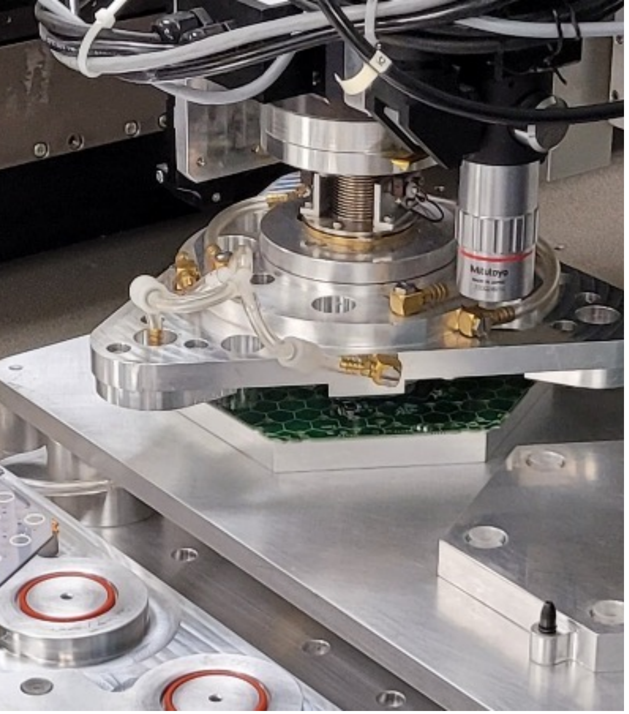
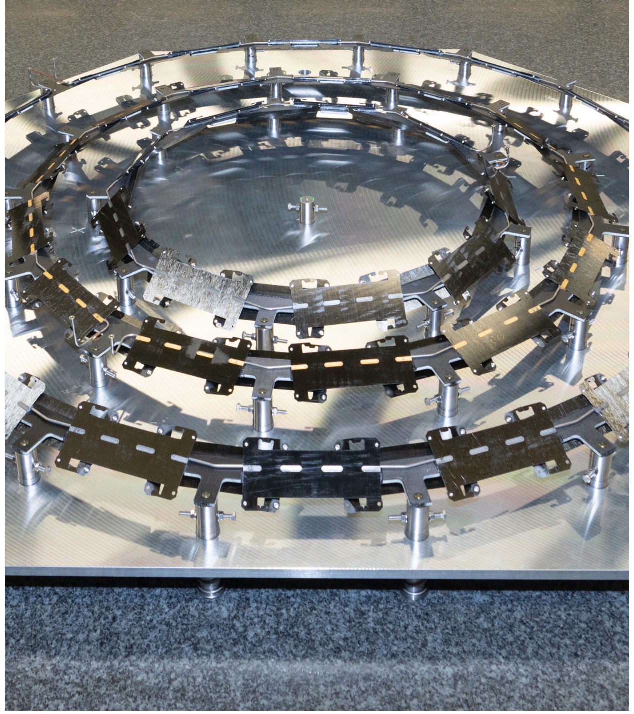
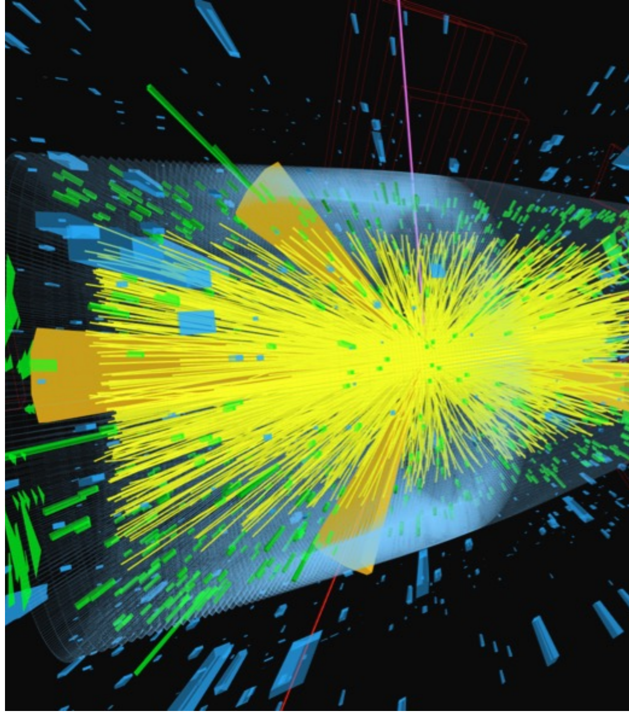
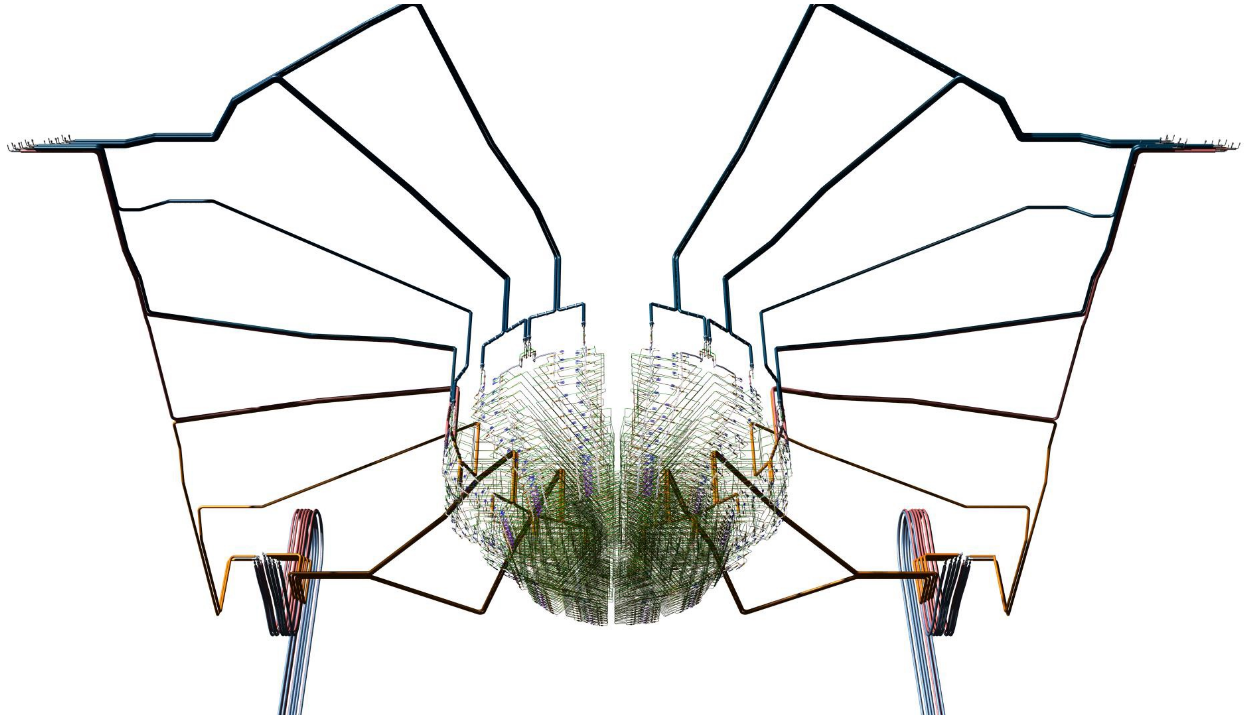








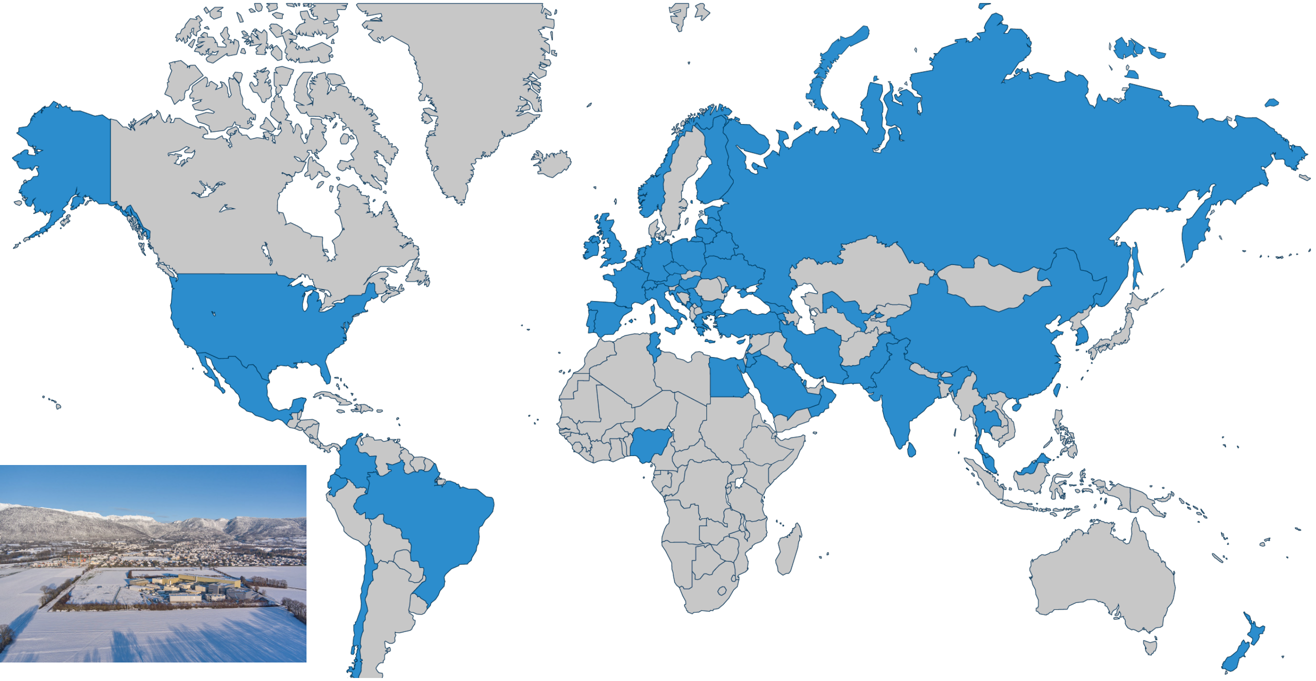
Technological developments for the CMS HL-LHC Detector Upgrade

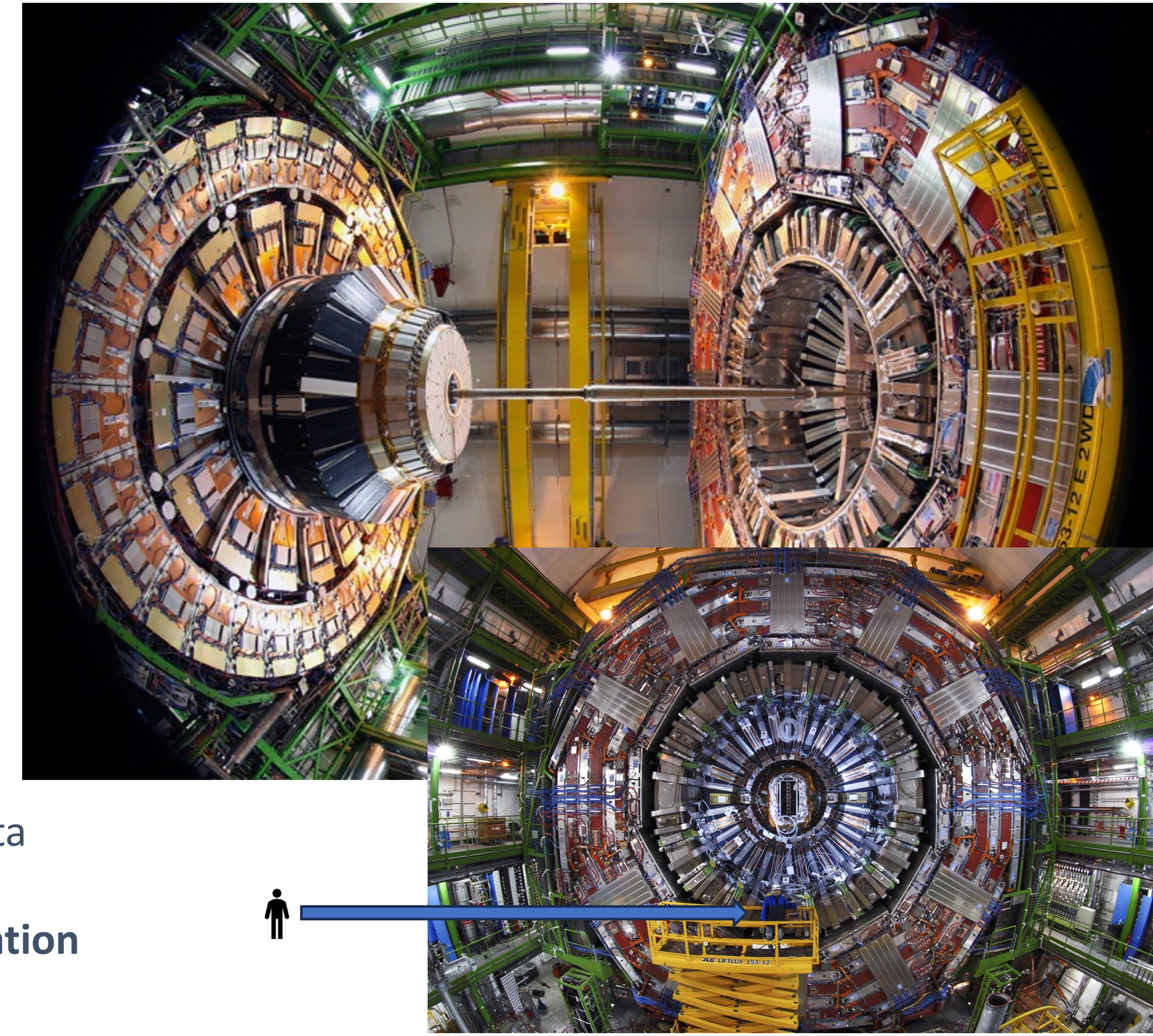
to enable a maximizing of new physics measurements …
at the highest rates ..
highest fluence …
highest pileup …

Anne Dabrowski (CERN)
On behalf of the CMS experiment

Thanks to special contributions from F. Hartmann, P. Rumerio and P. Tropea and all CMS sub-system Upgrade Coordinators

CMS Today - collaboration & detector

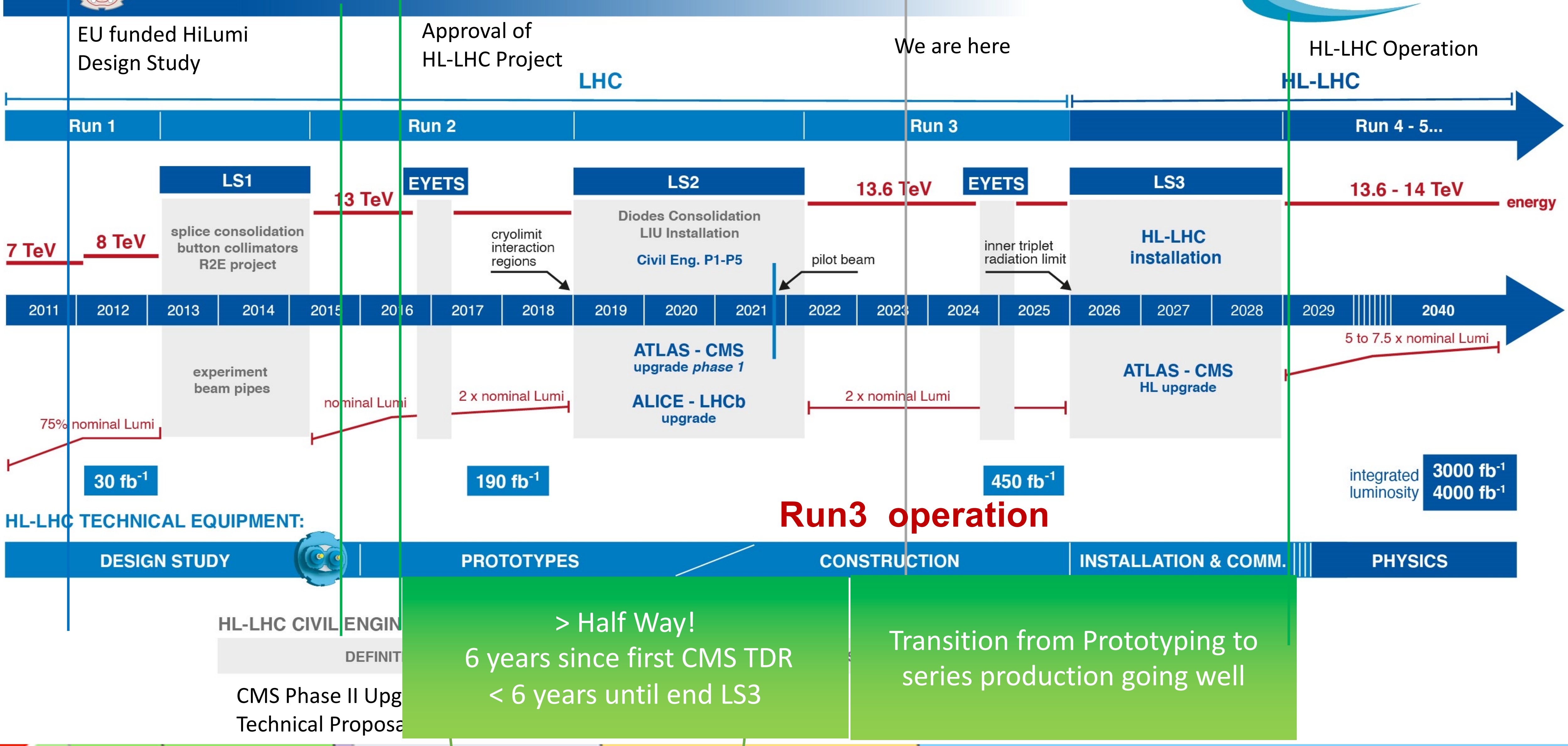




3394	1102	282	247	57
PHYSICISTS (1228 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

- Collected ~237 fb^{-1} of p-p data and > 1210 papers on collider data published or submitted to a journal
- Community committed to **physics exploitation**, **LHC Run 3 operation and maintenance** & **Phase II detector upgrade for HL-LHC**

LHC / HL-LHC Plan



> Half Way!
6 years since first CMS TDR
< 6 years until end LS3

Transition from Prototyping to series production going well

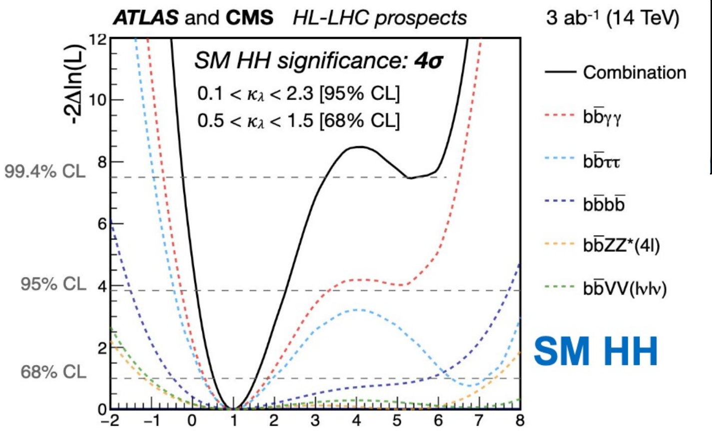
Physics @ HL-LHC … ``Higgs factory” and more

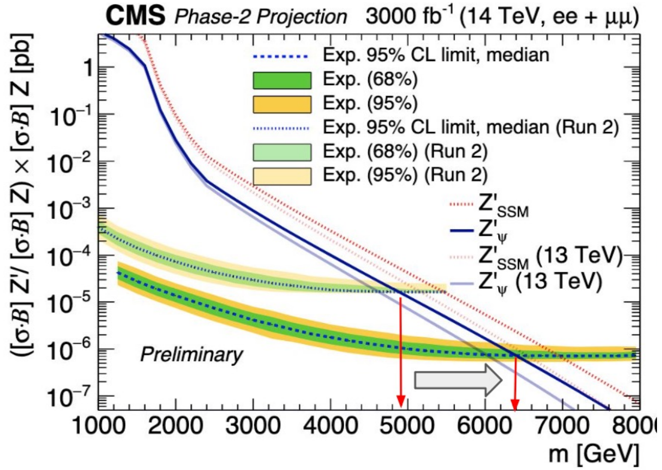
Precision tests of the standard model and Higgs physics, explore electroweak symmetry breaking, new physics via quantum loops, e.g.

- Higgs couplings at few %
  - HL-LHC will produce > 150 Million Higgs bosons
- di-Higgs production
  - HL-LHC will produce ~120k of pair-produced Higgs events
- Rare decays
- Longitudinal vector boson scattering

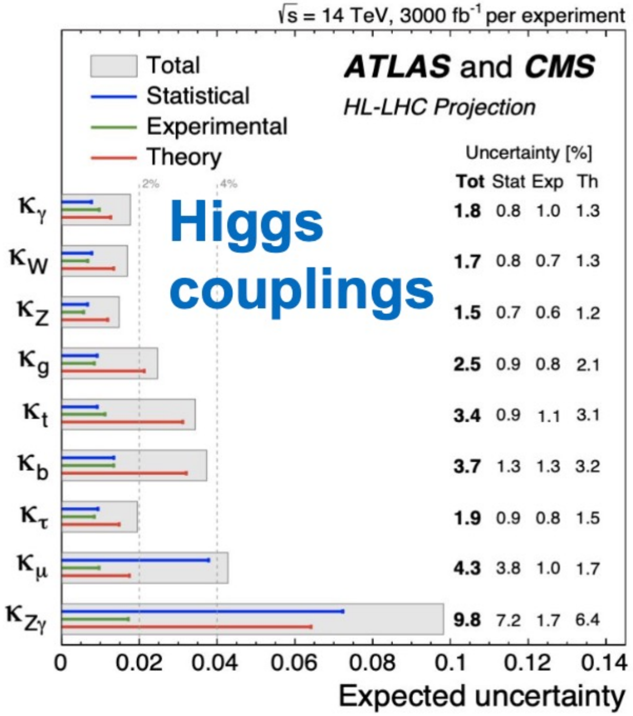
Hunt for rare exotic physics phenomena

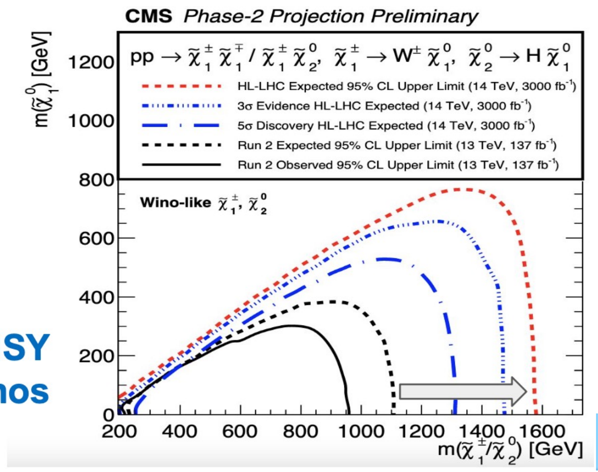
- Dark matter?
- New resonances?
- Long lived particles?
- Supersymmetry?
- Extra dimensions?



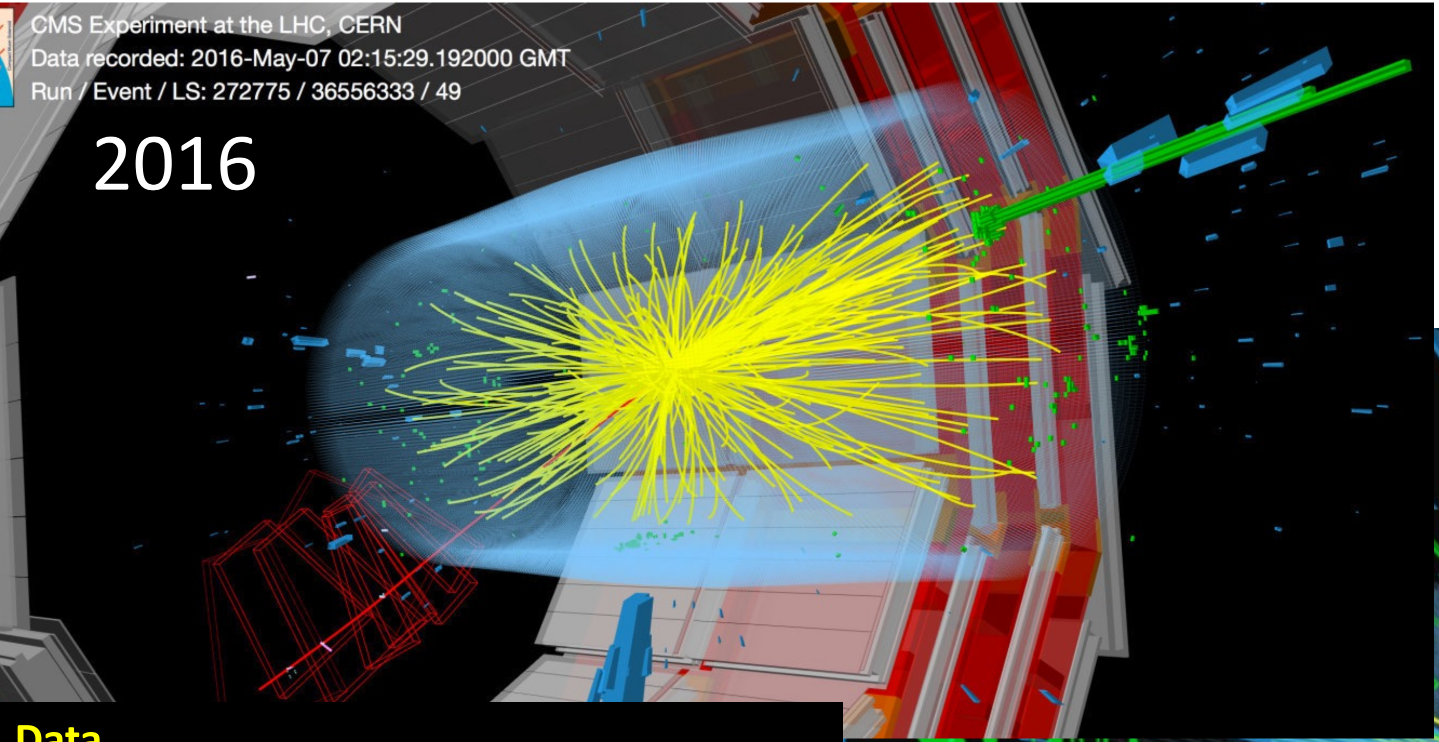


Dilepton resonances

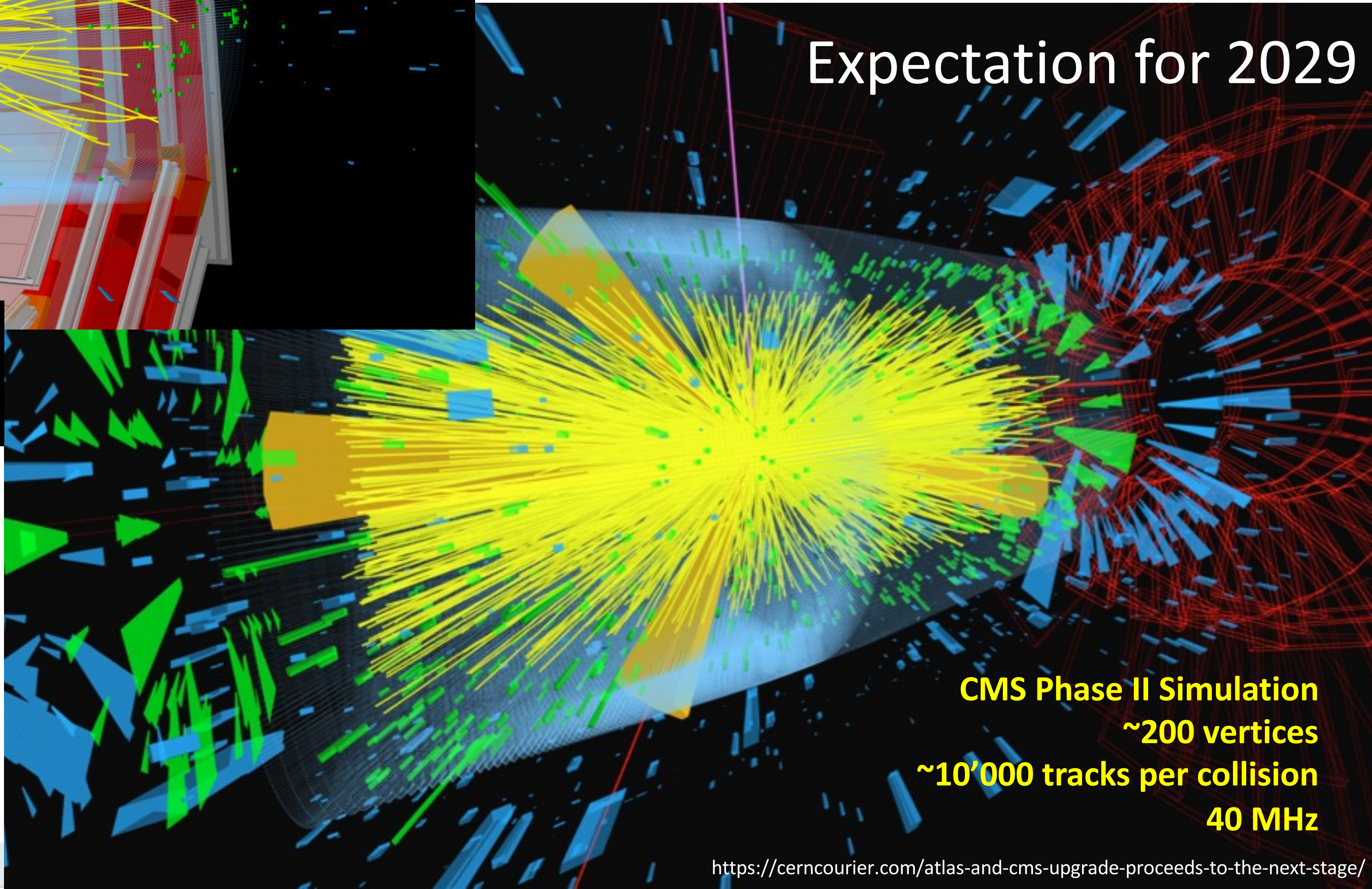




SUSY gauginos



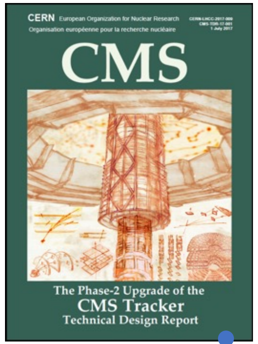
Data
~35 vertices = 40 collisions = pile-up
~2’000 tracks per collision bunch (40 MHz)

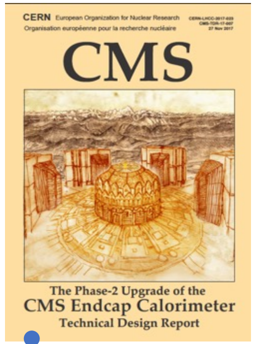


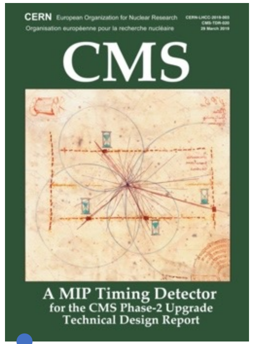
CMS Phase II Simulation
~200 vertices
~10’000 tracks per collision
40 MHz

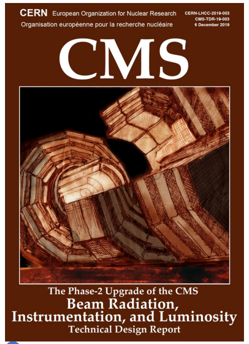
https://cerncourier.com/atlas-and-cms-upgrade-proceeds-to-the-next-stage/

CMS HL-LHC Plan





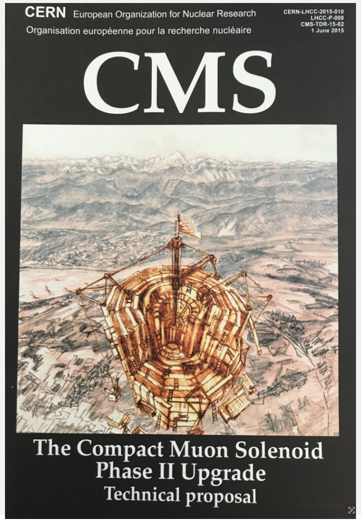


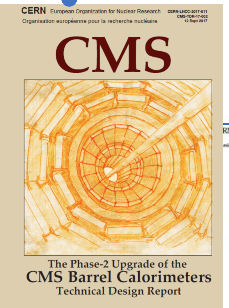


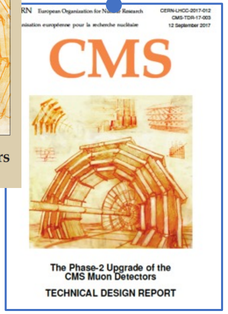
CMS Sub-system Phase-2 Upgrade Technical Design Reports (2017-2021)

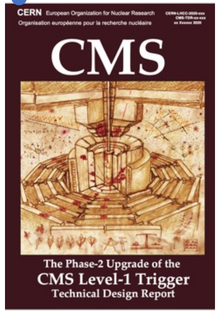
2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2040

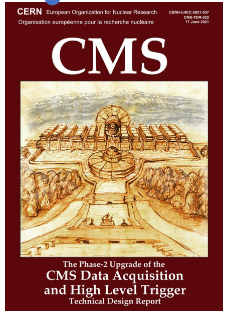
CMS Phase-2 Upgrade Technical Proposal







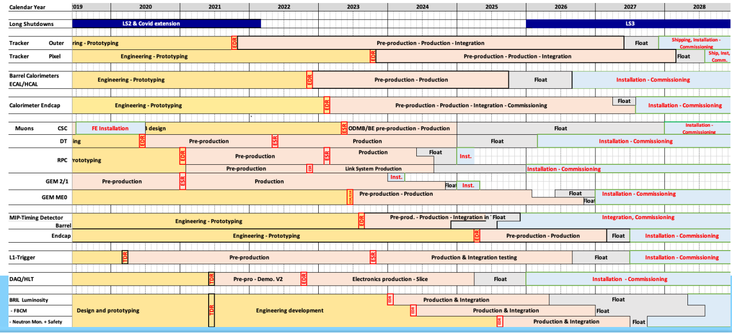




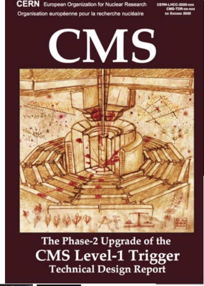
Intensive R&D and prototyping **prior** and **following** each Technical Design Report

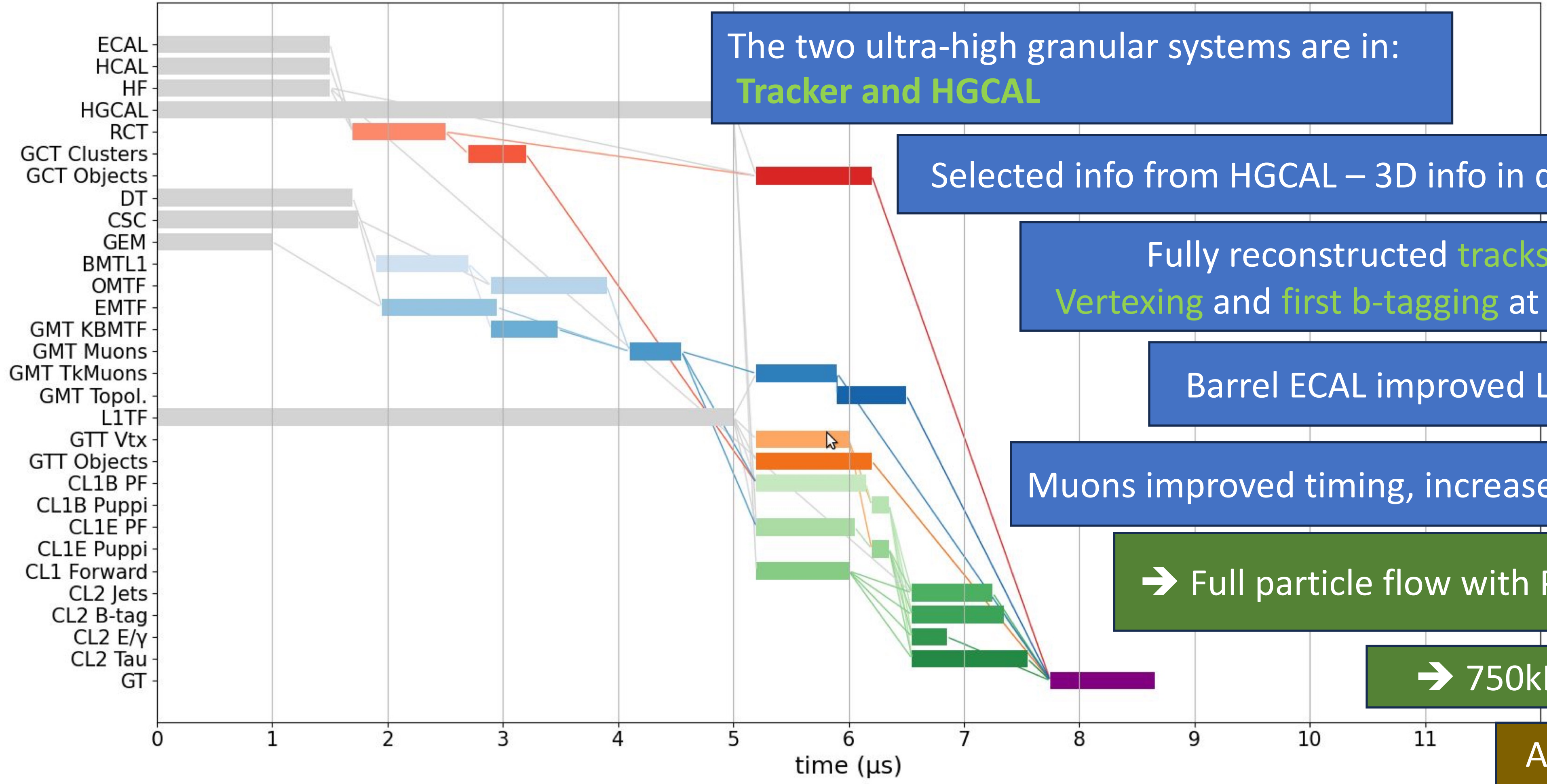
This culminates in a final Engineering Design Report (EDR)

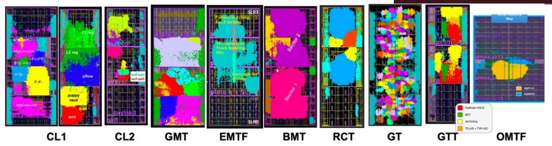
... after which production starts



Globally Incorporating **Level-1 Trigger** Aspects for Achieving **Equal or Lower PT** Thresholds in **HL-LHC** Compared to Run 3 in initial TDR designs







The two ultra-high granular systems are in:
Tracker and HGCAL

Selected info from HGCAL – 3D info in dedicated system stream

Fully reconstructed tracks above 2 GeV
Vertexing and first b-tagging at L1 – σ_Z about 1mm

Barrel ECAL improved L1 granularity: factor 25

Muons improved timing, increase redundancy and eta coverage

➔ Full particle flow with PU mitigation

➔ 750kHz to High Level Trigger

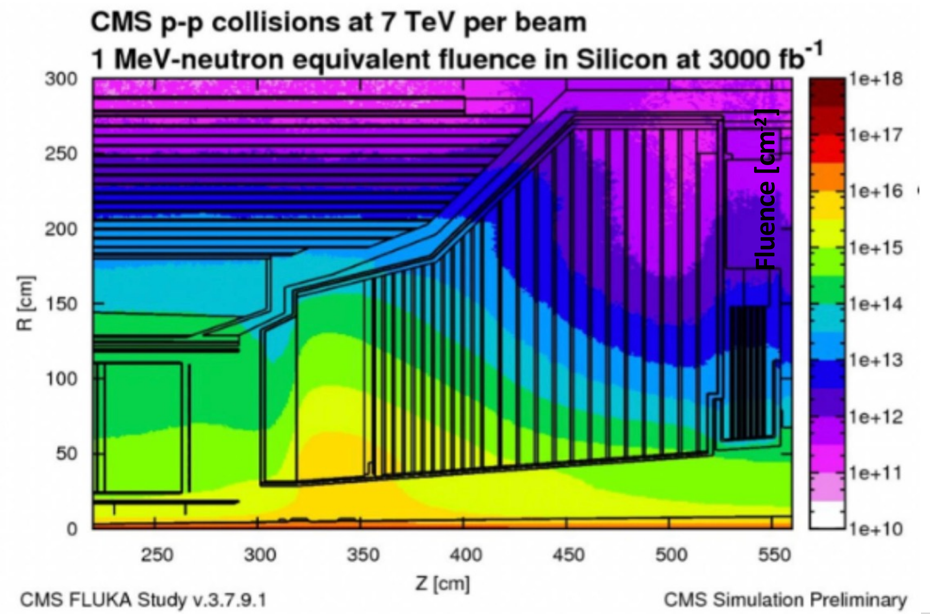
All Phase II systems compatible with 12.5 μs latency (3.5 μs today)

Level-1 Trigger latency – preliminary, based on algos in **firmware in test systems**

More info, comprehensive presentation at TIPP,
System Design and Prototyping for the CMS Level-1 Trigger at the High-Luminosity LHC, Alexandre Zabi
The Upgrade of the Level-1 Muon Trigger at the CMS experiment for the High-Luminosity LHC era, Prof. Jacobo Konigsberg

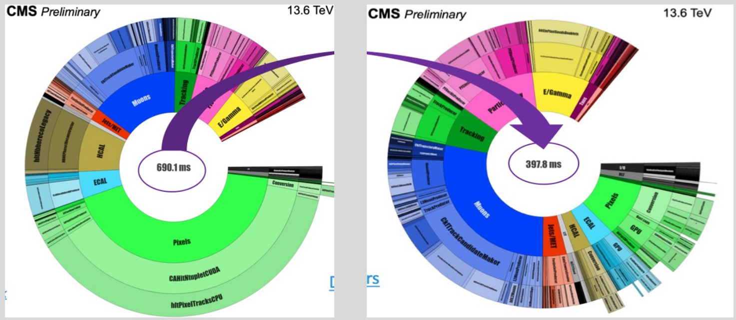
Constraints / challenges / opportunities

- Radiation environment → more tolerant technology
- Particle rates/density → granularity, readout
- How to increase $|\eta|$ coverage → Tracker & Muons
- Power in similar cable x-section → use DC-DC converters
- Power density and cold operation (~0.5 MW for HGCAL+ MTD+TK) → bi-phase CO_2 cooling at -35 ℃



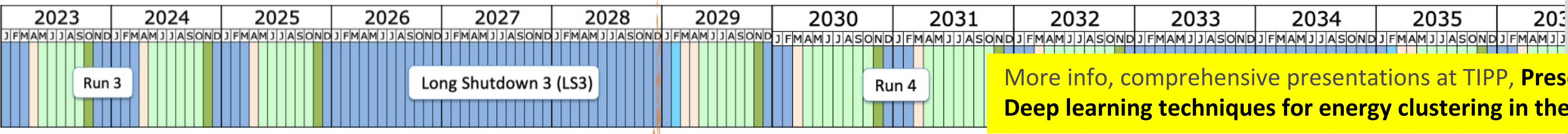
- New detectors must fit into already defined volumes
  - CMS to install new services for legacy and new detectors

- Schedule
  - Advance any work from long shutdown 3 earlier
    - Endcap Muon detectors GE1/1 installed LS2 and GE2/1 and RPC for YETS
    - CO_2 infrastructure, services and manifolds
    - Surface laboratories and labs to assemble the sub-systems
  - Continuous development
    - E.g. Run 3 deployment trigger algos ; heterogenous computing and migration of reconstruction algorithms to GPUs at High Level Trigger …



Run 3: 690 ms = ave. processing time per event for CPU Only Configuration

Run 3: 397 ms = ave. processing time per event for GPU & CPU Configuration



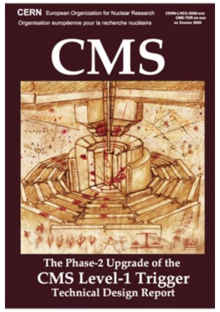
More info, comprehensive presentations at TIPP, **Present and future of tracking and vertexing in CMS** Marco Musich
Deep learning techniques for energy clustering in the CMS electromagnetic calorimeter Dr Polina Simkina

On the technology aspect

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."

