UPGRADE OF THE CMS CALORIMETERS FOR THE HIGH-LUMINOSITY LHC

Challenges and technological developments

P. Milenovic, Faculty of Physics Belgrade

Corfu, Mon-Repos Palace, 25 May 2024

The only voyage of discovery [...] consists not in seeing new landscapes, but in having new eyes.
M. Proust[1], 1923.

Brief overview of CMS calorimeters and challenges @LHC and @HL-LHC

- CMS calorimeters - performance and challenges at LHC
- Plans and challenges at High-Luminosity LHC (HL-LHC)

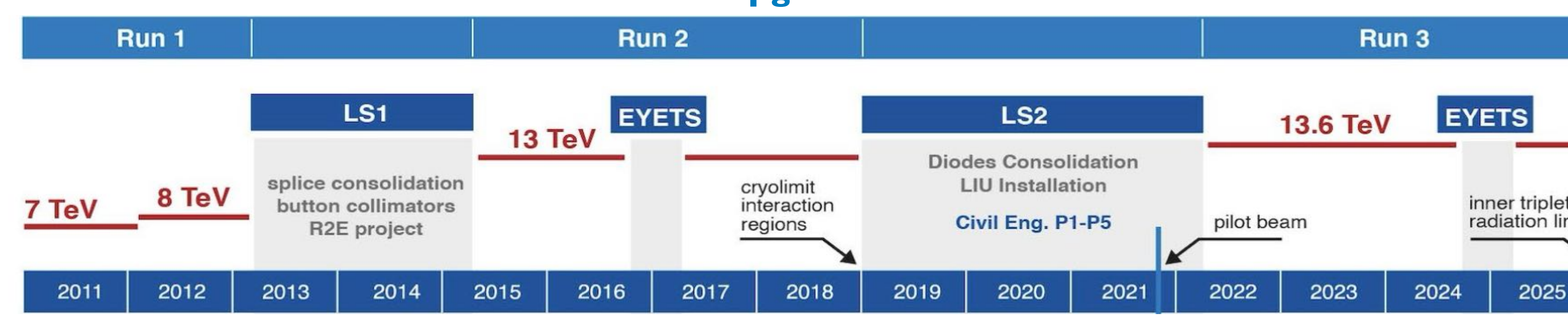
CMS @ LHC

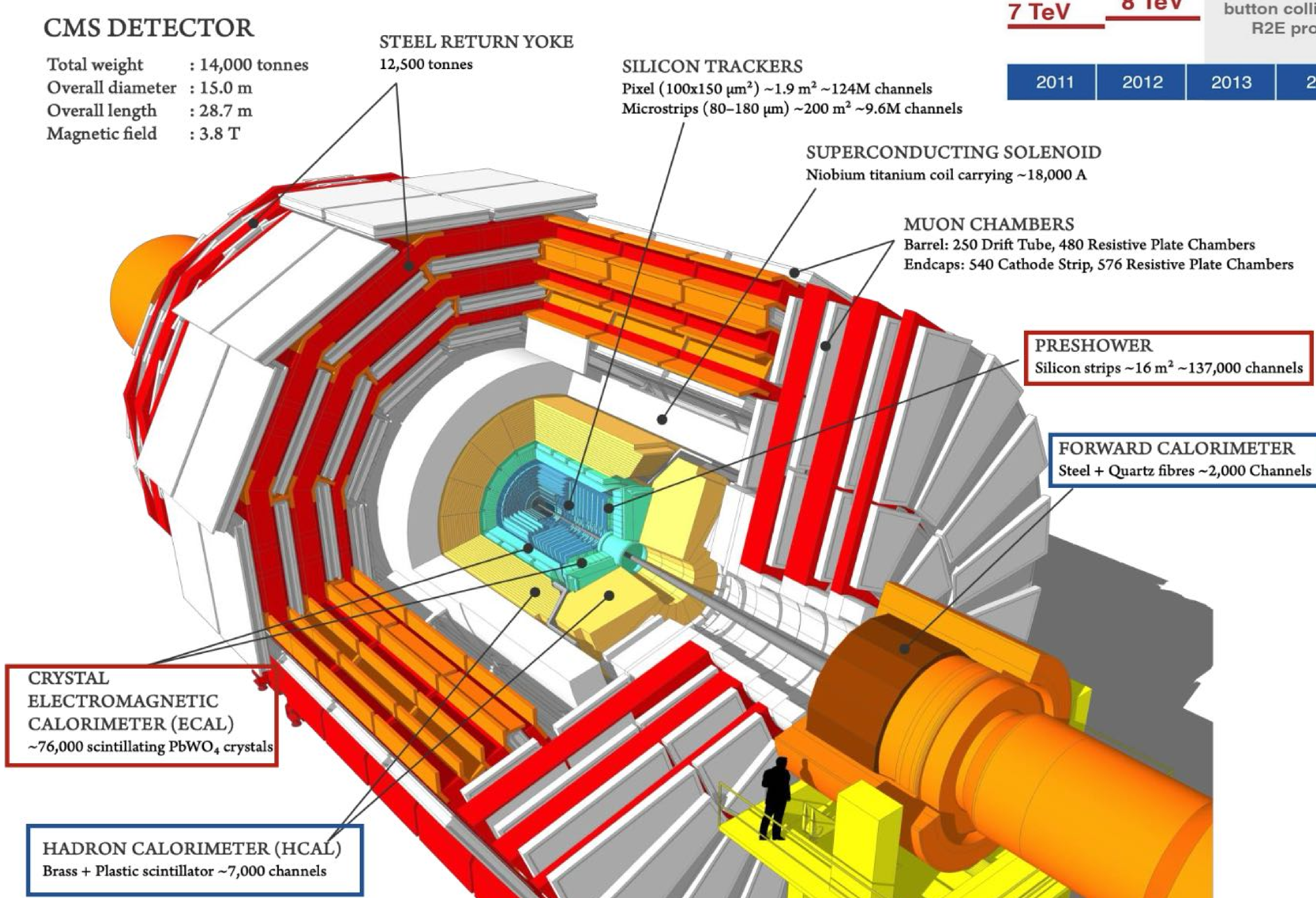
CMS experiment:

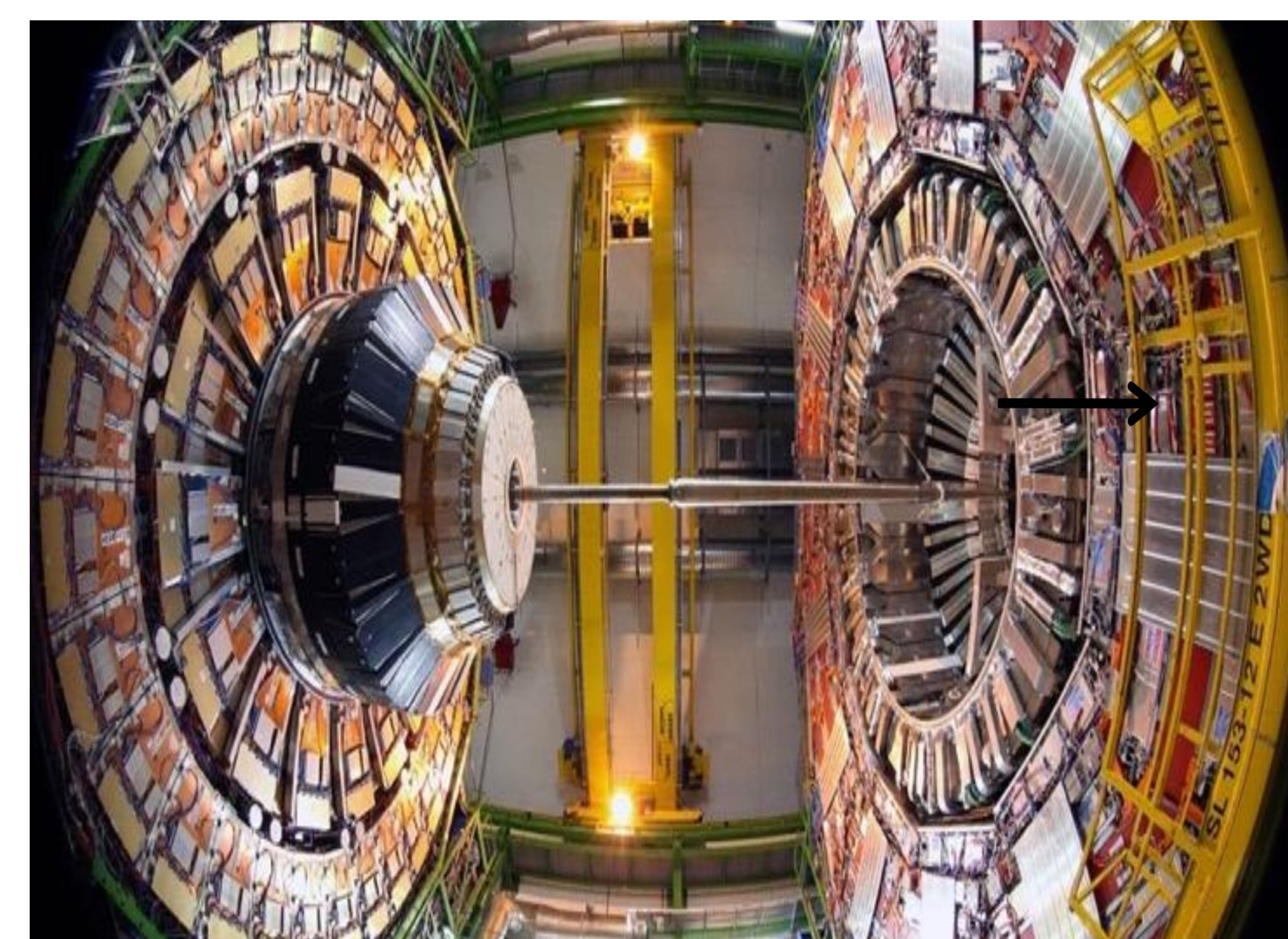
- General purpose detector, designed for identification and precise measurement of energy and momentum of electrons and photons, hadronic jets, taus, and muons originating from pp collisions in LHC (14 TeV)

Prototyping, testing, commissioning: ≳ 20y
Operation, maintenance (Runs 1-3): ~13 years
Phase-1 upgrades (LS2): ~3 years

LHC Phase-1 upgrade and Runs 1-3







CMS calorimetry @ LHC

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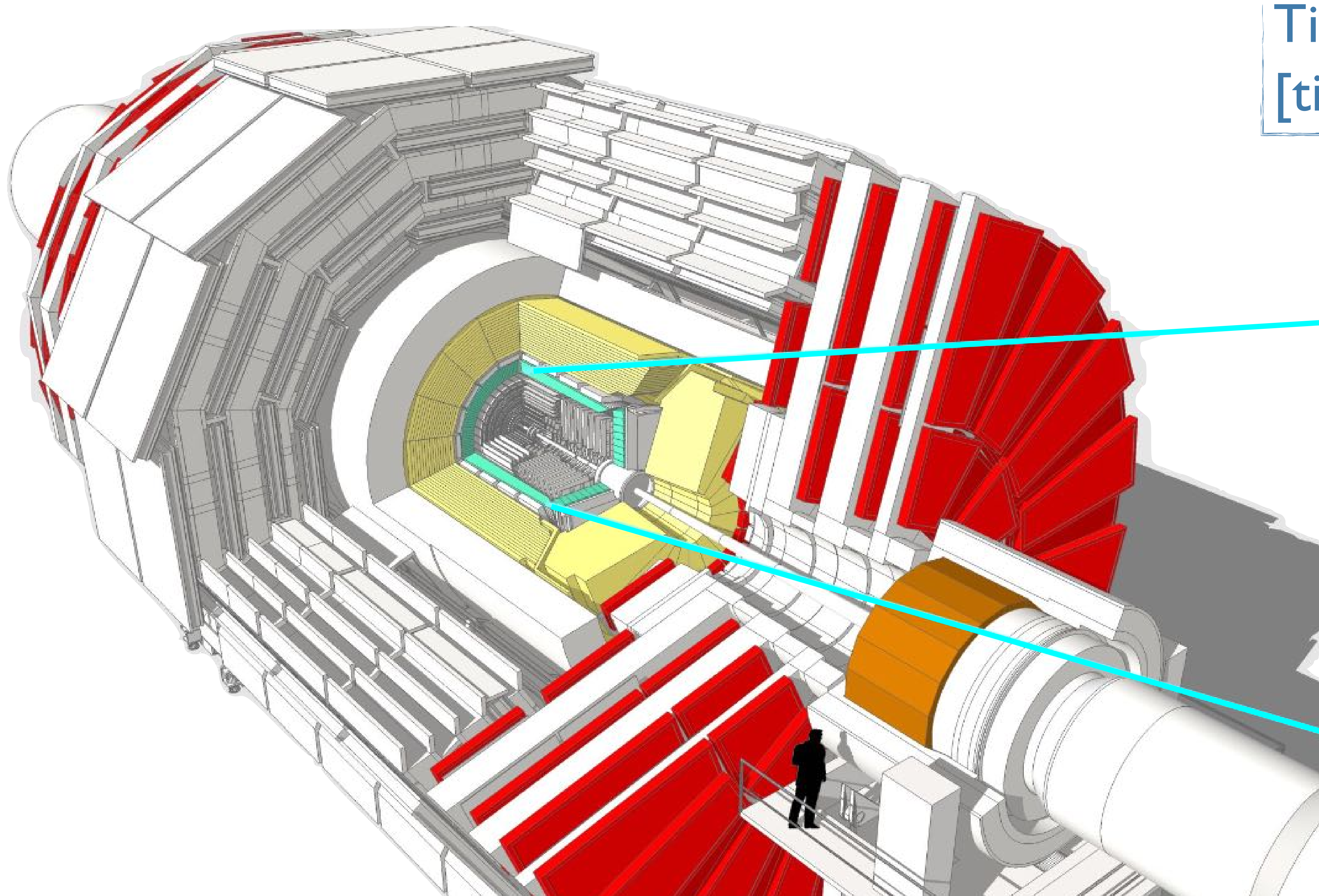
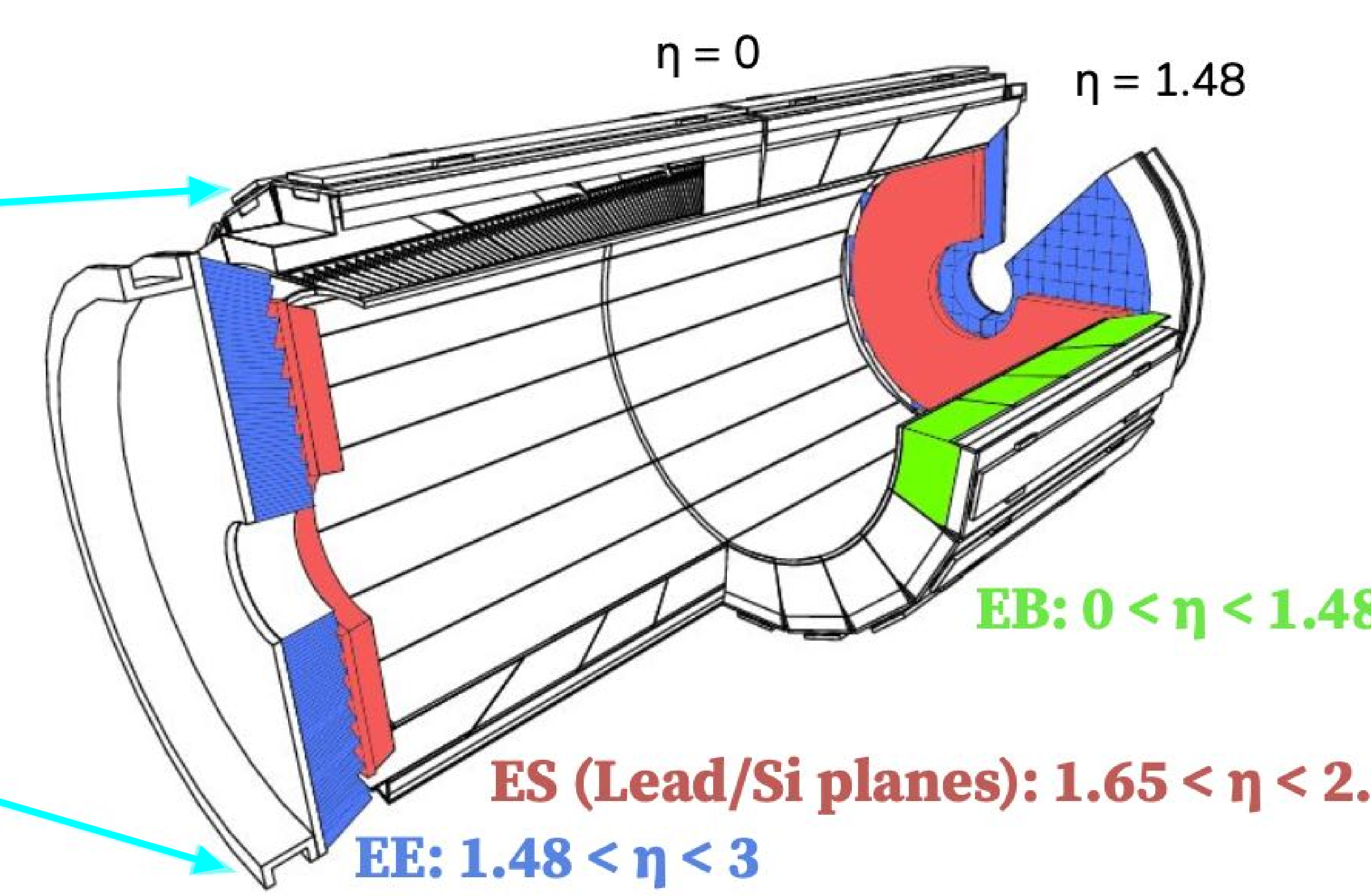
CMS Electromagnetic calorimeter (ECAL):

- Compact, homogeneous, laterally fine grained calorimeter, designed for **measuring energy of electrons and photons with excellent resolution** (< 0.5% for particles with E > 50 GeV)
- Based on **75848 lead-tungstate (PbWO4) scintillating crystals**, readout by **APDs / VPTs** in EB / EE regions

Timing resolution was not a driving design requirement
[timing stability O(1ns) for unbiased energy reconstruction]





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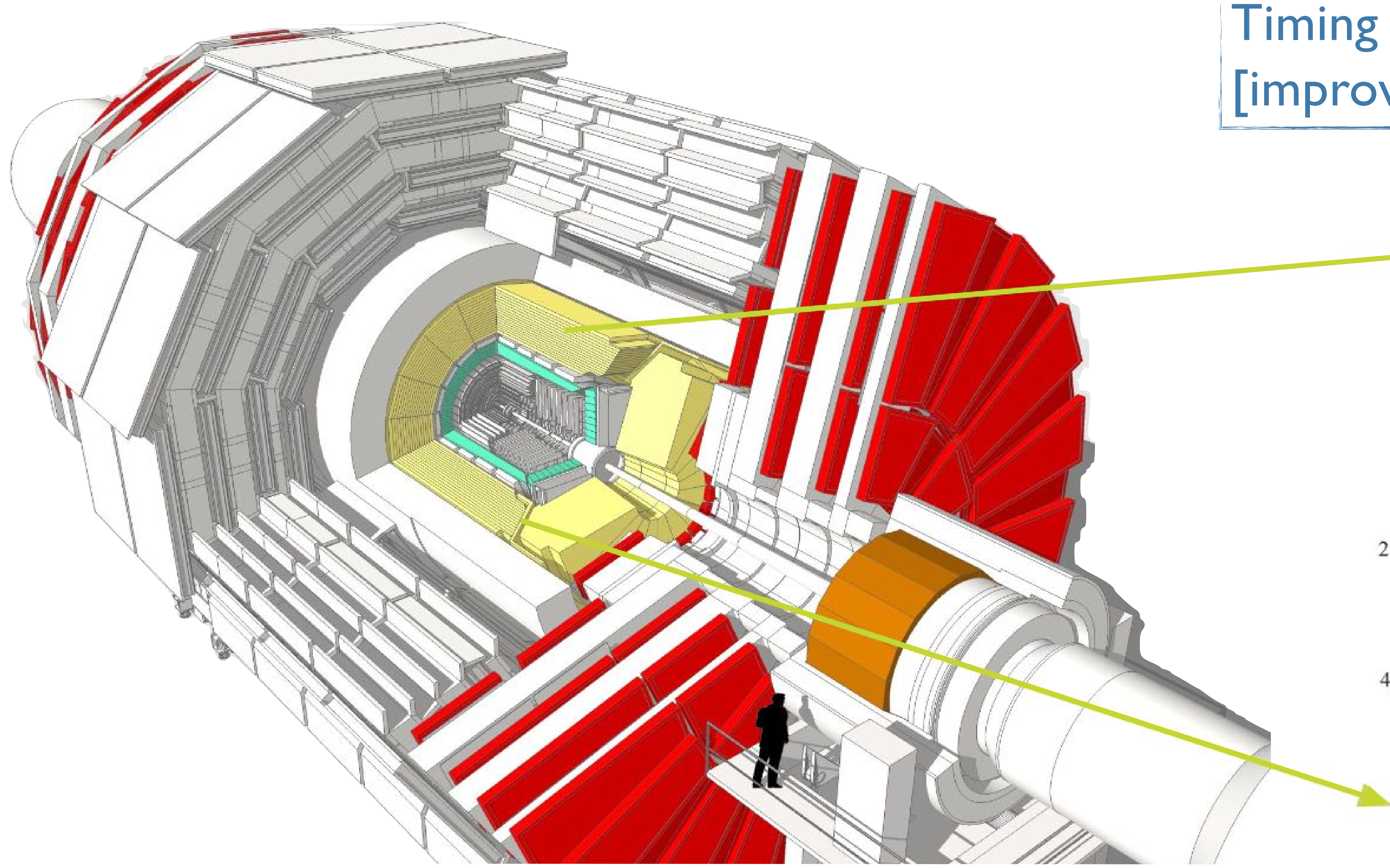
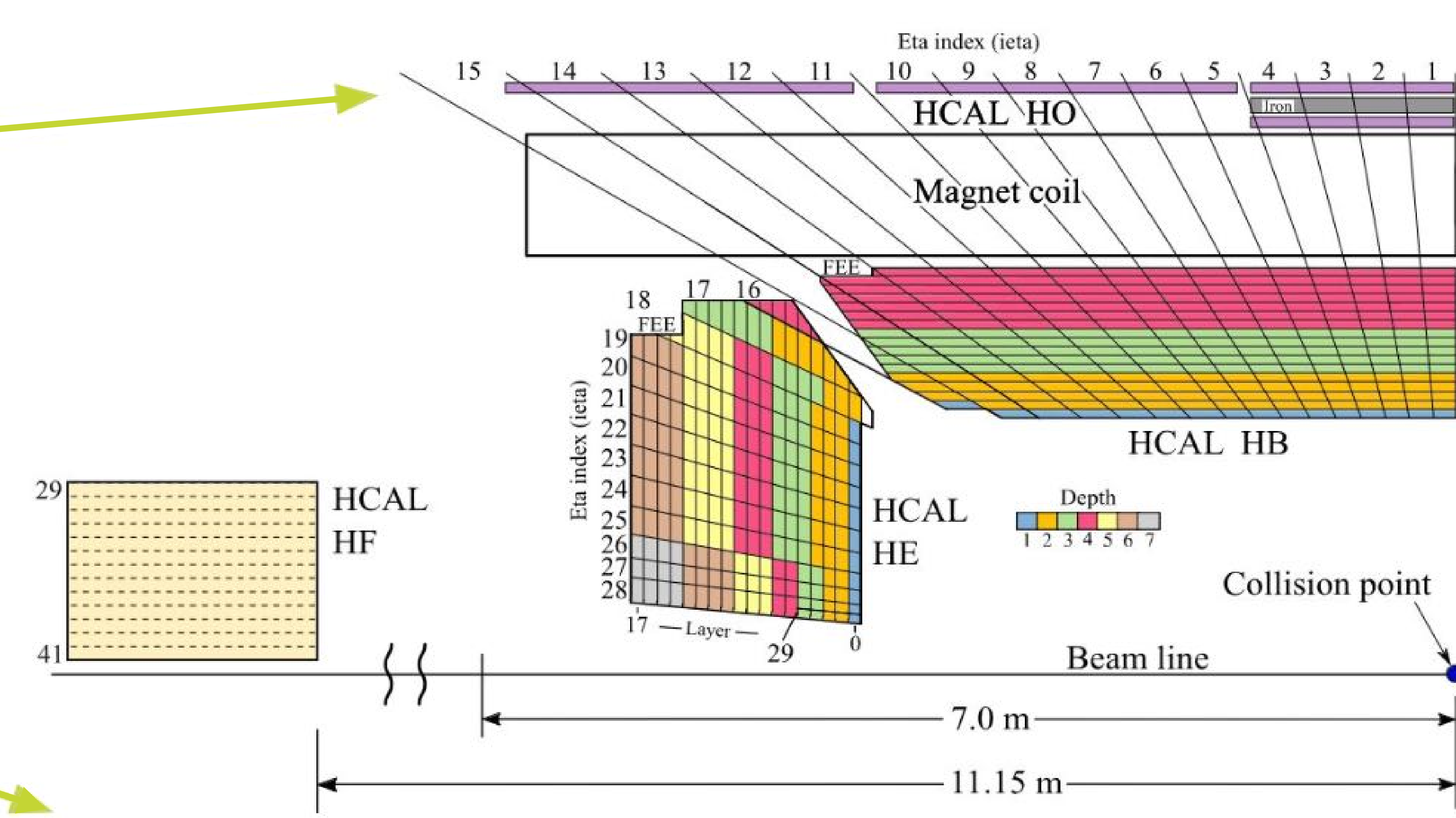
CMS Hadronic calorimeter (HCAL):

- Sampling calorimeter, designed for **measuring energy of hadrons (pions, kaons, protons and neutrons)**
- In total **9072 read-out channels** with layers of brass (iron) absorber and plastic scintillator read by **SiPMs** in HB/HE (HO), and steel layers and quartz fibres read by **PMTs** in HF region

Timing resolution was not a driving design requirement [improved by timing alignment during the Phase-1 upgrade]

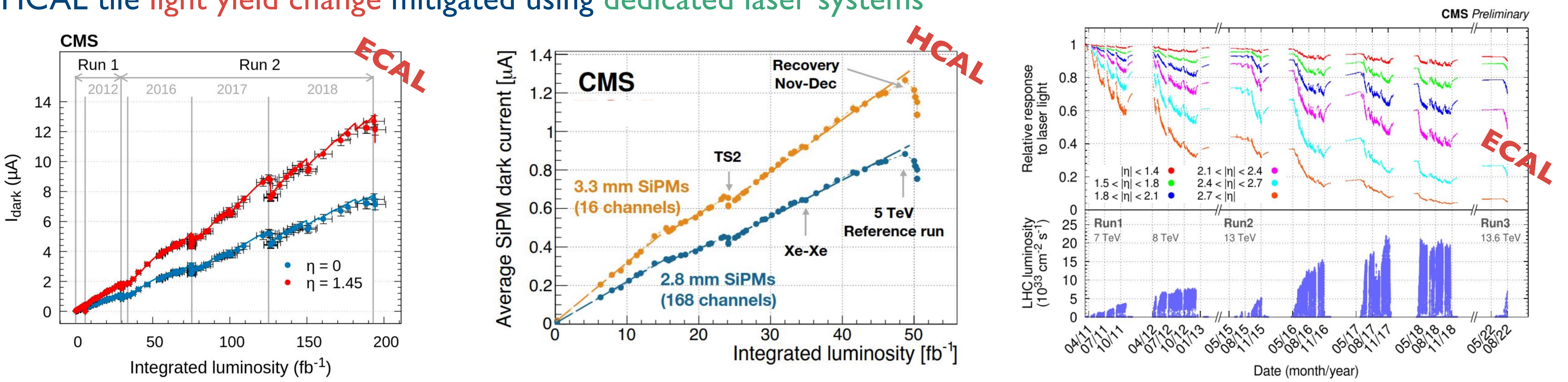




CMS calorimetry @ LHC - challenges & performance

Main challenges @ LHC from multiple overlapping interactions and detector aging effects:

- Increase of dark currents of photo detectors (APDs, SiPMs), ECAL crystal transparency change and HCAL tile light yield change mitigated using dedicated laser systems



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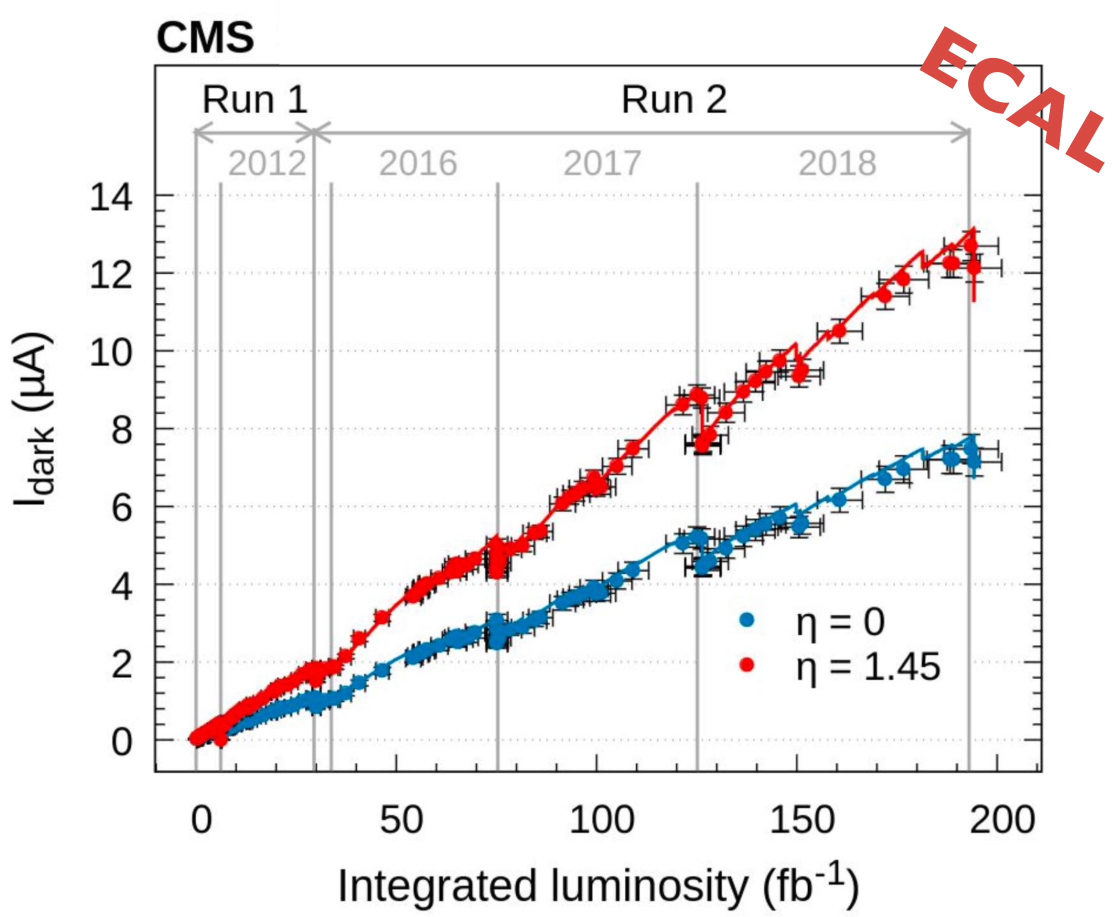
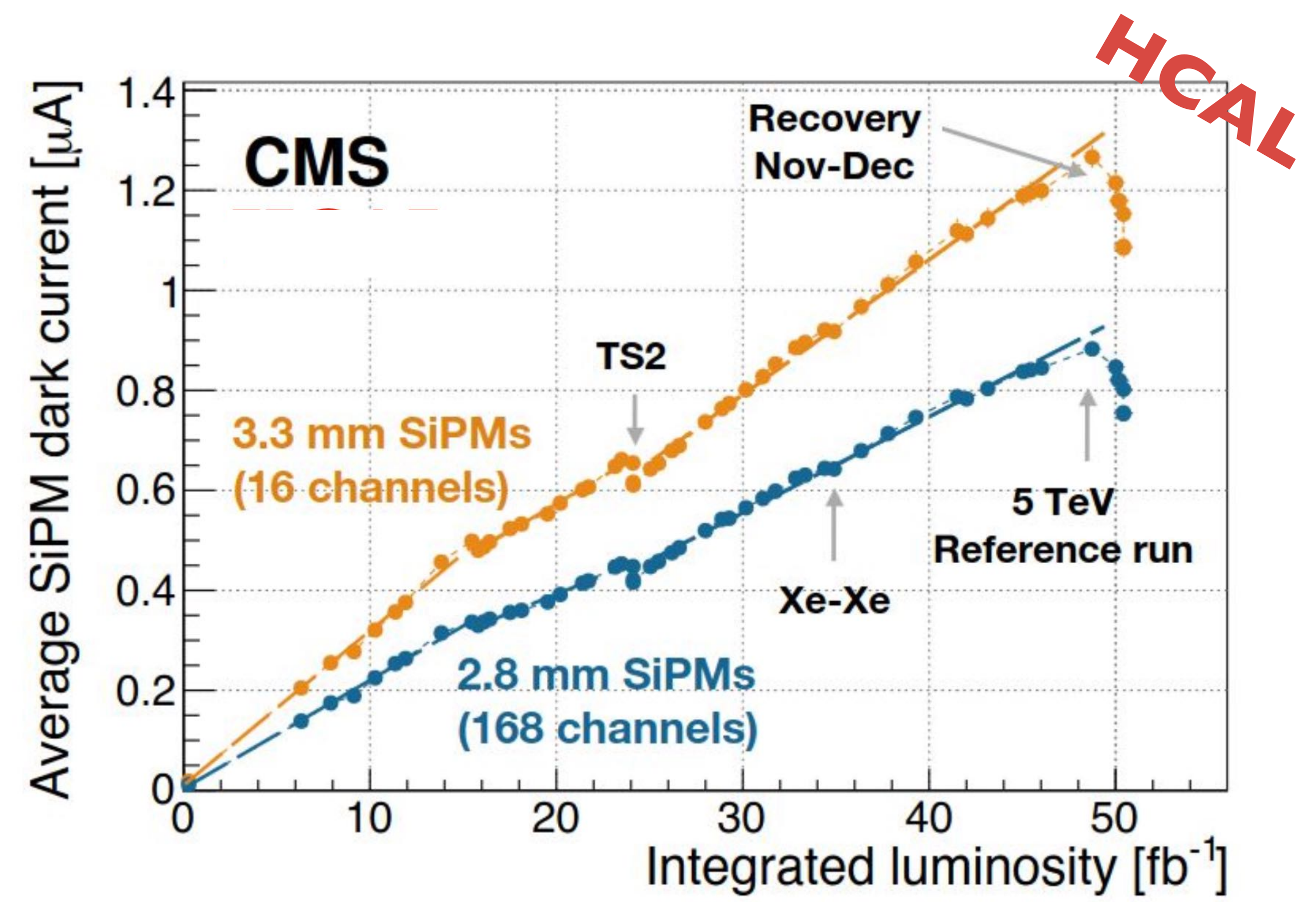
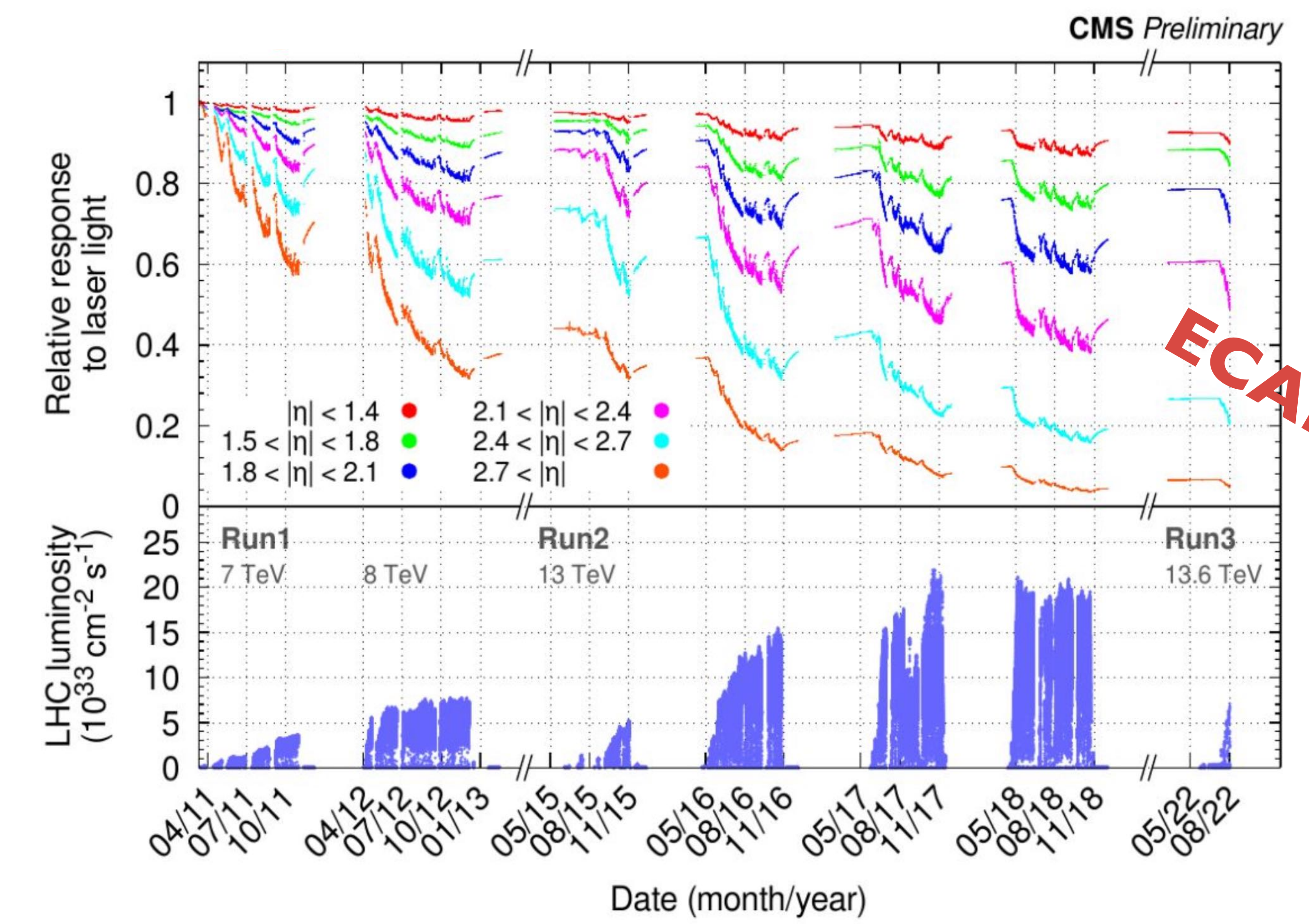
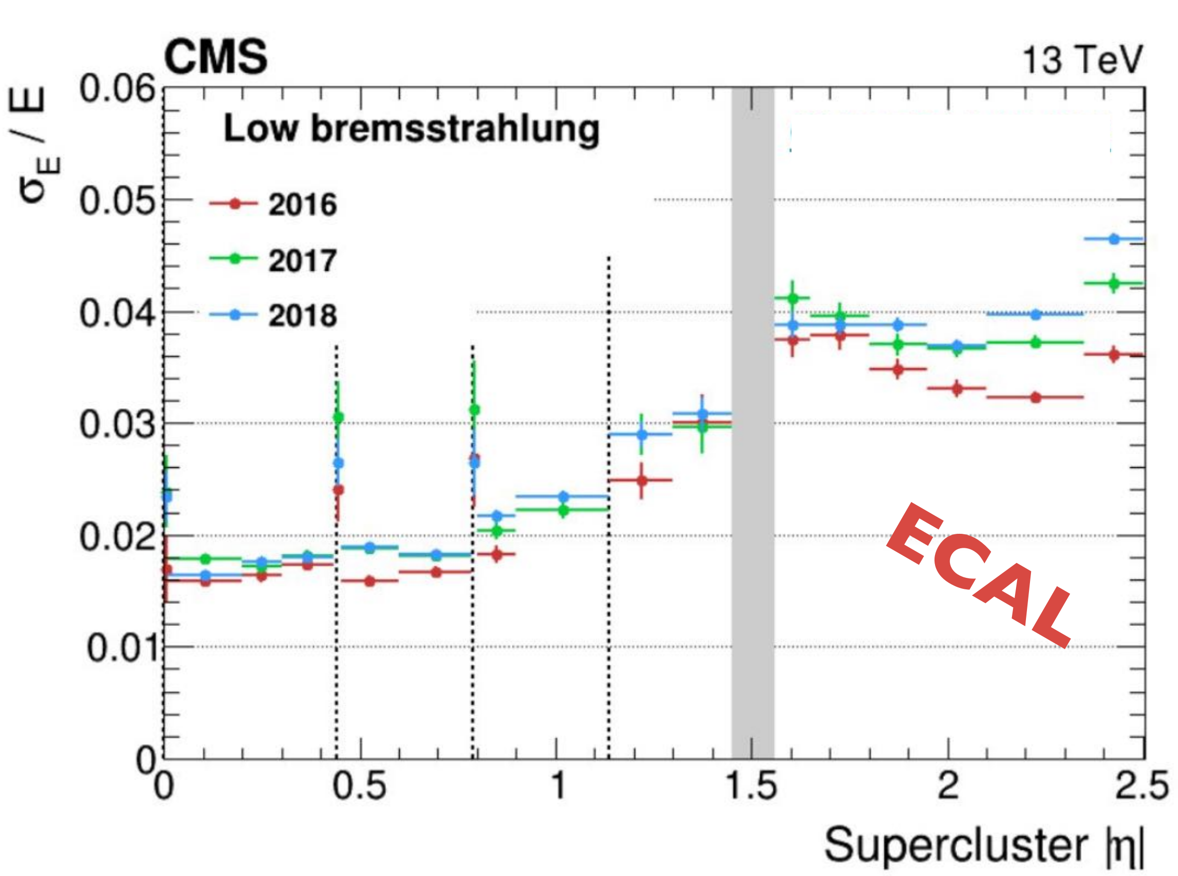


