CMS upgrades

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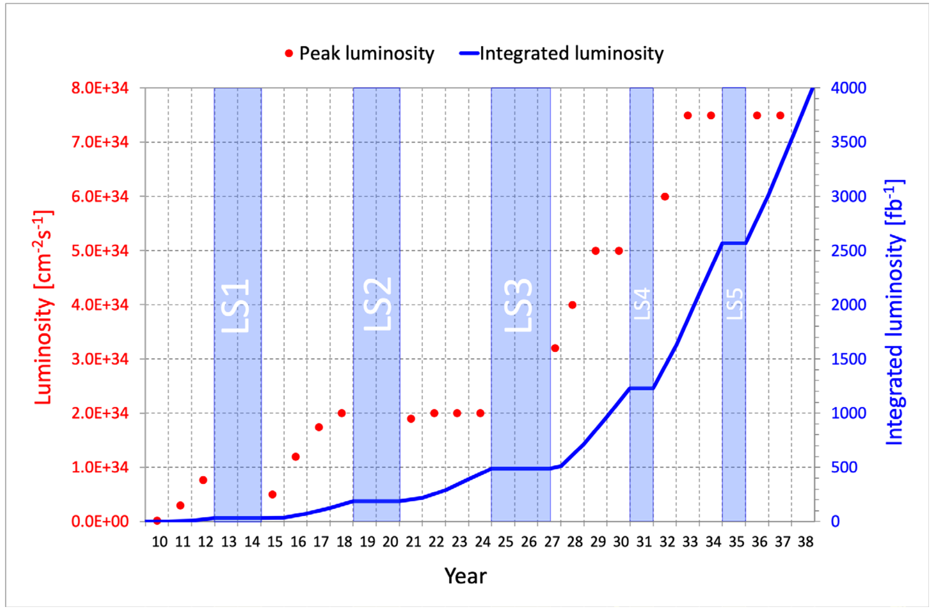
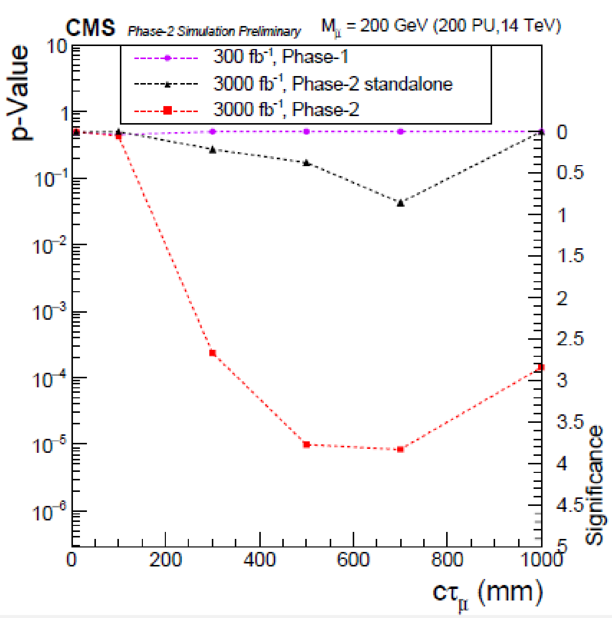
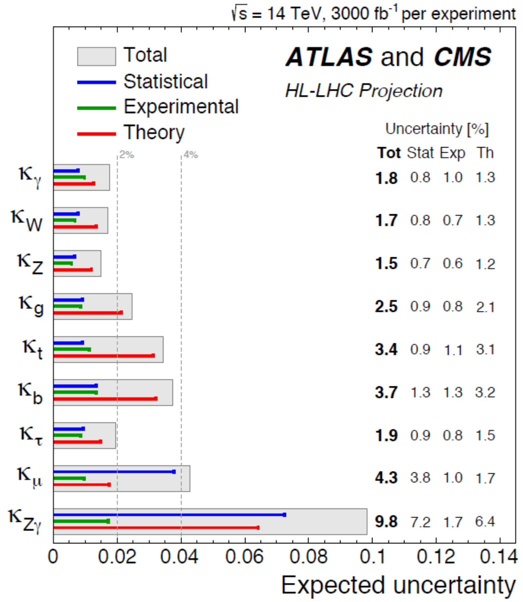
Why HL-LHC?

- HL-LHC upgrade offers an **unprecedented opportunity** to explore uncharted lands and achieve scientific progress.
- 10 times more data to what we will have by the end of Run 3 will facilitate a rich physics program.
- **Extend reach of new physics searches**: unexplored signatures (LLPs, HSCPs…) or regions of the phase-space will be within reach.
- **Improve current understanding of the SM and Higgs** sector by improving existing precision measurements and accessing rare decays ($H \rightarrow \mu\mu$) or production modes (HH) previously unseen at the LHC.
- However, this physics program will have to overcome **significant challenges** to succeed.







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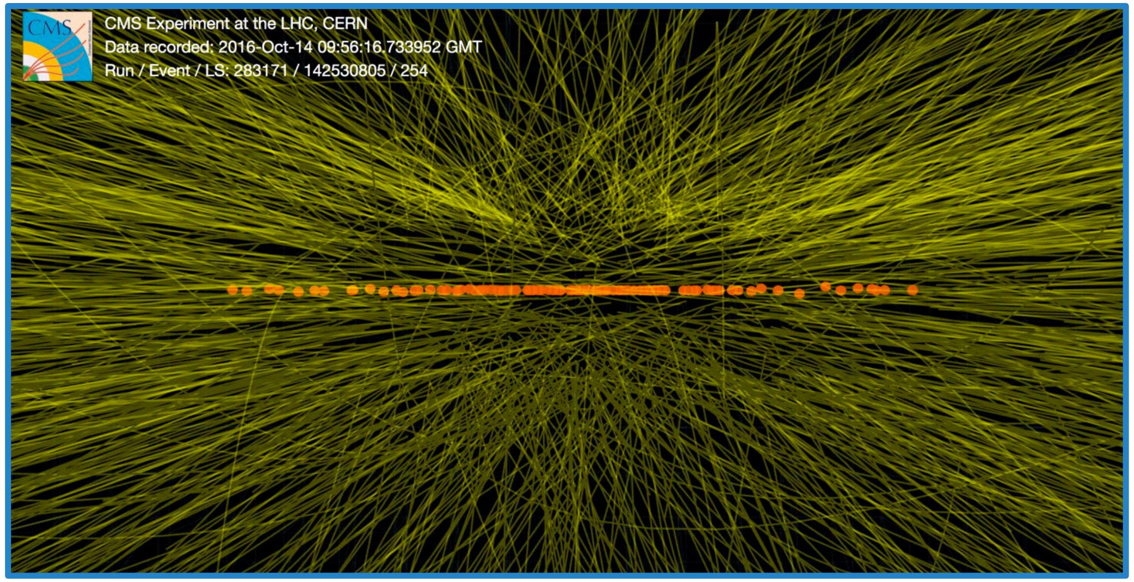
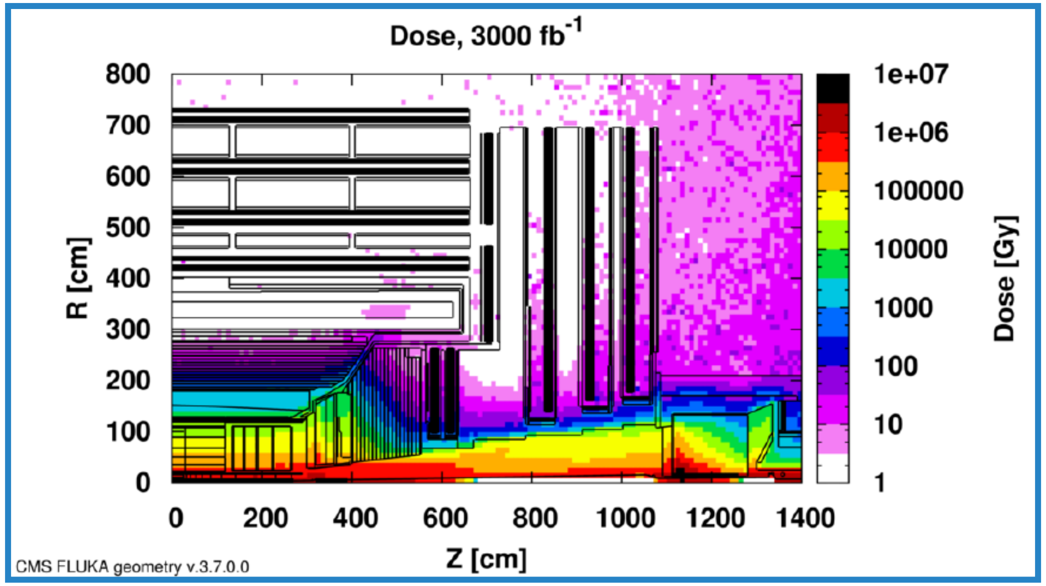
HL-LHC: challenges





- **Expected pileup** (PU): ~140 (nominal HL-LHC lumi)
- Motivates/requires:
  - Improved granularity wherever possible
  - Novel approaches to in-time Pile Up mitigation: Precision Timing detectors (30ps)
  - A complete renovation of the Trigger and DAQ systems for better selectiveness, despite the high PU.

- **Radiation damage / accumulated dose** in detectors and on-board electronics may result in a progressive degradation of the performance.
- Maintain detector performance in harsh conditions:
  - The complete replacement of the Tracker and Endcap Calorimeter systems.
  - Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

Replacements of existing system/detector
Electronics upgrade/replacement
New detector

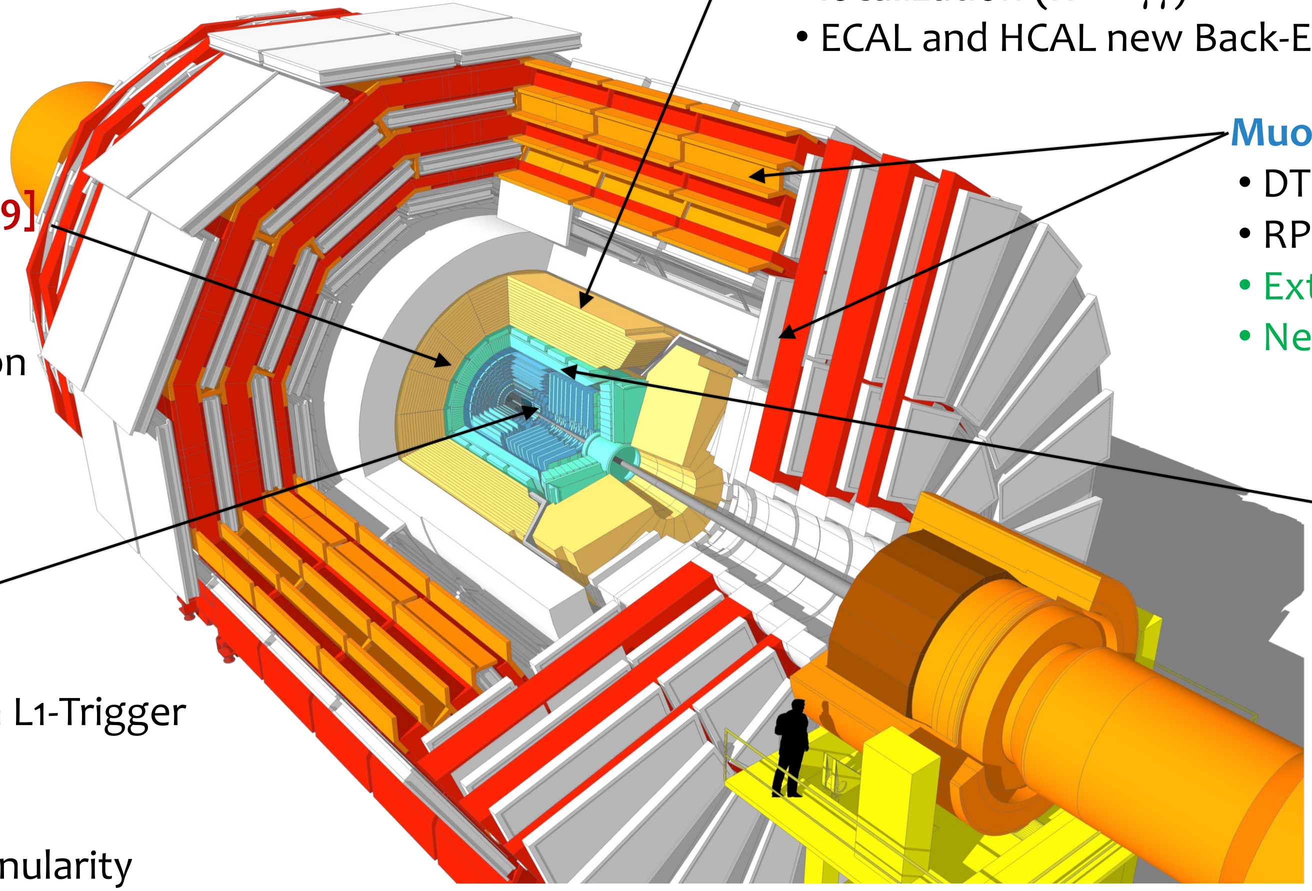
CMS Phase-2 upgrades

L1-Trigger/HLT/DAQ [CMS-TDR-021 / 022]
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters [CMS-TDR-015]
- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \to \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Muon systems [CMS-TDR-016]
- DT & CSC new FE/BE readout
- RPC back-end electronics
- Extended GEM coverage to $\eta \simeq 3$
- New GEM/RPC $1.6 < \eta < 2.4$

Calorimeter Endcap [CMS-TDR-019]
- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

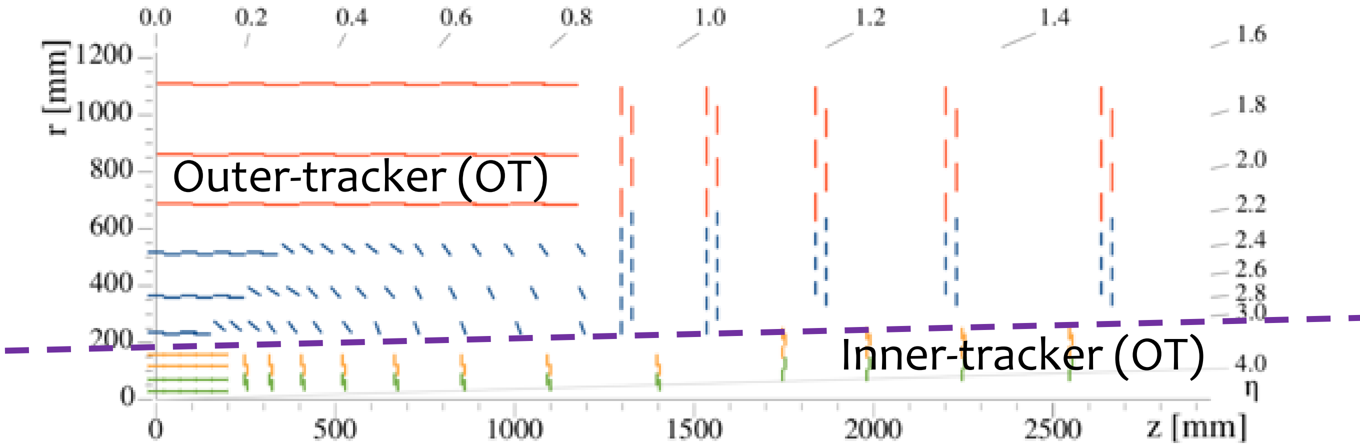


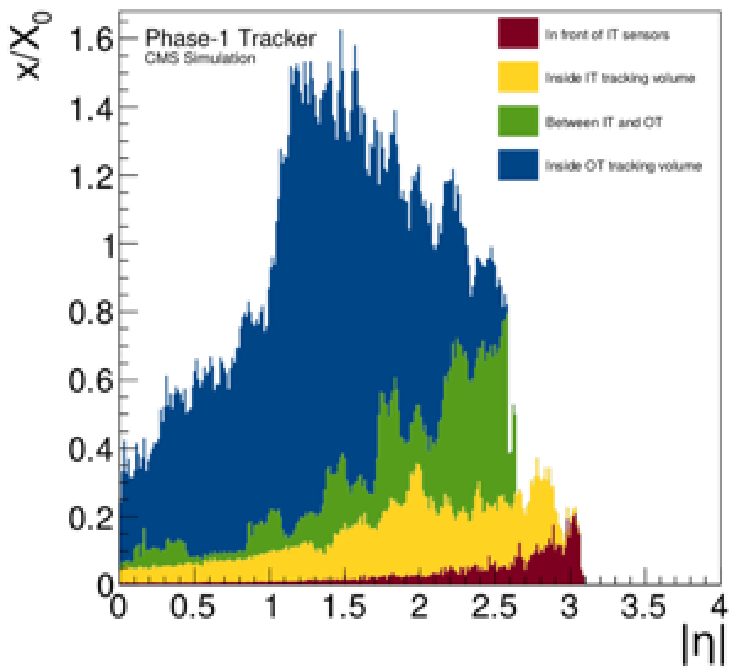
MIP Timing Detector [CMS-TDR-020]
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