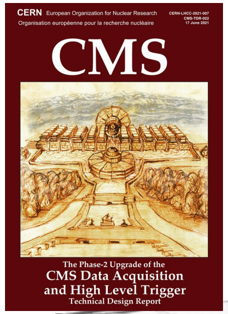
The CMS Phase 2 Upgrade



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

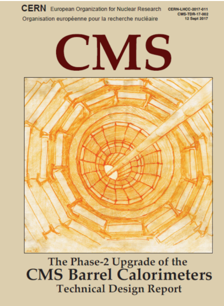
https://cds.cern.ch/record/2759072

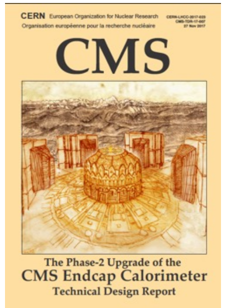
- Full optical readout
- Heterogenous architecture
- 60 TB/s event network
- 7.5 kHz HLT output

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

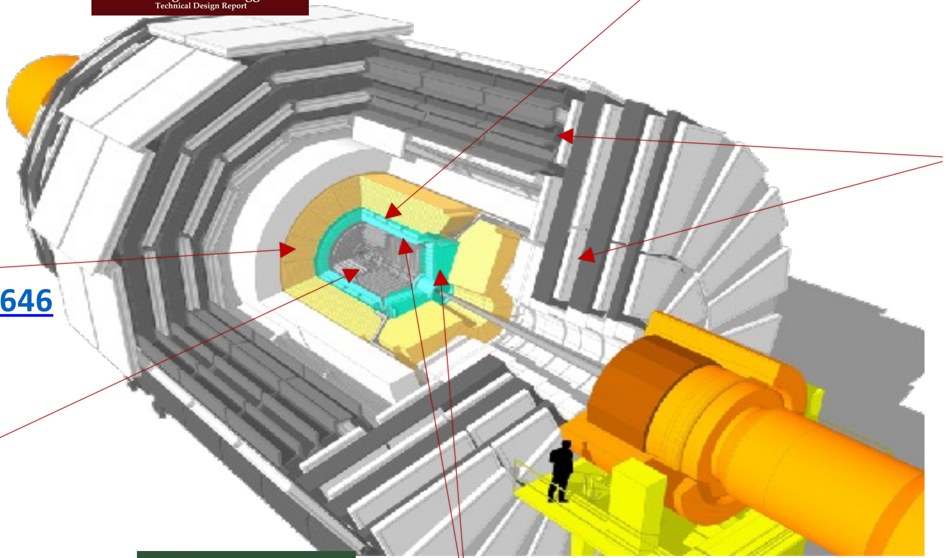




Calorimeter Endcap

https://cds.cern.ch/record/2293646

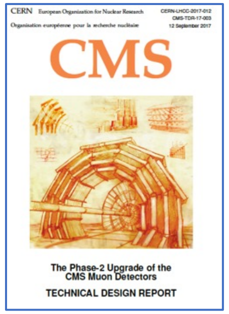
- Highly granular
- 3D showers and precise timing
- Silicon, Scint+SiPM in Pb/W-SS

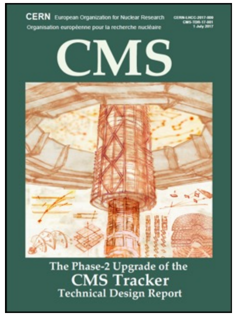


Muon systems

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

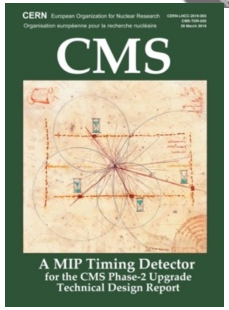




Tracker

https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8



MIP Timing Detector

https://cds.cern.ch/record/2667167

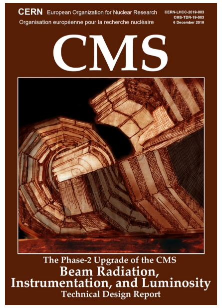
Precision timing with:

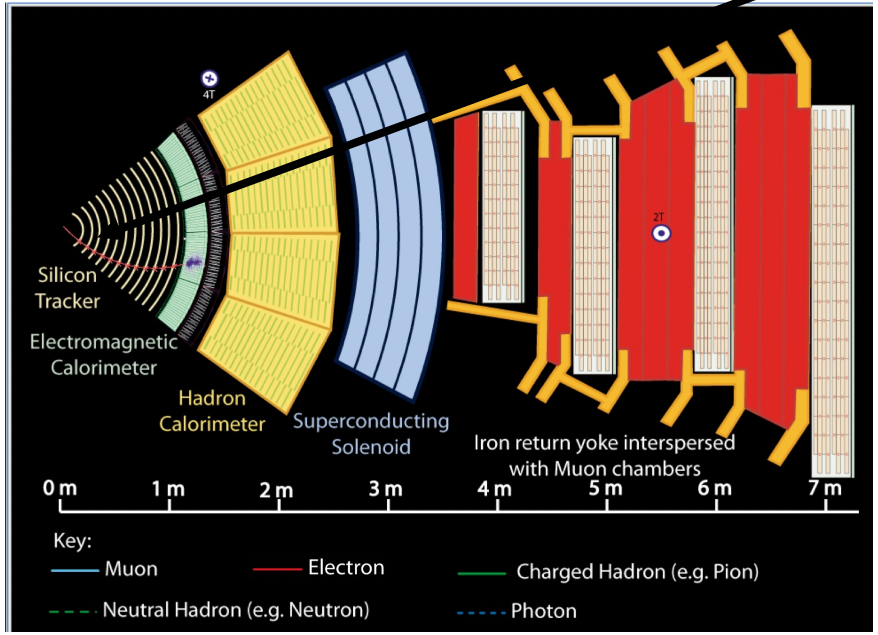
- Barrel layer: Crystals + SiPMs
- Endcap layer:
  Low Gain Avalanche Diodes

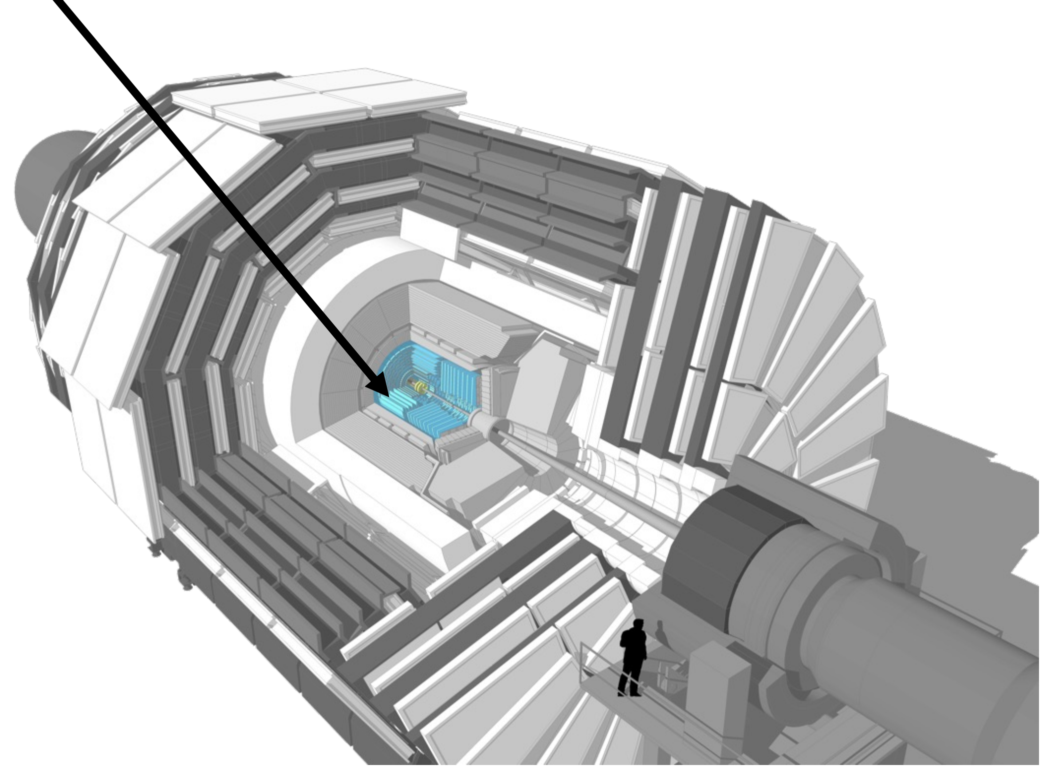
Beam Radiation Instr. and Luminosity

http://cds.cern.ch/record/2759074

- Beam abort & timing
- Beam-induced background
- Bunch-by-bunch luminosity:
  1% offline, 2% online
- Neutron and mixed-field radiation monitors







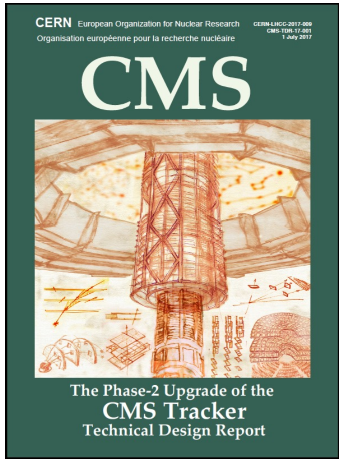
Design optimized for L1 Track Trigger at 40MHz - **world's first**

Extension of tracking to $|\eta|$ up to 3.8

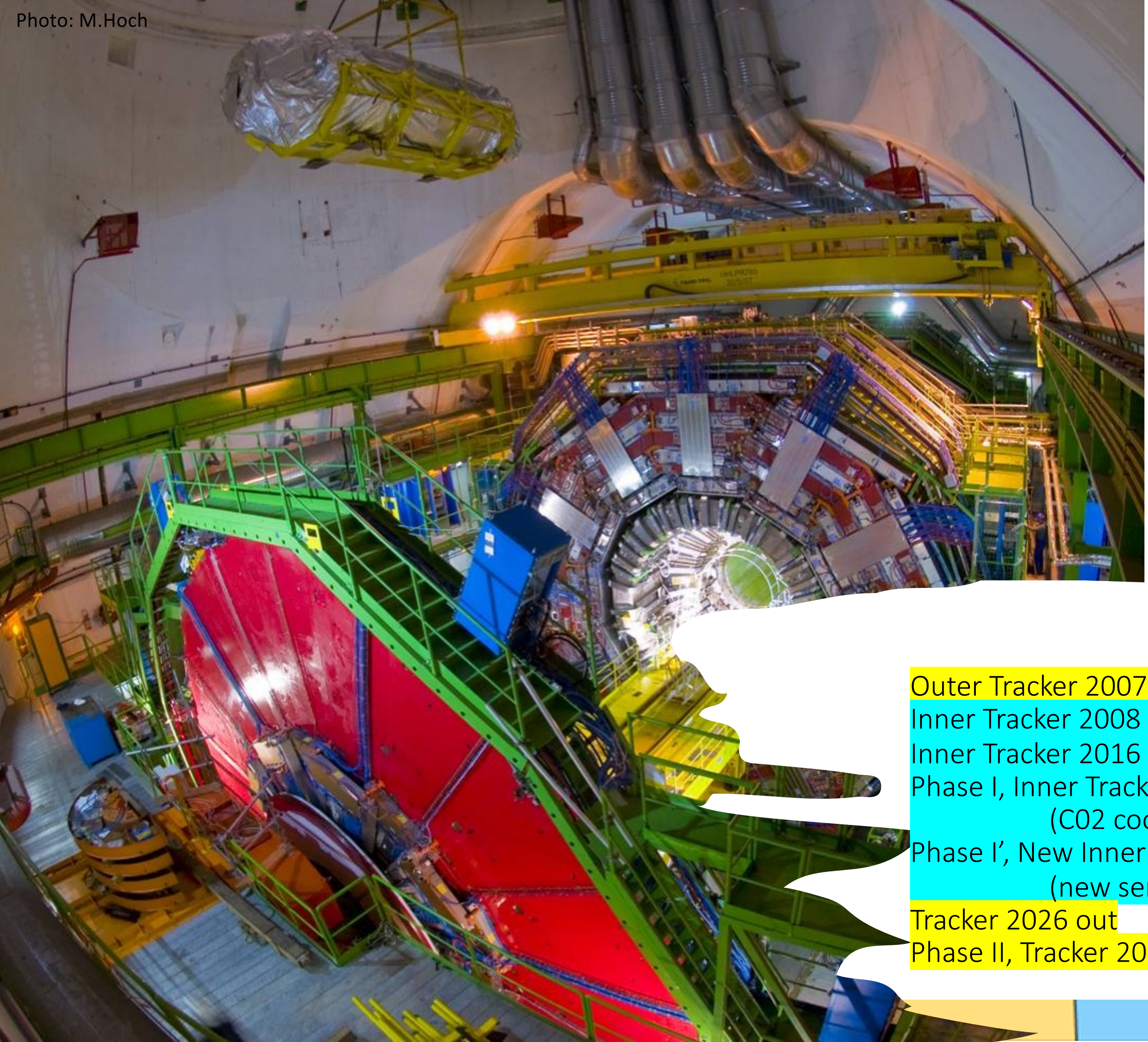
Radiation tolerant sensors with high granularity

Tracker

CO_2 cooling throughout, DC-DC & serial powering & ultra light mechanics



CERN-LHCC-2017-009 CMS-TDR-17-001



Outer Tracker 2007 in
Inner Tracker 2008 in
Inner Tracker 2016 out
Phase I, Inner Tracker 2017 in
(C02 cooling, lighter mechanics, higher rate frontend ASIC)
Phase I', New Inner Tracker barrel layer 1 2021 for Run 3
(new sensor, improved higher rate frontend ASIC)
Tracker 2026 out
Phase II, Tracker 2028 in

Phase II Tracker

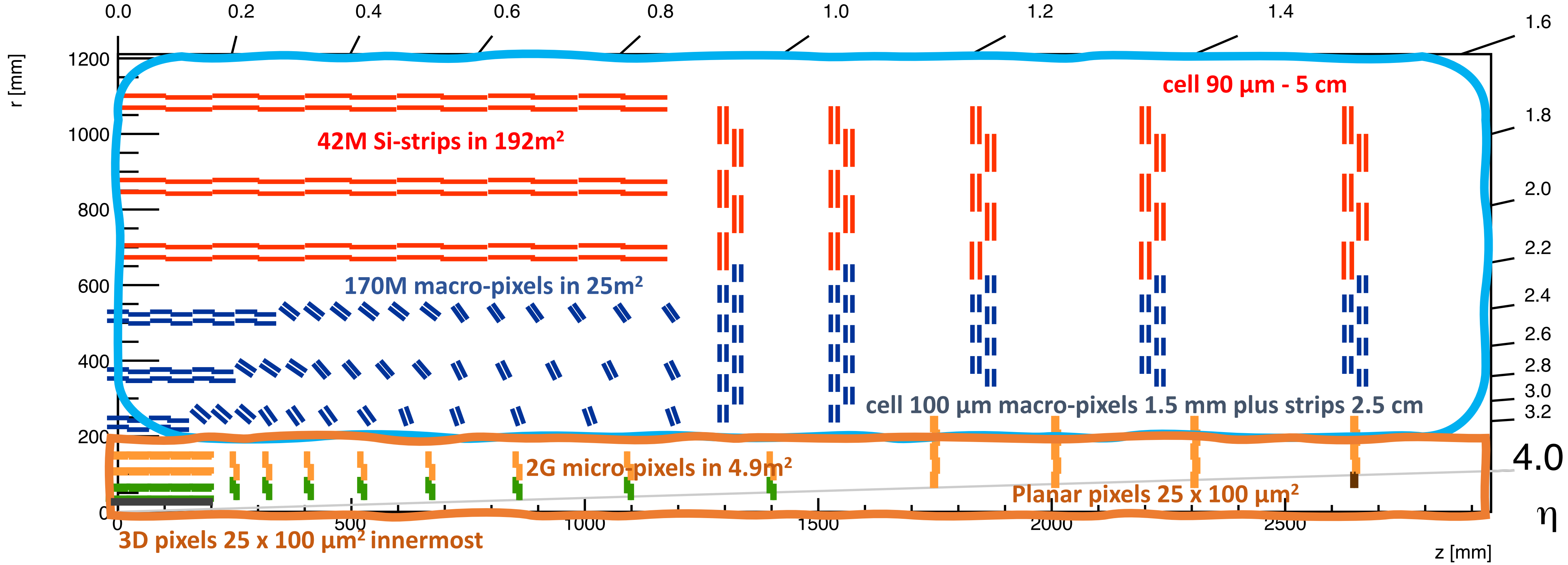
Outer Tracker

- ≃ 200 m² tilted geometry
- Track stub / double sided p_T module @ bunch crossing rate of 40 MHz
- Track finding implemented in FPGAs ➔ defined layout substantially
  - E.g. need 6 outer tracker for trigger redundancy
  - 1.5 mm macro-pixel → ~1 mm z- resolution at 40 MHz – vertexing at L1

For simplicity Tracker uses only **rectangular** modules
OT:2 version types (2S & PS)
IT: 2 planar + 1 3D

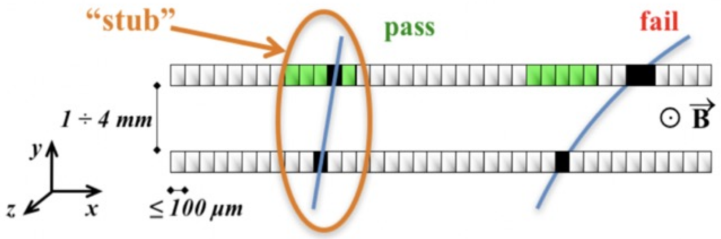
Inner tracker

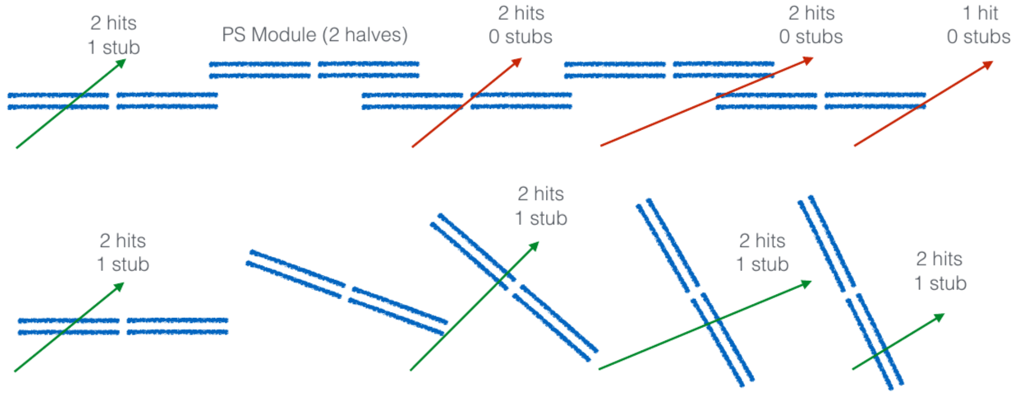
- ≃ 4.9 m²; up to **|η| =4**.0
- 4 barrel pixel layers, 8 forward double-disks, 4 endcap double-disks



HL-LHC Tracker Layout, p_T module "is the system" optimized for efficiently selecting stubs p_T > 2 GeV in high magnetic field

Programmable window ➔ p_T threshold for stub selection





Think of Outer Tracker Detector as:

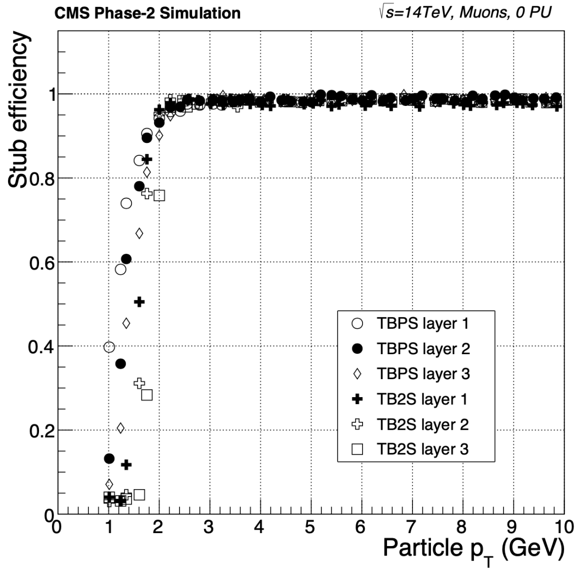
- "a collection of radiation hard Tracker modules", held in position by cooled, light weight mechanics

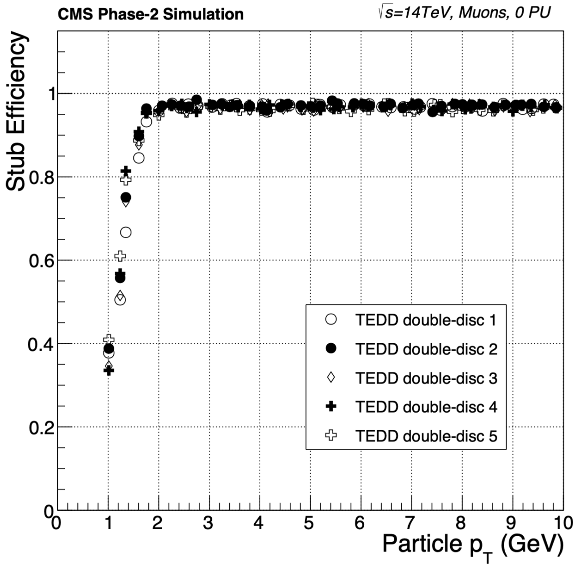
Module variation:

- Pitch of sensors
- Distance between sensors
- Angle of module wrt. to the interaction point - optimize for stub selection

Tracker finder system processes stubs to reconstruct a track for Level-1 trigger

Full hit information used in high level trigger (HLT) reconstruction

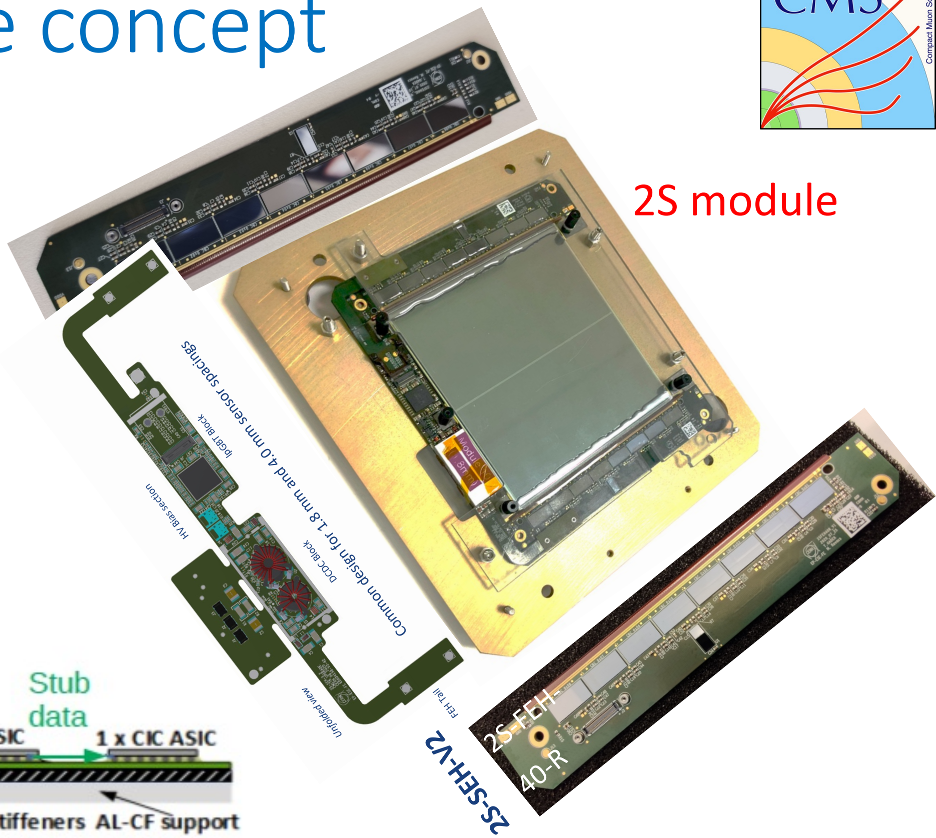




The backend electronics for the L1T track finder system (receiving stubs) is about the same size as the backend electronics for the full readout

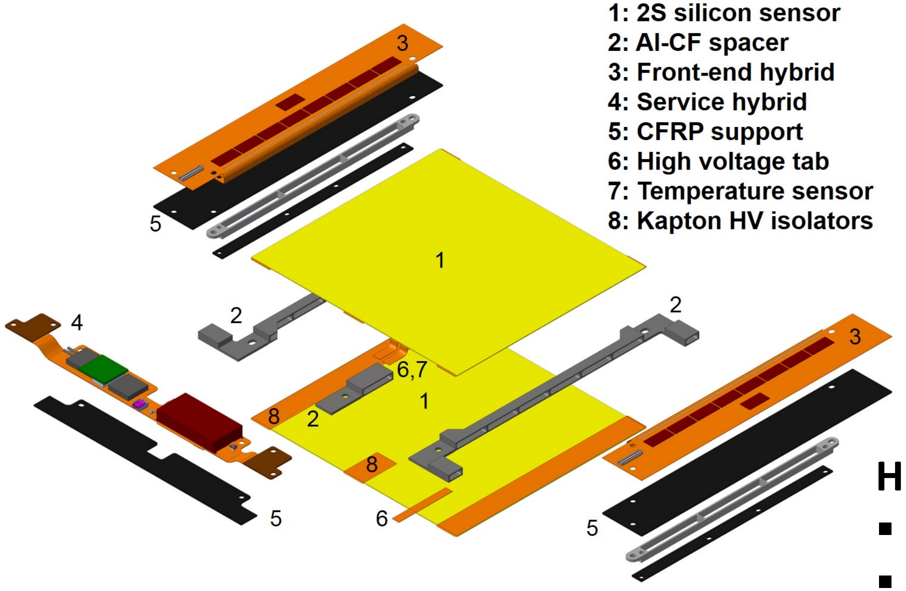
New Technologies – Tracker p_T Module concept

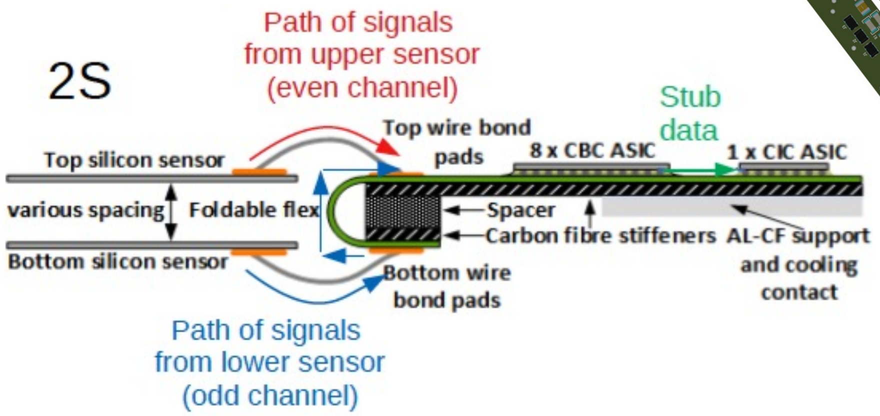
Modules provide p_T discrimination in front-end electronics



New concept

- Tag p_T segments > 2GeV/c
- Contains ALL electronics = full system – front-end, power and optics-I/O
- Effective way to have 2 space points in single mechanics – lightweight
- Frontend electronics gives Level-1 track finder 'vectors' instead of points





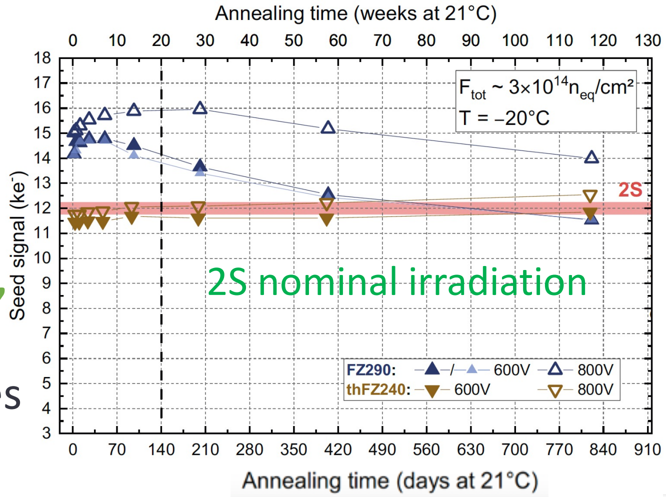
> 10 years of engineering and simulation

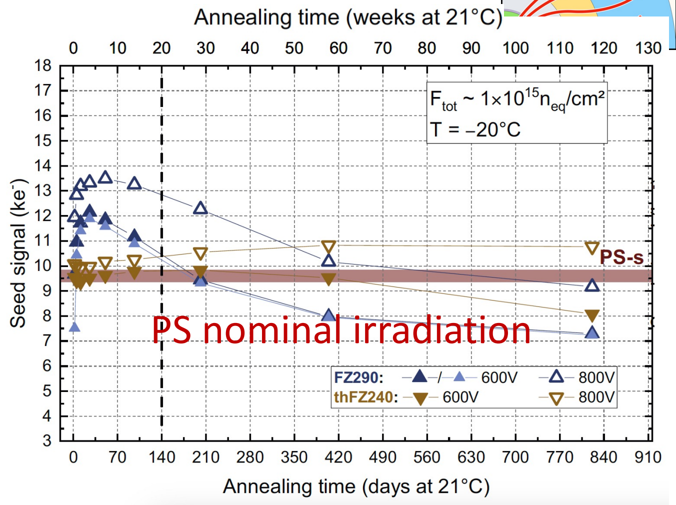
High Density interconnect hybrids

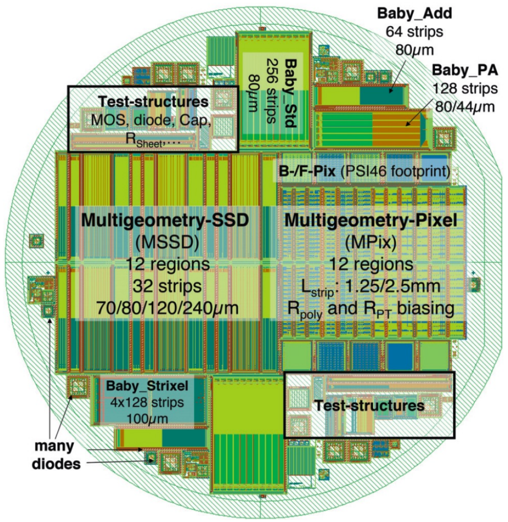
- Flexible circuits laminated to carbon fiber composite stiffeners
- Connects bottom and top sensors (to allow correlation) AND incorporates Pitch Adapter
- Features wire- and bump-bonding
- Extensive R&D on lamination process, thermal expansion (**flatness**), humidity, noise etc

Outer Tracker Sensors

- Years of dedicated effort in sensor technology research, ensuring robustness throughout the extended high luminosity period without the need for repairs
- **AC-coupled, n-in-p strip sensors with p-stop cell isolation, 290/320 um active/physical thickness**
- Comprehensive irradiation and prolonged annealing studies to gain insight into safety margins, employing the most challenging environmental conditions
  - The entire Outer Tracker system meticulously crafted and quality-assured for an operating voltage of 800V

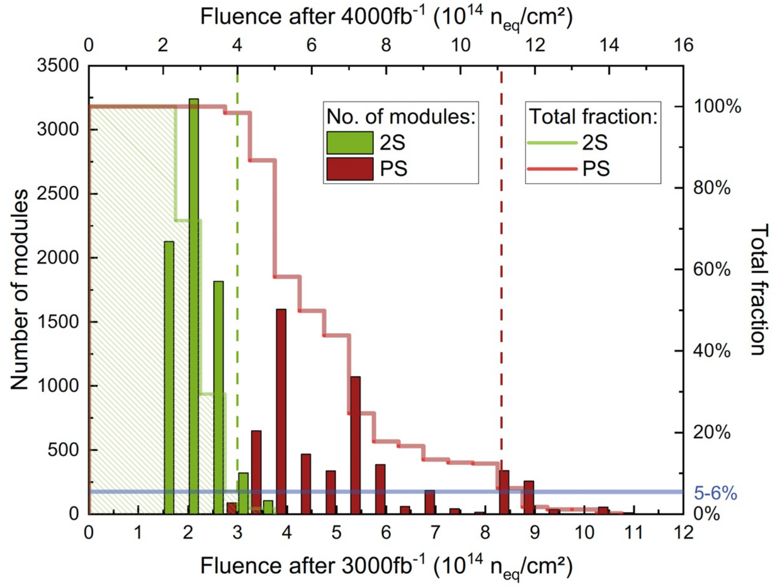






Couple of hundreds of R&D wafers of different thicknesses and material – many structures

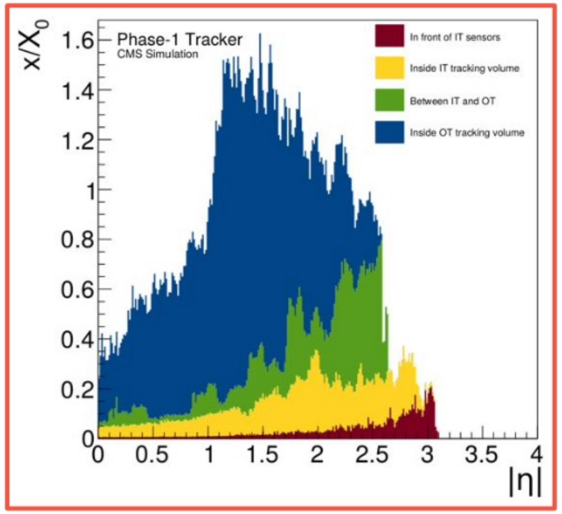
➔ Chose n-in-p (register electrons); confirm pitches, isolation, QA strategy

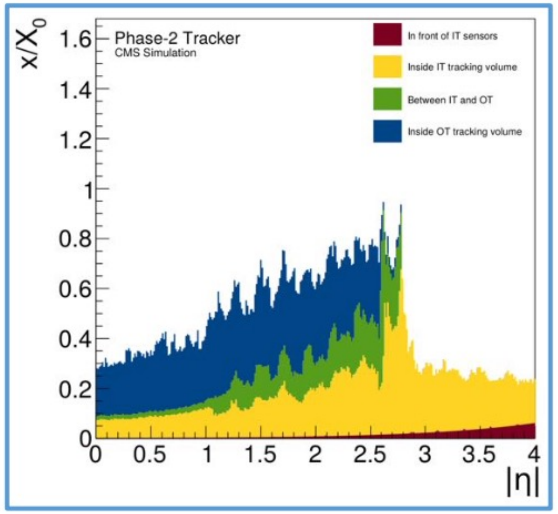


Selection of the silicon sensor thickness for the Phase-2 upgrade of the CMS Outer Tracker, JINST 16 P11028

P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC, JINST 12 P06018.

