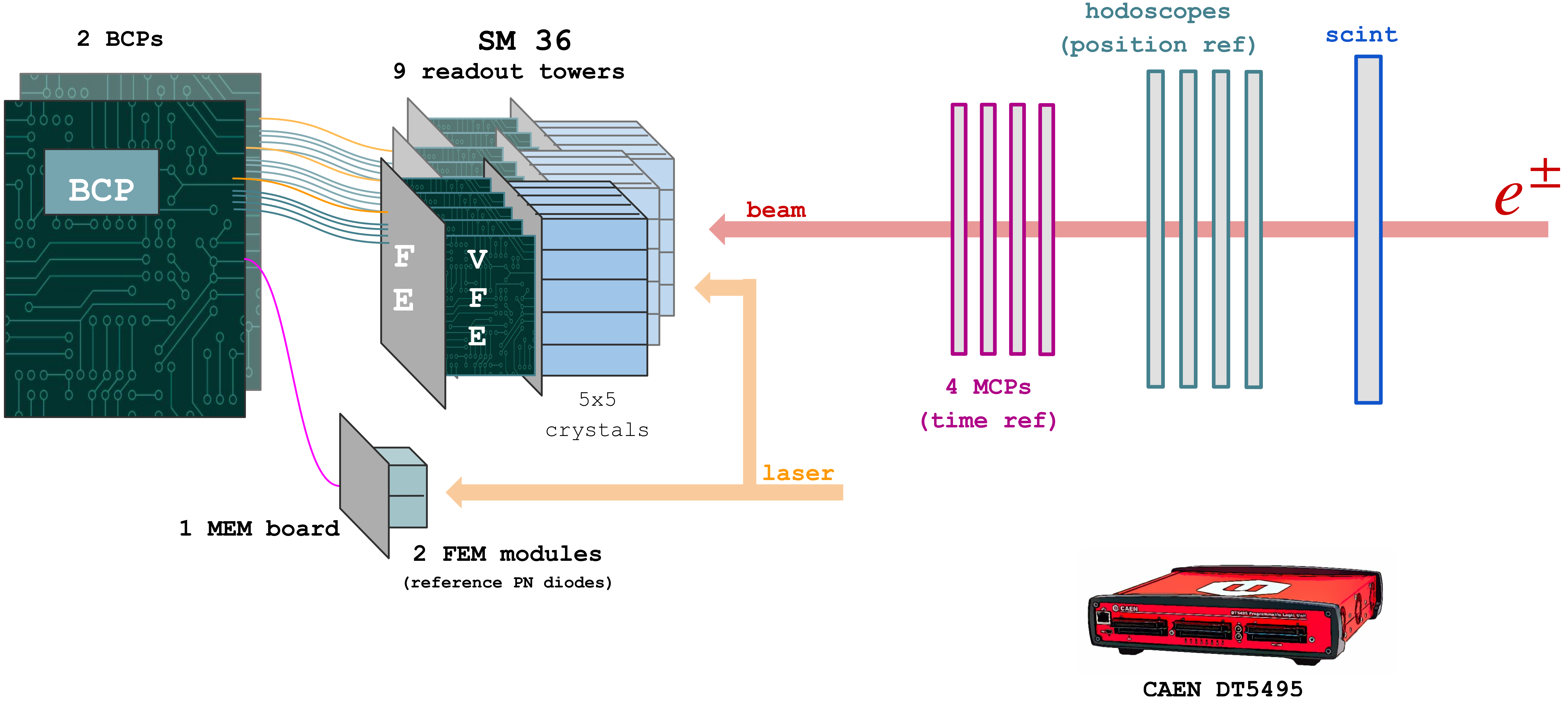
2022
full readout chain in place!
BCP firmware commissioning