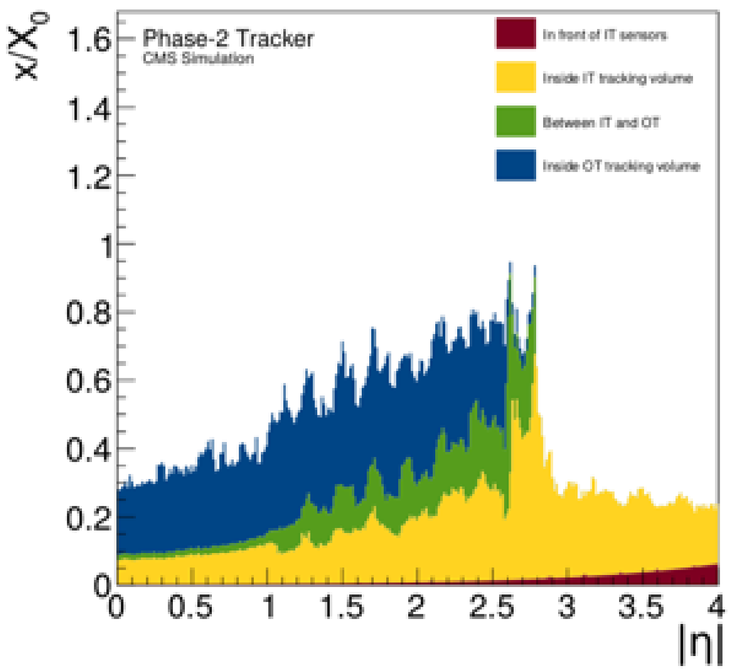
Tracker [CMS-TD-014]
- P_T module design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity

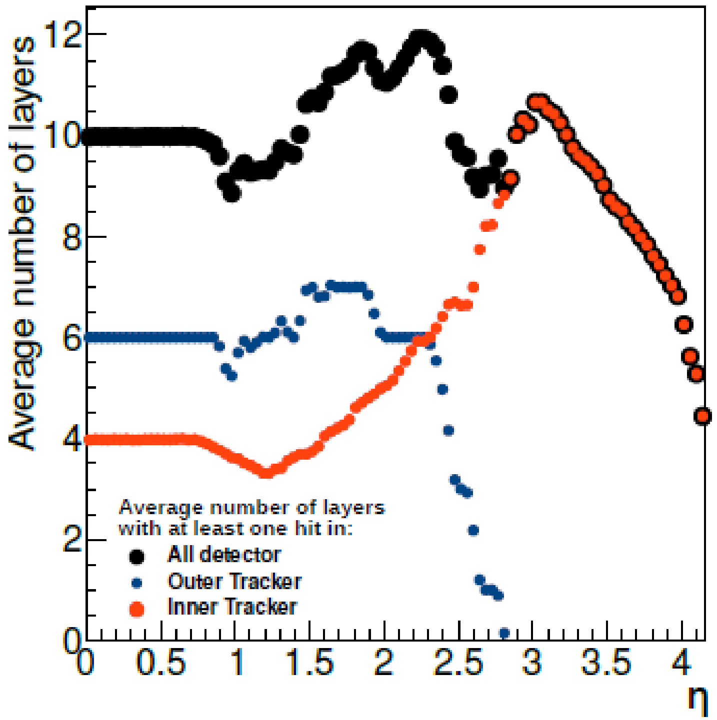
Phase-2 Tracker Upgrade

- **Key features:**
  - More granularity
  - Lower material budget
  - Extended coverage
  - Tracking included in L1 Trigger for the first time









Outer Tracker: p_T module

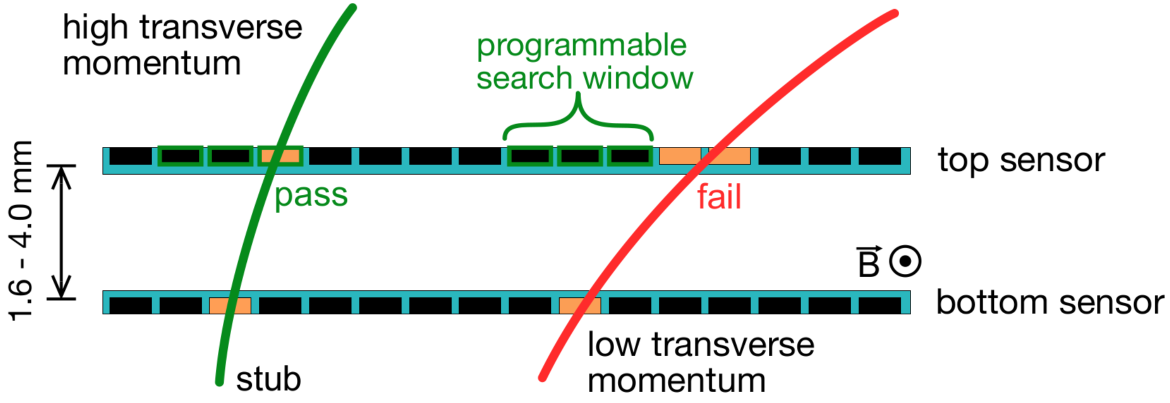
Introducing tracking at L1 trigger

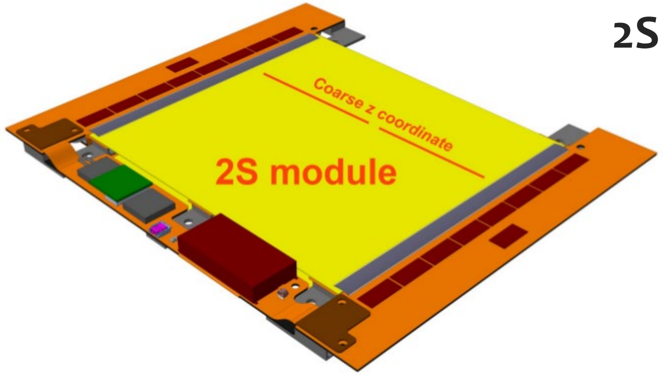
Local rejection of low-p_T tracks

- Exploit bending of charged particle tracks in CMS'4T B-field
- Correlate hits from 2 closely spaced sensors to form stubs compatible with a track p_T > 2GeV
- Tuneable offset and window for homogeneous p_T threshold throughout the Outer Tracker

Tracker input to the L1 trigger

- Stub information is sent out at BX frequency of 40 MHz
- Two data streams: trigger information and hit data
- Full data read-out at ~750 kHz



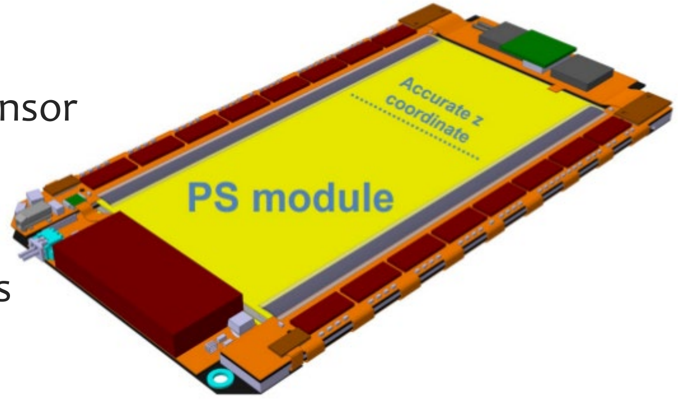


2S module

- 2 strip sensors with 2×10^{16} channels each
- 10×10 cm^2 sensors with 5 cm long strips
- 90 μm pitch, sensors spaced at 1.8 and 4 mm
- Radii > 60 cm

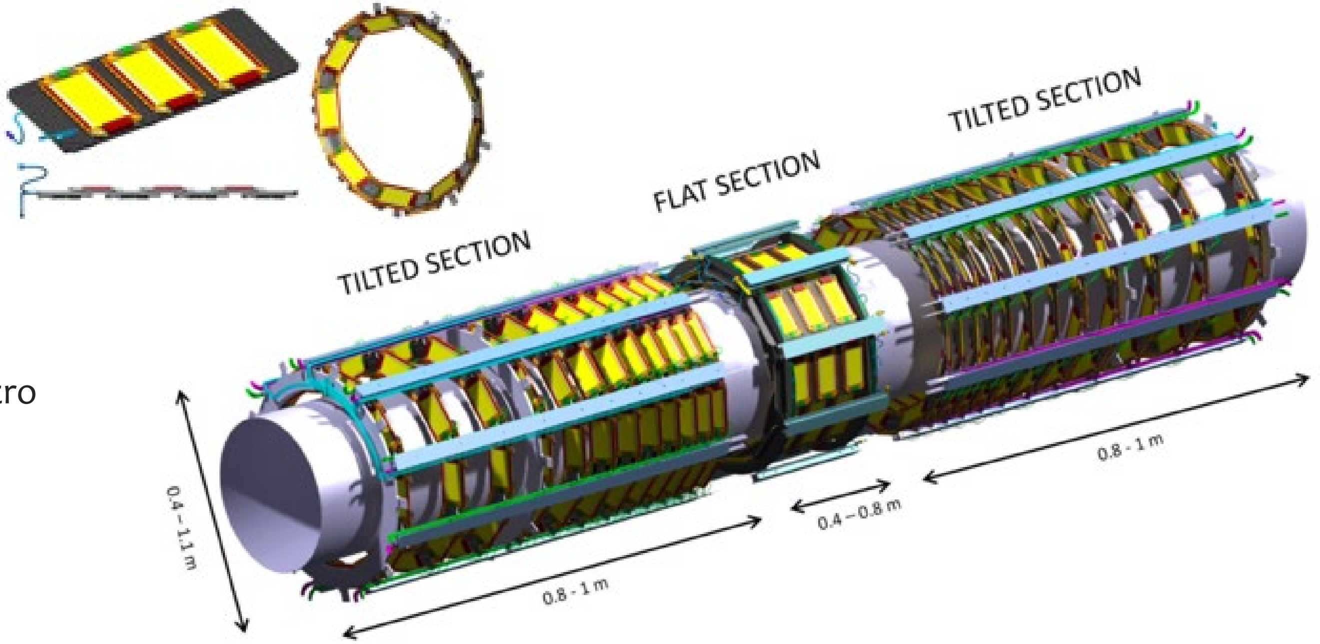
PS module

- Sandwich of 1 strip and 1 macro-pixel sensor
- $\sim 10 \times 5$ cm^2 sensitive area, 2×960 strips with 100 μm pitch
- 1467×100 μm^2 pixels, sensor spacings 1.6, 2.6 and 4 mm

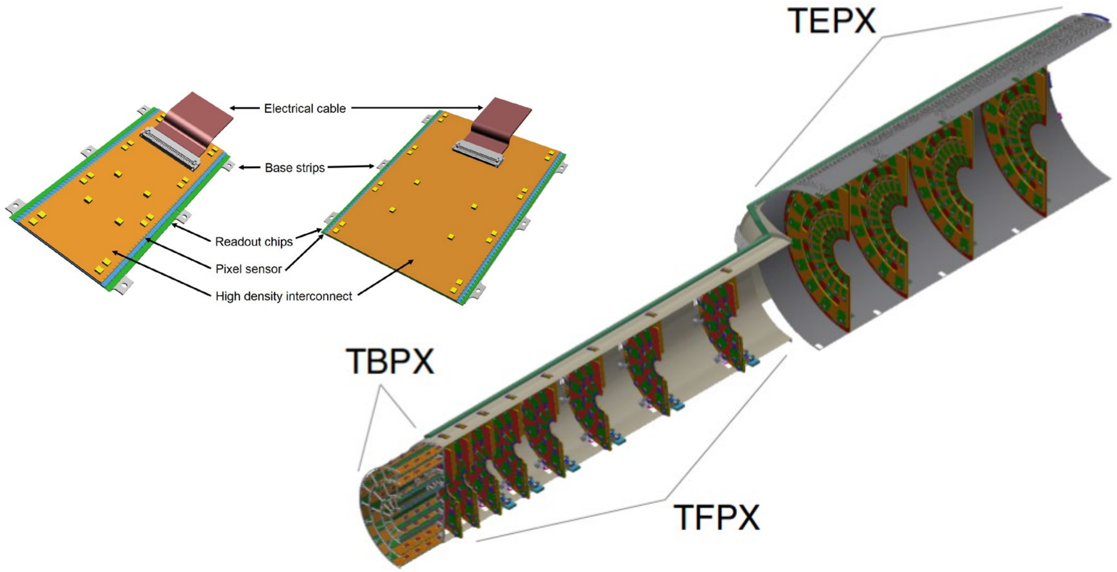


Future Layout

- **Outer tracker**:
  - Layout: 6 barrel layers, 5 discs per endcap
  - 9.5 million channels:
    - ~ 200 m^2 of active silicon sensors → 44M strips and 174M macro pixels (r < 60 cm)
  - Vastly **reducing** material:
    - light-weight mechanics and modules & improved routing of services
    - tilted barrel section

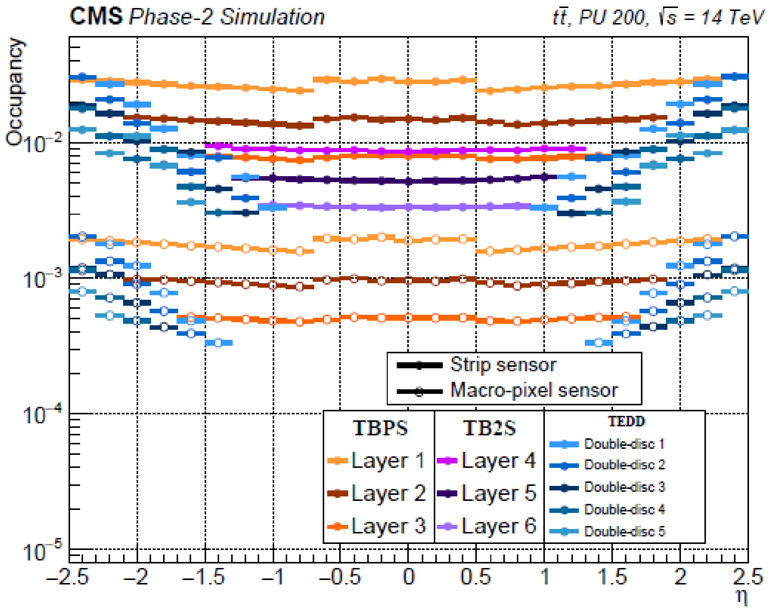


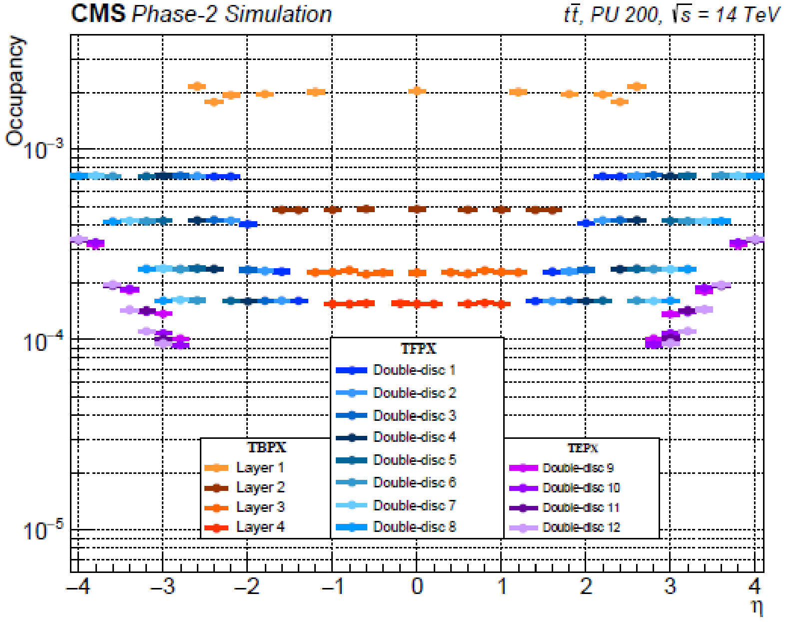
- **Inner tracker**:
  - Increased granularity with occupancy at per mille level: pixel size ~ 25 × 100 μm^2 or 50 × 50 μm^2
  - Coverage up to $\eta \sim 4$, with ~4.9 m^2 active area
  - Layout: 4 barrel layers, 8 small disks, 4 large discs per side
  - Mechanics and support: simple structure for **easy installation and removal** → potential replacement of inefficient parts possible!