Mechanics: reduction material budget

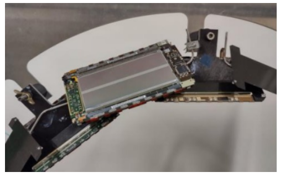




- DCDC converters – lower cable cross section
- CO_2 two-phase cooling – thin pipes
- Lighter materials
- Inclined geometry – fewer modules
- Optimized service routing – 3D modelling

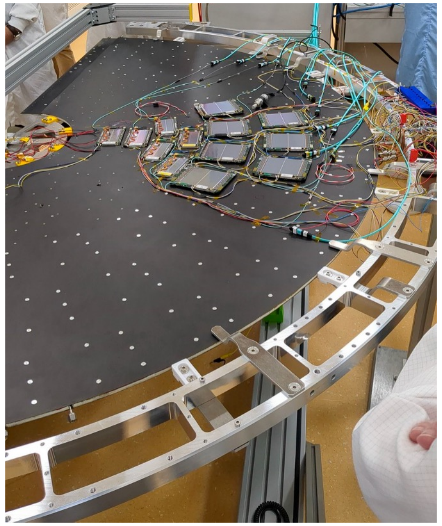
1st barrel ladders - OT

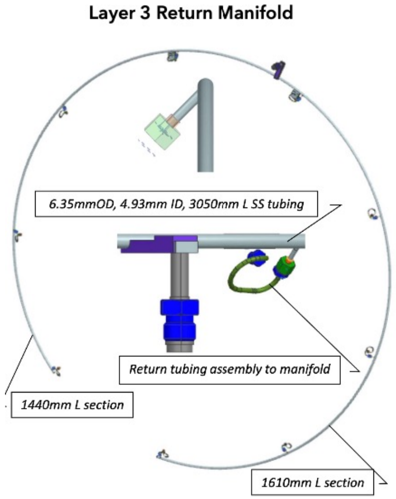
OT tilted rings



3 dummy PS modules on a ring

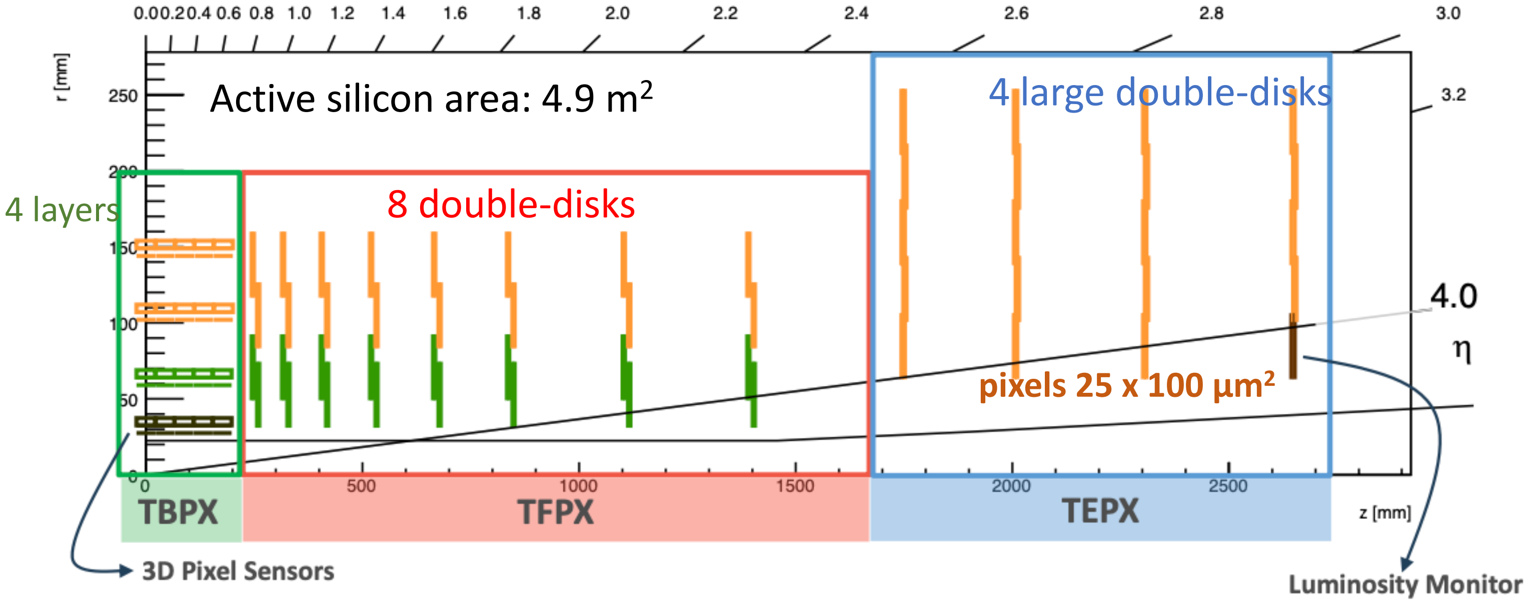
OT endcap dee

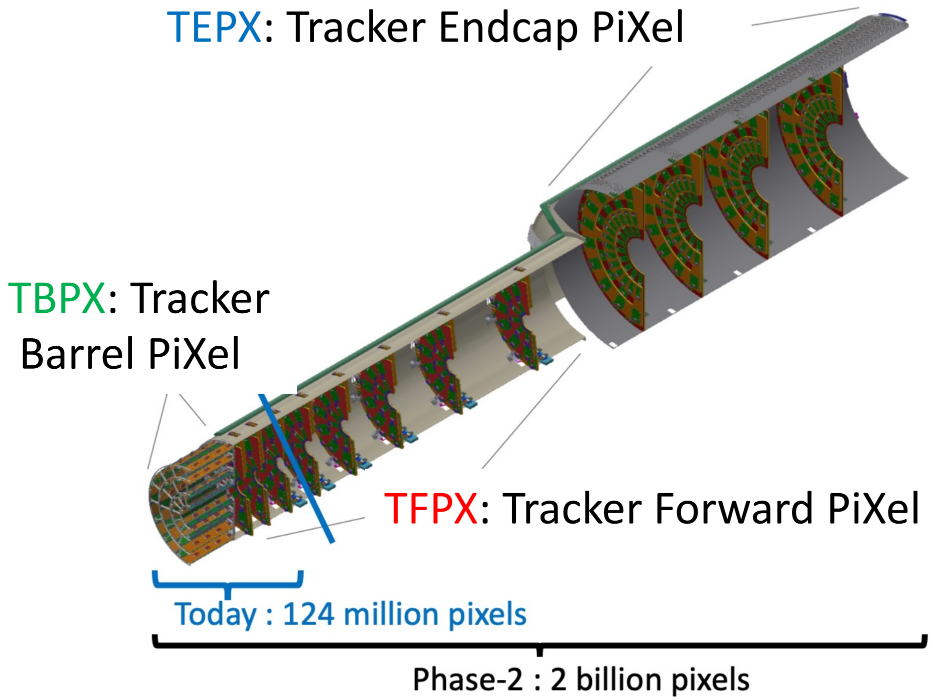




Inner Tracker, extension into the forward region

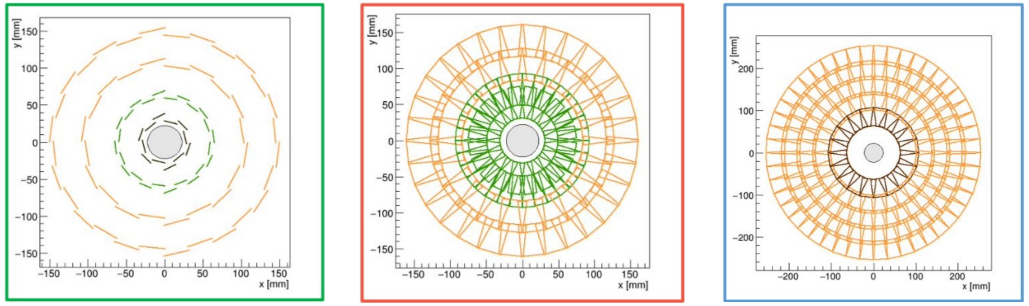
25 x 100 μm² pitch, ≃ 3 GHz/cm² (inner most layer) new technology 65 nm TSMC ASIC (RD53)

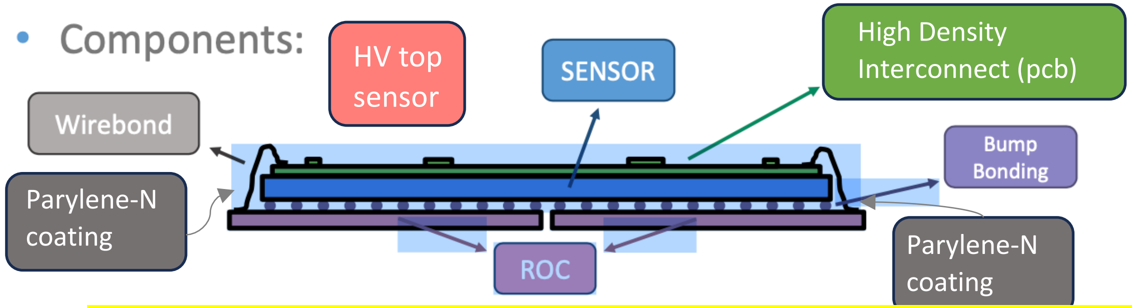




3892 Modules:

- CMS Read Out Chip (CROC – RD53 development) only active element on module
- (1156) 1x2 ROC module and (2736) 2x2 CROC module





More info, comprehensive presentation at TIPP:

TID effects study on the monitoring system of the RD53 chip, Mohsine Menouni

Prototype validation for the CMS Inner Tracker Phase-2 upgrade, Nazar Bartosik

Inner Tracker sensors

Choices based on radiation hardness tolerance, power consumption, high cooling efficiency,
And small cells: spatial resolution, low occupancy → track seeding, pattern recognition, b-tagging

n-in-p, 25x100 μm² pixel cells, 150 μm active thickness

All layers (except barrel layer 1) n-in-p planar sensors

- 25 x 100 μm² sensor pixels matched to 50 x 50 μm² in FE chip
- Rad tolerance: n-in-p to register electrons and 150 μm active thickness
- Thin also matches small pixels (thick would distribute charge to many channel
- No punch through bias dot; bitten implant reduces cross talk

Irradiated Sensor+CROC assemblies:

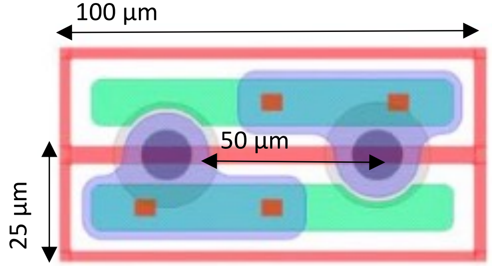
- Excellent performance – spatial precision
- Hit efficiency >98% ($1x10^{16}cm^{-2}$ 1MeV n_{eq} cm^{-2})

Barrel layer 1: 3D pixel sensors

- dissipate less power (lower HV & leakage current)
- n+ columns are connected to ROC, 150 μm active thickness,
- p+ columns reach the backside of the sensor (bias voltage)

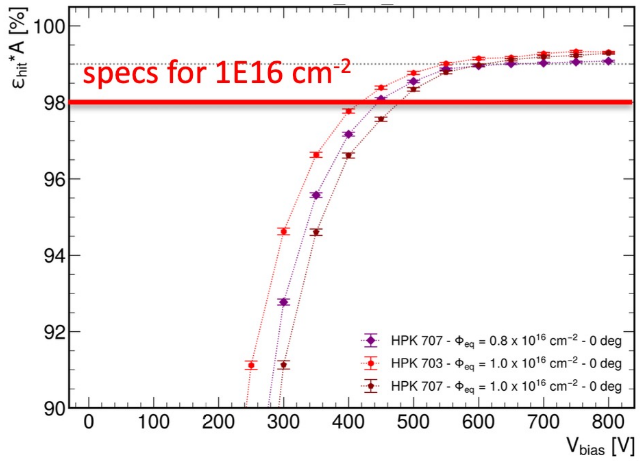
Irradiated 3D-Sensor+CROC assemblies:

- Hit efficiency >~97% (~$1x10^{16}cm^{-2}$ 1MeV n_{eq} cm^{-2})

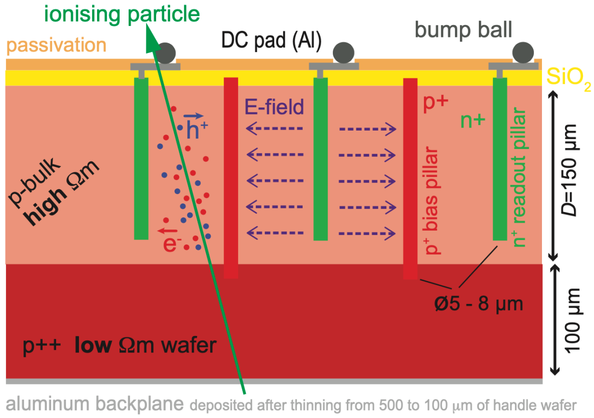


CMS planar n-in-p
“Bitten implant” design
2 neighbouring pixel cells

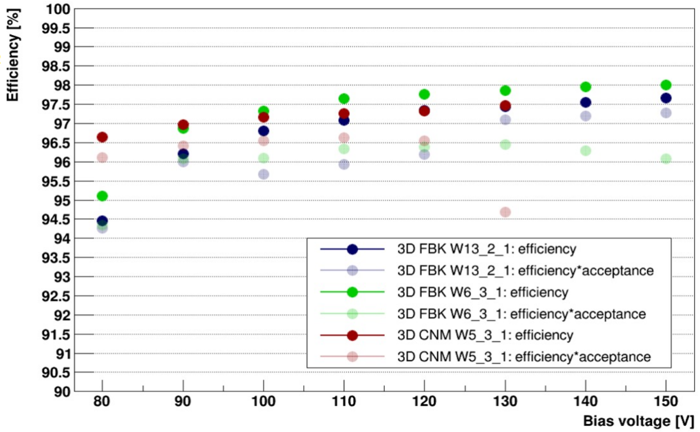
planar sensor+CROC hit efficiency vs bias voltage after ~$1x10^{16}cm^{-2}$ 1MeV n_{eq} cm^{-2}



3D sensor n-in-p



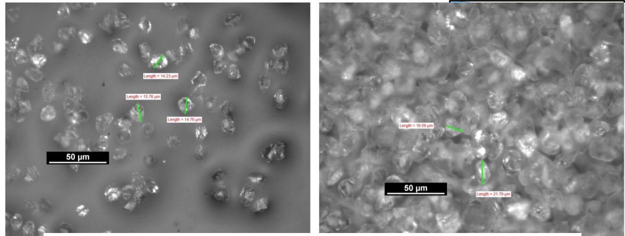
3D sensor+CROC hit efficiency vs bias voltage after (~$1x10^{16}cm^{-2}$ 1MeV n_{eq} cm^{-2})



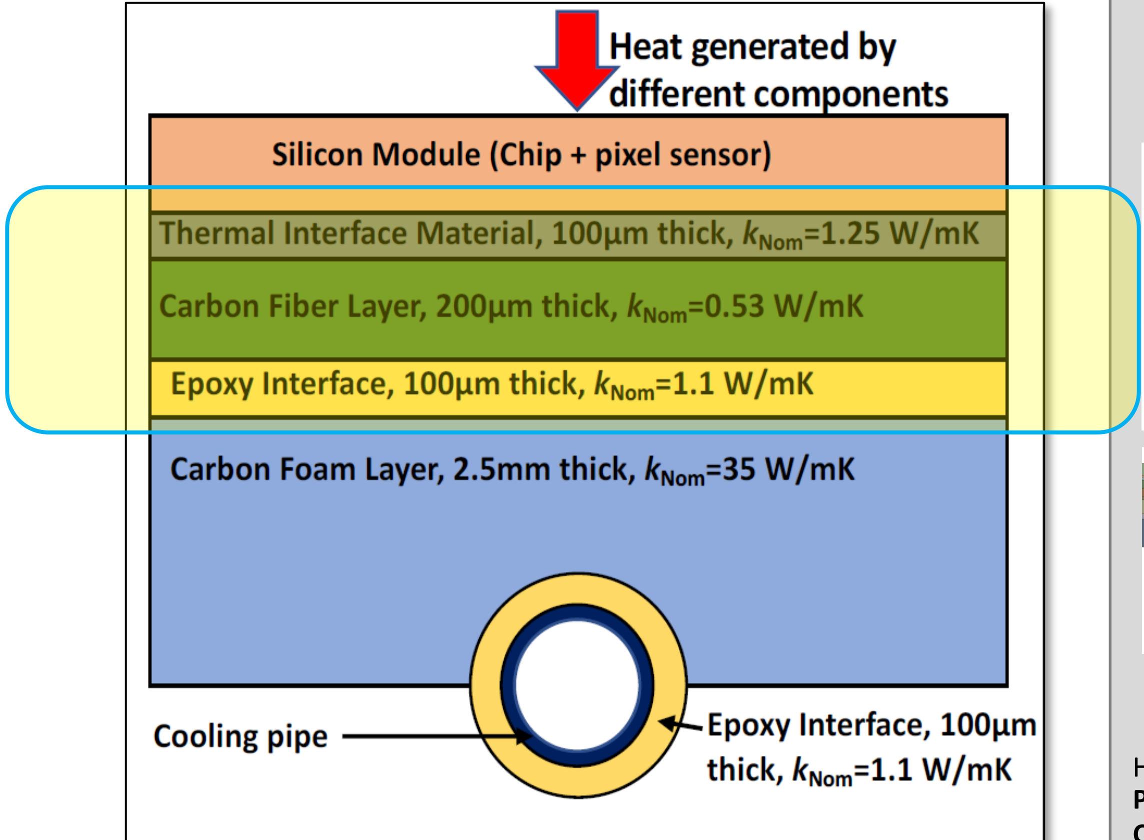
More info, comprehensive presentation at TIPP, Radiation Hard Pixel Sensors for the Phase 2 Upgrade of the CMS Inner Georg Steinbrueck

Inner Tracker Mechanics

Efficient thermal management to extract heat combined with minimizing material budget …



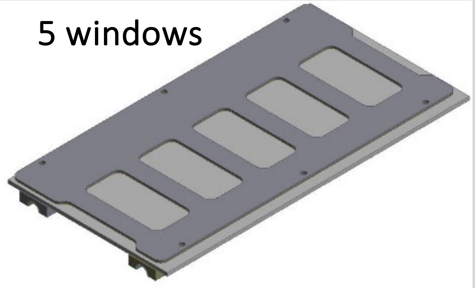
Microscopy of 20 µm diamond in Moresco thermal interface material 30% and 70% mass fraction

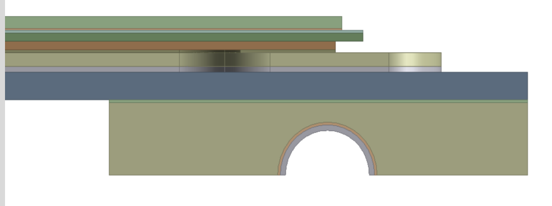


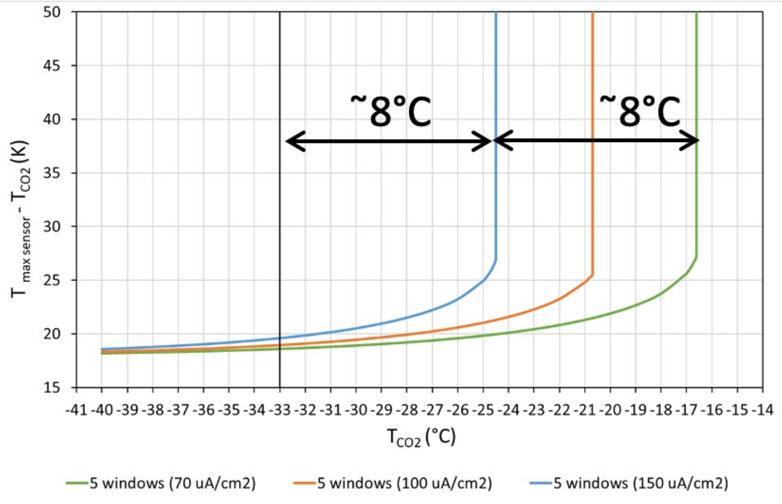
Schematic view of the cross-section of a representative multi-layer support structure inspired by the TFPX Dee

TBPX Layer 1
3D sensor modules optimization for thermal runaway

Fluence 1.5x10^{16} 1MeV n_{eq}cm^{-2}
Latest measurements confirm 70muA/cm^2 at 140V.
Luminosity 1740 fb^{-1}







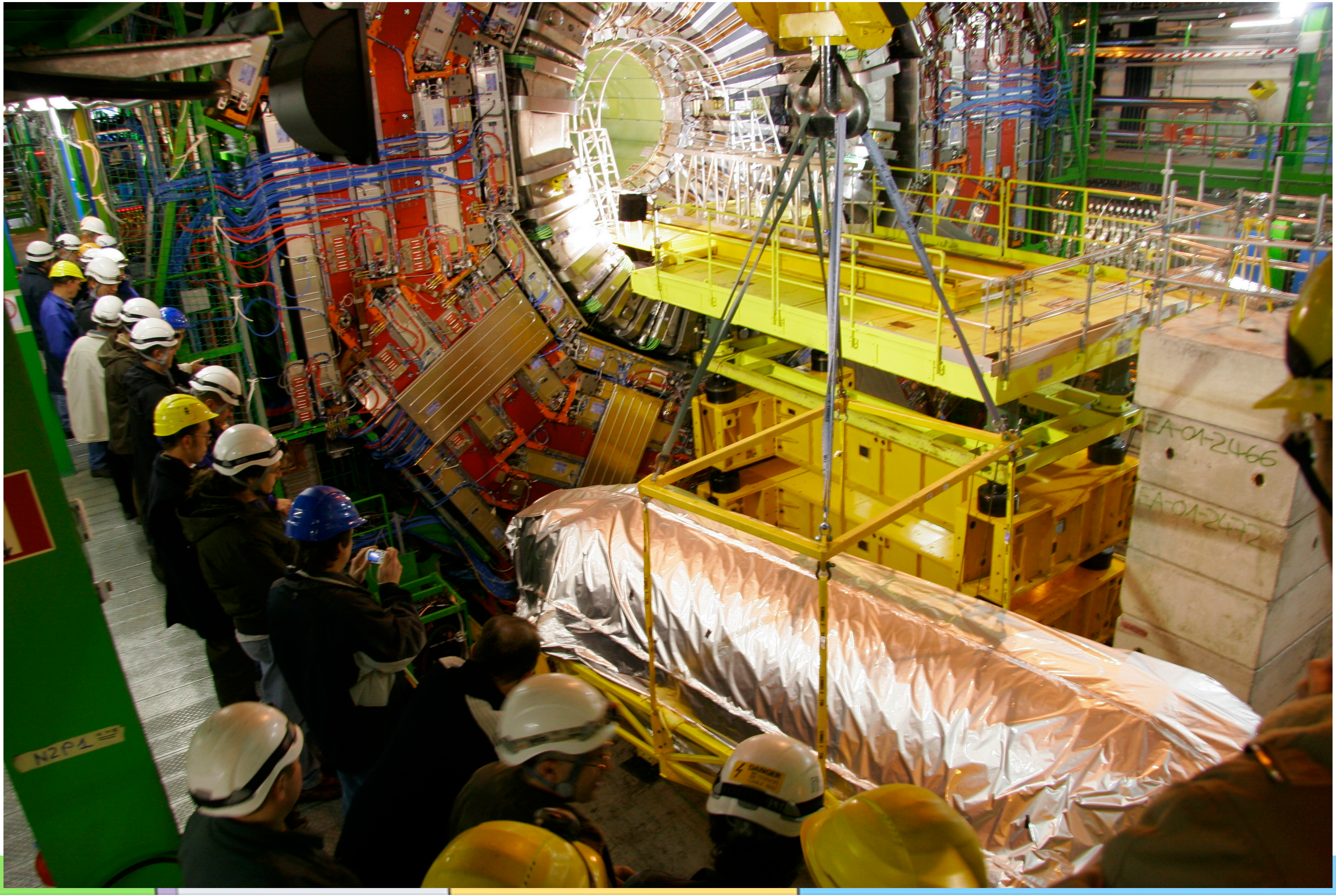
Components

HDI – 220 µm – Kapton+copper ; λ = 97 W/mK
Pixel Sensor – 150+50 µm – Silicon; λ = 148 W/mK
CROC – 150 µm - Silicon; λ = 148 W/mK
Module cooling plate – 250 µm; Alumina nitride - λ = 160 W/mK
High conductivity carbon fiber – 0.5 mm λ_{xz} = 200 W/mK - λ_y = 2 W/mK
Pipe – Stainless steel ; O.D. 1.8 mm - I.D. 1.6 mm; λ = 15 W/mK
Housing pipe- Carbon Foam - λ = 17 W/mK

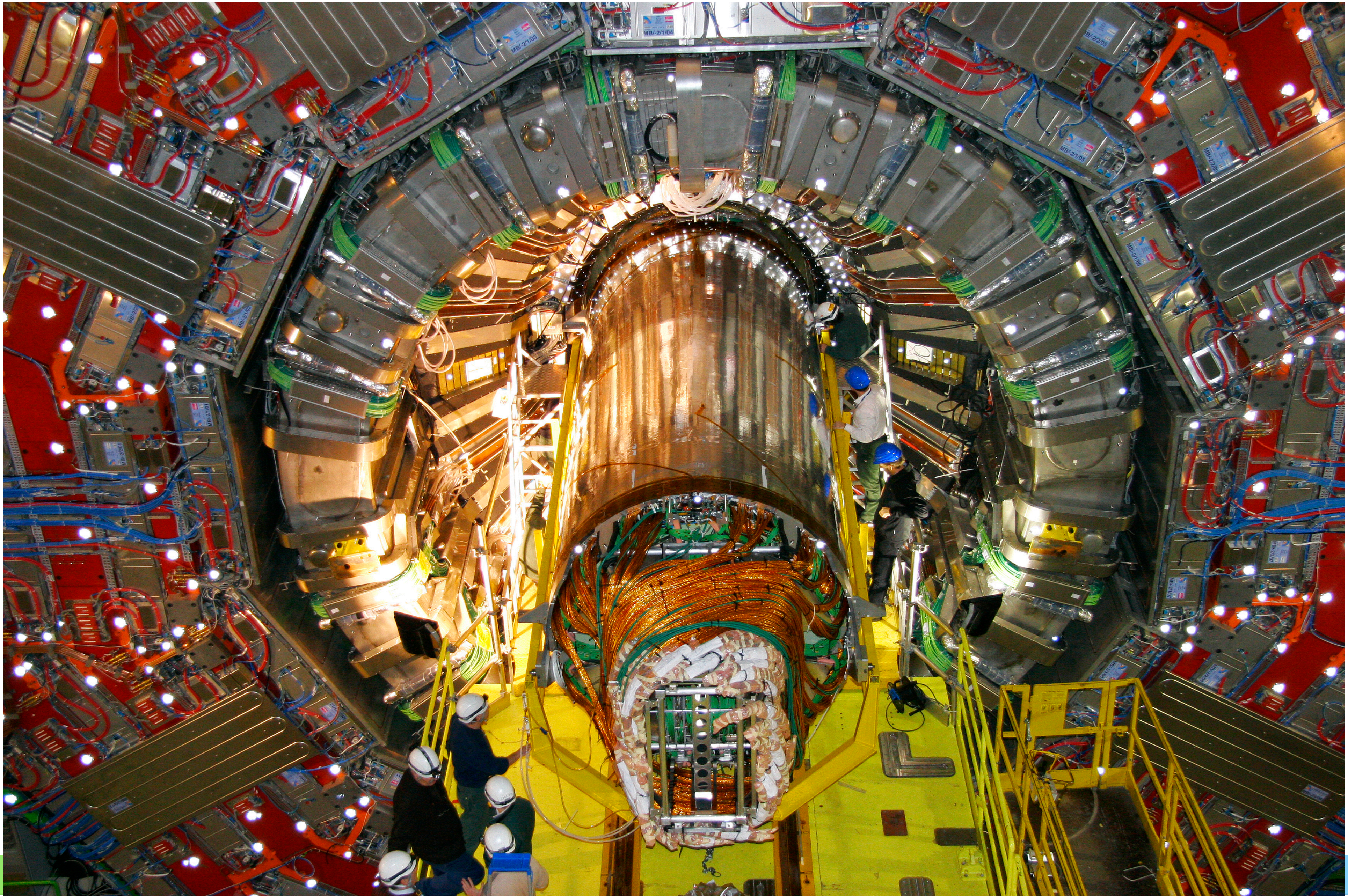
Interfaces

Epoxy+diamond - 50 µm; λ = 0.65 W/mK
Moresco+diamond 70% – 100 µm; λ = 0.89 W/mK
CO_2 Heat Transfer Coefficient: 5000 W/m^{2}K
Araldite - 50 µm; λ = 0.25 W/mK

The current Outer Tracker December 2007

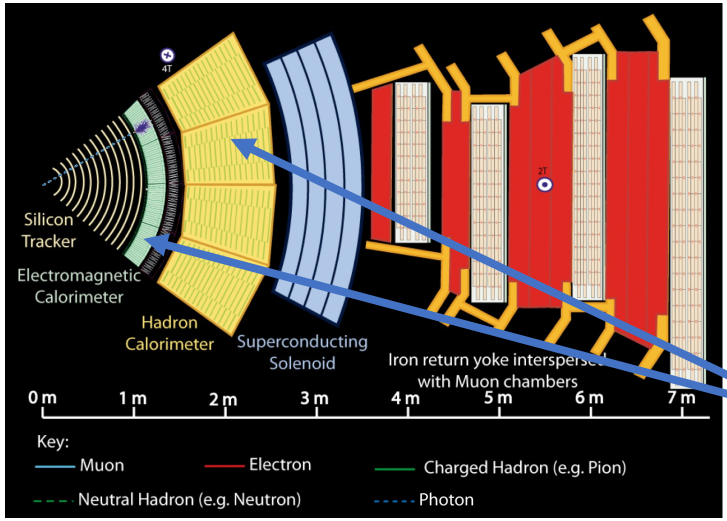


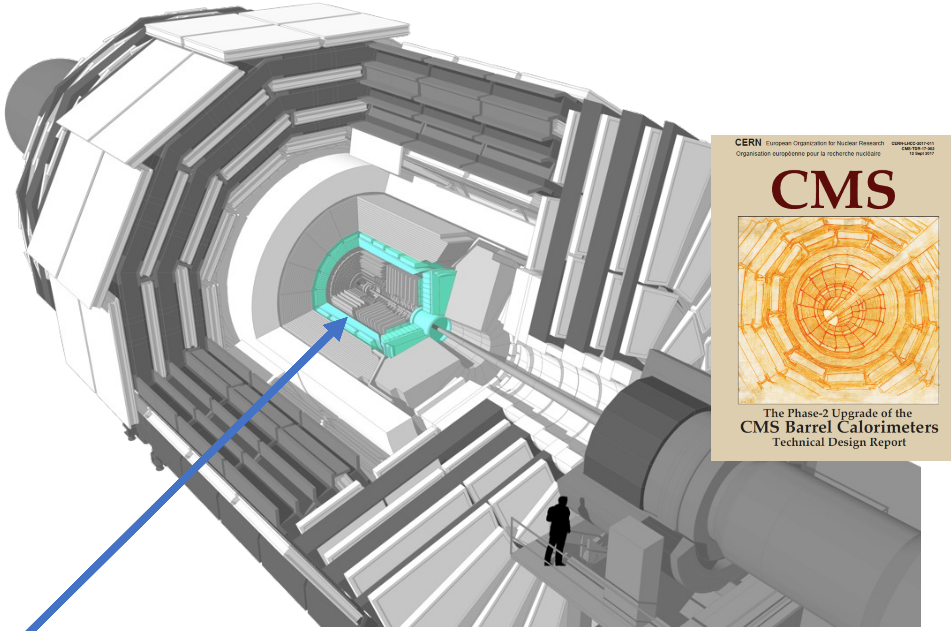
Insertion of the current Outer Tracker 2007

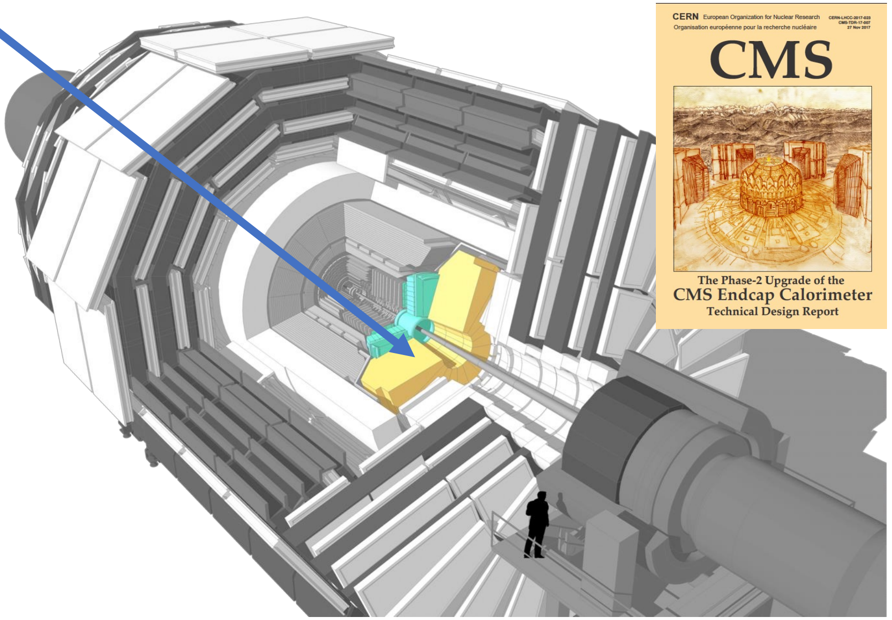


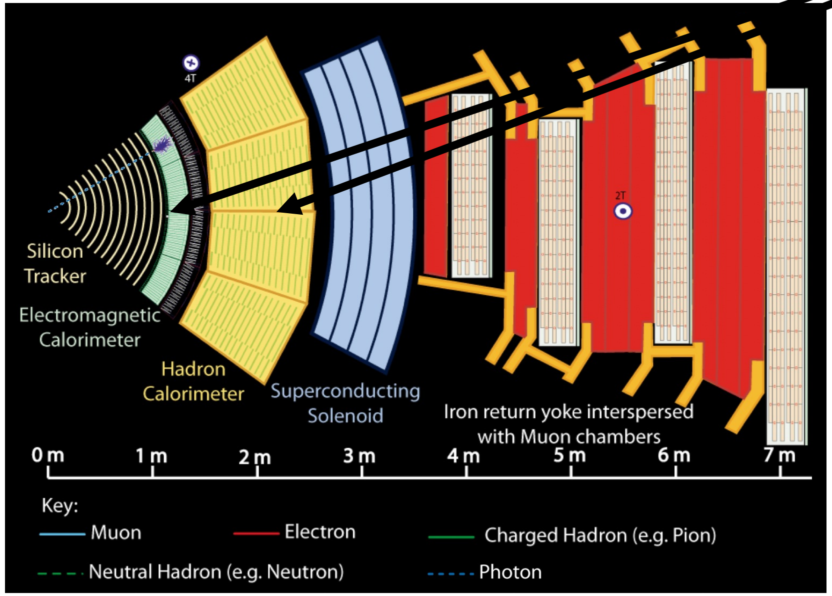
Calorimeter

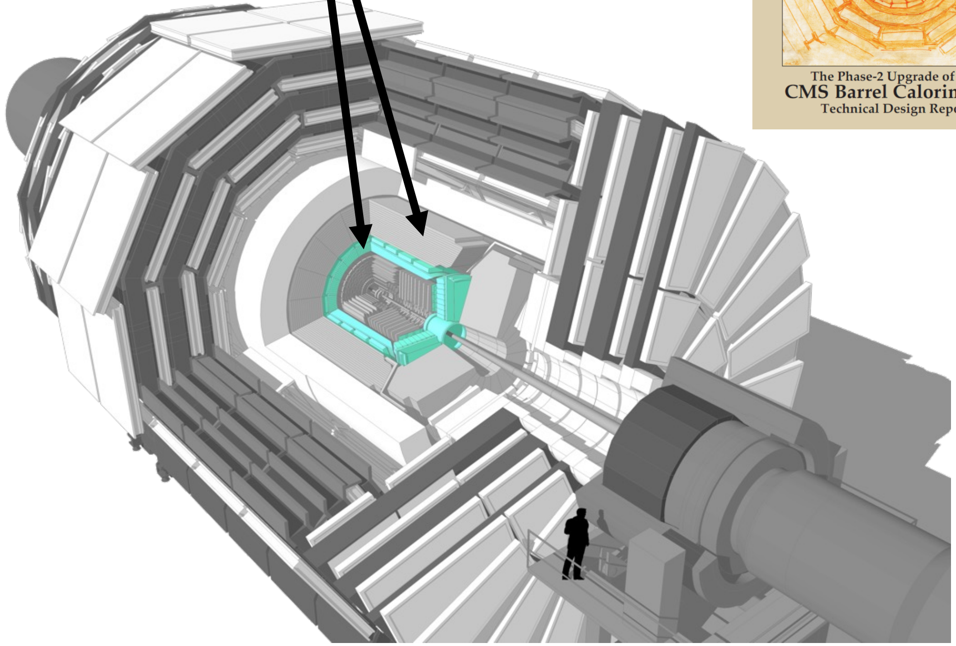
Barrel and endcap

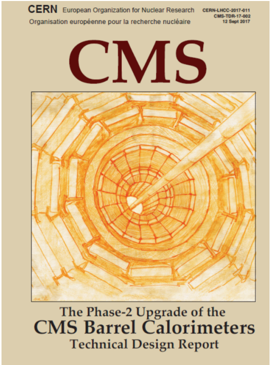












Barrel Calorimeter

Cool electromagnetic barrel (ECAL) calorimeter from 18 °C to 9 °C → APD dark current reduction.
Upgrade frontend (ECAL) + backend electronics (ECAL + HCAL)

Total of 61200 $PbWO_4$ crystals
Readout by two APD's

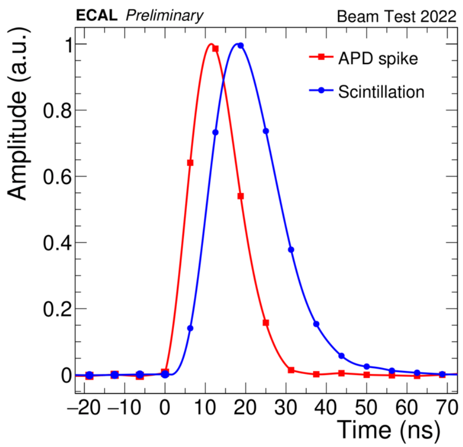
Electromagnetic Barrel Calorimeter

Replace all frontend (& backend electronics) during LS3 - remove, open and refurbish all 36 supermodules

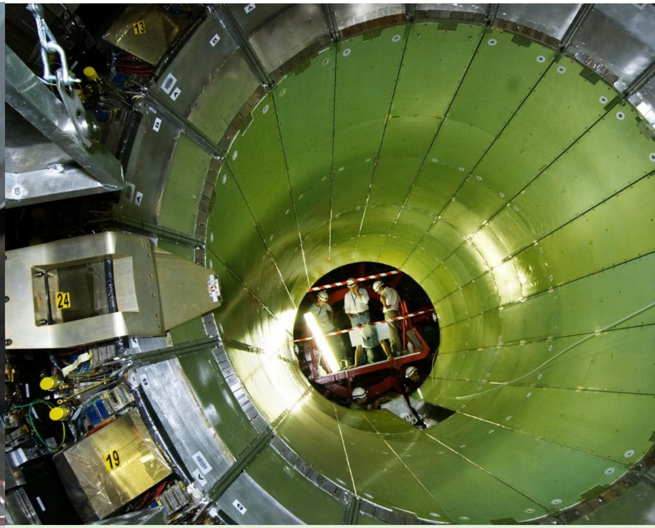
Dedicated frontend analogue and digital ASIC developments

Faster readout electronics 160 MHz allow:
- precise timing resolution of 30 ps for 20 GeV/60 GeV at the start / end of HL-LHC
- better rejection of anomalous signals (spikes) at Level-1

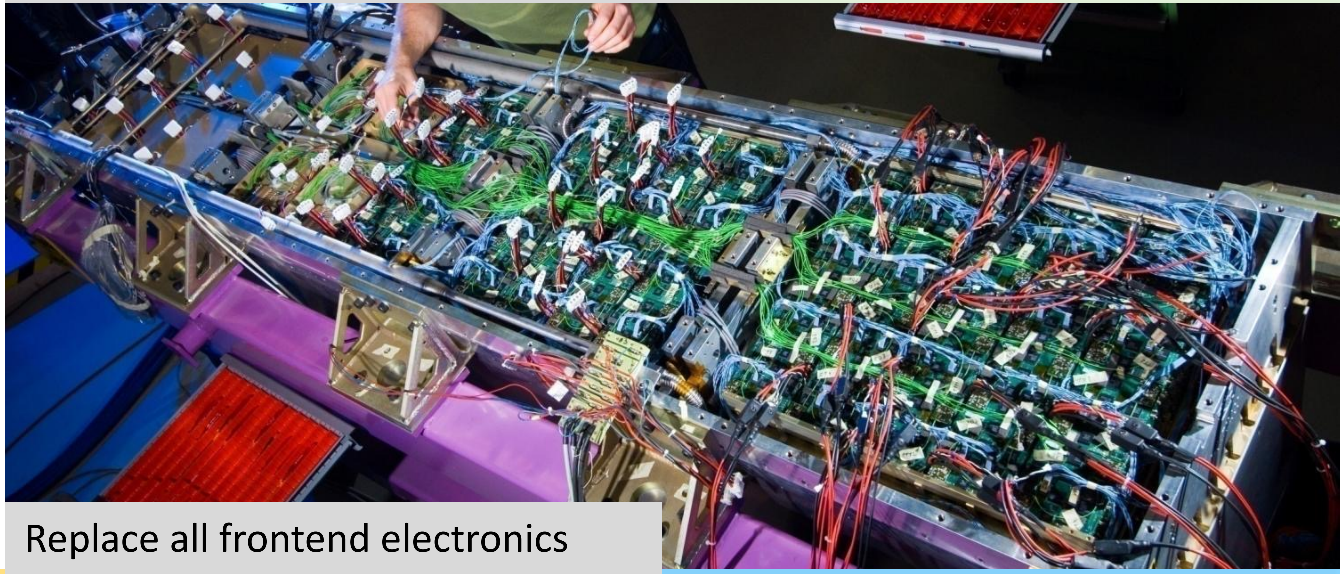
All samples – full streaming - are sent off-detector thanks to a compression mechanisms, and the Level-1 trigger decision will be processed in the FPGA off-detector



36 supermodules (1700 crystals/SM)
Total of 61200 PbWO4 crystals

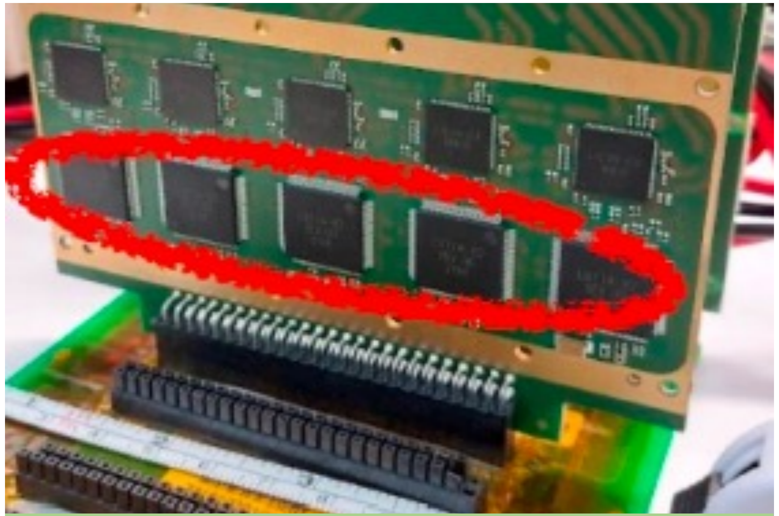


Electromagnetic barrel calorimeter before the installation of the tracker

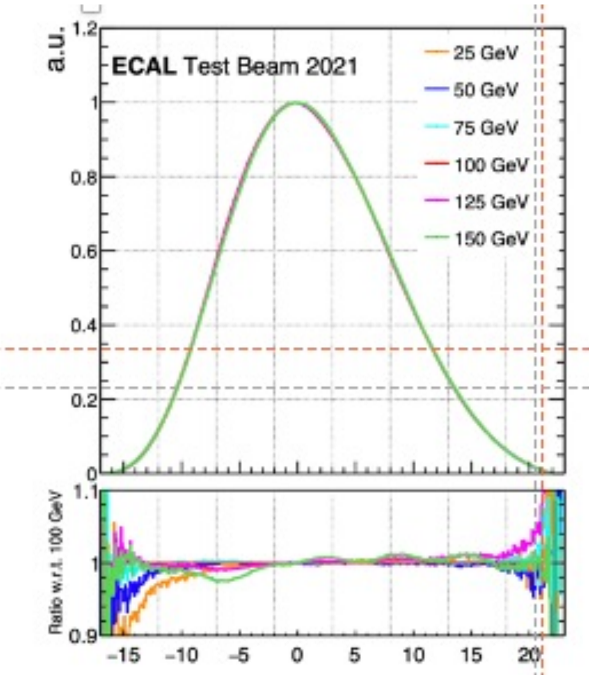


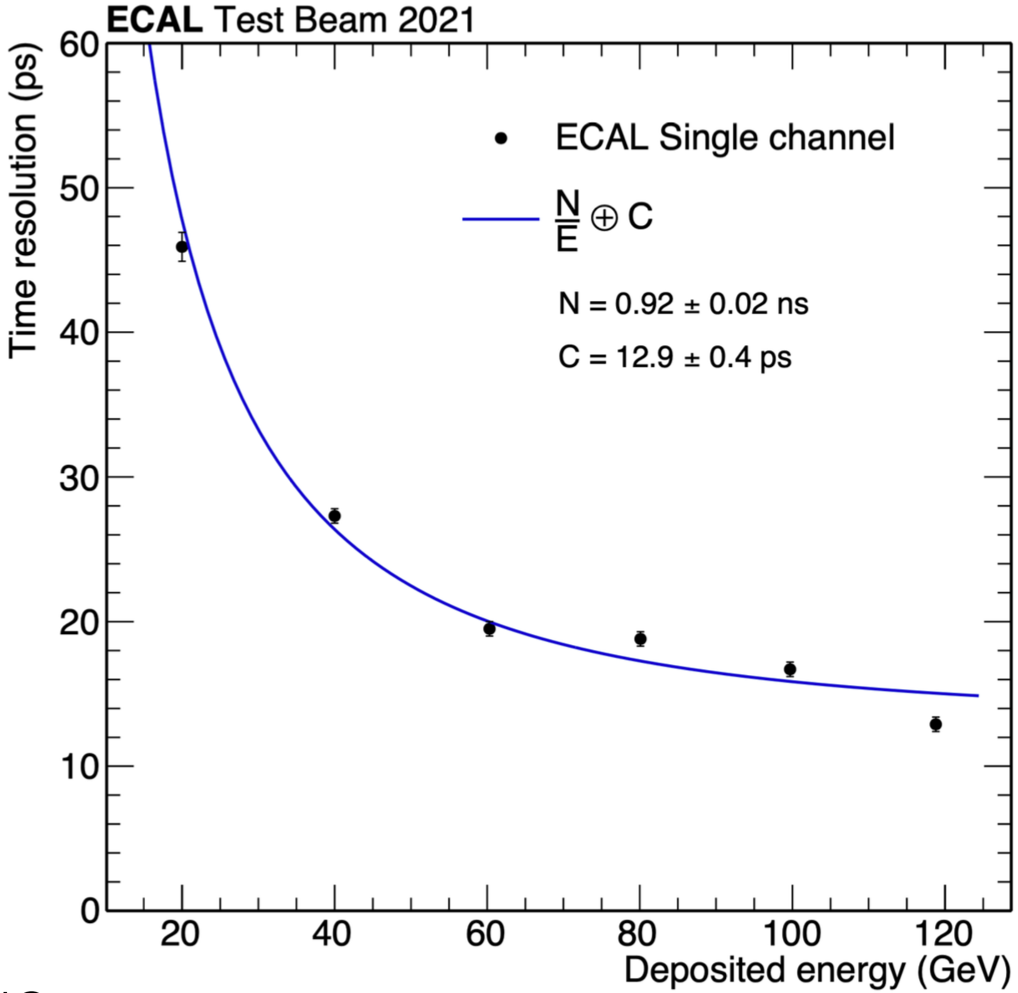
Replace all frontend electronics

ECAL Barrel System performance in test beam



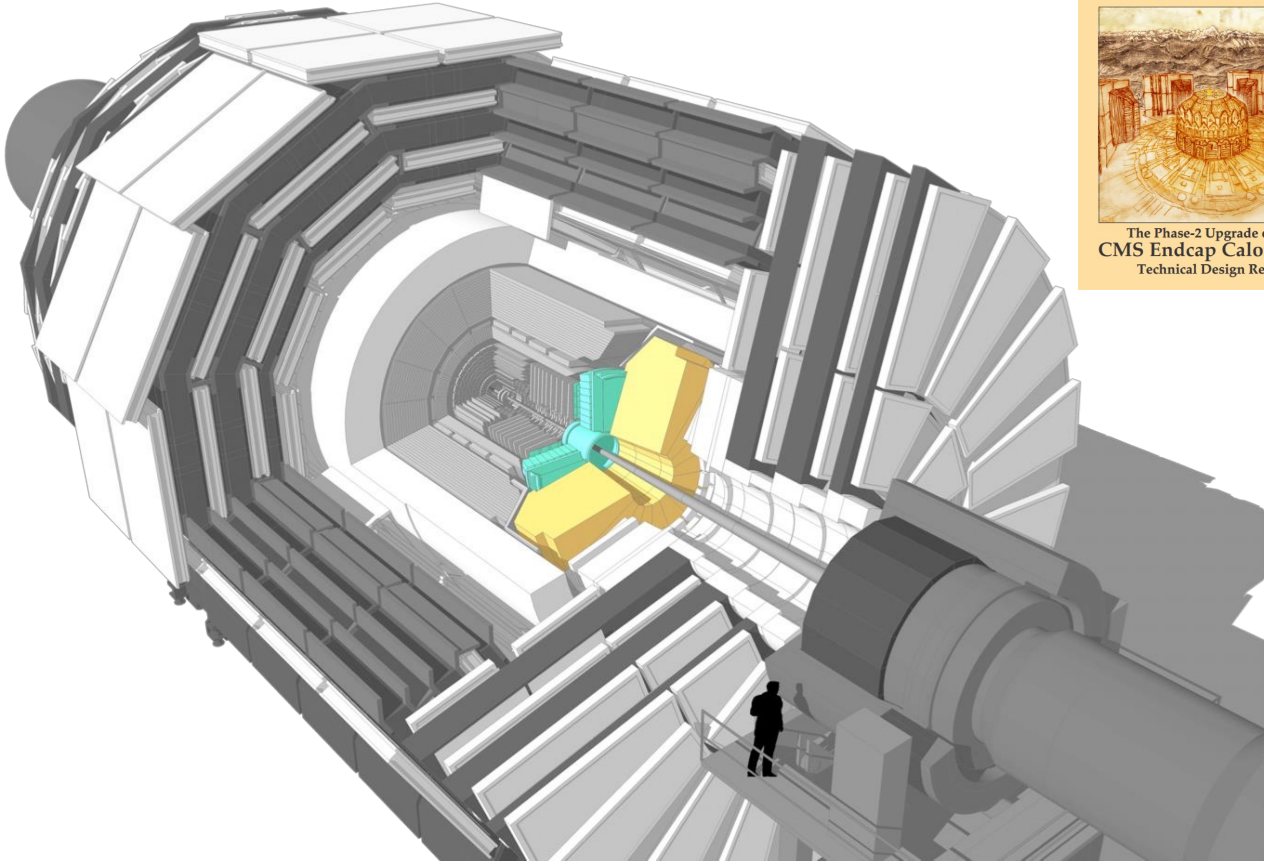
5 front-end ASICS (one per crystal) on the very frontend card