2023
common backend for
BCPv1 + FE v3.3
laser & ECAL readout

testing 9 readout units

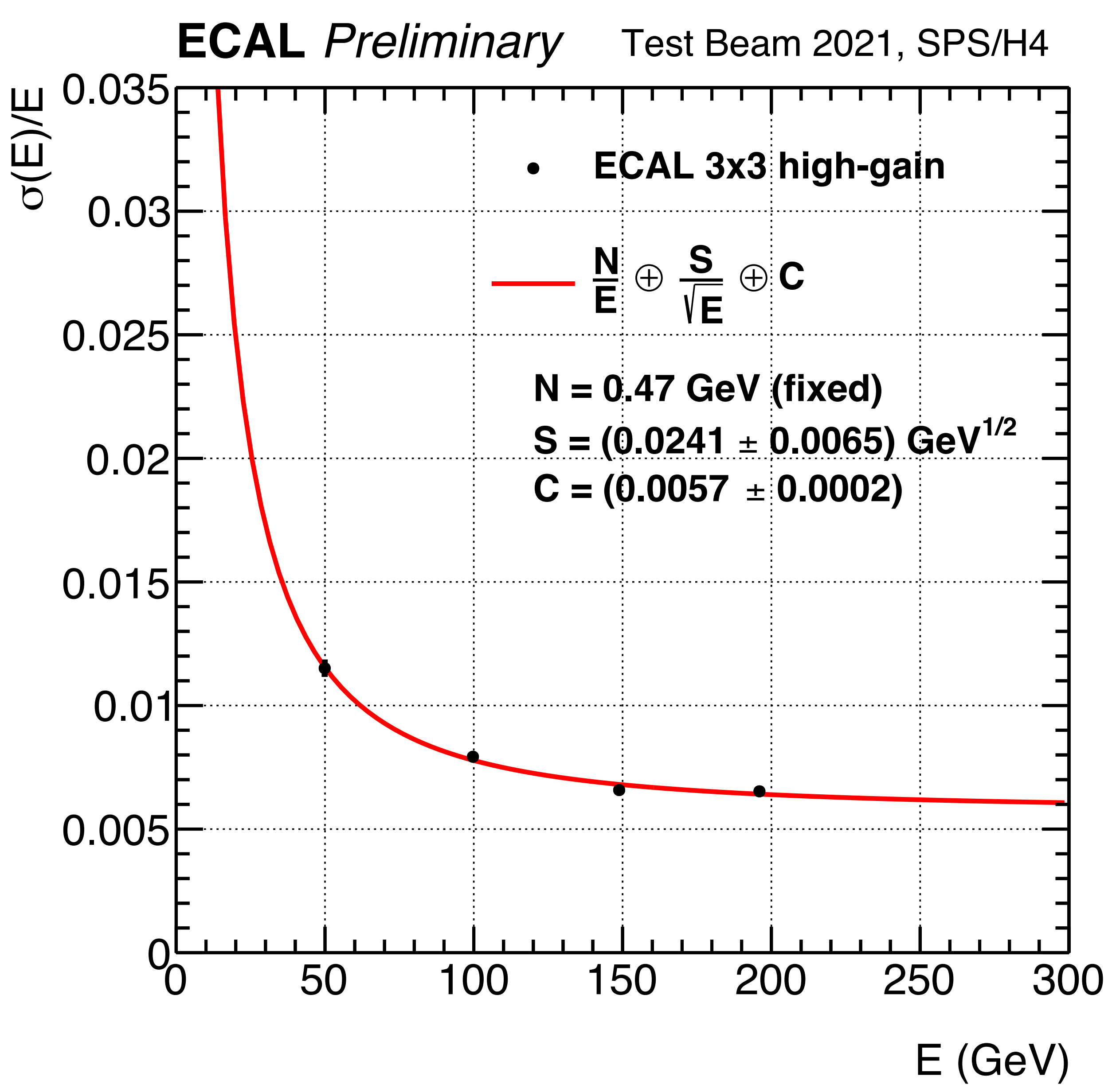
October 2024
BCPv2 + VFE v3.0

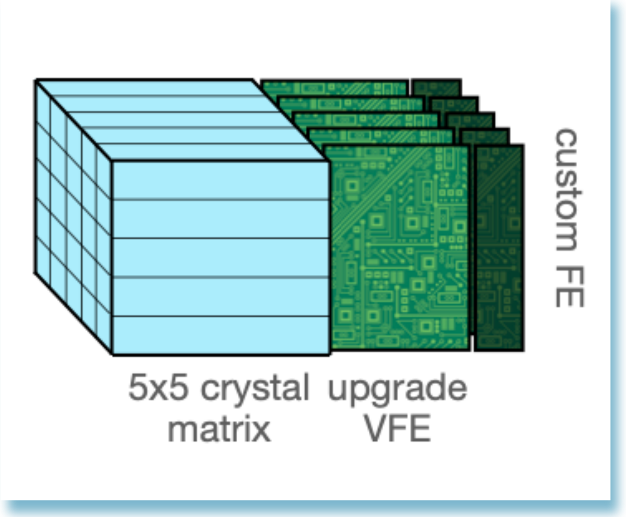
Test beam setup in a nutshell

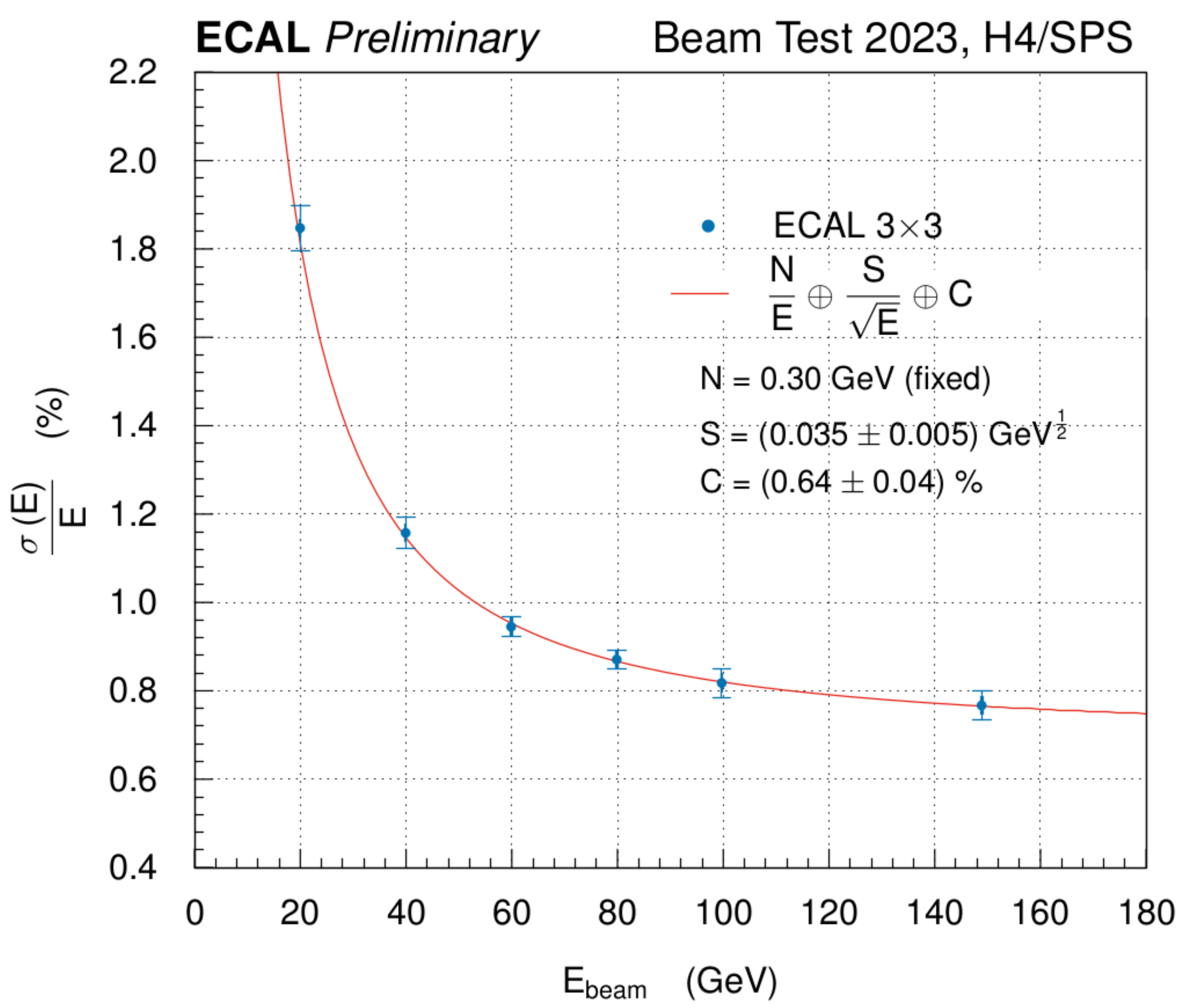


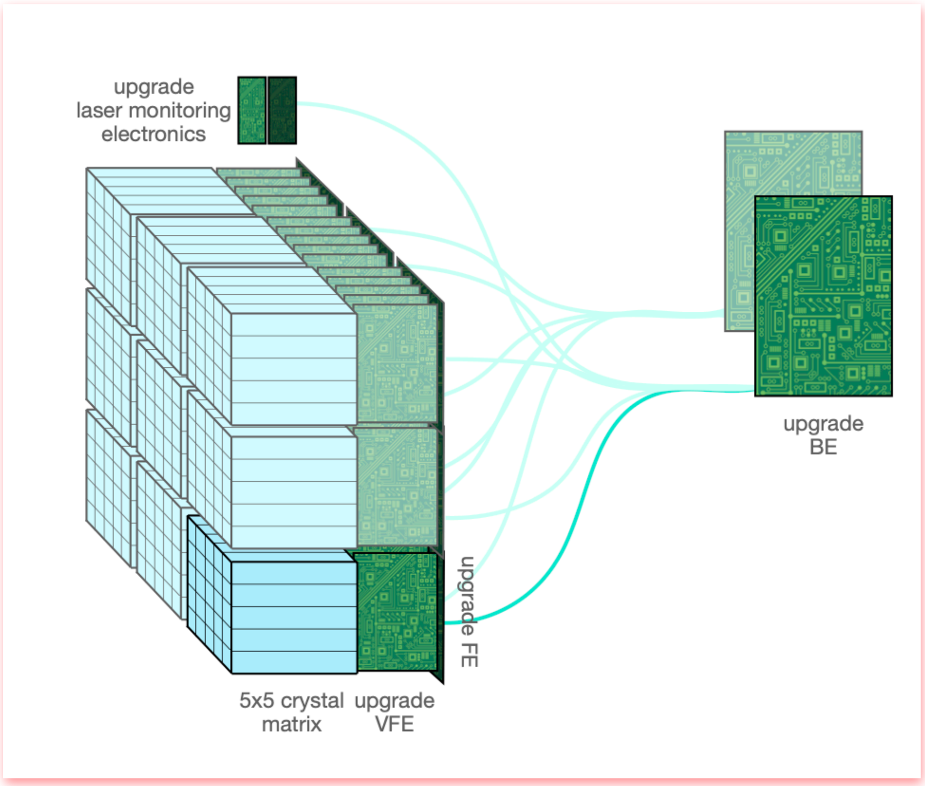
Energy resolution results

- Monochromatic beam hitting **one crystal center**
- Energy resolution of **3x3 channel matrix** around the target crystal → ~95% e.m. shower containment
  - **N** : noise term fixed from dedicated noise study in the 9 channels
  - **S** : stochastic term compatible with Phase1 measurement (0.028 $GeV^{1/2}$) ✔ [2007 JINST 2 P04004]
  - **C** : constant term < 1% for E >50 GeV ✔