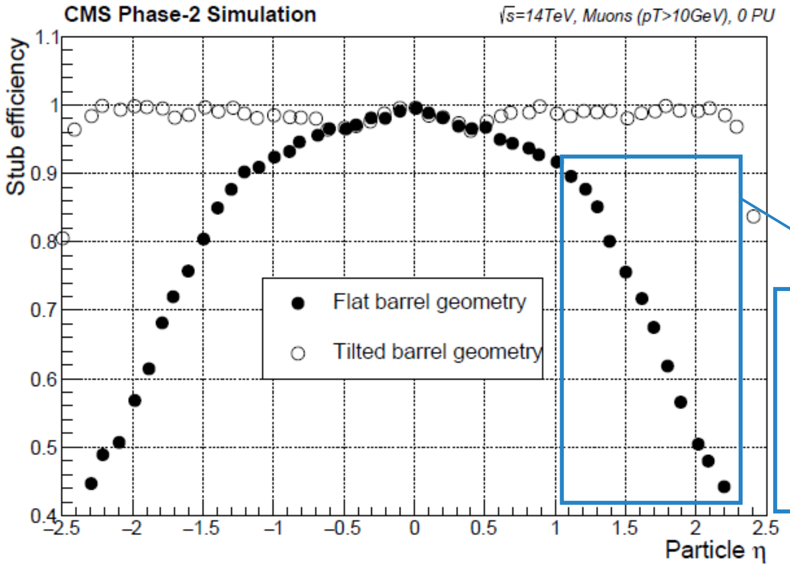


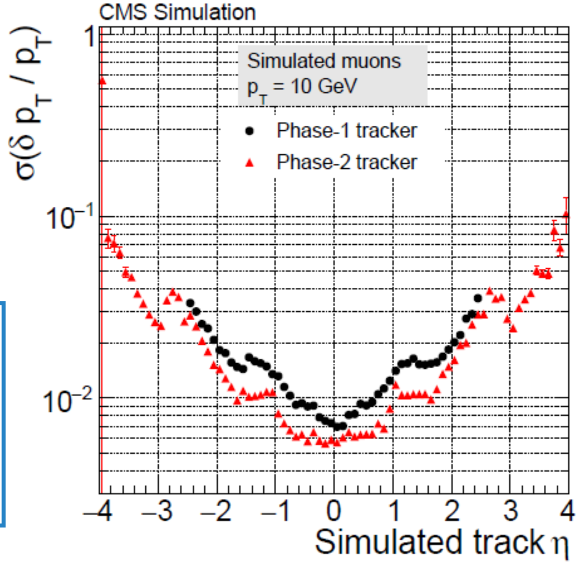
Expected performance

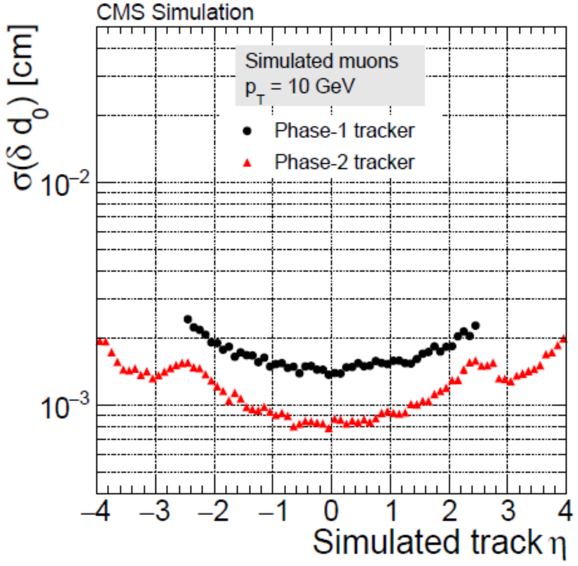
- **Occupancy will not exceed 3%**
- **Resolution:**
  - Momentum resolution deteriorates at higher η due to shorter lever arm
  - Transverse impact parameter, below 10μm in centre, 20μm at edge











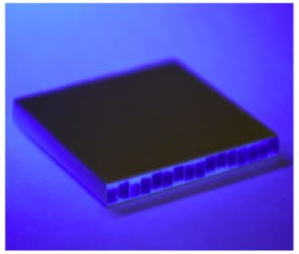
MIP Timing Detector

An overview

- Thin layer between tracker and calorimeters
  - Hermetic coverage for $|\eta| < 3.0$
- MTD will **feature**:
  - Time resolution of 30-50 ps for MIPs
  - 4D vertex reconstruction
- **Technology**:
  - Well-stablished technologies will be used
  - LYSO crystals with dual end SiPM readout in barrel
  - Low Gain Avalanche Detectors (LGAD) for the endcap

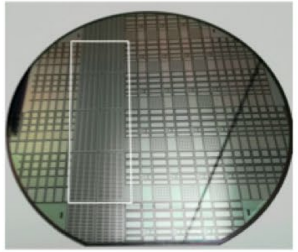
BTL: LYSO bars + SiPM readout:

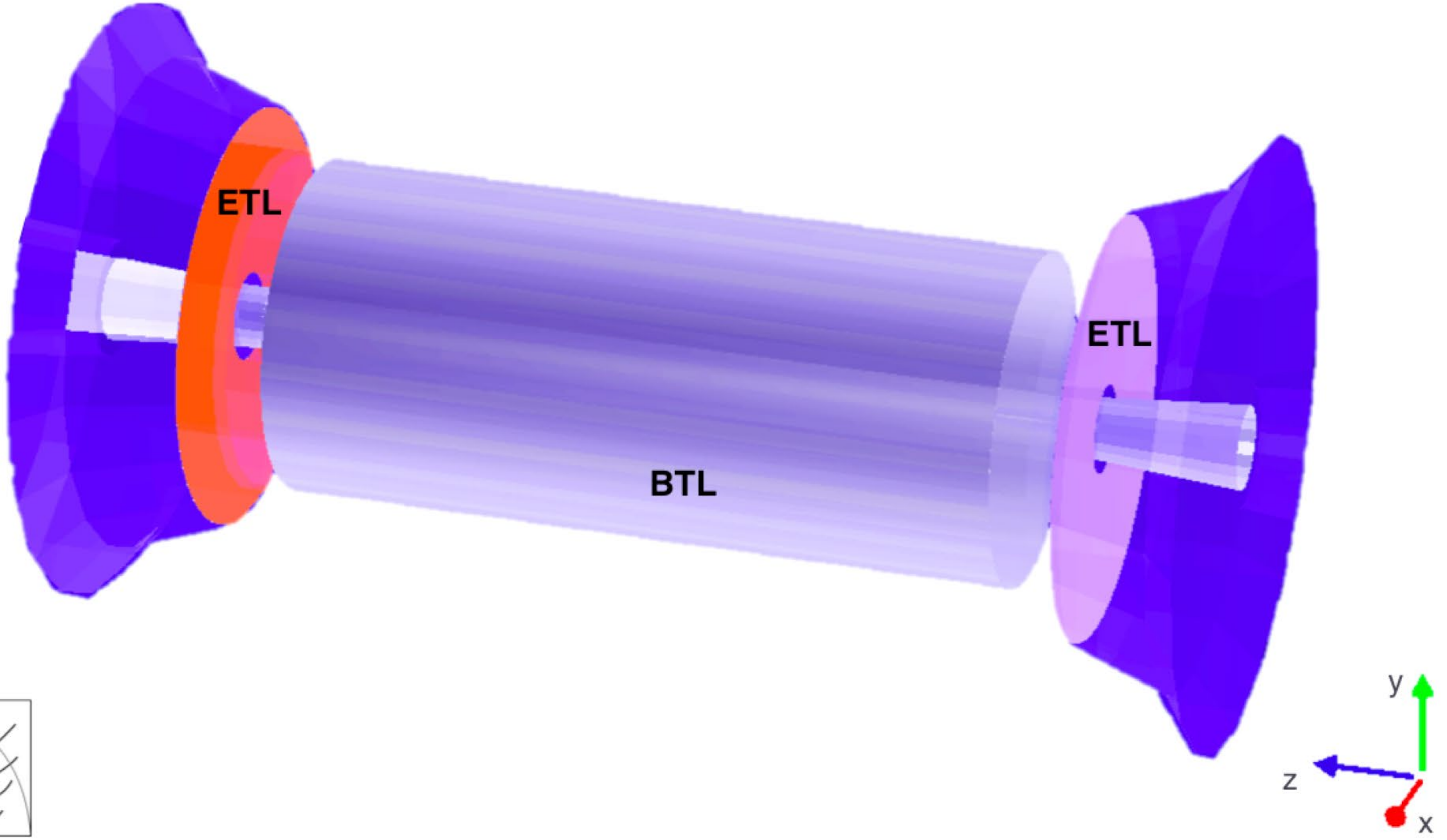
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2\times10^{14}\ n_{eq}/cm^2$



ETL: Si with internal gain (LGAD):

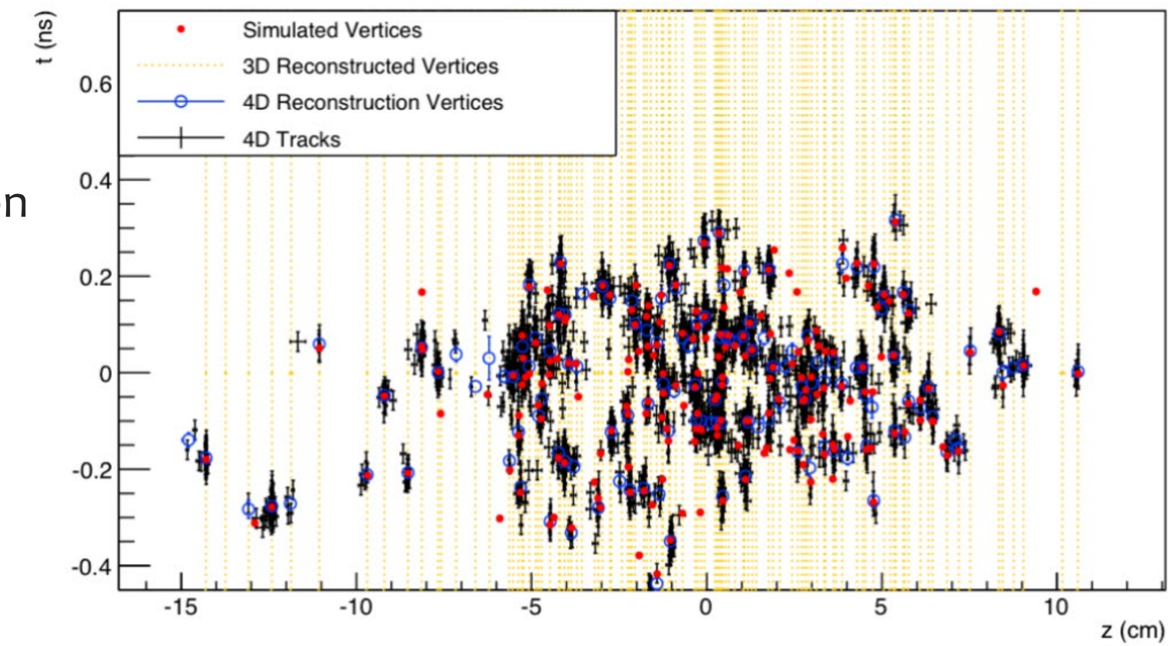
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2\times10^{15}\ n_{eq}/cm^2$



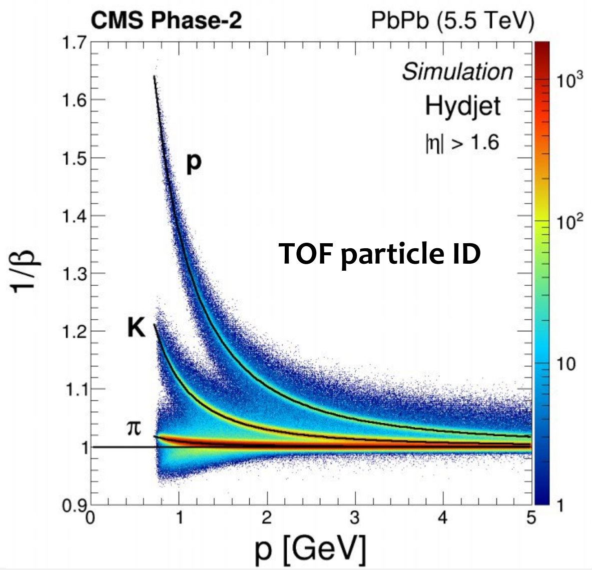


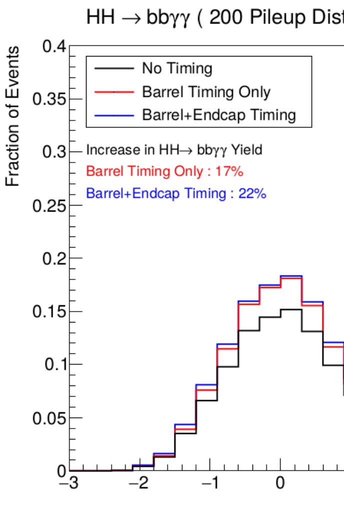
MIP Timing Detector

- **Time information** improves the quality of the reconstruction of physics objects.
  - Track time association allows to remove spurious pile-up tracks from reconstruction,
  - Impact on fake jet reconstruction, lepton isolation and ID, b-tagging, p_T^{miss} resolution.
  - Also adding the possibility to perform time-of-flight particle identification



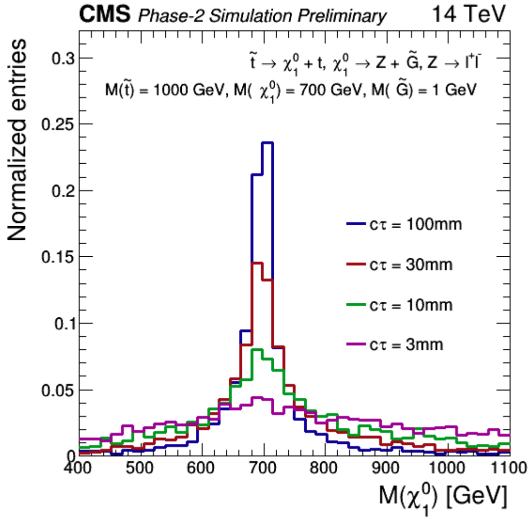
- Impact on the reach of physics analysis: both SM and BSM



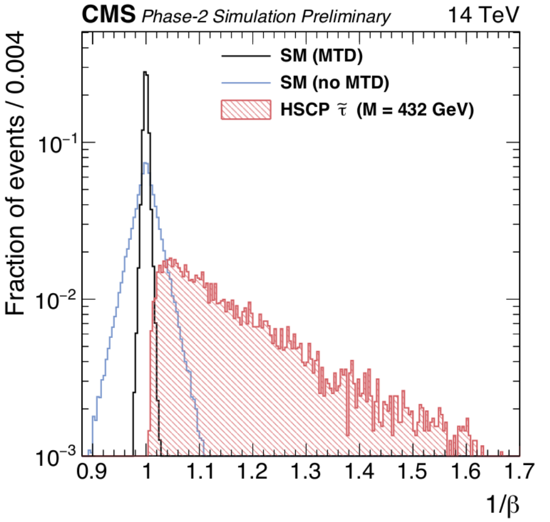


$H \rightarrow bb\gamma\gamma$ efficiency improved by 20%

LLP

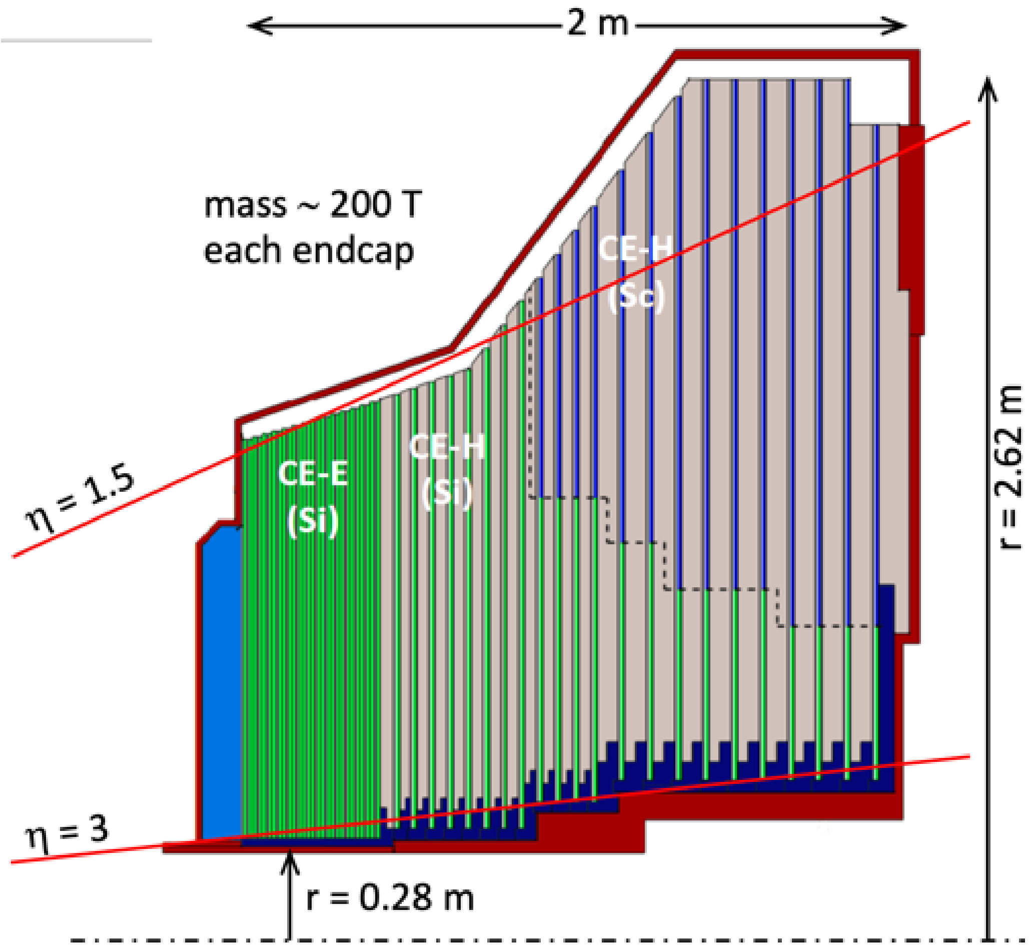


HSCP



High-Granularity Calorimeter (HGCAL): design parameters

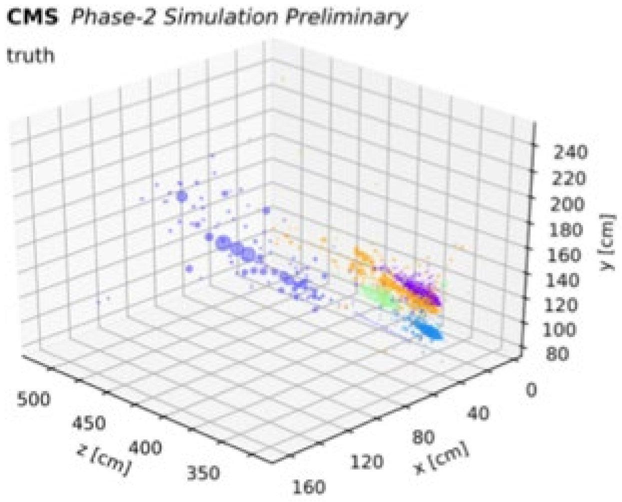
- **Key Parameters:**
  - The HGCAL covers $1.5 < |\eta| < 3.0$
  - 215 ton/endcap, full system at -30C
  - 620 m^2 of Si sensors in 30k modules: 6M Si channels, 0.5 or 1 cm^2 cell size
  - 400 m^2 of scintillator in 4k boards: 240k scintillator chan., 4-30 cm^2 cell size
- **Active Elements:**
  - Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
  - Scintillating tiles with SiPM readout in low-radiation regions of CE-H
  - "Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
- **Detector Configuration:**
  - Electromagnetic calorimeter (CE-E) : Si, Cu/CuW/Pb absorbers; 28 layers, 25.5 Xo and 1.7 λ
  - Hadronic calorimeter (CE-H) : Si & scintillator, steel absorbers; 22 layers and ~9.5 λ (including CE-E)