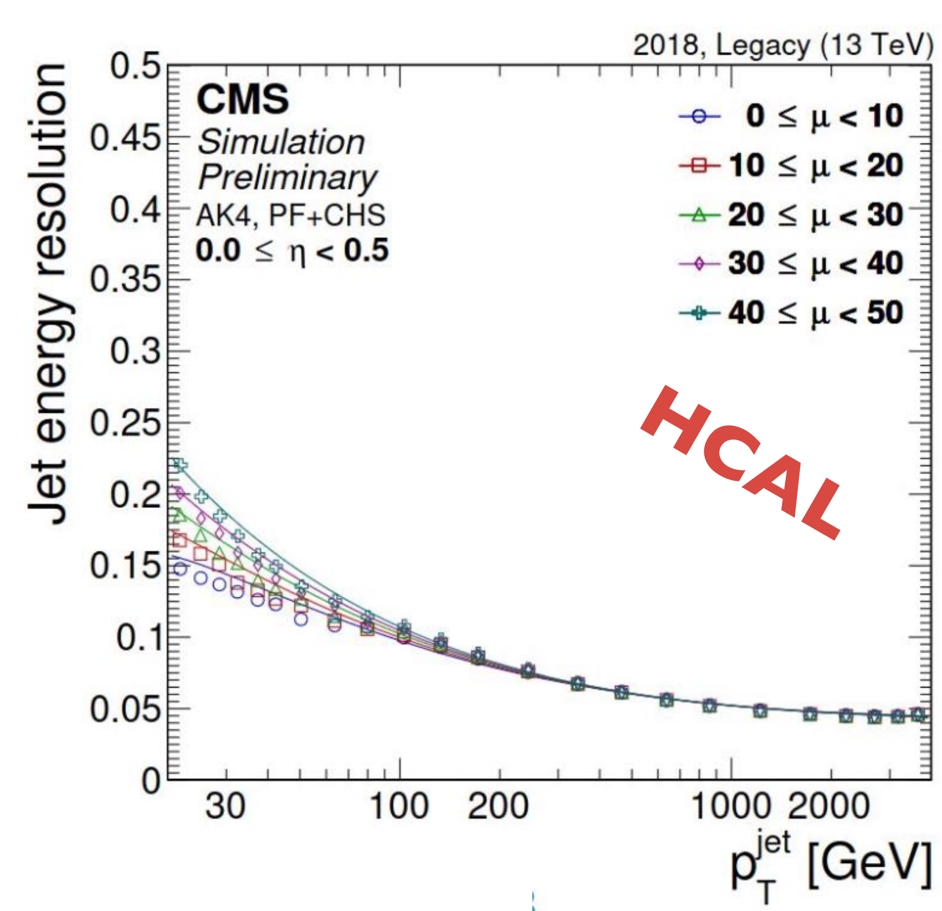


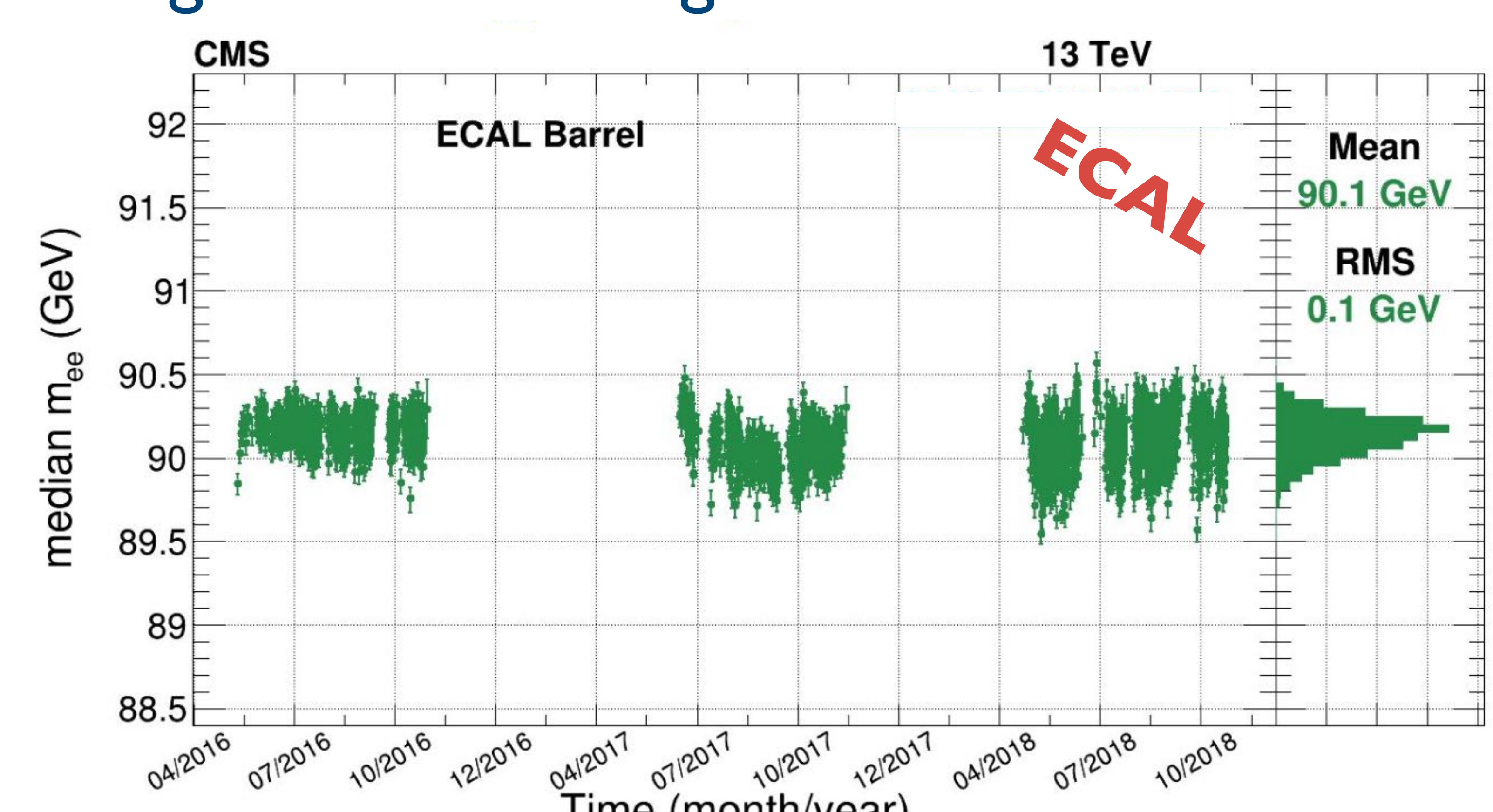


Good performance during LHC Runs 1-3, thanks to the in-situ and offline calibrations:

- Good energy resolution, data-MC agreement, and detector stability during the data-taking

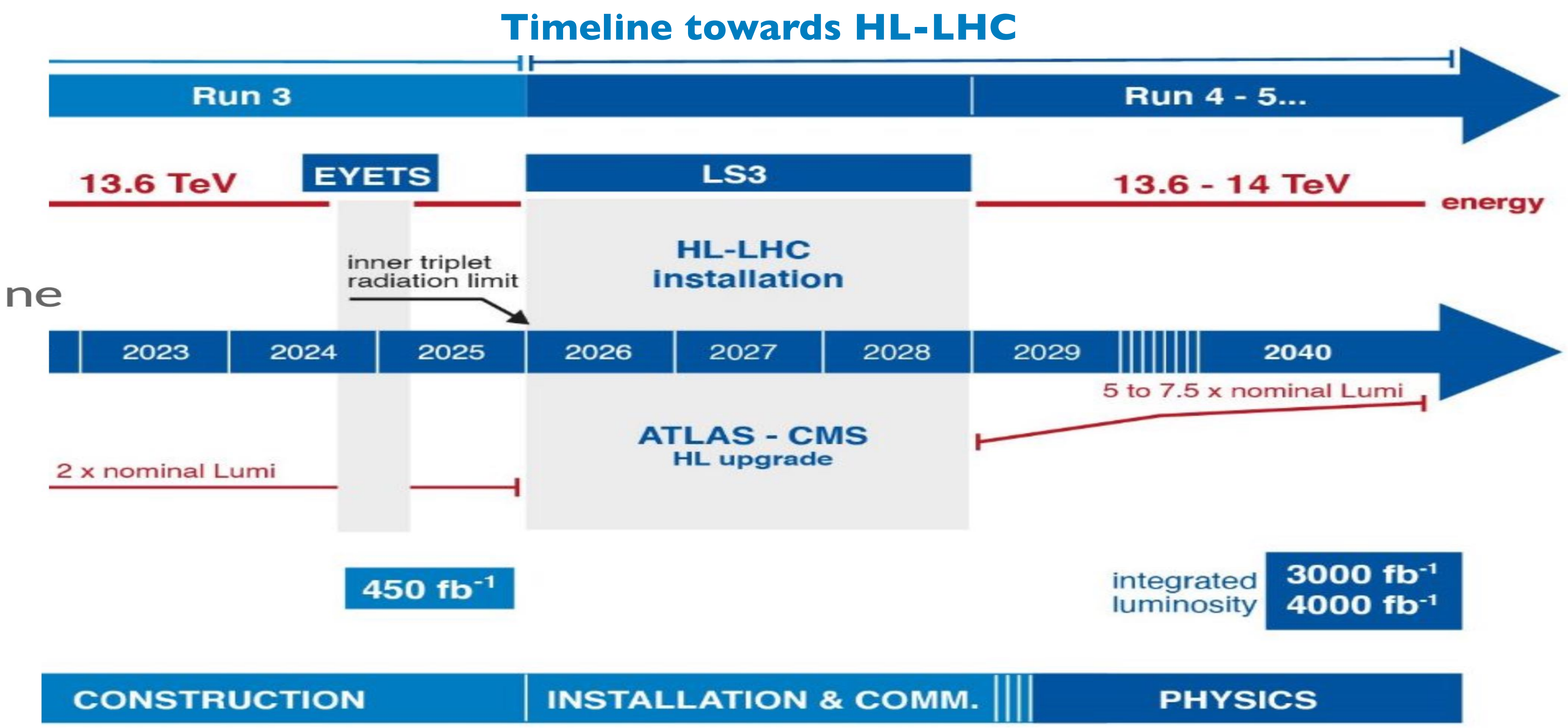


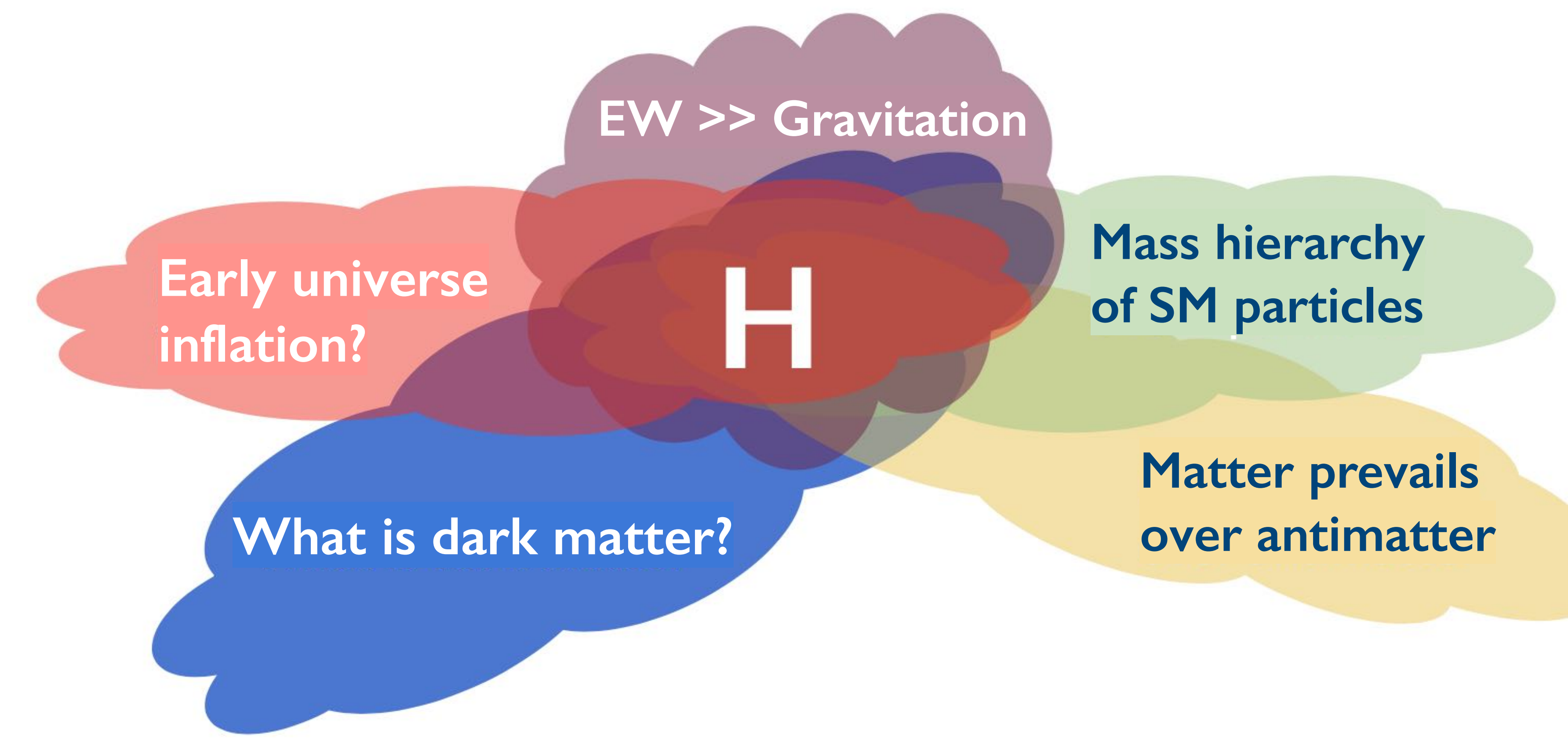




Towards the future: High-Luminosity LHC

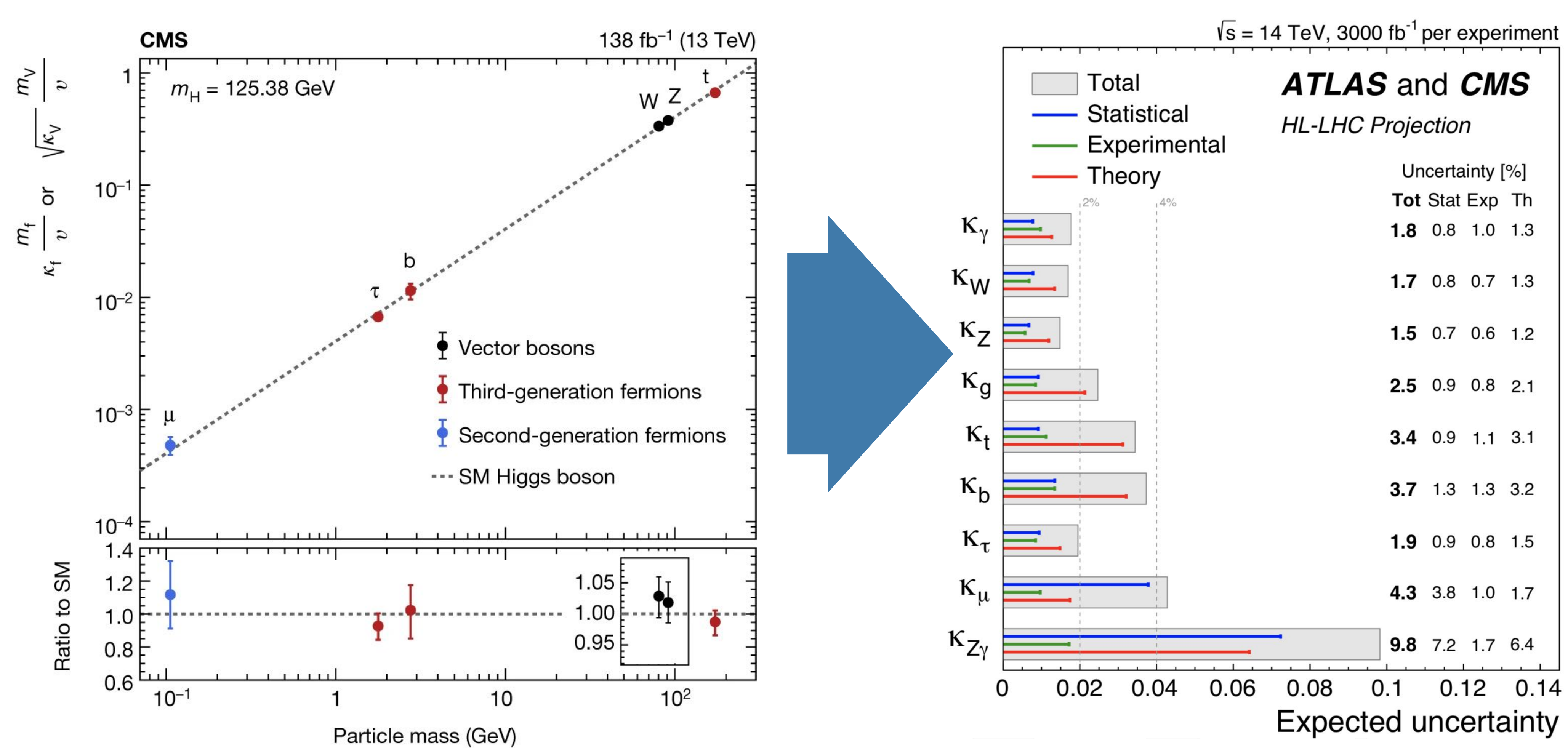
From the early discovery machine … to the Higgs factory and its full discovery potential!





HL-LHC goal: detailed topography of (the known) particle physics landscape:

- Deeper understanding of Higgs boson properties (fermions/bosons couplings, Higgs field potential).
- Precision measurements in QCD, EWK, TOP, Higgs sectors (ultimate goal to achieve O(1%)).
- Probing for new physics phenomena (directly & via precision measurements).



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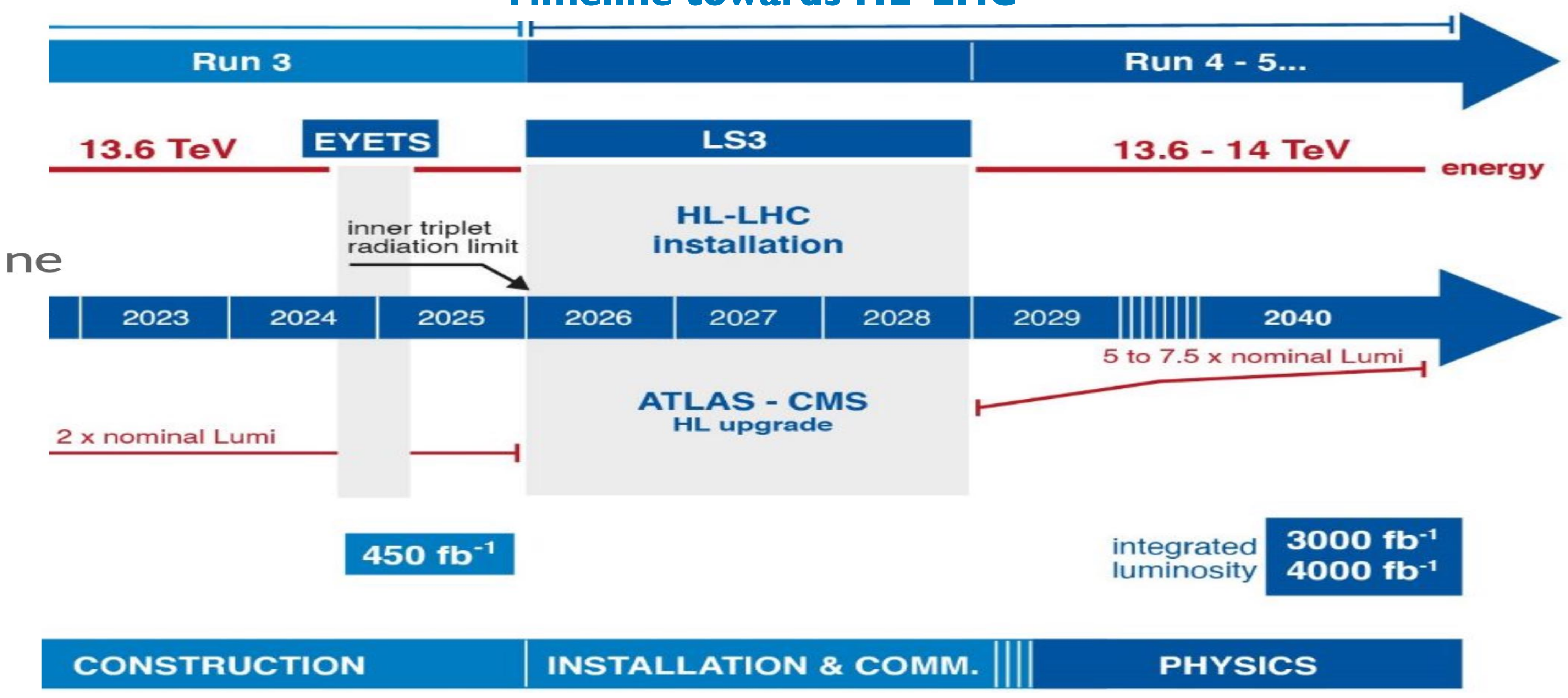
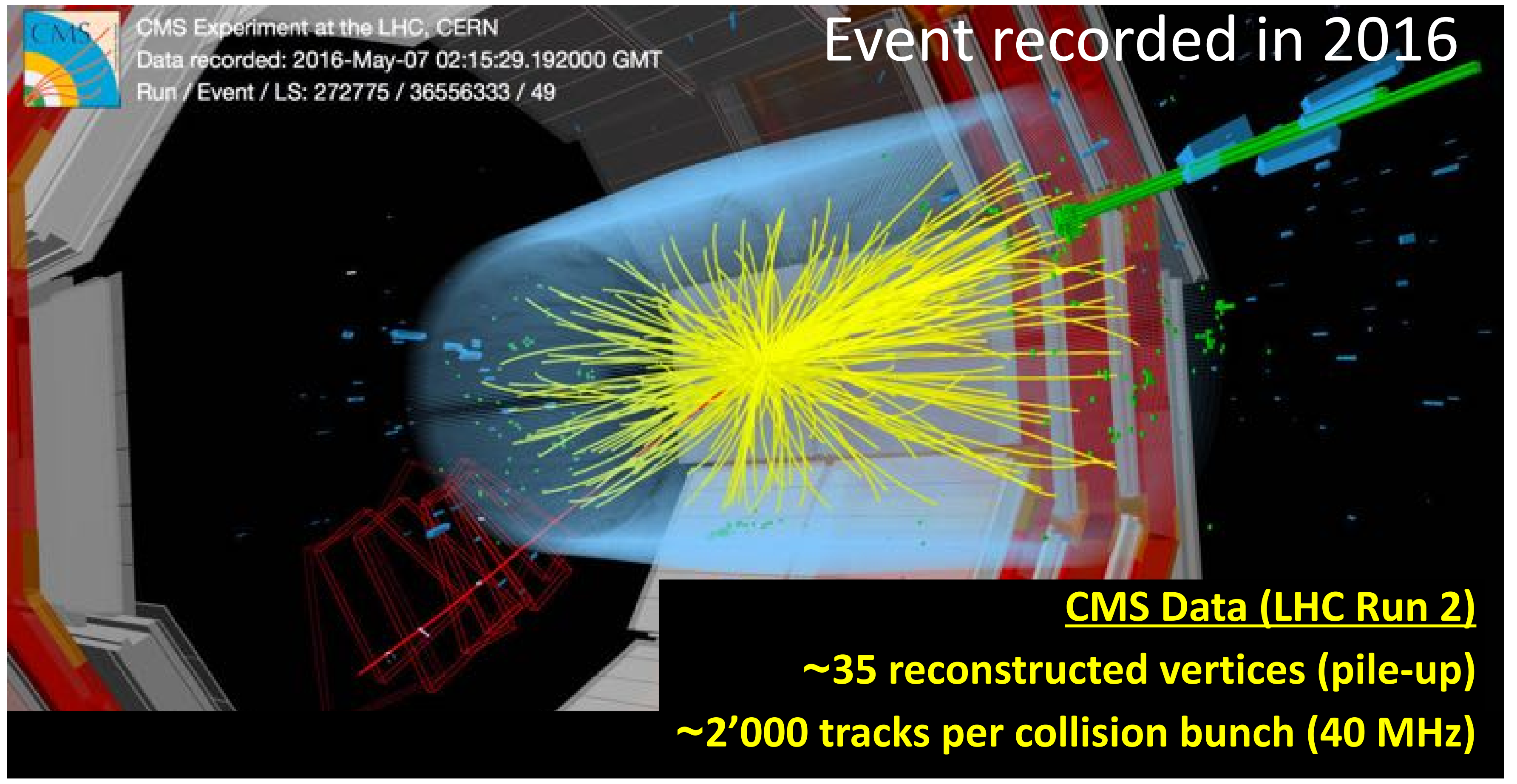
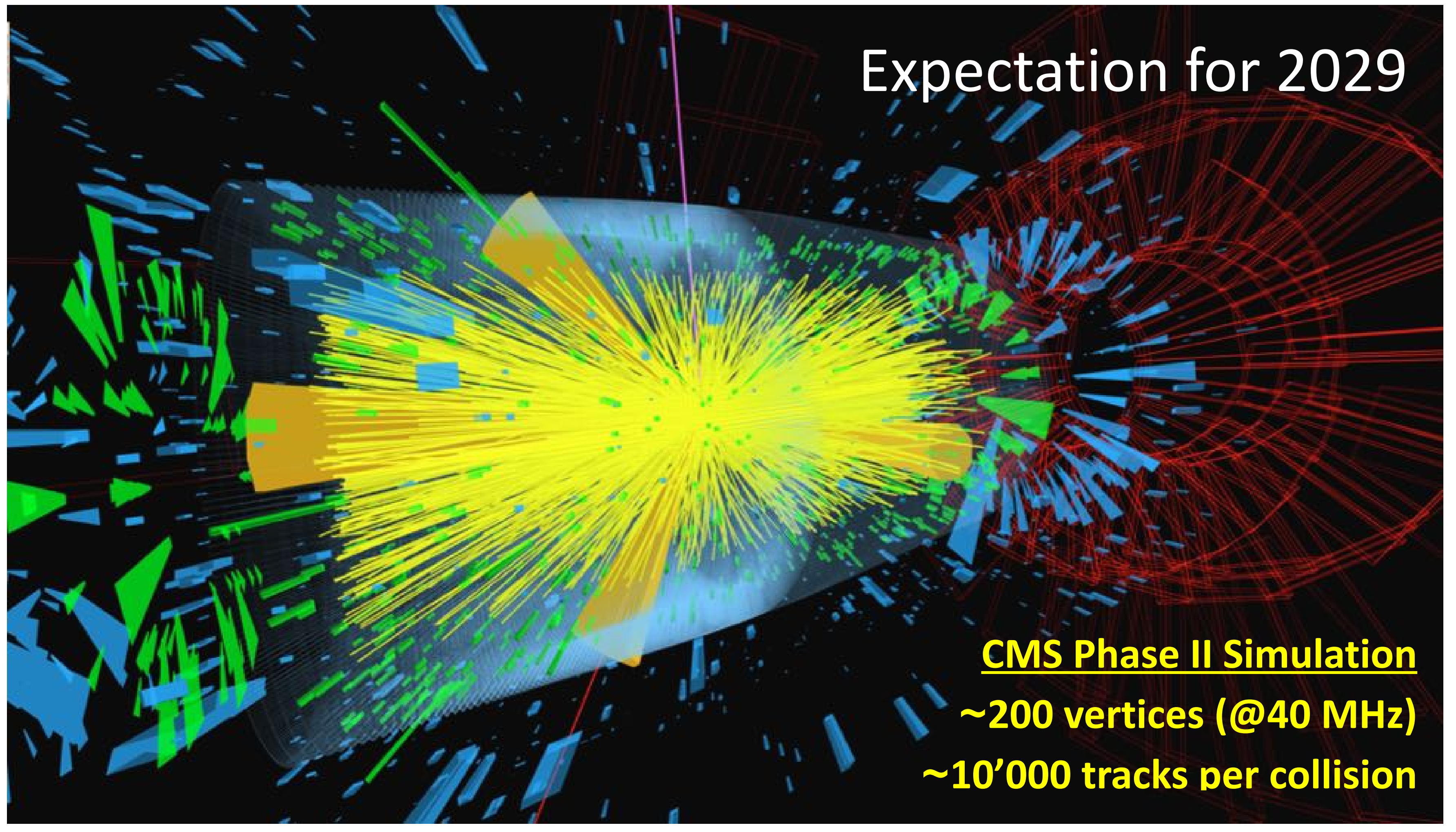




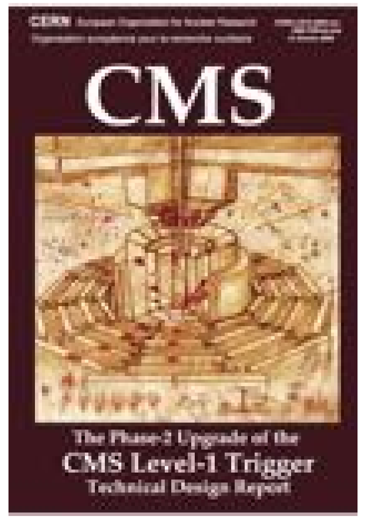


Challenges for the experiments:

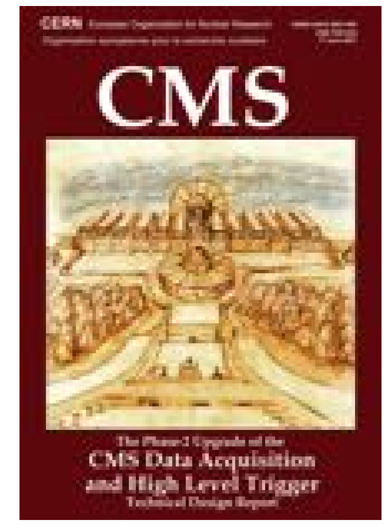
- Expected 140-200 collisions/bunch-crossing (each 25 ns)
- Detectors exposed to high fluence (up to 10^{16} n.eq./cm^2) and dose (up to 2MGy) after 3 ab^{-1}
- Major experiment upgrades to improve radiation hardness, replace detectors at end-of-life or extend coverage,
- Provide handles to mitigate pileup (overlapping interactions) and maintain/improve trigger acceptance.