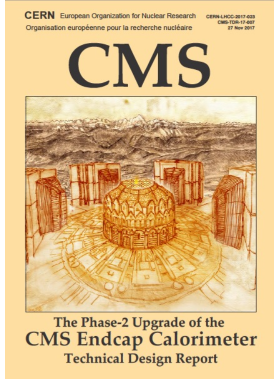




Uniform single crystal pulse shape across a wide range of energy
Verified in Test Beam with prototype new very frontend card (VFE)

Excellent internal non-linearity (INL) of ±1/1000 from front-end ASIC





World's largest scale

First at Hadron colliders

High Granularity Calorimeter (HGCAL)

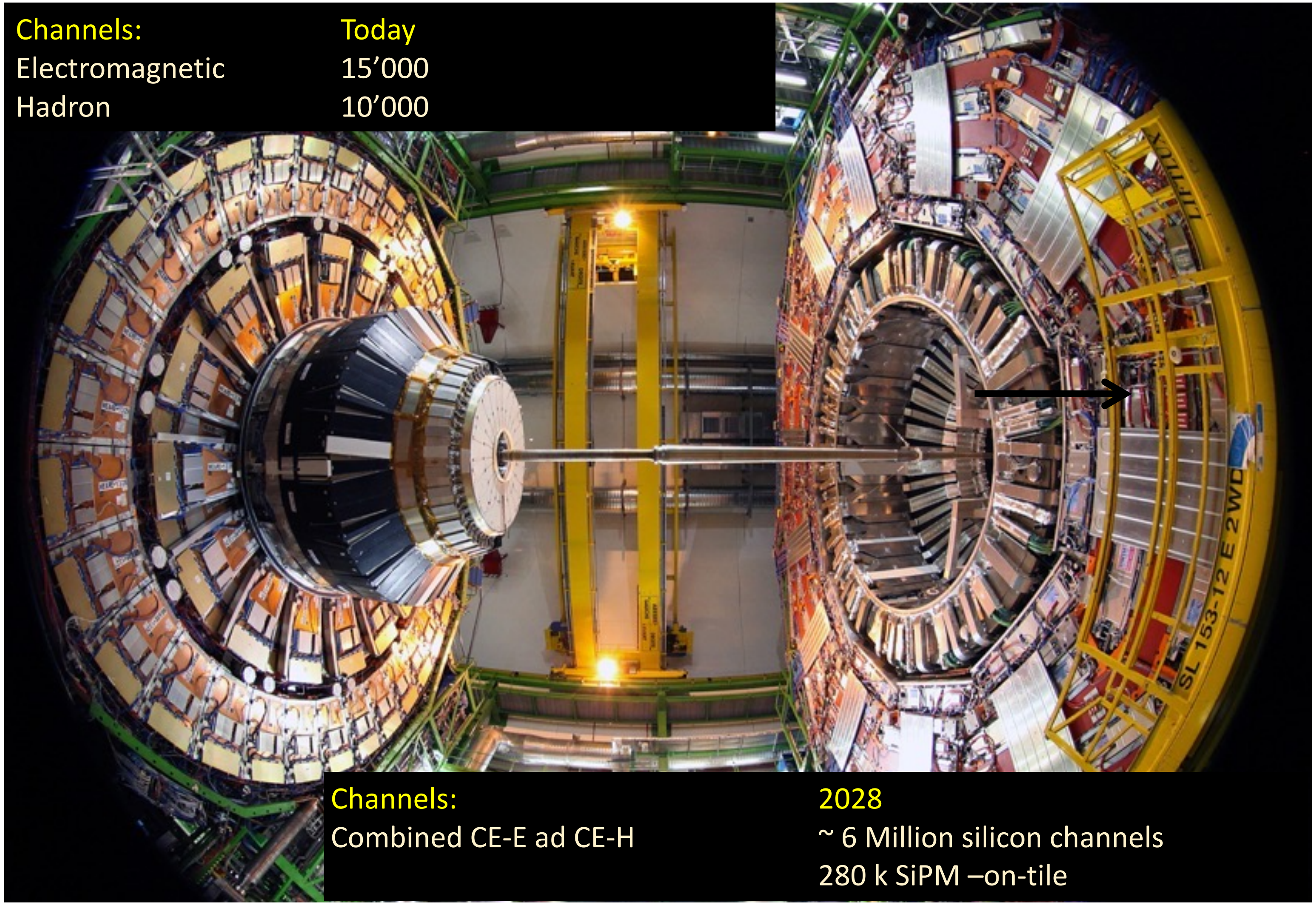
a 5D calorimeter imaging calorimeter
3x silicon area of the CMS tracker

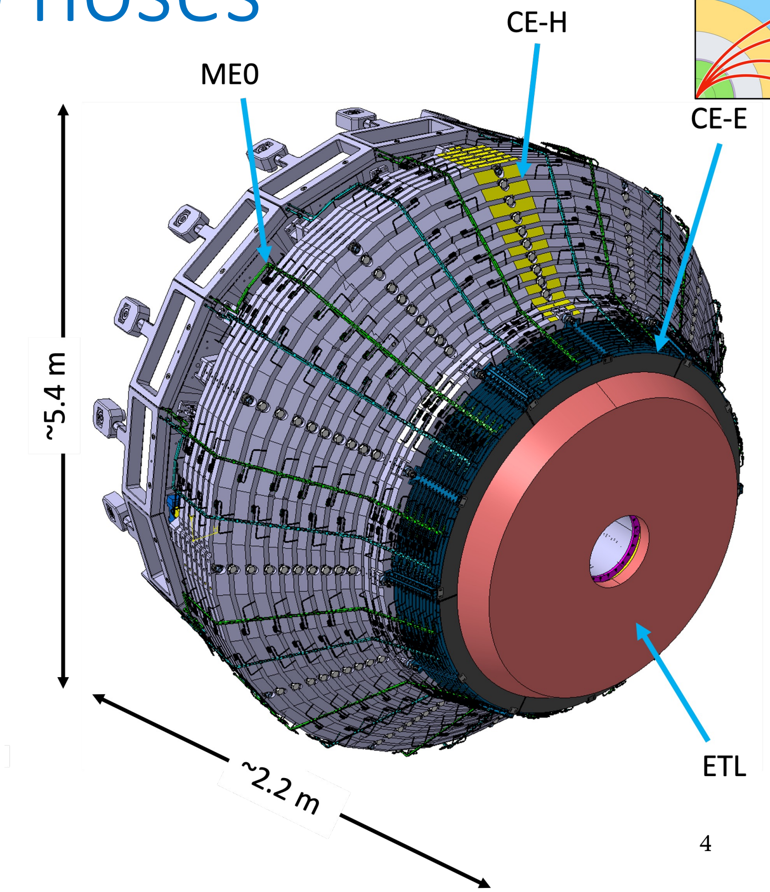
"5 dimensions" measured → (x,y,z,E,t)

CERN-LHCC-2017-023 CMS-TDR-019

HGCAL replaces both 230 ton endcap noses

Fit within the envelope of today's CMS endcap calorimeter





4

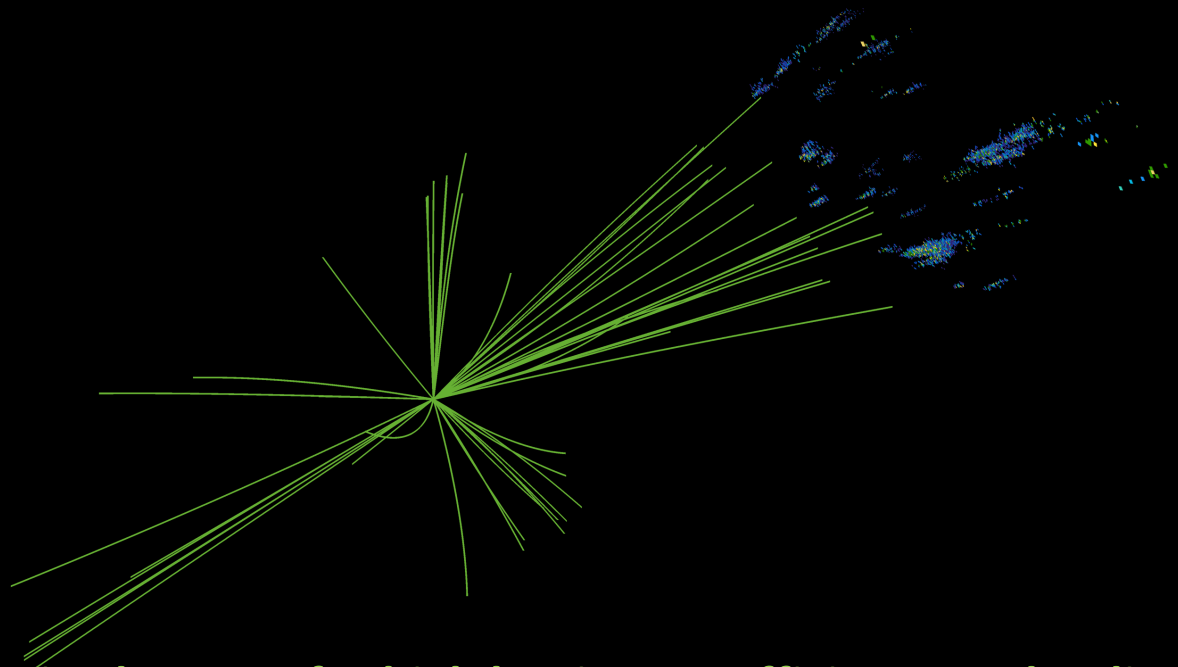
Requirements include:

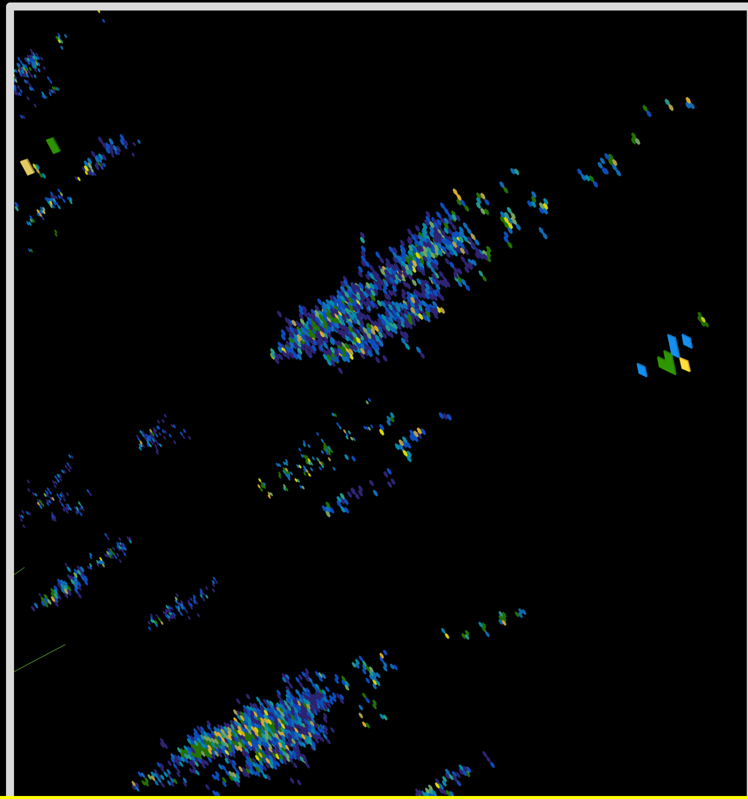
- Sustain radiation environment and S/N allowing for MIP calibration through full HL-LHC operation
- Highly granular for particle flow reconstruction, pileup suppression

HGCAL,

simulated shower propagation through all layers

- ‘track’ particles through the full system – a dream for particle flow





Highly optimized system for high lumi: cost, efficiency and radiation tolerance

The materials are chosen to survive the full high lumi operation

Silicon sensors provide required level of radiation hardness up to $1.5\text{x}10^{16}\text{MeVn}_{eq}/\text{cm}^2$

Lower-cost SiPM on plastic scintillator tile instrument the volume $< 0.5\text{x}10^{14}\text{MeVn}_{eq}/\text{cm}^2$

More info on reconstruction, comprehensive presentation at TIPP, **Machine learning based reconstruction techniques for CMS HGCAL** Dr Rajdeep Chatterjee

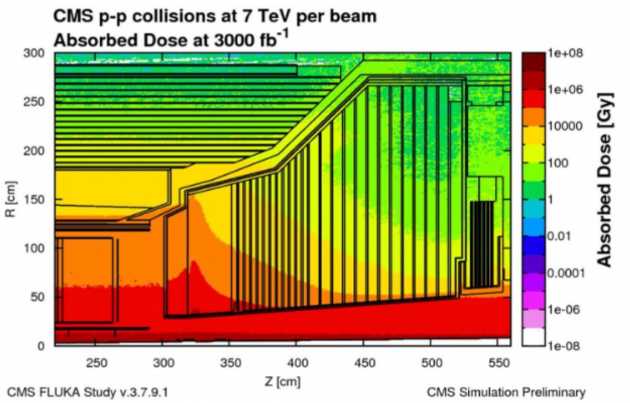
Development of Muon Tomography for the Geometry Validation of the CMS High Granularity Calorimeter, Dr Indranil Das

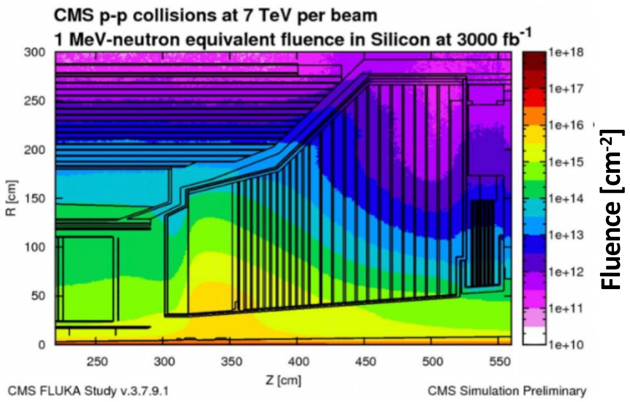
HGCAL: *Extreme radiation environment is a driver in the choice of technologies*

first experiment implementation of CALICE concept developed for linear collider detectors

26 Si layers in CE-E, with Pb/Cu/CuW absorbers; 8 Si layers & 13 mixed Si/Scint layers in CE-H, with Cu/SS absorber

Operate at T=-30°C

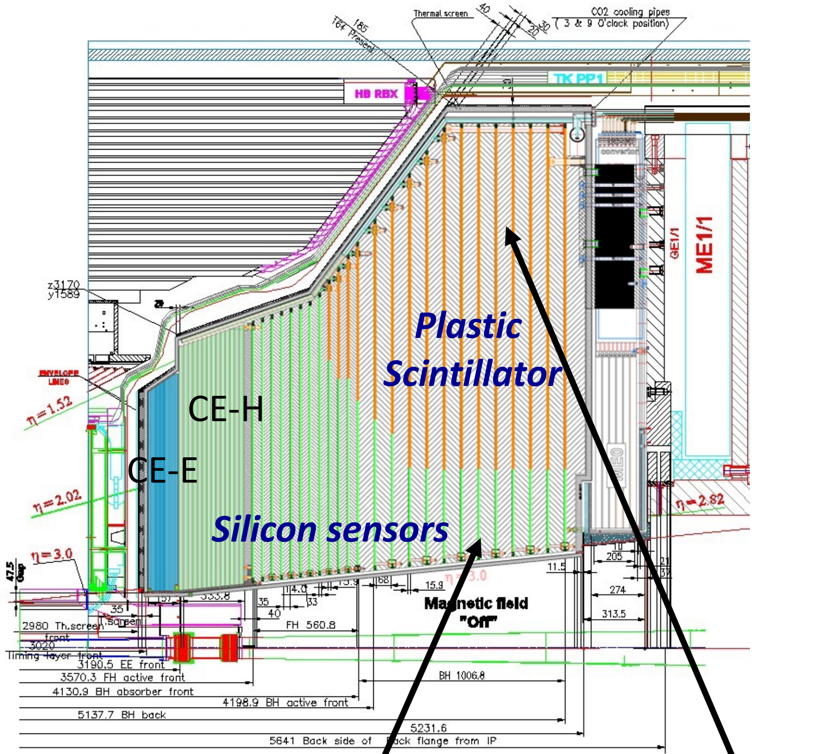




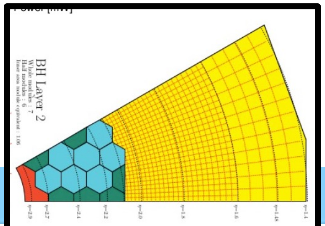
*CE-E: **26** sampling layers – 26 X_o + ~1.7 λ*

***CE-H 21** sampling layers – 9 λ*

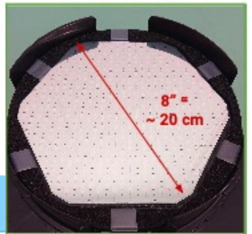
- **The silicon part** (*more rad tolerant*)
  - 600 m^2 of silicon (x3 of CMS Tracker)
  - 8" wafers – a first in High Energy Physics
  - 6M channels, 0.5 or 1 cm^2 cells
- **Plastic scintillator** (*less rad tolerant*)
  - ~370 m^2 of scintillators
  - 280k scintillator & SiPMs on tile
  - < 0.5×10^{14} 1 MeV n_{eq}/cm^2
- **High granularity**
  - 3D shower topology and time resolution of ~30 ps (p_T > few GeV) - **5D**
  - Particle Flow concept (PF)
  - High dynamic range 1- 5000 MIPs / channel
    - Frontend ASIC ADC (10-bit) & TOT TDC after preamplifier saturates (12-bit)



CuW stainless steel



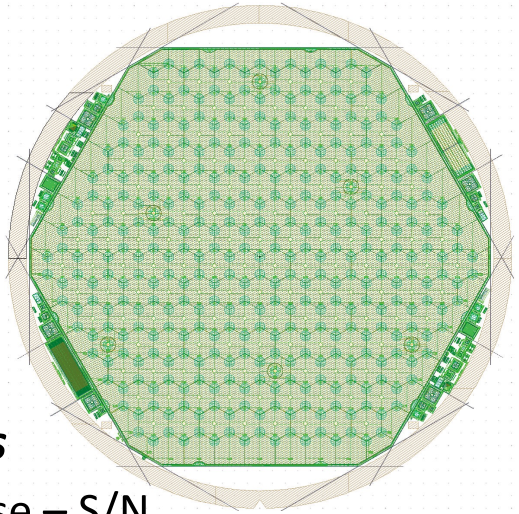
Silicon sensor



Scintillator tileboard

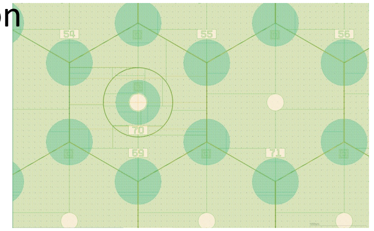
HGCAL sensors

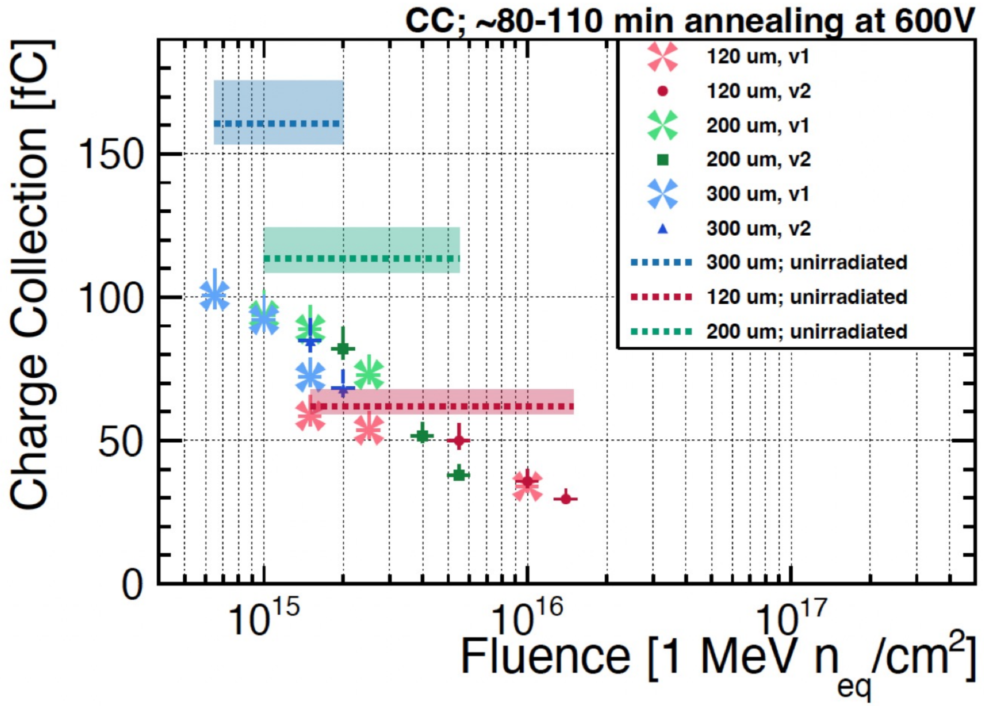
- n-in-p pad hexagonal sensors on 8inch wafer – **cost-effective usage of wafer area** – enabling 600m^2
  - with p-stop cell isolation



- Extensive neutron irradiation and annealing campaign on full sensors

- ***Sensor thickness*** and cell sizes adapted to radiation and particle density ***vs. radius***
  - Optimize occupancy and capacitance/noise – S/N
  - MIPs used for calibration – normal high energy signals are higher
    - A few per wafer calibration cells in addition





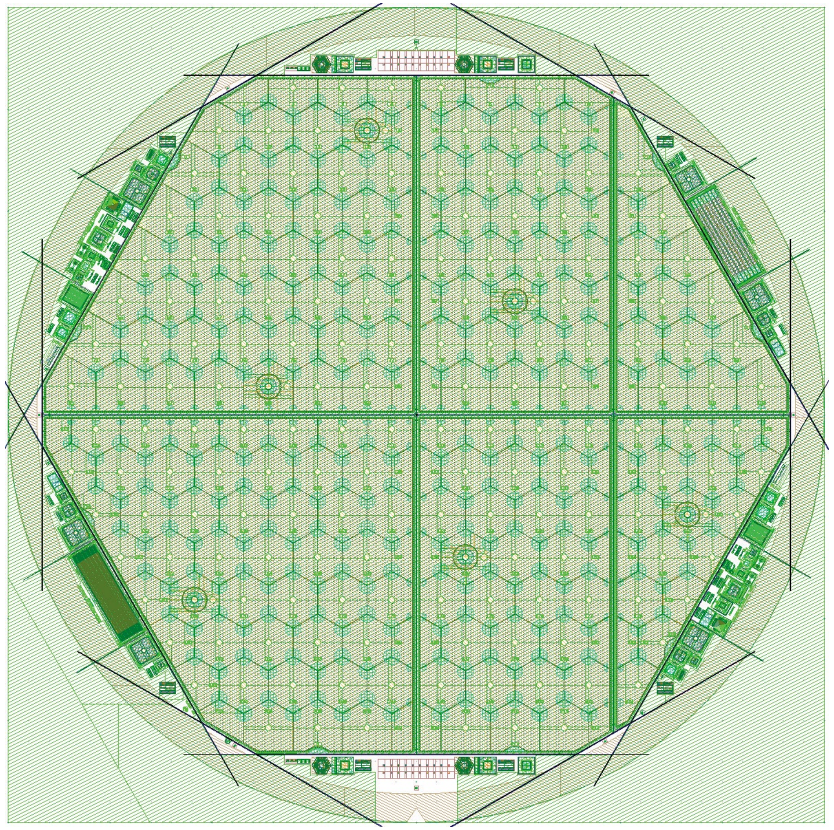
Leena Diehl et al, RD50 Workshop, June 20, 2023

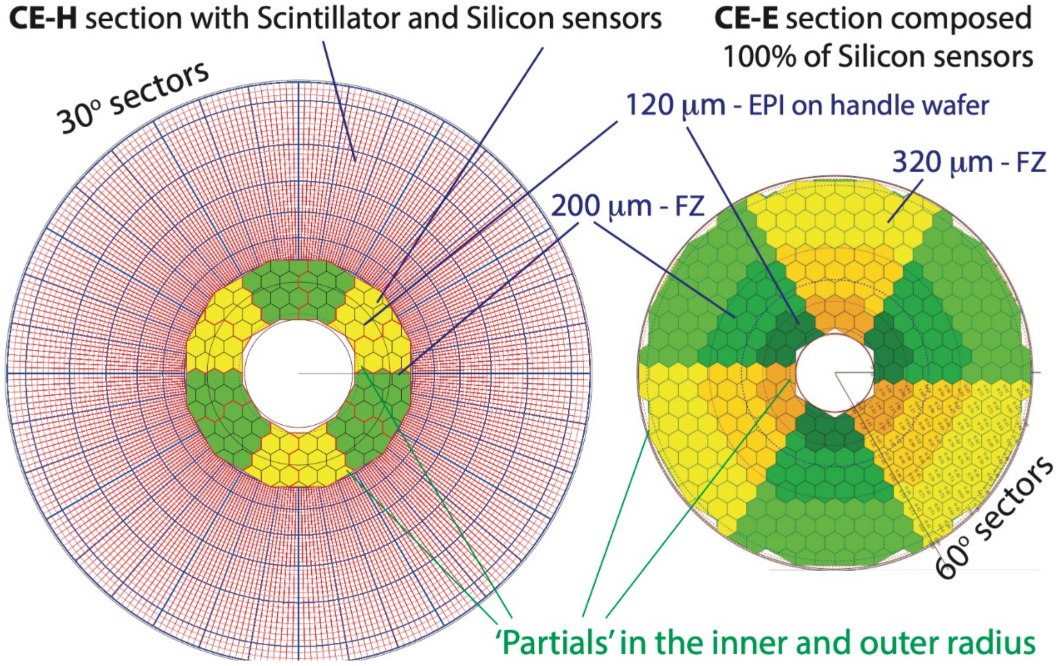
Thin sensors: keep fields high (at same voltage) after irradiation and annealing
After irradiation: thin sensor have the same or higher signal as thick sensors

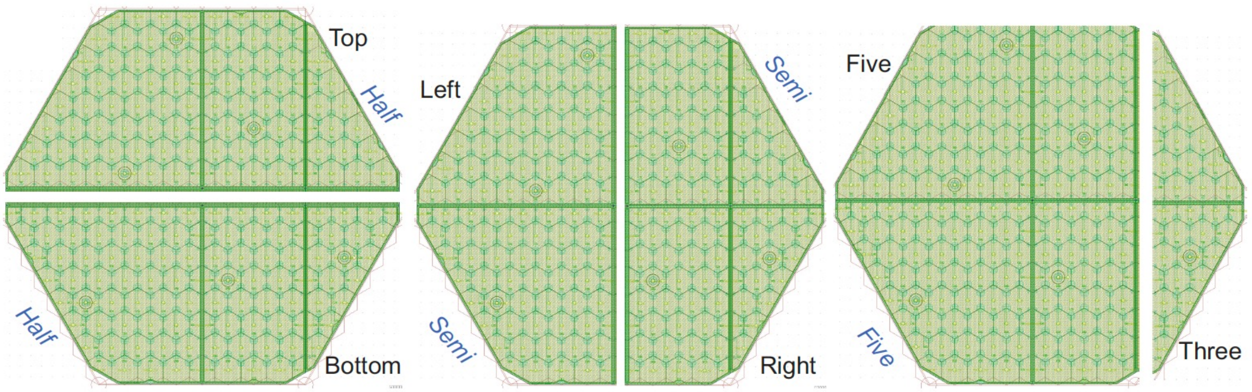
Active thickness (μm)	Cell size (cm^2)	Cell C (pF)	Fluence ($10^{15}\, n_{1\text{MeV}}/\text{cm}^2$)	Initial MIP S/N	MIP S/N (min) @ 3000 fb-1	Bulk material
300	1.25	44	0.1 - 0.5	7.8	5.8	FZ
200	1.25	65	0.5 - 2.5	5.5	3.6	FZ
120	0.56	48	1.5 - 7	4.2	2.3	EPI

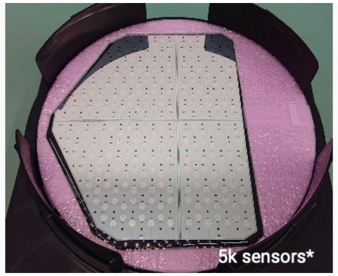
HGCAL sensor 2 - partials

- Optimise coverage at outer and inner radius
  – match hexagon to circle
- Several geometries out of a single wafer layout by different cutting









HGCAL Silicon modules

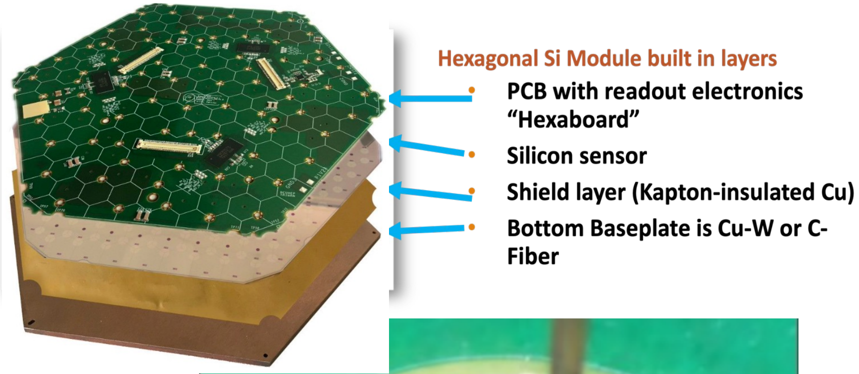
Design emphasizes performance, simplicity for automated assembly, robustness for 26000 modules

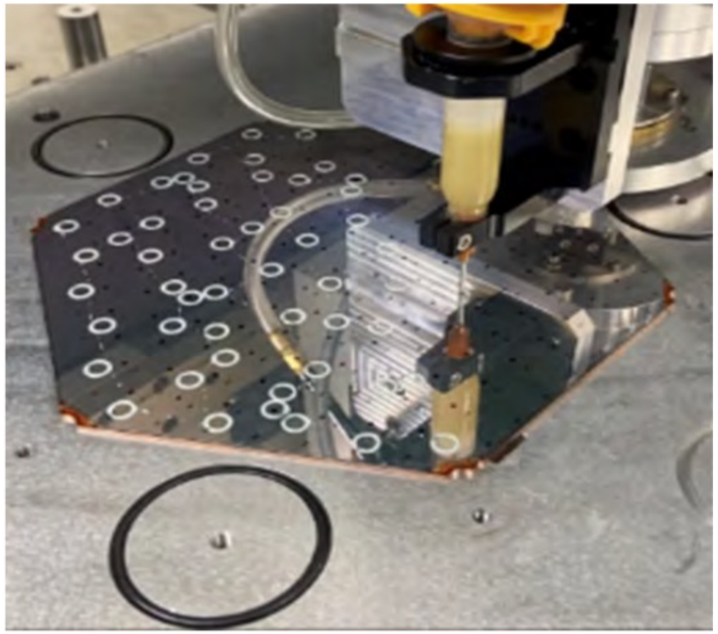
A Kapton foil is laminated onto the baseplate to provide bias (high) voltage protection, the grounded Cu inside shields against noise.

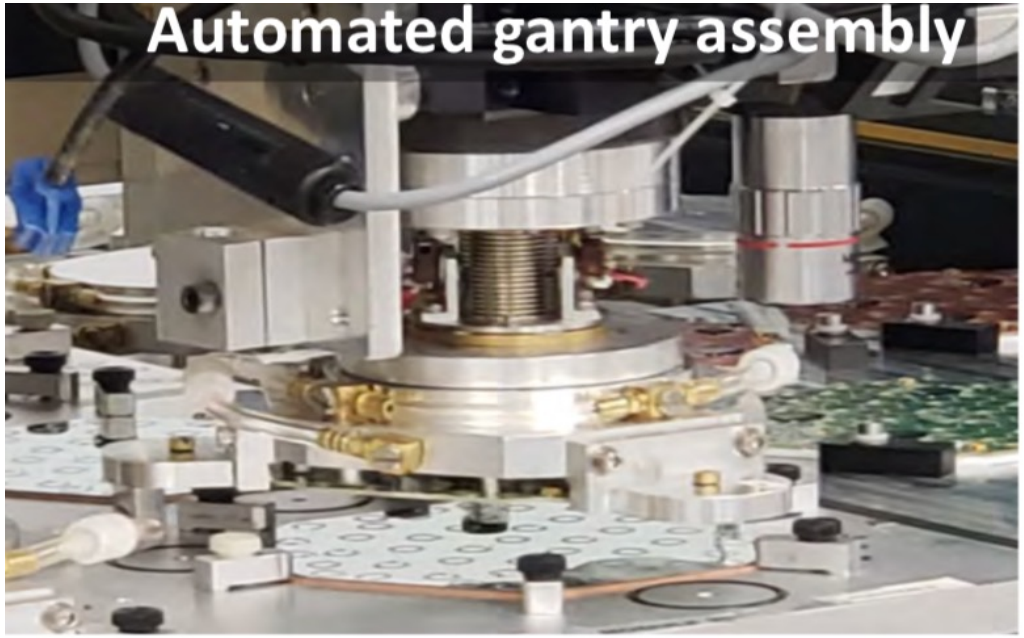
Base plate (CuW for CE-E and C-fibre for CE-H) onto which the sensor is glued.

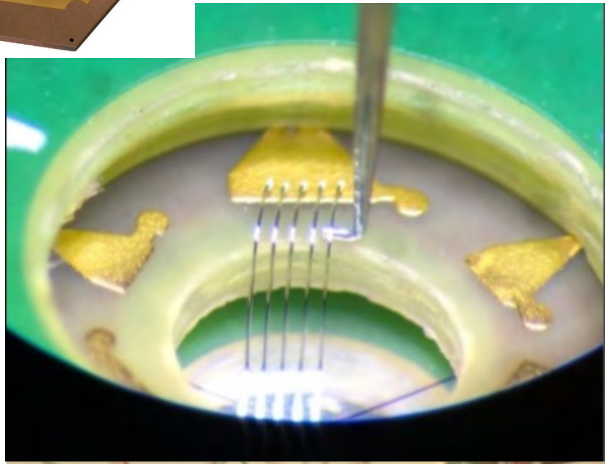
A front-end readout PCB "Hexaboard" is then glued on top of the silicon

The Sensor cells are wire-bonded and then potted.