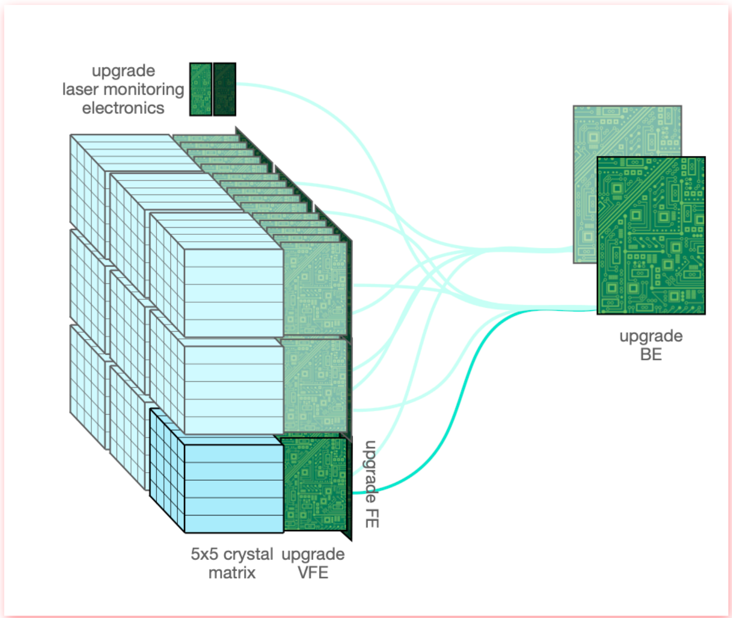


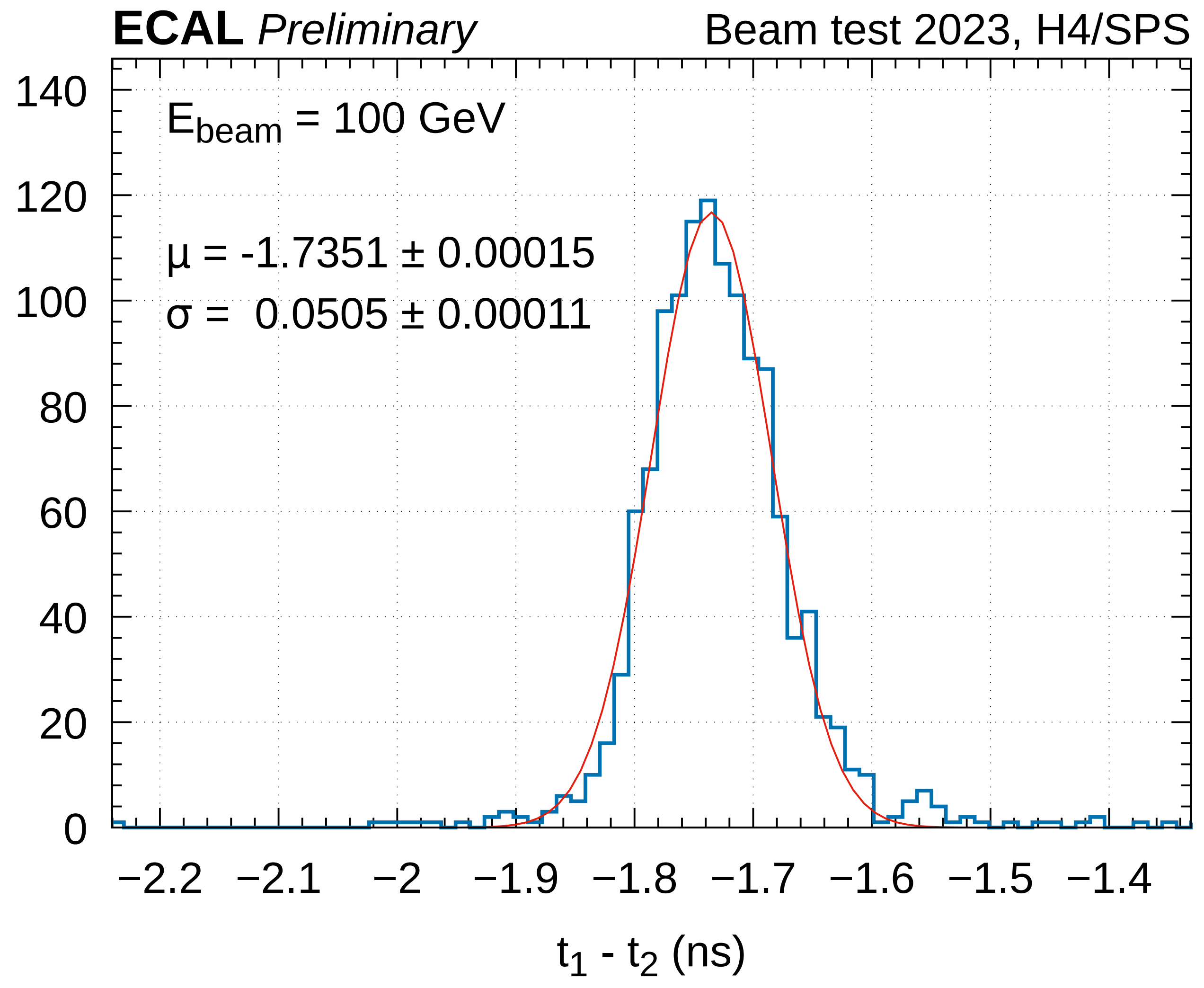


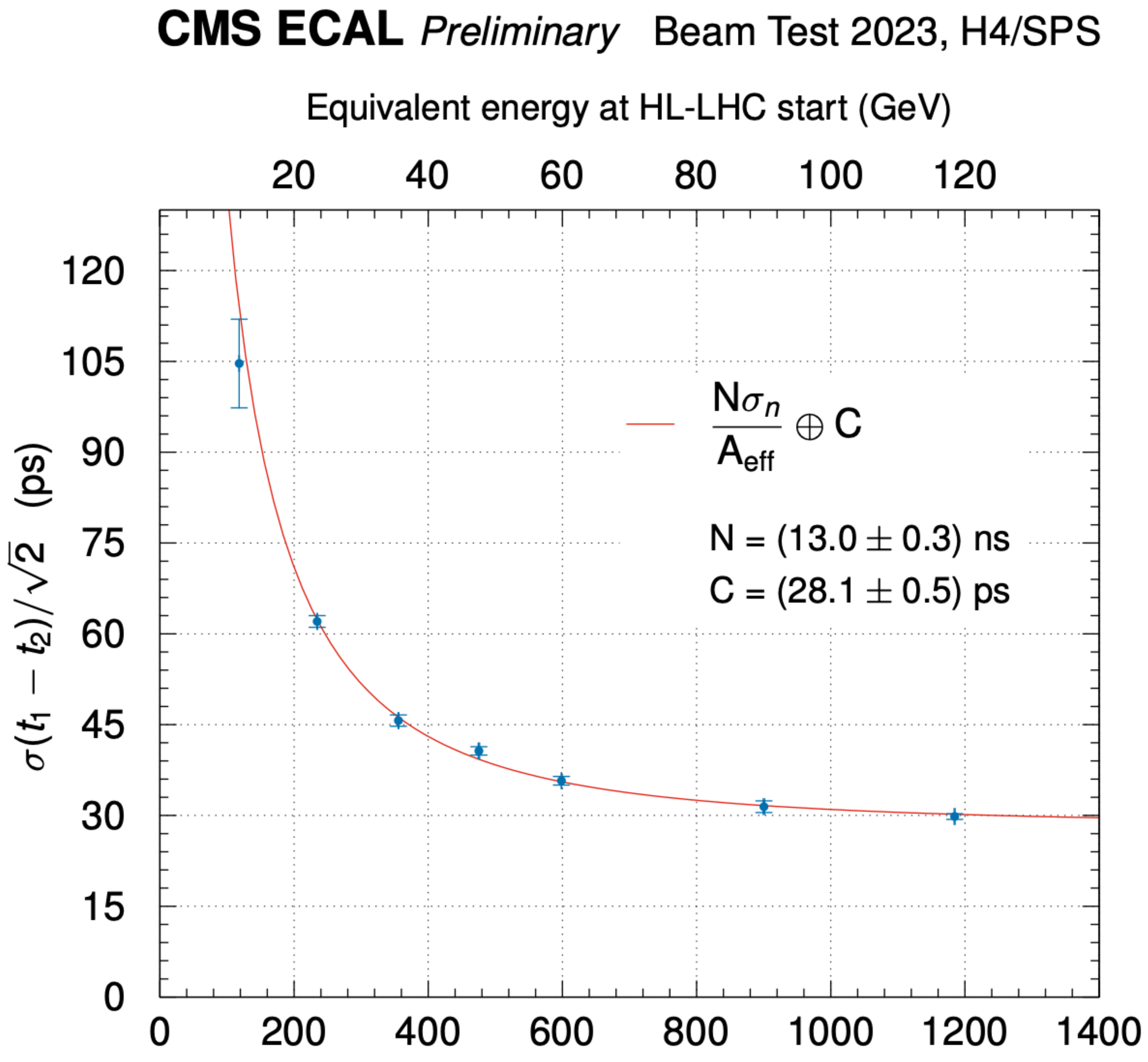


Relative time resolution results

- Monochromatic beam hitting edge between two neighboring crystals
- Arrival time difference spread→ gaussian fit in bin of signal effective amplitude
  - assuming same time resolution in both channels
  - **C** constant term < 30 ps within the target for HL-LHC ✔
- **Ongoing analysis**: single channel timing resolution w.r.t. MCP time reference