Brief summary of the CMS Phase-2 upgrade

detailed overview of the whole CMS Phase-2 upgrade program presented in the talk by Arnab Purohit

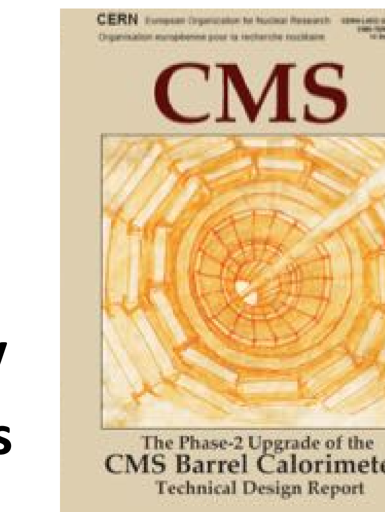


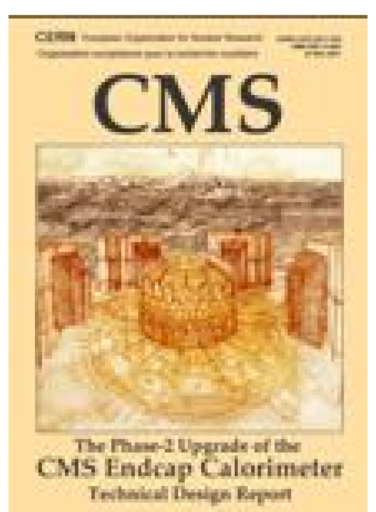
L1-Trigger
https://cds.cern.ch/record/2714892
- Tracks in L1-Trigger at 40 MHz
- Particle Flow selection
- 750 kHz L1 output
- 40 MHz data scouting



DAQ & High-Level Trigger
https://cds.cern.ch/record/2759072
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL single crystal granularity at L1 trigger
  with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards





Calorimeter Endcap
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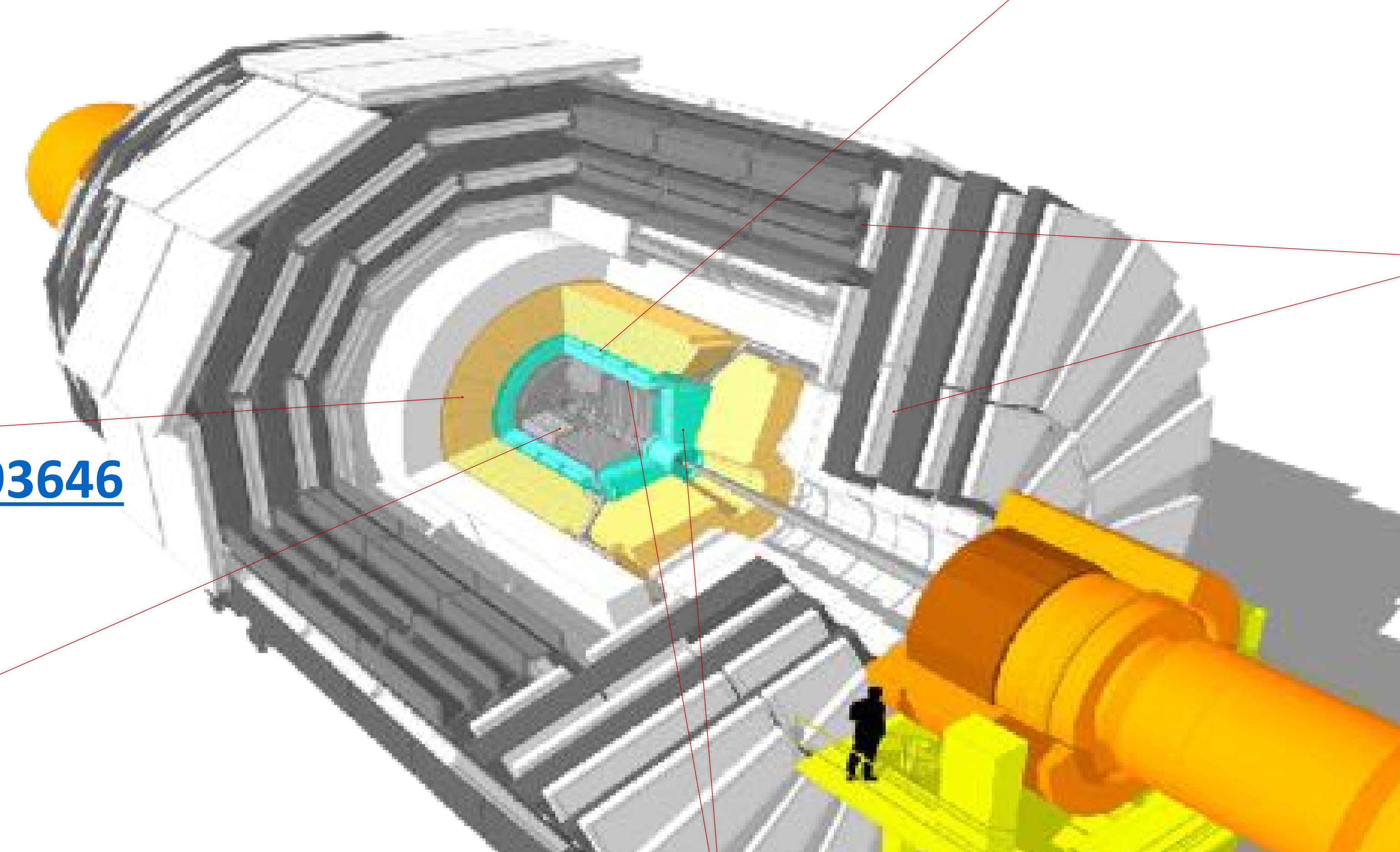
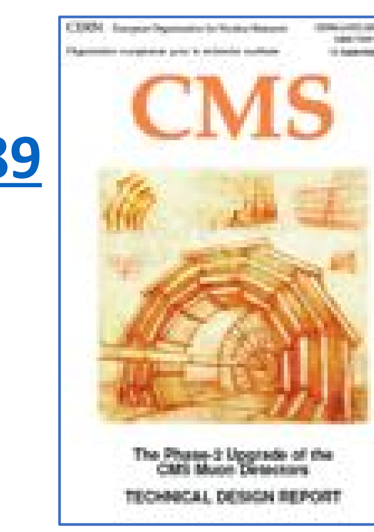
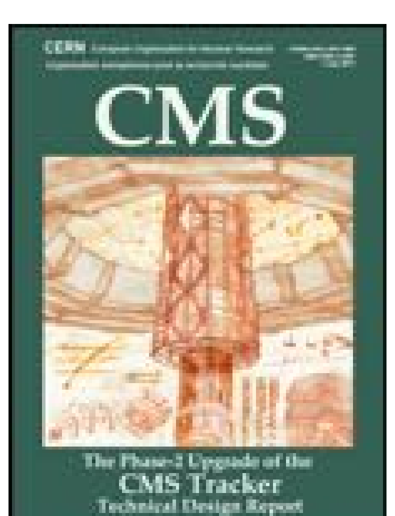
- Highly granular
- 3D showers and precise timing
- Silicon, Scint+SiPM in Pb/W-SS



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3





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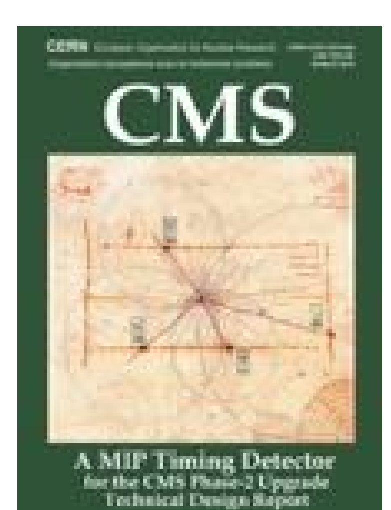
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8



MIP Timing Detector
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Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer:
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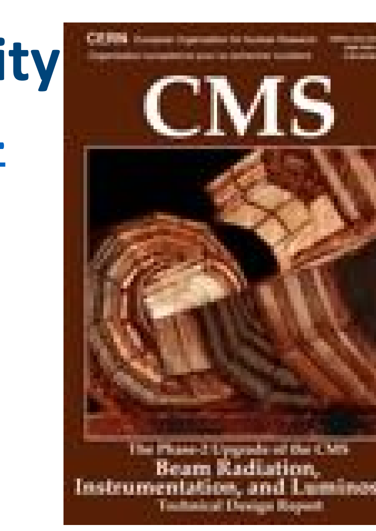

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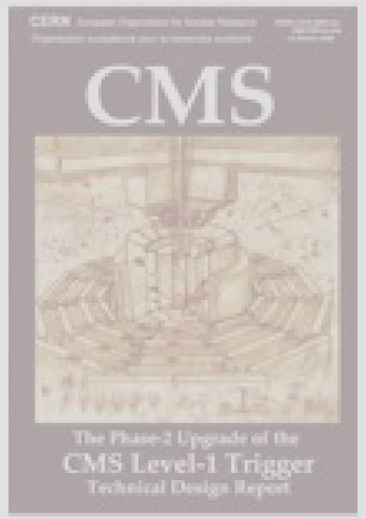

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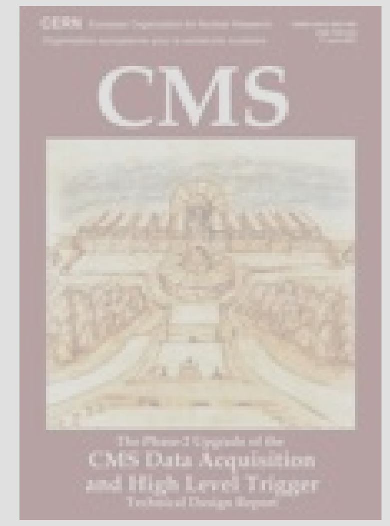

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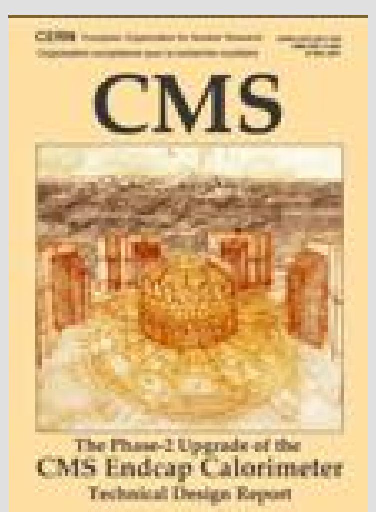


Quote from CMS Upgrade project external reviewers:

"We want to note (again) that these projects are unprecedented in scale in particle physics, shift various paradigms, and employ technologies that have never before been exercised by the field."

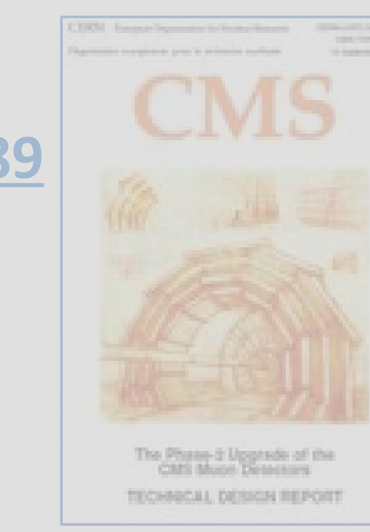
ecord/2283189

E readout

onics

< η < 2.4

to $\eta \simeq 3$



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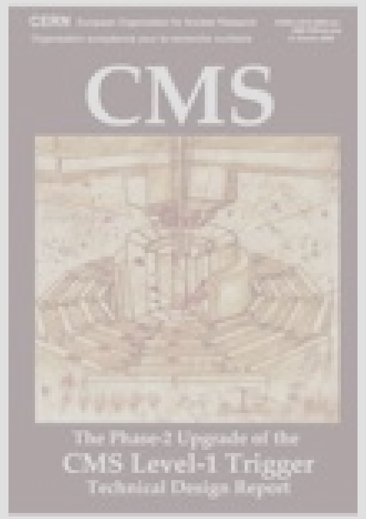

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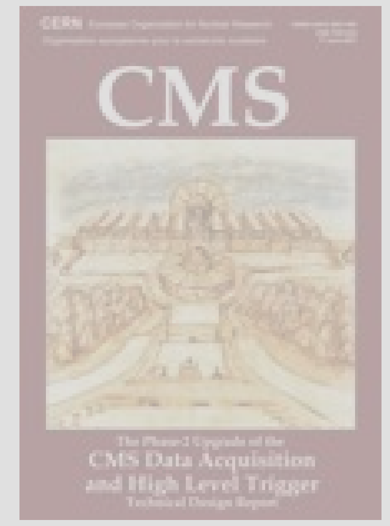

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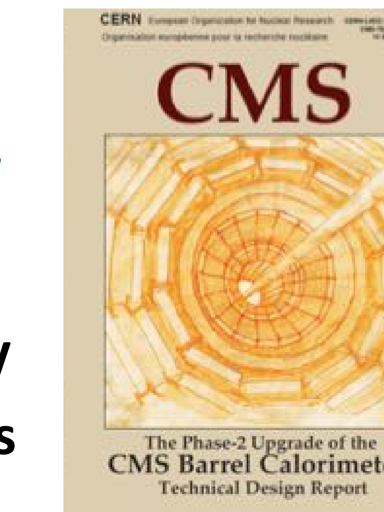

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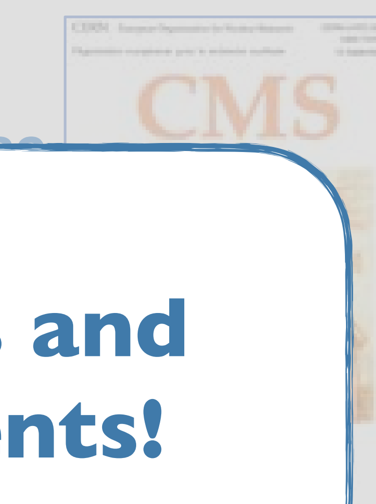

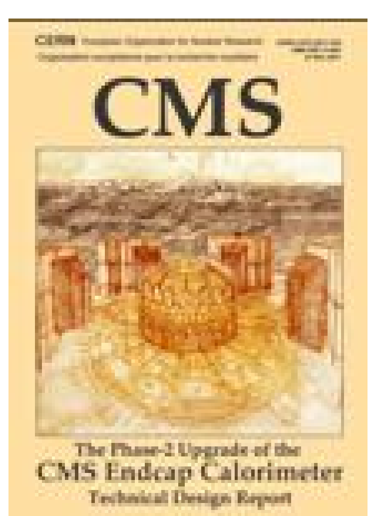

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Focusing on the upgrade of the calorimeters and challenges in energy and timing measurements!

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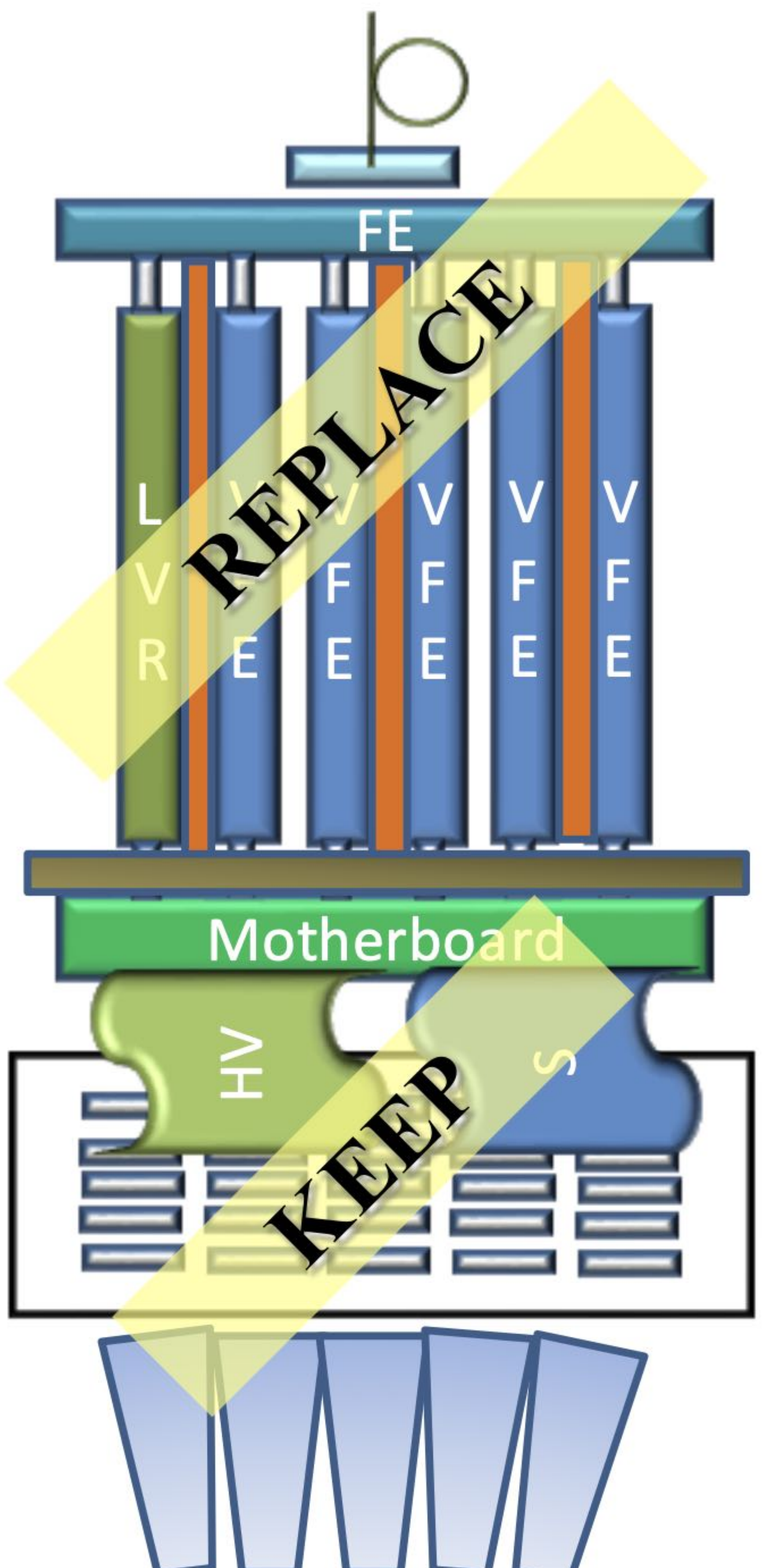
Upgrade of CMS Barrel Calorimeters

- Electromagnetic homogenous calorimeter (Phase-2 upgrade)
- Hadronic sampling calorimeter (Phase-1upgrade)

Upgrade of CMS ECAL

CMS ECAL Upgrade goals:

- Maintain the LHC physics performance for photons and electrons also during HL-LHC: Accommodate requirements on the Level-1 trigger latency and rate, provide more precise timing resolution, and help mitigate the increasing noise from the photodetectors, and transparency loss from the crystals.



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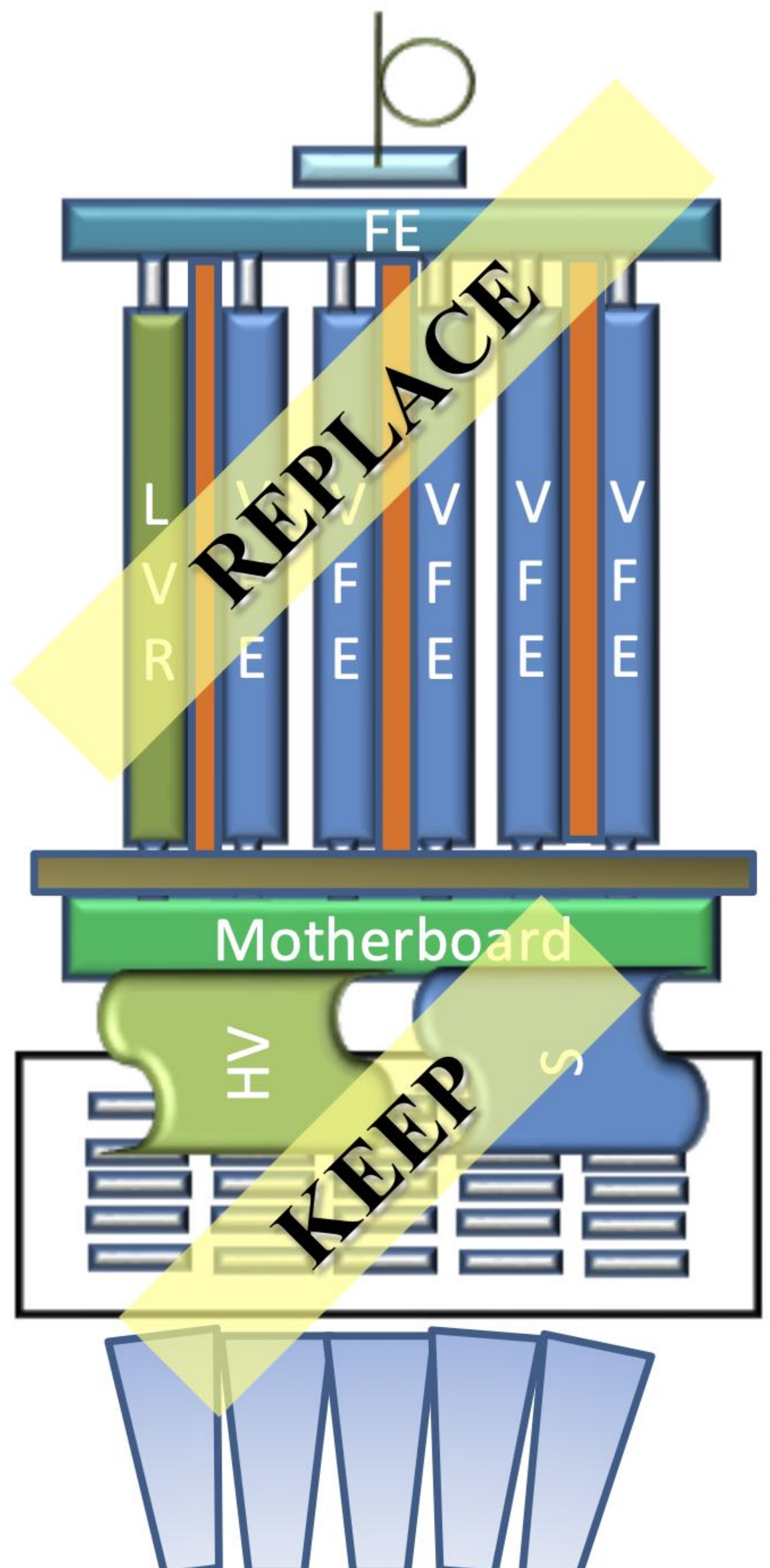

Addressing crystals longevity:

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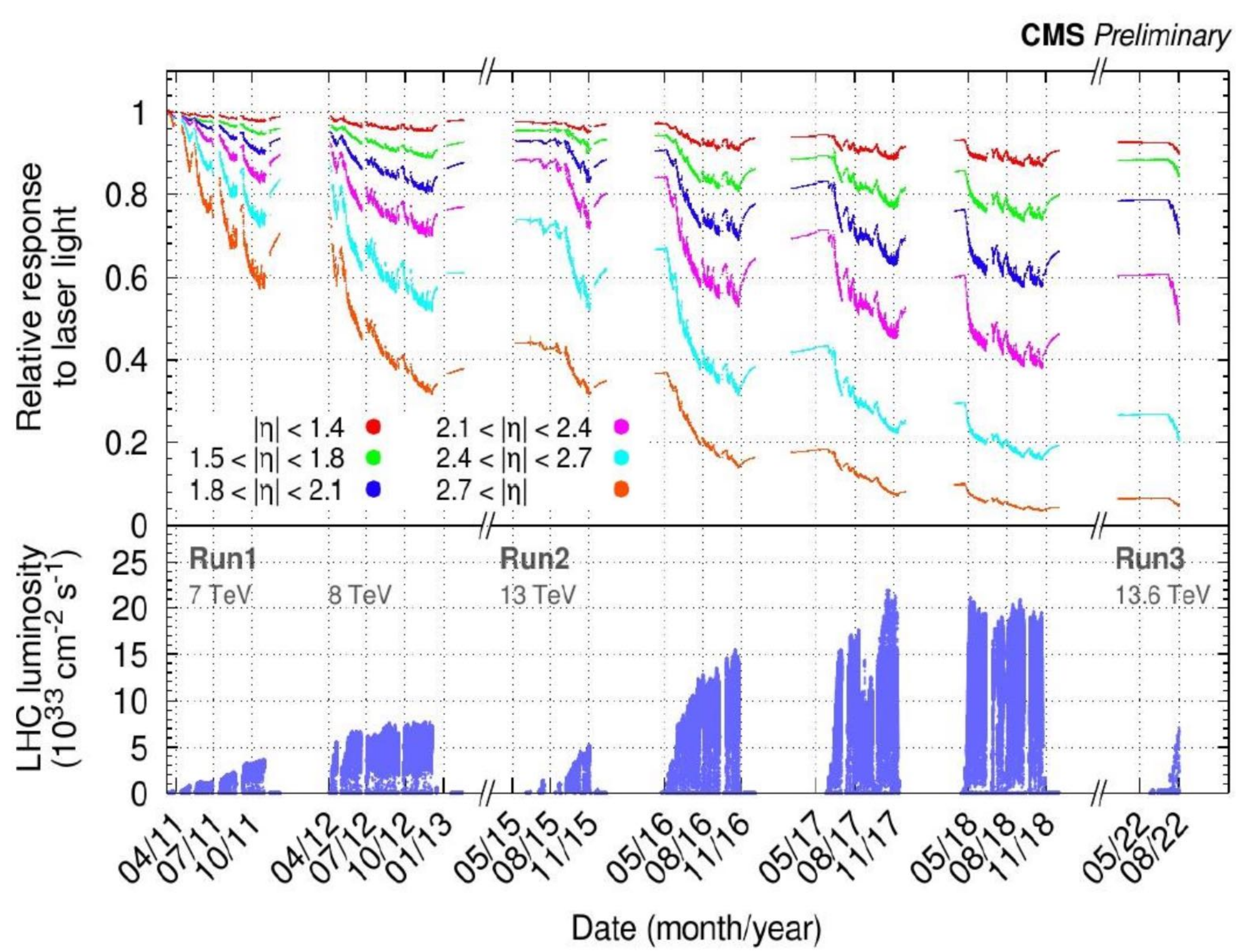

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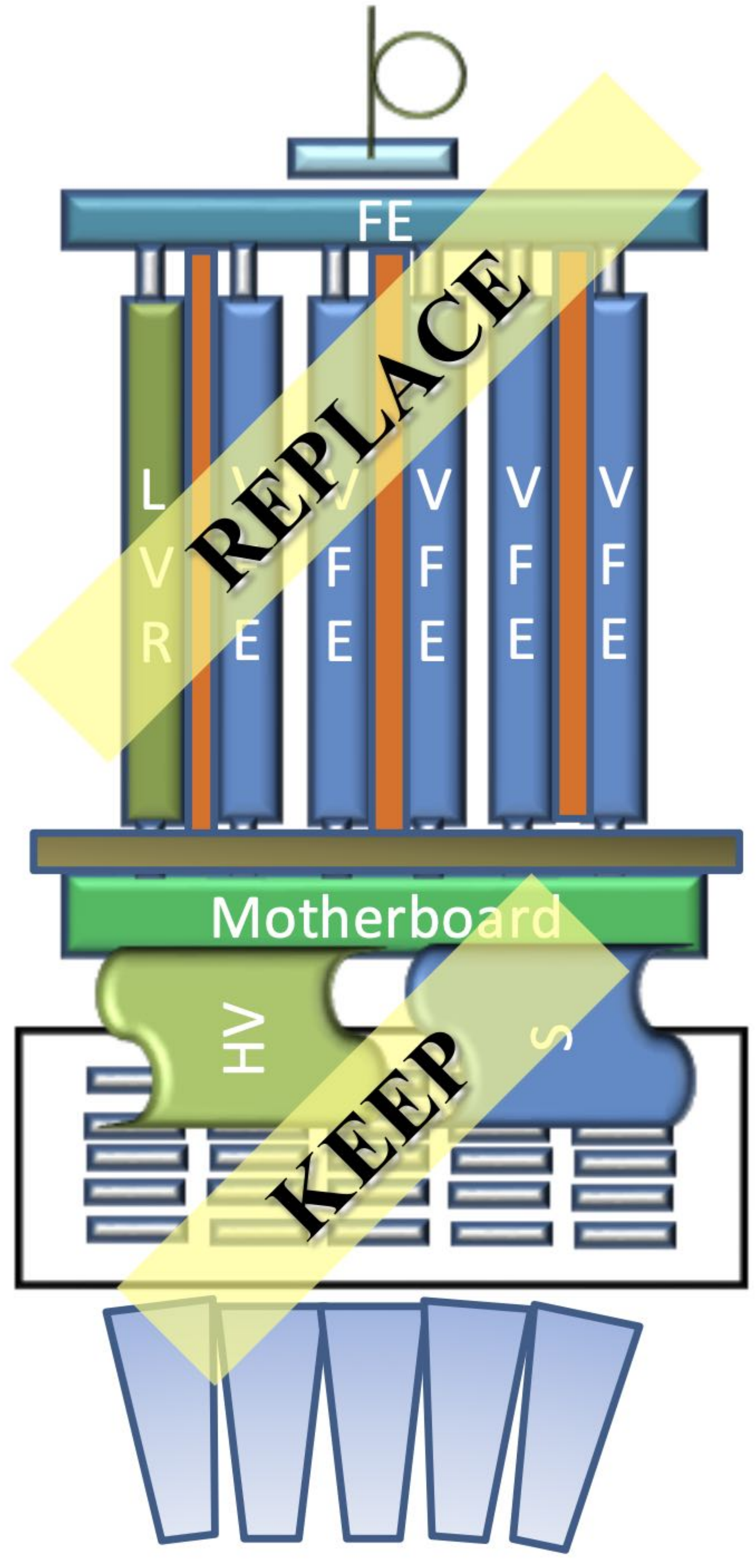

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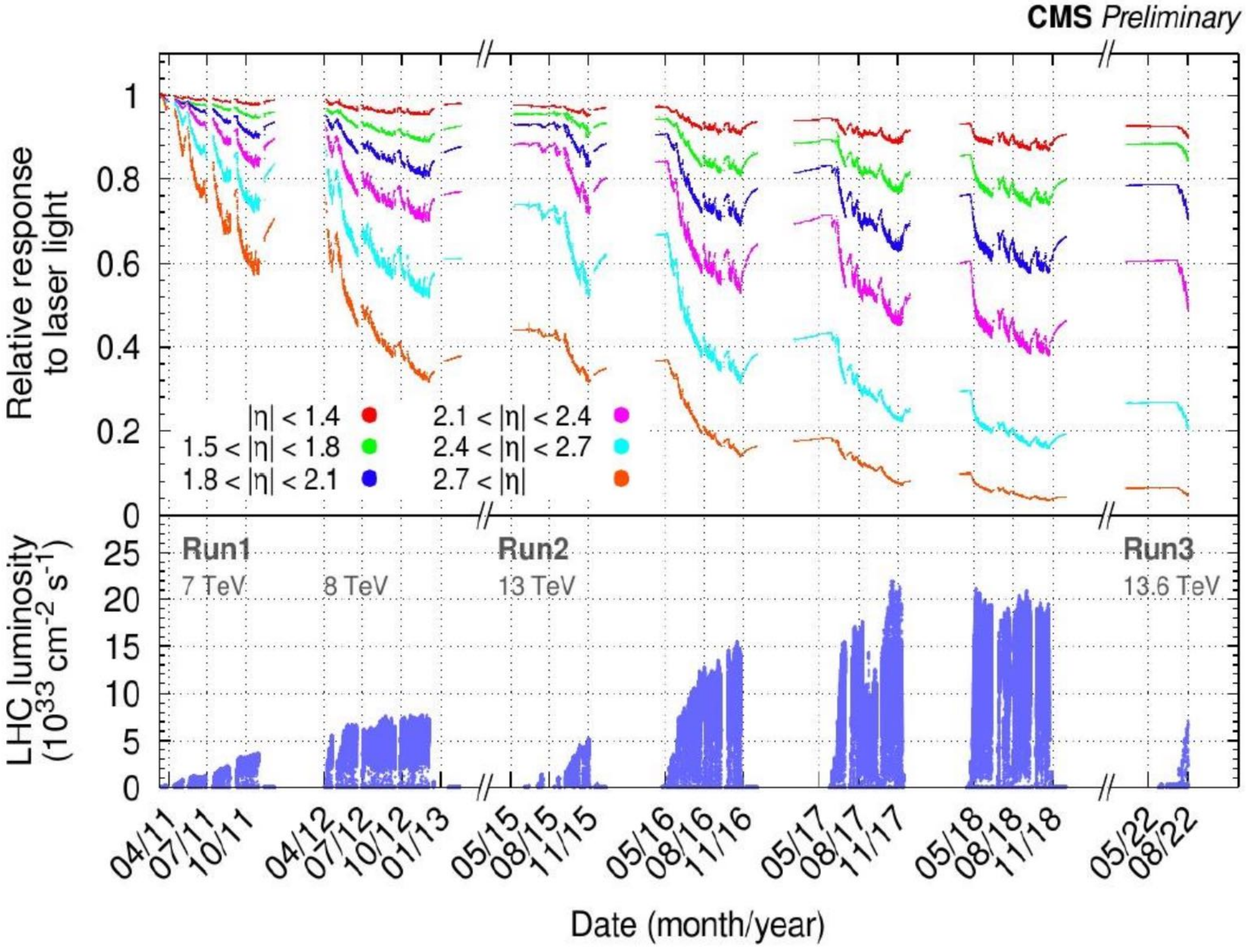
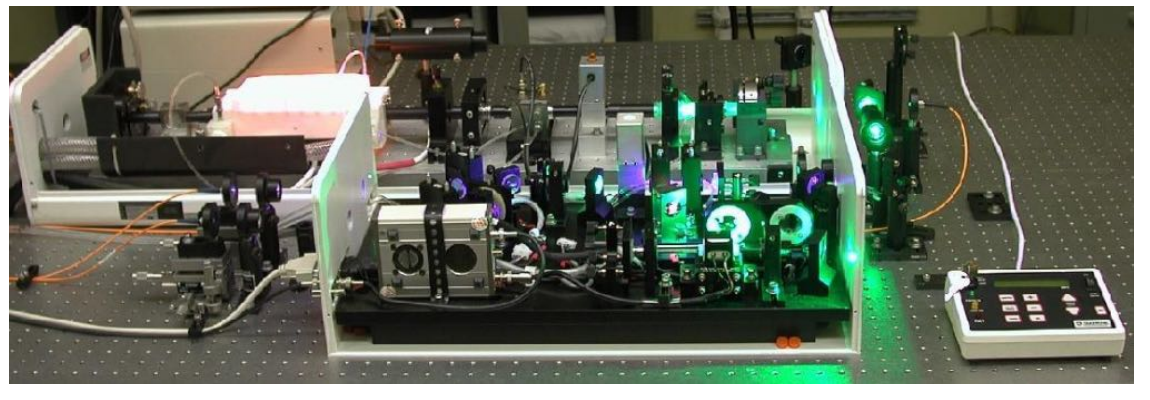


ECAL Endcap will be replaced at HL-LHC due to irreparable radiation damage.

Monitor ECAL Barrel crystal light output with the updated laser monitoring system.



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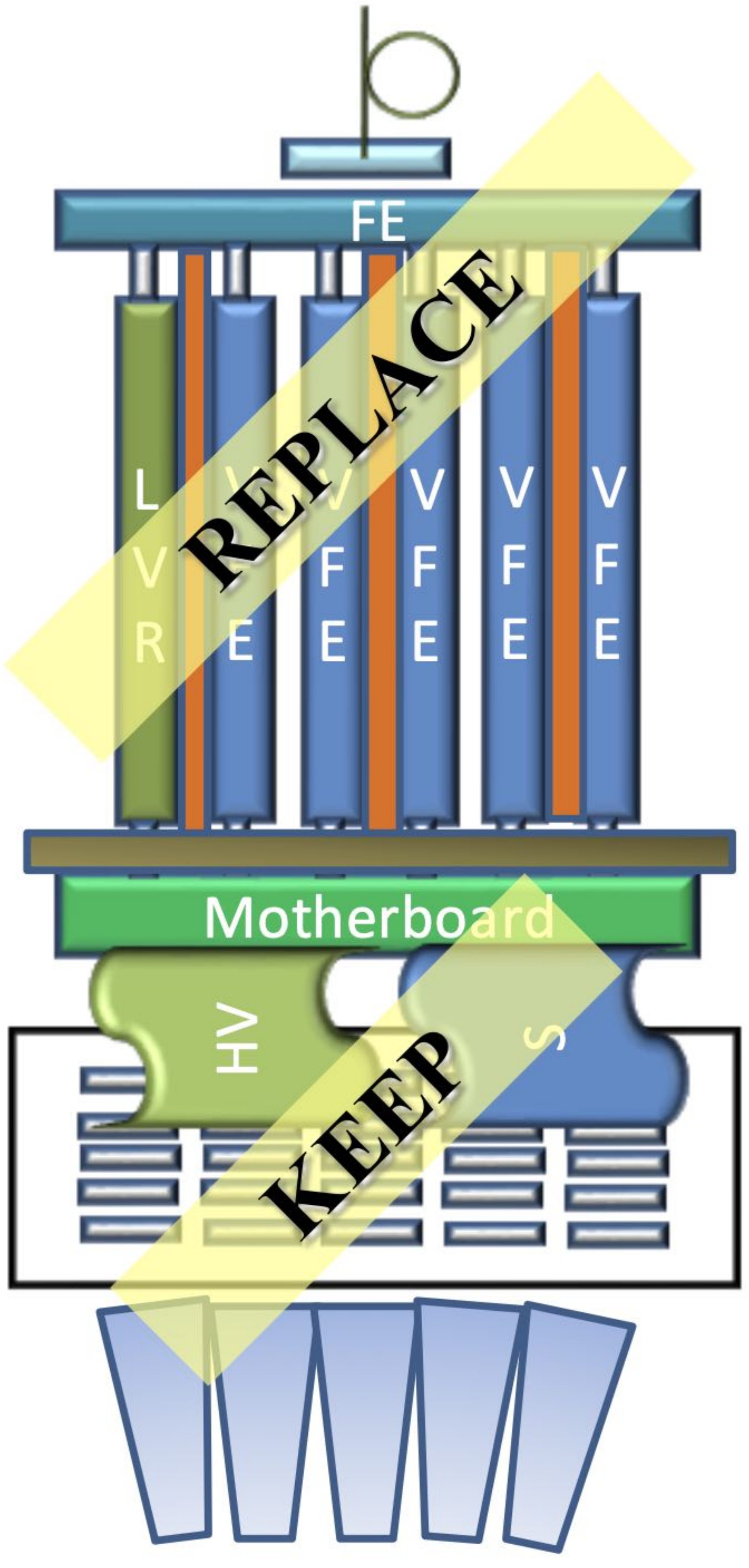

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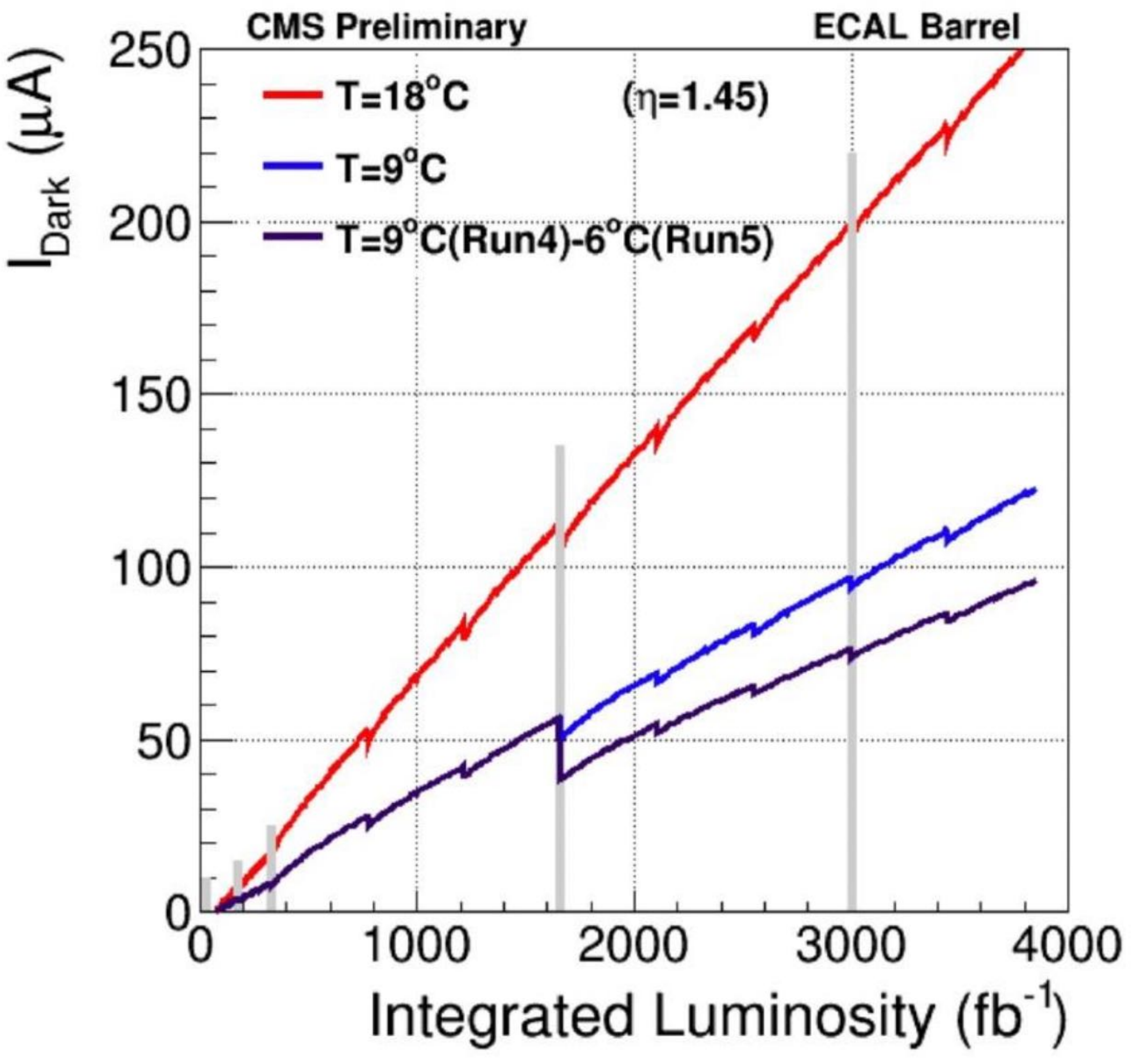