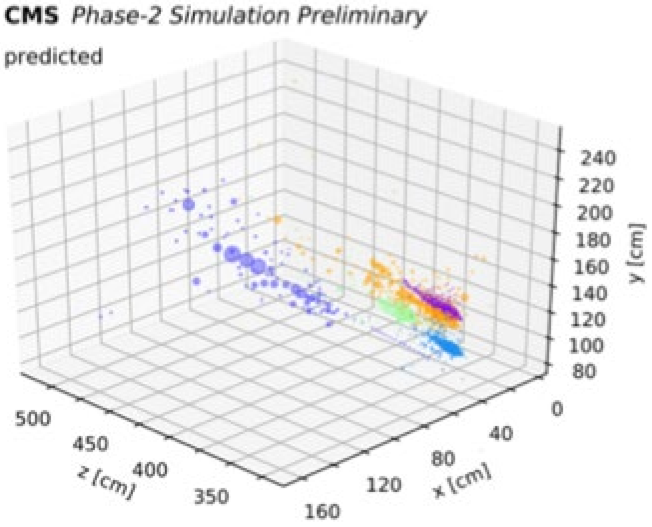
CMS HGCAL: Pattern Recognition and Reconstruction

ML exploration: Dynamic Graph Networks

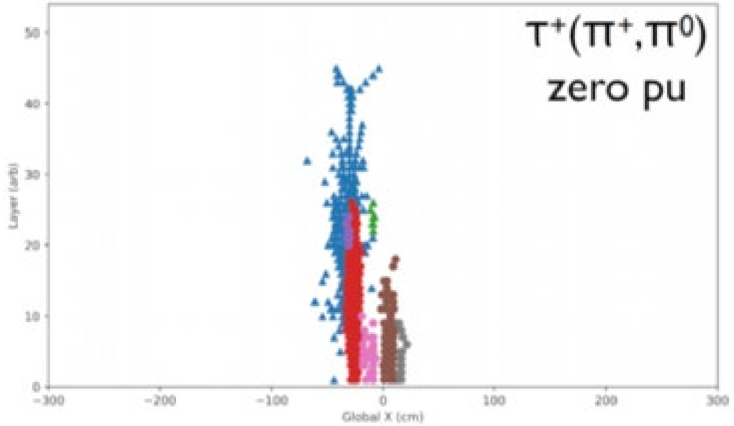
- Using graph neural networks for reconstruction
  arxiv:1801.07829v2
- Developed dedicated dynamic space transformation networks:
  GravNet arxiv:1902.07987

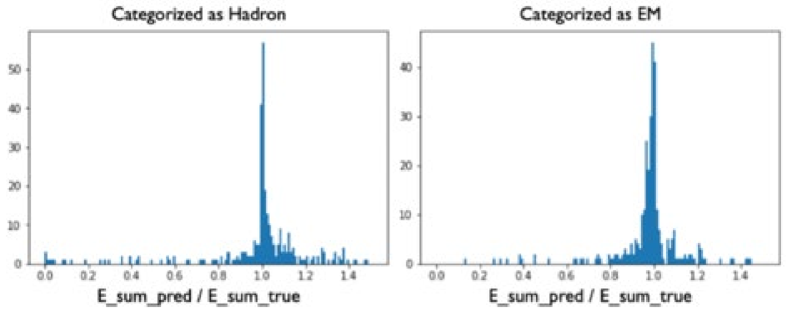


GravNet Results



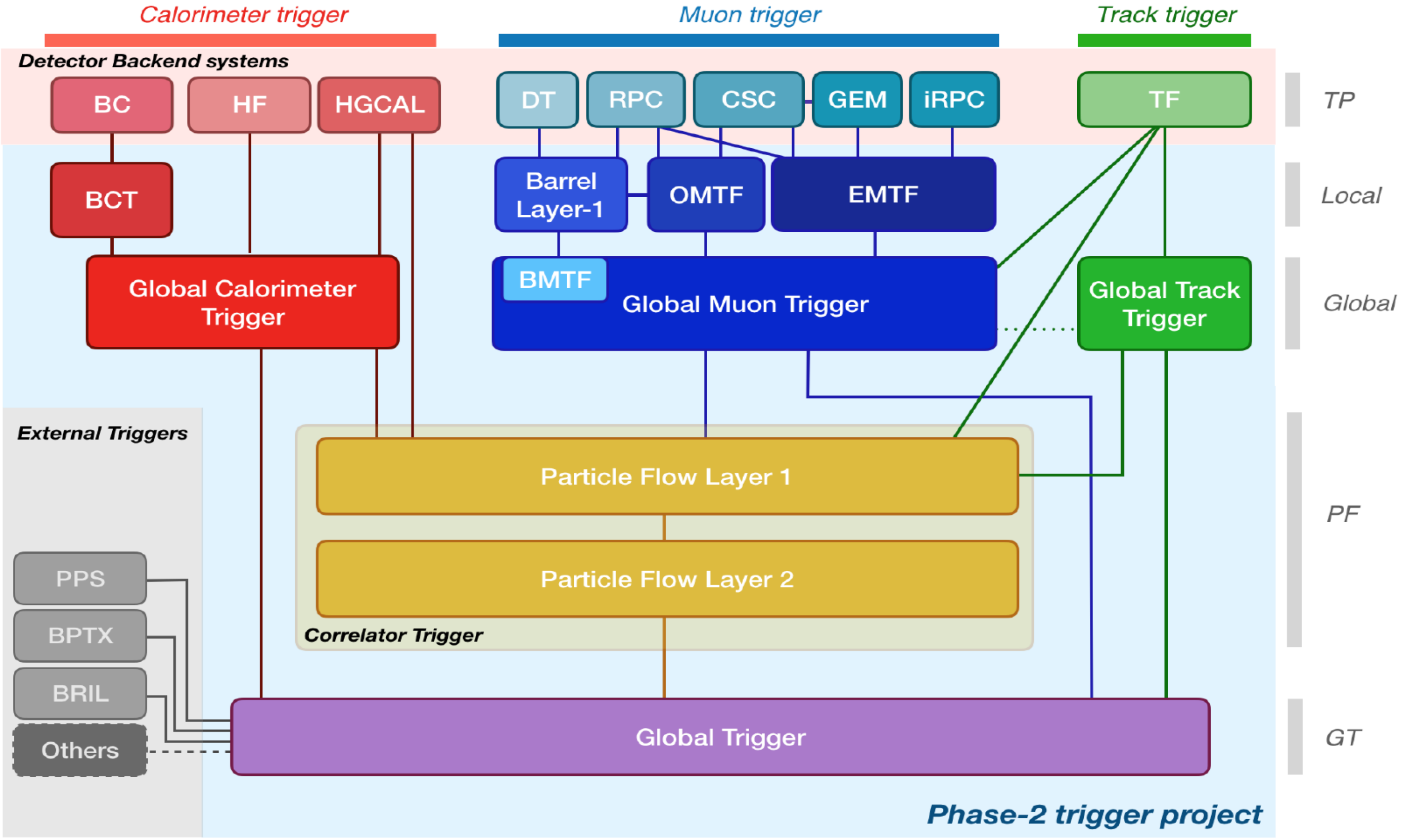
- **Edge Classifier Results:**
  - Edges are used to group together points of the same particle type:
    - Individual decay products of taus clearly separable
  - Accurate separation of EM vs HAD energy across multiple clusters





L1 trigger upgrade

- CMS will keep a 2-level triggering approach: L1 & HLT
- Key features of Phase2 Upgrade of Level-1 Trigger:
  - Increase bandwidth 100 kHz → 750kHz
  - Increase latency 3.8 μs → 12.5 μs
- Including info from tracker and HGCAL
- **Sophisticated FPGA-based algorithms:** using particle-flow (PF) reconstruction techniques or Machine-Learning based approaches.
- Increased trigger acceptance, and physics sensitivity, while maintaining Run-2 thresholds.
- Scouting into HL-LHC data @ 40 MHz: storing only high-level information.



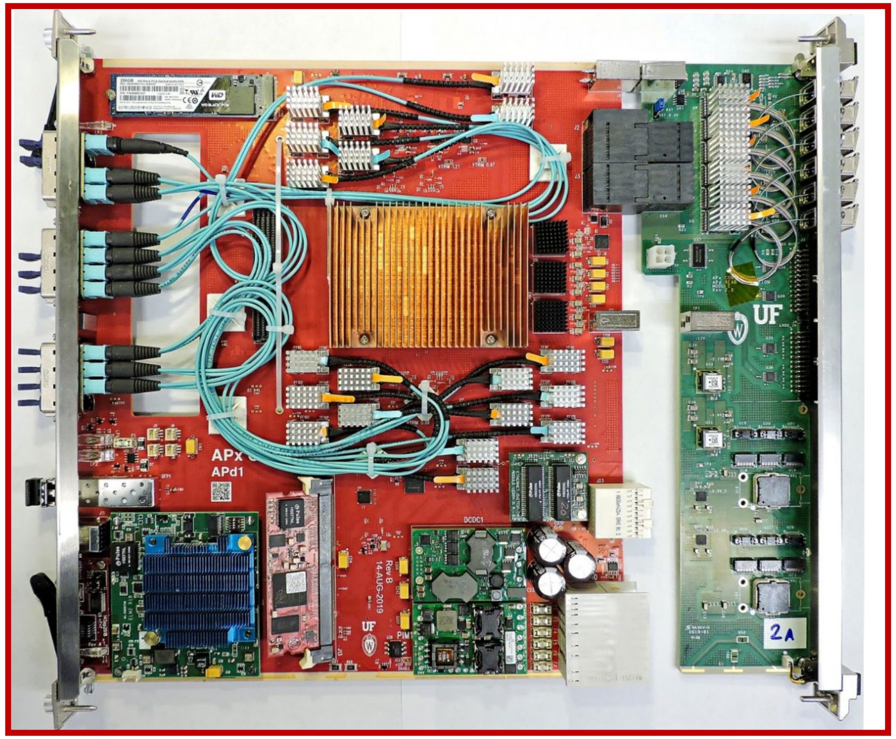
Four distinct and independent trigger processing paths: a calorimeter trigger, a muon trigger, a track trigger and a particle-flow (correlator) trigger

L1T: Hardware prototypes

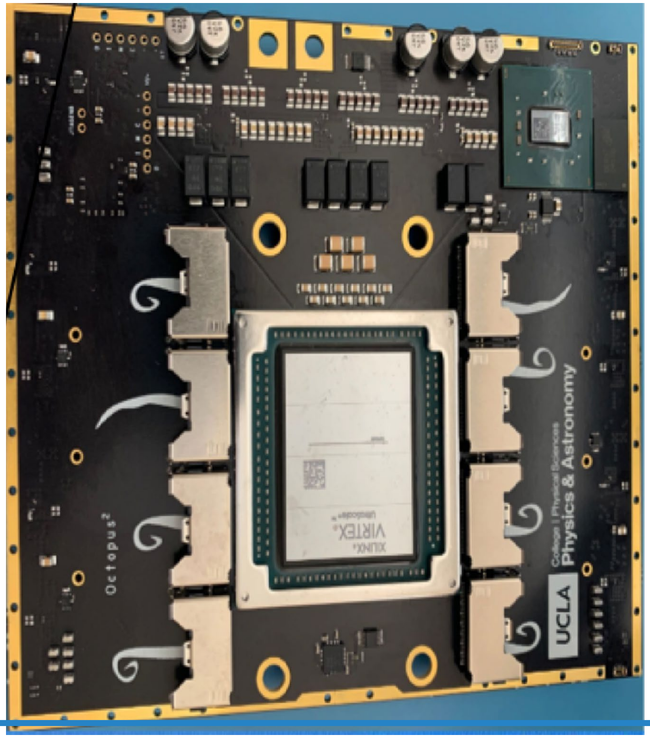
Design philosophy: Generic Processing Engines → I/O, FPGA

- FPGA : 1 or 2 Xilinx Virtex Ultrascale / Ultrascale+
- Optics : +100 high-speed. Samtec Firefly x4 /x12 flyover
- Processors on board running commercial linux for flexible configuration and monitoring

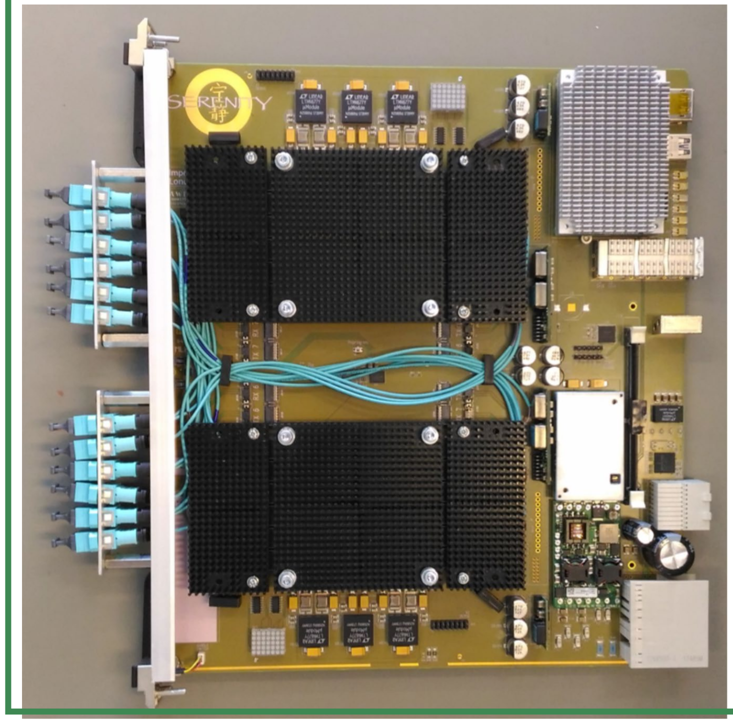
APx



X2O/Octopus (OCEAN prototype)

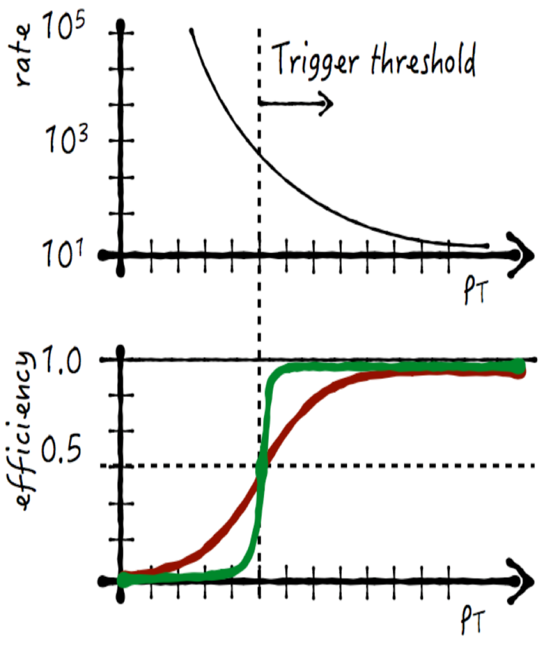


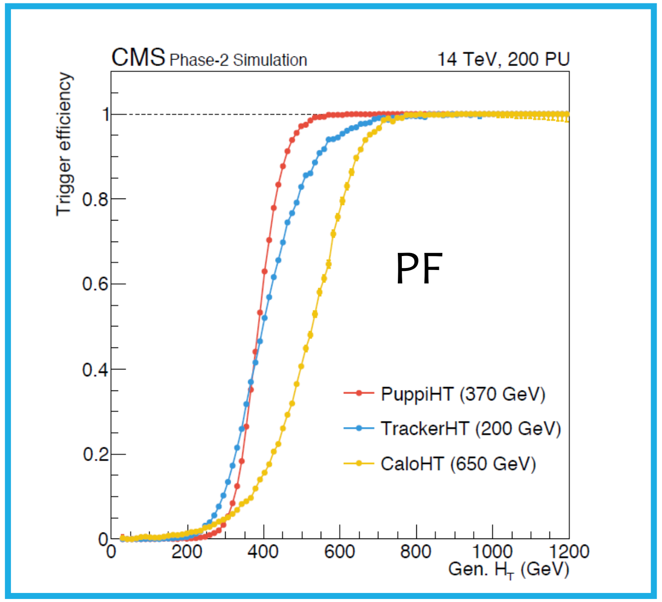
Serenity:

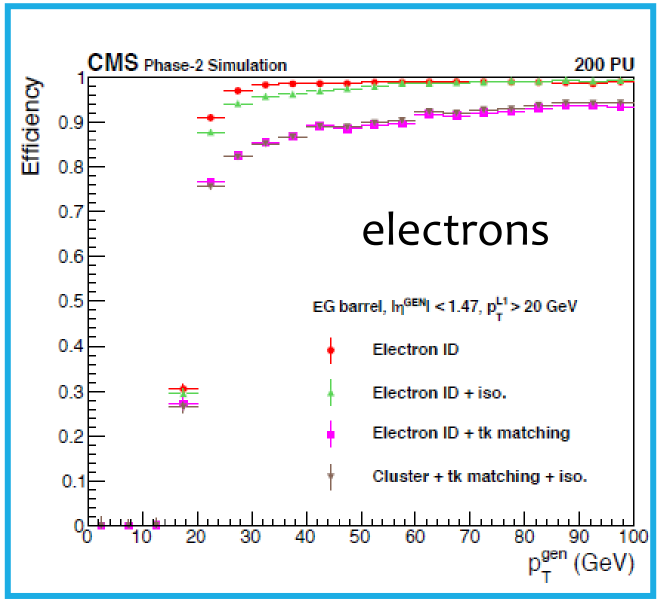


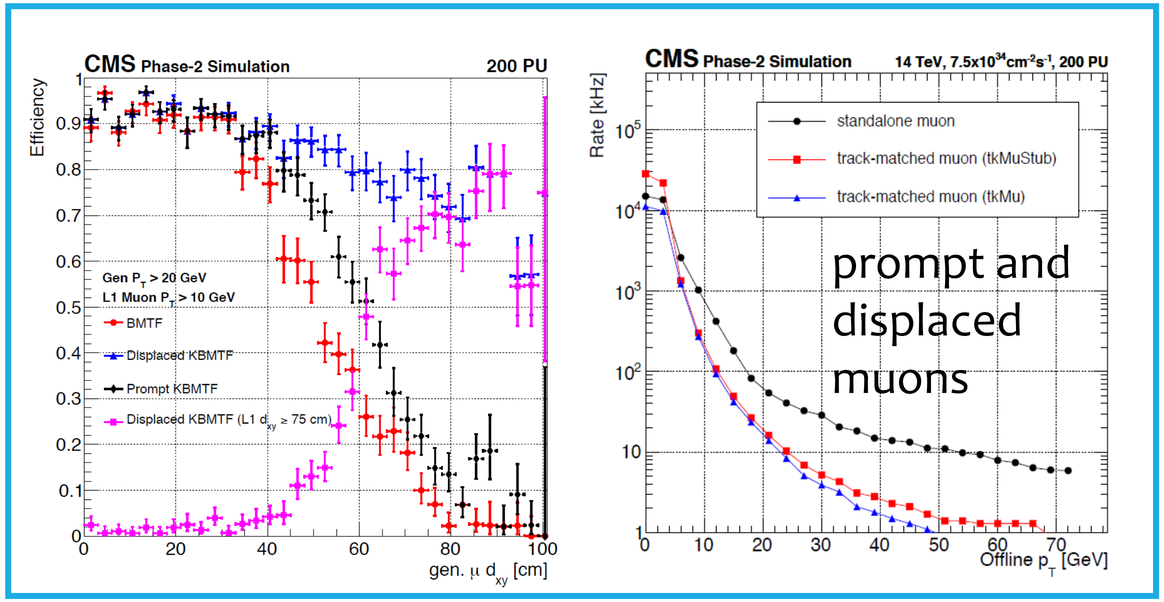
L1T: algorithms

- **Extensive use of tracking** to reach near offline performance (sharper efficiency turn-on curves) + reconstruction of Primary Vertex.
- Exploit **complementarity of different object flavor**:
  - Standalone objects: robust triggers based on independent sub-detectors
  - Track-matched objects: tracking used to confirm standalone objects, significant improvement with simple design
  - Particle-flow (PF) objects: ultimate performance improvement, combine all information to match offline algorithms, require most processing time and resources for calculation



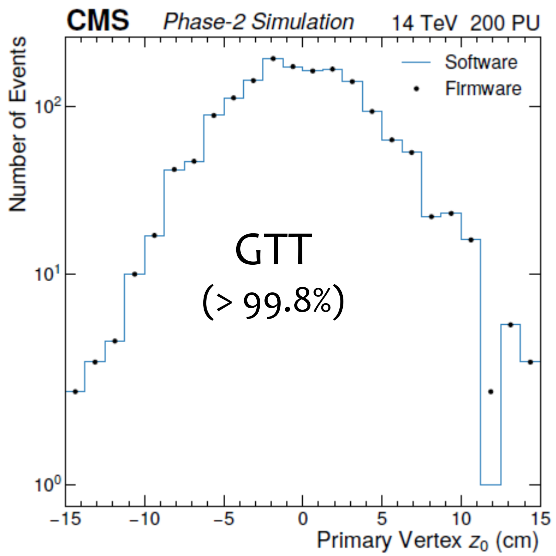


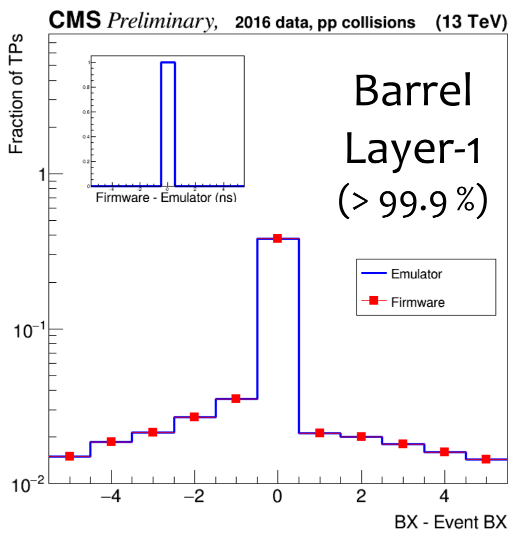


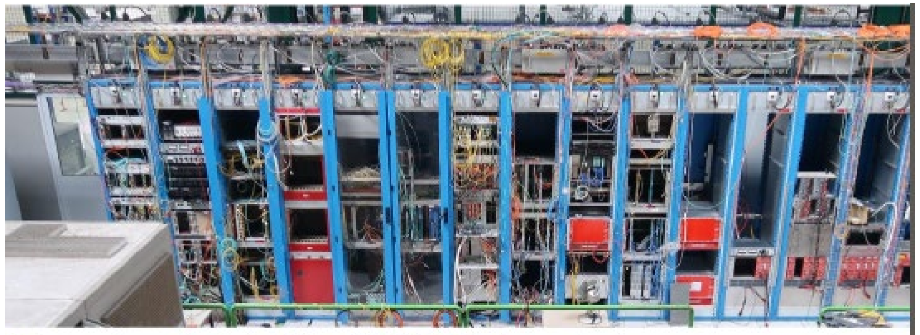


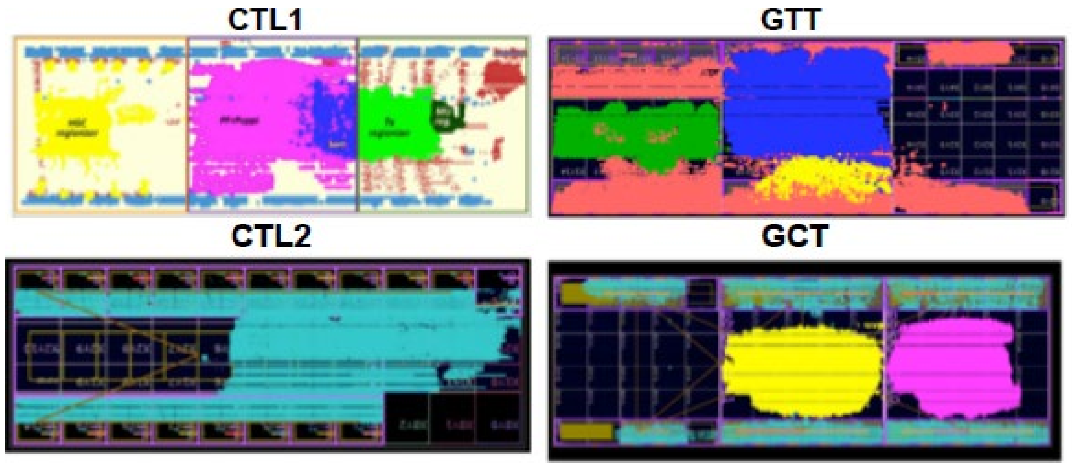
L1 trigger upgrade: testing and demonstrators

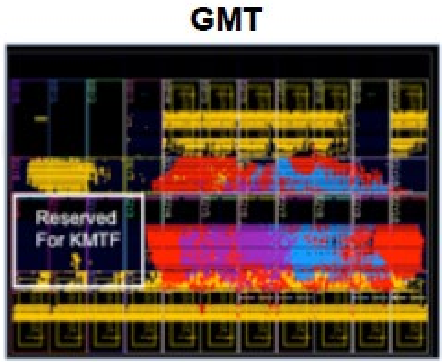
- **From SW to FW:**
  - Algorithm designed in C++ (with fixed-point precision arithmetic) and converted to HLS.
  - Timing, resource consumption and latency verified.
  - Close to 100% agreement between SW and FW implementation
- **System demonstrators:**
  - Single and multiple-board tests for every subsystem
  - Multiple sites, including a planned larger scale demonstrator @CERN.





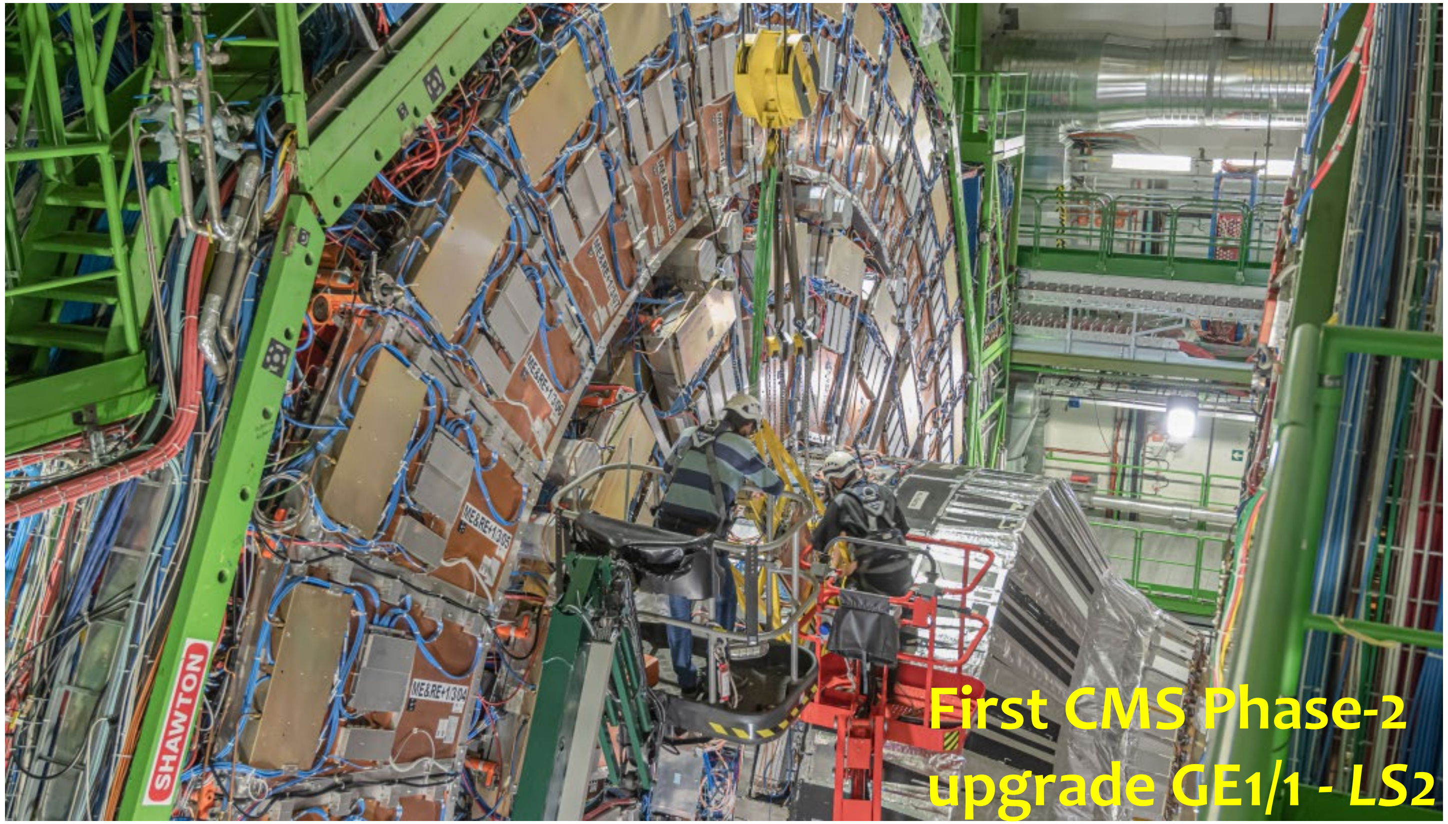

Electronics racks in building 904 (CMS electronics integration centre)





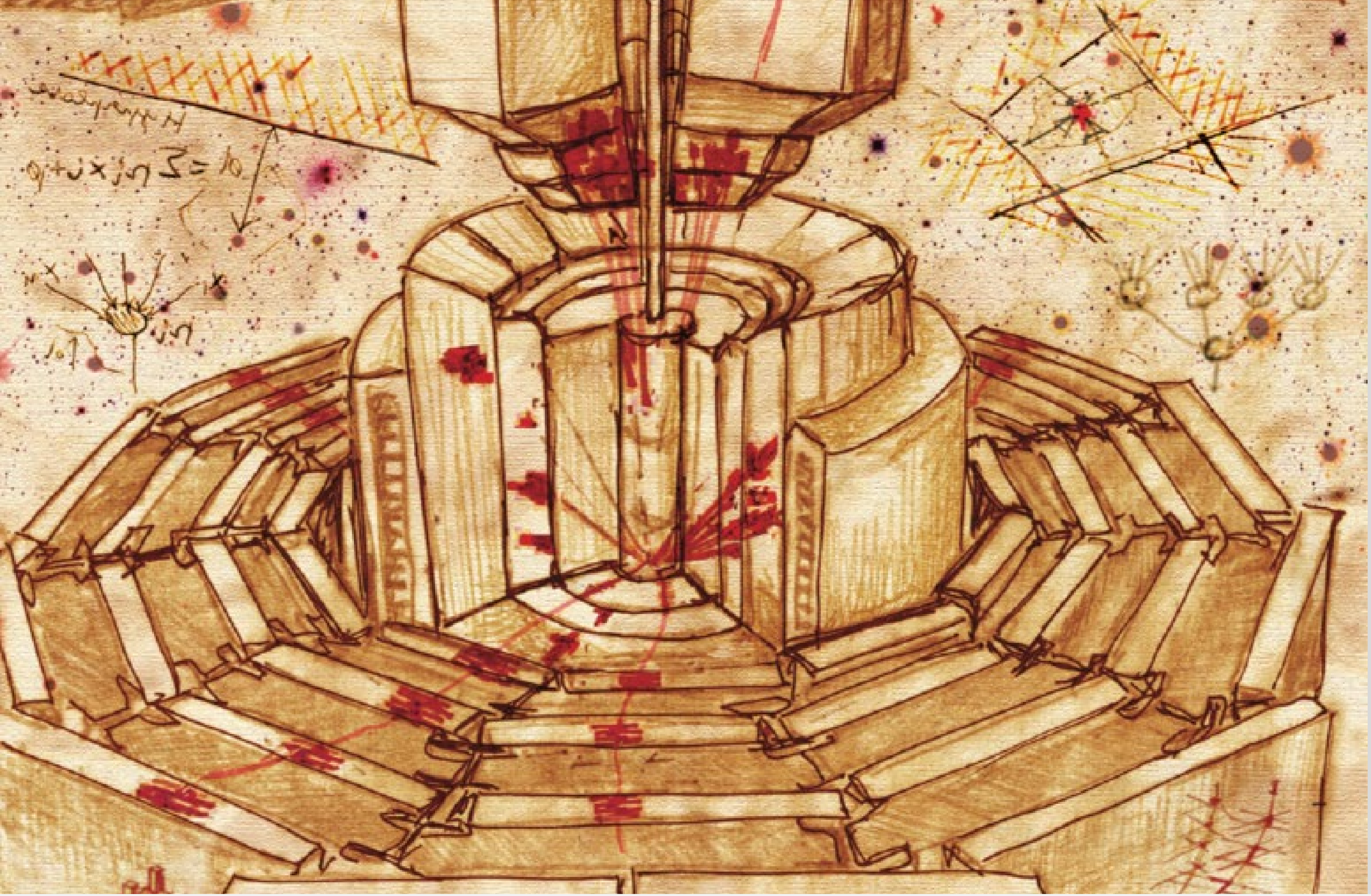
Summary

- In response to the unprecedented challenges of the HL-LHC environment and physics program, the CMS Upgrade introduces new paradigms
  - such as p_T modules for L1 Trigger Tracking, High Granularity Calorimetry and Precision Timing for PU mitigation
- Breaks new ground in detector technology.



