HGCAL detector performance and system validation with particle beams

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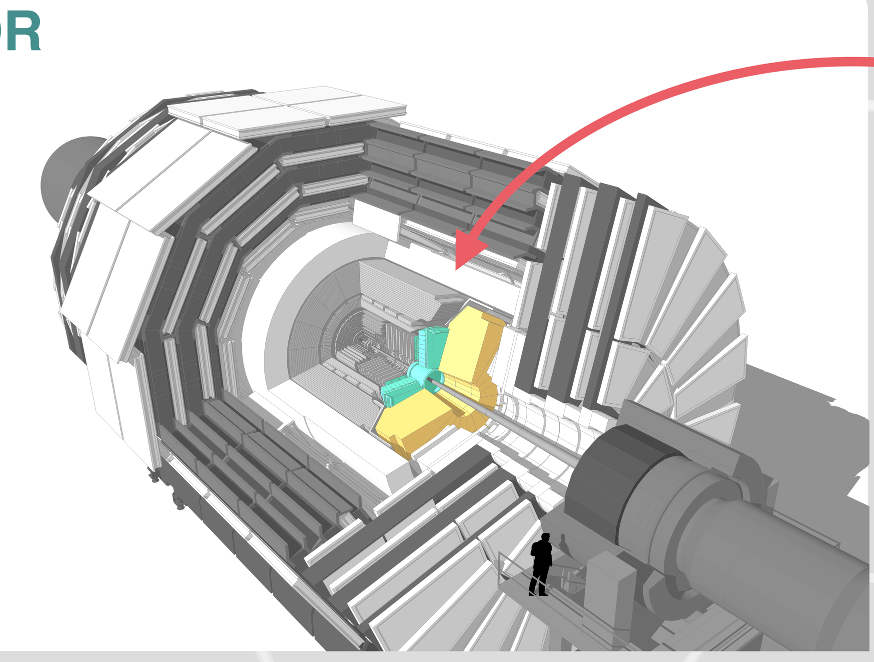
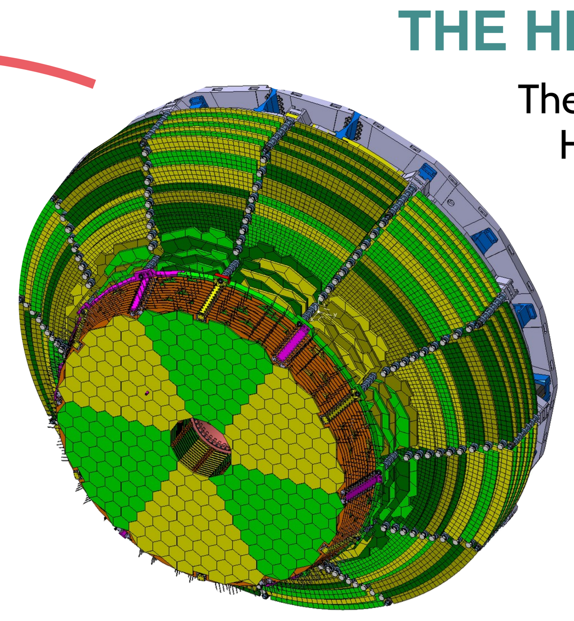
INTRODUCTION

THE CMS DETECTOR

The CMS (*Compact Muon Solenoid*) experiment, operating at the Large Hadron Collider (CERN, Switzerland), is a **multi-purpose detector**, consisting of sub-detectors nested around the interaction point of the LHC collisions. Their combined information is used to infer the **nature and properties of particles.**