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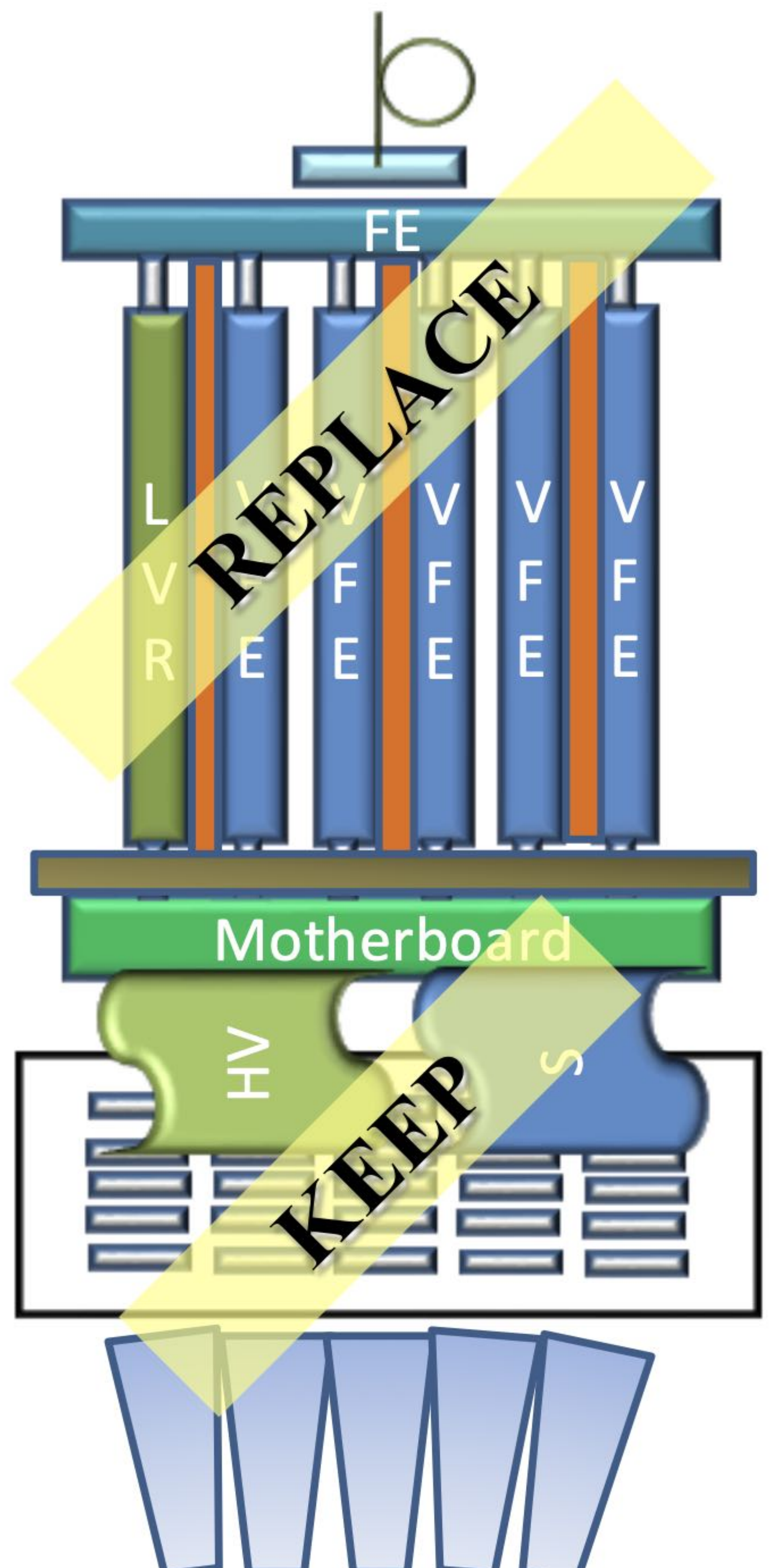

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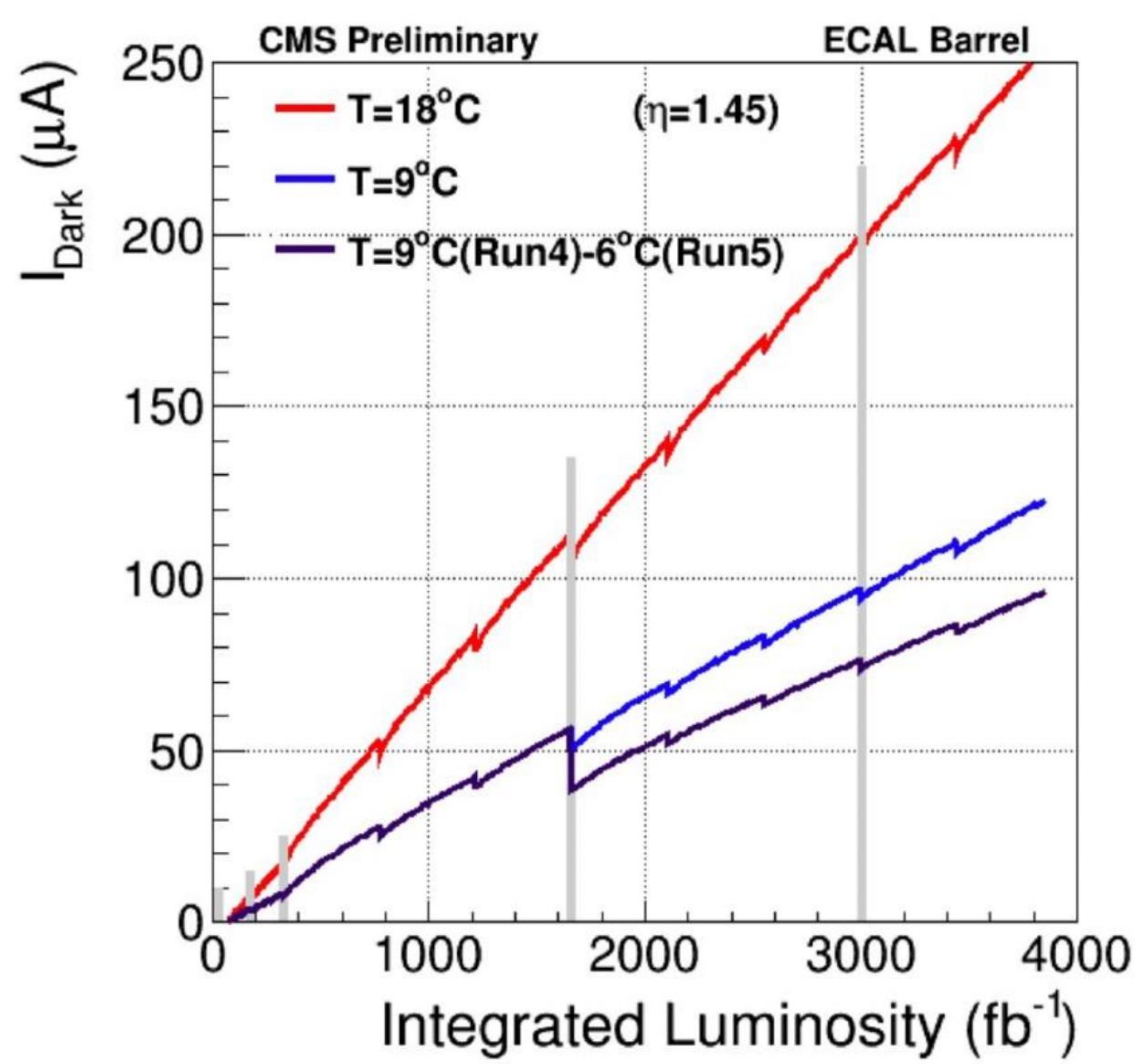


Operating temperature will be lowered* from 18 °C to 9 °C (6 °C).

[additional 10% gain in light yield]

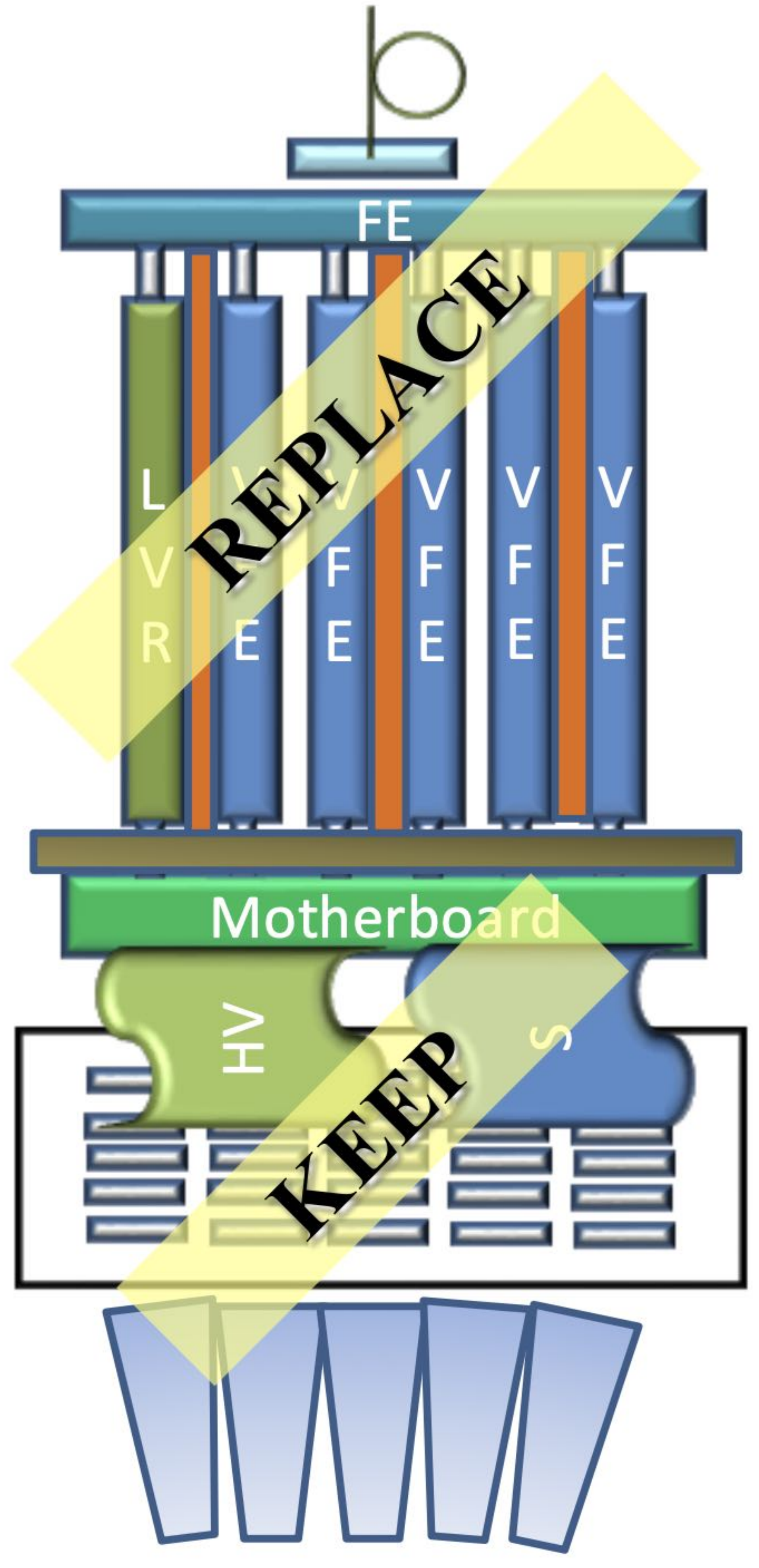
Redesigne VFE electronics to provide signal with narrower pulse shape.

* implies also redesign of several supporting detector services (cooling, slow control, etc.)

Upgrade of CMS ECAL

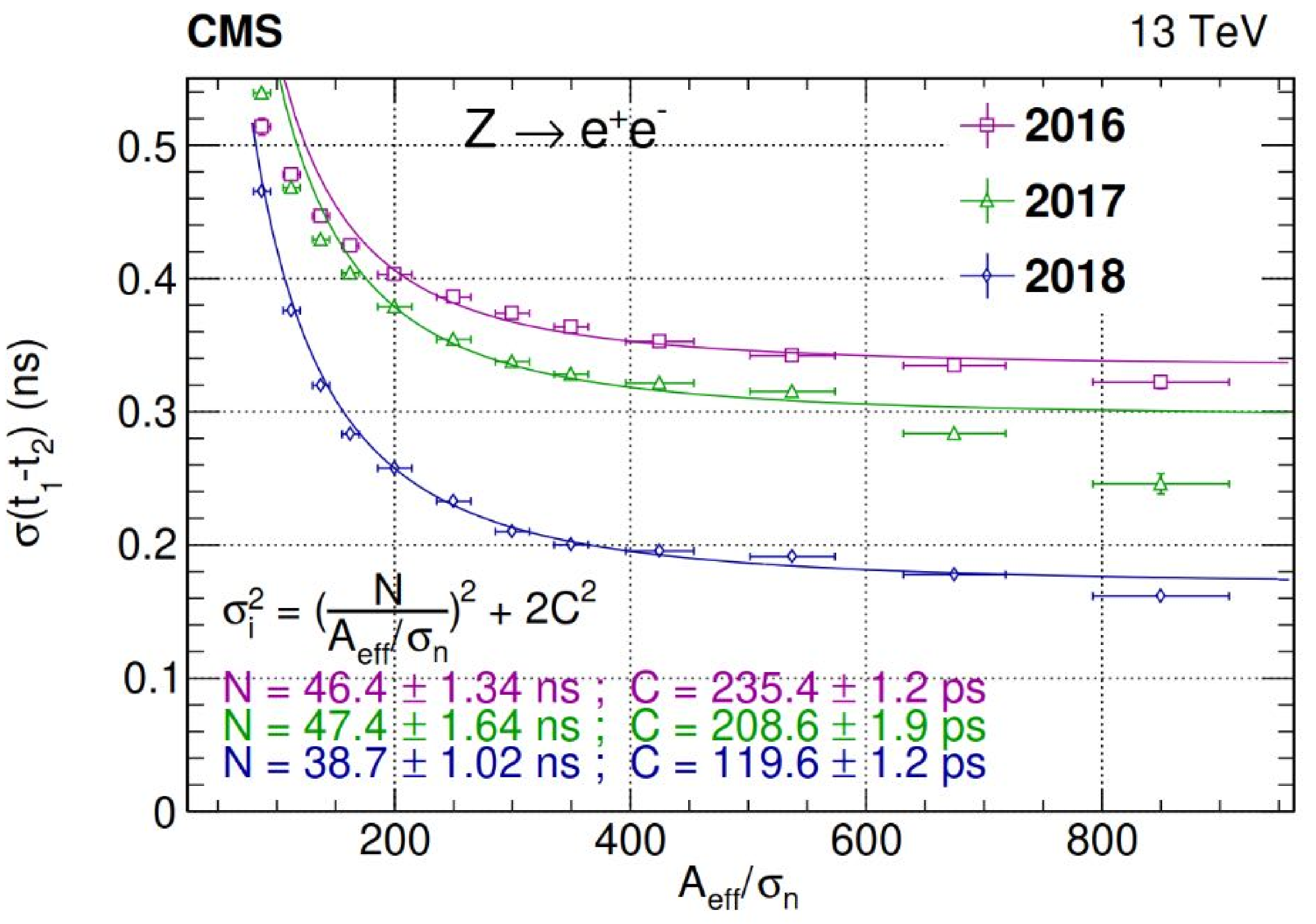
CMS ECAL Upgrade goals:

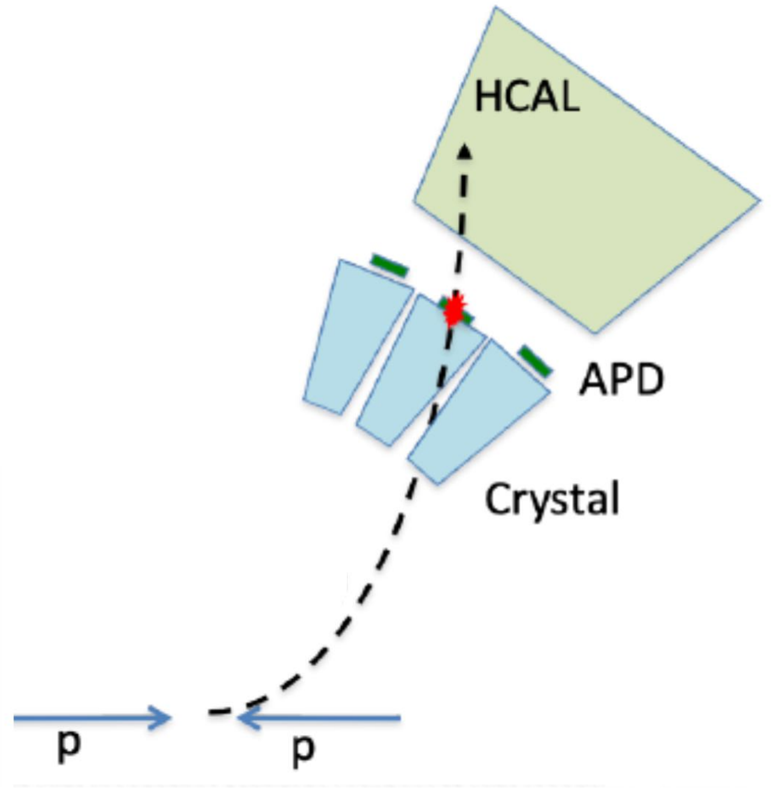
- Maintain the LHC physics performance for photons and electrons also during HL-LHC: Accommodate requirements on the Level-1 trigger latency and rate, provide more precise timing resolution, and help mitigate the increasing noise from the photodetectors, and transparency loss from the crystals.



Addressing timing resolution:

- Improve timing resolution for PU mitigation and rejection of anomalous (non-scintillation) signal.





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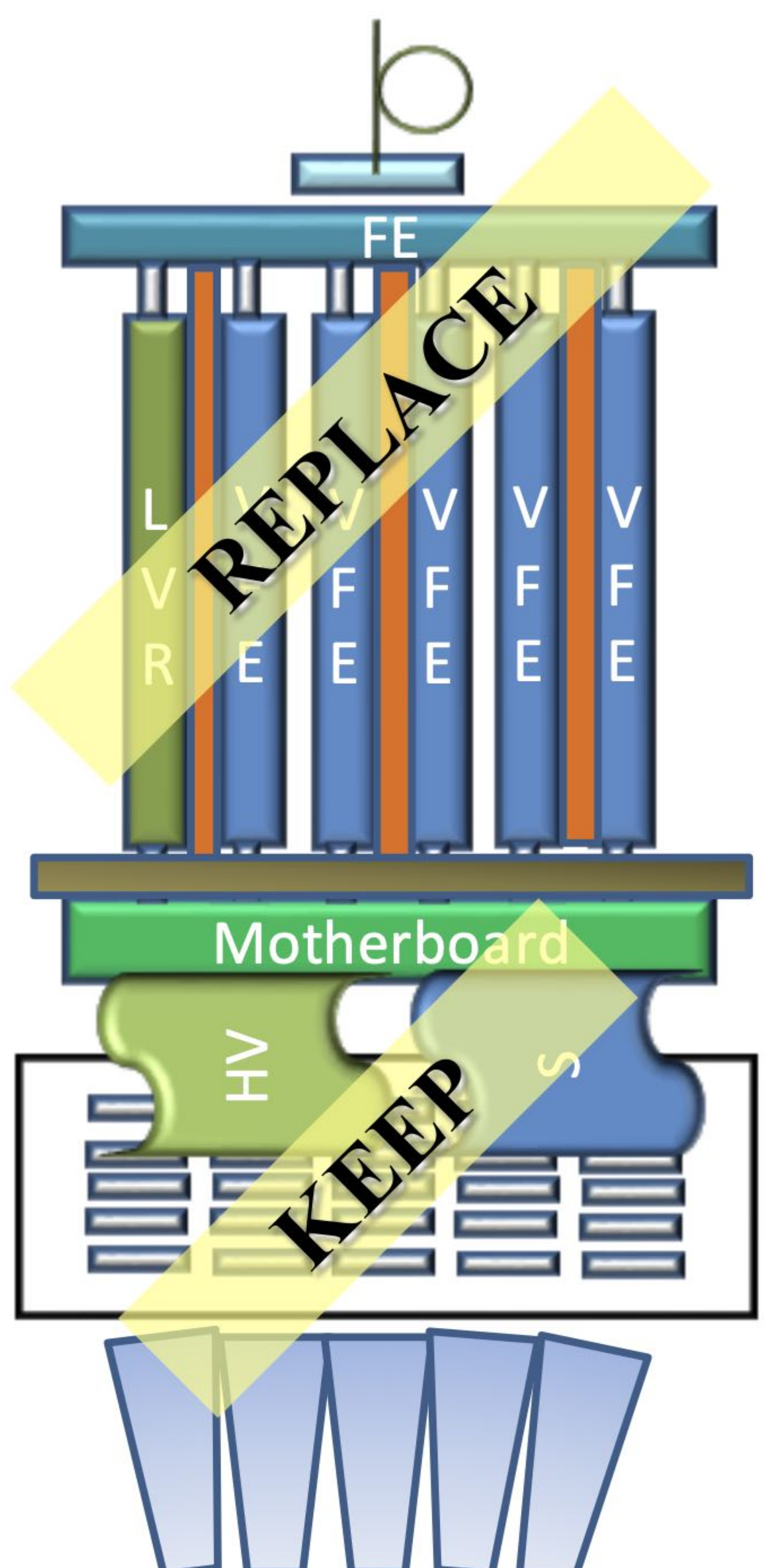

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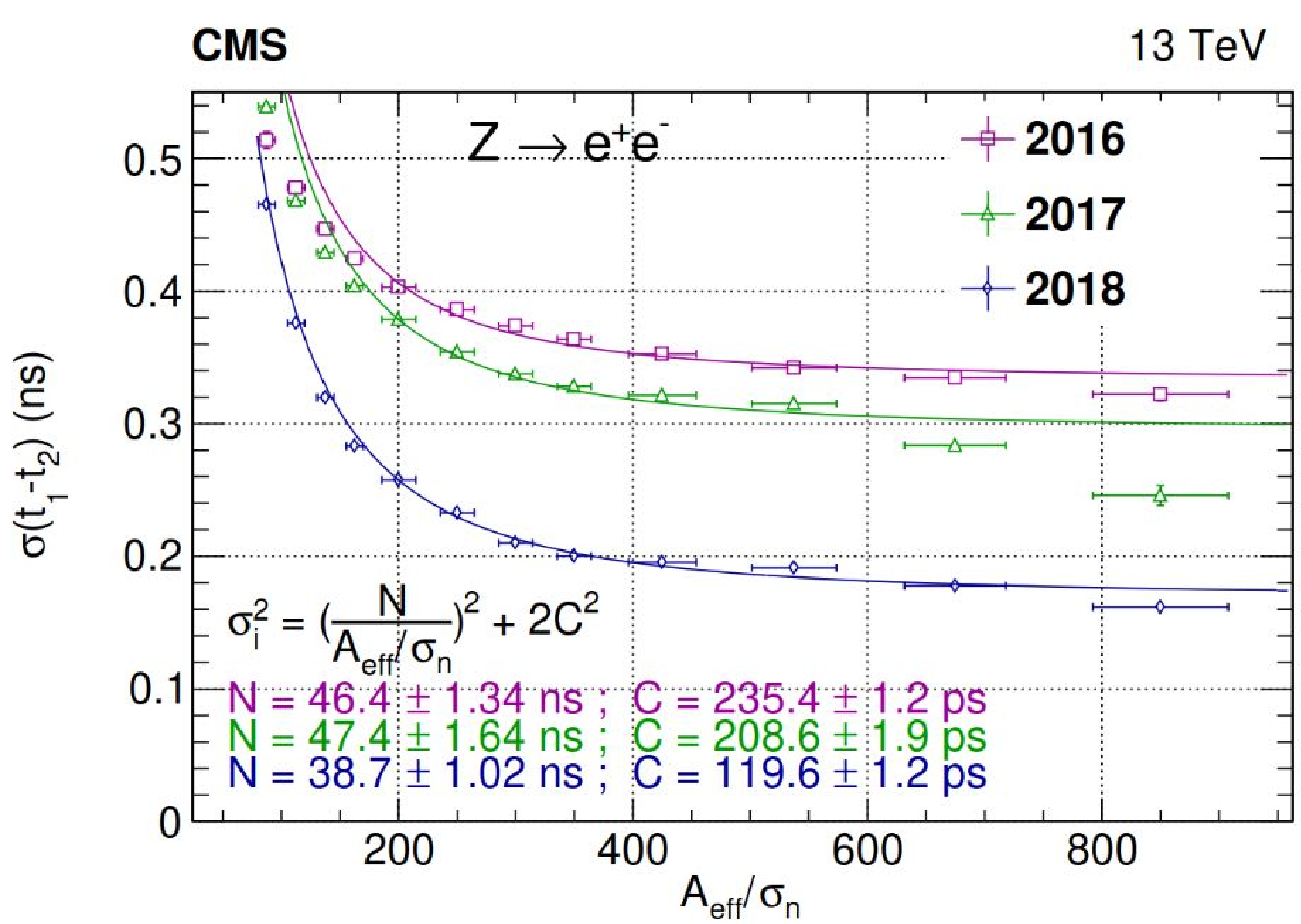

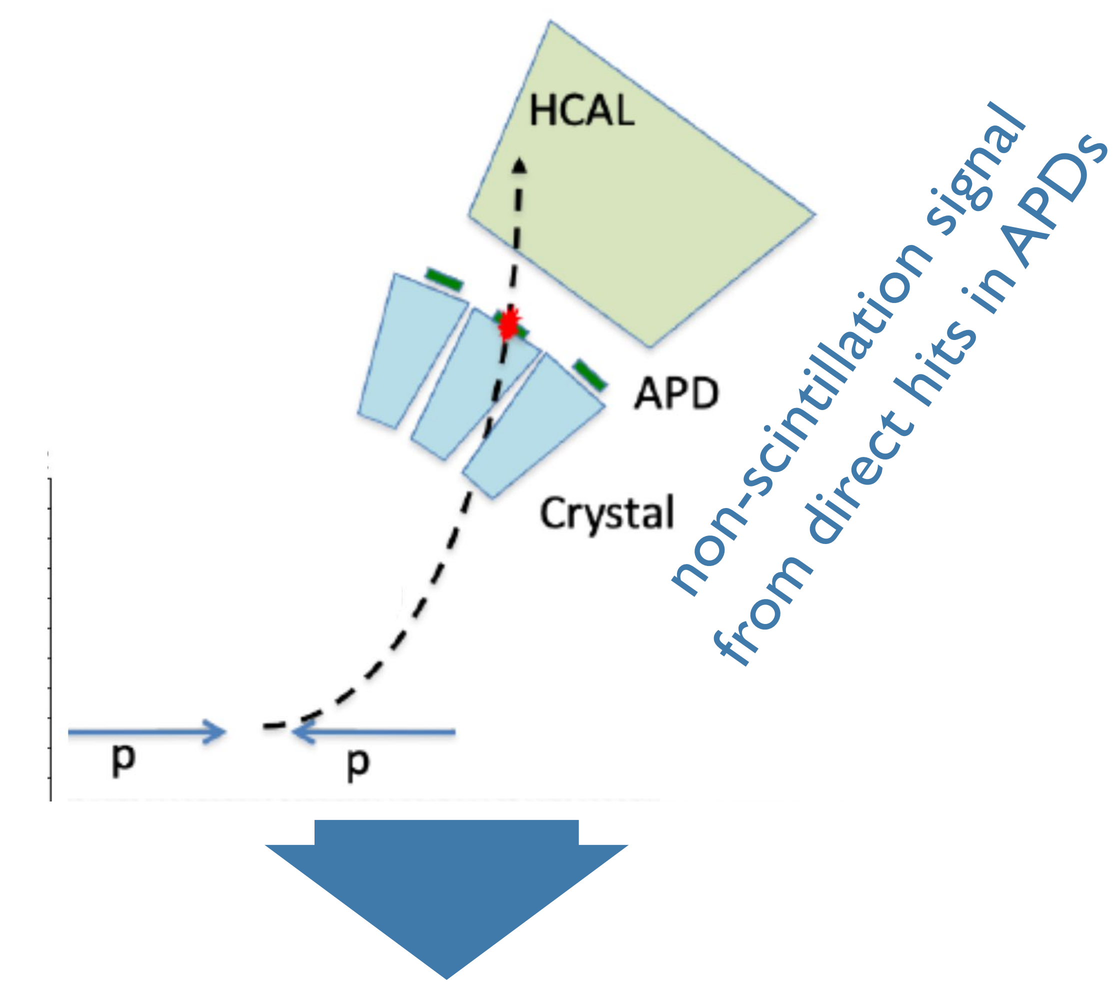

New VFE electronics to provide:

1) a narrower pulse shape for improved timing resolution [from 180 ps to 30 ps for E ≥ 50 GeV]

2) anomalous signal rejection efficiency better than 99.9%

Upgrade of CMS ECAL

CMS ECAL Upgrade goals:

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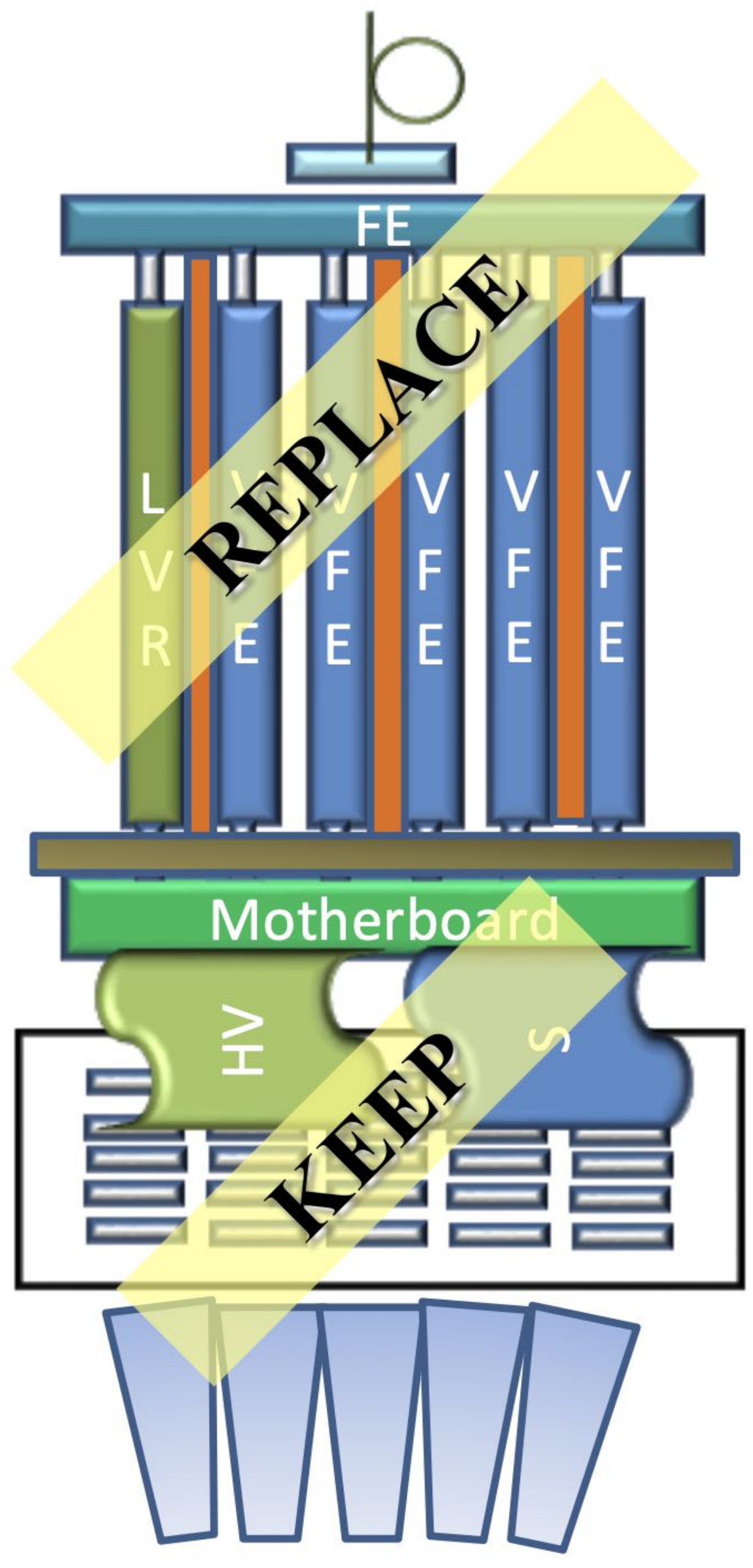


Addressing higher trigger rates:

- Accommodate higher L1 trigger rate (from 110 KHz to 750 KHz) and latency (from 4 µs to 12.5 µs) with single-crystal trigger information.

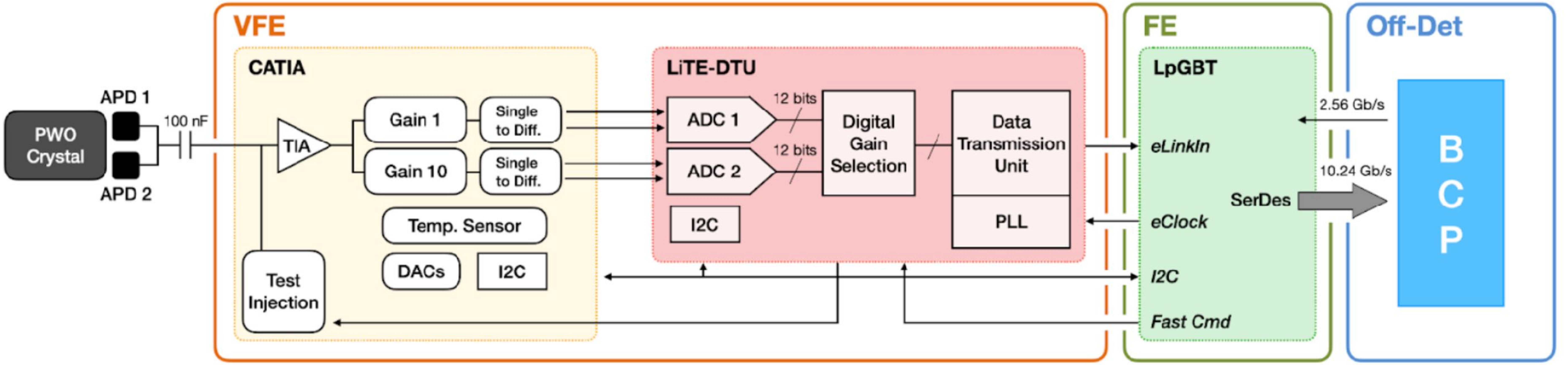
Redesign the front-end (FE) and back-end (BE) electronics:

- FE will handle data transmission, clock, and control.
- **Full detector readout at 40 MHz with upgraded links.**
- Off-detector electronics will accommodate higher transfer rates and generate trigger primitives (amplitude & timing reconstruction, anomalous signal flagging).