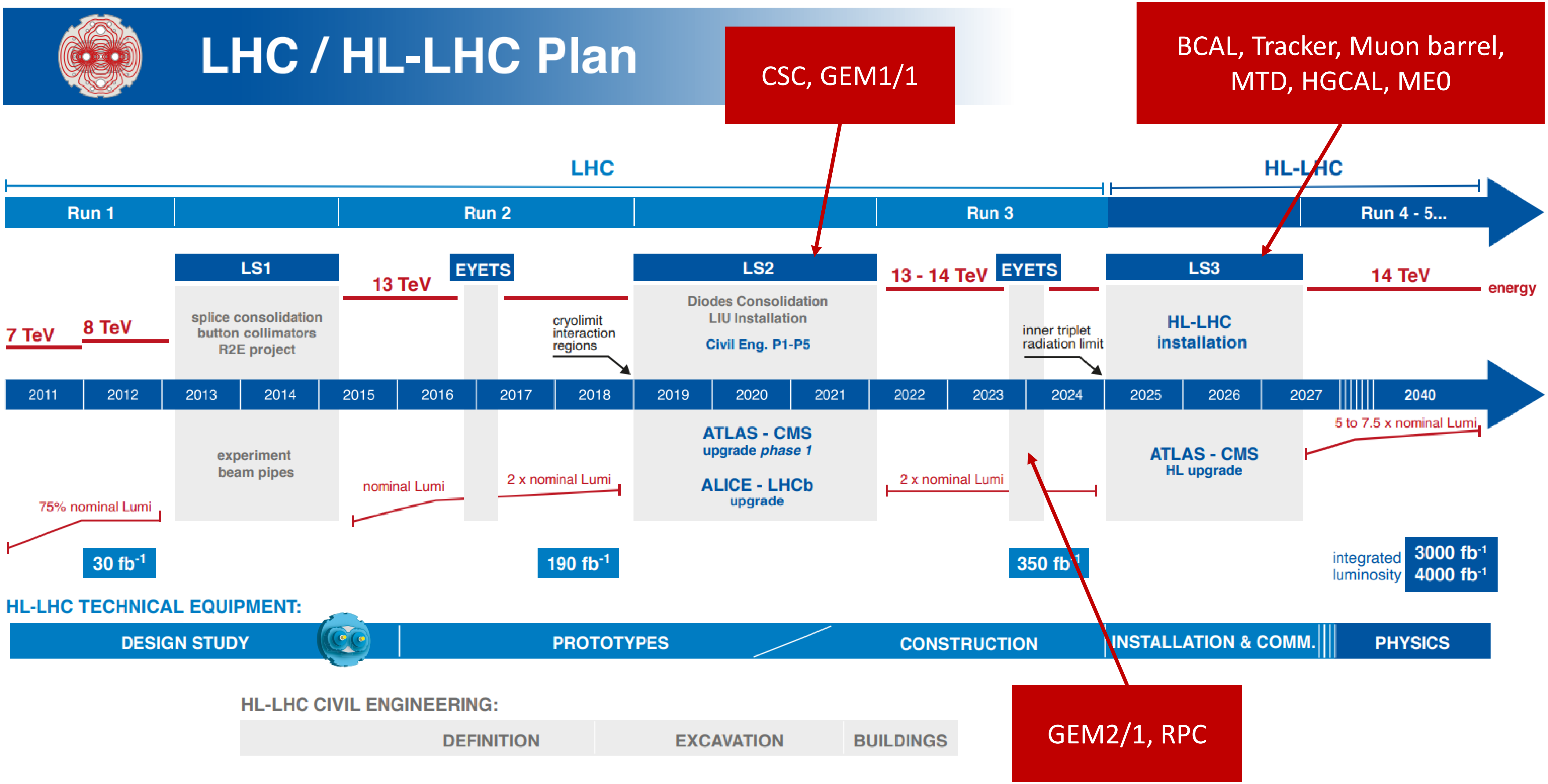
- The CMS HL-LHC upgrade program is by necessity ambitious, and many challenges still lie ahead.
- This, together with the commitment and support of CERN and of all the Funding Agencies and Institutes, provide a solid footing for successful completion of the HL-LHC Upgrade program.

Thanks!



backup

LHC / HL-LHC Plan



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- **… while vastly reducing mater**
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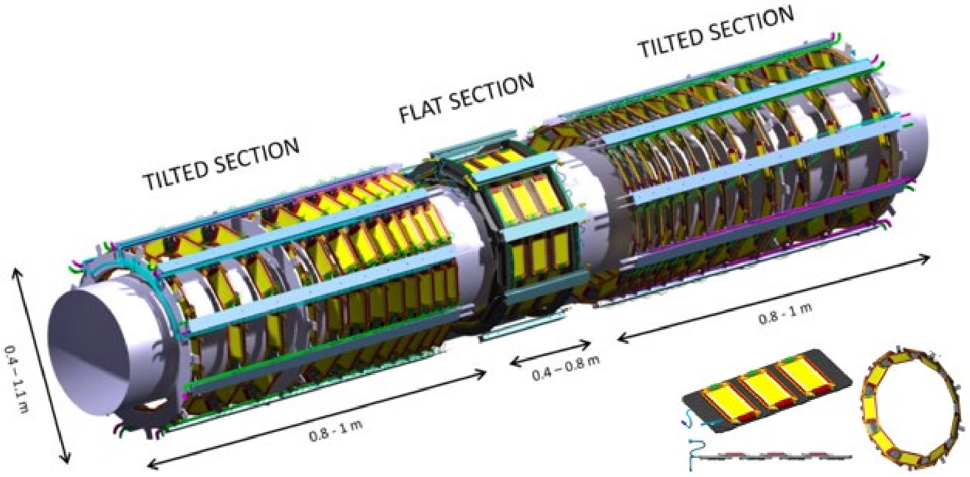
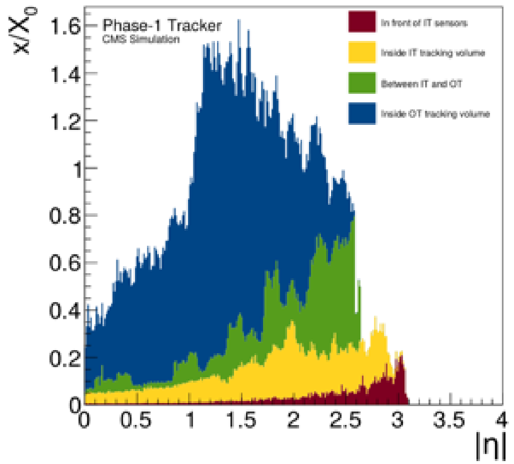
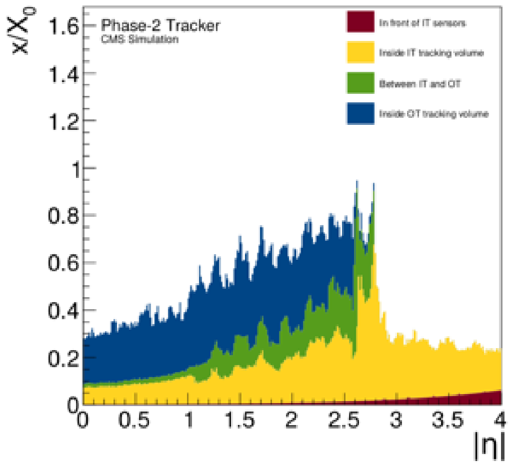
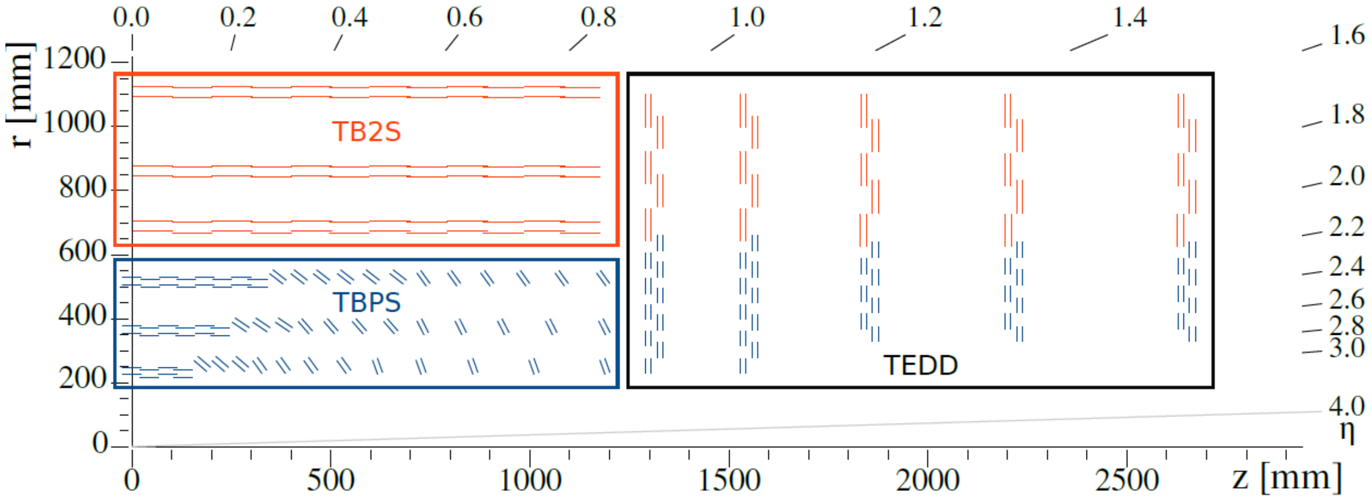
  - improved routing of services
  - tilted barrel section



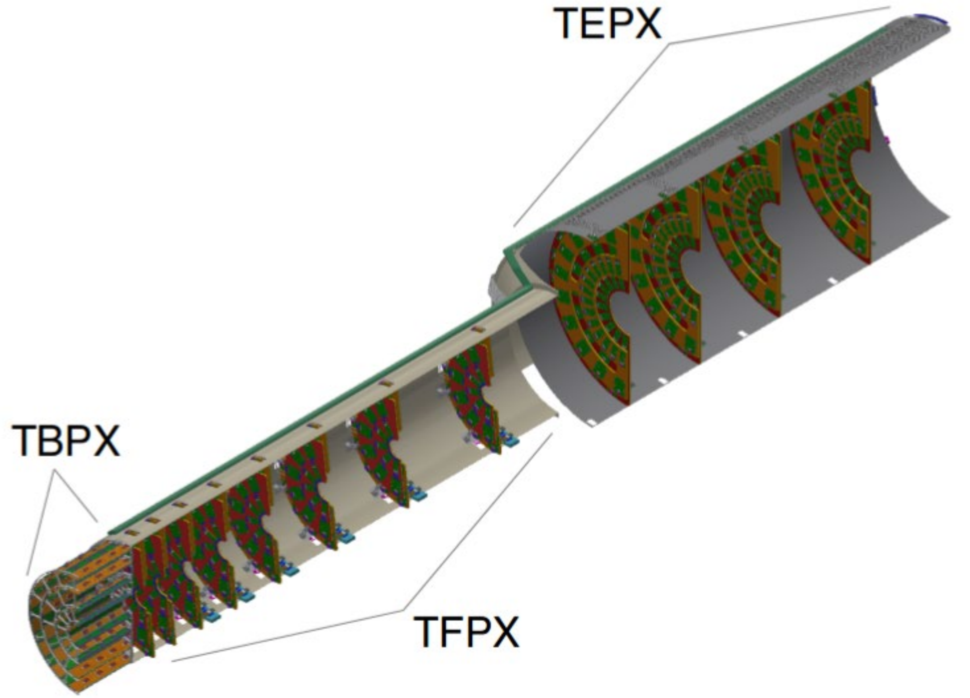


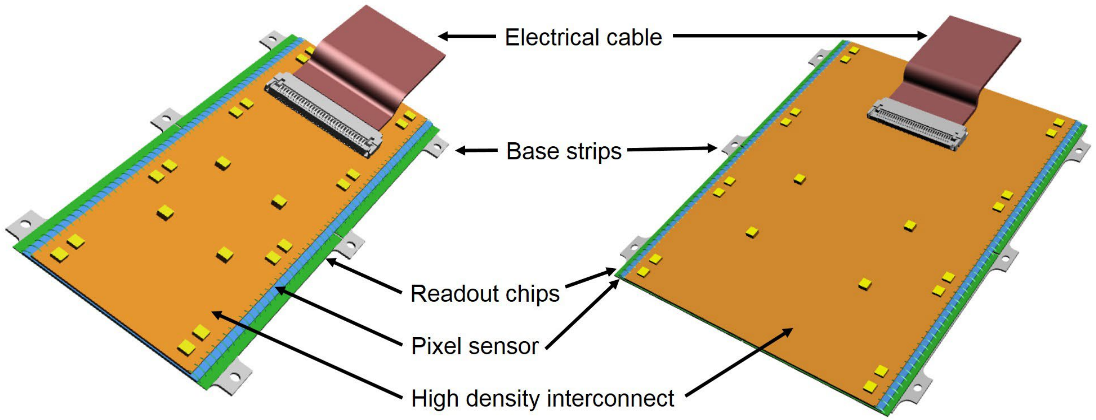




Inner tracker

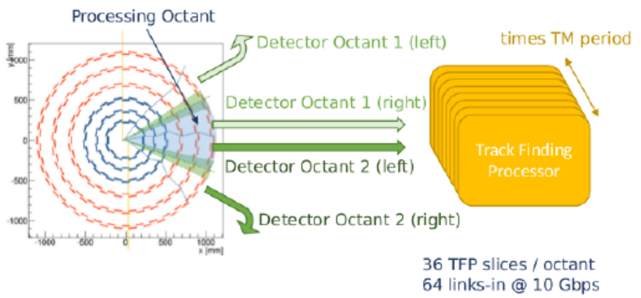
- **Radiation levels at HL-LHC:**
  - Ionizing radiation: 1.2 Grad
  - Hadron fluence: $2.3 \times 10^{16}\ \mathrm{n_{eq} cm^{-2}}$
  - Up to 3 GHz/cm² hit rate
- **Concept and design:**
  - Increased granularity with occupancy at per mille level: pixel size ~ 25 × 100 µm² or 50 × 50 µm²
  - Coverage up to η ~ 4, with ~4.9 m² active area
  - Layout: 4 barrel layers, 8 small disks, 4 large discs per side
  - capability to contribute to the real-time lumi measurement.
- **Mechanics and support:**
  - Simple structure for easy installation and removal → potential replacement of inefficient parts possible!
- **Two module variants:**
  - 2 ROCs (1x2) or 4 ROCs (2x2)
  - Flex circuit, glued to sensors, wire-bonded to ROCs



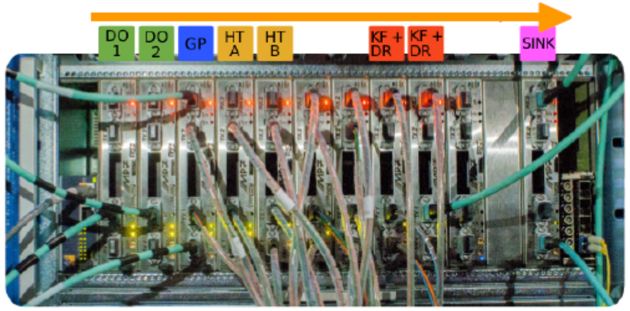


L1 tracks

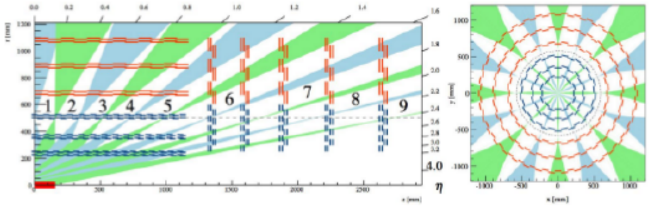
- **R&D activities**
  - Geometric processor
  - Hough transformation on the FPGA
  - Duplicate removal
  - R&D on TF prototype boards
  - Thermal performance
  - Improvements to the architecture
- **Production**
  - Assembly of a large fraction of boards
  - Commissioning



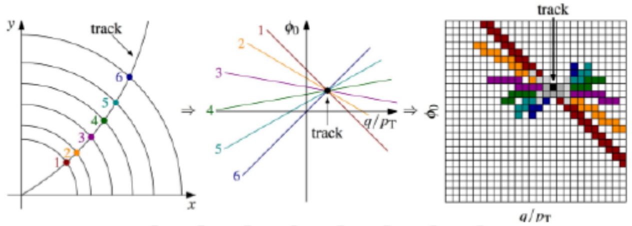
FPGA-based Hardware Demonstrator



Geometric Processor GP
Processes stub data, sub-divides octant into 36 sub-sectors

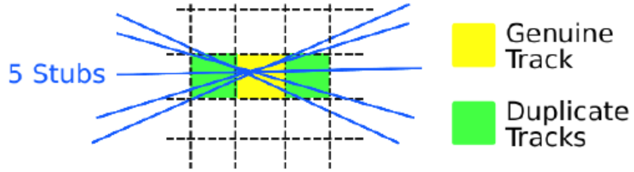


Hough Transformation HT
Track finder, identifies groups of stubs consistent with a track in r-φ



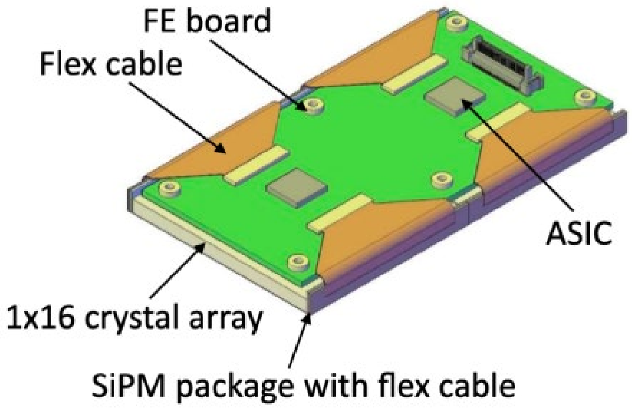
Kalman Filter KF
Candidate cleaning and precision fitting