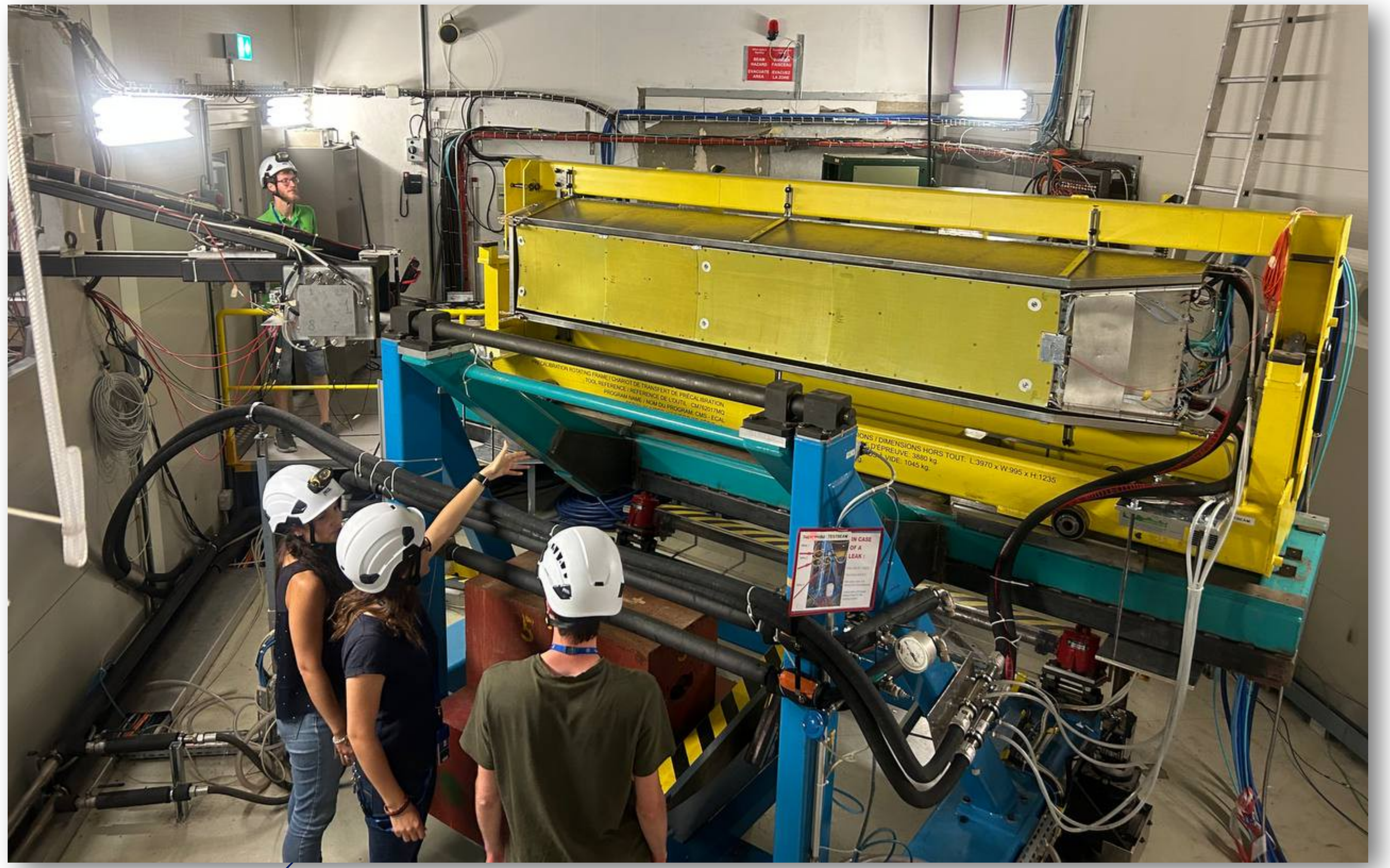






$$\frac{A_{eff}}{\sigma_n} = \sqrt{\frac{2}{\left(\frac{\sigma_1}{A_1}\right)^2 + \left(\frac{\sigma_2}{A_2}\right)^2}}$$

Conclusions and future plans



- ECAL barrel readout electronics is being fully upgraded for HL-LHC
  - APDs and $PbWO_4$ crystals will remain operational
- The upgrade target
  - mitigating **radiation induced noise** and **pile-up**
  - fast data transmission to match **L1 trigger rate**
  - Phase1 energy resolution and **improved timing** resolution ($\sigma_t < 30$ ps)
- Performance tested successfully during several **test beam campaigns**
  - **energy and time resolution within the requirements ✔**
- Full readout chain is being tested since 2022 campaign
  - components design is almost **fully finalized**
  - testing/optimizing data streaming and components synchronization → **next campaigns** foreseen in fall 2024 and 2025 !
- Component production already happening

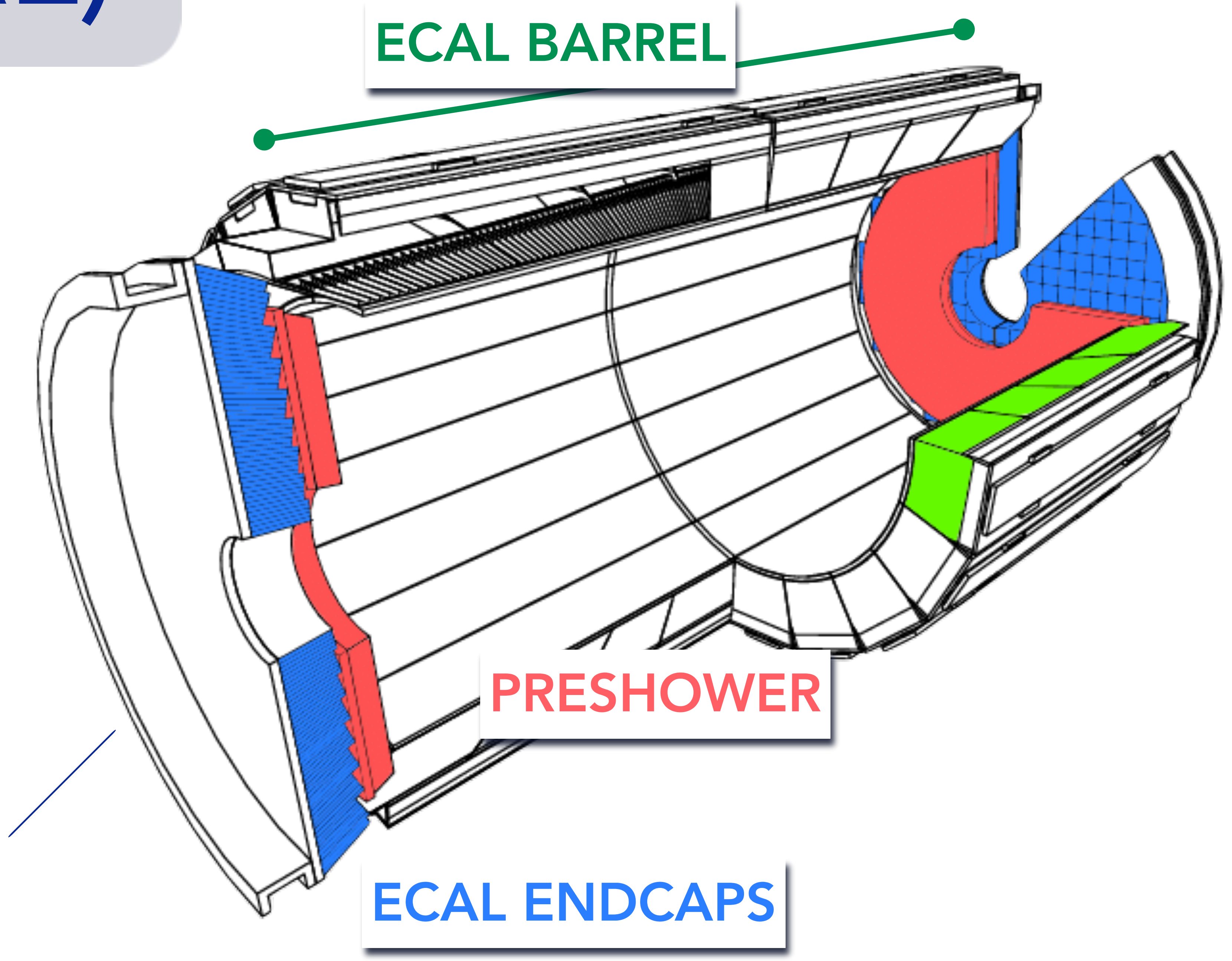
BACKUP

High Luminosity LHC

High Luminosity Upgrade for LHC (HL-LHC) targets unprecedented instantaneous luminosity and pile-up conditions

- CMS **2024 Run3** conditions compared to **HL-LHC baseline** (ultimate) target:
  - instantaneous luminosity $\mathcal{L} = 2.0 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow \mathcal{L} = 5.0\ (7.5) \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - peak pile-up PU = 65 → 140 (200)
- New data-taking conditions demand for a full renovation of many CMS sub-detectors

CMS electromagnetic calorimeter (ECAL)



Homogeneous calorimeter → 75848 lead tungstate ($PbWO_4$) scintillating crystals

- high density ρ = 8.28 g/cm^{-3}
- short radiation length X_0 = 8.9 mm and small Moliere radius R_M = 23 mm
- fast light emission: ~80% of scintillation light in 25 ns

- Central Barrel $|\eta| < 1.48$
  - quasi-projective crystal geometry towards the collision point
  - crystals scintillation read by Avalanche Phododiodes (APD)