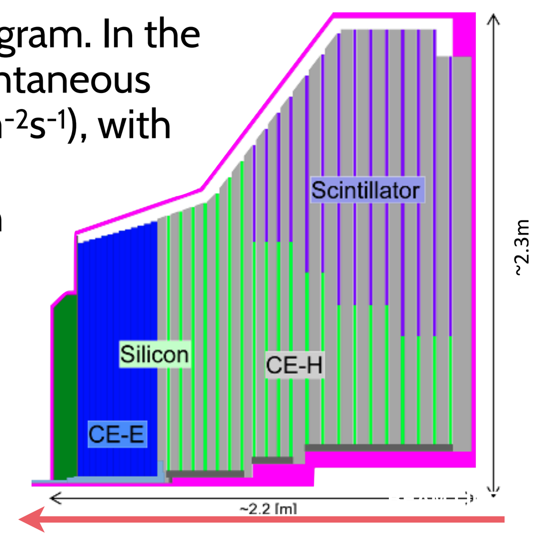


THE HIGH-GRANULARITY CALORIMETER (HGCAL)



The ongoing Run3 will conclude the first phase of the LHC program. In the HL-LHC phase, the accelerator complex will deliver an instantaneous luminosity up to 7.5x larger than the design value (10^{34} cm^{-2}s^{-1}), with typical pileup of 140-200.

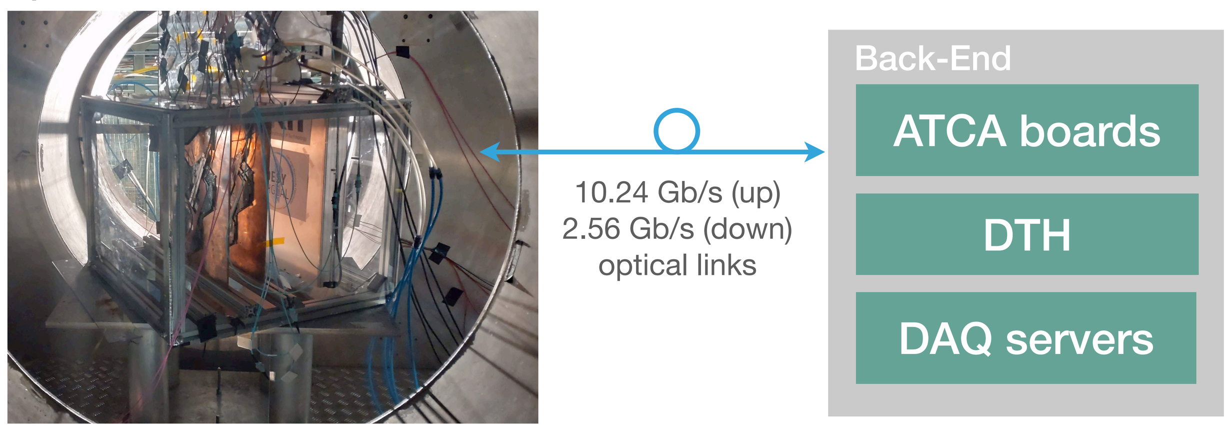
The **novel endcap calorimeter**[1] will be made of a silicon imaging section and silicon+scintillators hadronic section. The choice of the active materials reflects the need for **radiation hardness**,. The high **3D spacial granularity** (over 6M readout channels), together with **sub-nanosecond precision on timing timing reconstruction**, can be used to enhance the particle identification, energy resolution and pileup mitigation.