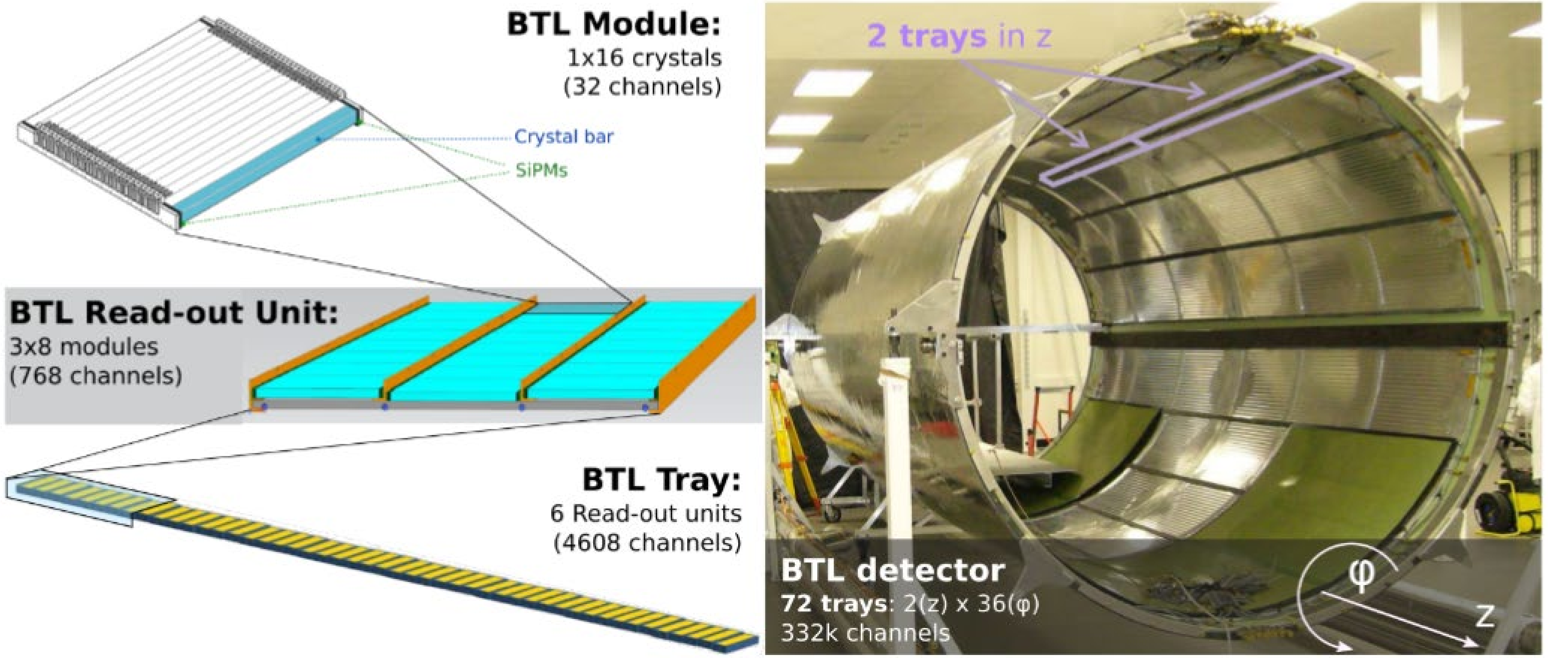
Duplicate Removal DR
Uses fit information to remove duplicate tracks generated by the HT



Data flow

The Barrel Timing Layer: Overview





Key features:

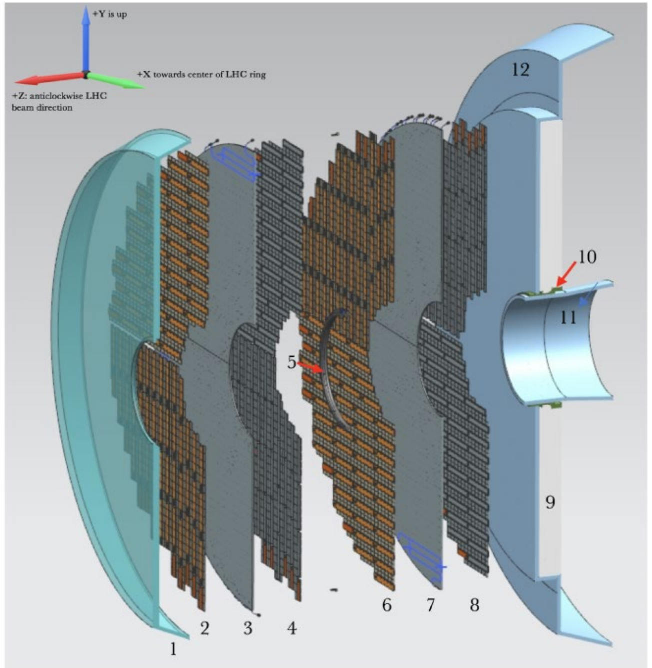
- LYSO crystals with dual end SiPM readout
- Basic unit : 1x16 array of crystals (~3x3x57 mm^3)
- Arranged in trays and segmented in readout units
- Coverage of $|\eta| < 1.45$, surface ~38 m^2, 332 k channels
- Nominal fluence : 1.9×10^{14} n_{eq}/cm^2

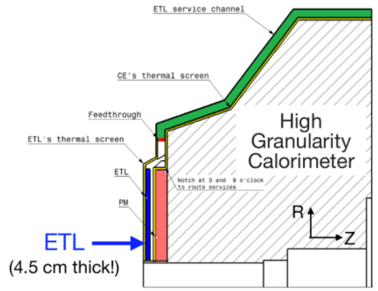
Recent Progress:

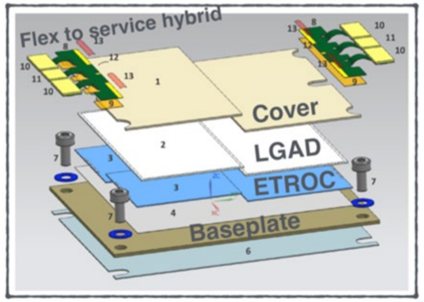
- LYSO qualification and testing
- SiPM characterization and procurement
- ASIC and FE prototyping and testing.
- System tests with FE/BE integration.
- Mechanics design.

The Endcap Timing Layer: Overview

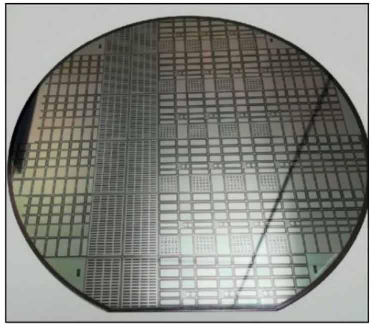
- **Key features:**
  - LGAD detectors
  - Basic unit : Module (~4x6 cm^2)
    - The LGADs are bump bonded to ETROC ASICs mounted on two sides of cooling plates.
  - Two disks per endcap mounted on the HGCAL nose.
  - Coverage of $1.6 < |\eta| < 3.0$, surface ~14 m^2, 8.5 M channels
  - Nominal fluence : $1.9 \times 10^{14}\ n_{eq}/cm^2$
- **Recent Progress:**
  - LGAD characterization
  - ASIC prototyping
  - System and Mechanics design prototyping

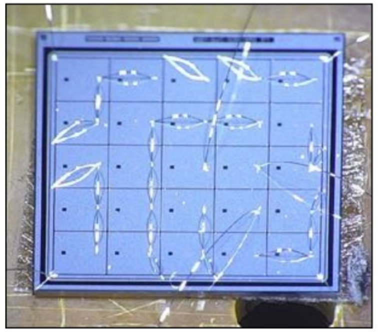






FBK UFSD3



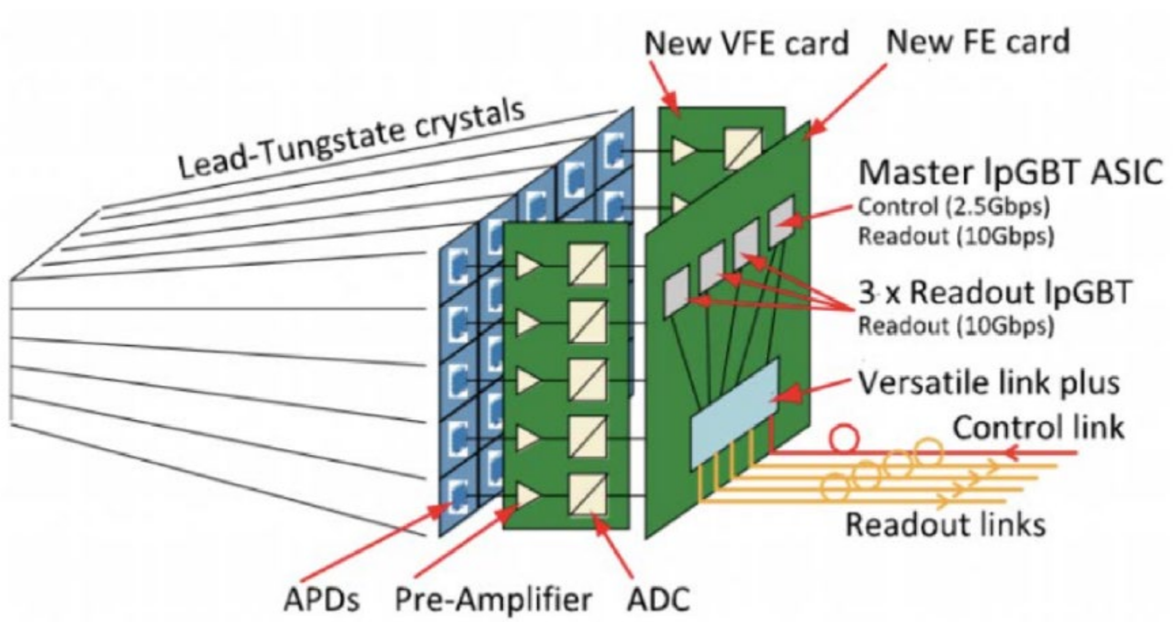


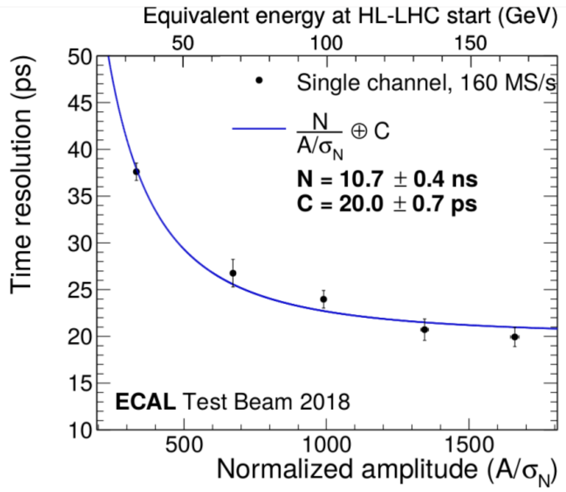
5x5 array from HPK

LGAD prototype sensors

Barrel Calorimeter (BCAL)

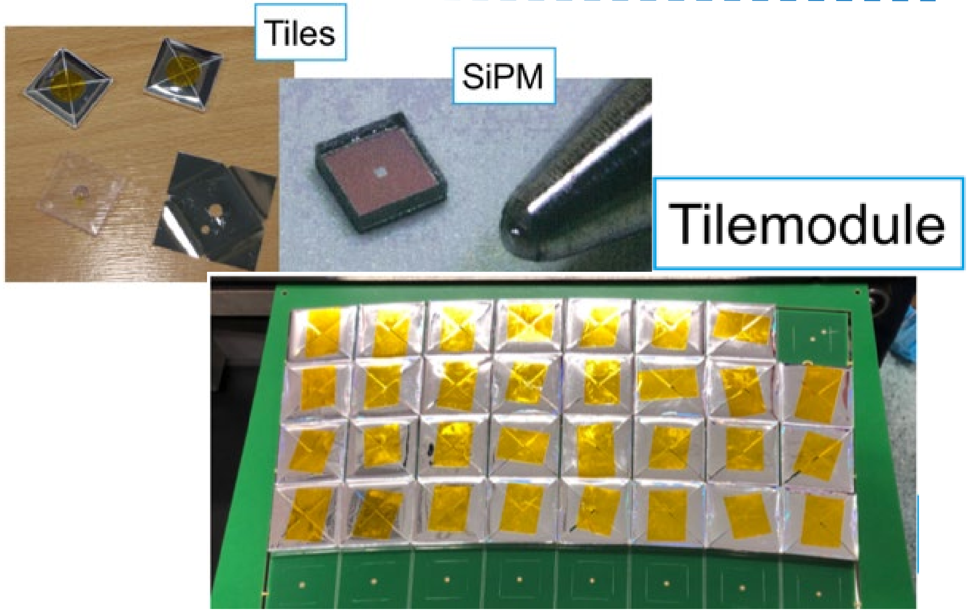
- **Replace all active on-detector electronics components (ECAL)**
  - Digitization at 160 MHz
  - On the fly pulse-shape discrimination o help discriminate against spikes
  - Oversampling - noise reduction, pile-up mitigation
  - Time resolution: 30 ps for E > 50 GeV
- **Streaming of all digitized data off-detector (using lossless compression)**
  - Lifts Phase-1 trigger latency bottleneck of 3.8 µs
  - trigger primitive generation off-detector
  - Cell information - 5 x 5 crystals → single crystal
- **Replace all off-detector electronics components (HCAL+ECAL – ATCA)**
- Reduce the operating temperature from 18oC to 9oC to mitigate APD ageing effects.





HGCAL: Active material

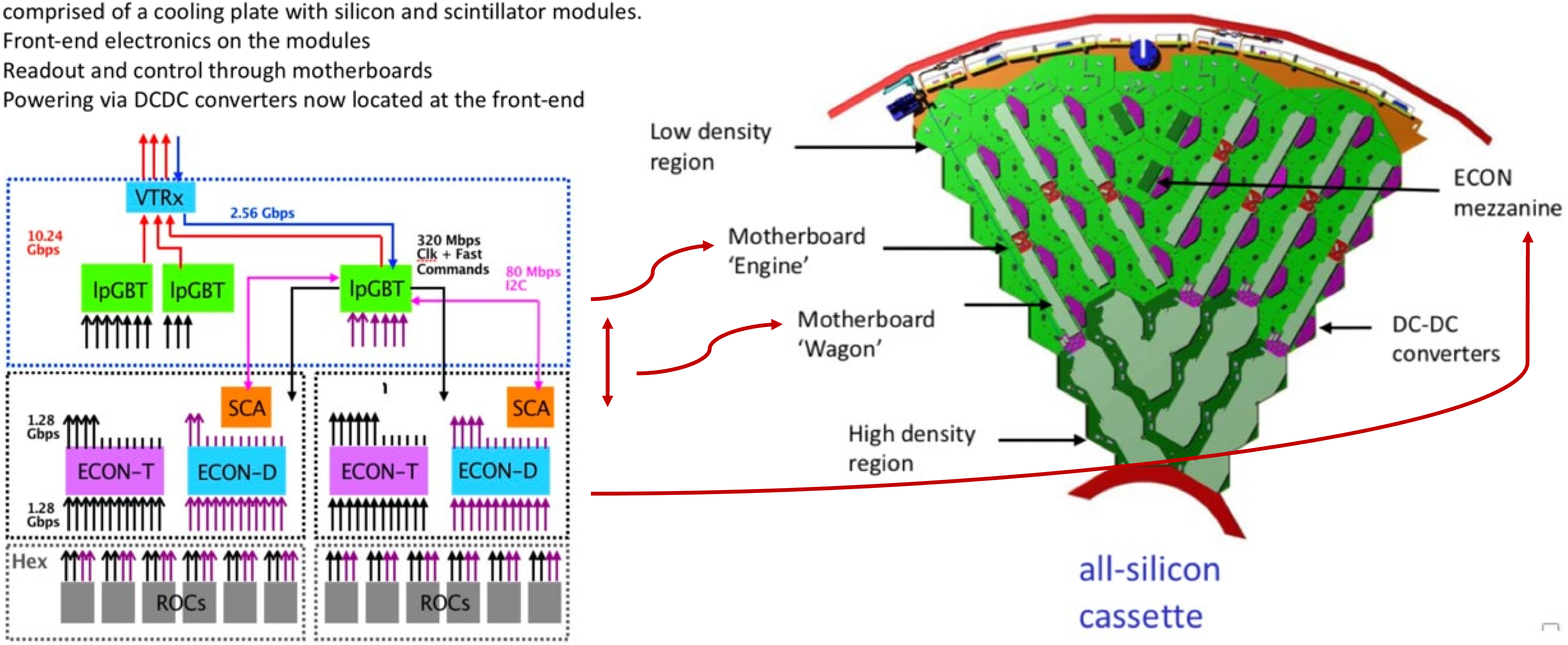
- **Silicon Sensors:**
  - The Silicon sensors are first use of 8" technology for large-scale HEP Sensors
    - Hexagonal geometry to maximize use of wafer area
  - Robust module constructed from a baseplate, insulating layer, silicon sensor, and readout PCB
  - Comprehensive test program including full-sensor tests with custom probe cards and reactor-based neutron irradiations



- **Scintillator Tiles and SiPMs :**
  - Scintillator tiles will be produced using both injection molding and machining of cast scintillator
    - Tiles will be wrapped with ESR foil in an automated wrapping machine.
  - SiPM photodetectors have been produced which provide sufficient signal-to-noise over the life of the experiment
- Tile modules constructed by automated pick-and-place of tiles onto tile PCB containing the SiPMs, readout chip, and other components

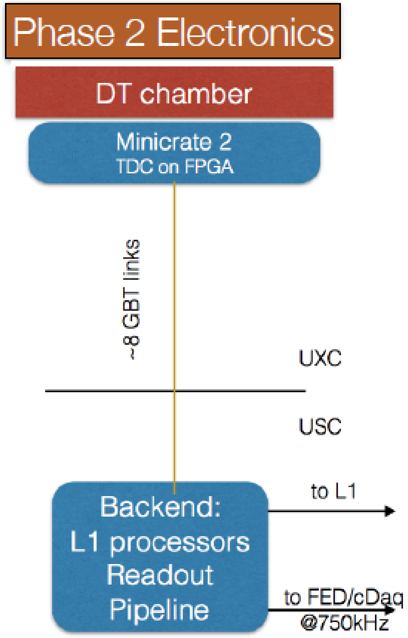
CMS HGCAL: Front-End Electronics Architecture