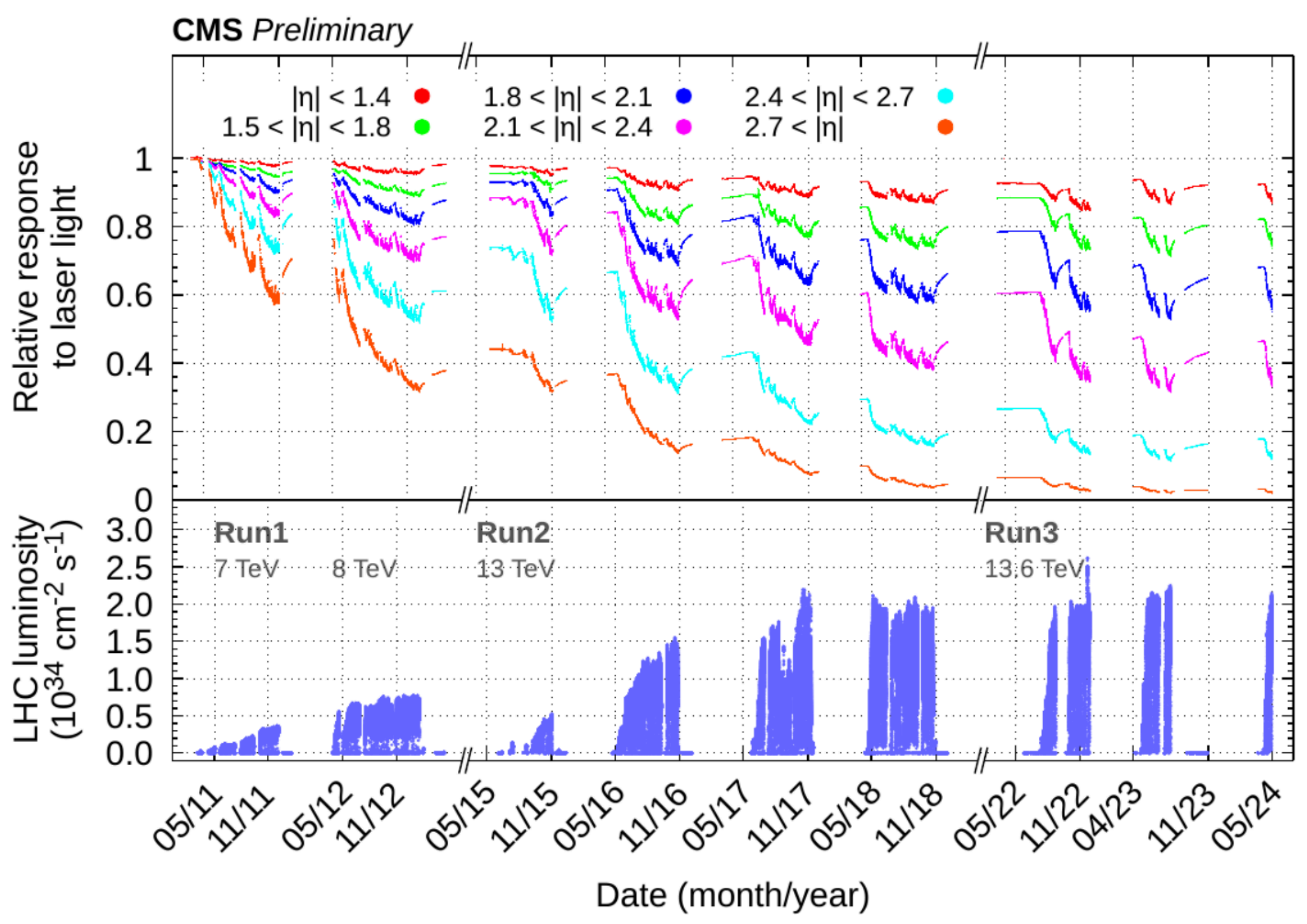
→ **electronics fully renovated**
APDs and $PbWO_4$ remain operational

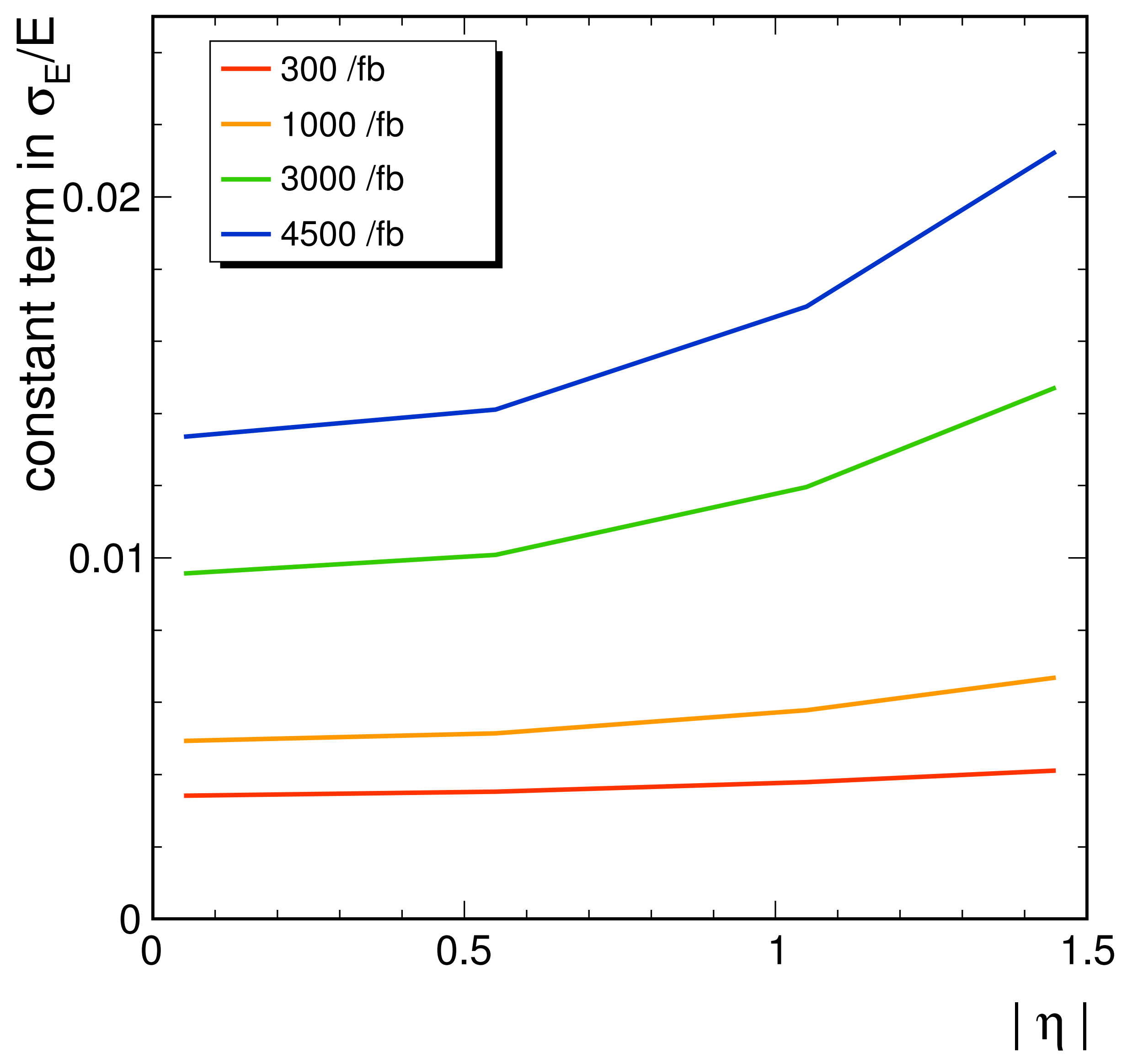
- Forward Endcaps $1.48 < |\eta| < 3.0$
  - crystals scintillation read by Vacuum Phototriodes (VPT)