PERFORMANCE UNDER PARTICLE BEAMS

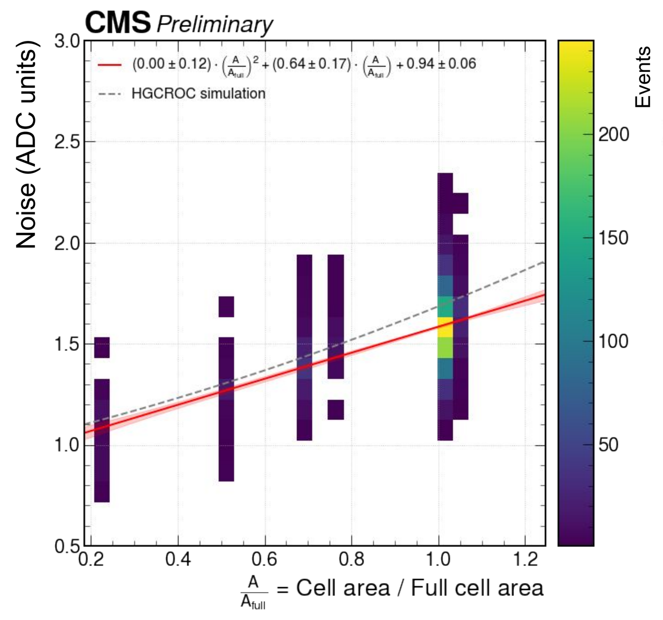
THE TEST BEAM SETUP

The latest test beam campaigns, carried out in 2024, featured a setup of two layers of multiple silicon modules and one of scintillators, read out by **close-to-final prototypes of the full vertical chain**. The detector prototypes were placed within a 3T magnetic field along the H2 secondary beamline branching from SPS (*Super Proton Synchrotron*, CERN)[2].

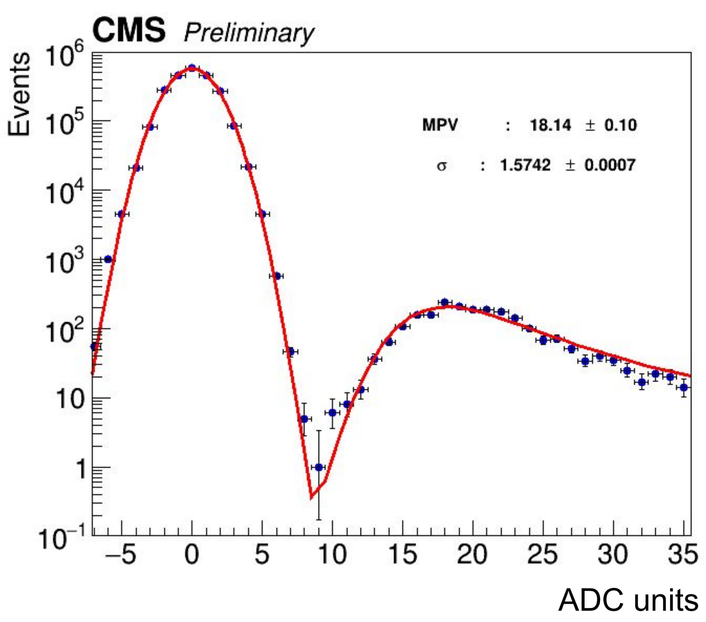


The back-end system implemented a Serenity Z board equipped with a VU7P-2 FPGA and a DTH-P1 board, with a software based on HERD and XDAQ.

SILICON SYSTEM

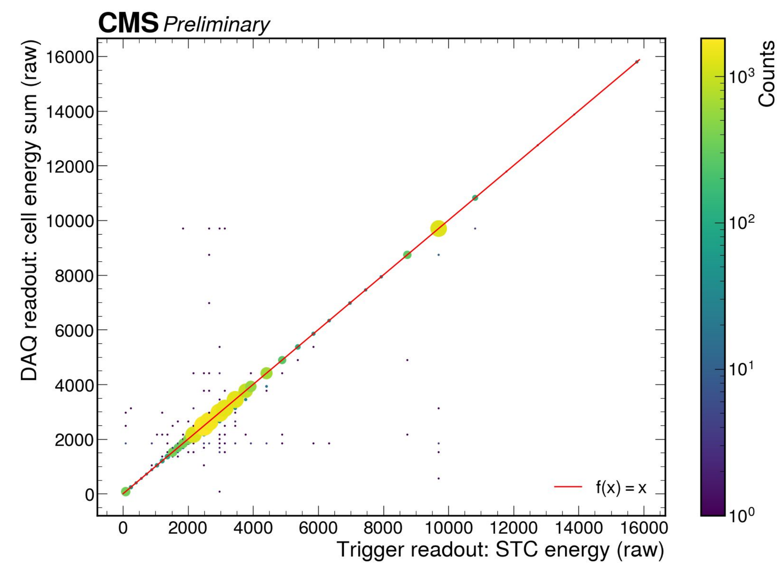


The noise scales with the cell area (i.e. with the capacitance) prior to leakage current induced by irradiation. Noise is measured after correcting for event-by-event baseline shifts ("common mode noise").