Upgrade of CMS ECAL : New Readout Electronics

Redesigned Very Front End (VFE) electronics:

- CAlorimeter Trans-Impedance Amplifier (**CATIA**) with two gains: x1 (low-gain) and x10 (high-gain)
- Lisbon-Turin ECAL Data Transmission Unit (**LiTE-DTU**) with two 12 bits 160 MHz ADCs

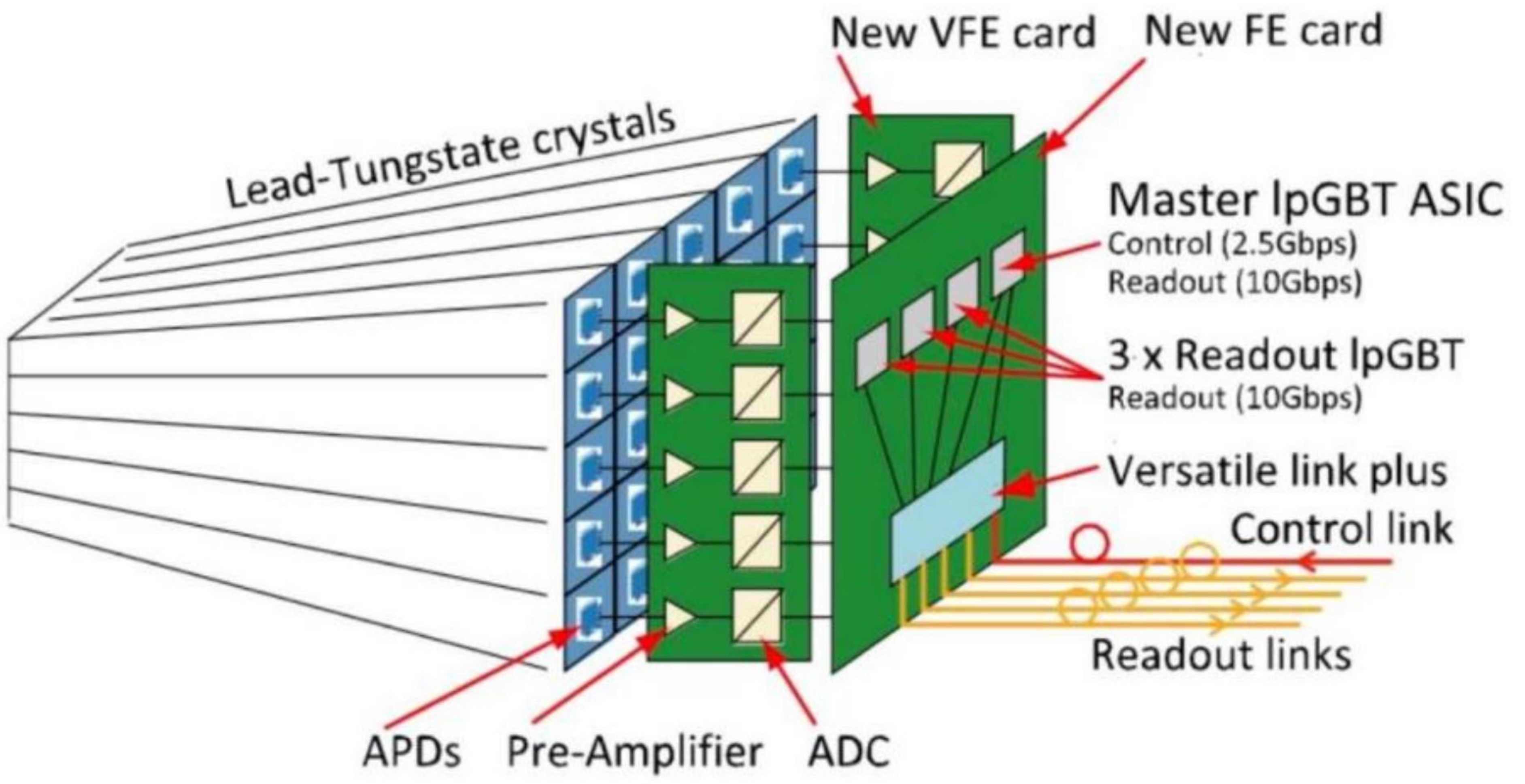


New Front End (FE) electronics:

- Data transmission, clock, and control
- **LpGBT** optical radiation tolerant transmission system

New off-detector (Off-Det) electronics:

- **BCP board** with FPGAs handling clock and control signals distribution, trigger primitives generation, and high-rate data transmission



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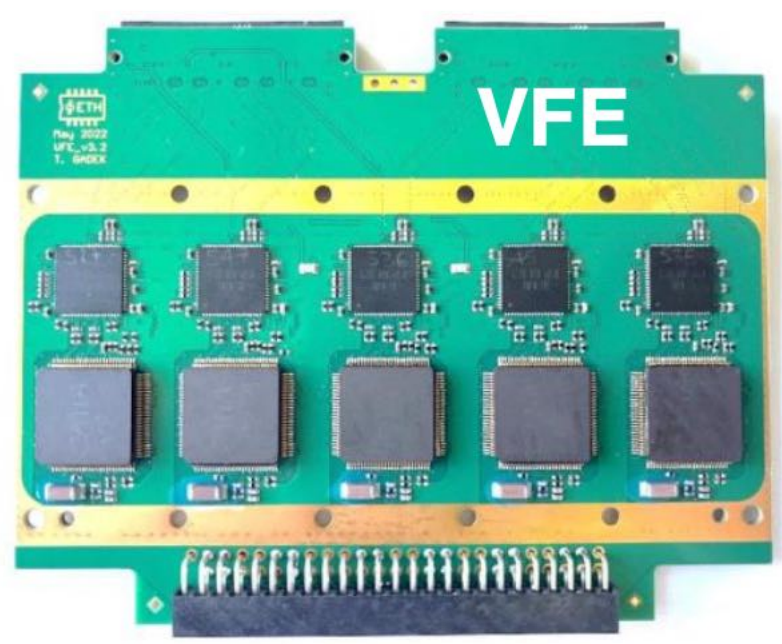

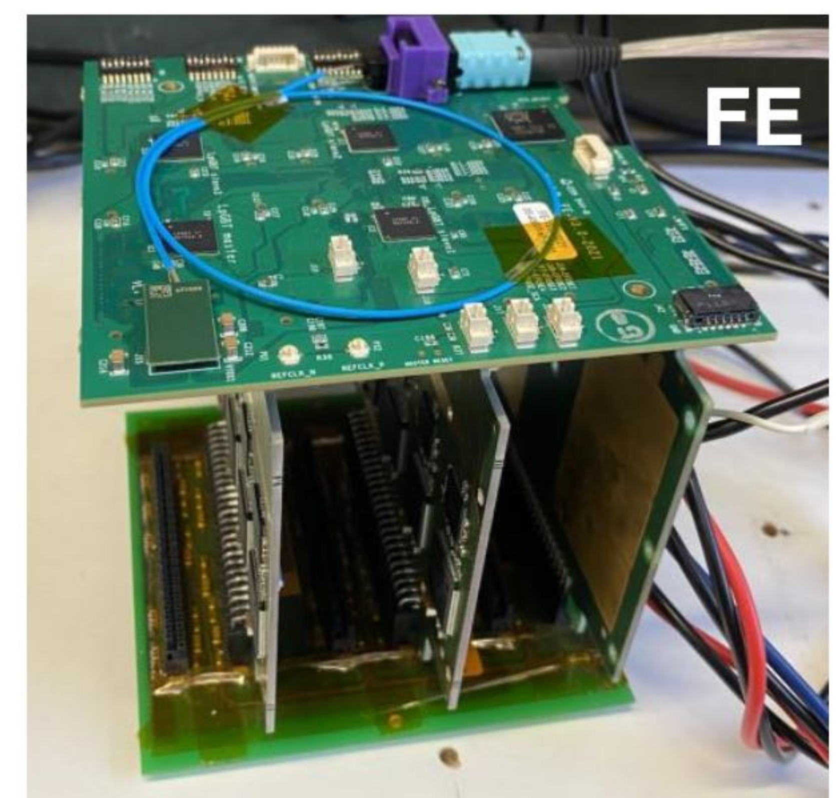

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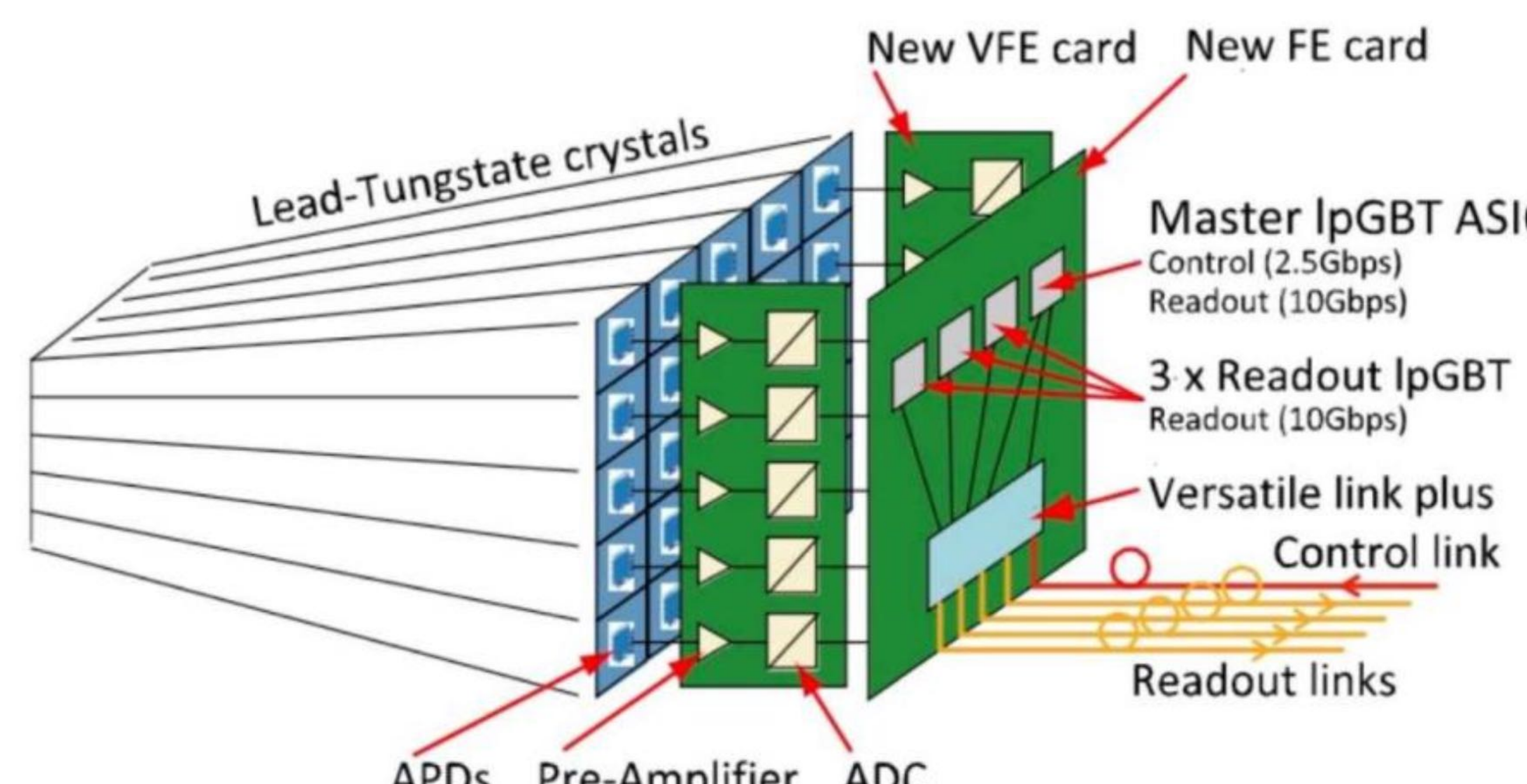


Upgrade of CMS ECAL : Testing & validation

Irradiation and ageing tests (with active readout):

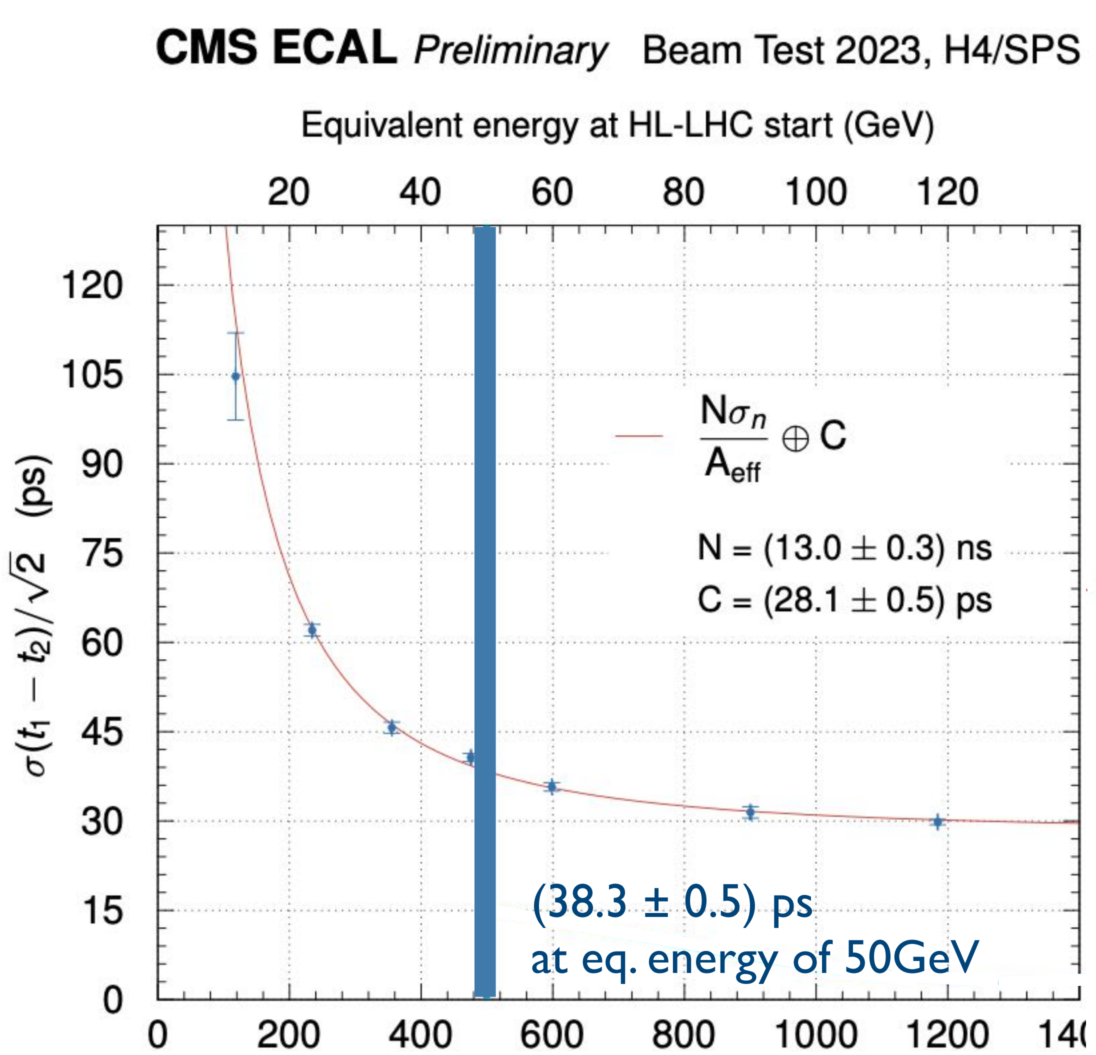
- Irradiated one full tower in CMS-like future conditions @CHARM in 2023
- Accumulated **24% of HL-LHC dose** (in future planned 200% dose @PSI)

Validation at the test-beam campaigns:

- Technologies validated at five test beam campaigns (2016-2023)
- Test-beam setup in 2023 with all "near-to-final version" components

H4@CERN electron beam 20 - 250 GeV

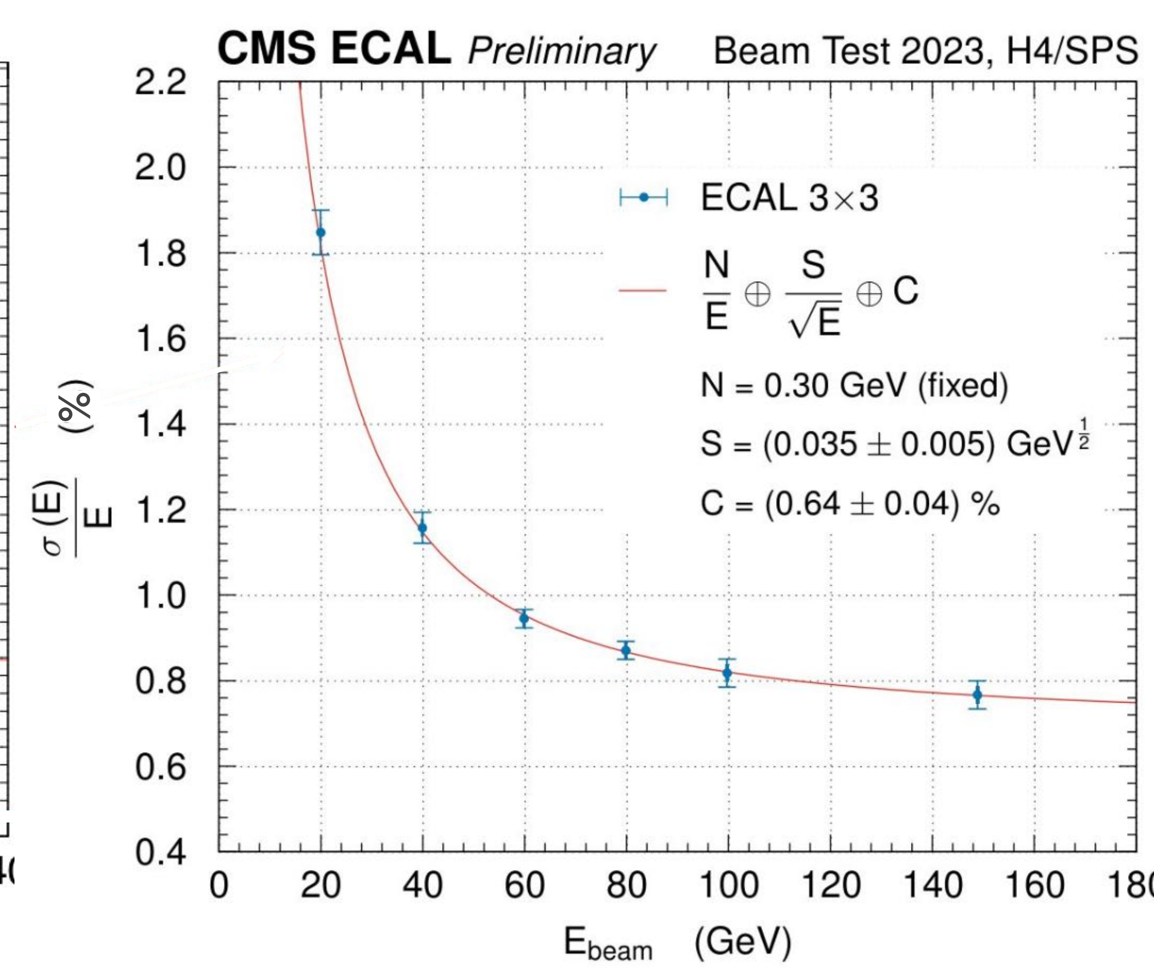
Setup 2023: SM 36 , 225 channels, full chain, 2 BCP



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

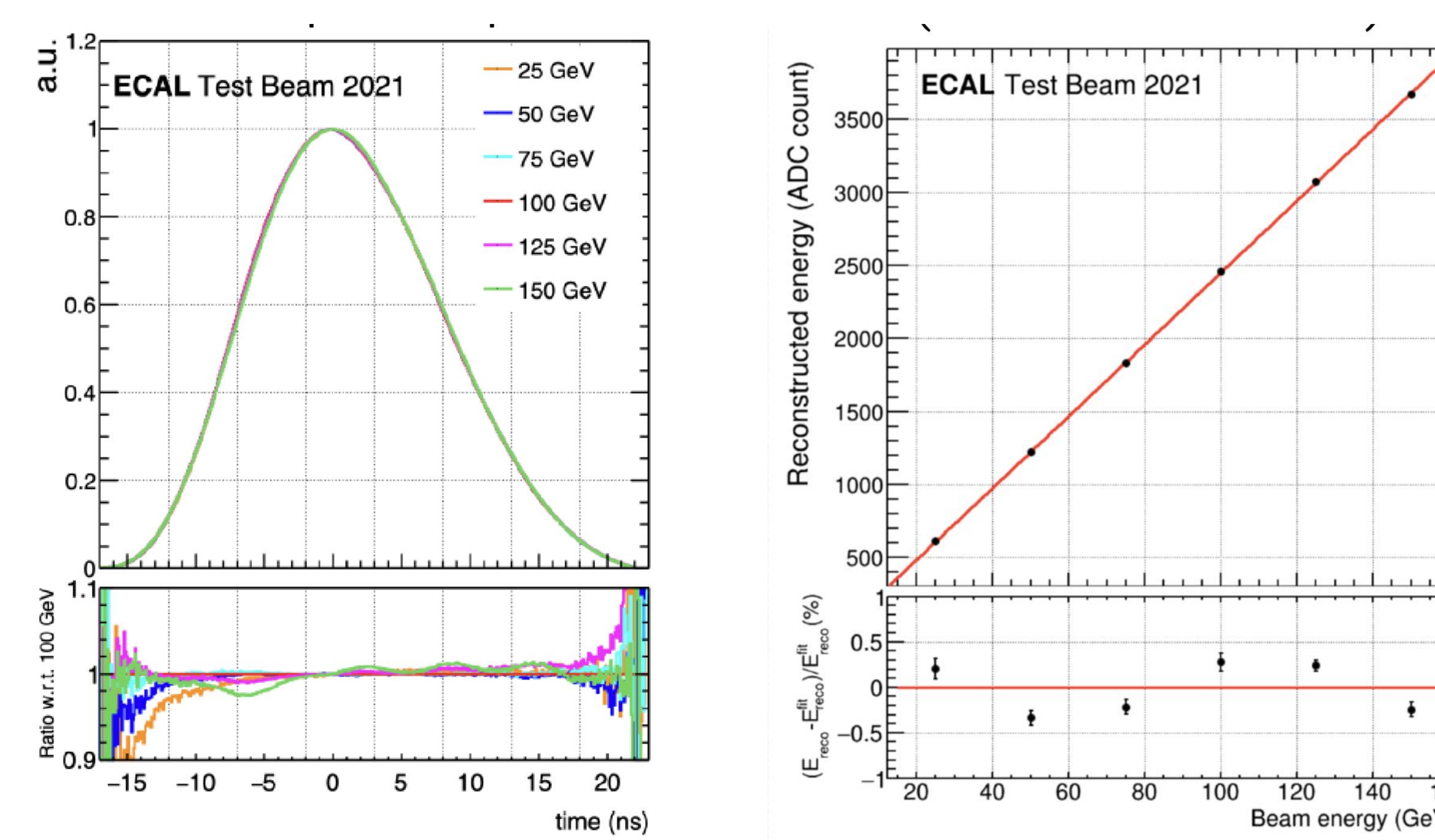
Timing Resolution

better than 40 ps for E > 50 GeV



Energy Resolution

~ 1% for energies of H → γγ photons



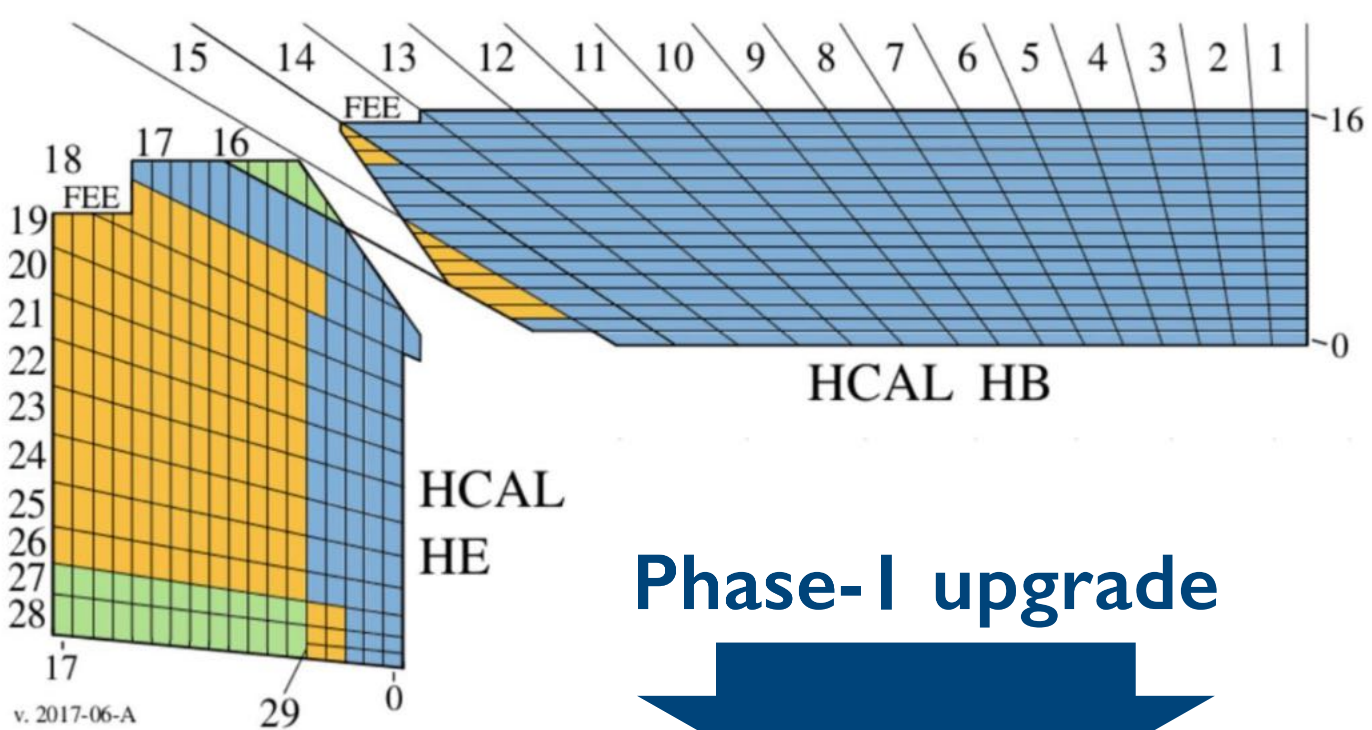
Linearity and uniformity

Excellent linearity of response and uniformity of pulse shape across wide range of energies with new VFE electronics

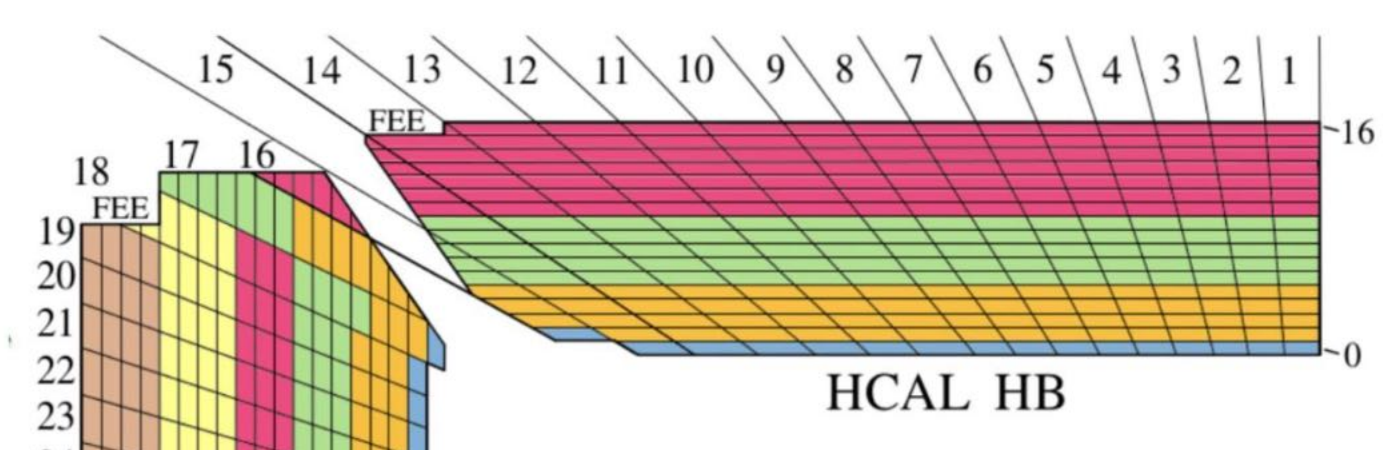
Upgrade of CMS HCAL

CMS HCAL Upgrade (during LHC Phase-1):

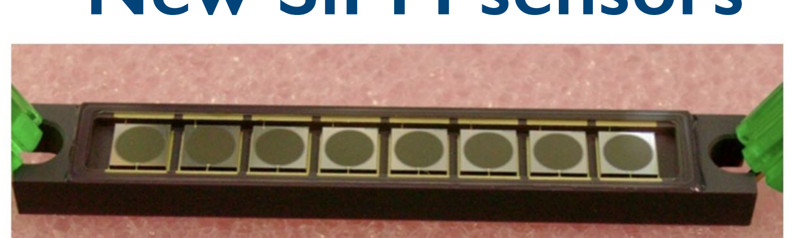
- Maintain/extend the physics performance for hadrons/jets during LHC Run 3 and HL-LHC: Mitigate the increasing noise from the photodetectors, and light yield change in the tiles, introduce finer spatial segmentation with improved timing/energy resolution, extend the possibilities at the Level-1 trigger level.



Phase-1 upgrade



New SiPM sensors



Upgraded photodetectors:

- Hybrid Photo Diodes (HPDs) replaced by Silicon photomultipliers (SiPM)
- Improved photon sensitivity, spectrum resolution, high rad. resistance

Upgraded electronics:

- Increased readout granularity (achieving finer longitudinal segmentation)
- Improved L1 trigger performance, with new physics possibilities at L1

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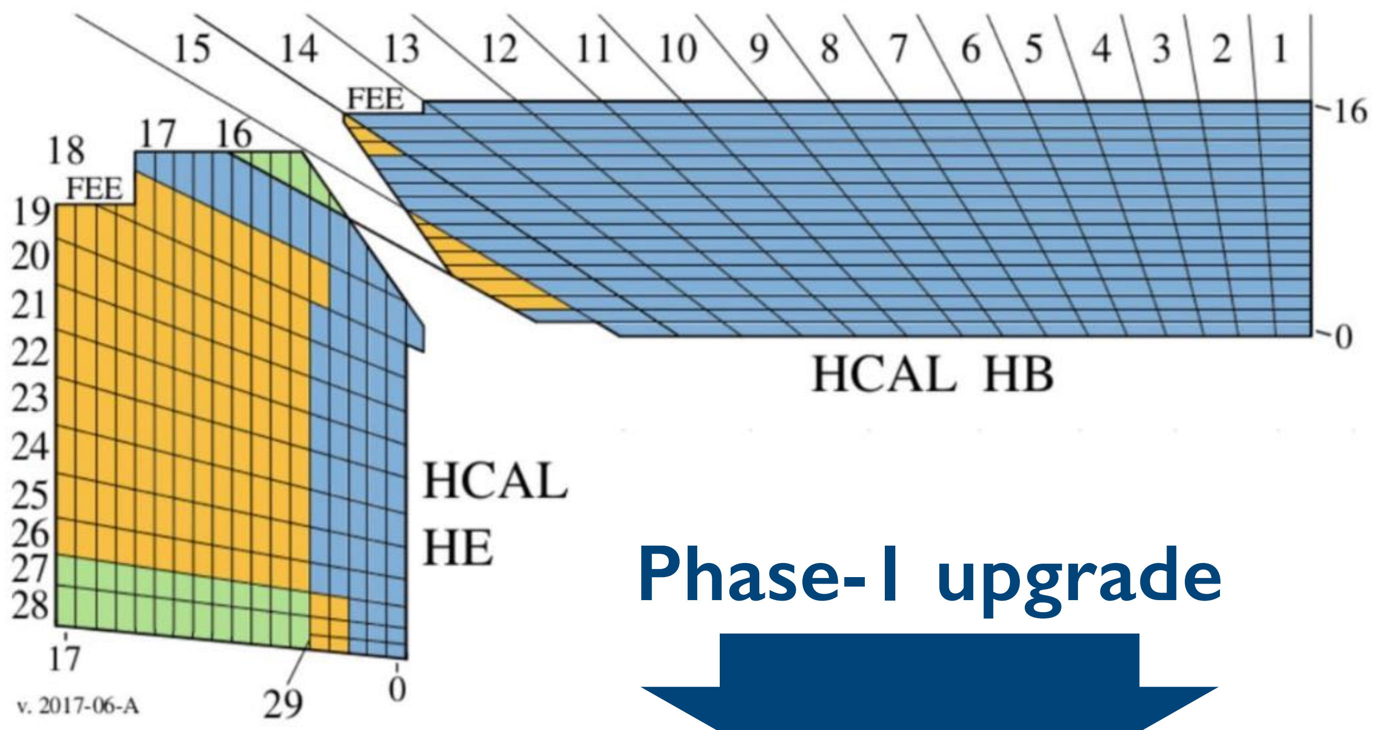
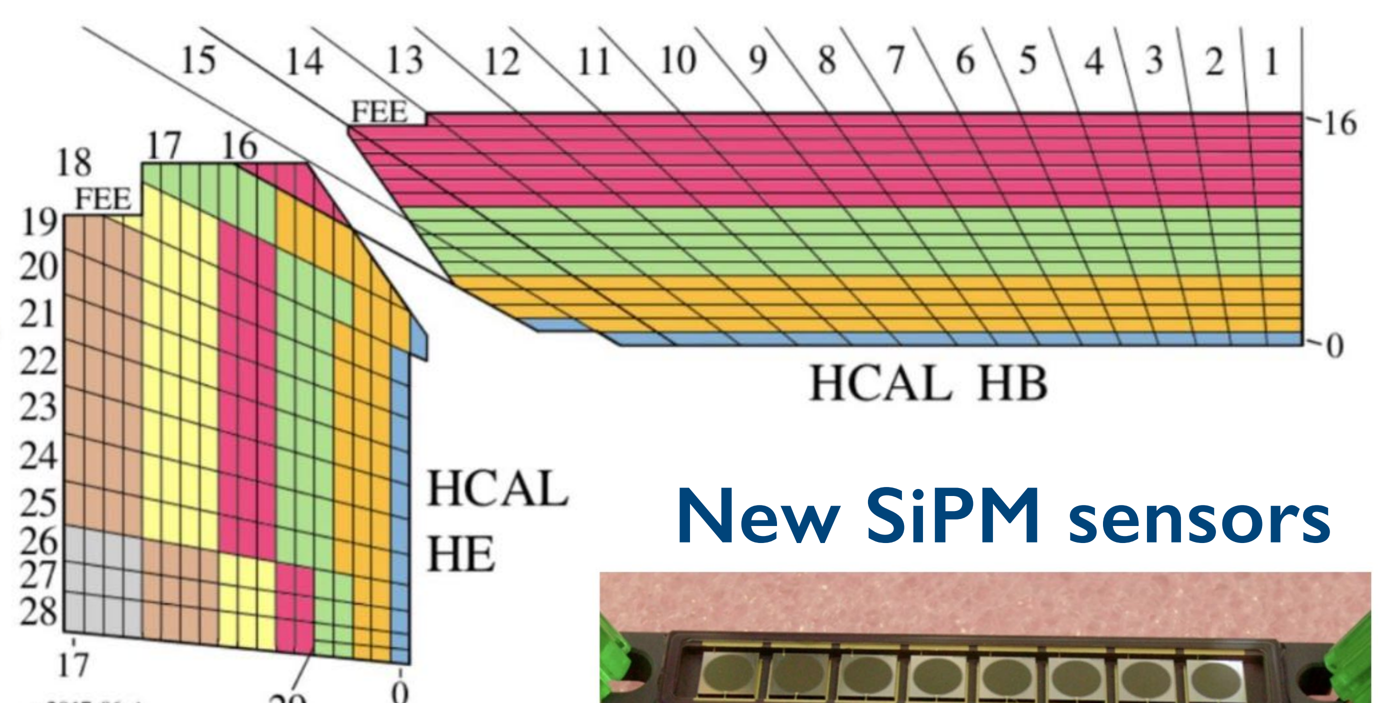
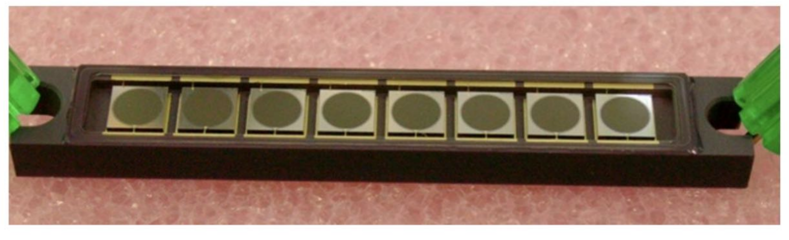


Phase-1 upgrade



New SiPM sensors



Upgraded photodetectors:

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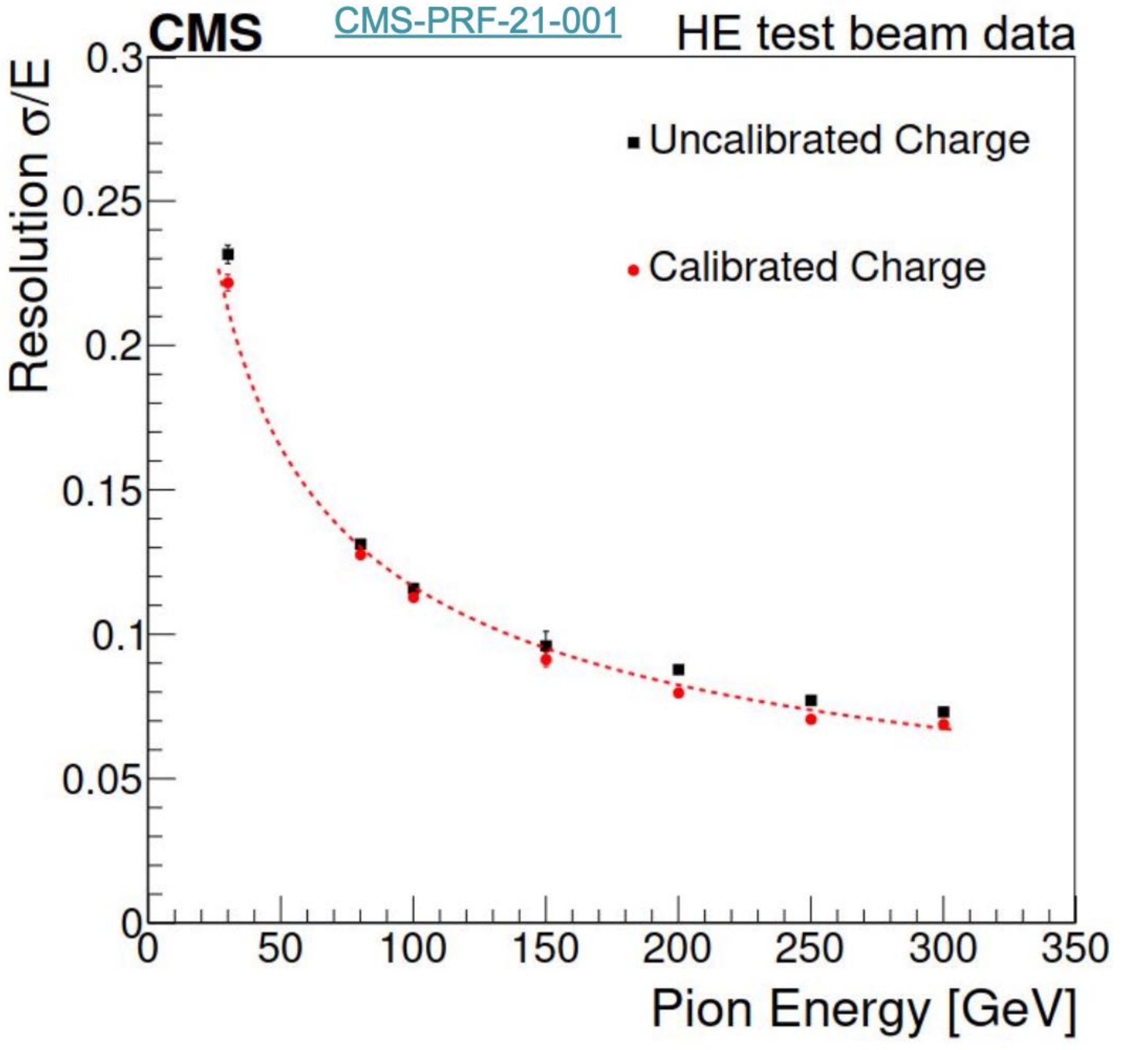
Upgraded electronics (+ improved time alignment):

- Increased readout granularity (achieving finer longitudinal segmentation)
- Improved L1 trigger performance, with new physics possibilities at L1



Energy resolution (HB, HE)

$$\frac{\sigma}{E} = \frac{84.7\%}{\sqrt{E}} \oplus 7.6\%$$

improvement of timing/energy resolution with time alignment

HCAL Endcap will be replaced with new detector at HL-LHC.

The only voyage of discovery [...] consists not in seeing new landscapes, but in having new eyes.
M. Proust[1], 1923.