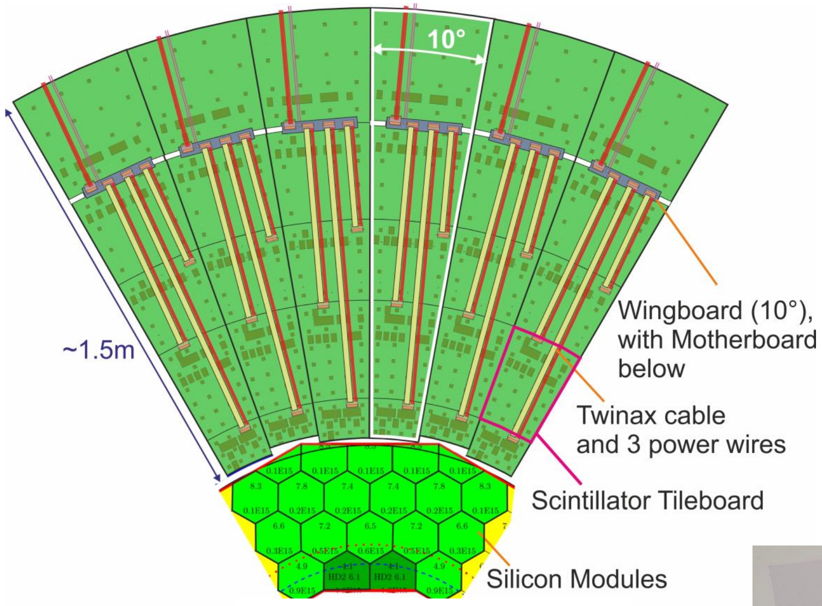




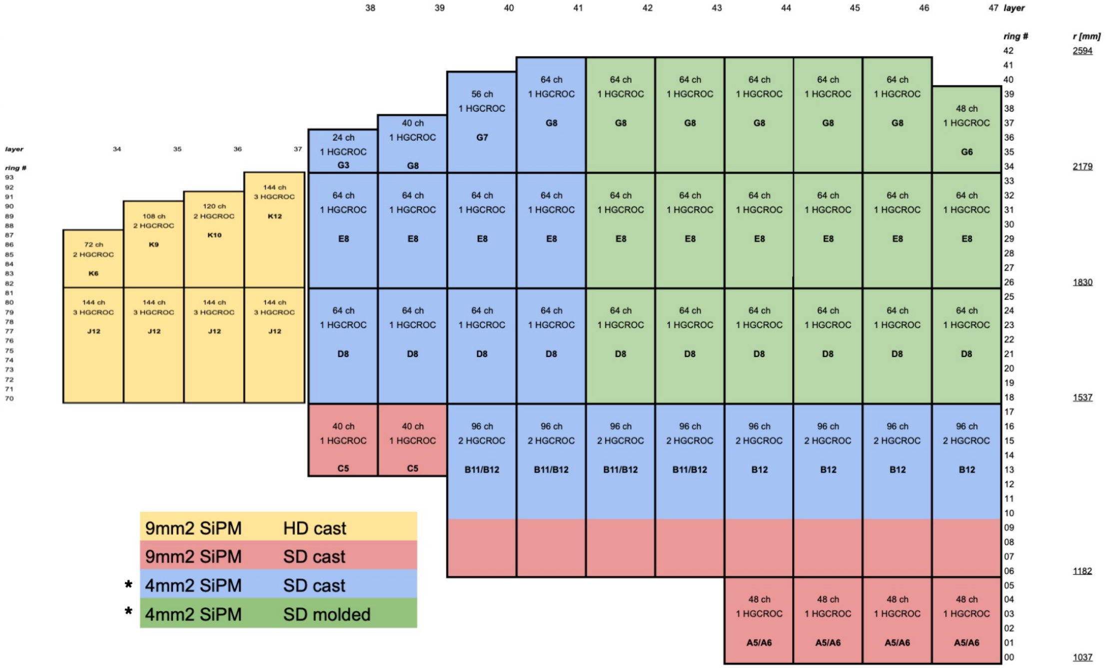
SiPM-on-tile system: 370m^2 ,280 000 tiles & SiPMs

Large detector 3744 pcbs, 3744 assembled tile modules

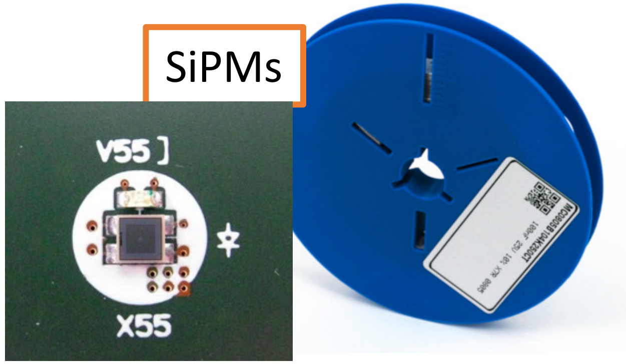
*Small **cast-**scintillator tiles in high radiation zone, larger **moulded** scintillators in low radiation zone*

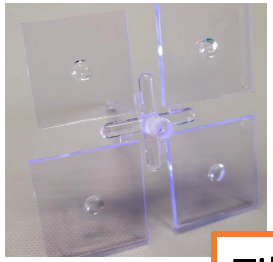


Layout is optimized for S/N relative calibration with MIPs > 2.5 after 3000 fb^{-1}

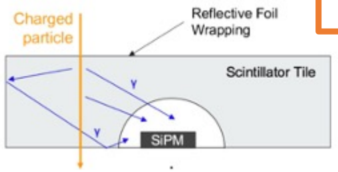


SiPMs





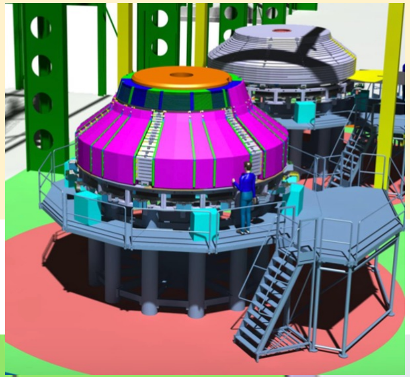
Tiles



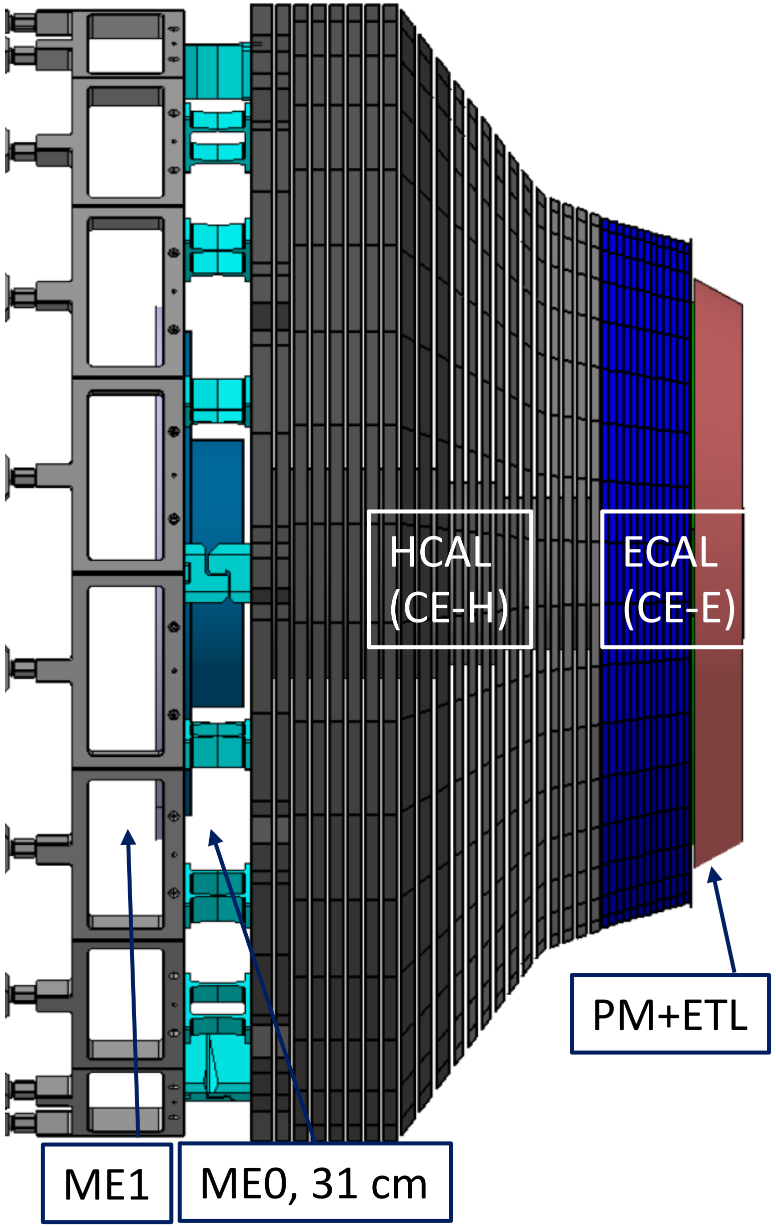
207 m^2 cast ; / 163 m^2 injection-moulded scintillator tiles
4 mm^2 and 9 mm^2 SiPMs below wrapped tile “dimple”
8 types + sub-variants of tileboards

Engineering challenges

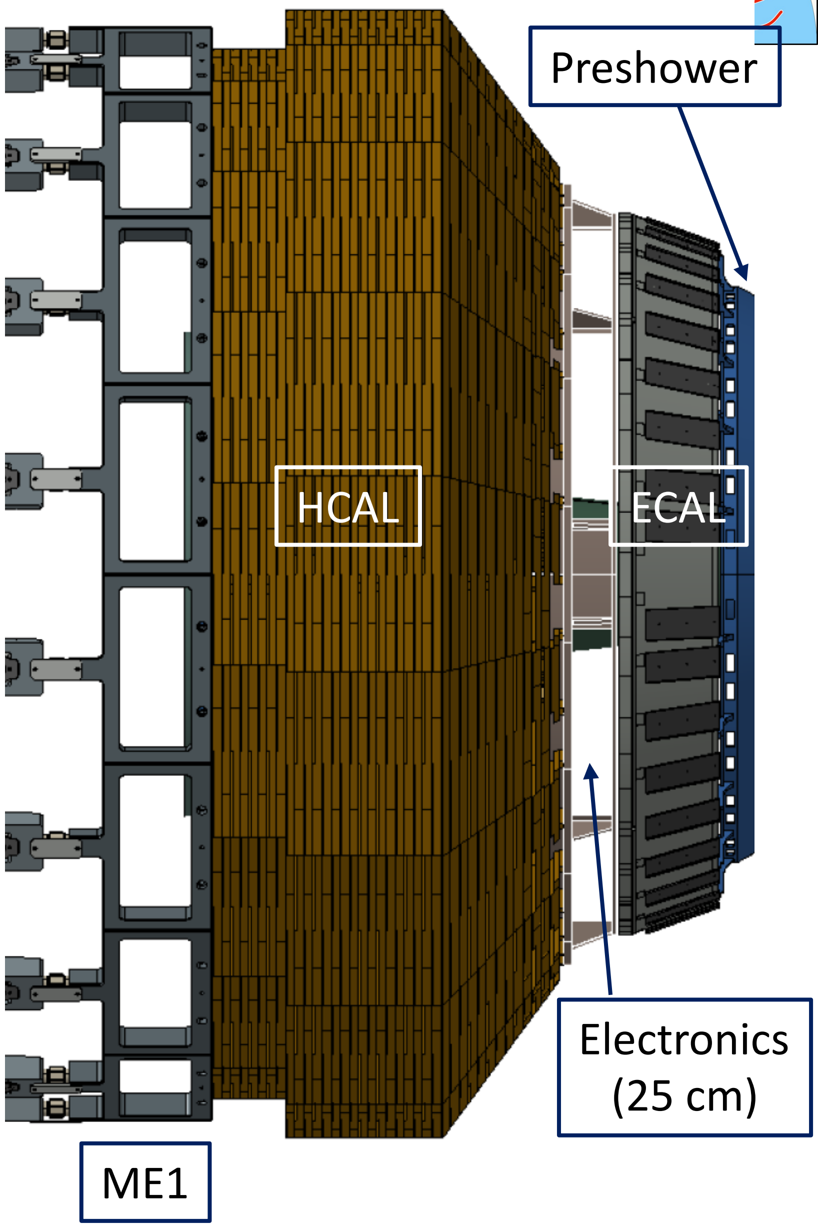
- High precision
- High density
- High mass
- Electronics integrated into each layer
- Warm-cold transition
- Services integration
- Insertion tooling
- Lower 230 ton down into the cavern (-100 m underground)
- Constrained by fixed envelope



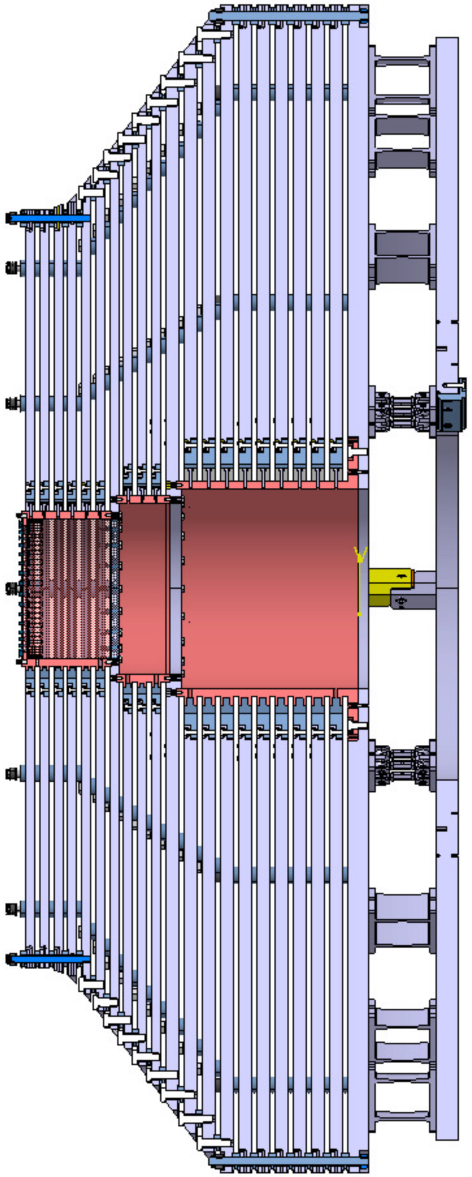
New HGCAL LS3



Today's Endcap Calorimeter

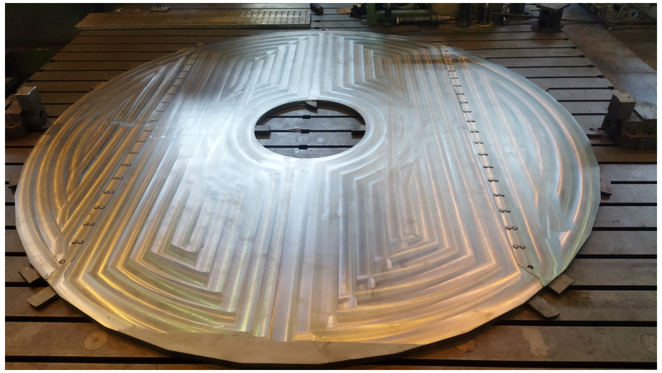


Selected HGCAL (heavy) Mechanics

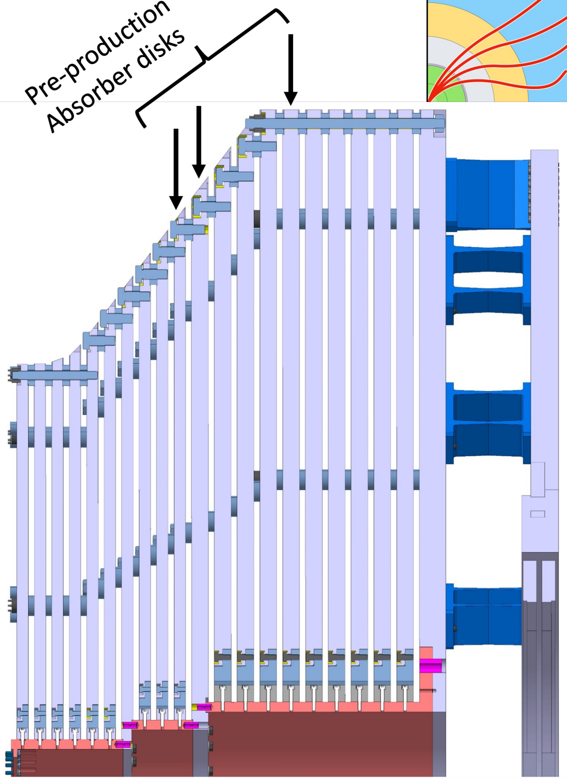


132 Stainless steel absorber plates (μ_{max} = 1,05 SS304L)

Machined to intermediate thickness – flatness < 1mm

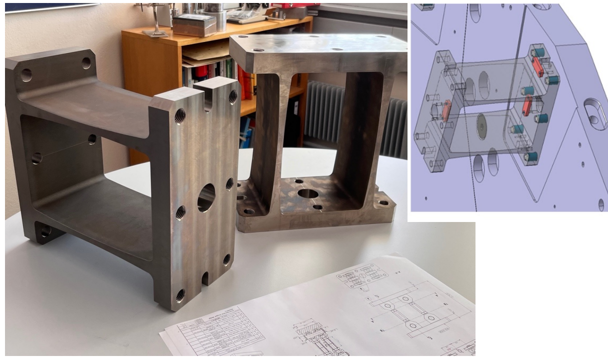


First absorber disk being machined by PAEC/HMC-3



CE-H Ring inner support cylinders

Titanium-Grade 4 wedges machined (interface CE-H backplate and YE-1),Low heat conduction, low Young's modulus, High strength yet ductile



Support wedges machined by KIT

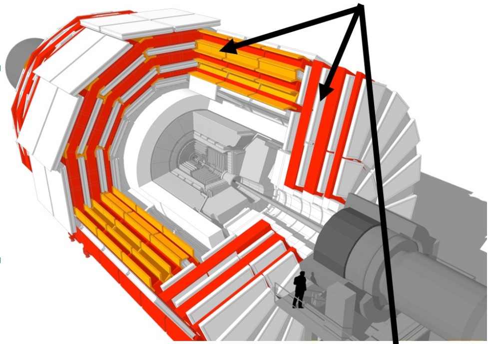
CMS Muon Detector Upgrade

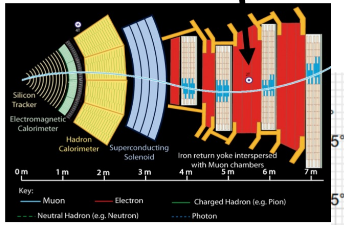
new electronics for legacy system, improved coverage to $|\eta| < 2.8$ & p_T resolution for trigger, sustain high rates

Existing DT, CSC , RPC muon detectors remain with upgraded electronics

- sustain x10 higher rates enhance performance
- Improve RPC trigger hit time resolution from 25 ns to 1.5ns

Installed electronics CSC (ME) and all GE1/1 ***during LS2***
Installed GE2/1, RE4/1 and RE3/1 demonstrators in LS2 and all services

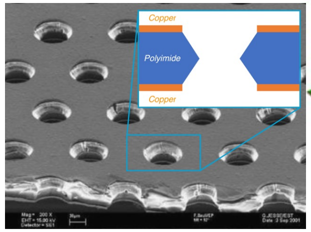


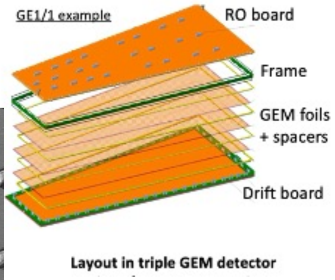


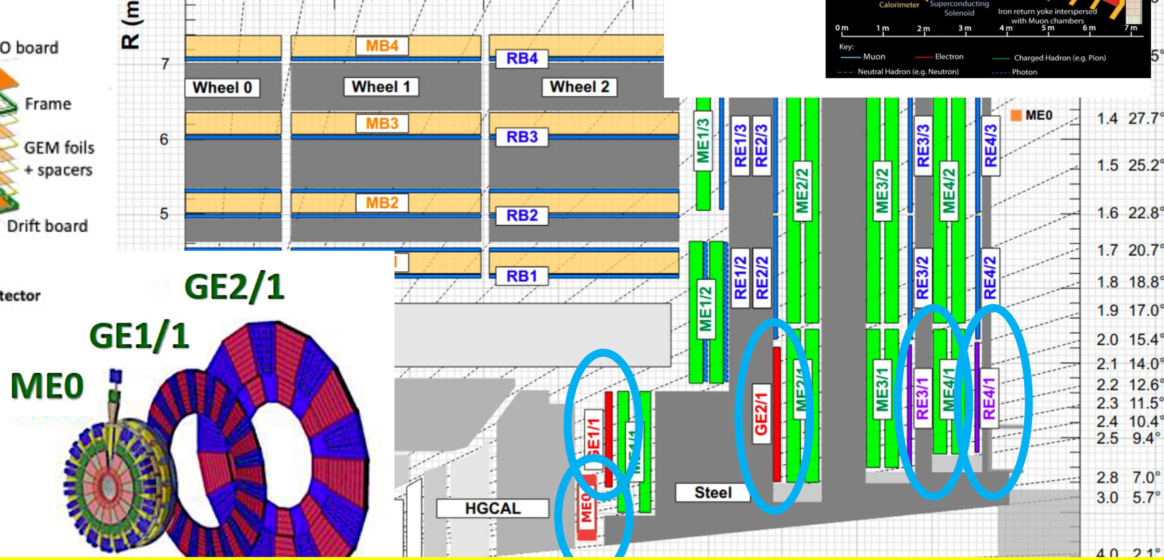
New detectors in challenging (high rate, high background) forward region

- Enhance tracking performance
- Allow bending angle measurement at trigger level

- Triple-Gas Electron Multiplier (GEM) detectors:
  - GE1/1 : (2 layers) LS2
  - GE2/1 : (2 layers) YETS before LS3
  - ME0 : (6 layers) LS3
- New: improved RPC detectors
  - iRE3/1 & iRE4/1: 1 layer each for redundancy







Investigate eco-friendly gas solutions and recuperation (eff 80%)

More info, comprehensive presentations: **The upgrade of the CMS Muon System for the LHC Phase 2,** Gabriella Pugliese
Longevity Studies of the CMS Muon System for HL-LHC Lisa Borgonov
Long-term Performance Studies of Resistive Plate Chambers with Environmentally Friendly HFO/CO2 Gas Mixtures at the GIF++ Facility, Gianluca Rigoletti

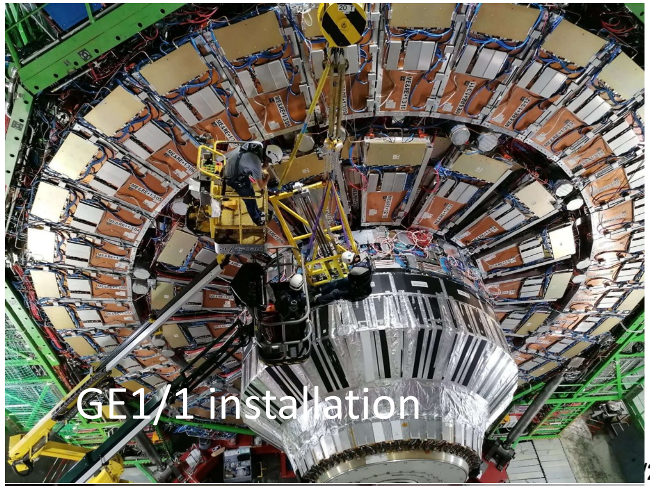
CMS GEM detectors

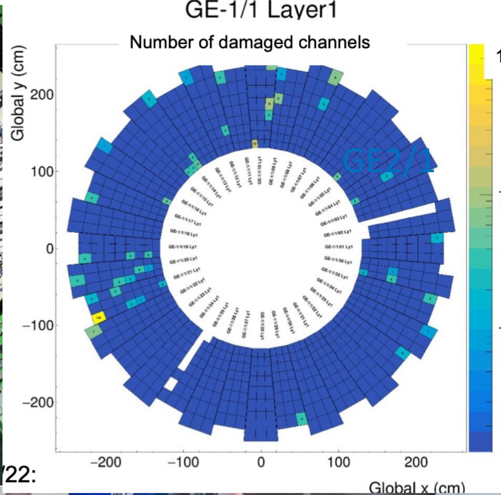
Successful completion of GE1/1 – 72 super chambers per end

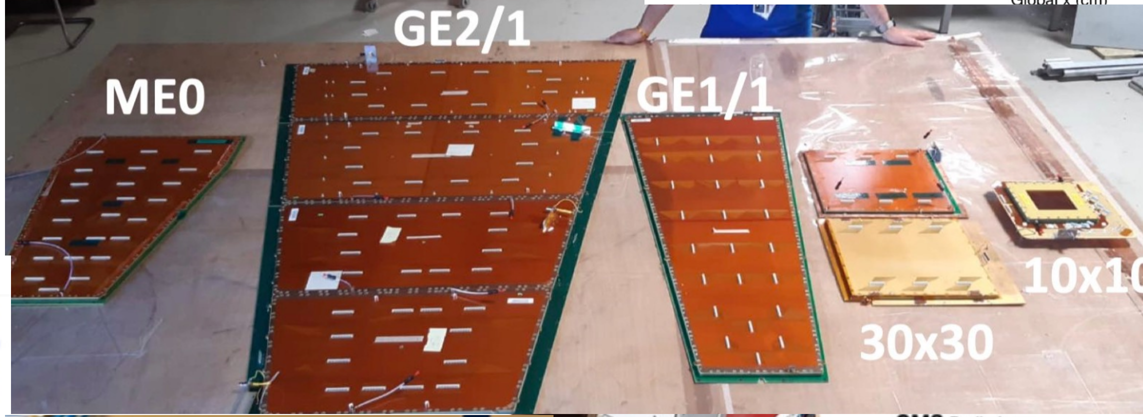
GE2/1 demonstrator installed, production ongoing

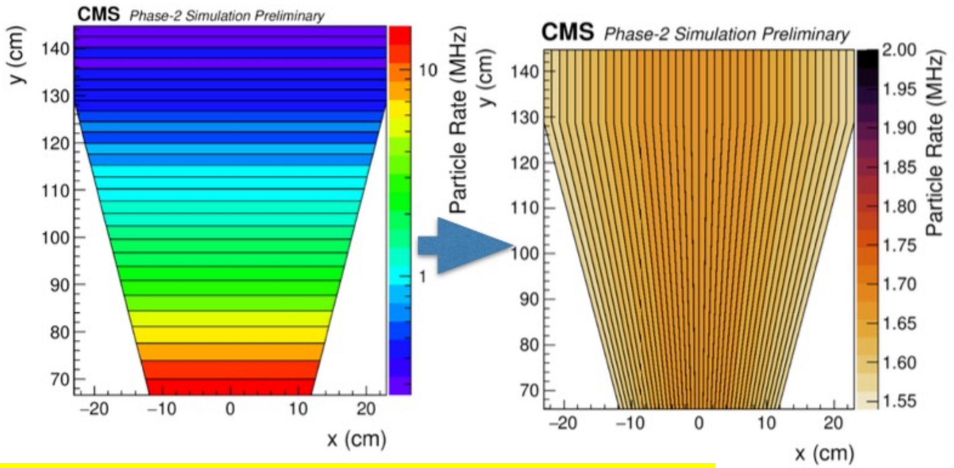
ME0:

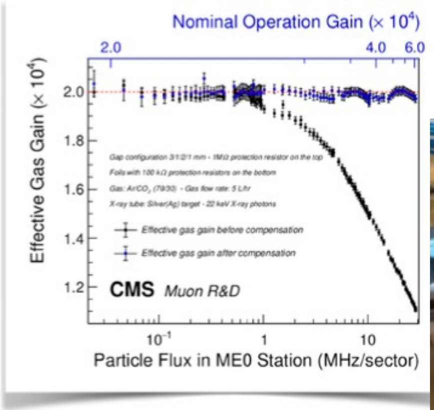
- Stack of 6 layers of triple-GEM
- Operate in a challenging environment with hit rates up to 150 kHz/cm^2
- New GEM foil design to mitigate the problem of gain drop:
- Change the orientation of HV segments from horizontal to azimuthal

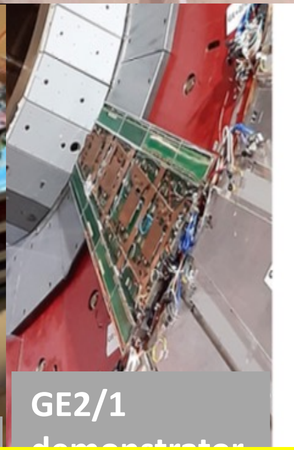


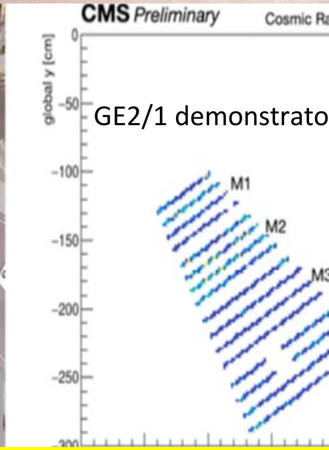








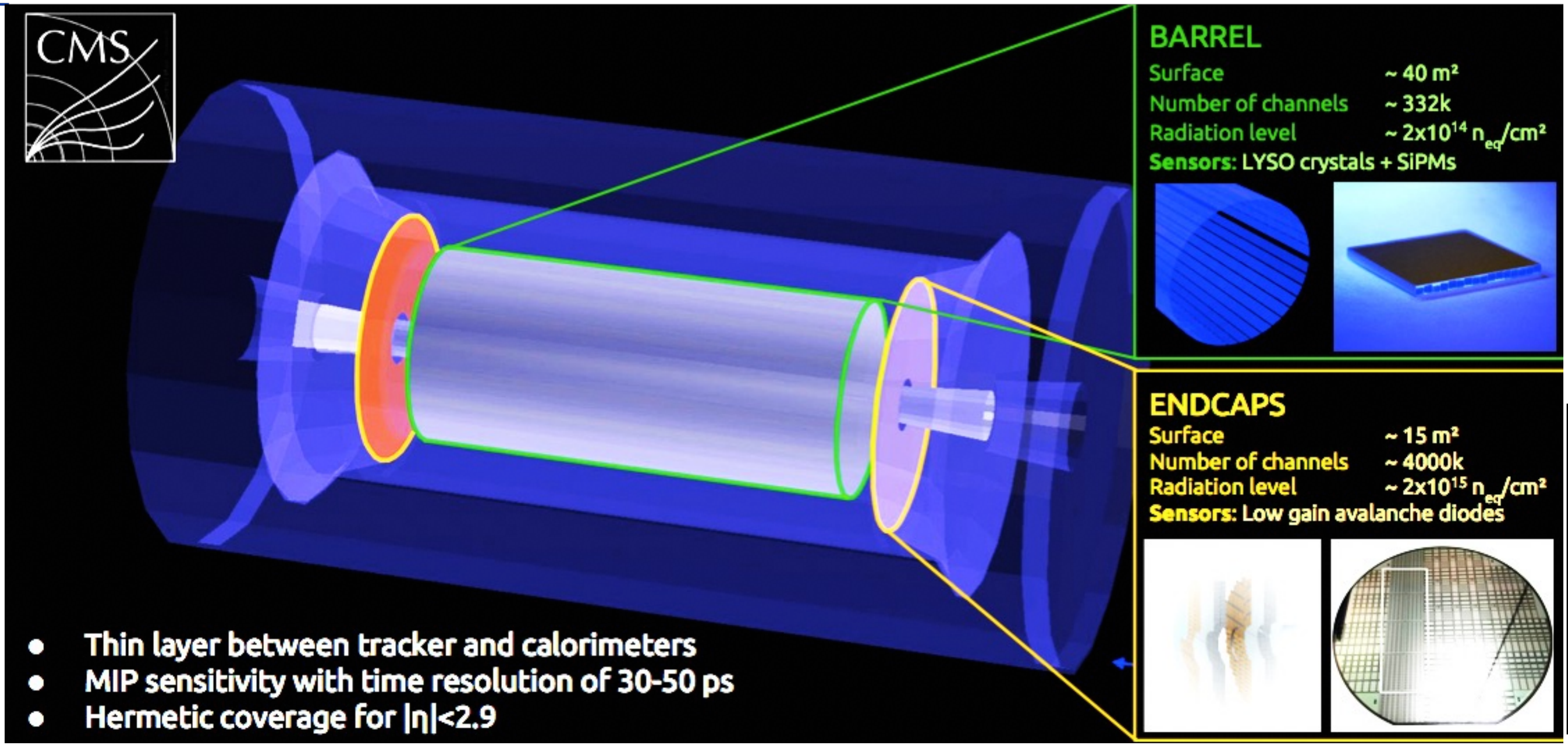




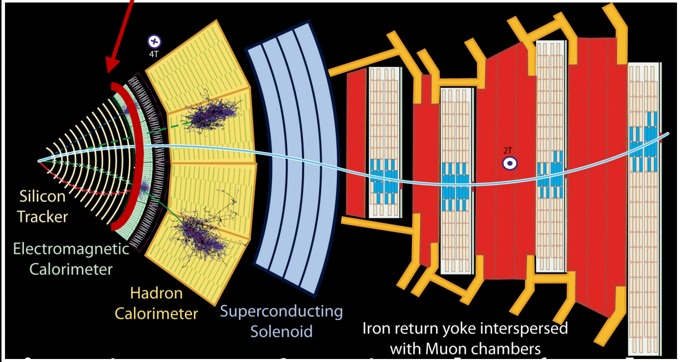
Foil & pcb technology covered in Plenary talk tomorrow “**MicroPattern Gaseous Detectors**” by Dr Rui de Oliveira

More info, comprehensive presentations: **The upgrade of the CMS Muon System for the LHC Phase 2,** Gabriella Pugliese

The Power System of GEM-Muon Sub-Detector for CMS Phase-II upgrade Shimaa AbuZeid



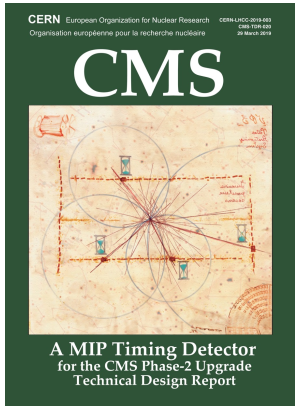
Between Tracker and Calorimeter



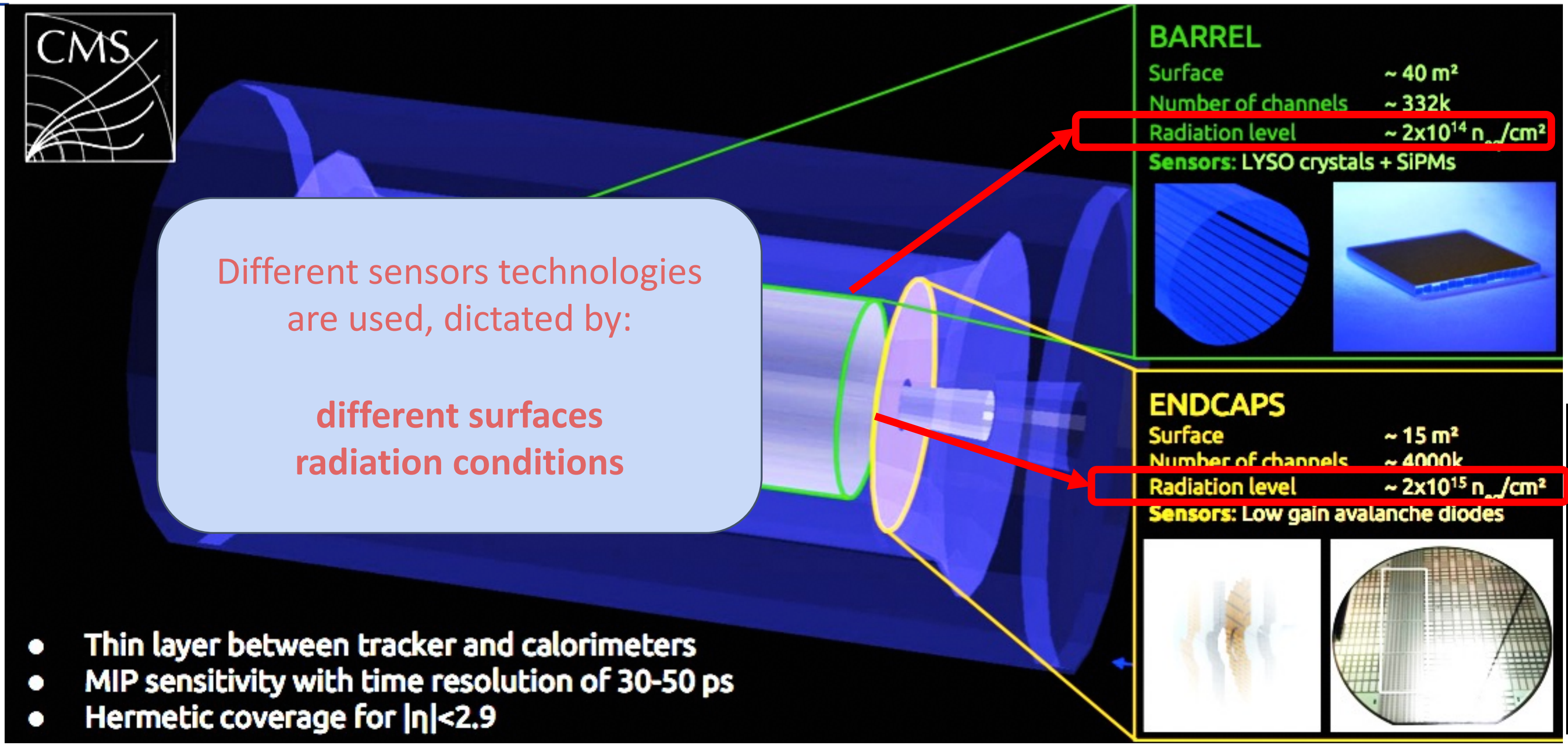
30-60 ps timing on arrival timing of minimum ionising particles – an extra parameter to associate tracks to vertex

Coverage 0 < |η| < 3.0

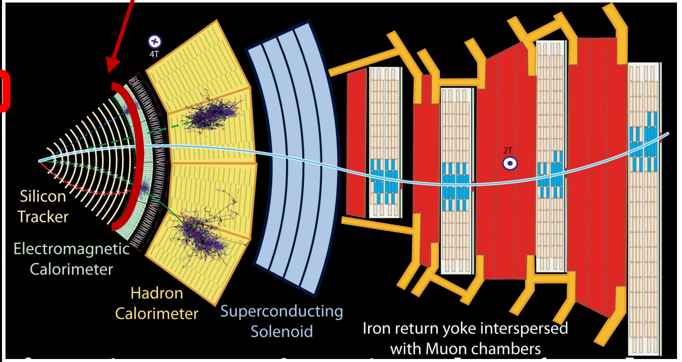
MTD MIP Timing Detector



CERN-LHCC-2019-003 CMS-TDR-020



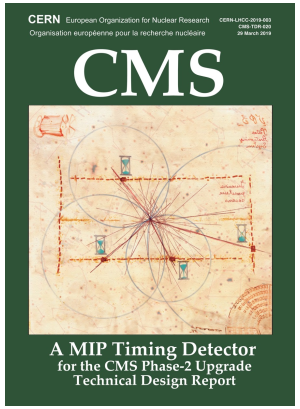
Between Tracker and Calorimeter



30-60 ps timing on arrival timing of minimum ionising particles – an extra parameter to associate tracks to vertex

Coverage $0 < |\eta| < 3.0$

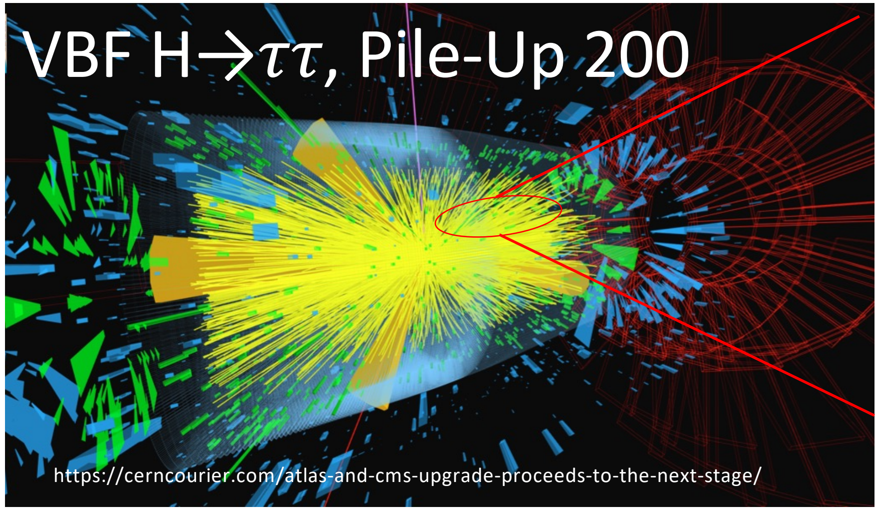
MTD MIP Timing Detector



CERN-LHCC-2019-003 CMS-TDR-020

Precise timing to associate tracks to a vertex

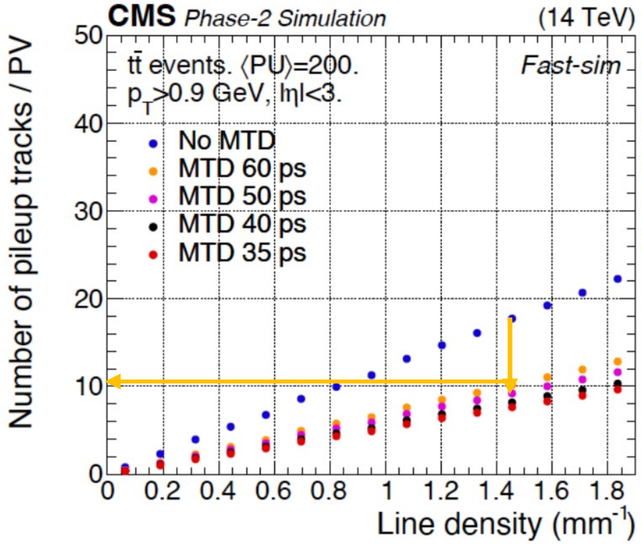
reduce tracks from pileup vertices that are incorrectly associated with the hard interaction vertex

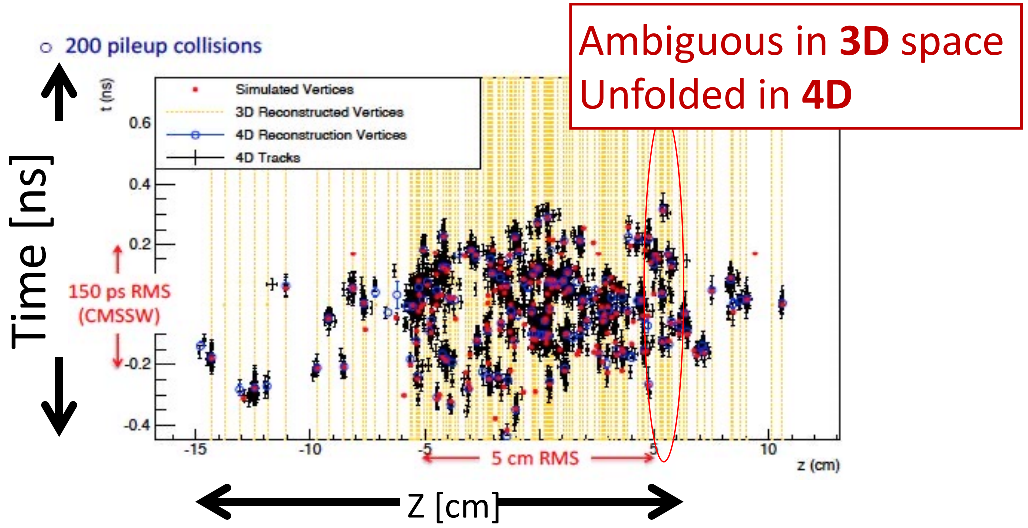


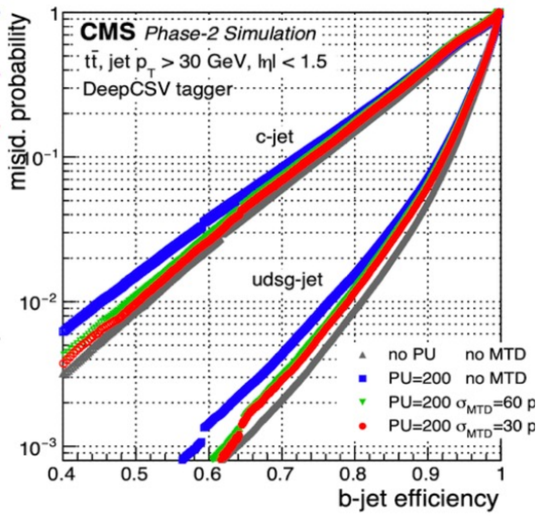
improving the efficiency in reconstructing the physics objects
- better *lepton isolation* efficiency
- reduced *pileup jet* rate
- improved *b-jet tagging* efficiency
- For many channels, the gain is equivalent to 25-30% increa of integrated luminosity (see talk. P. Meridiani)

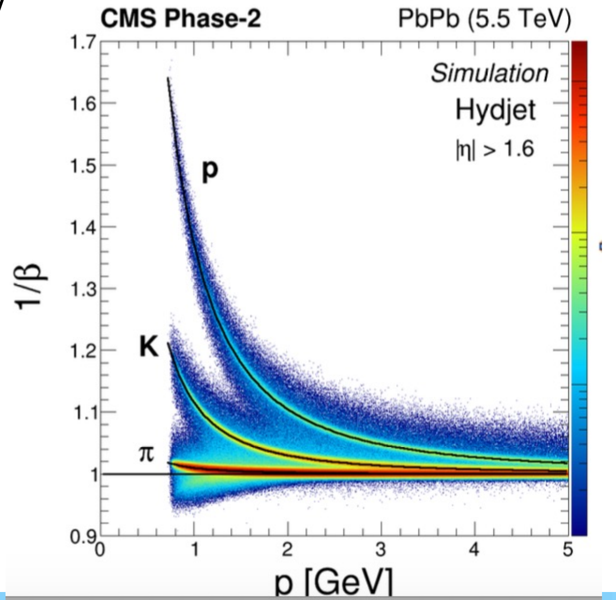
identifying charged particles based on the time-of-flight e.g.
- searching for long lived particles etc.

particle ID in heavy ion program
- **π**/K separation up to 2-3 GeV and K/p separation up to 5 GeV









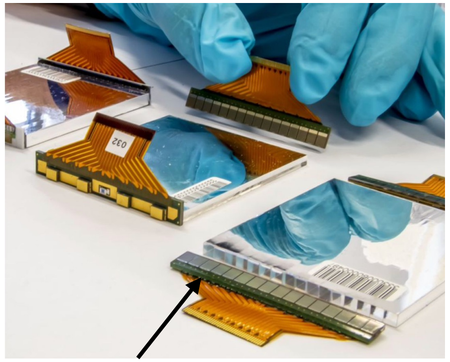
MTD – **Barrel** Timing Layer (BTL) Technology

first HEP experiment “PET-like” system

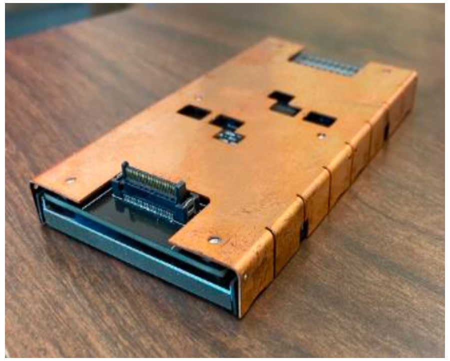
thin layer of LYSO:Ce crystal bars + SiPM + thermal electric coolers providing $\sigma_t \simeq 30/60$ ps before/after irradiation