Muon signal and pedestal in a silicon sensor cell after an overnight muon run. The pedestal-subtracted distribution is fit a Gaussian plus a Landau-Gaussian convolution for the μ signal contribution.

SCINTILLATOR SYSTEM

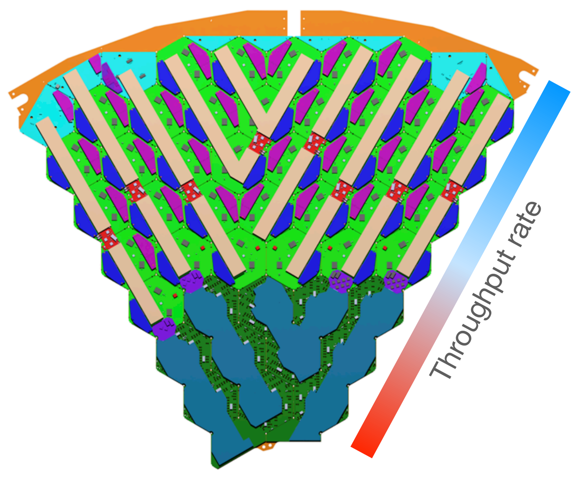


The energy value of a super trigger cell (STC) matches the sum of ADC or Time-over-Threshold from the DAQ readout for all channels in this STC.

THE OPTICAL FIBRES PLANT

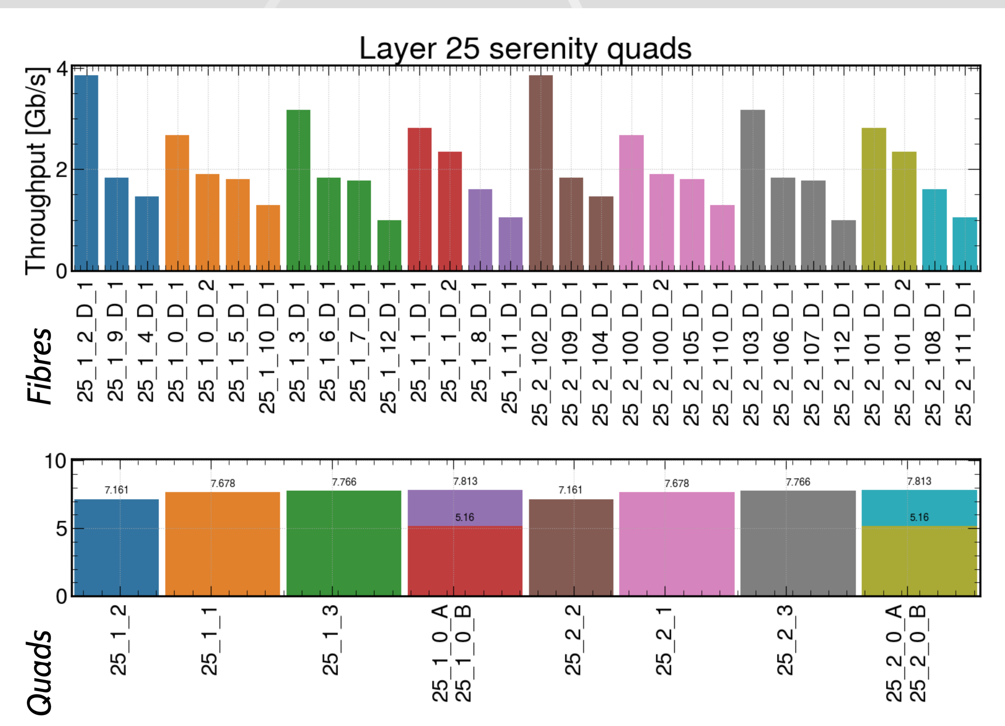
TOWARDS ROUTING THE FULL SYSTEM

Groups of DAQ and trigger front-end concentrator mezzanines (ECON-D and ECON-T) transmit data via VTRx+ modules, resulting in approximately **12000 optical fibres** per endcap. These fibres must be routed through several patch panels to reach the back-end boards, and grouped in a way that balances data volume to simplify firmware implementation. Logical and mechanical constraints must also be respected, making the routing and grouping process **a complex combinatorial problem**.