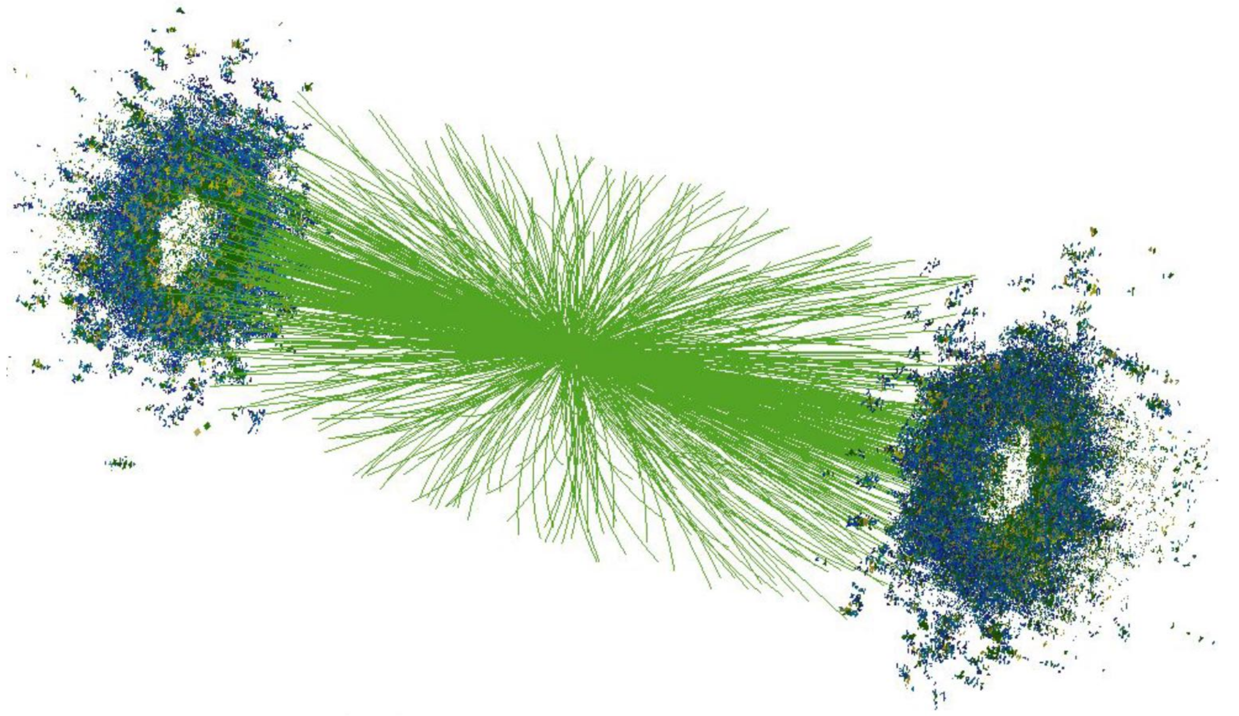
New CMS Endcap Calorimeter

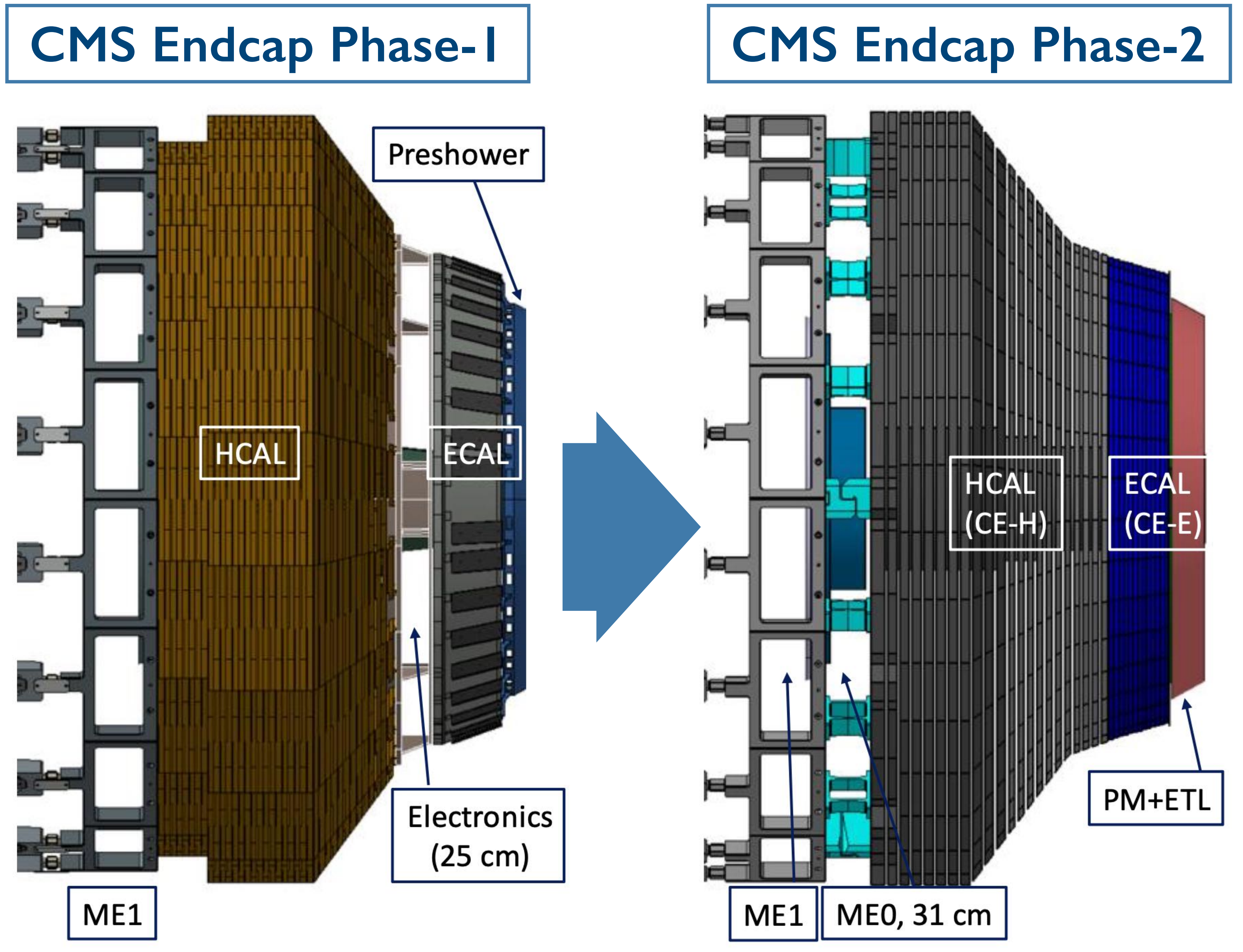
- Requirements & engineering challenges
- Technological developments and expected performance

New CMS Endcap Calorimeter (HGCAL)

Technical requirements:

- Sustain radiation environment and S/N ratio through full HL-LHC operation.
- Highly granular detector for particle flow reconstruction, pileup suppression.
- Fit within the envelope of today's CMS Endcap calorimeters.
- Optimized taking into account: cost, efficiency and radiation tolerance.





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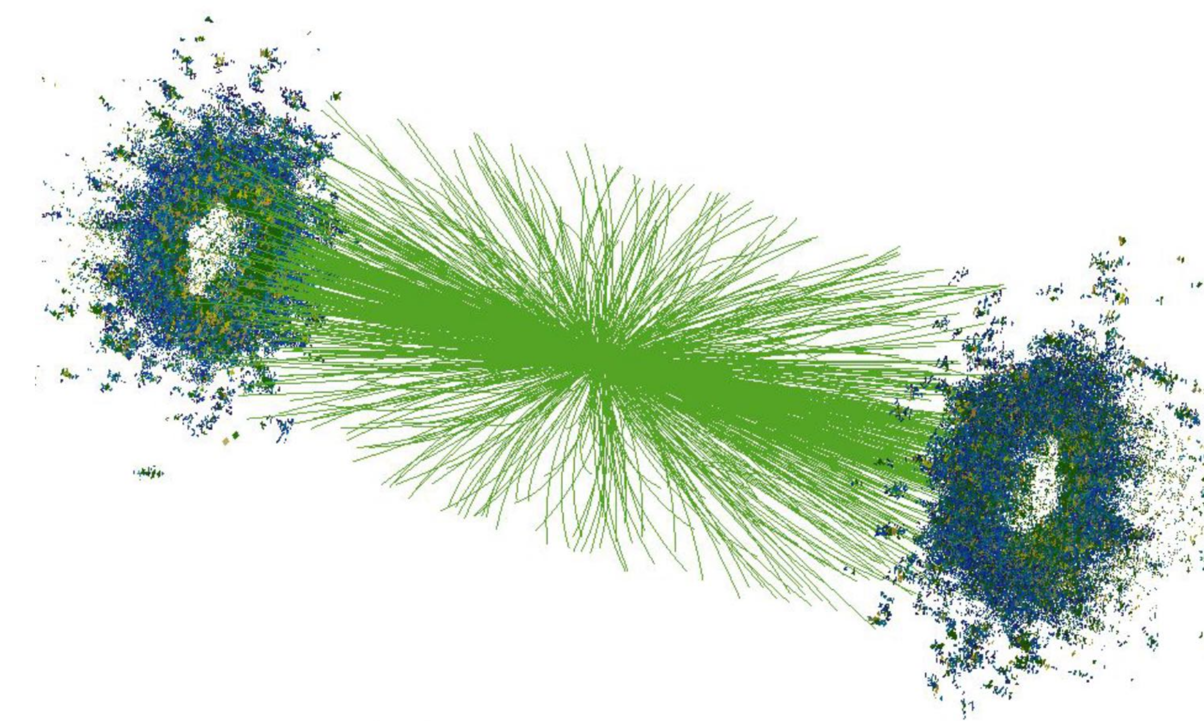
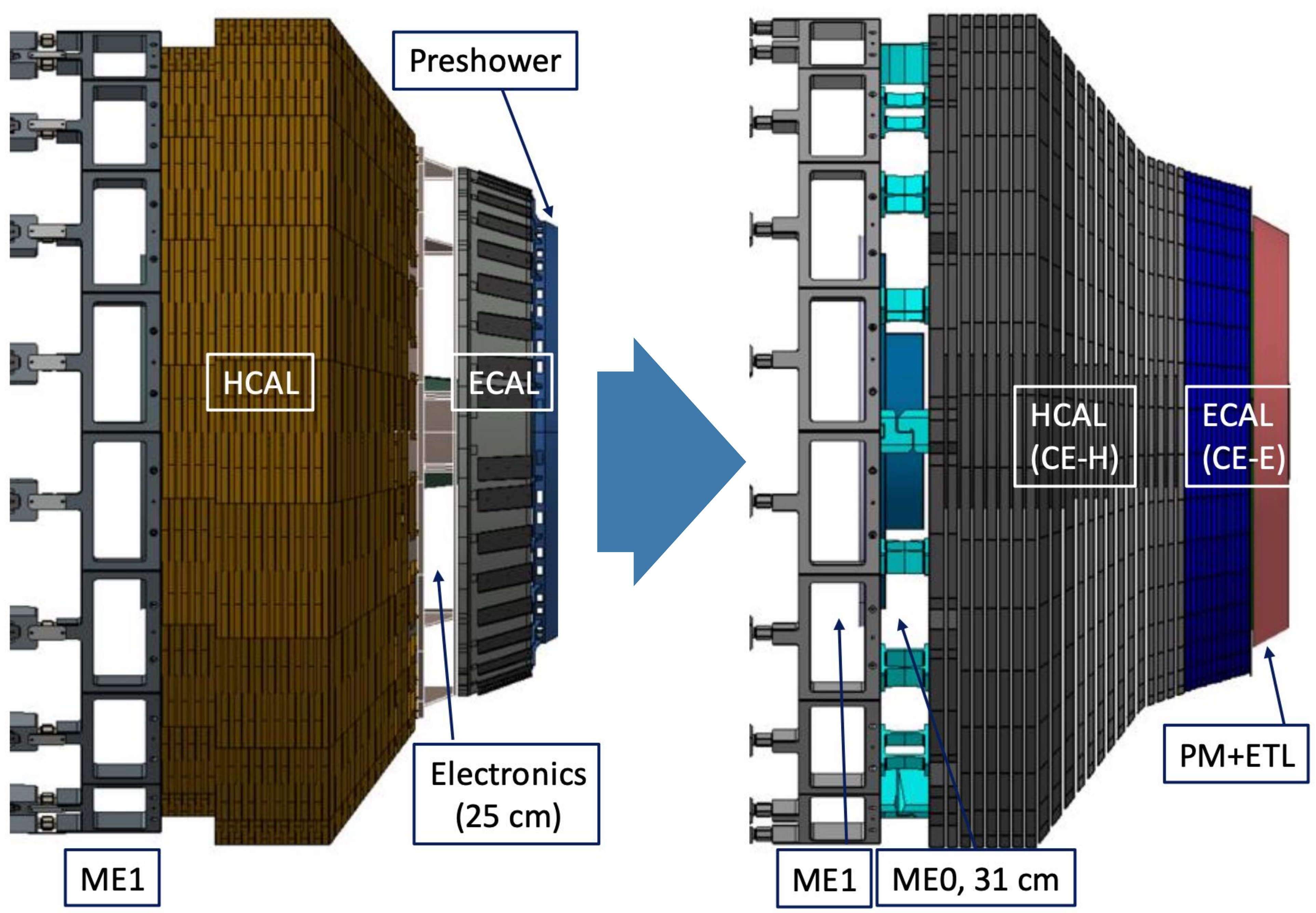


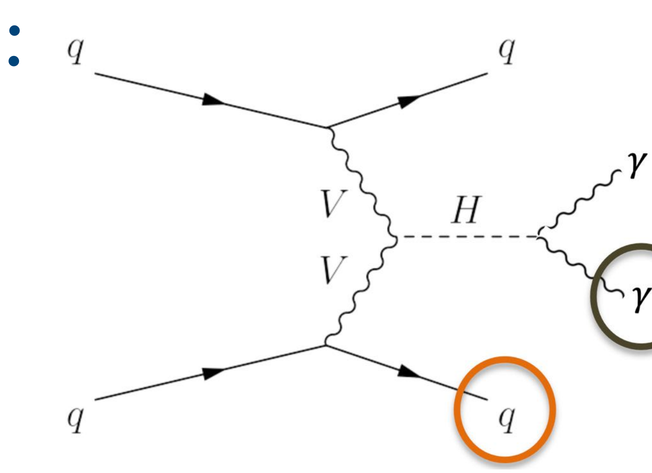
CMS Endcap Phase-I

CMS Endcap Phase-2

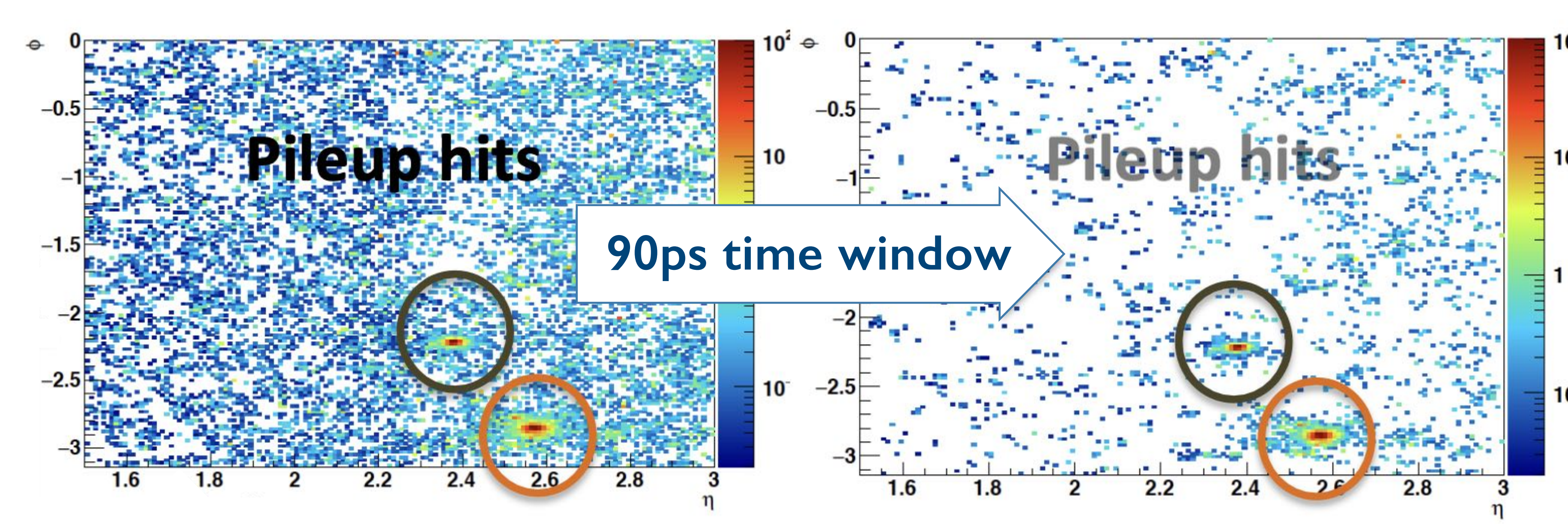


Physics requirements:

- Measure individual showers, characterise jet (sub-)structure, mitigate PU contamination
- Provide also good energy resolution: $\Delta E/E<1\%$ for photons from $H\rightarrow\gamma\gamma$
- Provide measurements of energy, position and time (5D information).



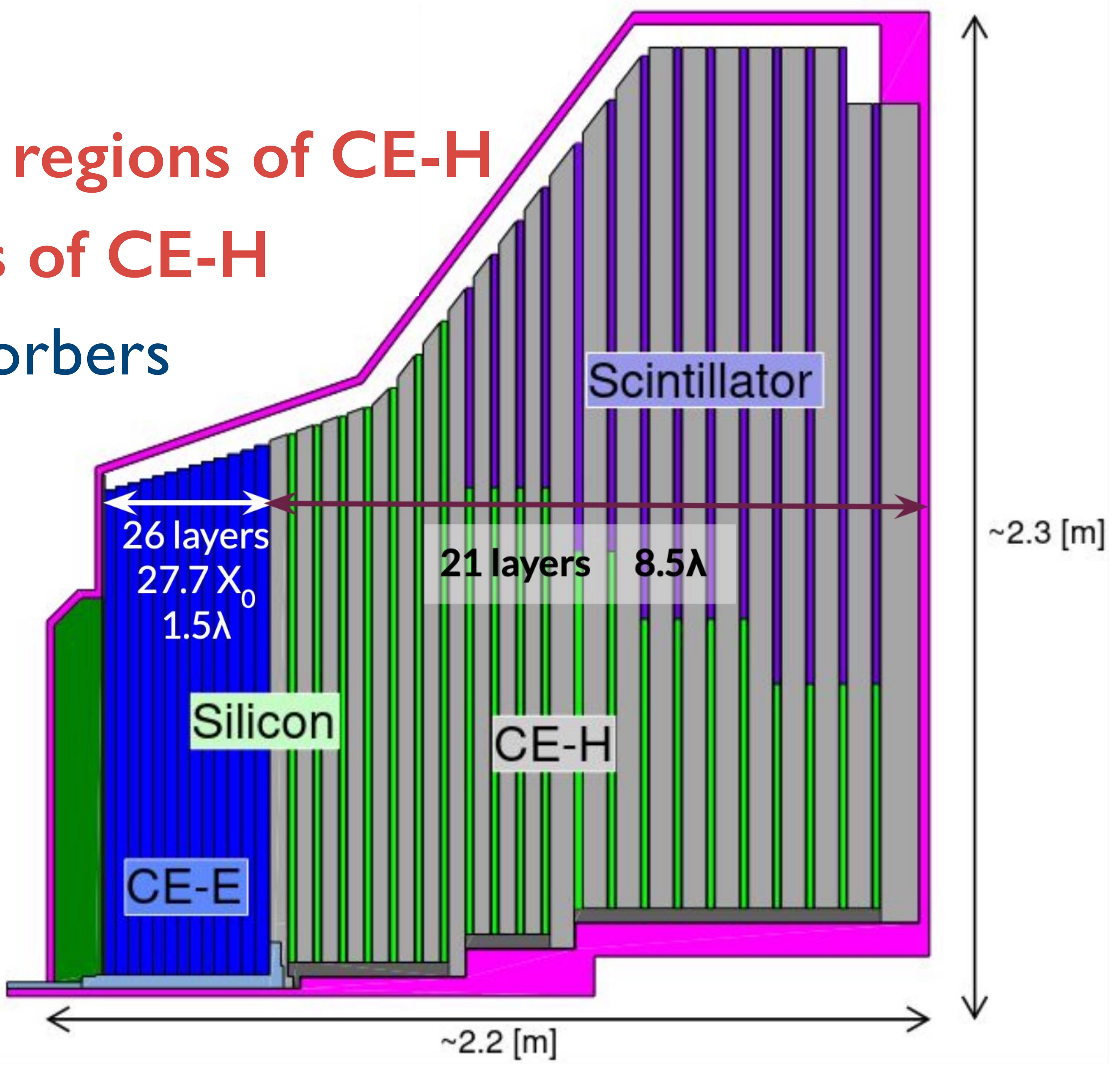
VBF H → $\gamma\gamma$ + 200 PU



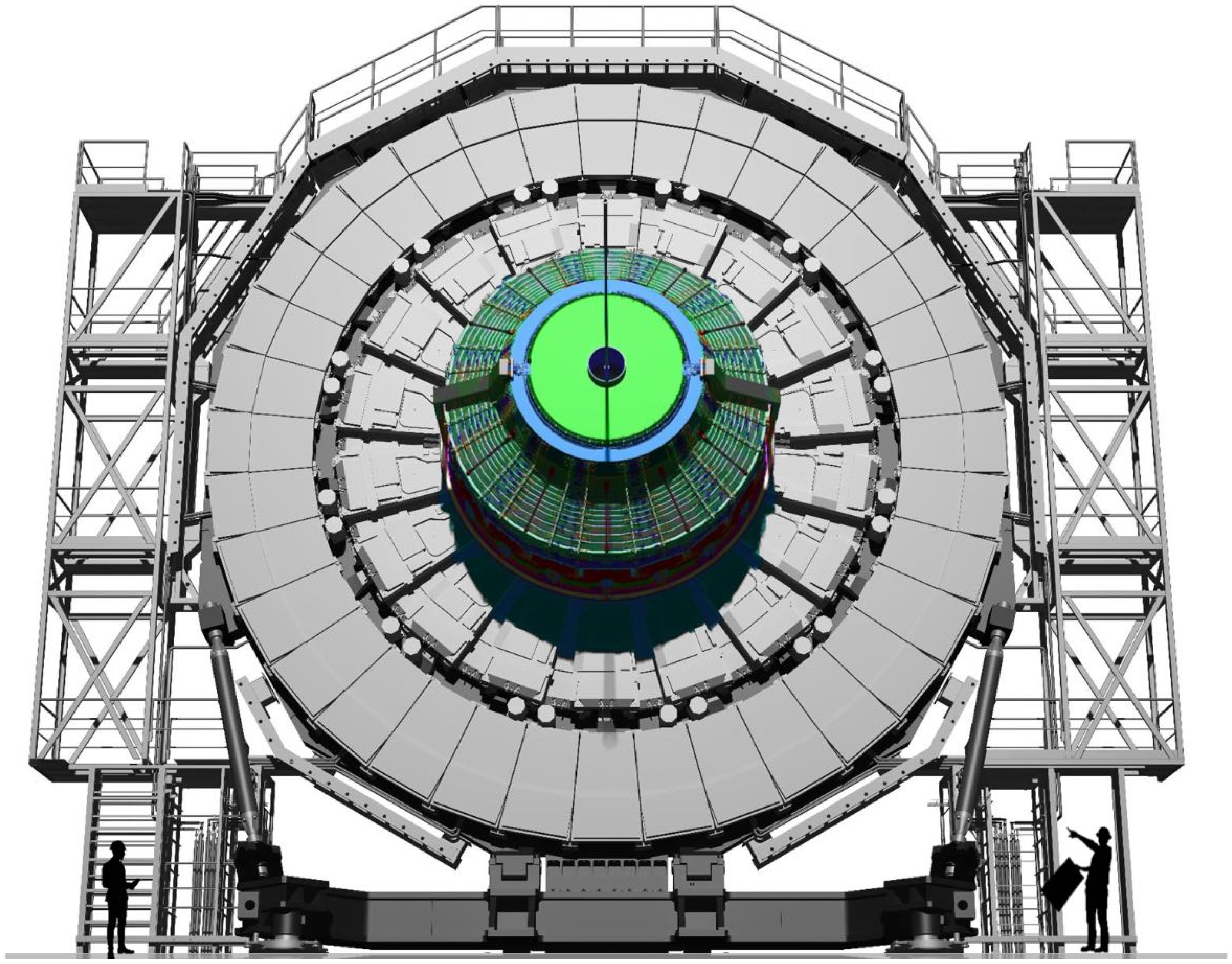
New CMS Endcap Calorimeter (HGCAL)

Active elements:

- Hexagonal modules based on **Si sensors in CE-E and high-radiation regions of CE-H**
- **Scintillating tiles** with on-tile SiPM readout **in low-radiation regions of CE-H**
- Multiple modules mounted on cooling plates with electronics and absorbers



CMS Endcap Phase-2



Key Parameters:

- **Coverage:** $1.5 < |\eta| < 3.0$
- **Absorbers:** Cu, CuW and Pb in CE-E, Steel in CE-H
- **Silicon sensors:** 6M channels in 26k modules cover 620 m² (3x area of CMS tracker)
- **Tiles:** 240k channels in 3.7k boards cover ~370 m²
- **Projected power at HL-LHC end:** ~125 kW / endcap

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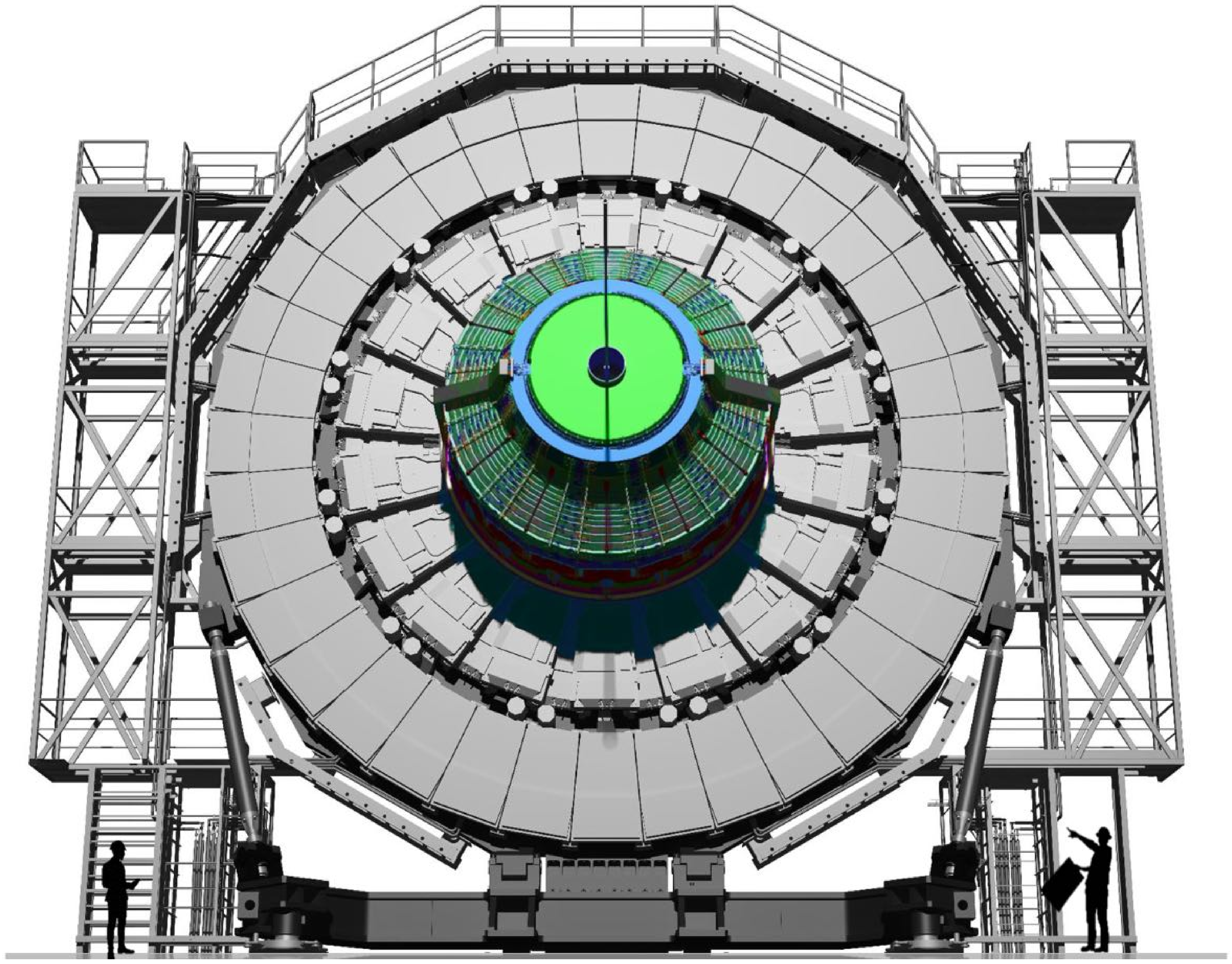
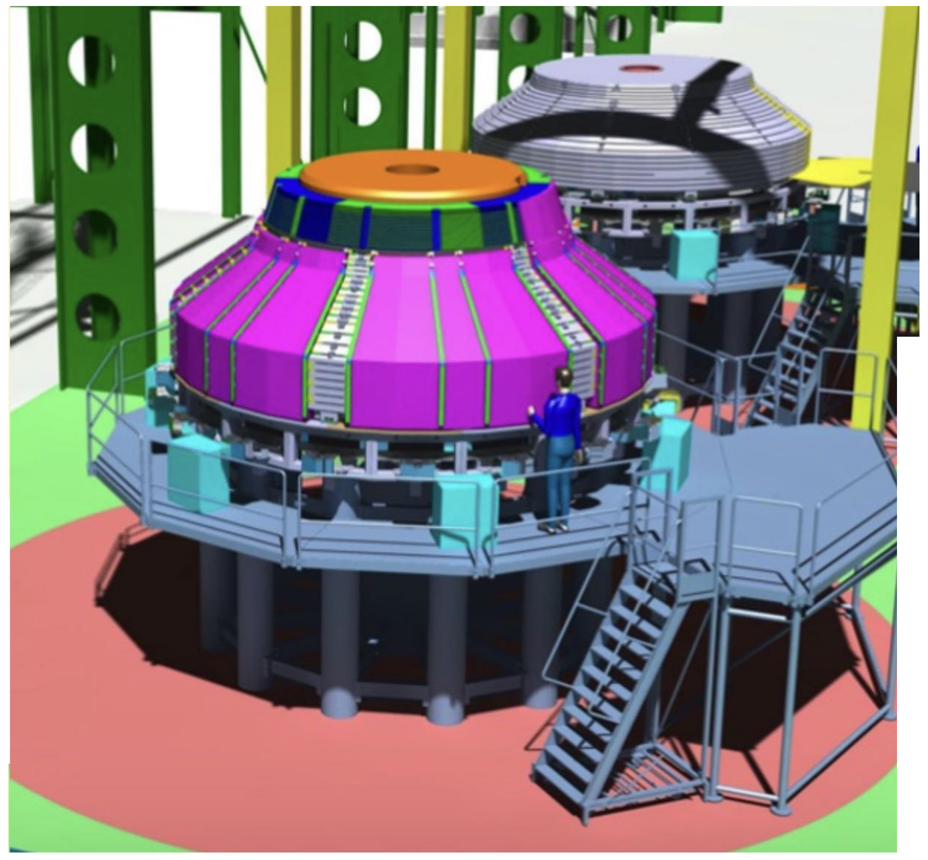
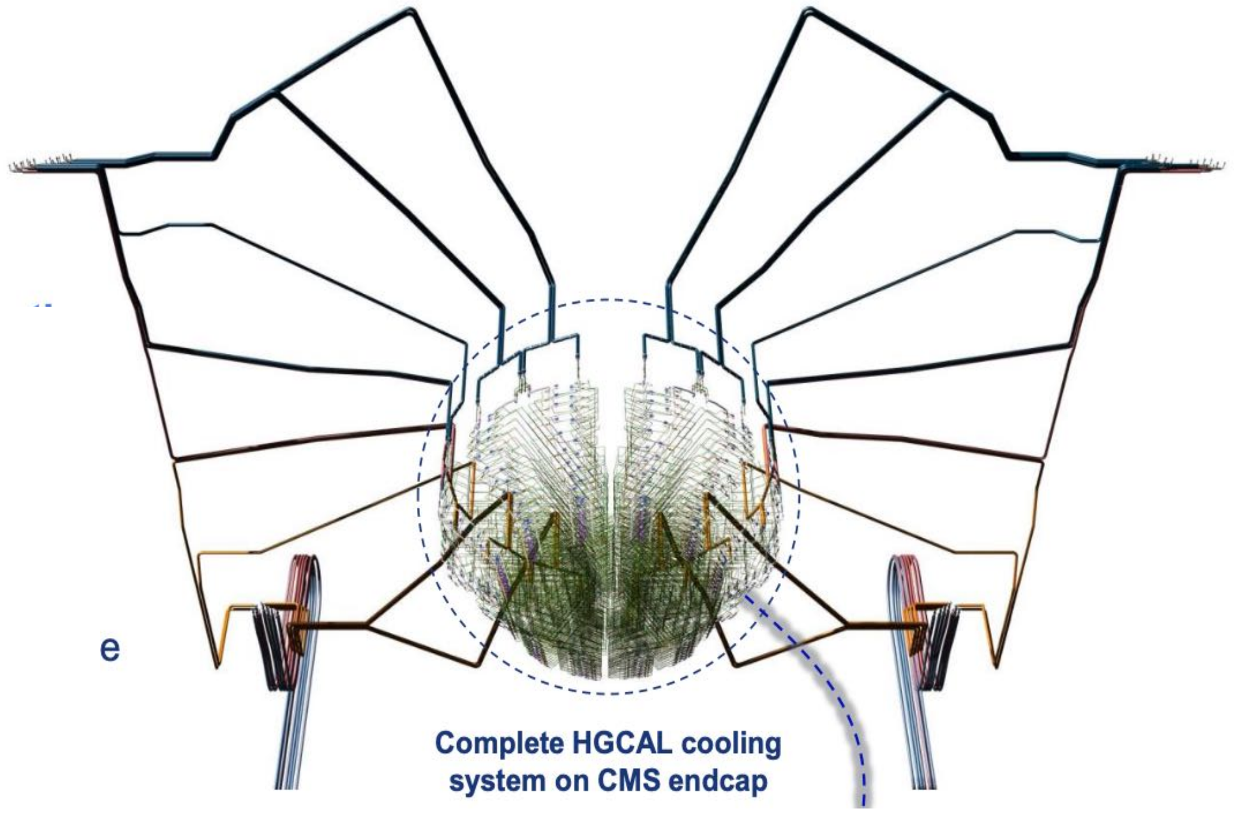


Engineering challenges:

- High precision / density / mass;
- Electronics integrated into each layer;
- Warm-cold transition & services integration;
- Insertion tooling, constrained by fixed envelope;
- Lower 230t down into the cavern (-100 m underground).





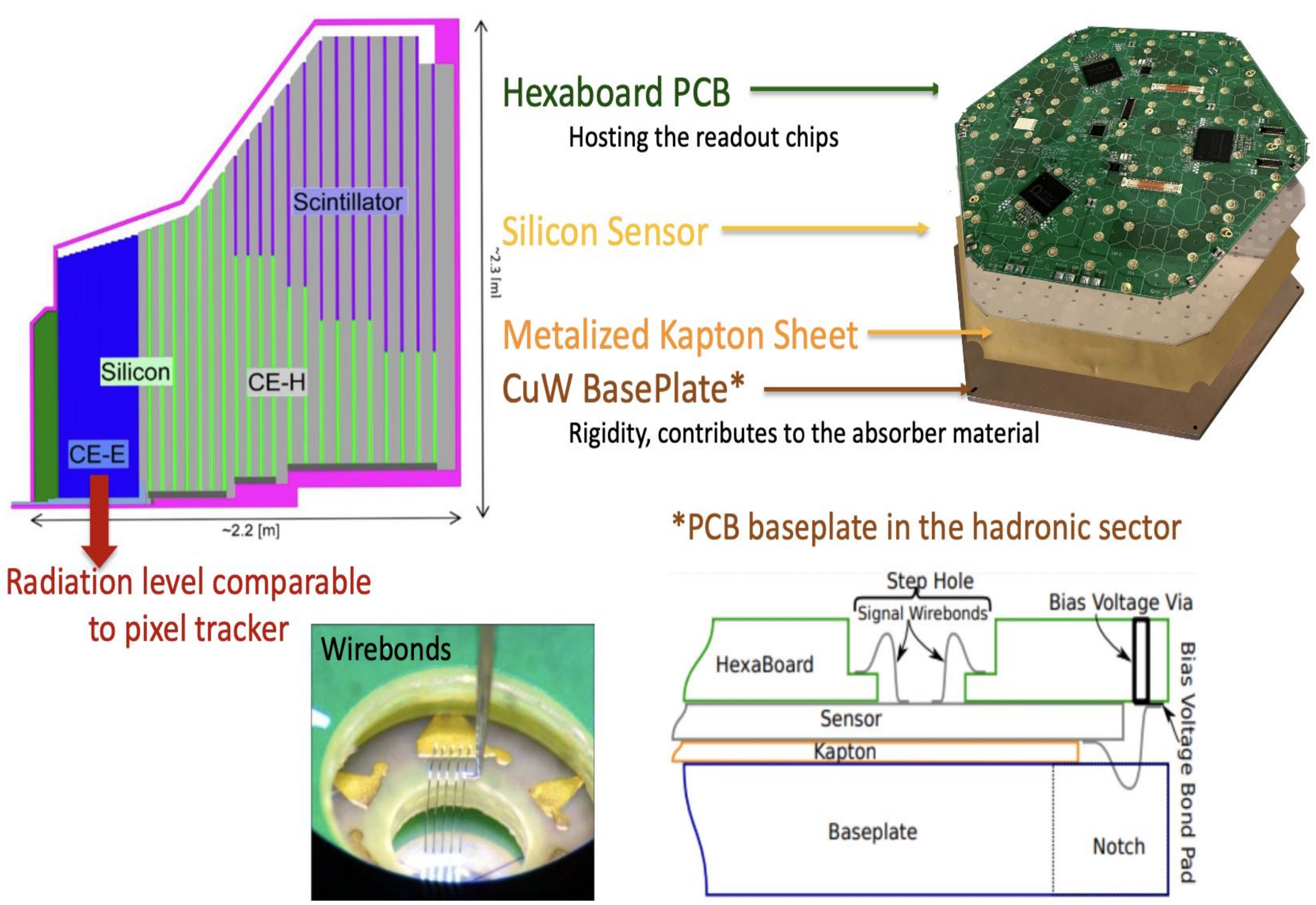
HGCAL Sensors

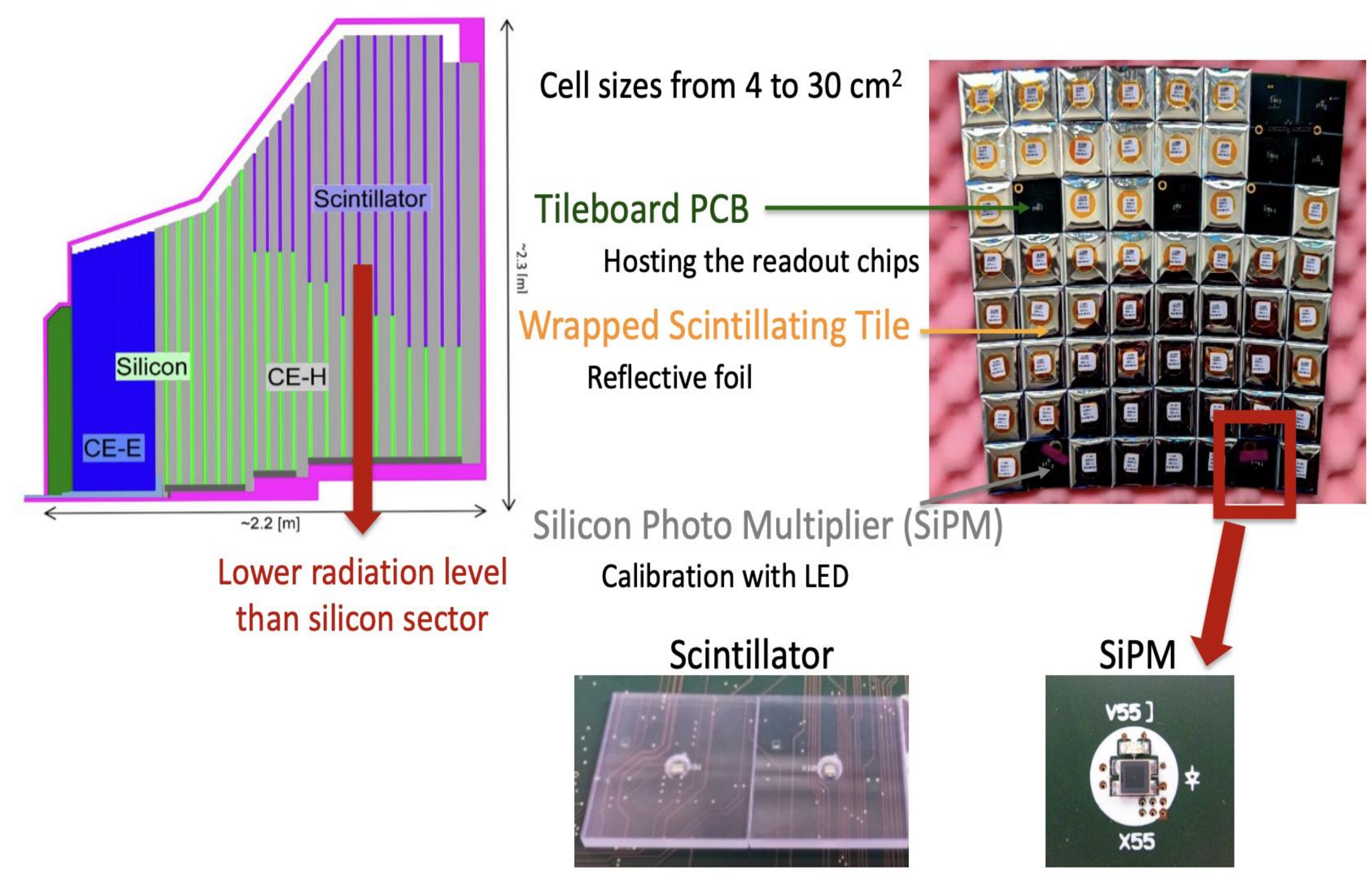
Active – Silicon:

- n-in-p pad hexagonal sensors with p-stop cell isolation
- Tiling of the endcap made with 8” hexagonal wafers
- Designed to ensure sufficient S/N for MIP calibration
- Cost-effective usage of wafer area enabling 600m2

Active – Scintillator (SiPM-on-tile):

- Ensure S/N>2.5 for detector lifetime in last 13 layers
- LED-based calibration foreseen at startup (rely on reconstructed muons throughout lifetime)
- In total 240k SiPMs/tiles in 3744 tile-modules





HGCAL Readout Electronics

HGCROC:

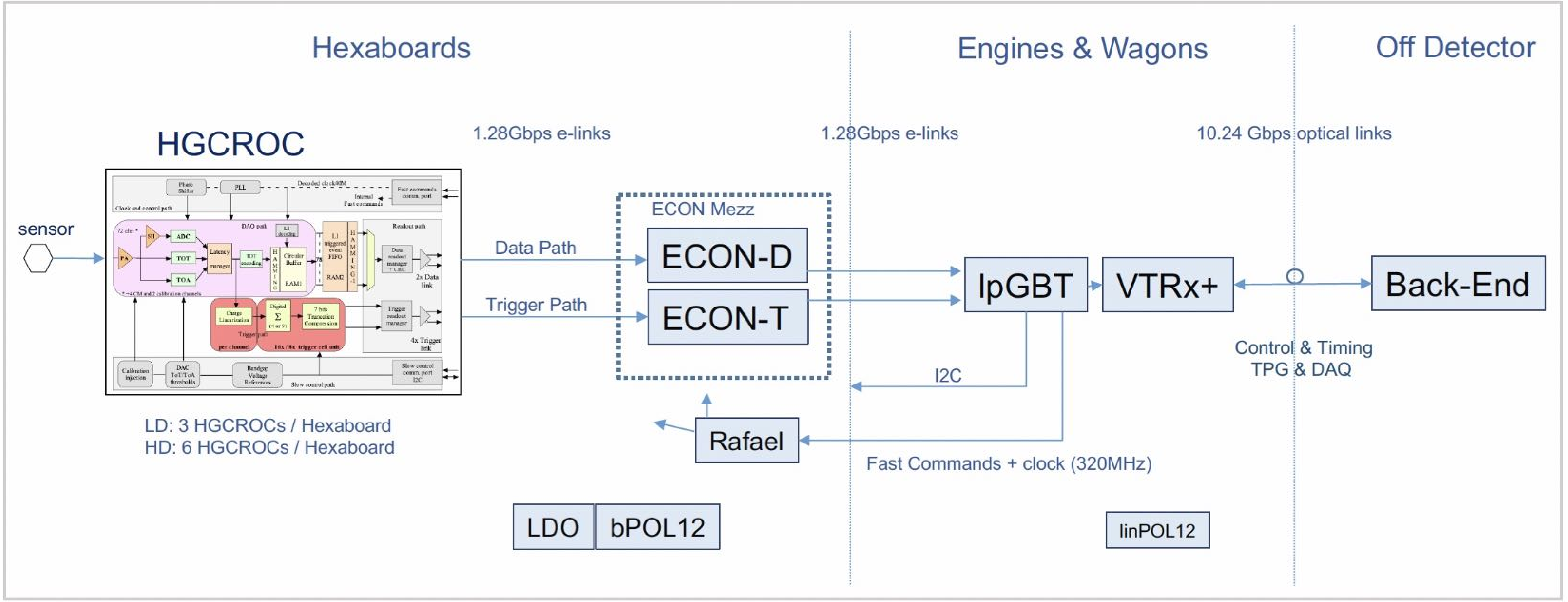
- Front-end ASIC for charge and time measurements
- Sync. control @ 320 MHz, latency up to 12.5 μs, trigger primitives @ 40 MHz

ECON-D/T:

- Data packets from HGCROC, zero suppression, transmission @ 750 KHz
- Select/compress trigger data, transmission every 40 MHz

Engines/Wagons/Off-det:

- Transmission to off-det, clock distribution, fast commands
- Custom FPGA-based boards, Receive data from VTRX+, transmit data to central DAQ.