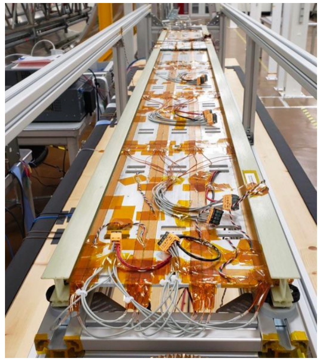
- Fluence at the end of HL-LHC $< 1.85 \times 10^{14}\ n_{eq}/cm^2$, Dose : < 20 kGy
- LYSO: Ce crystals – high light yield ~40000 ph/MeV ; decay time ~45ns, very fast rise time (~100ps), good radiation tolerance
- SiPMs: fast timing properties, magnetic field tolerant, compact and robust. 3x3 mm^2 SiPMs glued at each end of the bar
  - Two timing measurements per event, readout ASIC
  - Thermal electric coolers (TEC): cooling (**ΔT=10** to -45 °C) to reduce dark count rate (~x2) and annealing (+60 °C) the SiPM

16 LYSO bars polished on both ends (56 x 3 x 3.75 mm^3) per module ($\simeq$ 21000)

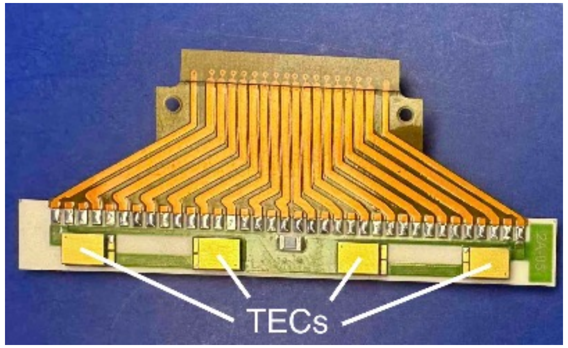


SiPM on both sides

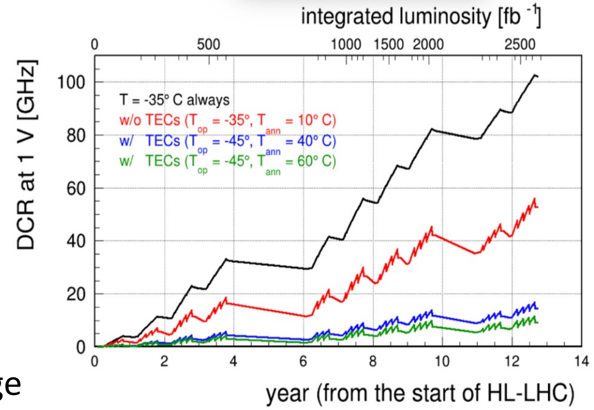




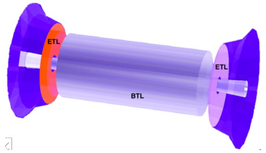
24 modules readout unit grouped in trays



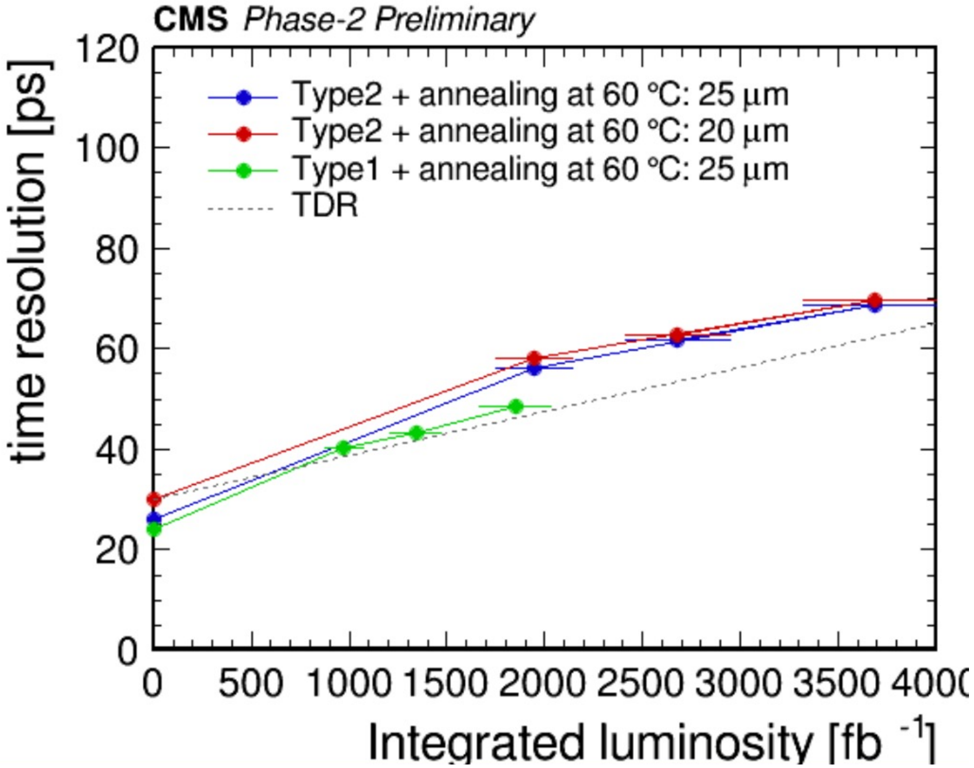
Company delivers SiPM+TEC package

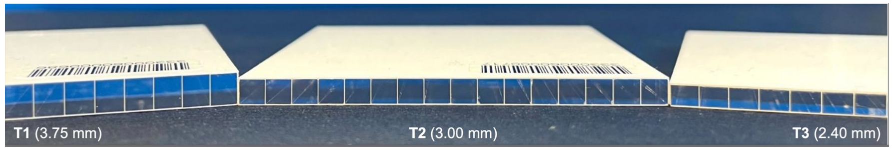


MTD – Barrel Timing Layer (BTL) Performance



- **Significant optimization of configuration to optimise σ_t performance through HL-LHC**
  - Smart thermal management with integrated TECs
  - SiPM technical choice of 25 μm cell size to boost signal (15 μm TDR)
  - Thicker LYSO arrays for larger energy deposits
  - TOFHIR2C ASIC optimization for electronic noise reduction

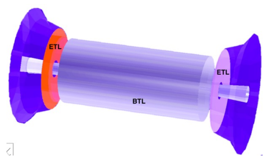




BTL: Barrel Timing Layer

More info, comprehensive presentation at TIPP, [Precision Timing at High-Luminosity LHC with the CMS MIP Timing Detector](), Paolo Meridiani

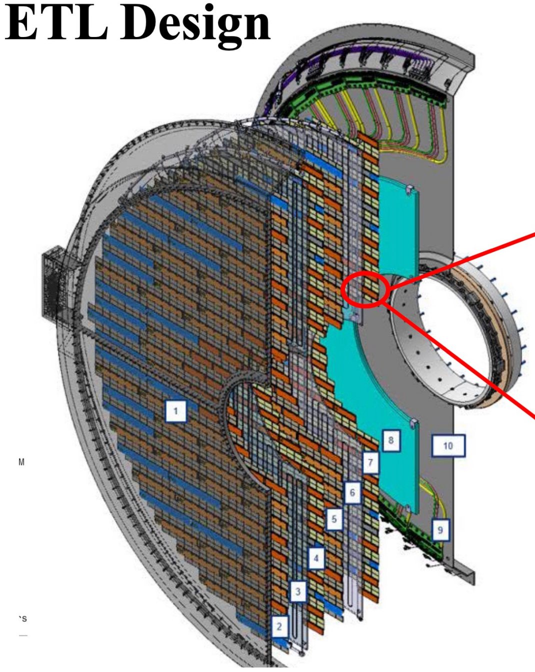
MTD – Endcap Timing Layers (ETL)

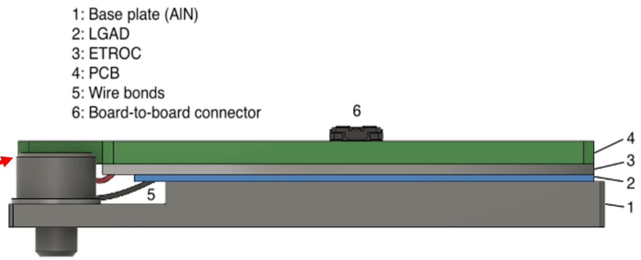


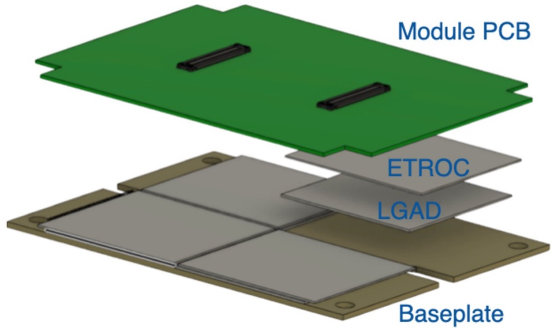
ETL first use (ATLAS&CMS) of Low Gain Avalanche photo Diodes (LGAD) on large scale readout by dedicated ASIC

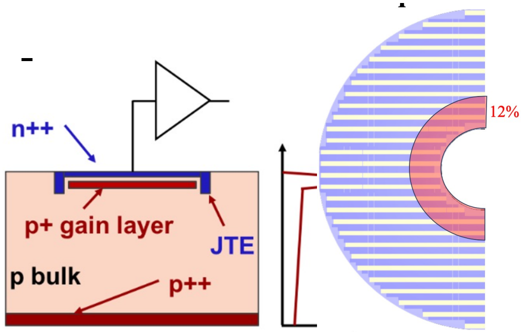
$1.6 < |\eta| < 3$, 2 double sided thin layers with 1.3 x 1.3 mm^2 pads providing 8.5 M channels $\sigma_t \simeq 35$ ps /track

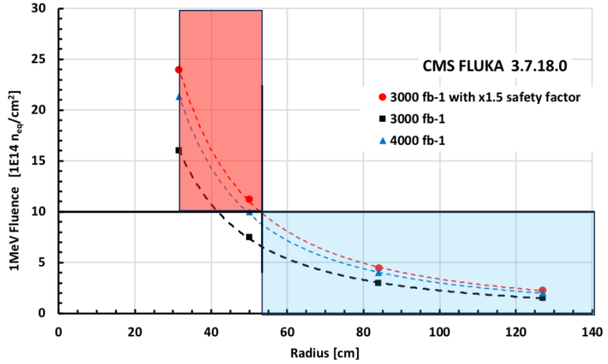
ETL Design

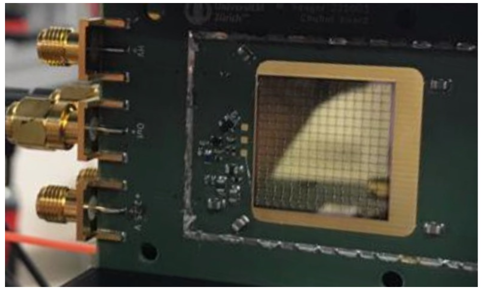


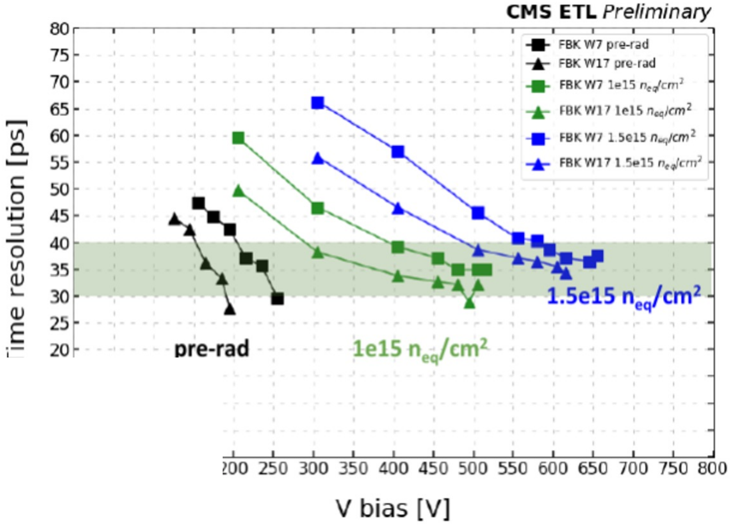












Half-shell design, can be extracted/installed with beam pipe in place

ETL Requirements:

- **Fill-factor** (ratio of active and total detector surface): >95%
- **Low occupancy**: <0.1% at low η, 1% at highest η
- **Radiation tolerance**: up to 1.7x10^{15} 1MeV n_{eq}/cm^2

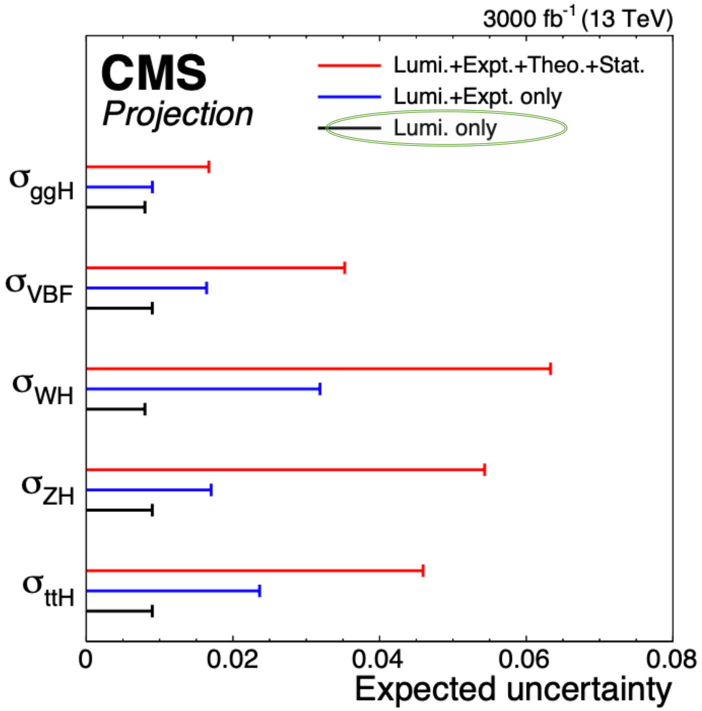
(12% of surface will reach higher fluences than 1x10^{15} 1MeV n_{eq}/cm^2)

- **Sensor choice: 50 µm-thick, 16×16 pads array with 1.3×1.3 mm² pads**

More info, comprehensive presentation at TIPP, Precision Timing at High-Luminosity LHC with the CMS MIP Timing Detector, Paolo Meridiani

CMS Luminosity Measurement @ HL-LHC

One of the largest sources of experimental systematic uncertainty in many physical analysis



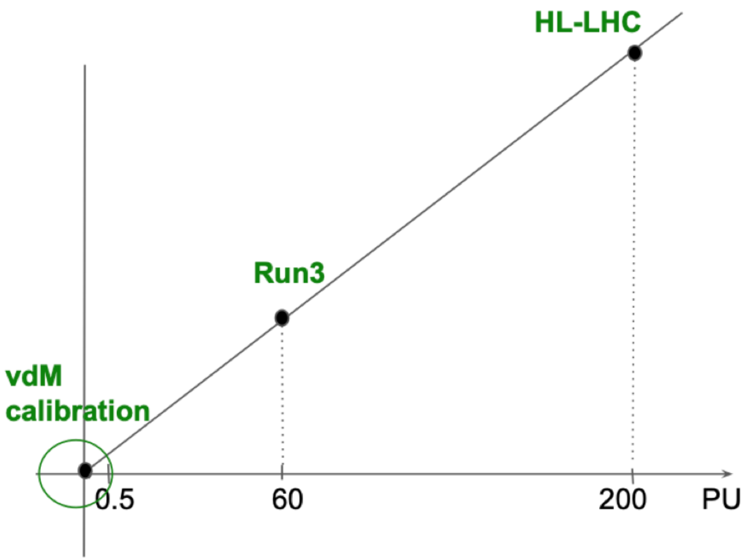
Precision goal for HL-LHC

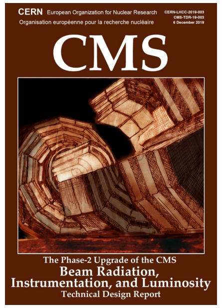
- **2%** online and **<1%** offline

  to match and even surpass other experimental uncertainties

https://cds.cern.ch/record/2759074

Instrumentation requirements:





- **Exceptionally linear response** over four orders of magnitude in total instantaneous luminosity (a factor of 400 in PU and about 20 in number of bunches)
- **Stability** and **longevity** over 3000fb^{-1} (>10 years)
- **Real-time** bunch-by-bunch measurements for precise machine optimization (e.g. luminosity levelling)

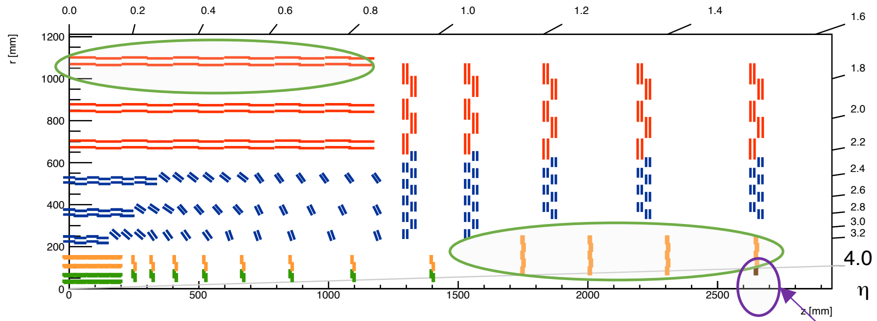
Require multiple luminometers to understand systematics of detector-related effects (<% level) and disentangle from beam effects

CMS Strategy Luminosity Measurement @ HL-LHC

CMS Sub-detector frontends

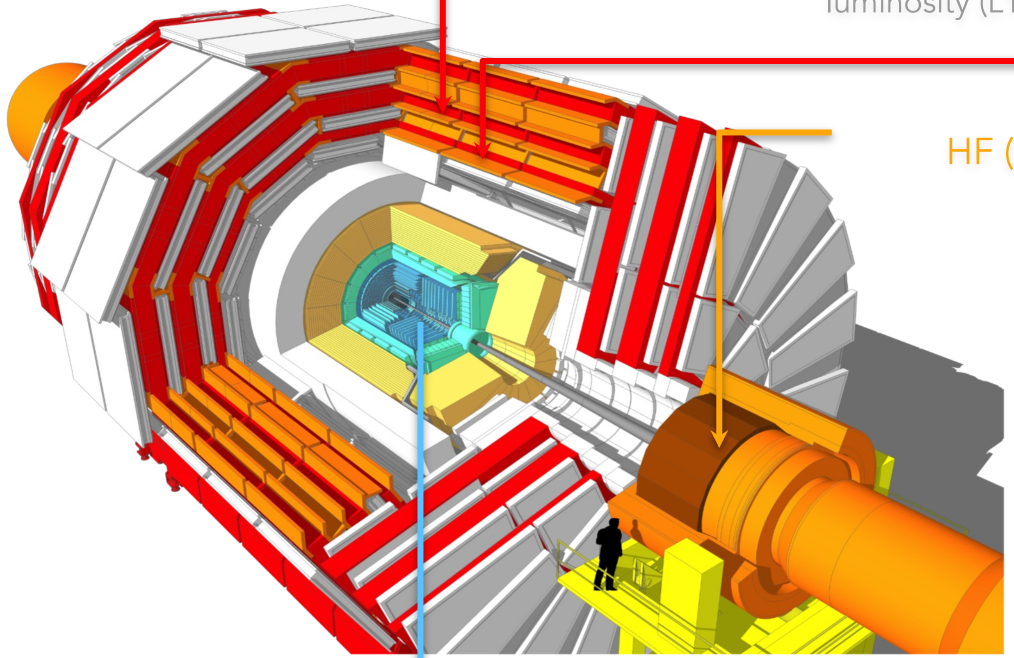
- **With dedicated luminosity readout**
- Exploit SoC & FPGAs in backend electronics for dedicated, real-time luminosity object processing

OT (Outer Tracker Layer 6)



TEPX-Disk4-Ring1

FBCM



40 MHz trigger scouting
luminosity (L1 muons, tracks, calorimeter objects)

Muon Barrel
luminosity (L1 trigger primitives)

HF (Hadronic Forward Calorimeter)
luminosity (Transverse energy sum, quartz fibers)

OT (Outer Tracker Layer 6)
luminosity (Si strip sensor coincidences stubs)

TPEX (Tracker Endcap Pixel Detector)
luminosity (Si pixel cluster counting)

detectors exclusive for luminosity beam monitoring

FBCM (Fast Beam Condition Monitor)
luminosity (Si pad zero-counting)

TPEX_Disk4_Ring1 (outside eta=4)
luminosity (Si pixel cluster counting)

https://cds.cern.ch/record/2759074

CMS Strategy Luminosity Measurement @ HL-LHC

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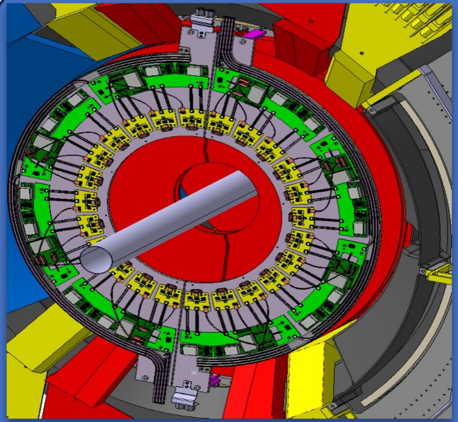
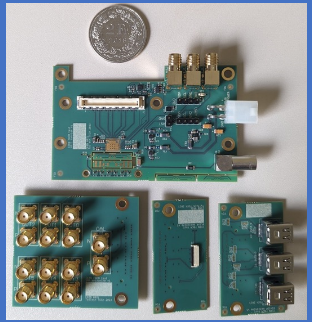
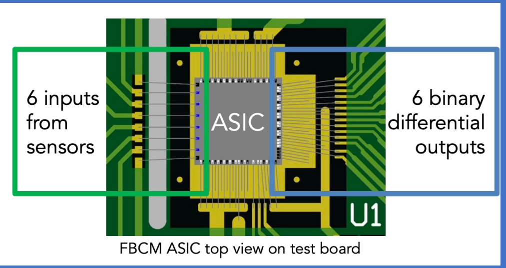
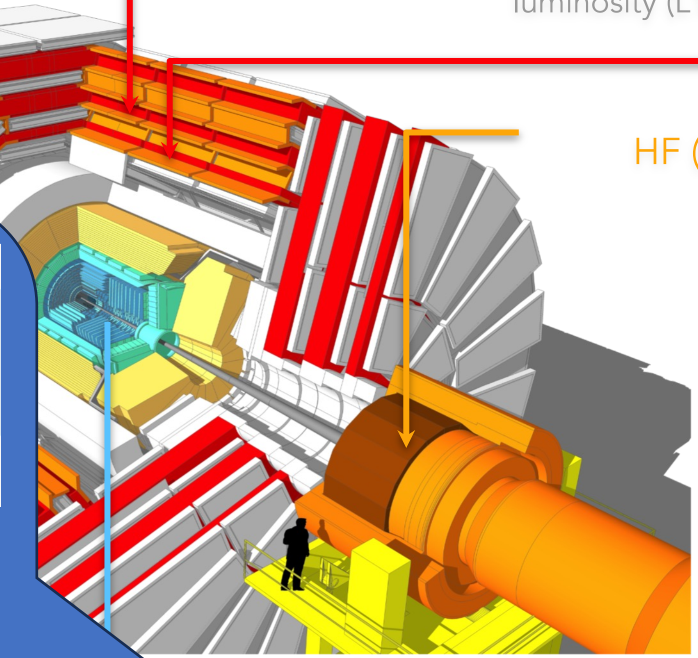






FBCM ASIC top view on test board

Dedicated, triggerless frontend ASIC development, see TIPP talk Konstantin Shibin



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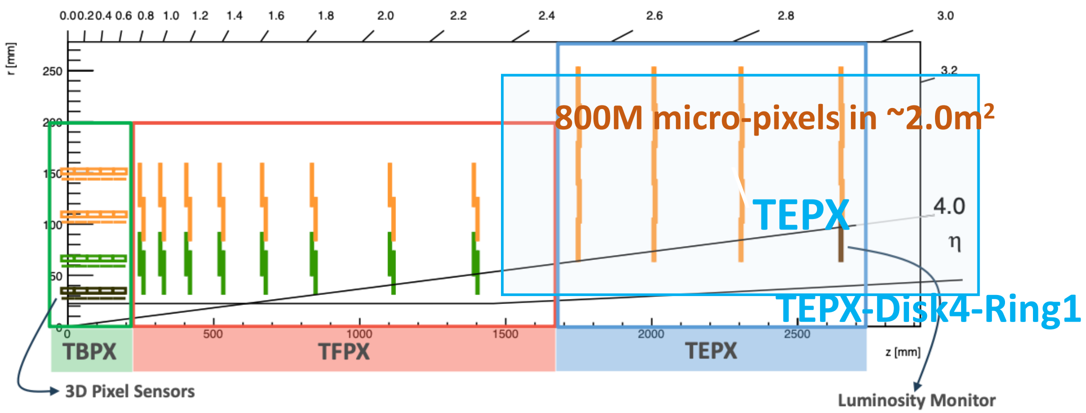
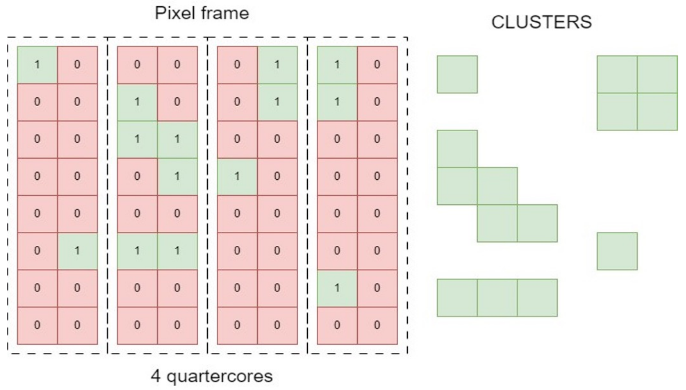
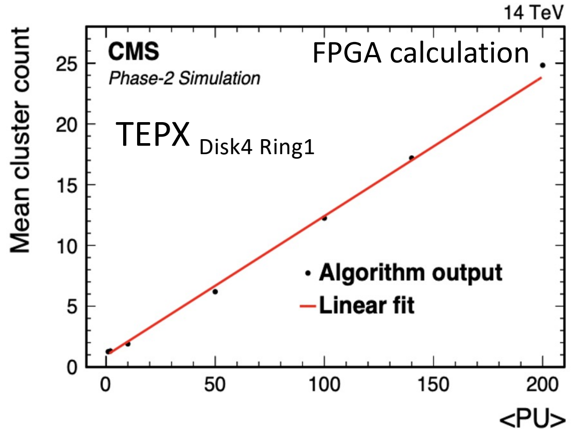
More info, comprehensive presentation at TIPP, Electronics design and testing of the CMS Fast Beam Condition Monitor for HL-LHC, Konstantin Shibin

TEPX: Luminosity triggers for real-time cluster counting on FPGA

Exploitation of CMS hardware with dedicated luminosity data processing



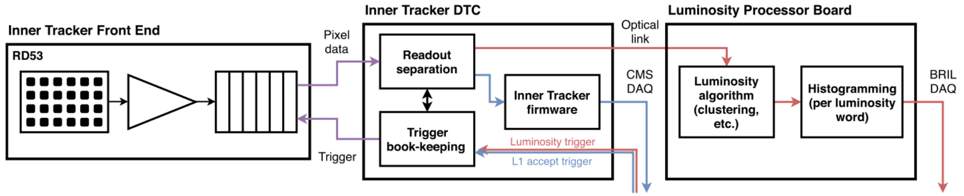




TEPX –750 kHz of CMS L1 triggers + 75 kHz luminosity trigger

- Backend electronics, decode trigger type and process luminosity triggers in a dedicated luminosity stream

Pixel Cluster Algorithm instance tested with margin available in both logic and memory resources.



TEPX-Disk4-Ring1

- 825 kHz of luminosity triggers only via special trigger board

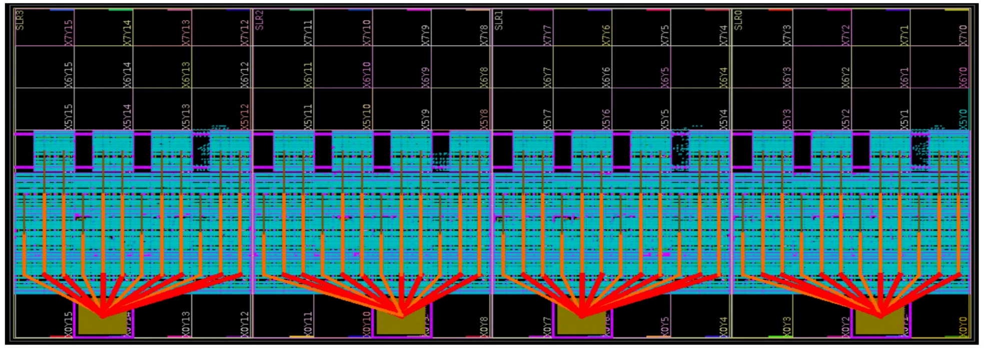


Figure 12.20: Placement of 176 clustering instances on a VU13P FPGA.

TEPX as a high-precision luminosity detector for CMS at the HL-LHC, M. Haranko et al
DOI 10.1088/1748-0221/17/03/C03001

https://cds.cern.ch/record/2759074

Infrastructure for the CMS Phase 2 upgrade

Profound infrastructure evolution

- Adapt to higher cooling and electrical power needs -> new technologies (CO2 evaporative, vacuum insulation, etc.), higher reliability demands (power backups, cold detector dry gas flushing…)
  - Detector racks: from 600 kW to 1500 kW
  - Cold detectors (sub-zero): from 120 kW (Tracker & Preshower) to 550 kW (=750kW @ primary system). High pressure. Vacuum jacket insulation pipes.
  - DAQ system: 1 MW to 2.5 MW (Run3) to up to 5 MW at end of Hi-Lumi operation

Electrical power evolution

- Detector power increase to 2 MW from max 1.5 MW
- Electrical power supply for CO2 cooling (with primary & ancillaries) about 2.5 MW

Complex work of integration

- Fit legacy detectors and new ones with higher readout, higher cooling power, etc into existing volumes – cannot re-do the full detector geometry -> 3D reconstruction, integration of cables, etc

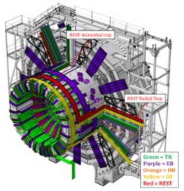
Challenging schedule

- decommission part of the legacy without damaging the detectors and infrastructure that remain, maintain and consolidate all that needs to increase lifetime up to end of Run 3, install new detectors and commission them to take new data in Run4!

Services per end Phase 1 vs Phase 2

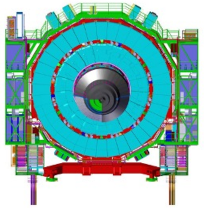
Barrel

	TK-Power	TK-Cooling	EB-LV	EB-Cooling	HB-Cooling	REST	OF	TOTAL
Per END Phase 1 (cm2)	1650.7	1376.0	910.9	1296.0	36.0	590.0	474.0	**6333.6**
Per END Phase 2 (cm2)	2559.9	729.1	910.9	1296.0	36.0	691.8	212.6	**6436.4**
Delta (cm2)	909.2	-646.9	0.0	0.0	0.0	101.8	-261.4	**102.8**

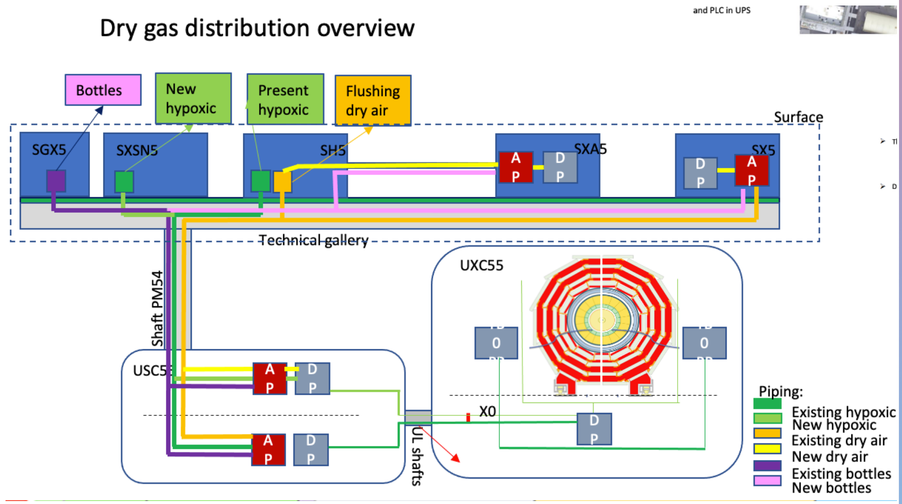


Endcap

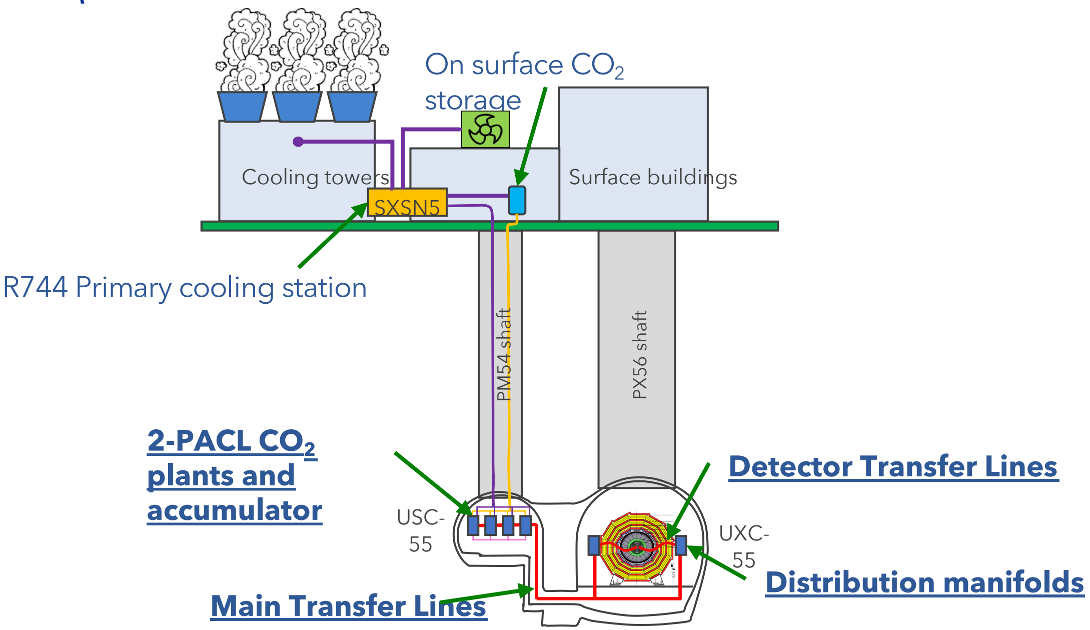
Per endcap Phase 1	RE1/3	ME1/3	RE1/2	ME1/2	ME1/1	RE1/1		HE	EE	ES	Total area [cm2]	Total number of services
	258,8	443,3	258,8	499,8	546	12		182,4	608,5	453,6	**3263,1**	**3895**
Per endcap Phase 2	RE1/3	ME1/3	RE1/2	ME1/2	ME1/1	GE1/1	ME0	HGCAL		ETL		
	273,6	470,1	273,6	526,6	486,5	193,0	223,4	2384,5		245,[illegible]	**5077,2**	**4994**
Delta(cm2)	14,9	26,8	14,9	26,8	-59,5	193,0	223,4	1593,6		-207,[illegible]	1814,1	1099,0



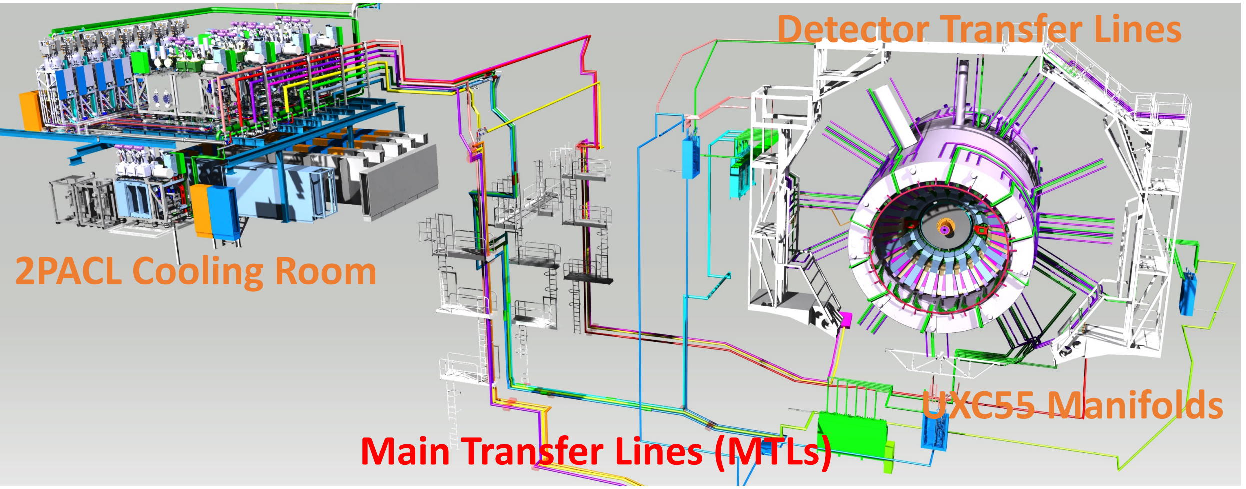
Dry gas distribution overview

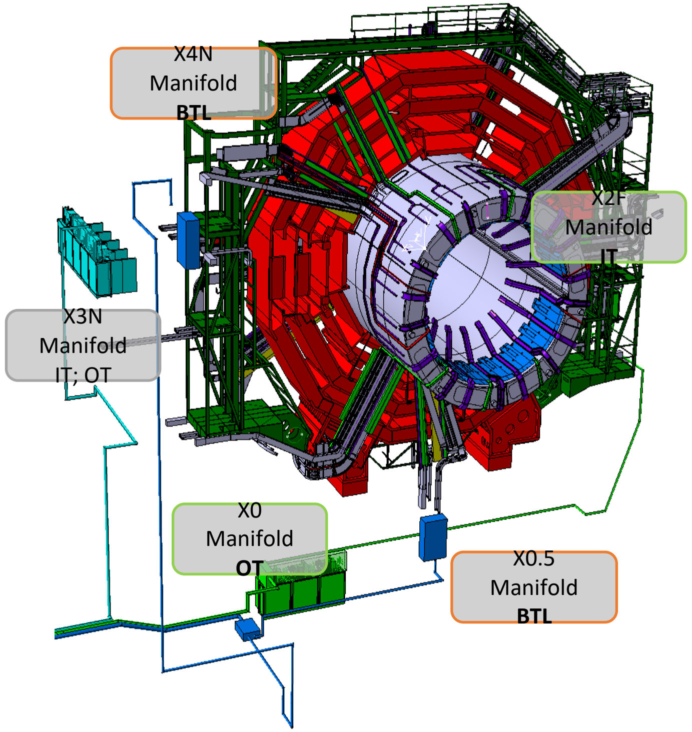


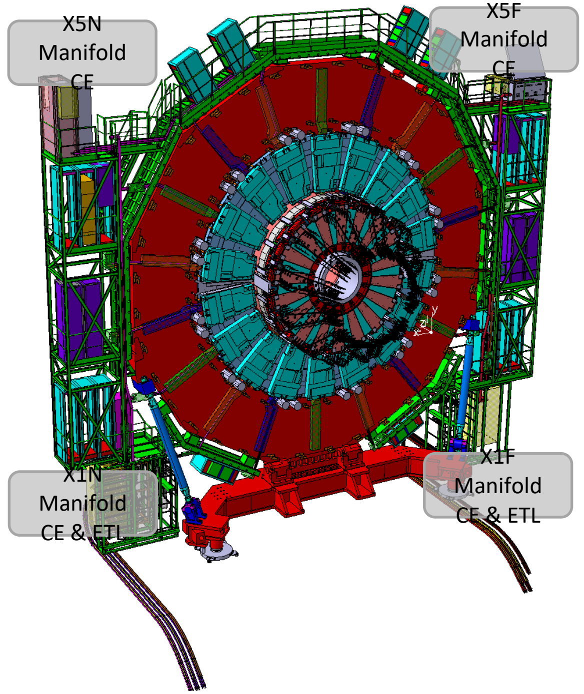
CO_2 evaporative cooling @ CMS



- Serves Tracker, HGCAL, MTD detectors with coolant temperatures down to -35 C
- Substitute C6F14 and R404a with liquid CO_2 (on detector pumped loops) and R744 (primary system)
- High reliability, complex system: design for high pressure (100 bar), low temperature
- Vacuum insulation for all transfer lines, to cope with stringent quality and space requirements



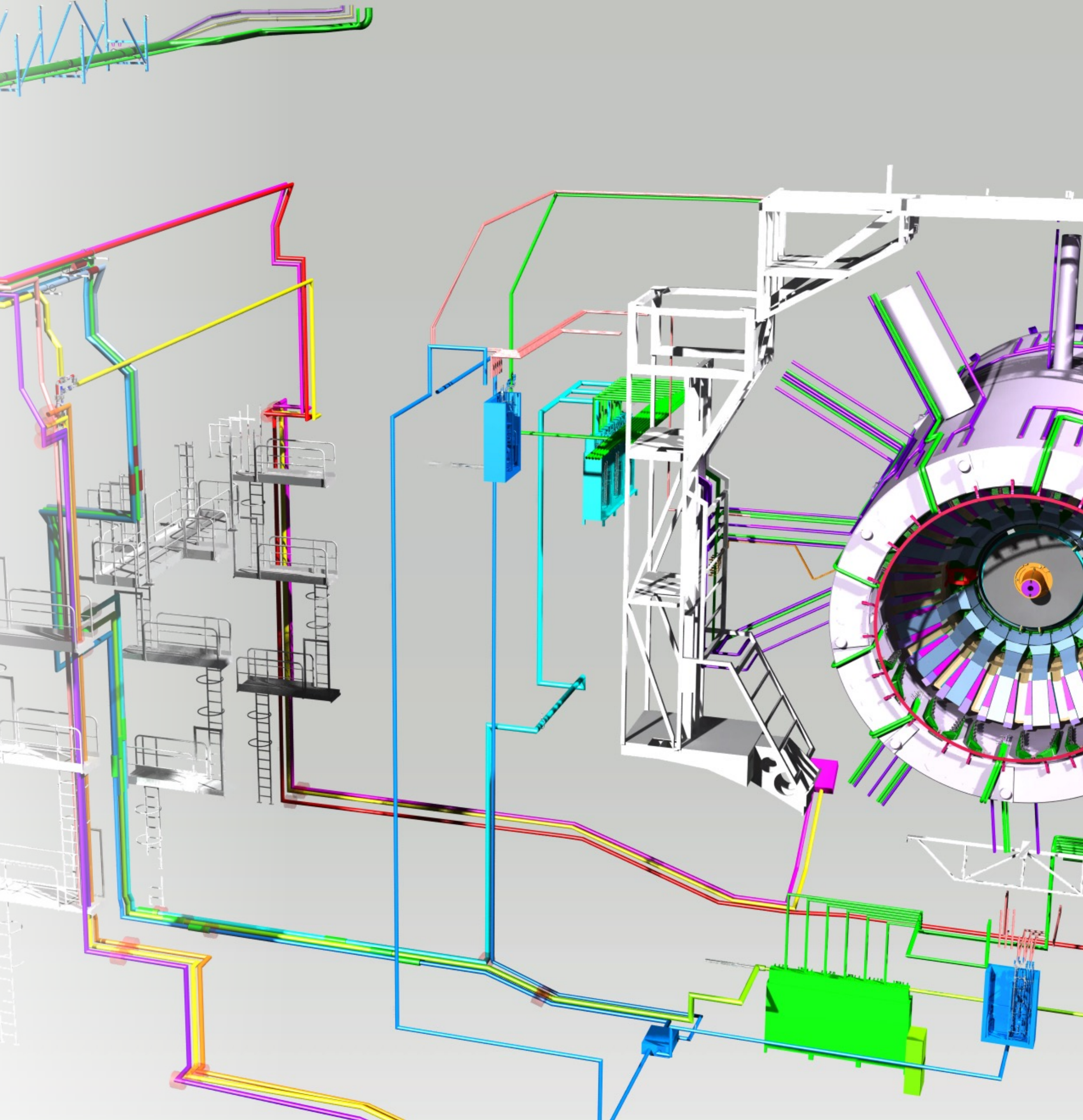




Conclusions

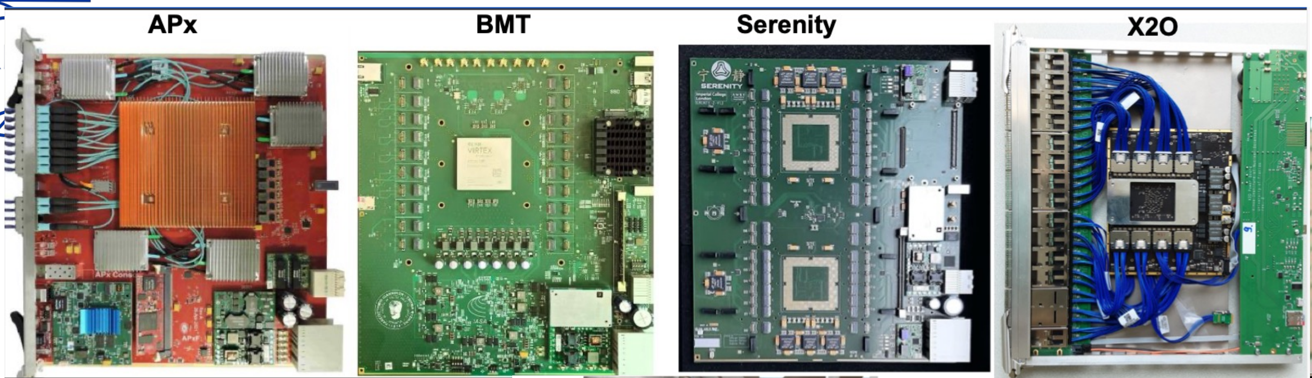
CMS Phase II Upgrade Project is an exciting endeavor, pushing the boundaries of high energy detector physics

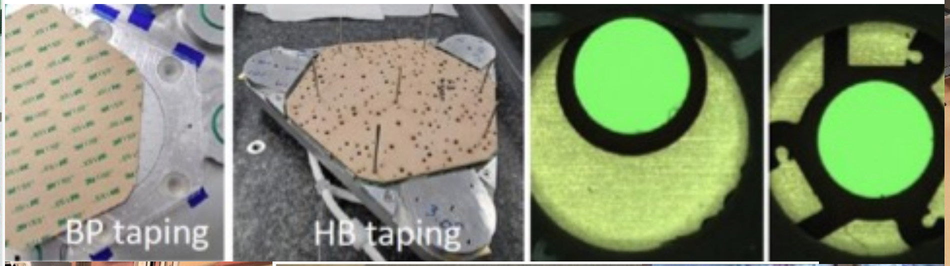
- Track Trigger at Level 1
- Fast timing
- Highly Granular Calorimetry with timing for pileup rejection (5D)
- Extended muon coverage in forward region
- Sophisticated Level 1 trigger and heterogenous computing for fast parallel computing with reduced power consumption
- Redundant realtime luminosity systems to understand systematics at sub % level
- Huge infrastructure upgrade with challenging schedule!