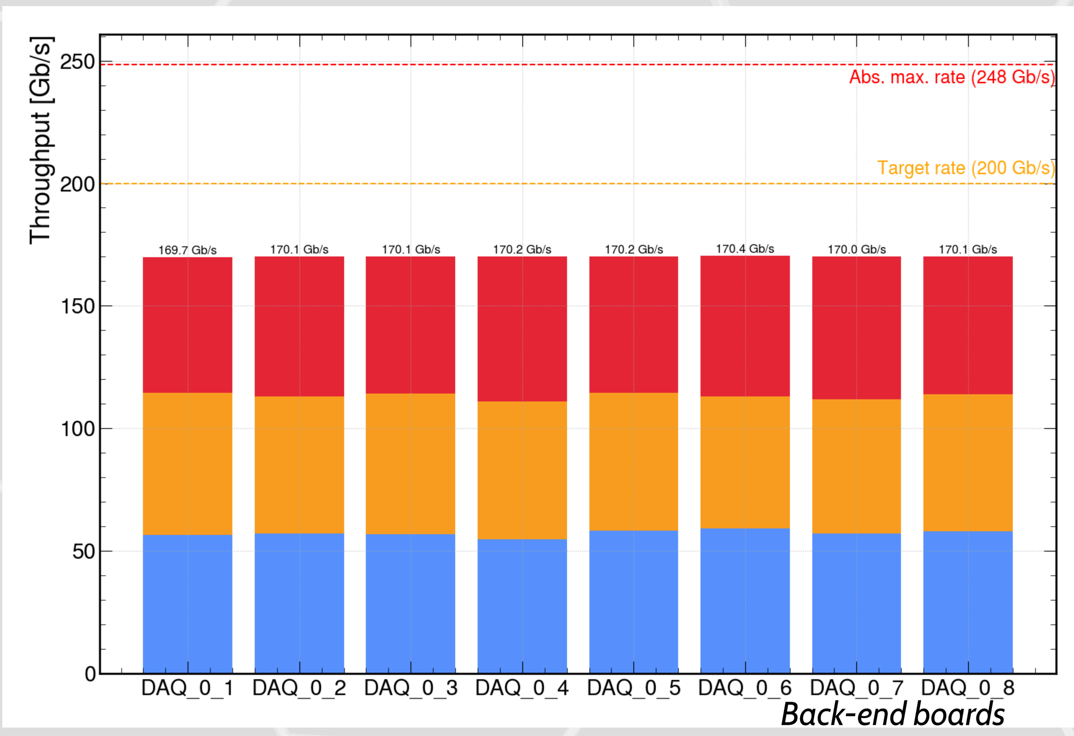


*Within a 30° or 60° wide assembly (**cassette**), the nominal throughput rate can span over one order of magnitude.*