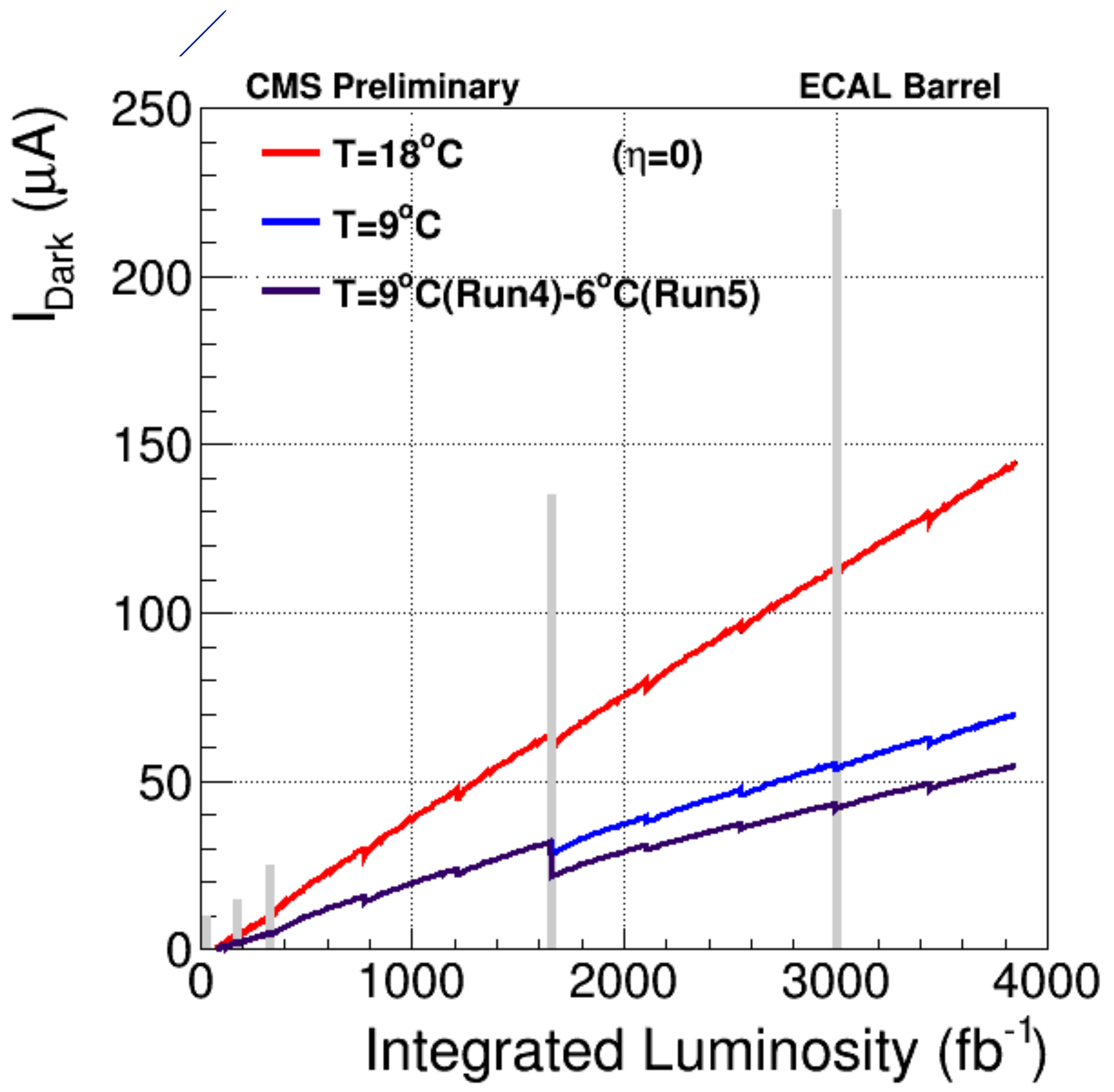
→ replaced by **new detector** High Granularity Calorimeter (**HGCAL**)

PbWO4 crystals & APDs longevity

- $PbWO_4$ crystals radiation damage impacts on scintillation light yield
  - retain 20-40% light output for 3000 fb-1 int. luminosity
  - impact on energy resolution constant term
- ECAL barrel photosensors will operating at 9° during HL-LHC
  - limit increasing APDs leakage current from radiation damage
  - increase light yield recovery time