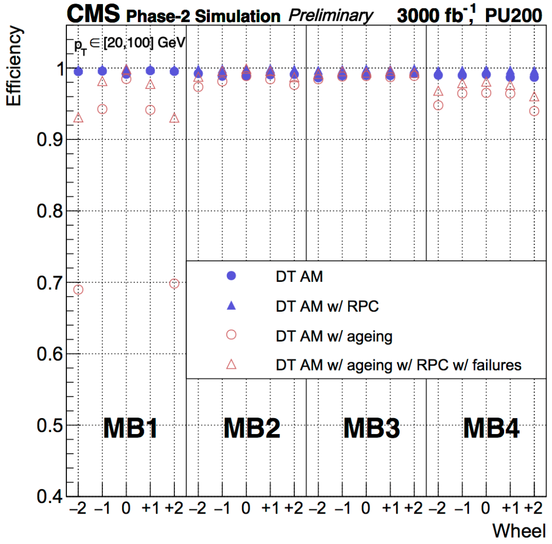
Active detector organized into **cassettes**
comprised of a cooling plate with silicon and scintillator modules.
Front-end electronics on the modules
Readout and control through motherboards
Powering via DCDC converters now located at the front-end

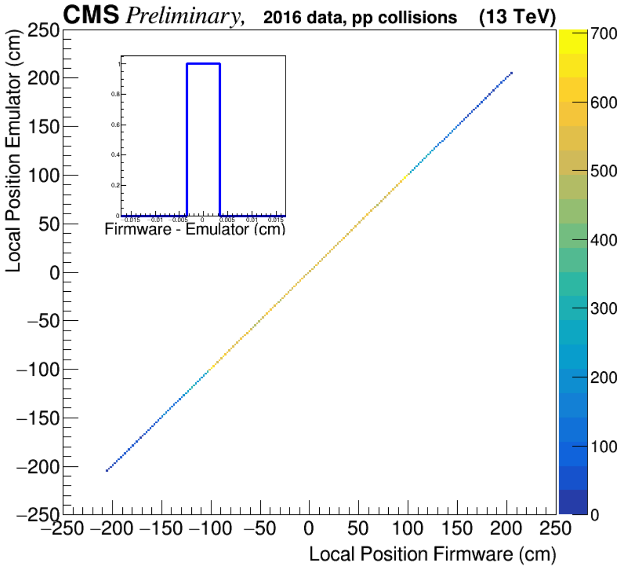


CMS Muon upgrade: DT

- **Replace FE and BE electronics LS3**
  - 40 MHz readout with improved z/t-precision
- Move trigger primitive (TP) functionality to BE:
  - more flexibility in combining DT and RPC hits to form Trigger Primitives (TP)
  - higher efficiency (use more than 4 layers for TPs)
  - better timing at L1 Trigger and improved resilience to ageing.



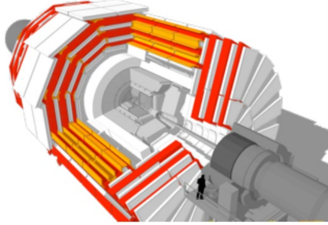




Slice installed during LS2: parallel ops in Run-3: DT sector has been instrumented with prototypes of OBDTs and operated with a full Phase-2 electronics demonstrator implemented on Phase-1 HW

- MB1/MB2: perform integration as in Phase-2, with only new electronics
- MB3/MB4: run legacy and Phase-2 chains in parallel to validate Phase-2 data quality using legacy information

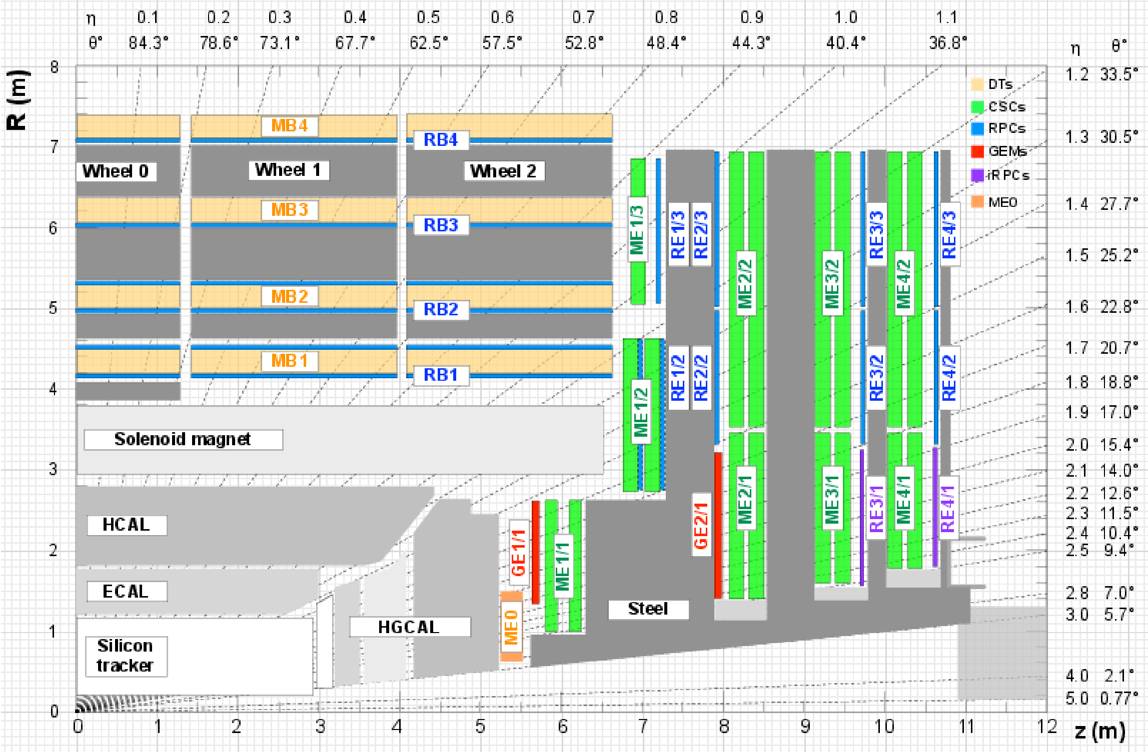
CMS Muon upgrade

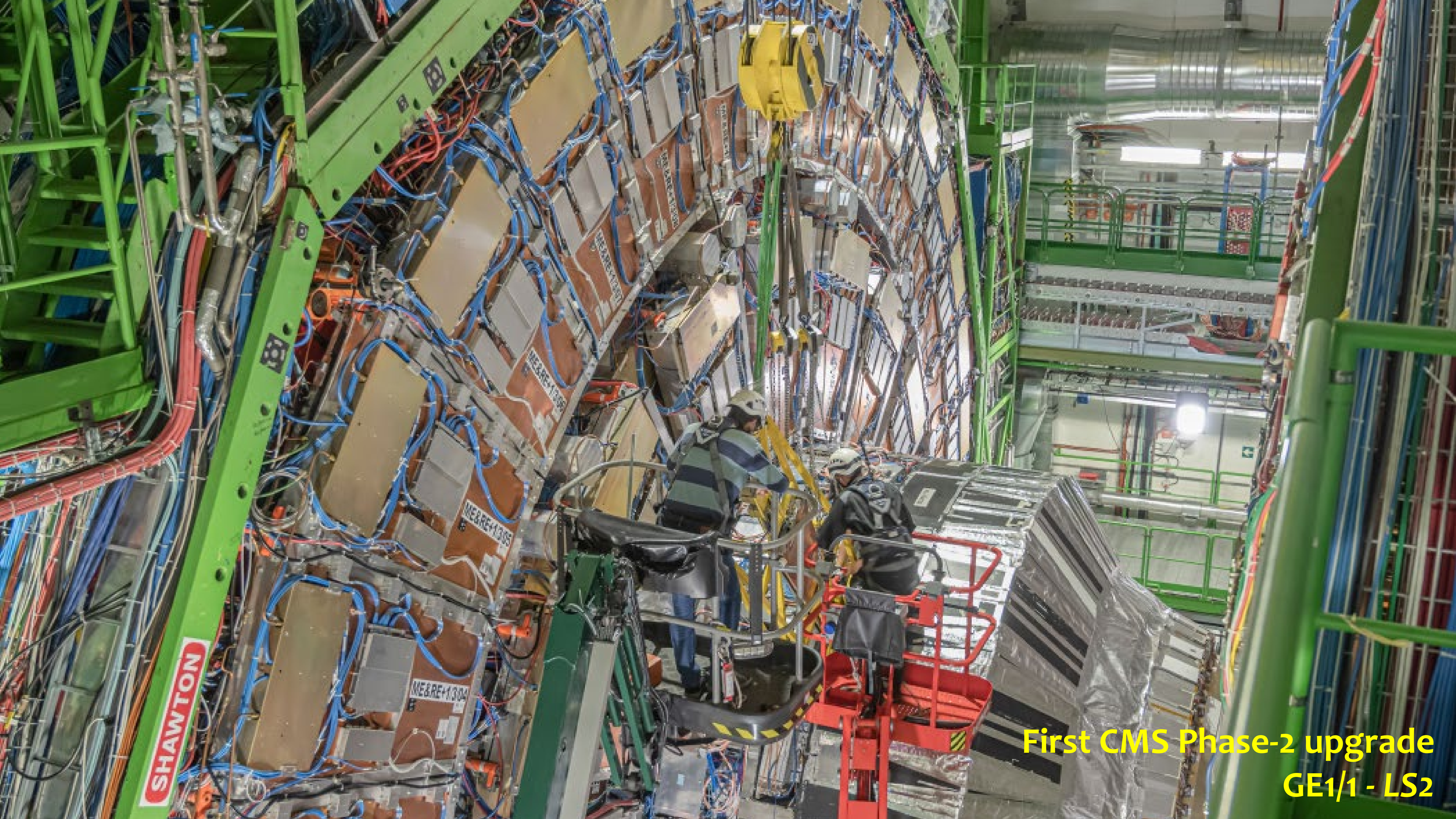


Current muon detectors are **expected to withstand HL-LHC radiation** levels.

Upgrading/replacing the electronics of the existing DTs, CSCs and RPCs to **ensure longevity and improve trigger performance**.

- **DT Drift Tubes barrel chambers:** 40 MHz readout with improved z/t-precision
- **RPC Resistive Plate Chambers:** readout with improved t-precision
- **CSC Cathode Strip Chambers:** readout with higher bandwidth and latency in ME234/1 using current ME1 and replace ME1 with higher radiation tolerance components
- **New stations:**
  - GEM: **GE1/1, GE2/1**, iRPC: **RE3/1, RE4/1,** 1.6 ≤ η ≤ 2.4
  - GEM: **ME0** extended coverage 1.15 ≤ η ≤ 3



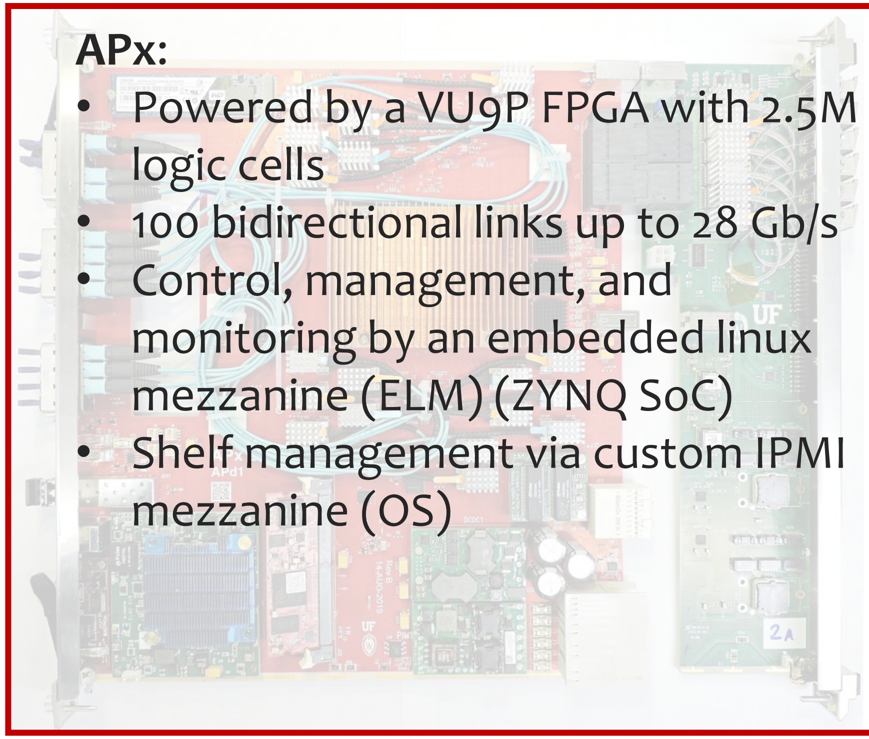


First CMS Phase-2 upgrade
GE1/1 - LS2

L1T: Hardware prototypes

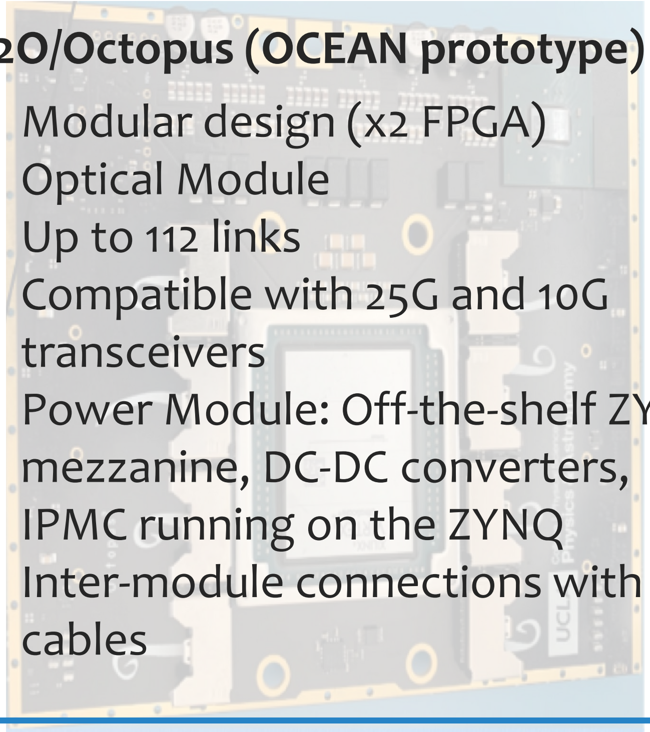
Design philosophy: Generic Processing Engines → I/O, FPGA

- FPGA : Xilinx Virtex Ultrascale / Ultrascale+
- Optics : Samtec Firefly x4 /x12 flyover
- Processors on board running commercial linux for flexible configuration and monitoring



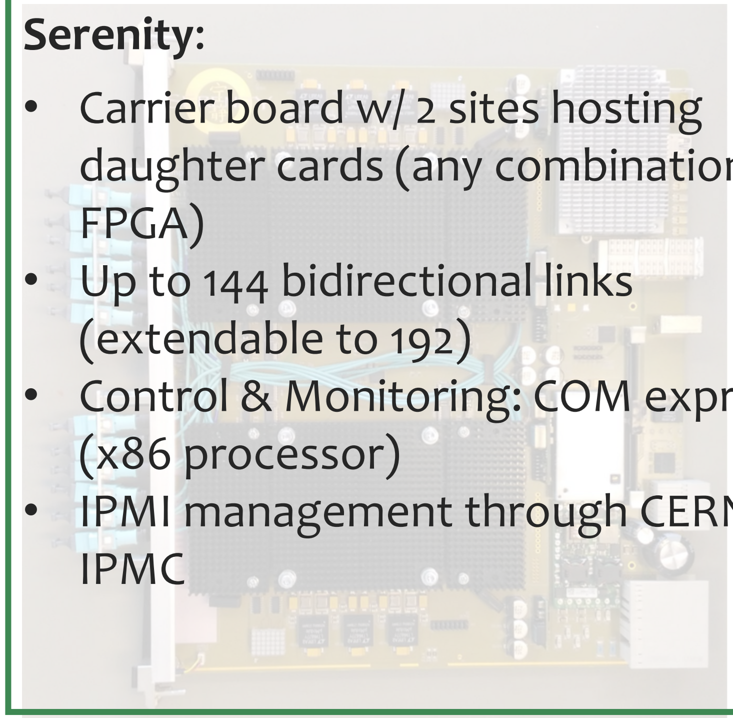
APx:

- Powered by a VU9P FPGA with 2.5M logic cells
- 100 bidirectional links up to 28 Gb/s
- Control, management, and monitoring by an embedded linux mezzanine (ELM) (ZYNQ SoC)
- Shelf management via custom IPMI mezzanine (OS)



X2O/Octopus (OCEAN prototype)

- Modular design (x2 FPGA)
- Optical Module
- Up to 112 links
- Compatible with 25G and 10G transceivers
- Power Module: Off-the-shelf ZYNQ mezzanine, DC-DC converters, IPMC running on the ZYNQ
- Inter-module connections with cables



Serenity:

- Carrier board w/ 2 sites hosting daughter cards (any combination of FPGA)
- Up to 144 bidirectional links (extendable to 192)
- Control & Monitoring: COM express (x86 processor)
- IPMI management through CERN IPMC

L1T: Particle-Flow @L1

- Huge step forward that will vastly increase physics performance at L1
  - Availability of tracks & high-granularity calorimetry.
  - Further help to mitigate pileup.
- **Demonstrated a working PF+PUPPI algorithm**
  - PF+PUPPI hugely reduces the event complexity
  - Allows for a lot of flexibility in downstream design
  - L1 Algorithms looks like offline reconstruction
  - PF+PUPPI developed with Vivado HLS that meets HW requirements (latency, resources occupancy,...)