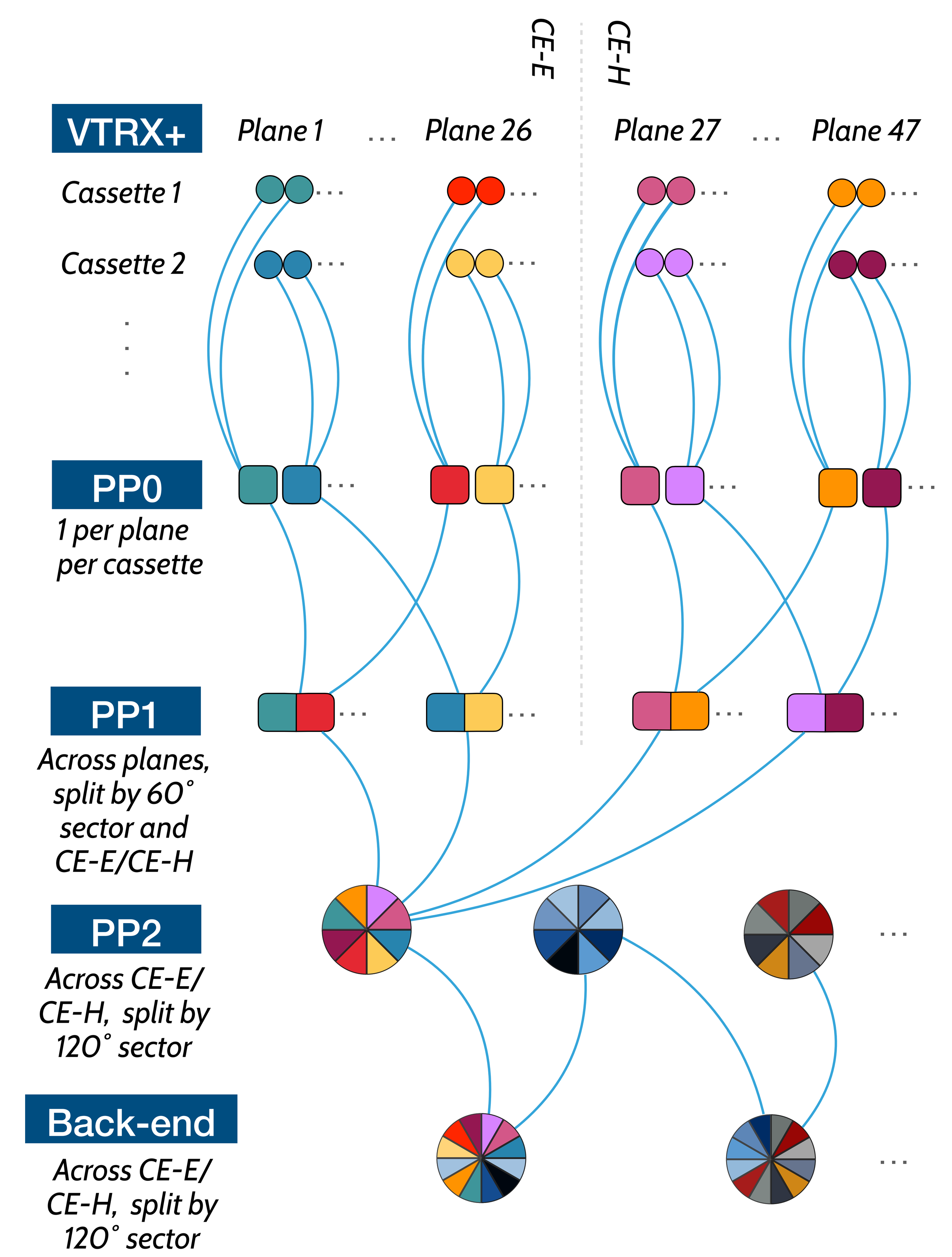
The DAQ back-end system implementation is significantly simplified if data are balanced over SLink quads, and the TPG back-end system needs trigger cells links to fit within the Stage-1 to Stage-2 capacity. Both systems are implemented on Serenity boards.



Fibres are carried across patch panels and grouped into sets representing back-end quads.



The DAQ back-end grouping algorithm deals with chunks already balanced, resulting into a flat throughput distribution across boards.



CONCLUSION AND OUTLOOK

The busy collision environment of the upcoming HL-LHC program requires a complete change of paradigm in detector technology. The HGCAL addresses this challenge with excellent capabilities in spatial, energy, and timing measurements. System integration and validation are progressing swiftly, and the readout chain has been exercised under beam and magnetic field, together with calibration routines and data quality monitoring. Further studies on the detector performance will be made using data from upcoming test beam campaigns. Meanwhile, the mass production of cassettes and modules is ongoing. Strategies for routing the data and trigger fibres are in place, and are being validated along with the cassettes assembling program.

References
[1] The Phase-2 Upgrade of the CMS Endcap Calorimeter, CMS Collaboration (CERN-LHCC-2017-023, CMS-TDR-019)
[2] HGCAL system performance tests conducted in 2024 using pre-series components in electron, pion, and muon beams, CMS Collaboration, (CMS DP -2025/022)