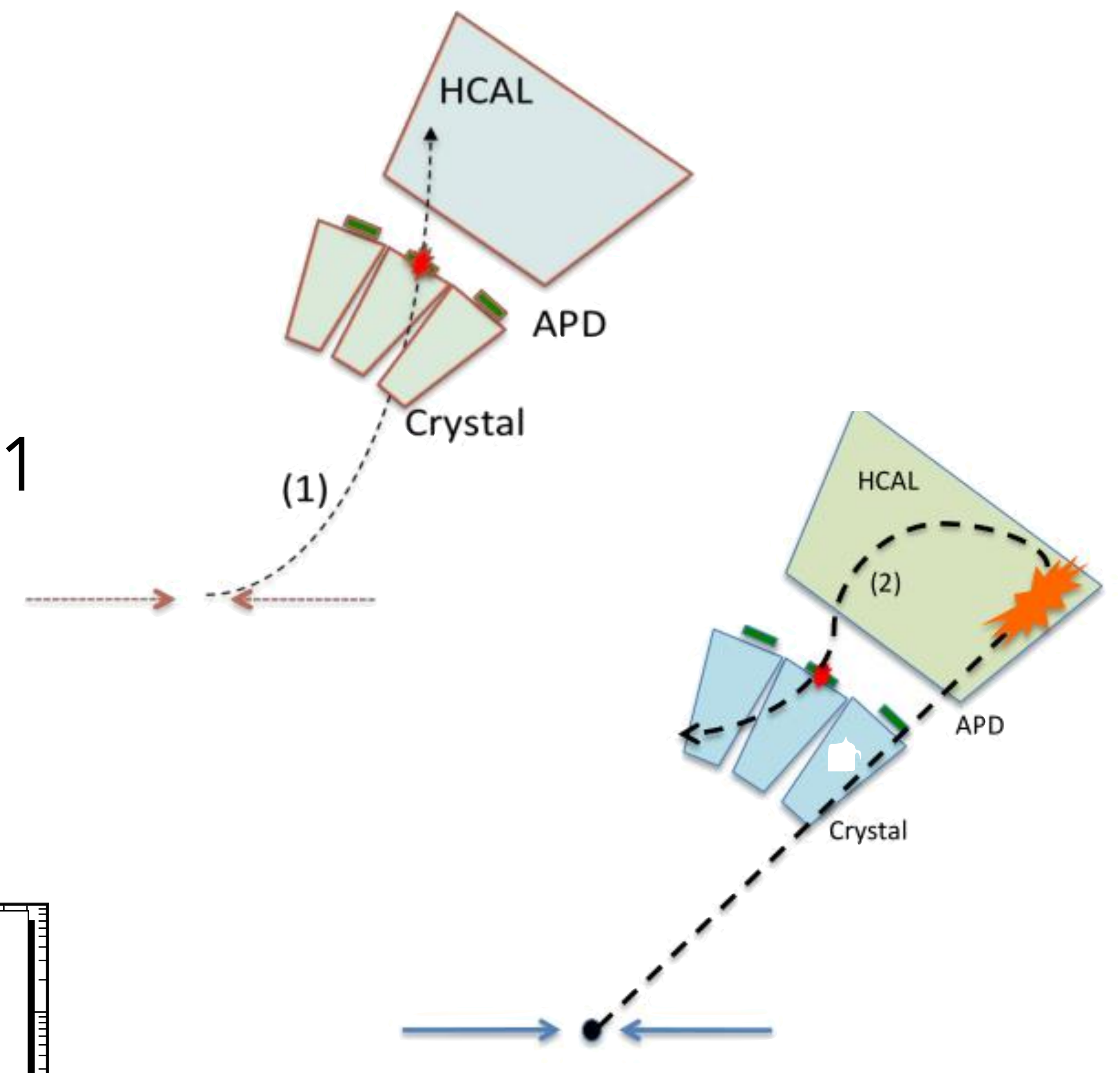


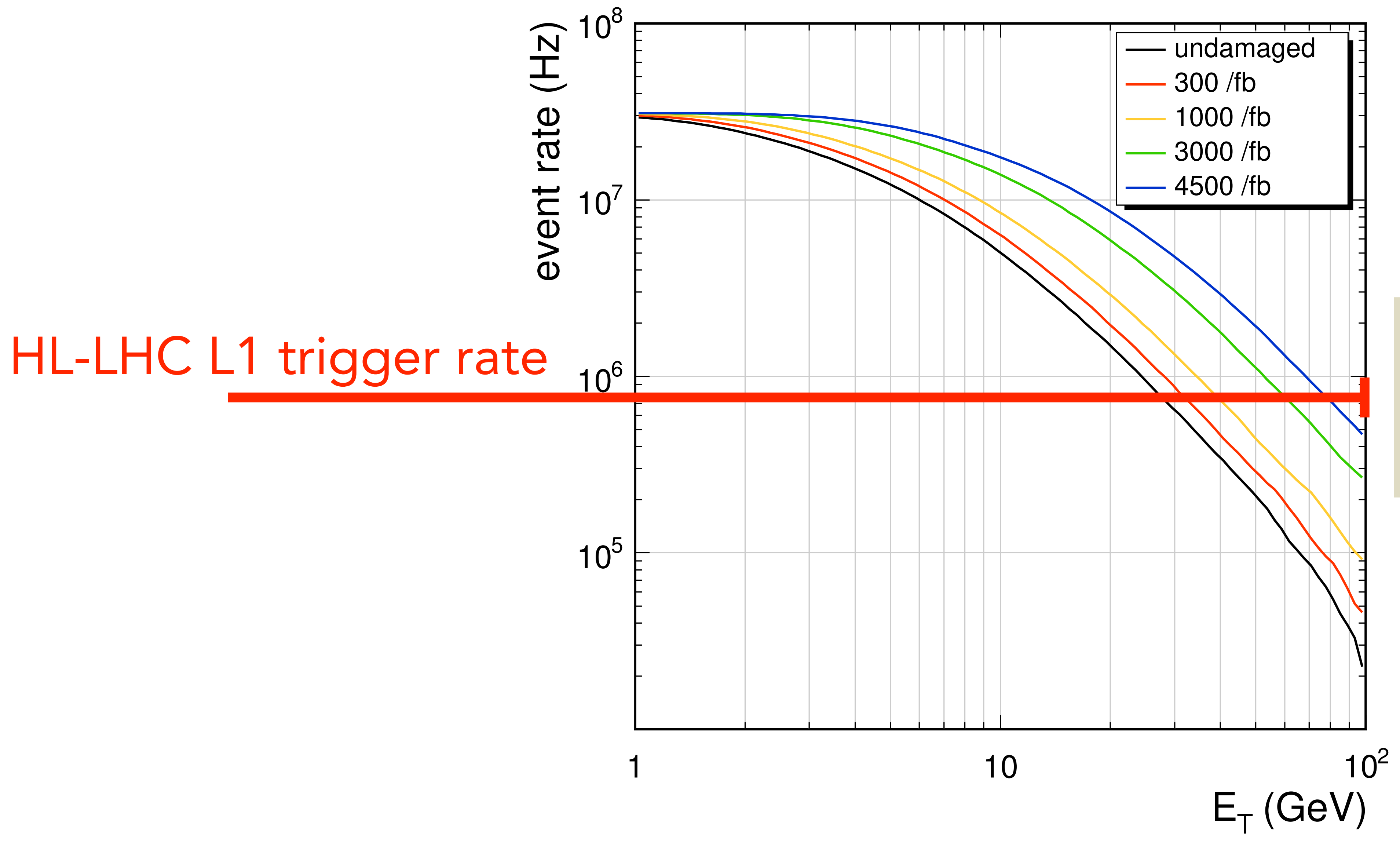


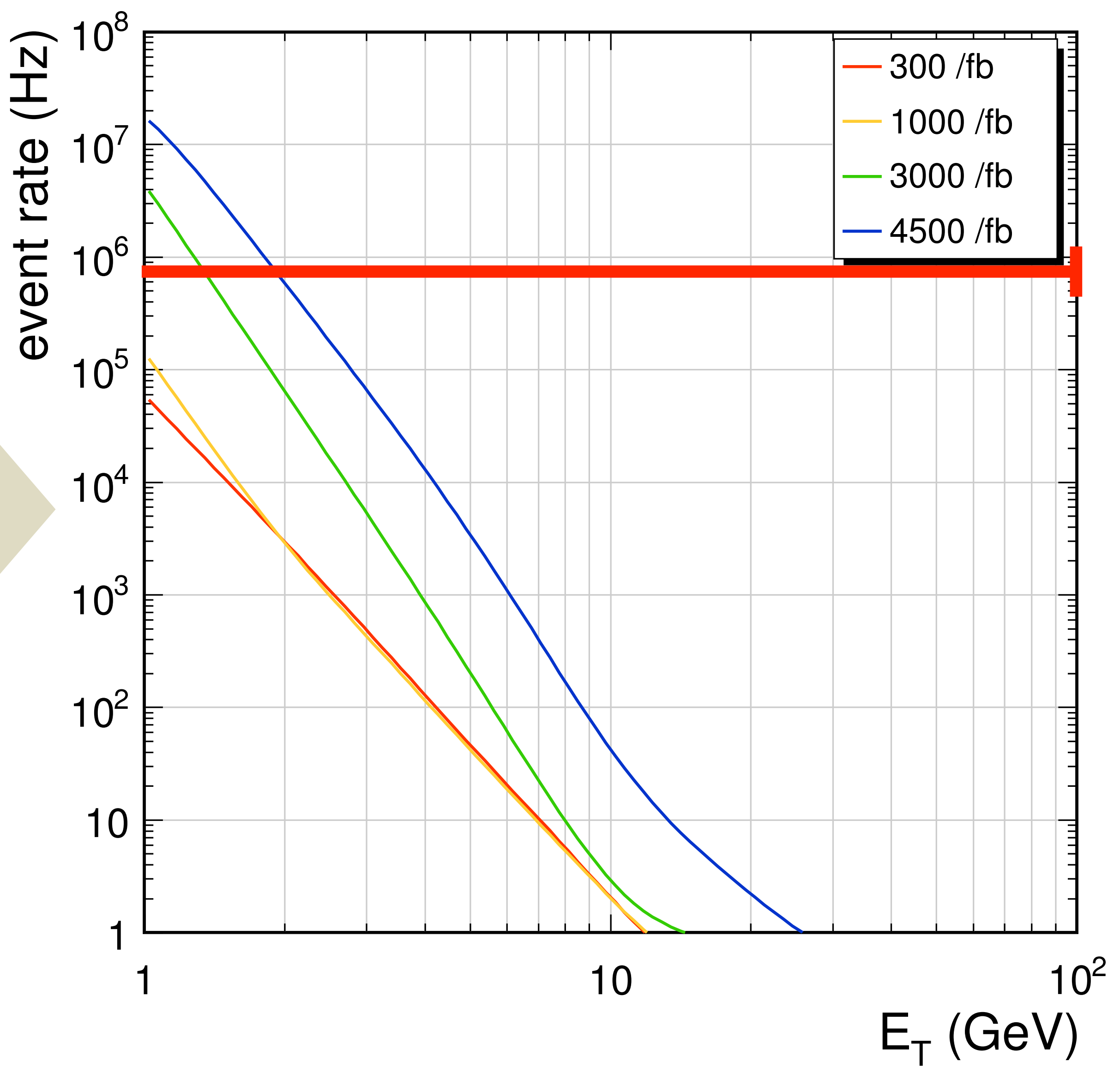


Spike killing algorithm for HL-LHC

- Spikes events are direct ionization in APDs
  - energy deposit is in a single channel
  - spike signal are faster while scintillation signal have a longer evolution in time
- At HL-LHC condition spike events would saturate the L1 trigger → spike killer algorithm @ L1
  - shorter pulse shaping and higher sampling rate
  - single crystal granularity at L1







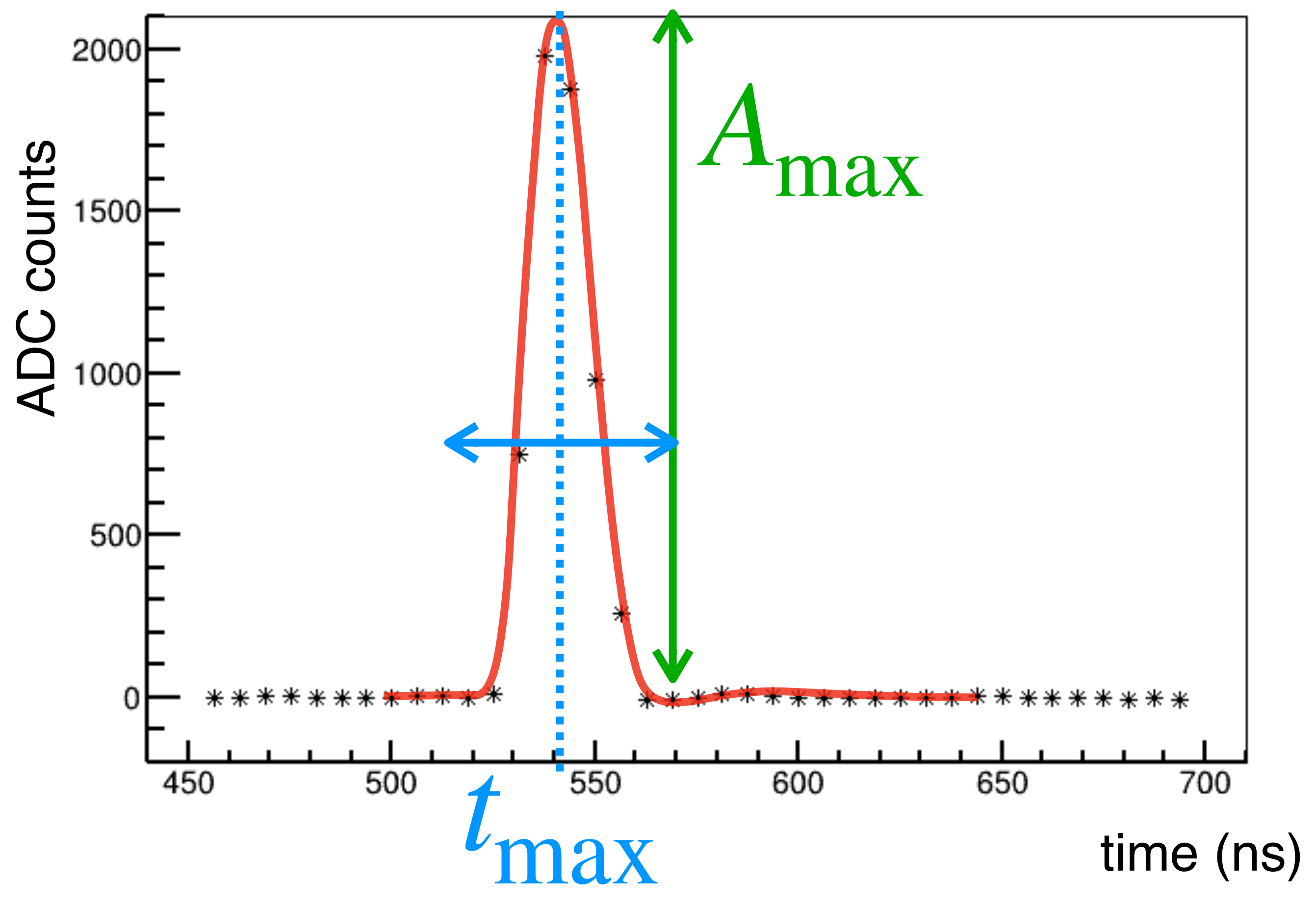
ECAL signal reconstruction

Quality cuts

- **Hodoscope plates** beam transverse position
- **Micro Plate Chambers (MCP)** (σ_t/t =15 ps) particles arrival time reference