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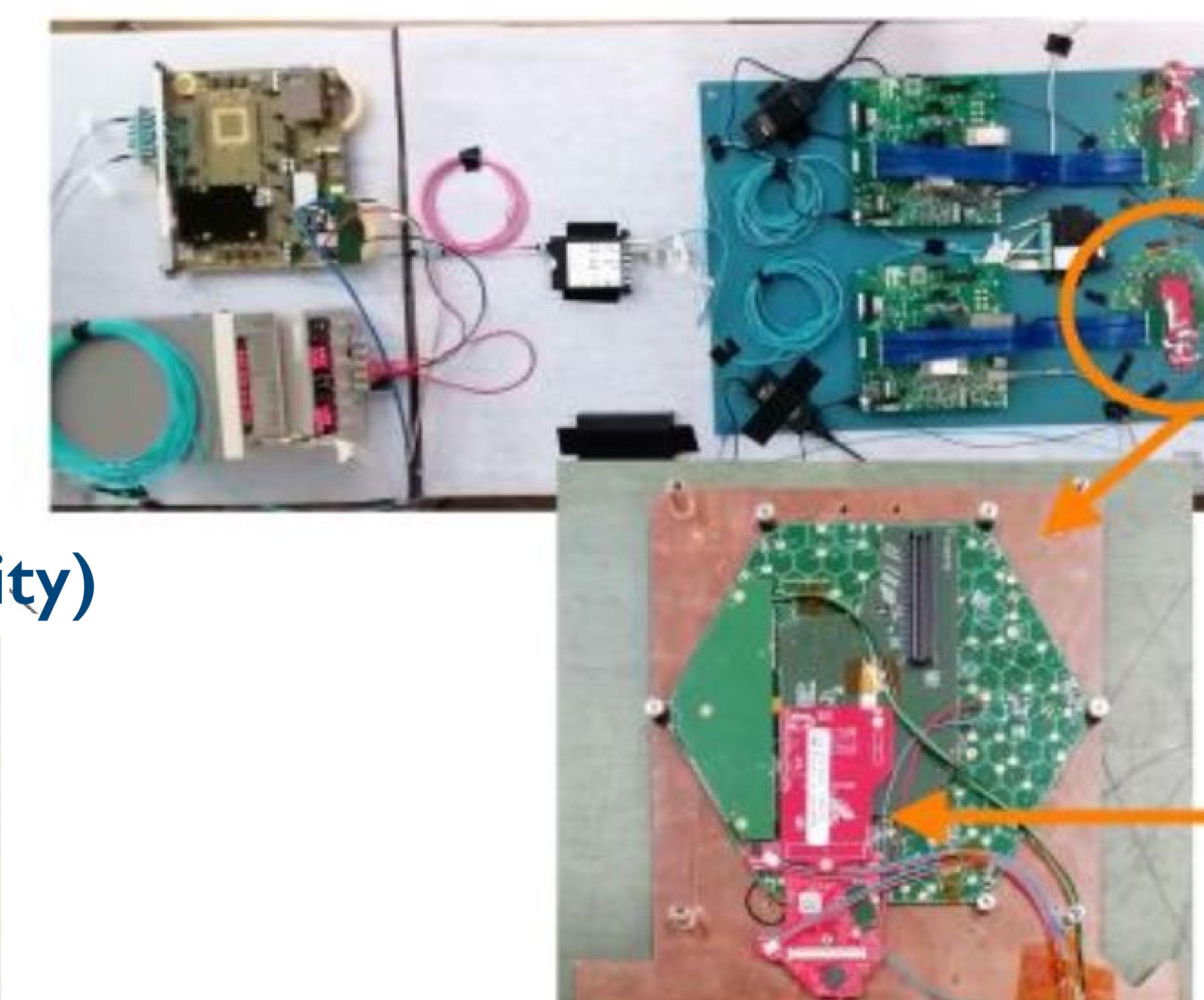
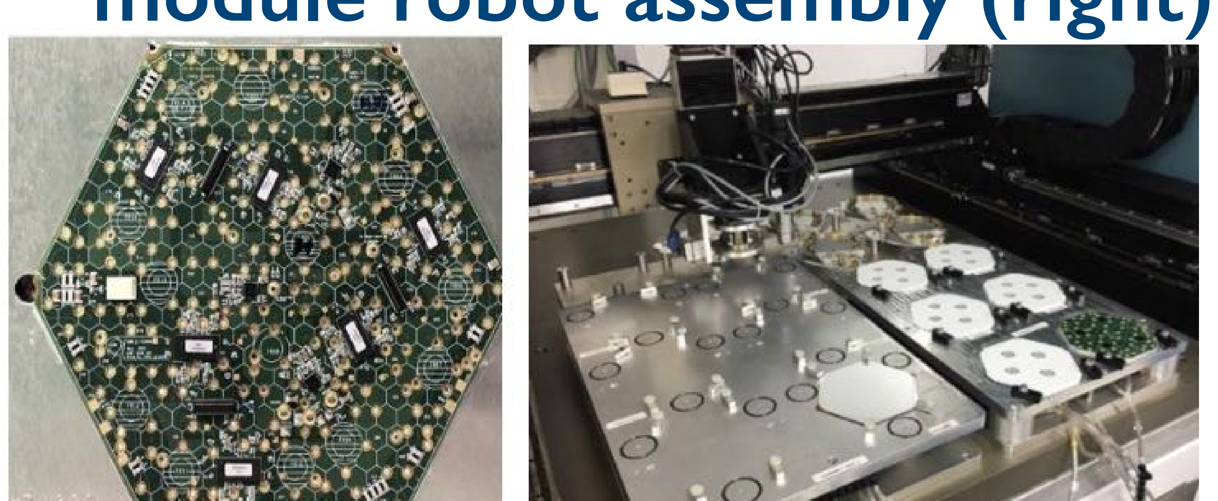
Final FE ASIC submitted (in BGA left)
trigger & data transfer ASICs in test (right)

Frontend system integration in beam tests in 2023

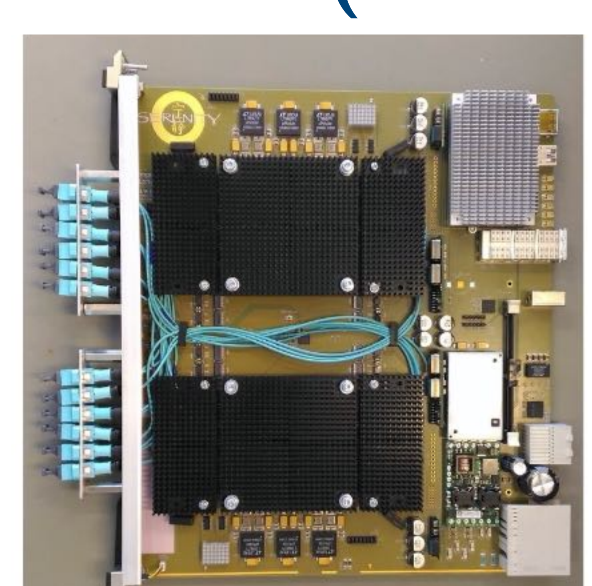


Engines & Wagons

Hexaboards pre-series on going (left)
module robot assembly (right)



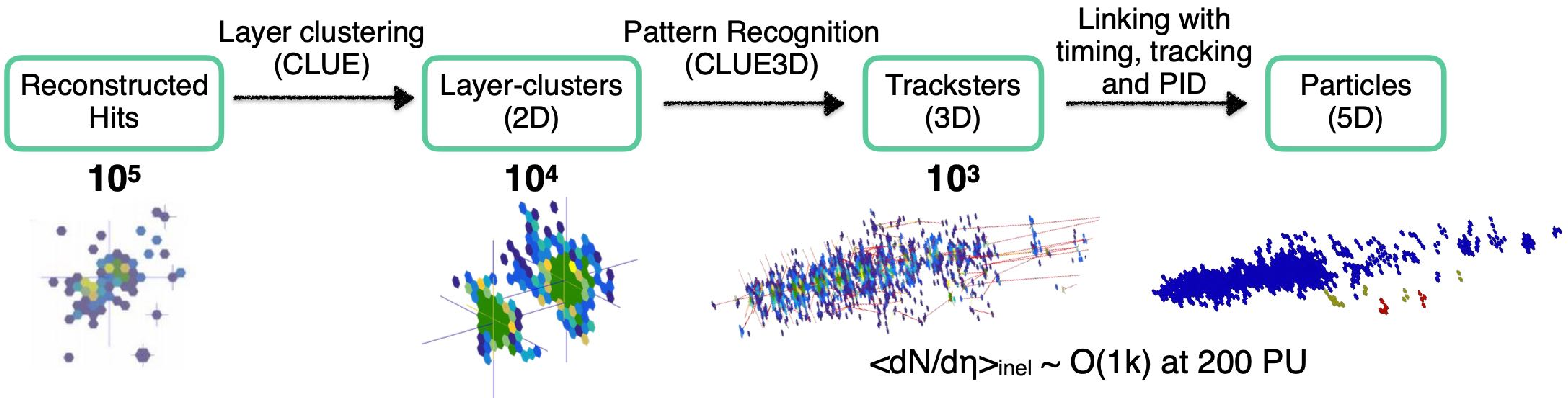
Back-End (Serenity)



HGCAL validation & performance

HGCAL reconstruction:

- **Particle showers reconstruction:** novel iterative clustering framework that exploits 5D information:

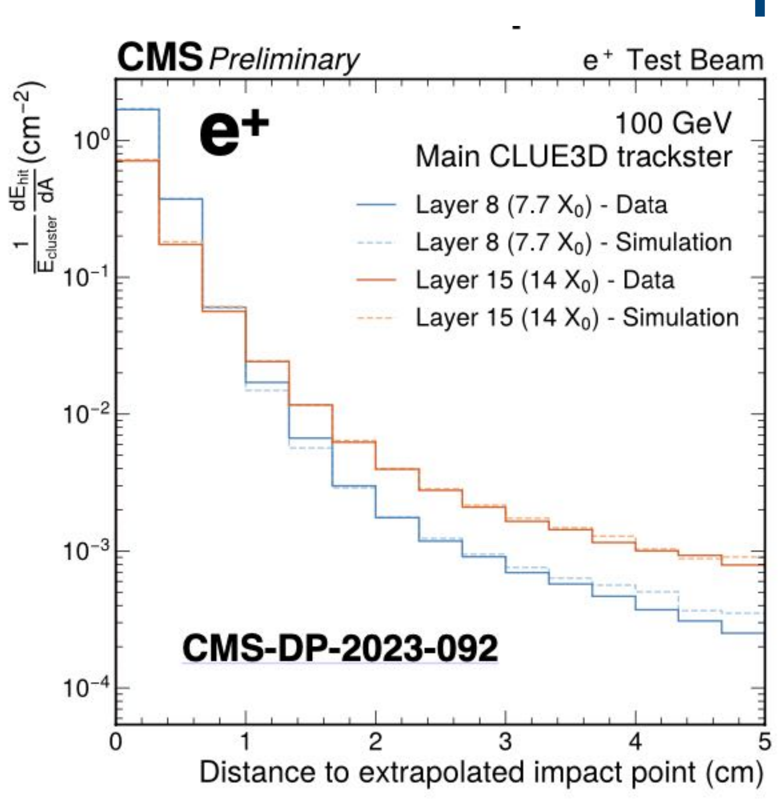


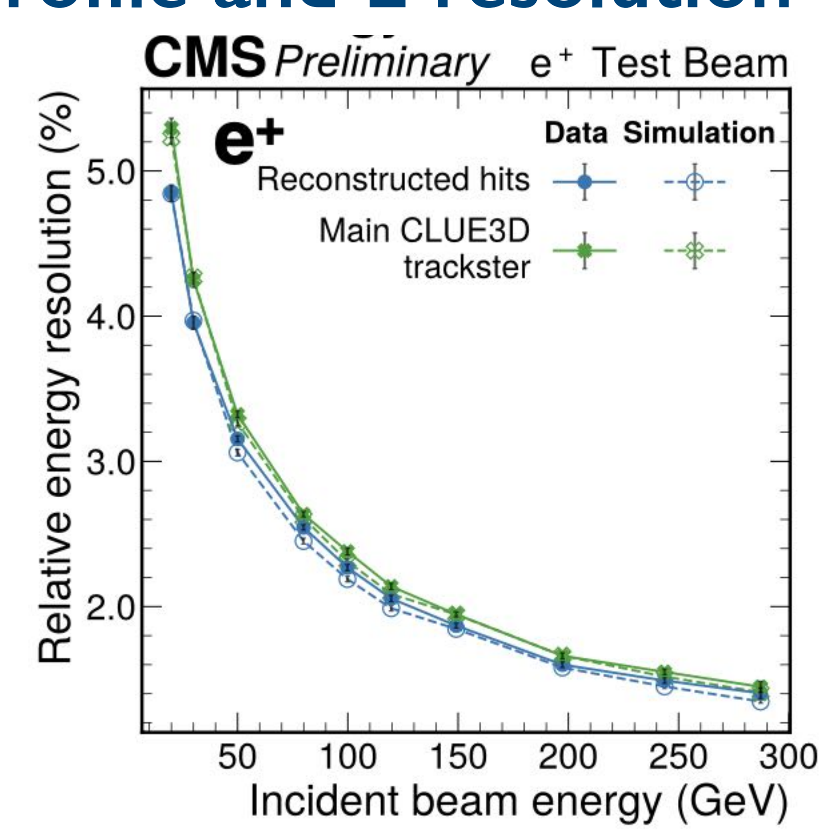
Energy estimation for pions based on Dynamic Reduction Network (DRN)

Performance and validation:

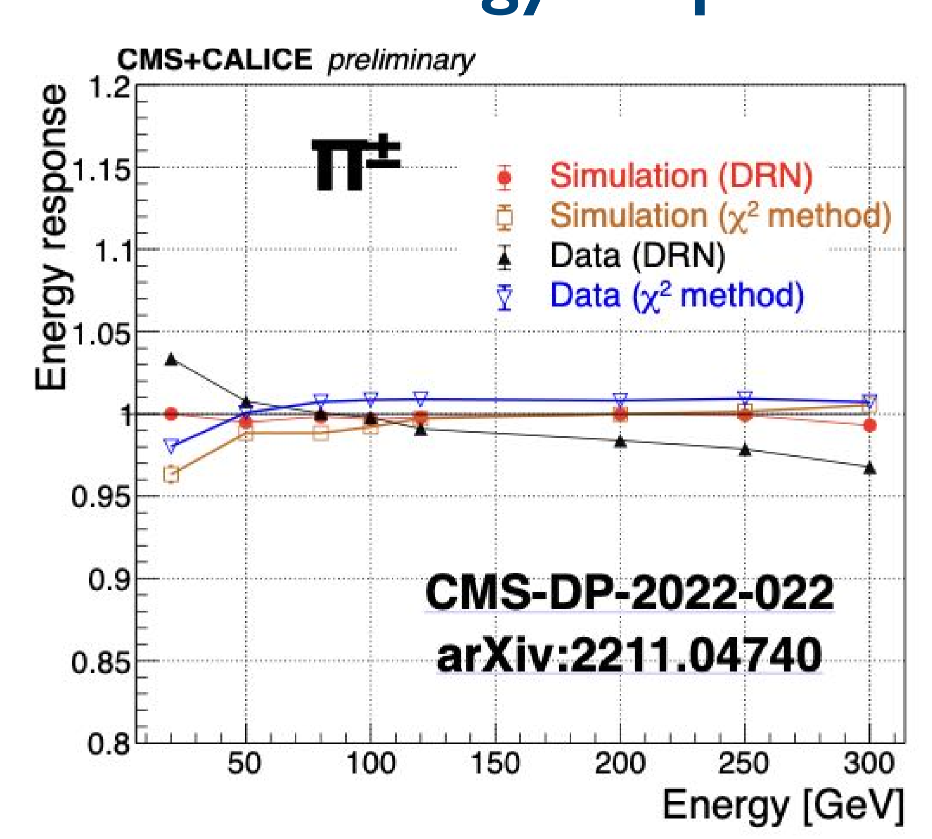
- Algorithms/methods developed using simulation and validated in test beams (e.g. positron/pion response):

Electrons: transv. profile and E resolution

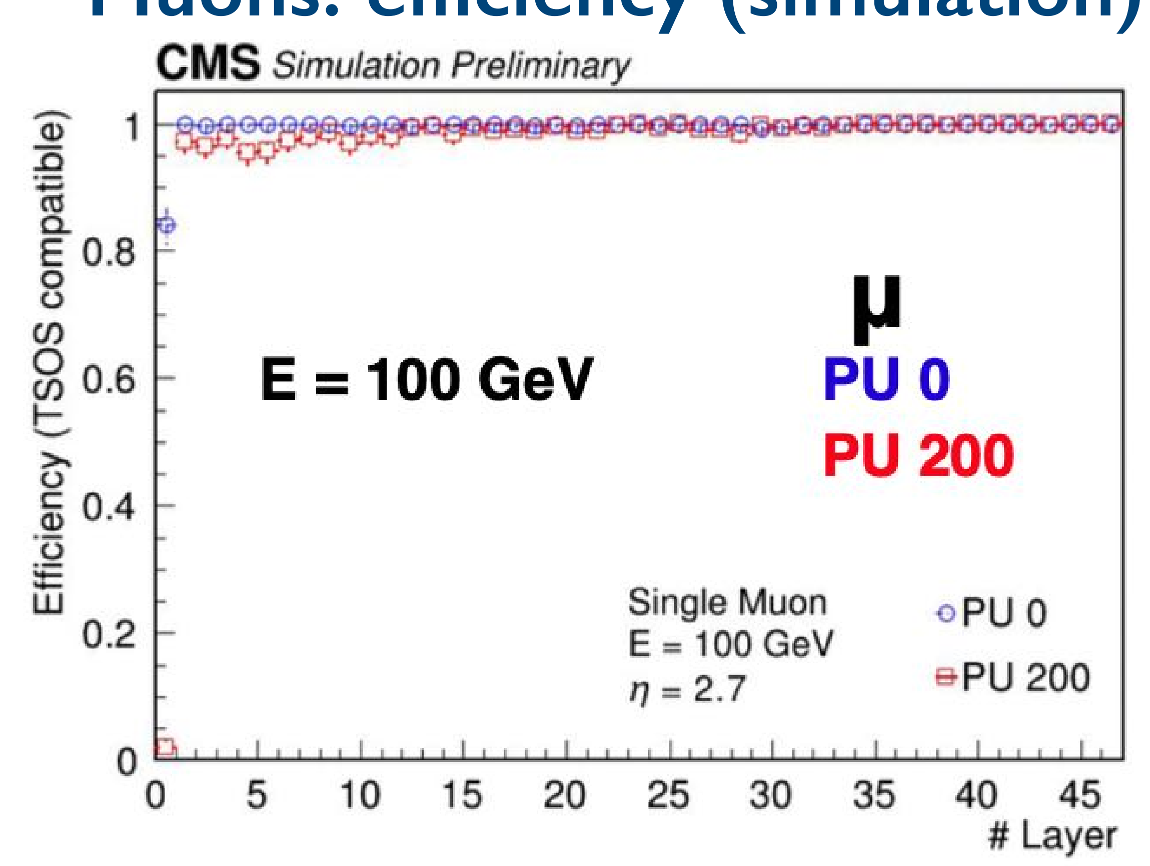




Pions: energy response



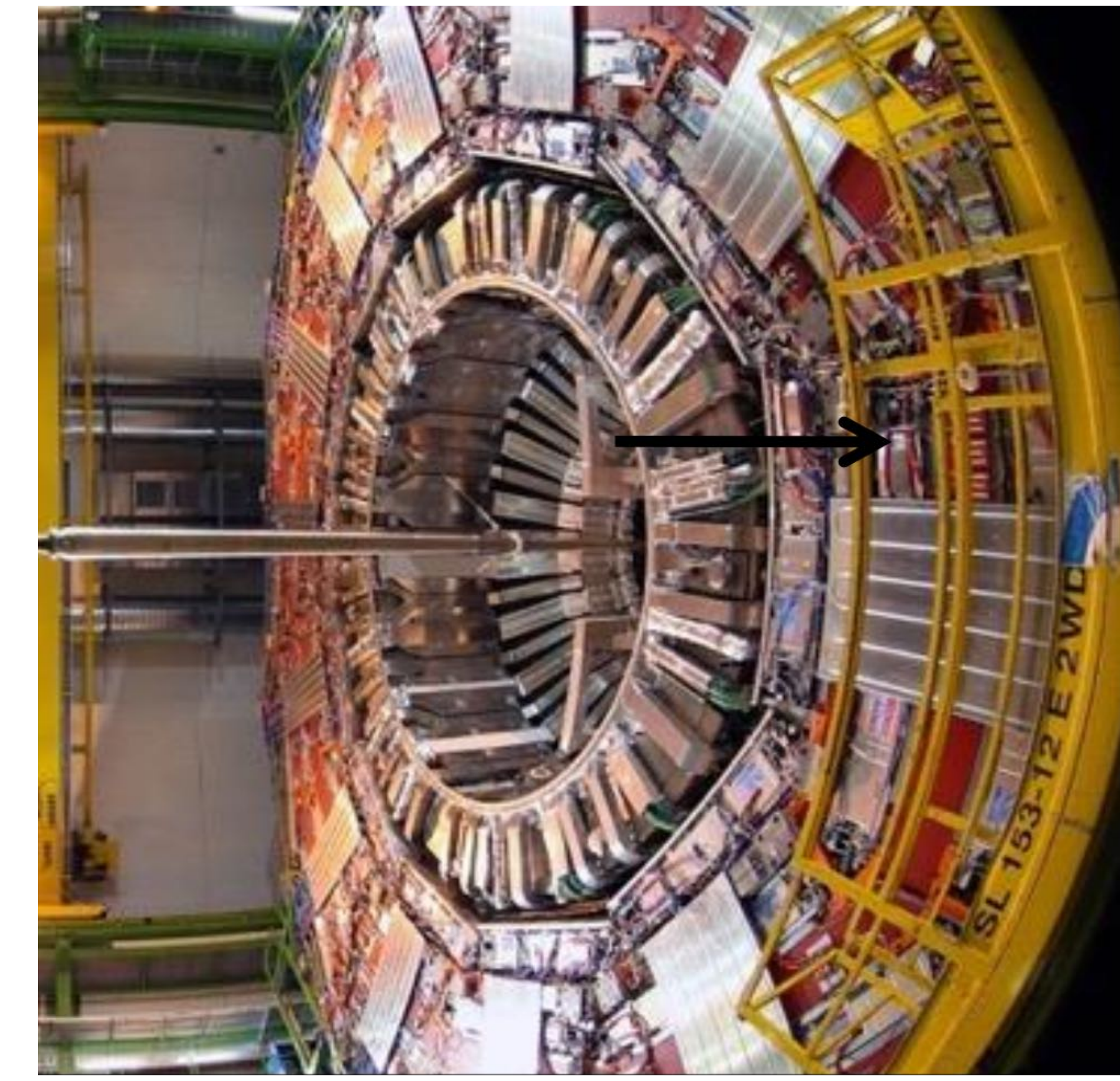
Muons: efficiency (simulation)



Instead of a summary

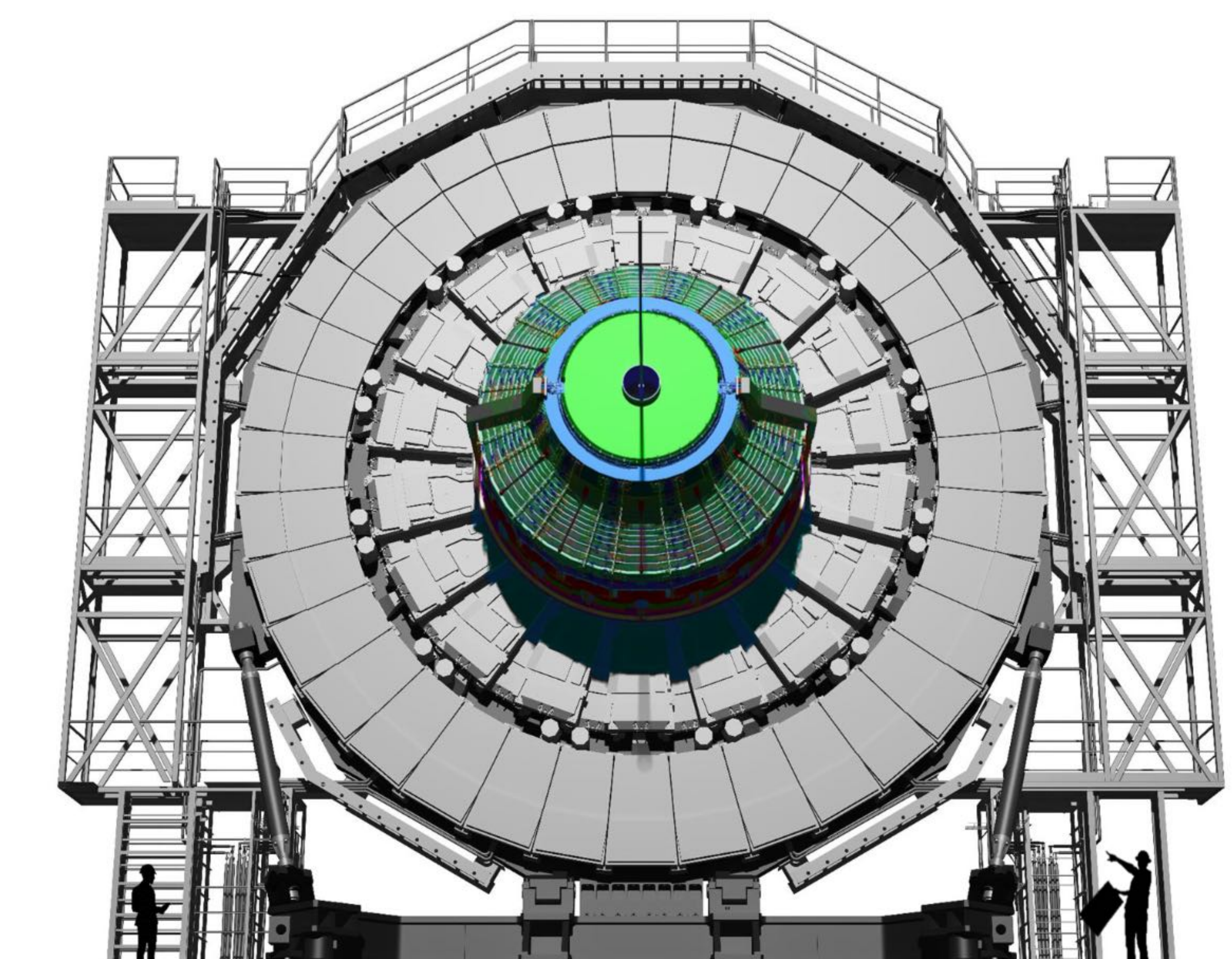
Challenges and potential of HL-LHC:

- HL-LHC expected to establish detailed topography of (the known) particle physics landscape
- Challenging conditions **impose important challenges to LHC experiments**.



CMS calorimeters for precisions calorimetry and timing:

- CMS detector was designed for **precision calorimetry**, and calorimeters performed well @ LHC; **HCAL Barrel already upgraded, ECAL Barrel will be upgraded for Phase-2.**
- CMS Endcap calorimeters will be replaced with a **cutting-edge HGCAL detector** for Phase-2, aimed at **high granularity and precise timing** for particle shower reconstruction.
- Upgraded CMS detector will bring **new capabilities and open new frontiers** for the LHC physics program!



> If your experiment needs statistics,
> you ought to have done a better experiment.
> E. Rutherford

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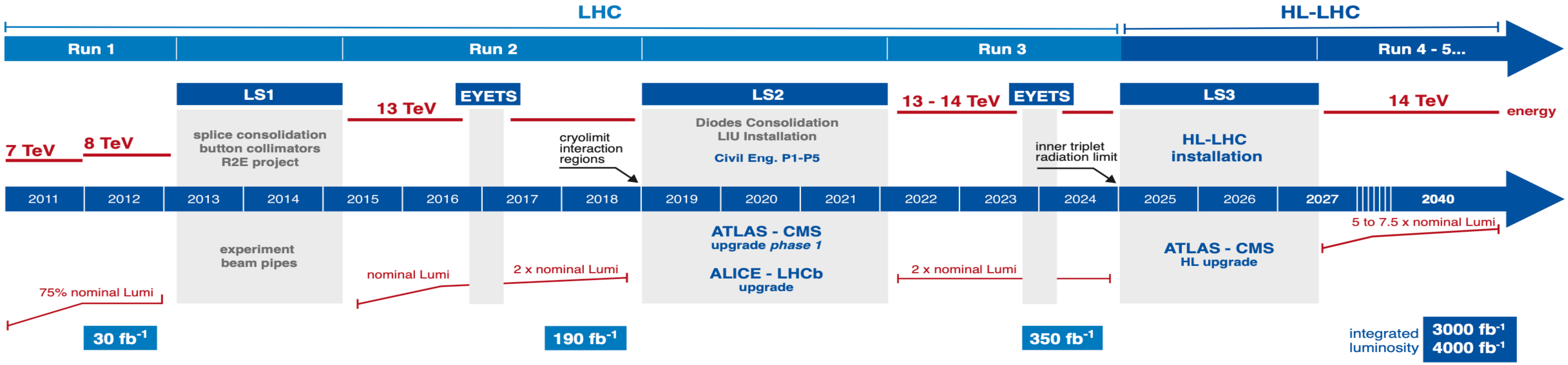
Additional material

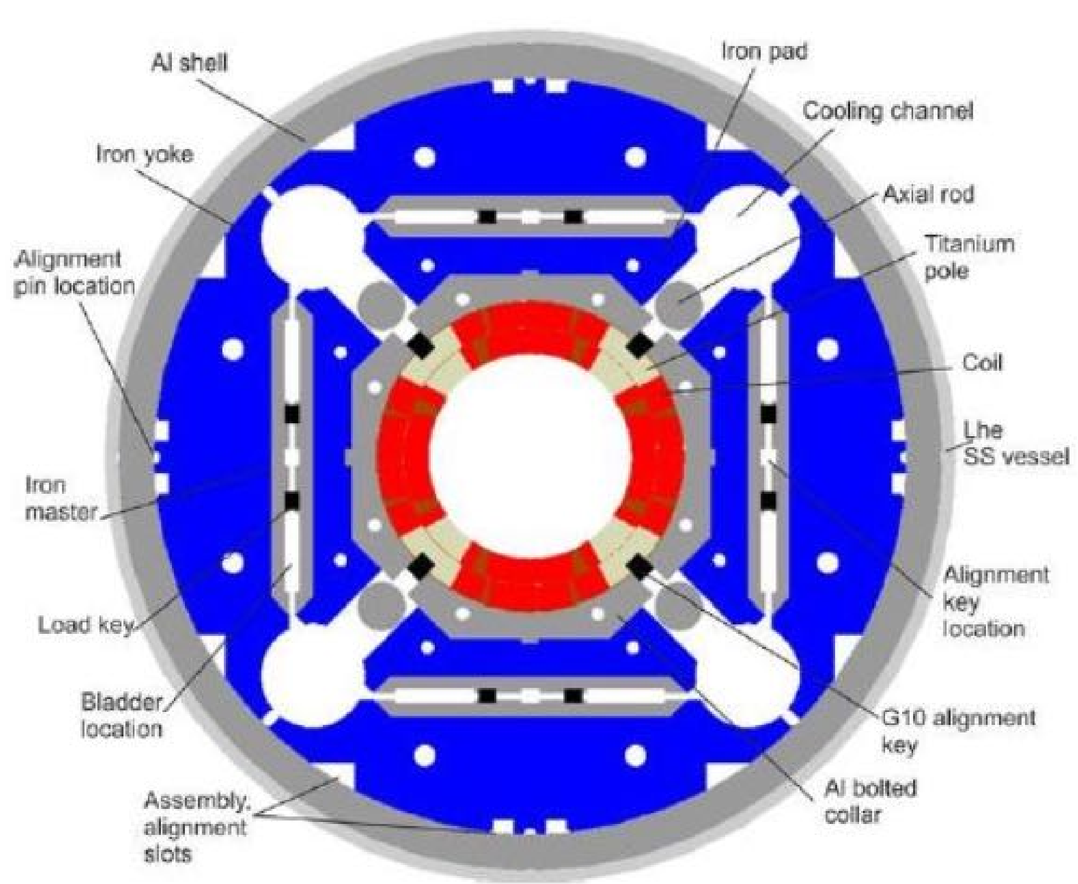
Towards the future: High-Luminosity LHC

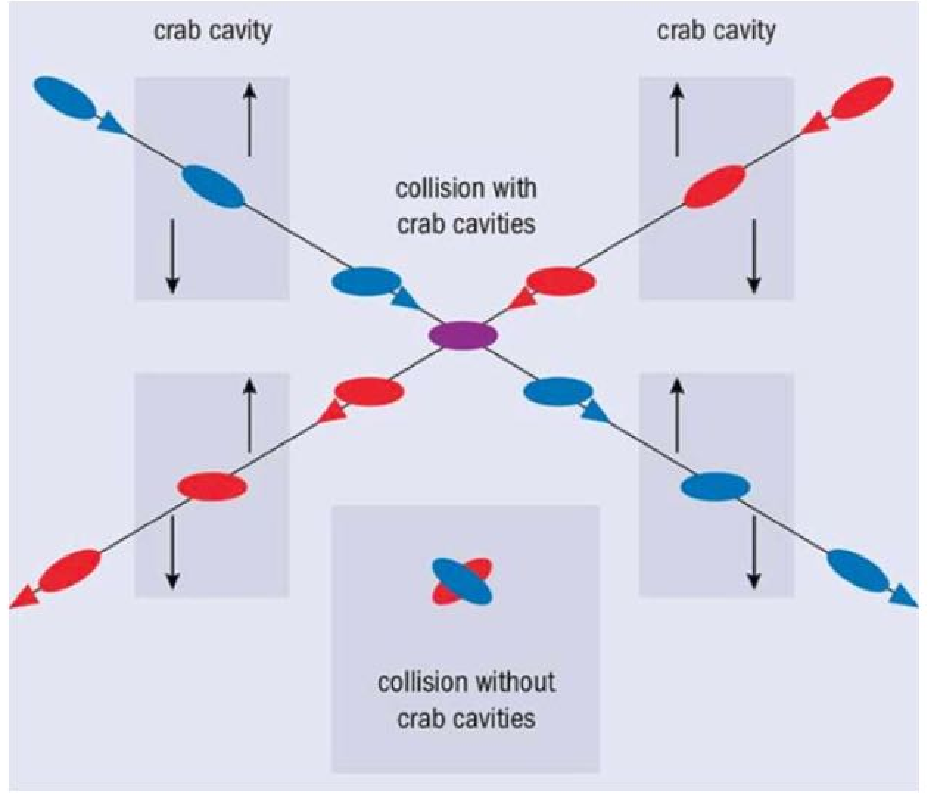
From the early discovery machine … to the Higgs factory and its full discovery potential