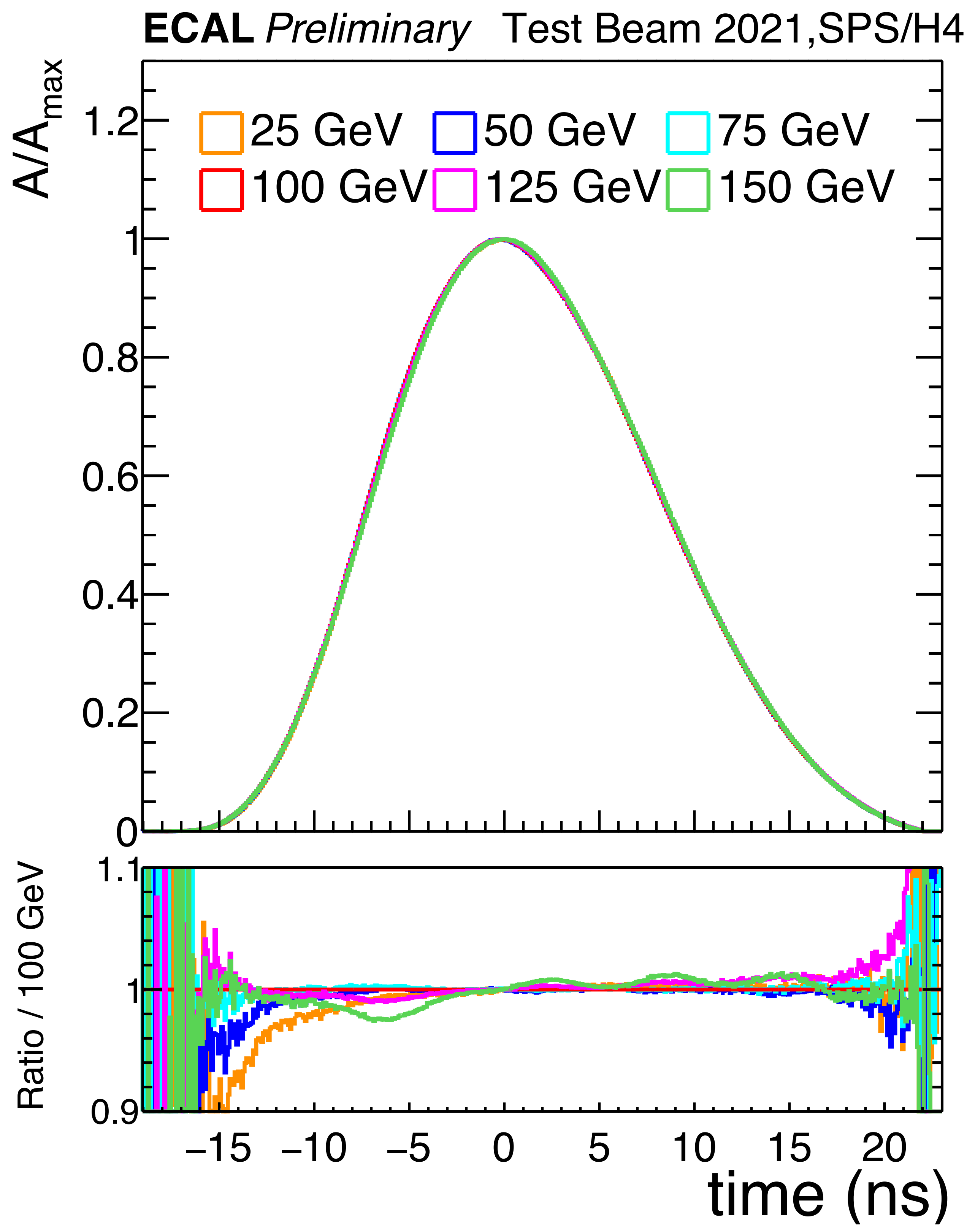
Particle signal reconstruction

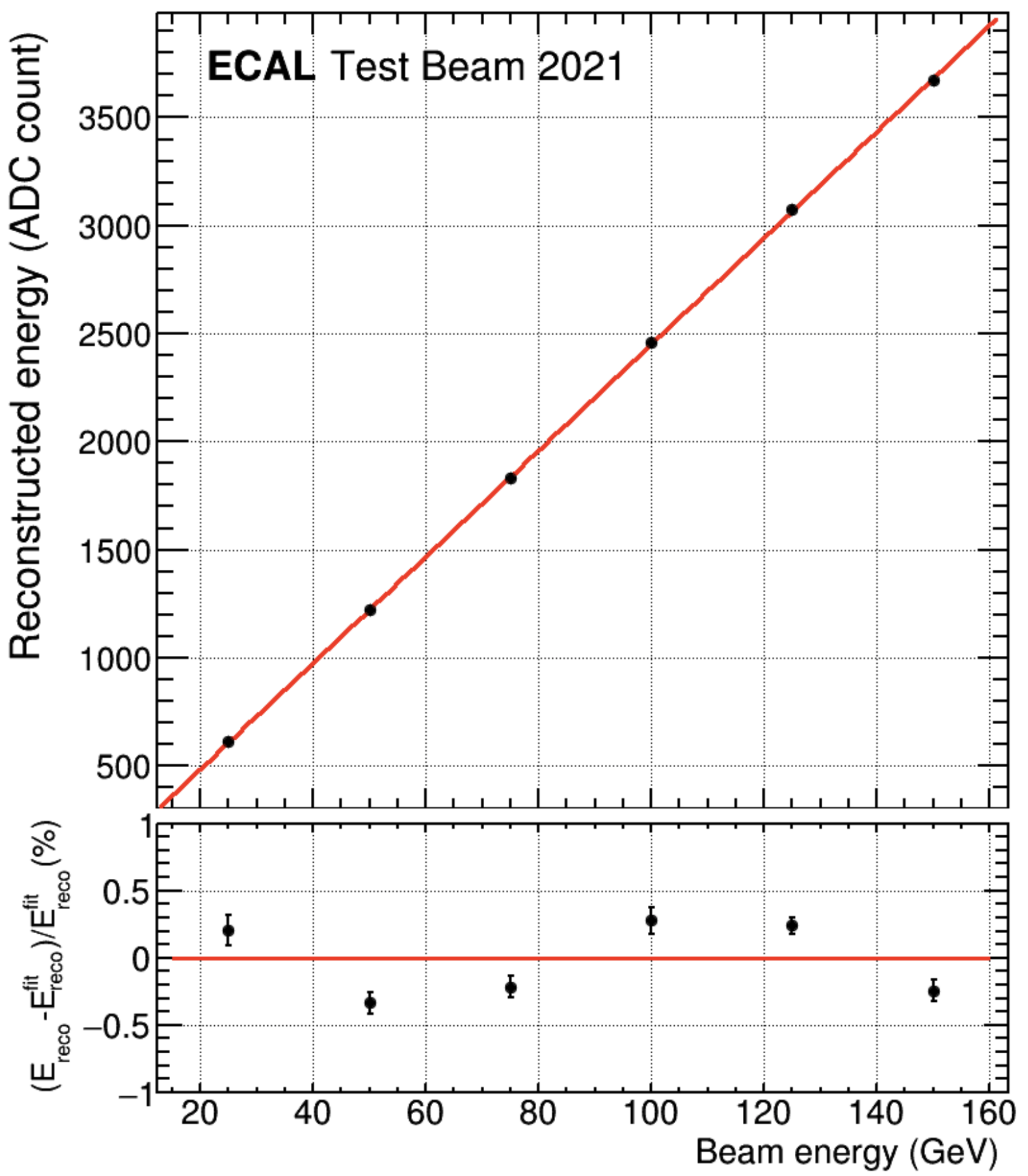
- Template fit to digitized pulse shape → signal amplitude and arrival time
- Signal amplitude distribution for given beam energy
  - average signal amplitude and width → linearity and energy resolution
- Time difference distribution between
  - 2 neighboring channels → relative timing resolution



Single channel response with ASIC prototypes

- **2021 TB** : complete Very Front End ASICs (CATIAv1.4+LiTeDTUv1.2)
- Single crystal response for different beam energies
  - templates from pulse shapes aligned in time
  - normalized templates not depending on incident particle energy ✔
- Test signal amplitude linearity w.r.t. beam energy
  - maximum deviation from linearity < 0.3% with only statistical uncertainty ✔
  - ECAL linearity tested also in lab and proved at CMS





Statistical uncertainties only

2018 results

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