HL-LHC - essential changes to the machine:

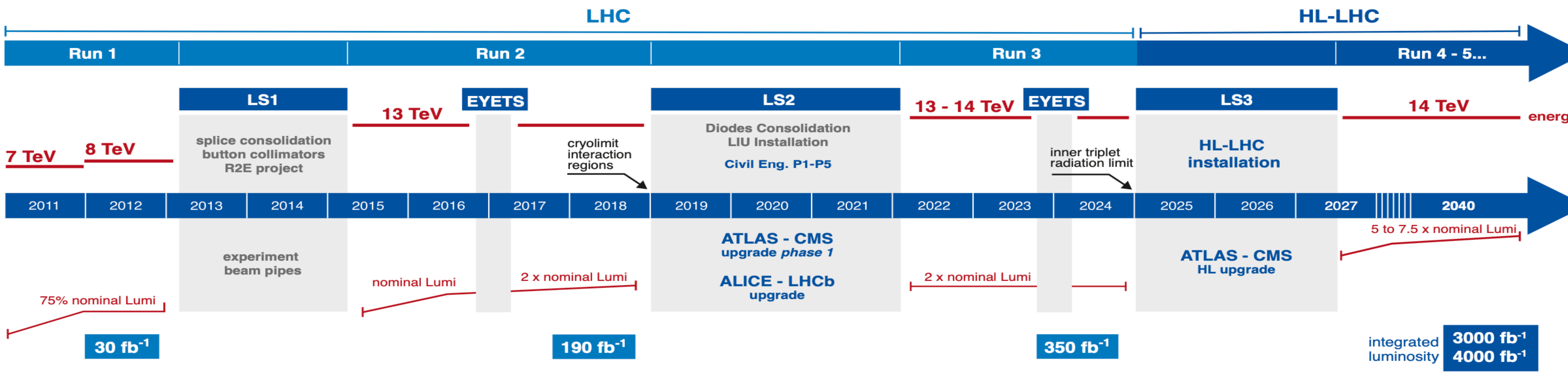
- Reduce β* at ATLAS and CMS. Achieved through new inner triplet made out niobium-tin superconductor.
- High bunch population, requires larger crossing angle. RF crab cavities are used to ensure a head-on collision.
-





Towards the future: High-Luminosity LHC

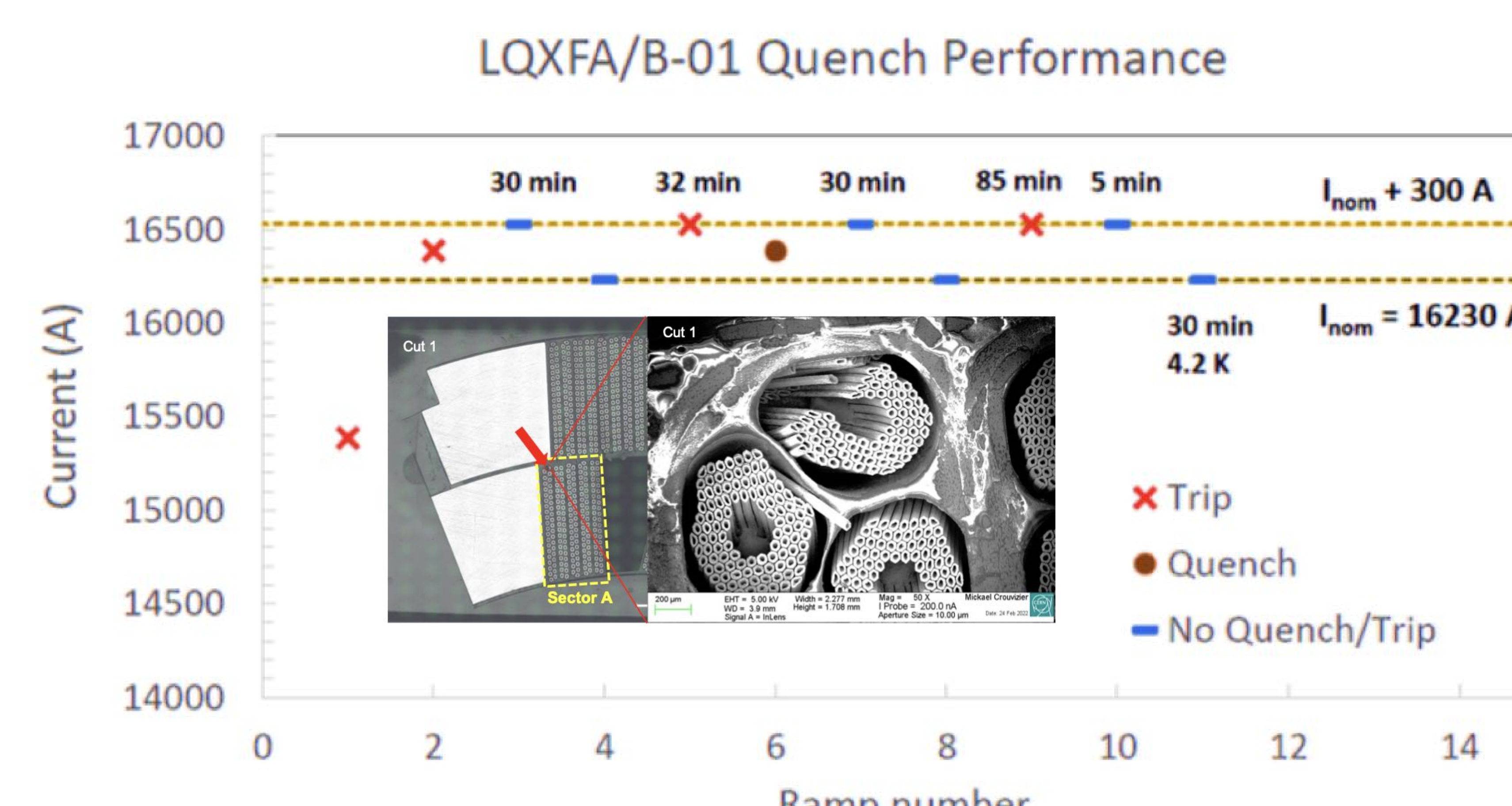
From the early discovery machine … to the Higgs factory and its full discovery potential



Latest new on HL-LHC implementation advancement:

- Significant progress on all fronts/tasks (including work on new superconducting magnet technology).
- Main civil engineering completed with only vertical cores remaining to be excavated.
-

Civil engineering progress



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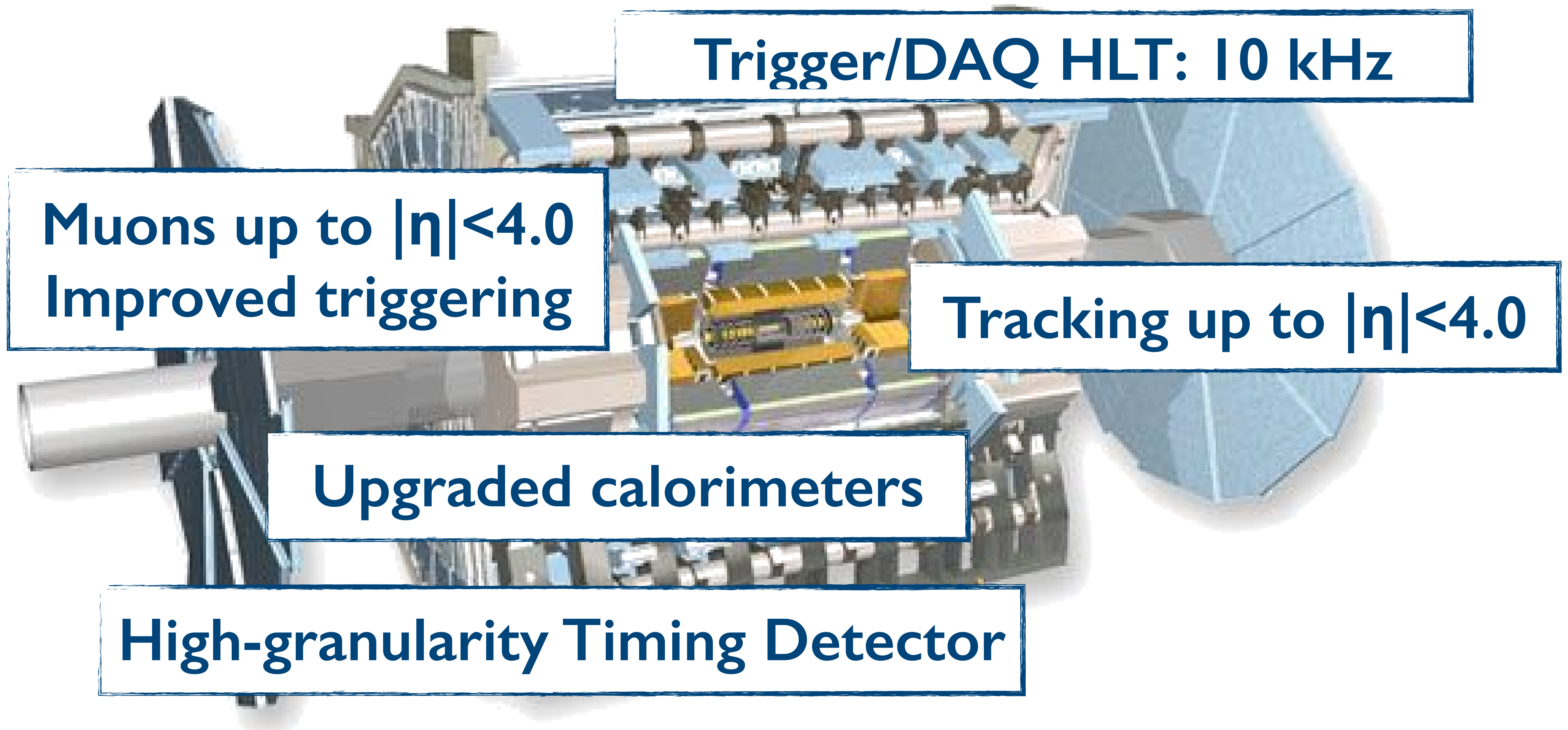
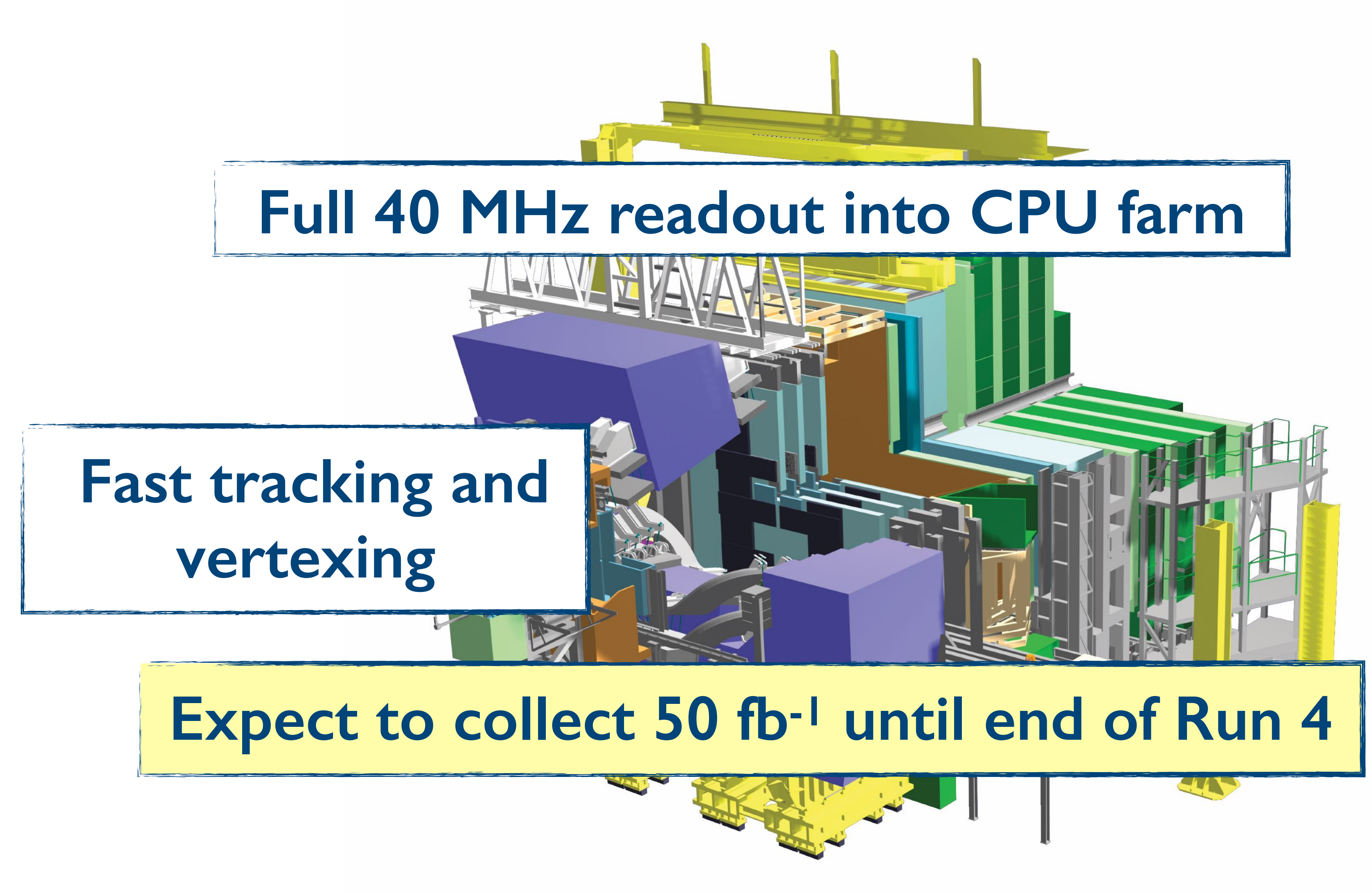
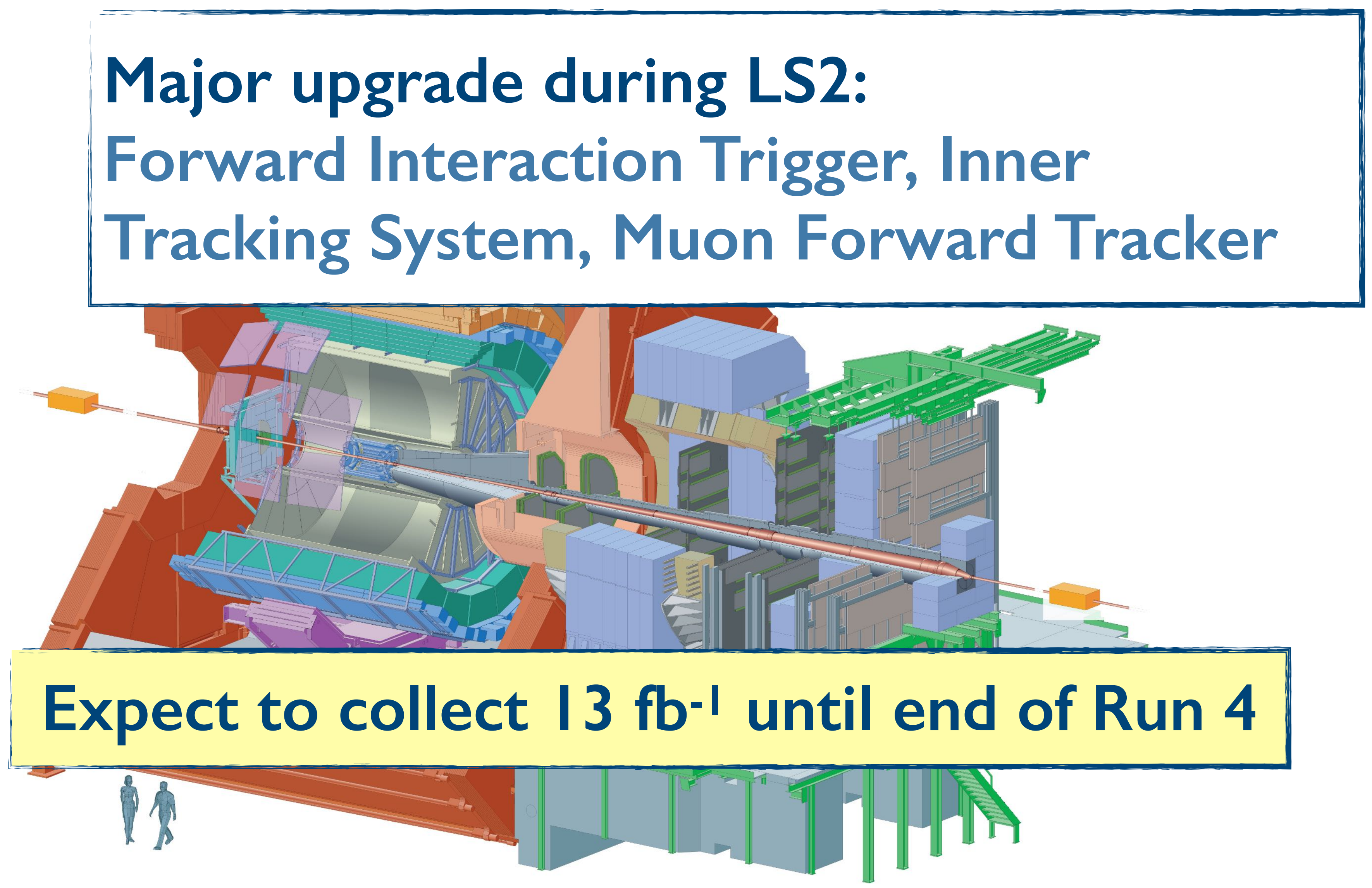
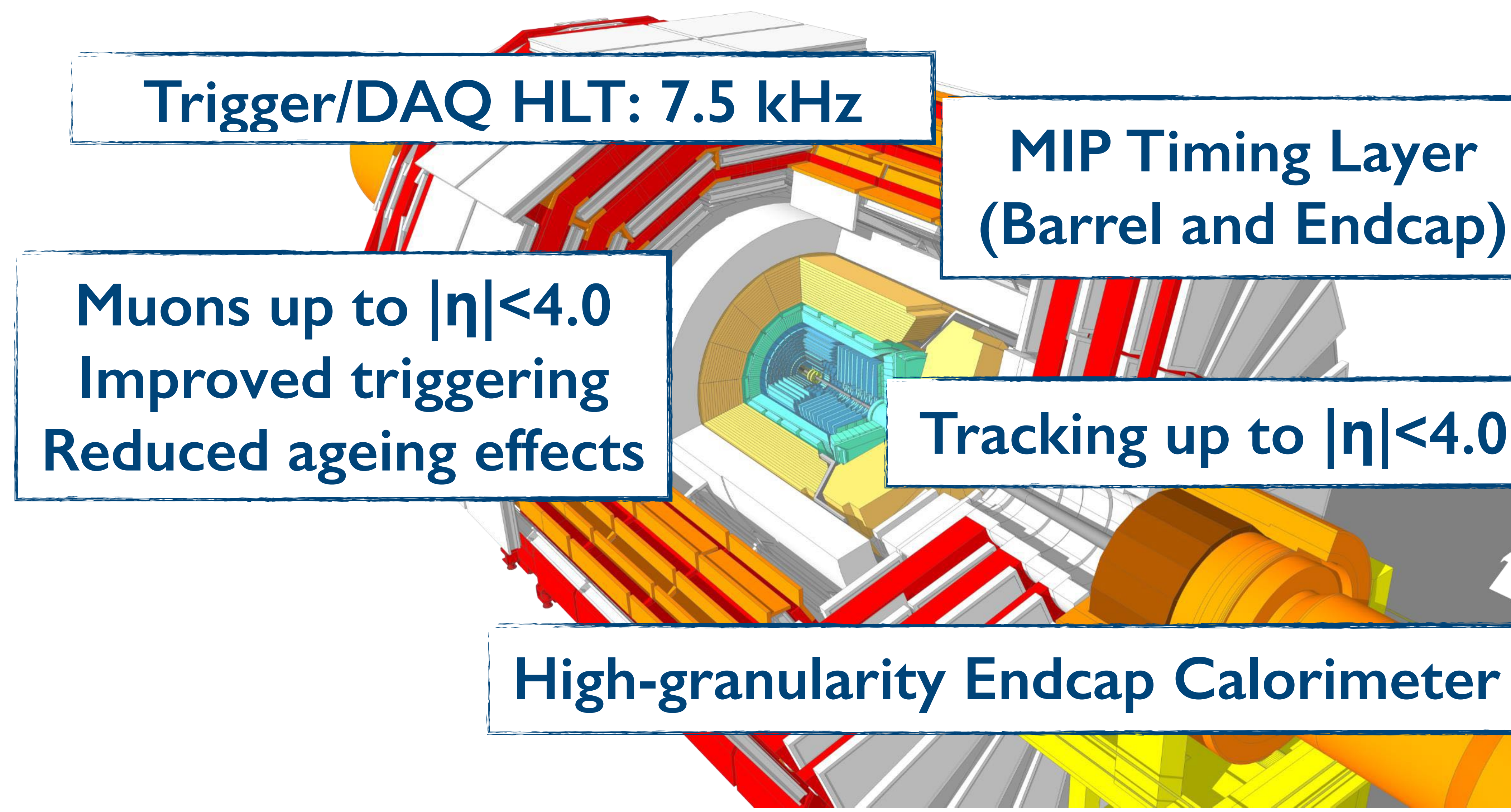
Upgraded detectors @ HL-LHC









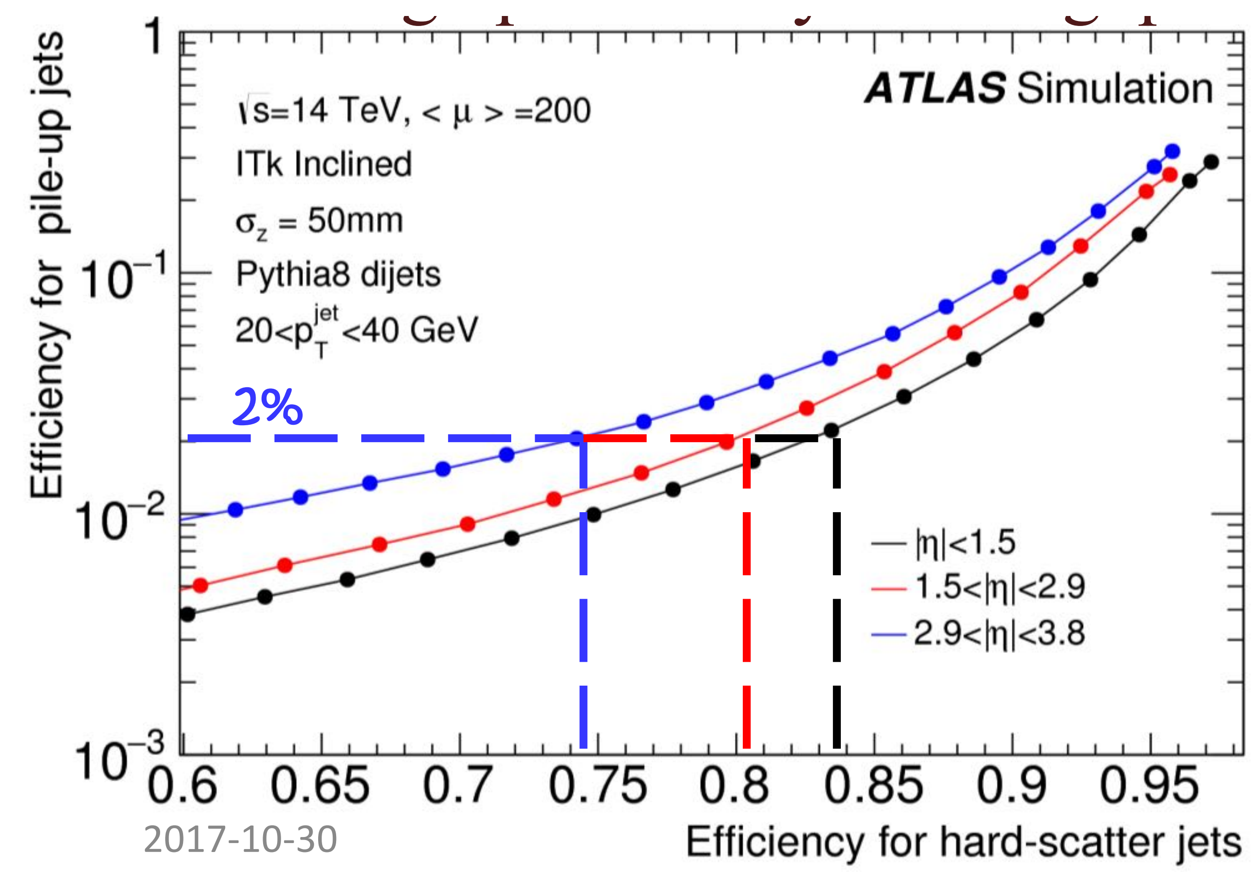
Experiments' TDRs

Detectors performance @ HL-LHC

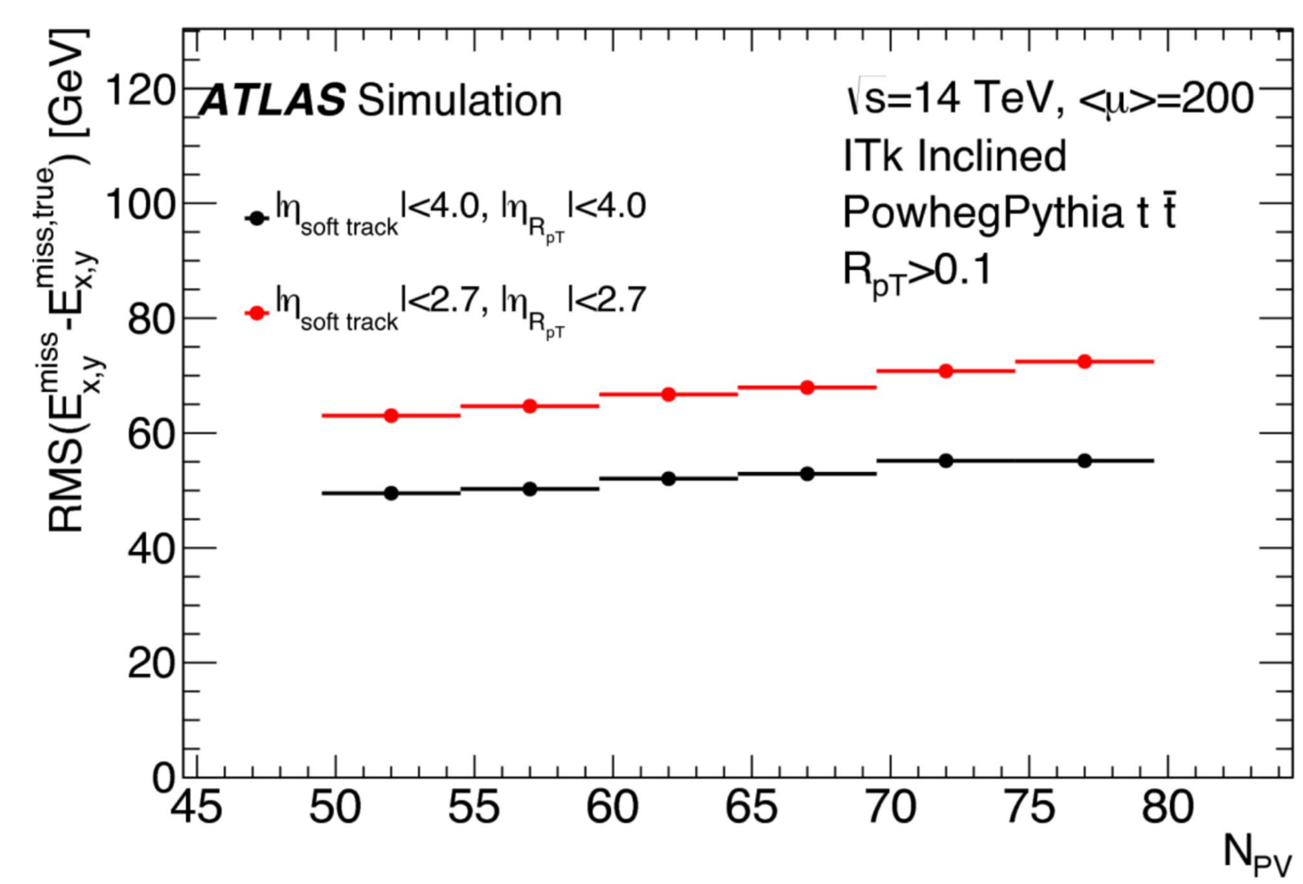
Detector performance after Phase-2 upgrades:

- Effective pileup mitigation
- Overall performance similar or better than during Run 2
- Extended capabilities with new algorithms

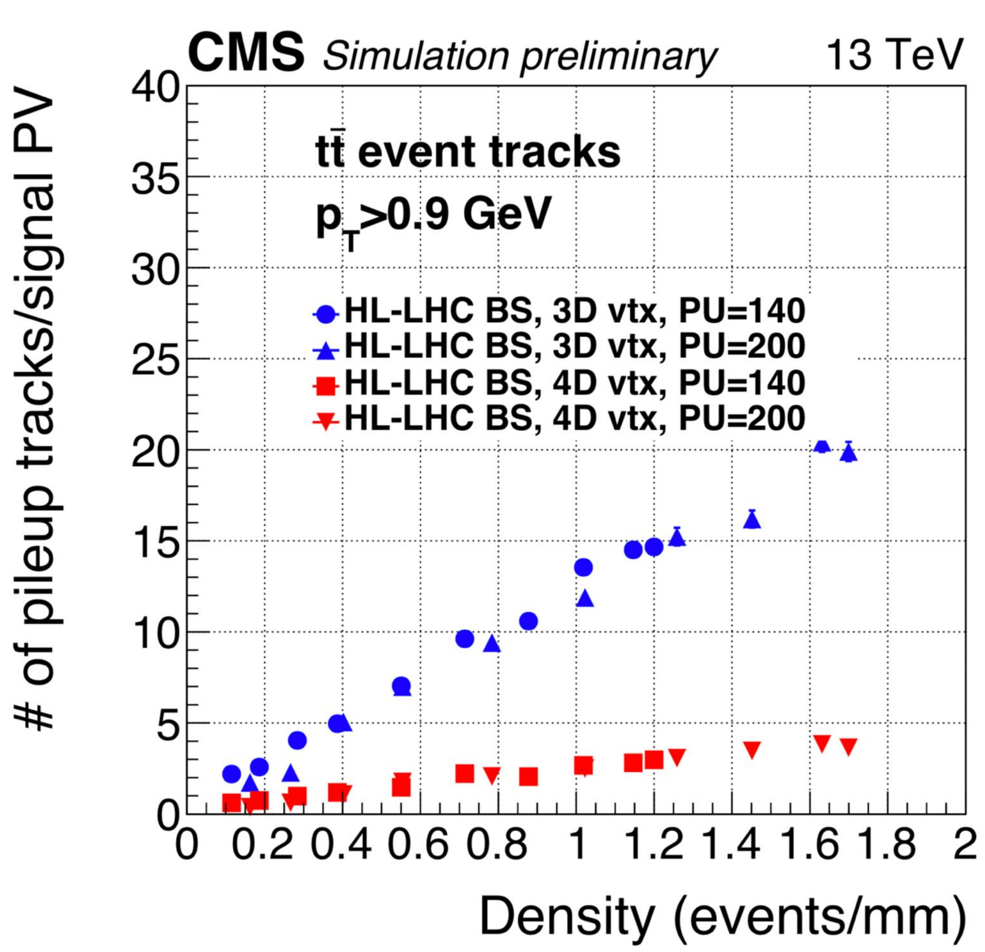
Jets



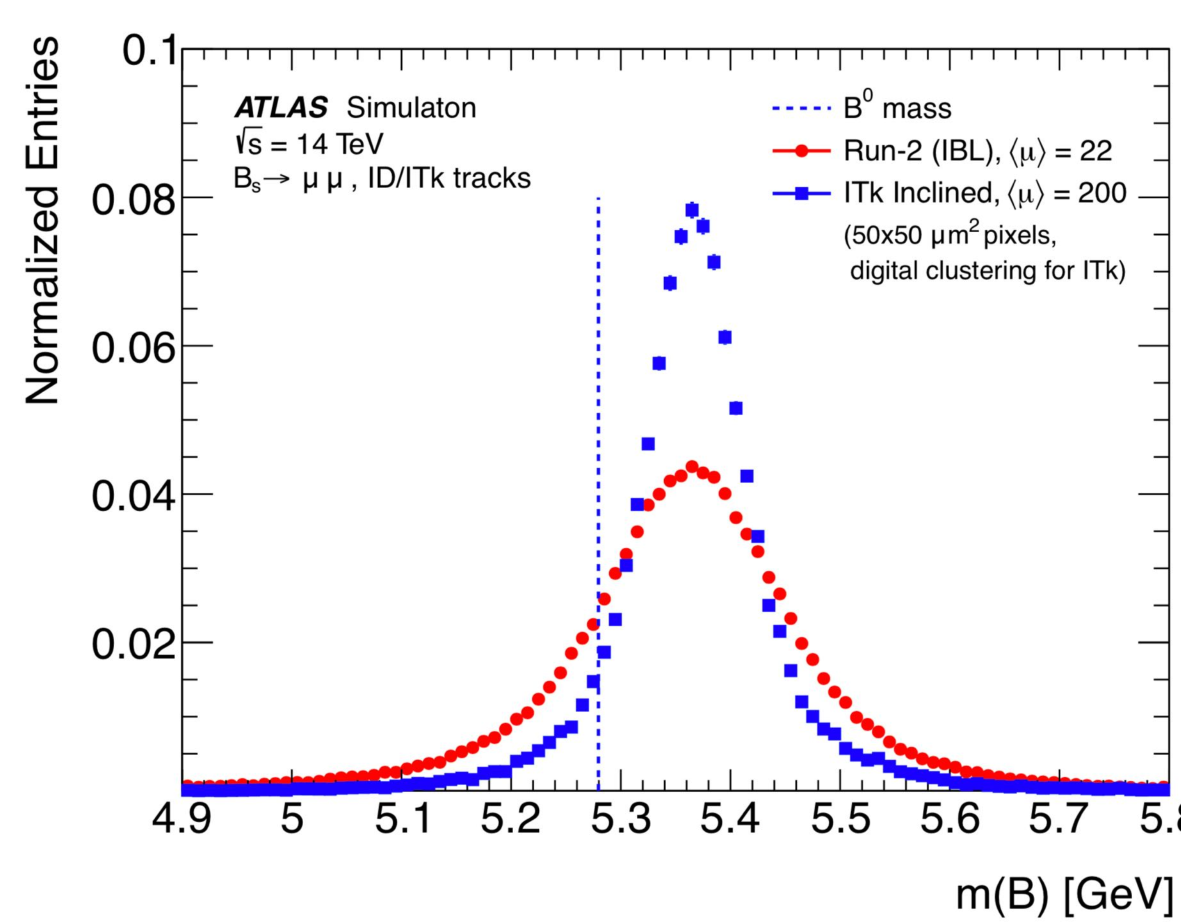
MET resolution



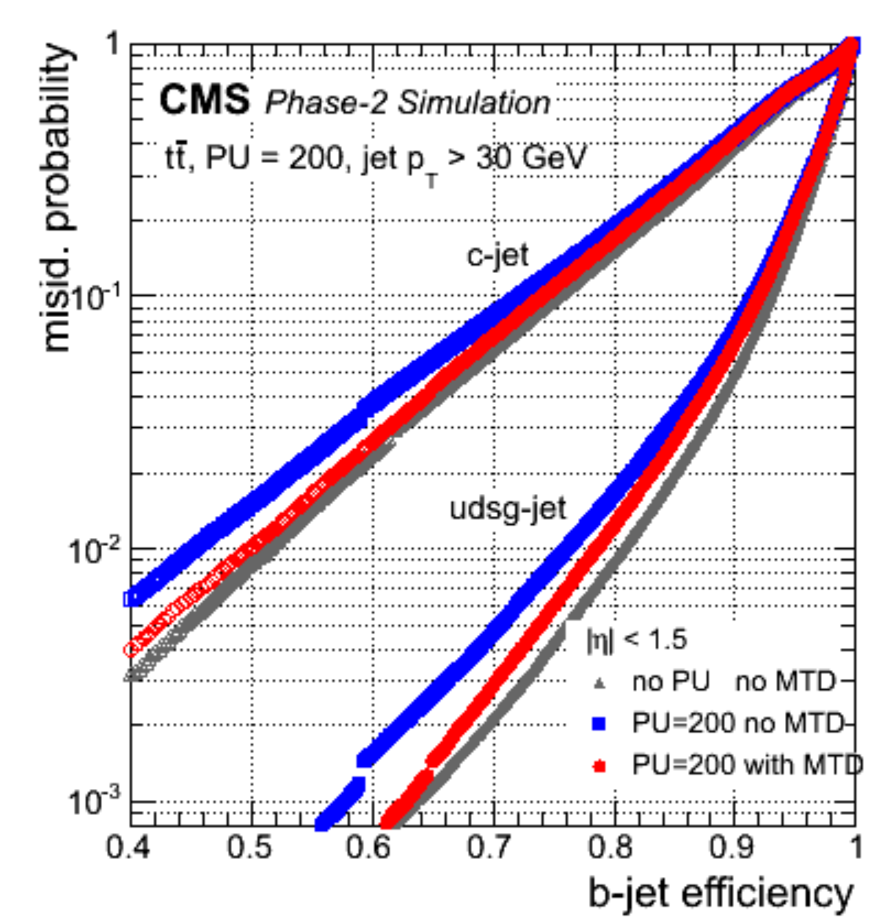
Pile-up suppression



Mass resolution



B-tagging



LHCb Vertex Locator