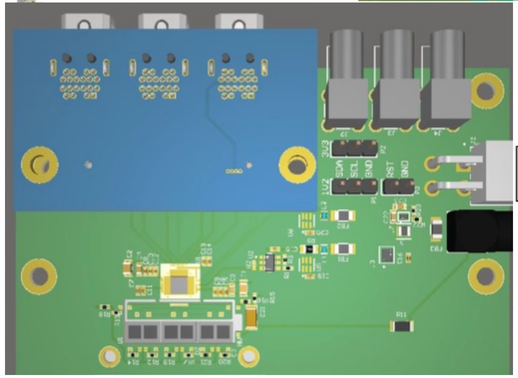


backup

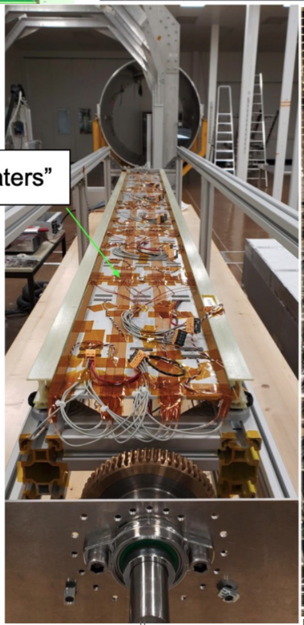
CMS Upgrade for HL-LHC

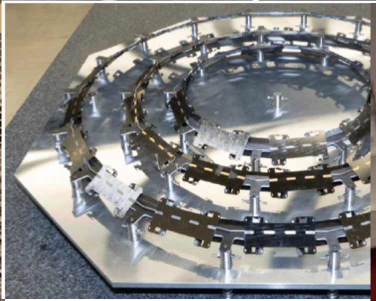


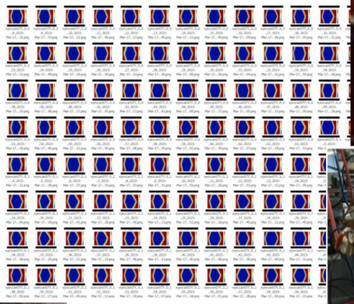


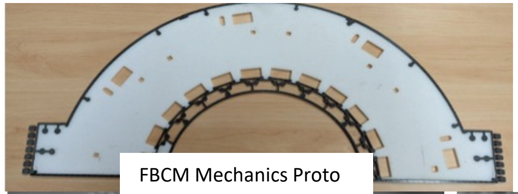


BRIL FBCM ASIC Test board

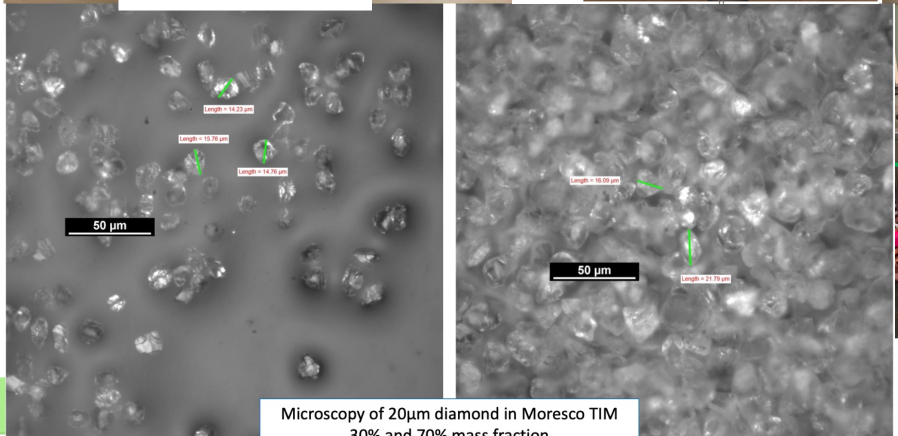




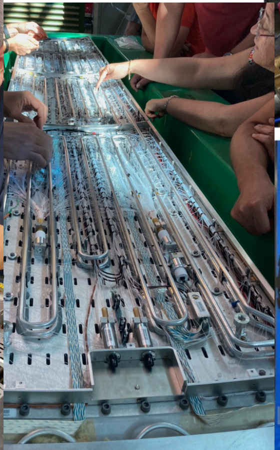


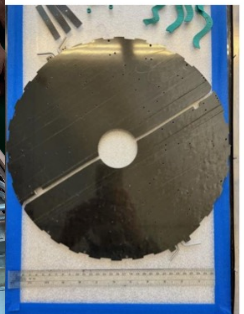


FBCM Mechanics Proto



Microscopy of 20µm diamond in Moresco TIM
30% and 70% mass fraction





Tracker

Inner tracker electronics chain, dense environment

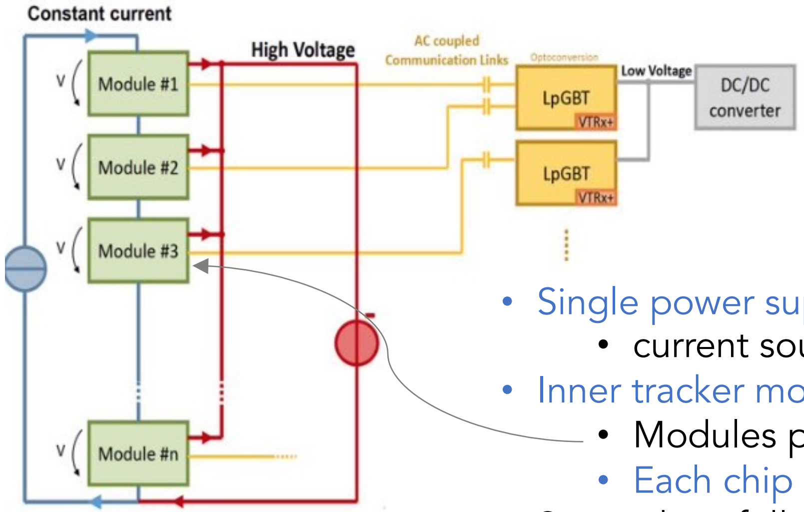
Common ASIC** CMS/ATLAS (RD53) [1] development enabling 50(25) x 50(100) μm^2 pitch at ≃ **3 GHz/cm^2

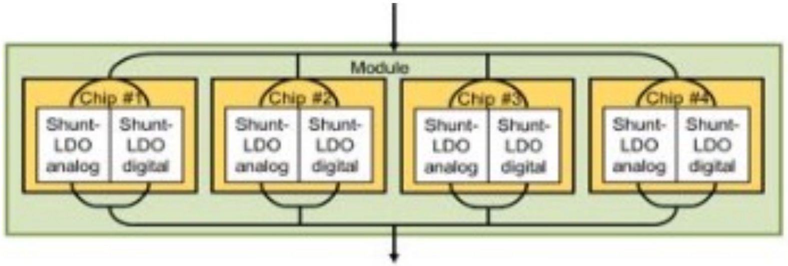
Front–end ASIC new technology 65 nm TSMC ASIC, radiation hard to 1 Grad

- Hit rate ~ 3 GHz/cm^2 (inner layer), trigger latency 12.8 μs (ASIC buffer length)
- ASIC, 336x432 – 145152 pixels, zero suppression
- Power < 1 W/cm^2
- Time-over-threshold hit charge measurement with 4 bits ADC
- CMS: linear analogue front-end [2,3]
- LDO for serial powering in the ASIC
- Data aggregation and drive signal over 50 cm – 120 cm

A Single Chip Card (SCC) with a CROC_v1 chip

***Serial powering** - only way to power 50 kW detector with reasonable material budget*





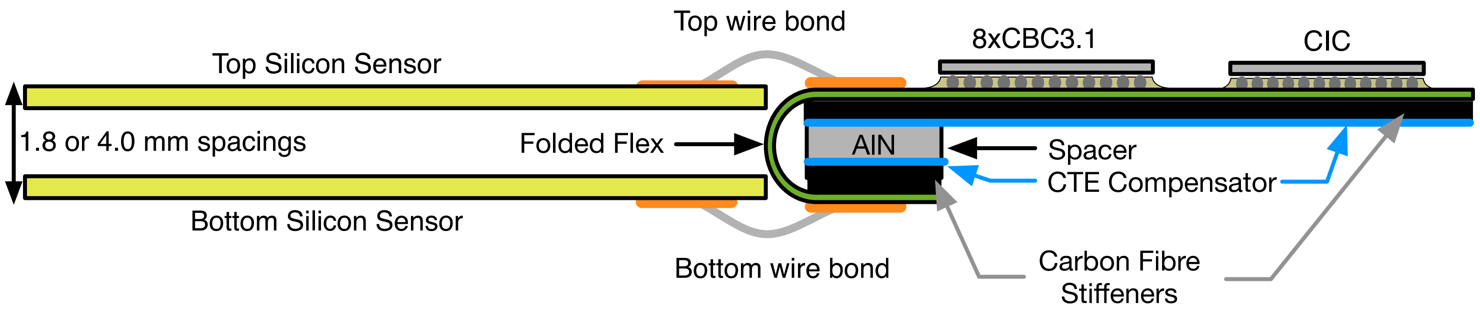
- Single power supply module:
    - current source (SP), HV for sensor (0-800V), LV for portcards and pre-heaters for CO2 cooling
- Inner tracker modules grouped in 576 serial power chains, up to 11 modules in each chain
    - Modules powered in series, with chips within each module powered in parallel
    - Each chip has a shunt-LDO (SLDO) for voltage regulation while maintaining a constant current
- Sensor bias following the serial power chains with a single return line

[1] RD53B user guide.
[2] 2021 JINST 16 P12014.
[3] CERN-RD53-PUB-20-002.

Front-end hybrids topologies

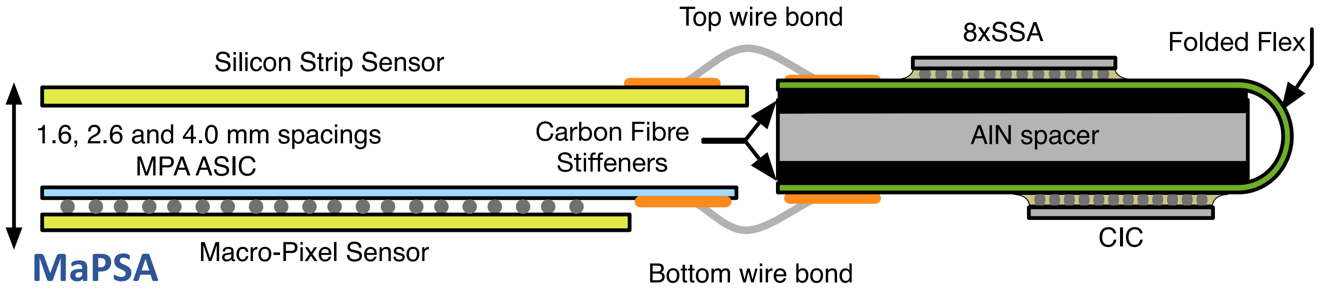
2S-FEH Hybrid

Sensor spacings: 1.8 mm and 4.0 mm



PS-FEH Hybrid

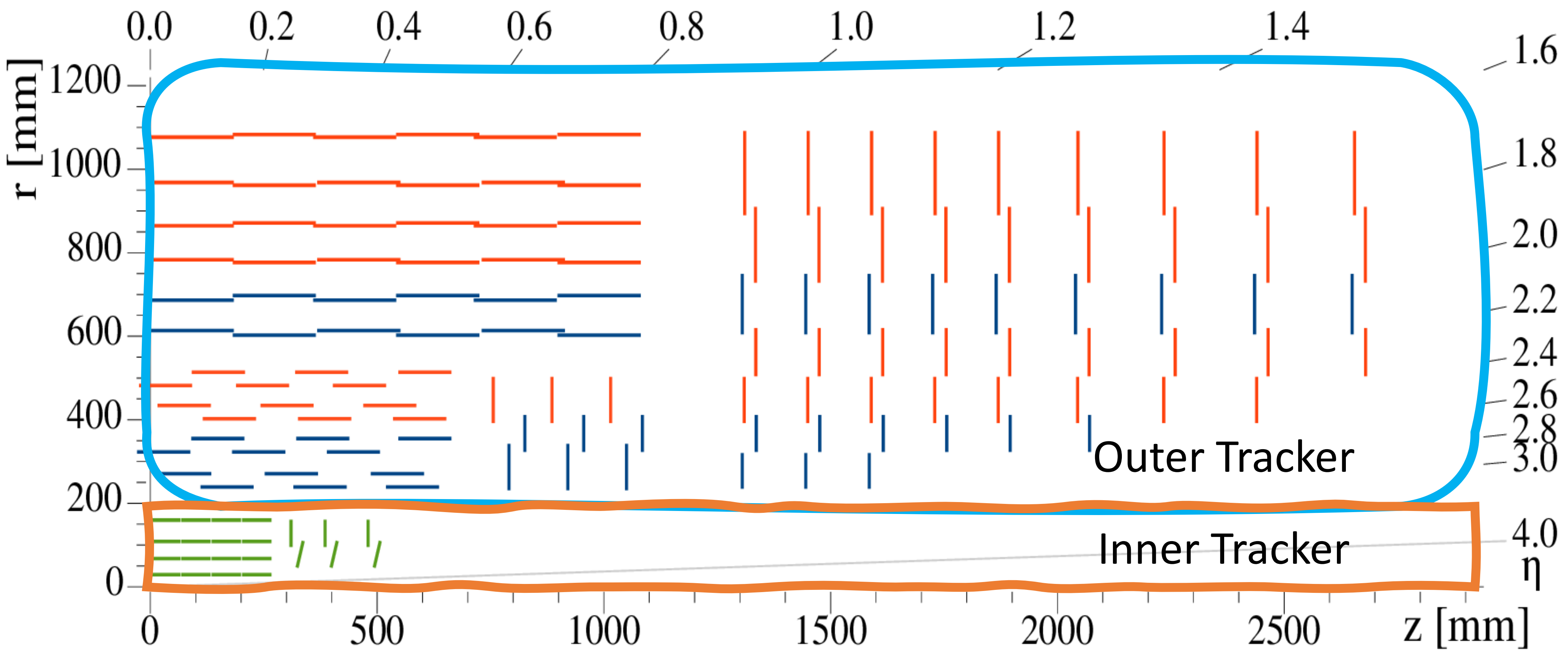
Sensor spacings: 1.6 mm, 2.6 mm and 4.0 mm



- HDI polyimide flex circuits.
  - 42.5 µm tracks width and spacing.
  - 25 µm laser copper filled microvias.
  - Down to 500 µm radius tight fold.
- 250 µm pitch flip chips with high pin-count:
  - CBC3.1, SSA, CIC.
- High speed differential pairs.
  - 90 Ω in 150 µm, 4 layers thin flex.
- Carbon fibre stiffener.
  - High thermal conductivity laminates.
- CTE compensators.
  - To eliminate bow.
- AlN spacers.
  - To align with sensor spacings.

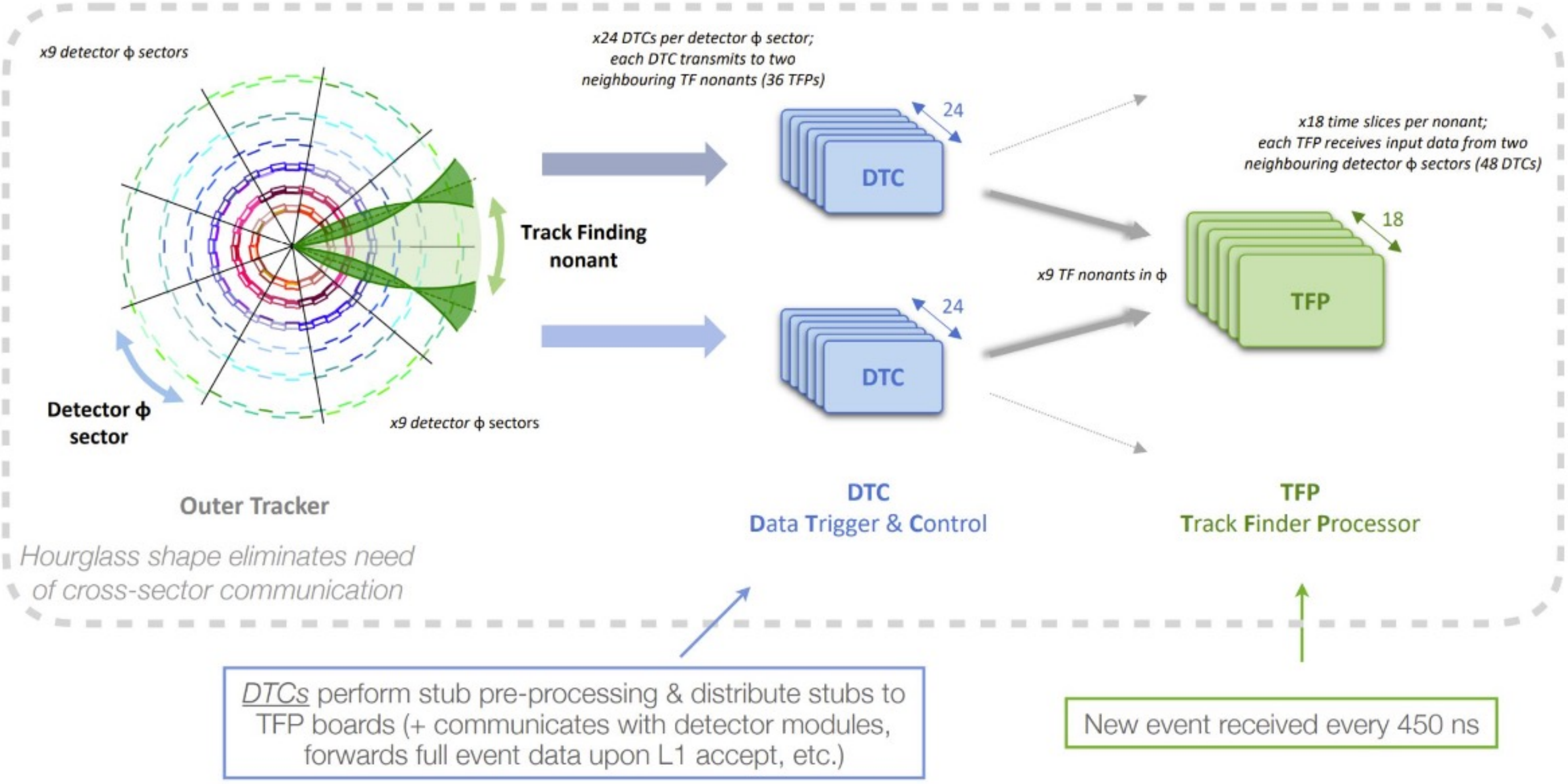
Today's CMS Tracker

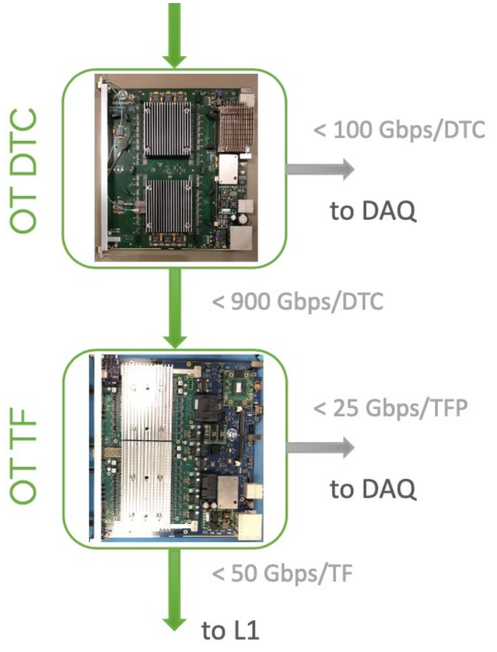
- **Outer Tracker**
  - ≃ 9.3 M strip channels (198 m^2), Mono-phase cooling
- **Inner tracker**
  - ≃ 125 M pixels (~1.9m^2) , Bi-phase $C0_2$ cooling



Outer Tracker Level 1 track finding finding data architecture

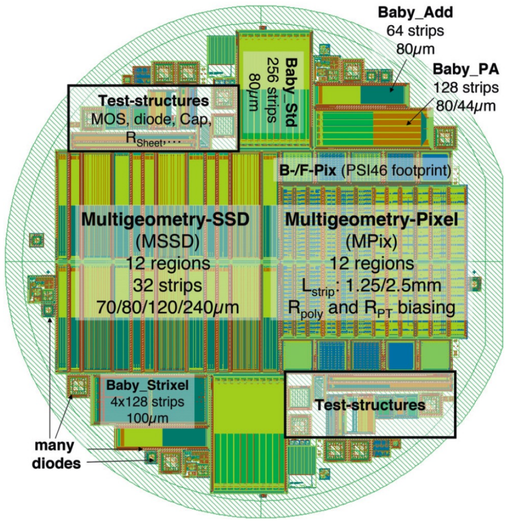
- Two-stage processing architecture for Track Finding: Layer 1 DTC system and Layer 2 TFP
- Total system include 378 ATCA boards: 216 DTC and 162 TFPs (electronics for trigger and readout are of comparible size)

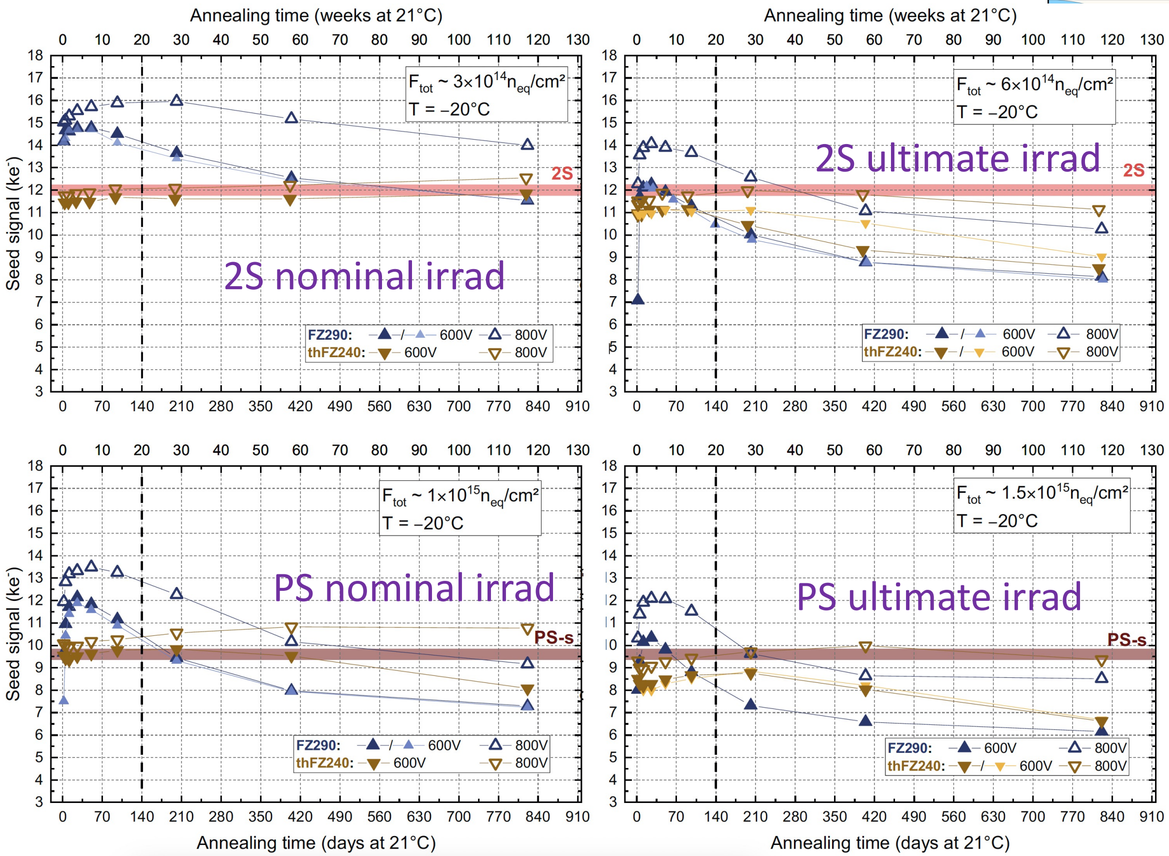


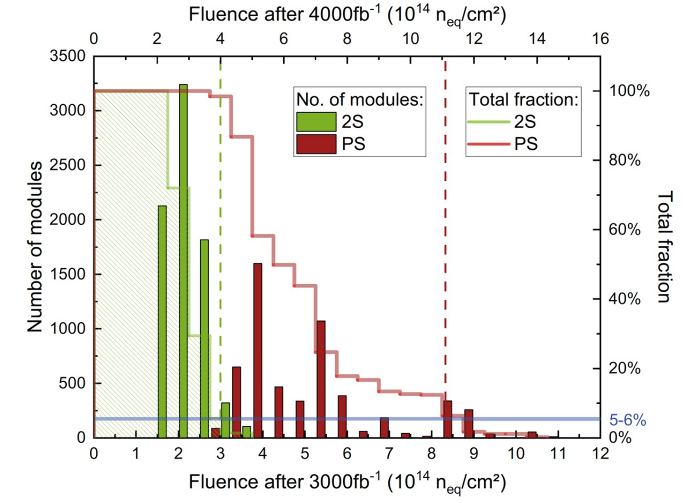


Outer Tracker Sensors

- Tens of man-year-long campaigns to identify sensor technology, surviving the whole high lumi period without any repair
- **AC-coupled, Rpoly biased n-in-p strip sensors with atoll p-stop cell isolation – 290/320 um active/physical thickness**
- Dedicated irradiation and long-term annealing campaigns to understand margins and based on ‘worst’ environment corner
  - The whole OT system is designed and QAed for 800V







Selection of the silicon sensor thickness for the Phase-2 upgrade of the CMS Outer Tracker, JINST 16 P11028

Couple of hundreds of R&D wafers of different thicknesses and material – many structures
➔ Chose n-in-p (register electrons); confirms pitches, isolation, QA strategy

P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC, JINST 12 P06018.

BRIL

Fast Beams Conditions Monitor (FBCM)

Dedicated ASIC development (65nm) submitted – expected Sept. '23

- Continuous untriggered readout
- Internal fast peaking time (6-8ns)
- Binary output proportional to TOT ➔ sampled downstream with lpGBT

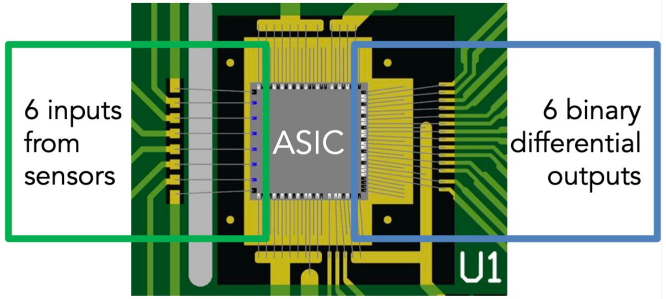
:

Silicon Sensors pad area 2.89 mm^2 at a radius of 14.5 cm

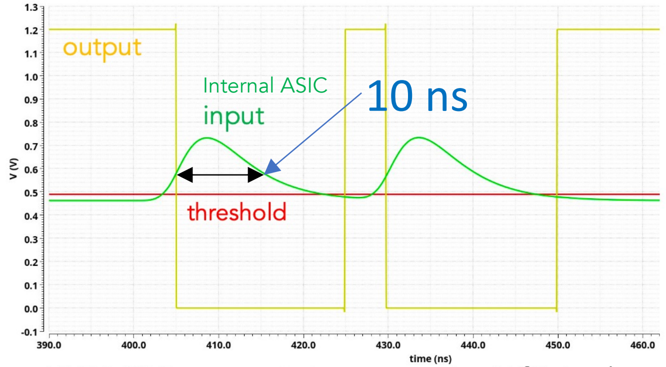
- 2.5×10^{15} 1 MeV n eq fluence for 3000 fb^{-1} (sensor)
- 290 um thickness sensors produced as diodes on Outer Tracker PS-s wafers
  - Alternative 150 um thickness diode submitted on CMS IT wafer design submitted
- 288 channels

Modular design uses standard HL-LHC electronics components

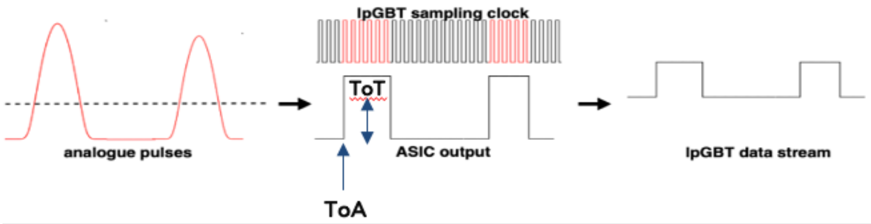
Integration compatible with CMS inner tracker and C02 cooling will be shared.

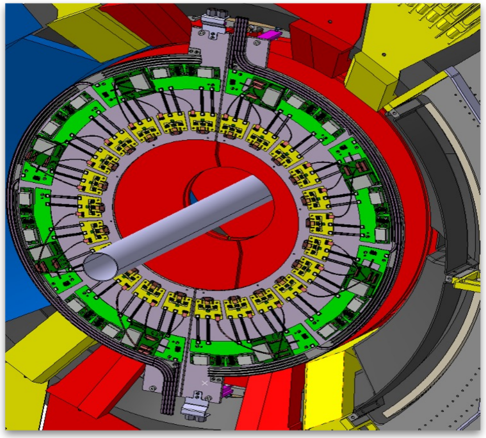


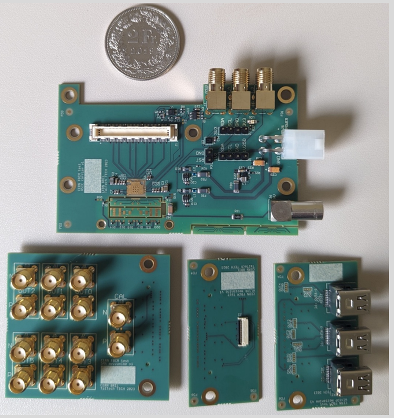
FBCM ASIC top view on test board



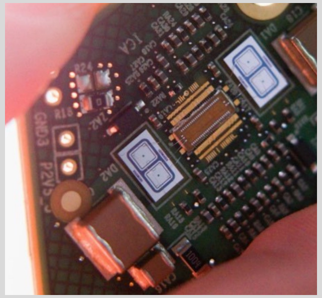
FBCM ASIC response to two consecutive 4.5fC signals







ASIC test board produced



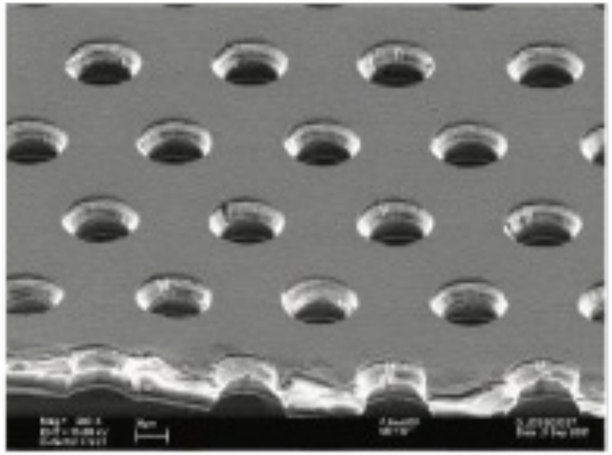
290 um sensors installed BCM1F for run 3

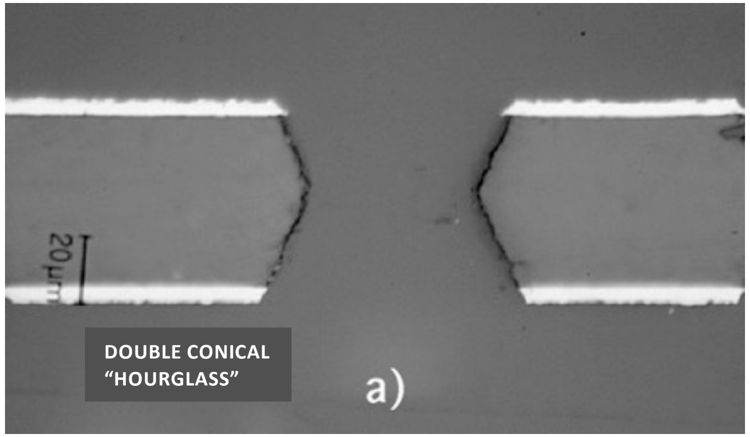
More information, K. Shibin, TIPP2023 Thursday

More info, comprehensive presentation at TIPP, [Electronics design and testing of the CMS Fast Beam Condition Monitor for HL-LHC](), Konstantin. Shibin

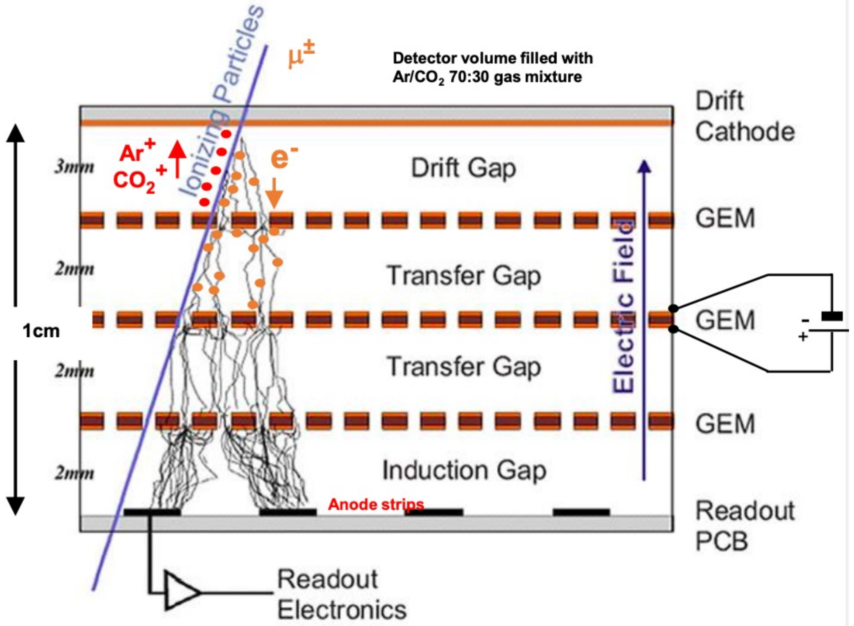
muons

New Technology for CMS Phase II - Gas Electron Multiplier (GEM)

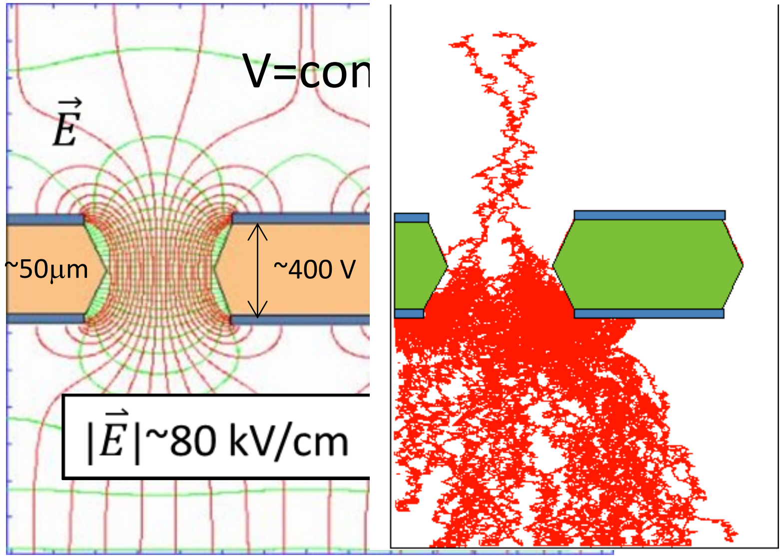




Foil & pcb technology covered in Plenary talk tomorrow **"MicroPattern Gaseous Detectors"** by Dr Rui de Oliveira



Avalanche across a GEM



Muon upgrade scope

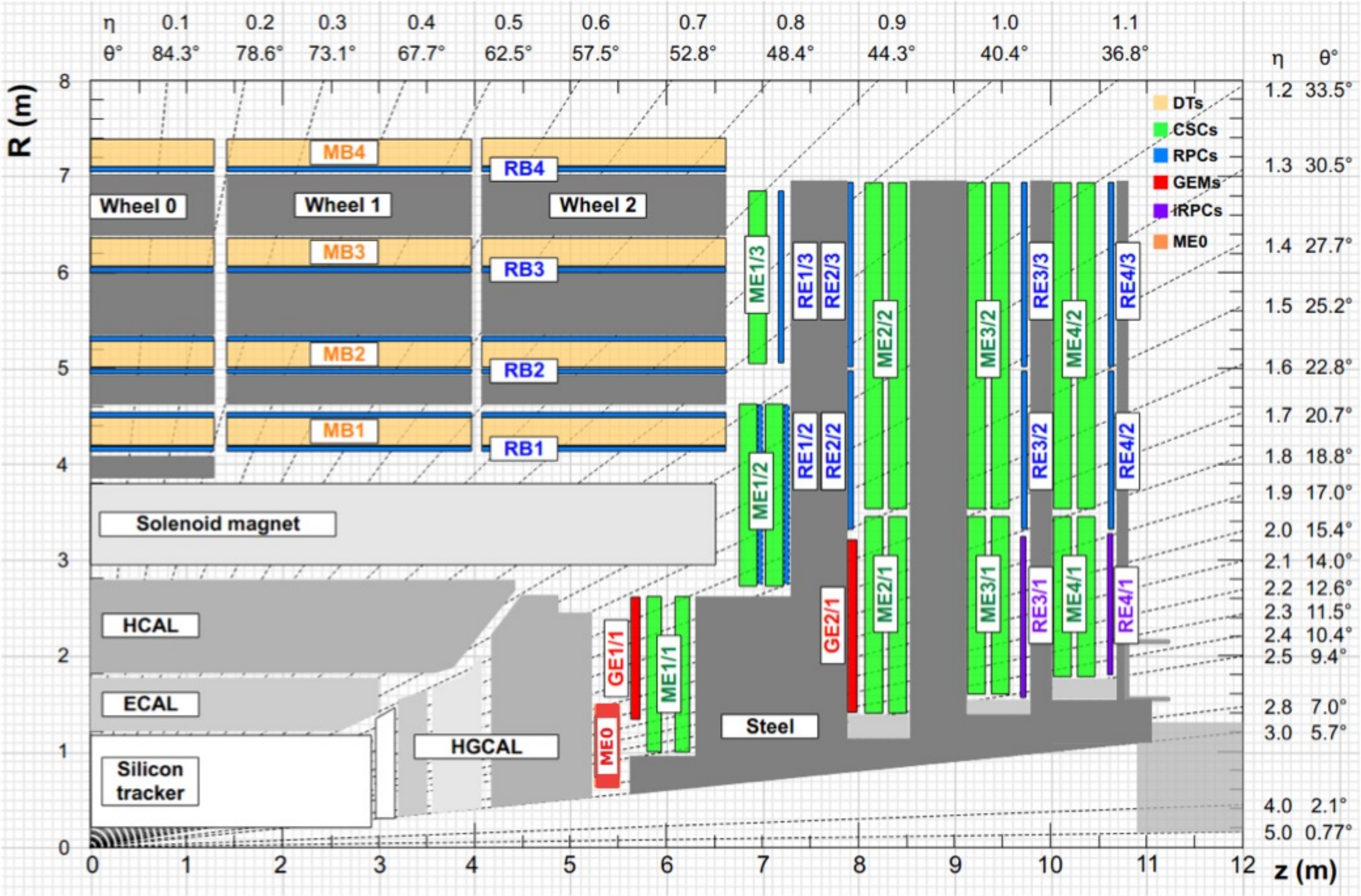
Present DT, CSC, RPC detectors remain

→ upgrade electronics to cope with HL-LHC rates and enhance performance

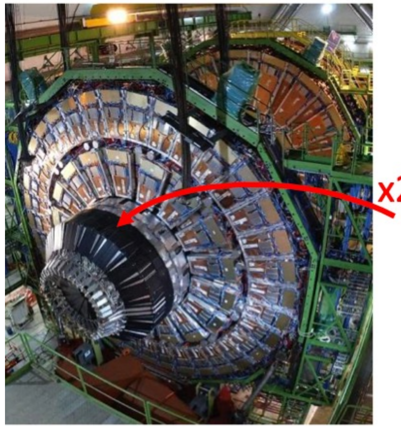
New detectors to improve tracking and coverage at high η:

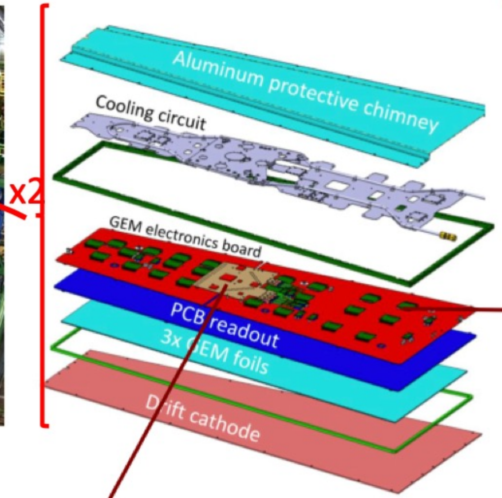
- **ME0**: 6 layers, extend coverage to 2.4 < |η| < 2.8
- **GE1/1**: 2 layers
- **GE2/1**: 2 layers
- **RE3/1**: 1 layer
- **RE4/1**: 1 layer

Evaluate longevity for HL-LHC and find eco-friendly solutions

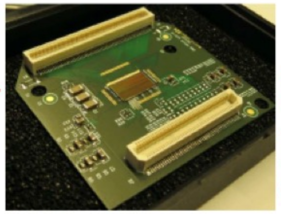


Full 144 chambers for GE 1/1 built, installed (2020) & fully operational



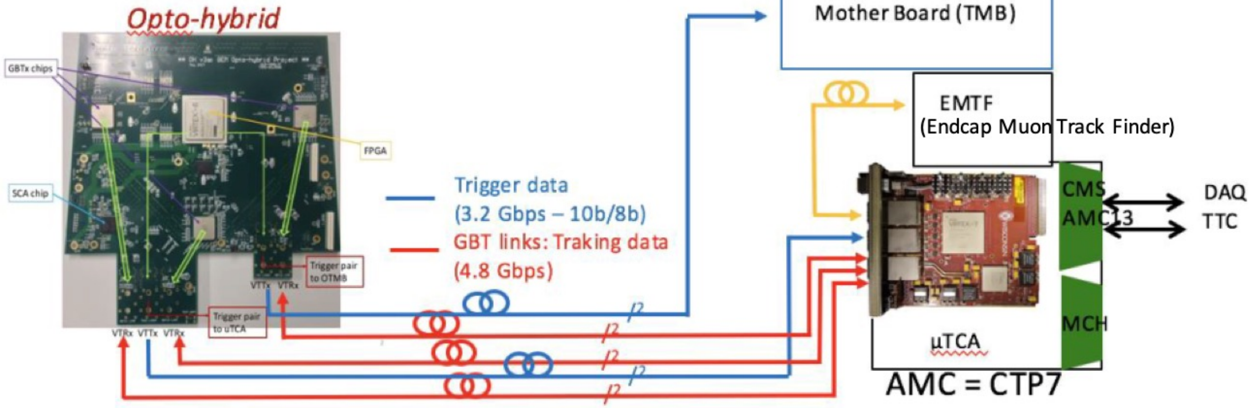


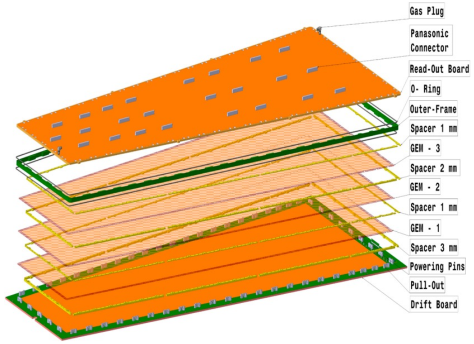
- GE11 system
  - 72 Super-Chambers (SC)
    - Each made of 2 detectors back-to-back
  - 3456 VFAT3 FE chips
  - 432 GBTx + VTRx optical links (DAQ path)



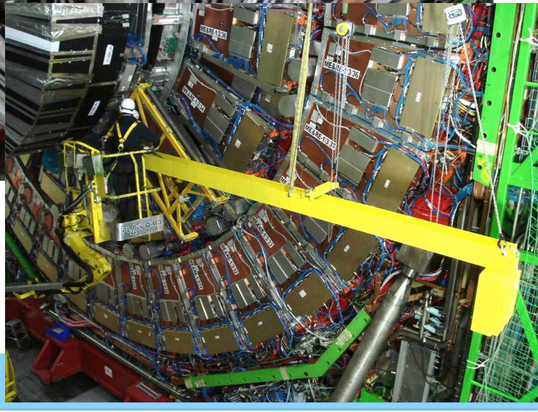
FE chip: VFAT3
- 24 VFAT3 / chamber
- 128 channels / chip
- Binary readout
- Tracking + Trigger data

GE1/1 Electronics



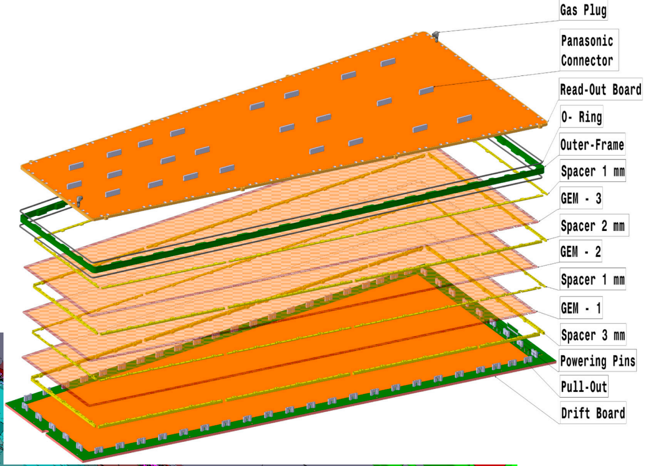


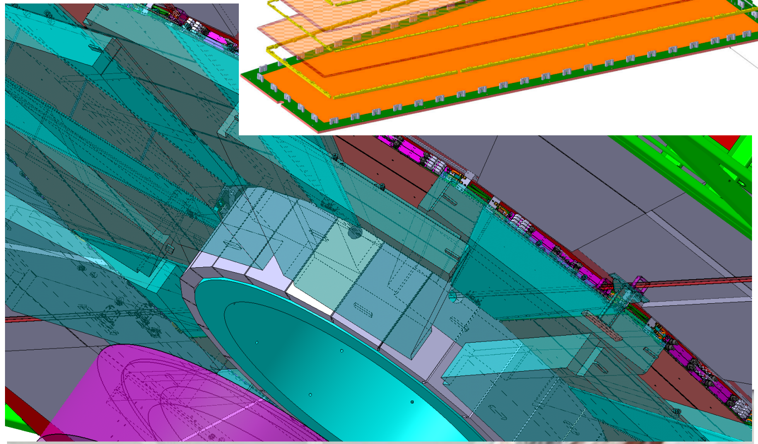
"Layout and Assembly Technique of the GEM Chambers for the Upgrade of the CMS First Muon Endcap Station"
https://doi.org/10.1016/j.nima.2018.11.061



Unprecedented scale of GEM installation!

Full 144 chambers for GE 1/1 built, installed fully operational





Unprecedented scale of GEM installation!

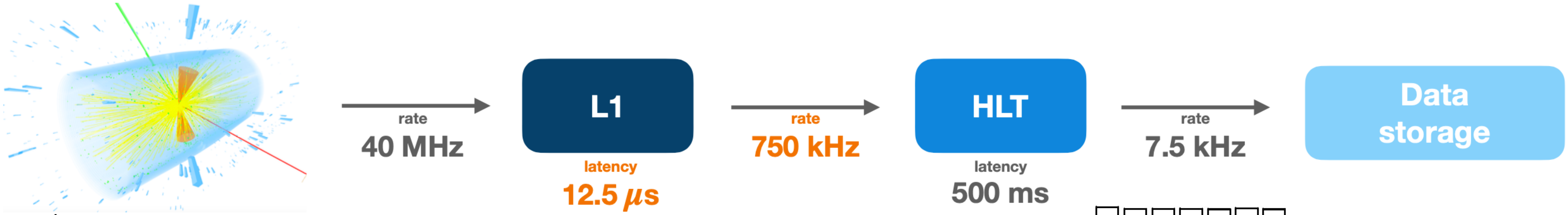
Trigger & HLT

CMS Phase II Trigger

Two-level trigger architecture with Level-1 (L1) and High- Level-Trigger (HLT)

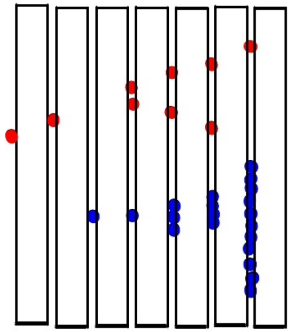
The **L1 trigger** will operate **at hardware level** implementing processor boards equipped with FPGAs and high-speed links

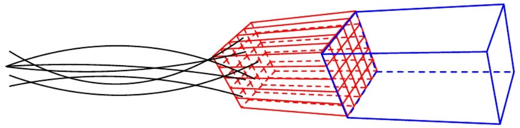
The **HLT** will operate **at software level** using as input the CMS detector full-granularity information and more sophisticated algorithms & heterogeneous computing



New Hardware inputs

- Tracking information: **new** objects available – First L1 Tracker trigger
- Barrel Calorimeter: 25x resolution improvement
- Endcap Calorimeter: 3D High Granularity (transverse and deapth)
- Muon objects - ME0 extending muon coverage 2.4<|**η**|<2.8



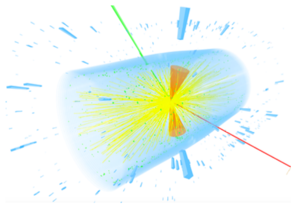


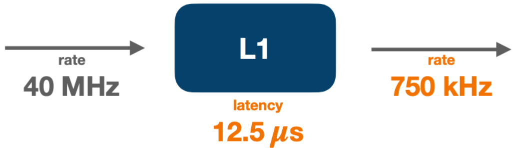
Algorithms

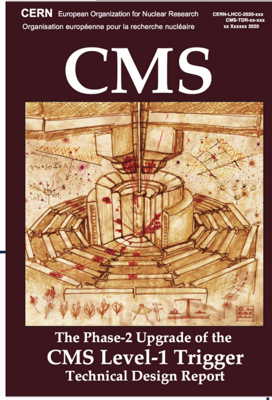
- Particle flow, matching track/muon and calorimeter objects in correlator trigger, machine learning …

Dedicated "scouting" stream, enable trigger-less analysis at collision rate

L1 Trigger – hardware & latency

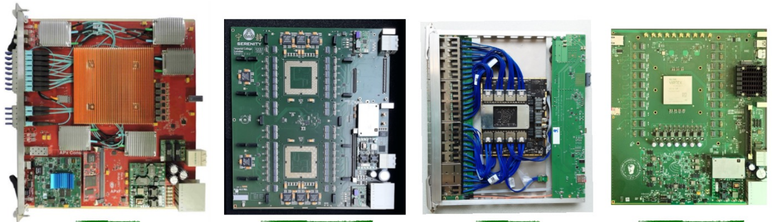






Hardware features of L1 Trigger

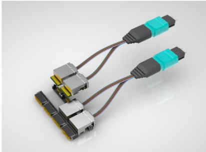
- ATCA industry standard processor boards
- very-high-speed optical links
  (28Gb/s against the 10Gb/s in Phase-1)
- the extensive use of state-of-the-art FPGAs
  (Xilinx UltraScale+ VU9P → 8 × Phase-1 Virtex 7)
- the implementation of a highly modular architecture



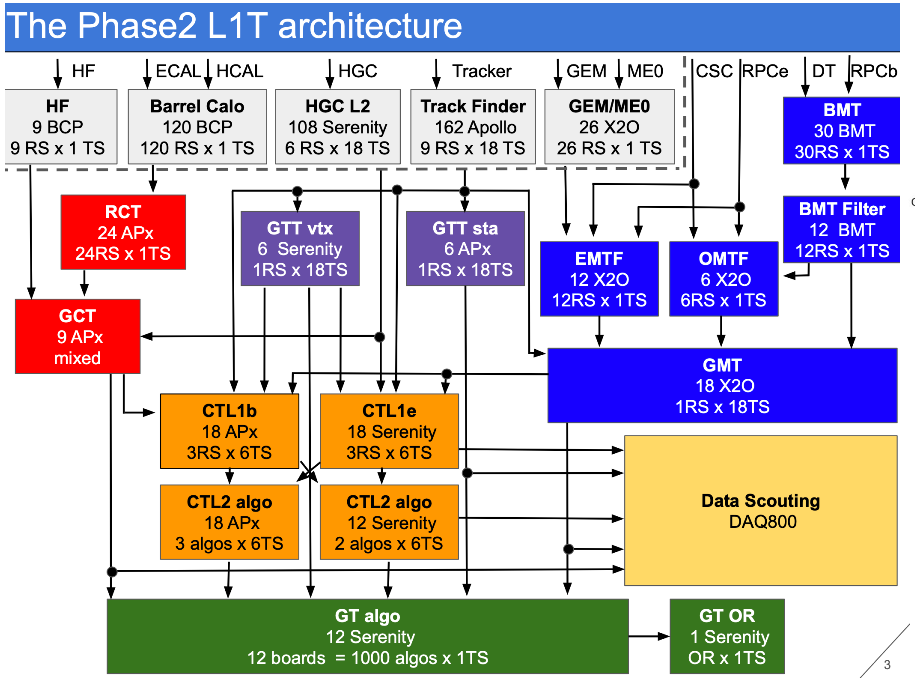
APX Serenity X2O BMT-L1

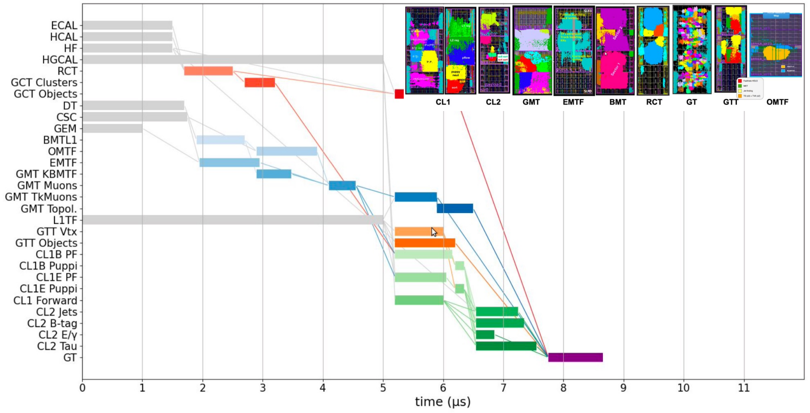
- L1 trigger boards in pre-production
- Optics under test

Samtec Firefly Optics



Flyover copper to QSFP

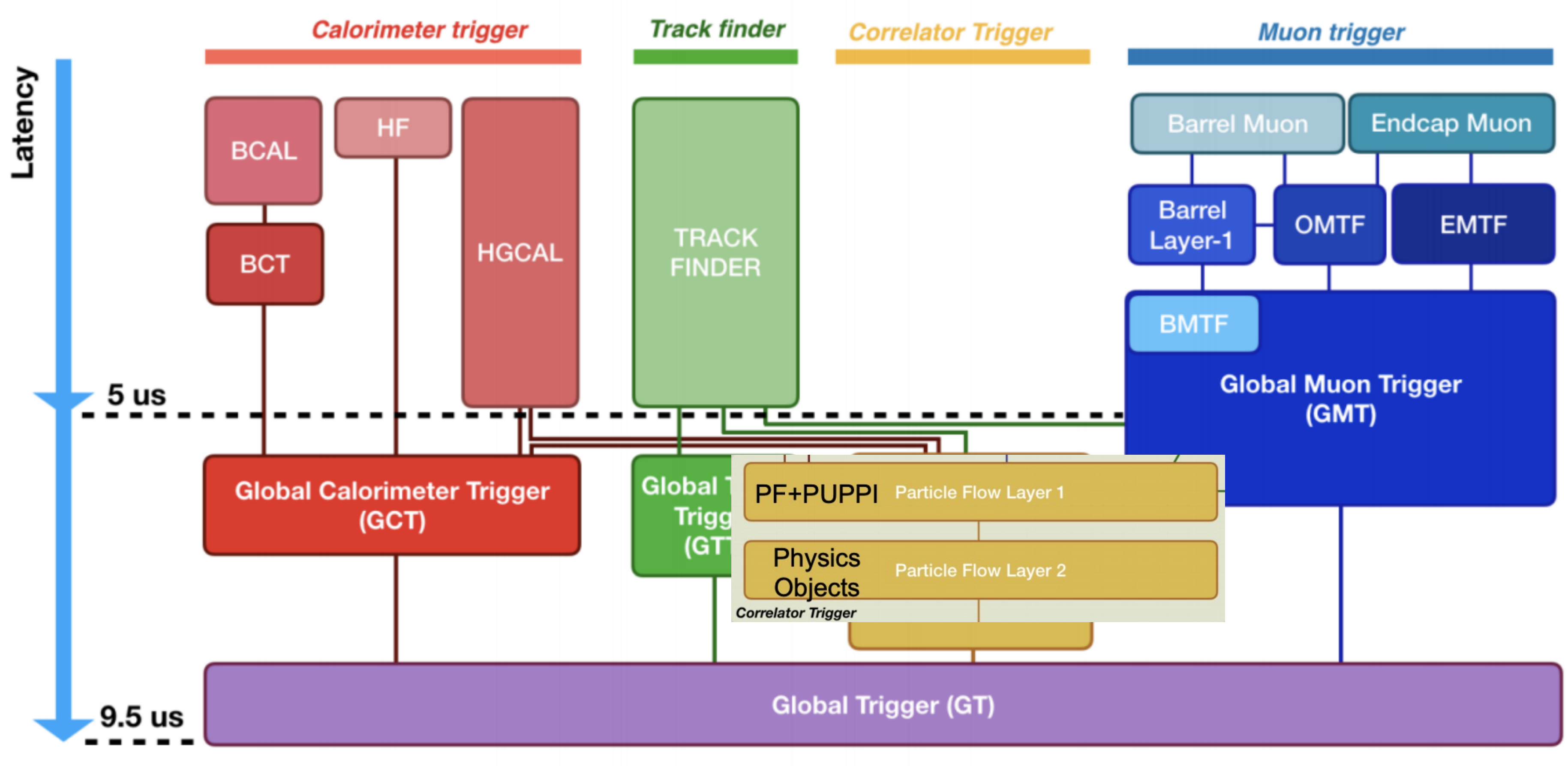




Time µs

- Algorithms developed and implemented in FPGA
- L1 Latency estimates 8.9 µs + 1 µs to propagate back to front ends < 12 µs

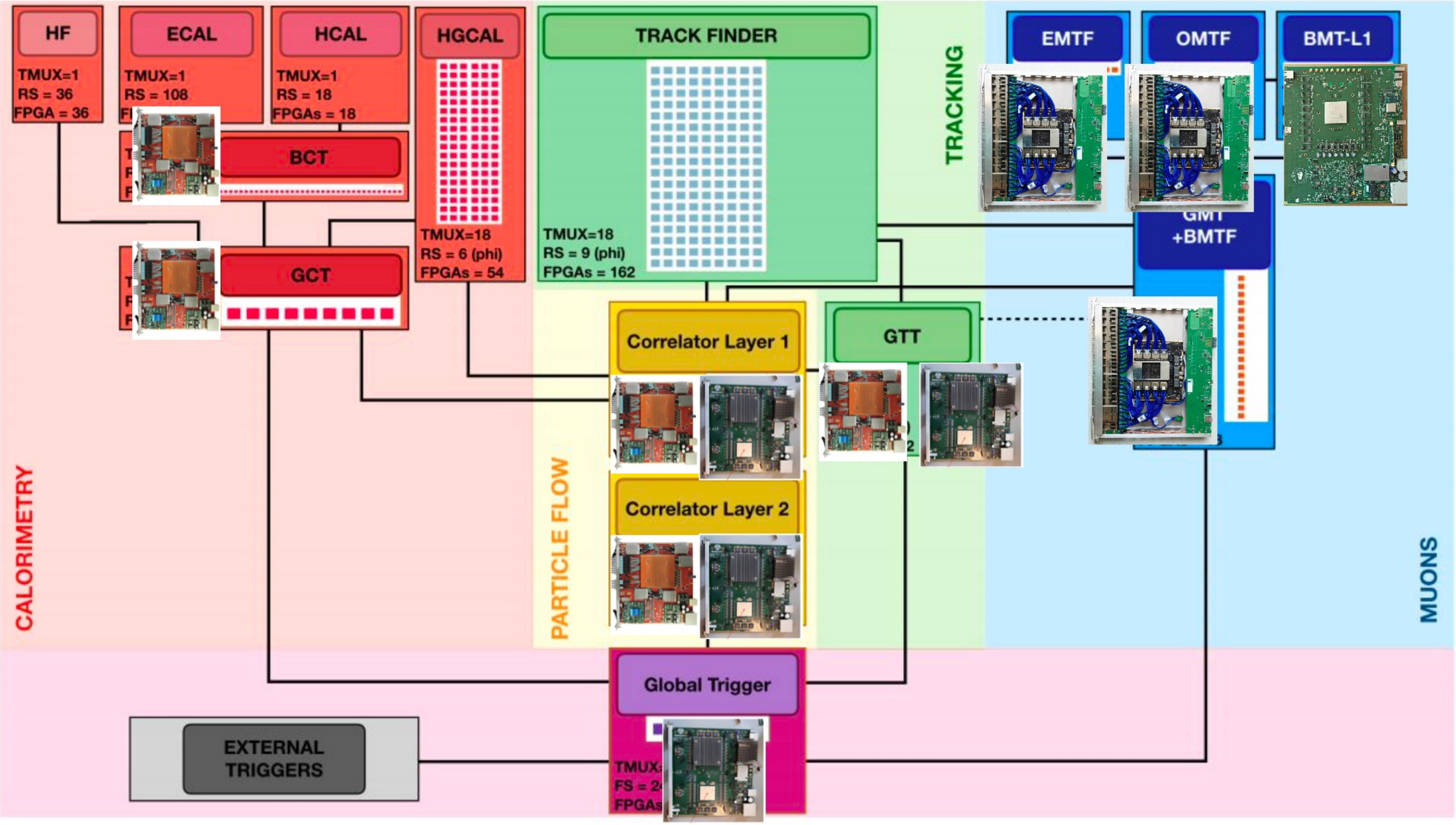
More info, comprehensive presentation at TIPP, System Design and Prototyping for the CMS Level-1 Trigger at the High-Luminosity LHC, Alexandre Zabi



In Phase2 CMS Trigger will be using algorithms much closer to offline:

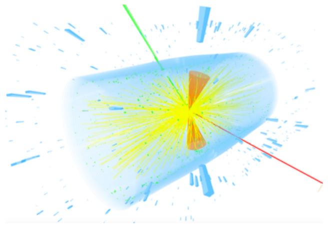
- PUPPI for PU removal (extremely needed with PU 140-200)
- Capability to run complex algorithms
  - Written in C++ and deployed on FPGA via **High Level Synthesis**
  - Machine learning algorithms trained on standard systems and then again synthesized on FPGA (**hls4ml**, for example)

Board map

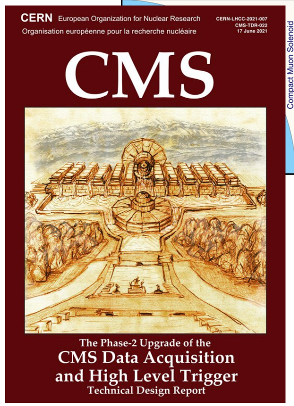


- Serenity used in the backend of the Tracker, MTD and HGC
- X2O used in the backend of GEMs/ME0 and CSC

CMS Phase II High Level Trigger (HLT)

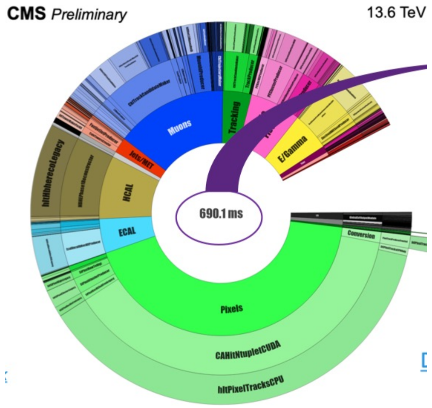


rate 40 MHz → L1 (latency 12.5 μs) → rate 750 kHz → HLT (latency 500 ms) → rate 7.5 kHz → Data storage

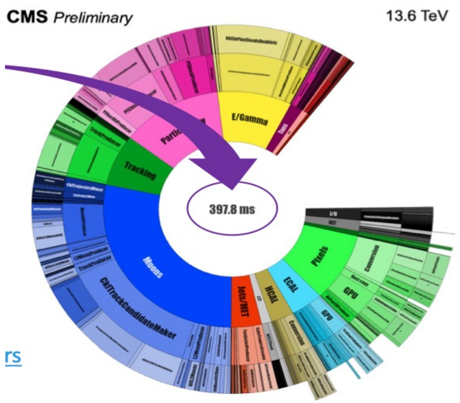


HLT @ Run 3 – heterogenous computing in production

- Need for High throughput requires HLT to take advantage of parallelism wherever possible – and event reconstruction in detectors can be parallelised
- CMS profiting from heterogenous hardware availability in markets
  - added 200 machines to the HLT for Run3
  - Reduction in average processing time 40% (pileup ~60)
- Parallelization requires re-engineering the existing code – and in the process CMS achieve gains in physics performance
- Run 3 - HCAL, ECAL, Pixel Local Reconstruction, Pixel-Only Track and Vertex Reconstruction (which seeds the full tracking, also used standalone for scouting) are running on GPUs
- GPUs more efficient in terms of costs and more energy efficient
  - 30% reduction in power consumption Run 3



Run 3: 690 ms = average processing time per event for CPU Only Configuration



Run 3: 397 ms = average processing time per event for GPU & CPU Configuration

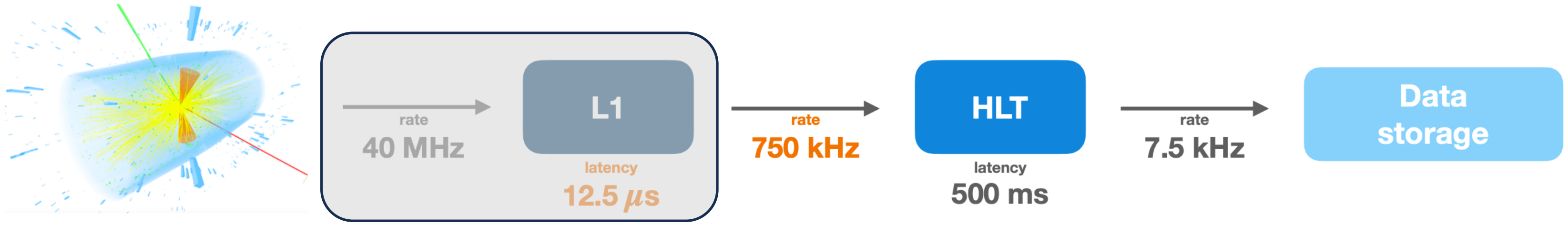
200 machines:
- 2x AMD EPYC 7763 "Milan" 64-core processors (128 Cores, 256 threads)
- 2x NVIDIA T4
- System Memory – 256 GB

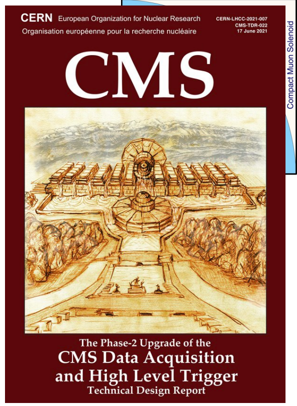
Each T4 has 2560 CUDA "threads" running at 1.59GHz, 16GB GDDR6 DRAM and 6MB L2 cache

Power Consumption:
- 2x AMD CPU ~ (2 x 280W) = 660 W
- GPU ~ (2 x 70W) = 140W
- System Memory ~96W

More details, see talk G. Parida, "Run-3 Commissioning of CMS Online HLT reconstruction using GPUs "International conference on computing in high energy & nuclear physics-2023

CMS Phase II High Level Trigger (HLT)





Challenges for HL-LHC compared to Run 3

- Approximately 2.5 increase in instantaneous luminosity
- Additional information from detector upgrades, e.g. HGCAL, new tracker to eta < 4, new muon chambers
  - factor 30 increase in computing resources for similar physics goals

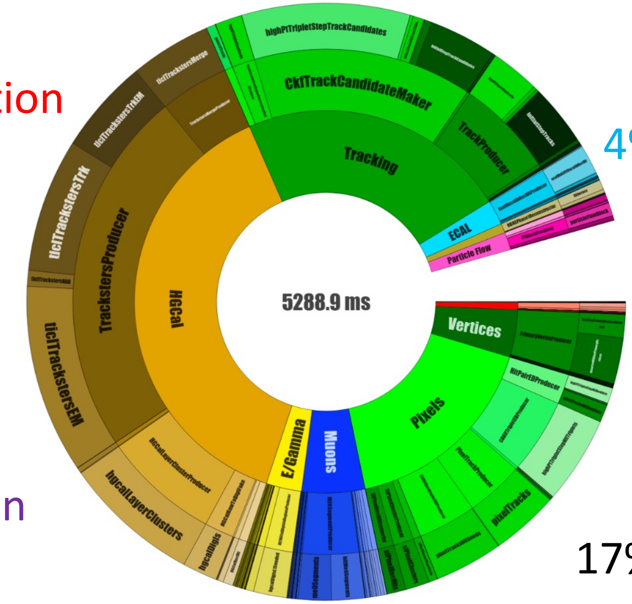
HLT development HL-LHC ongoing

- Work on all reconstruction paths
  - Many more offloaded to GPU since TDR
- Exploiting additional timing precision ongoing

23% Outer Tracker Reconstruction

38% HGCal Reconstruction

4% Vertex reconstructio



5% Muon Reconstruction

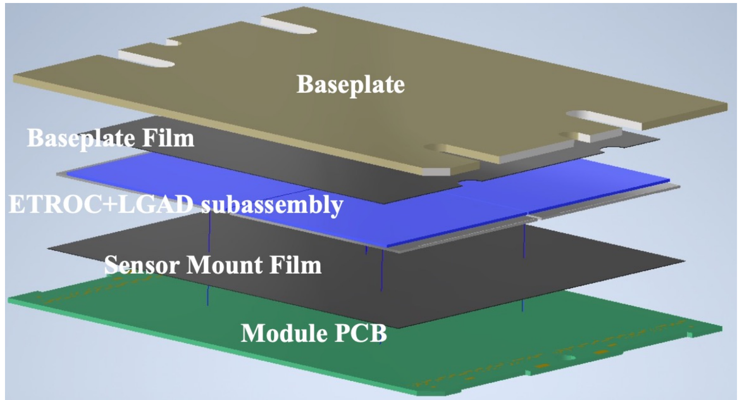
17% Pixel reconstruction

DAQ&HLT TDR: Average processing time per event & composition of the HLT reconstruction weighted by the relative processing time, sample of L1- accepted minimum-bias events with ⟨PU⟩ = 200

MTD

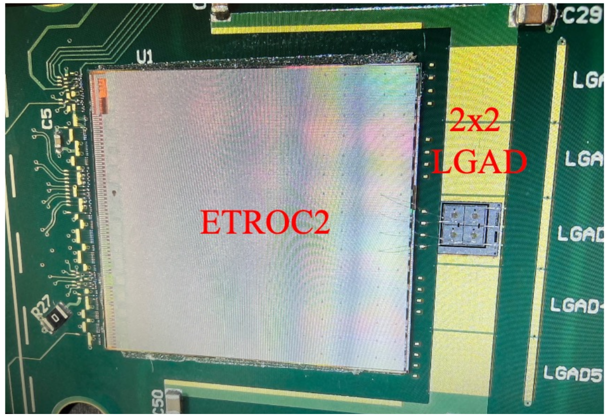
ETL – readout readout & modules

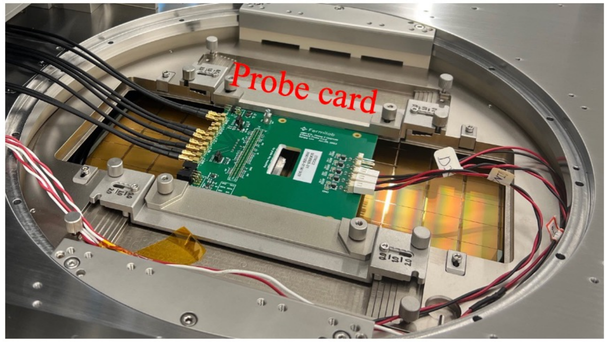
- **ETROC+LGAD** should achieve a time resolution **< 50 ps** per single hit
  - ETROC(0,1,2,.) is developed in stages, 65 nm technology, 100 MRad (TID spec)
  - low noise + fast rise time
  - power budget: 1 W/chip, 3 mW/channel
  - ETROC measures arrival time of signal (6 –20 fC)
  - **ASIC** contribution to time resolution **< 40 ps**
  - L1 buffer latency: 12.5 us
  - ENC = ~ 0.3 fC
  - 16x16 pixels

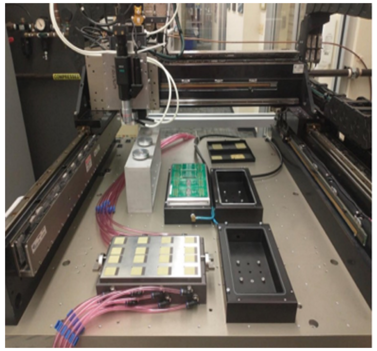


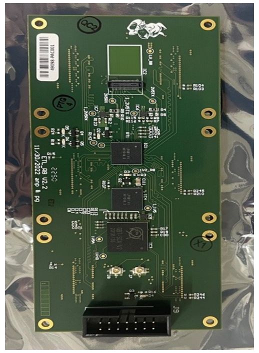
ETROC2: full functionality final prototype ASIC

- – received June 2023 – initial tests excellent, qualification ongoing
- Test beam verification of LGADs bump-bonded to ETROC2 will start in September





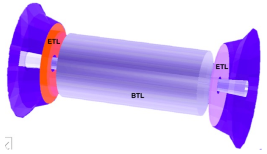




Readout board and module assembly demonstrated
9 k modules (1 or 2 sensors)

More info L/ Markovic, *The Endcap Timing Layer detector for the CMS Phase-2 upgrade*, 2023 FAST Workshop, 31/05/2023

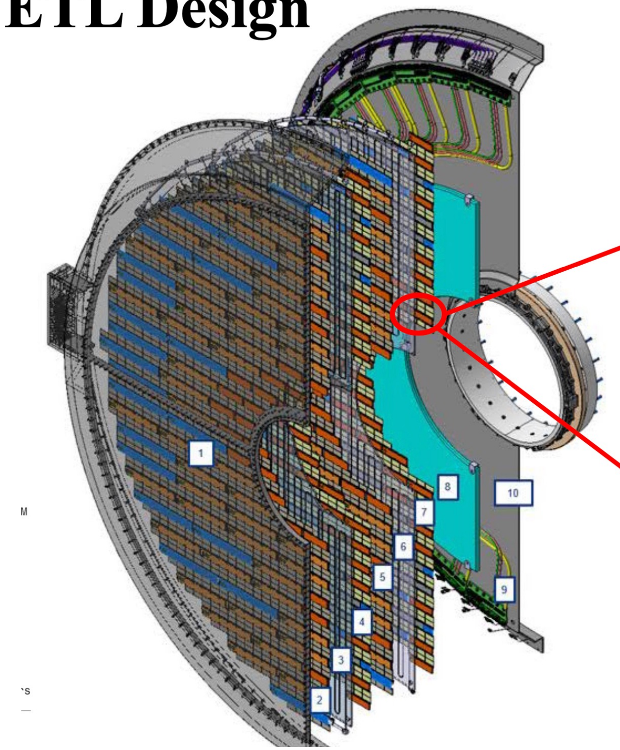
MTD – Endcap Timing Layers (ETL)

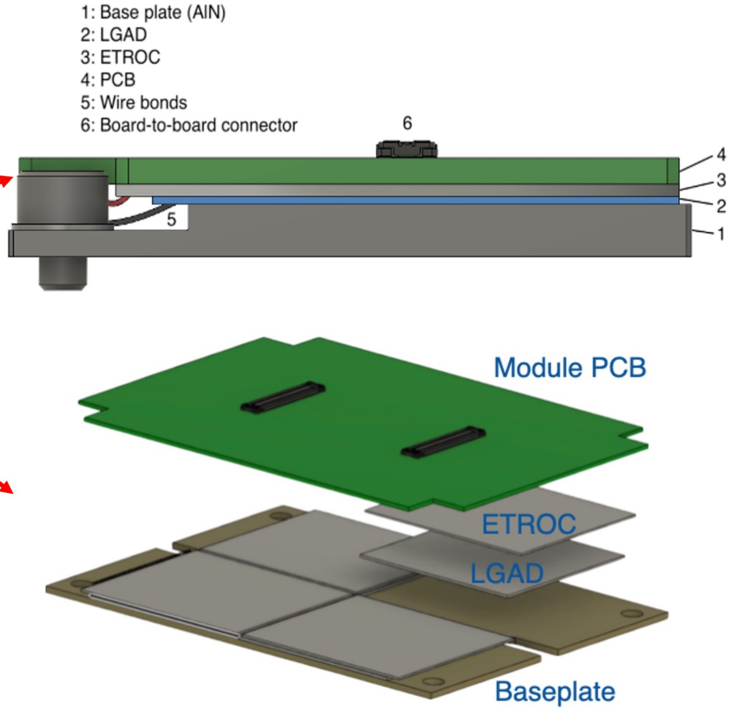


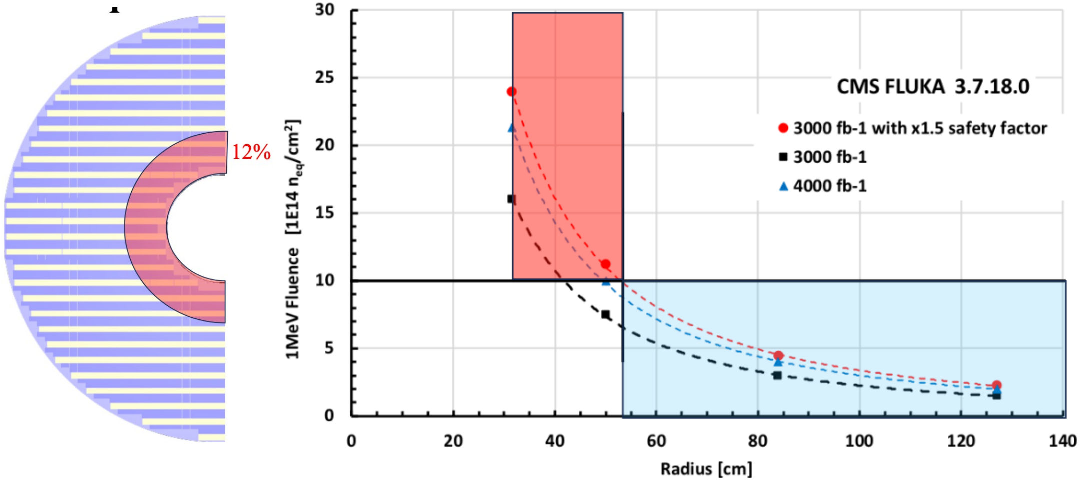
ETL first use (ATLAS&CMS) of Low Gain Avalanche photo Diodes (LGAD) on large scale readout by dedicated ASIC

$1.6 < |\eta| < 3$, 2 double sided thin layers with 1.3 x 1.3 mm^2 pads providing 8.5 M channels $\sigma_t \simeq 35$ ps /track

ETL Design







Half-shell design, can be extracted/installed with beam pipe in place

ETL Requirements:

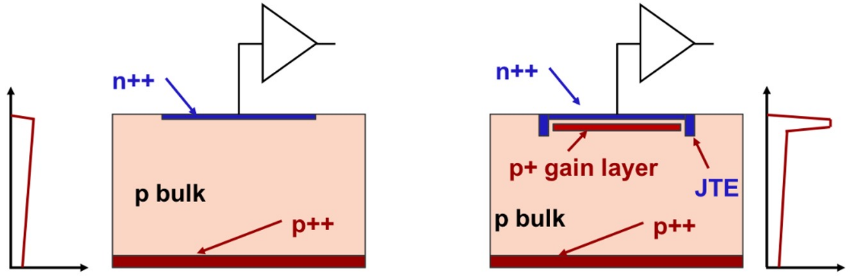
- **Fill-factor** (ratio of active and total detector surface): >95%
- **Low occupancy**: <0.1% at low η, 1% at highest η
- **Radiation tolerance**: up to 1.7×10^{15} 1MeV n_{eq}/cm^2

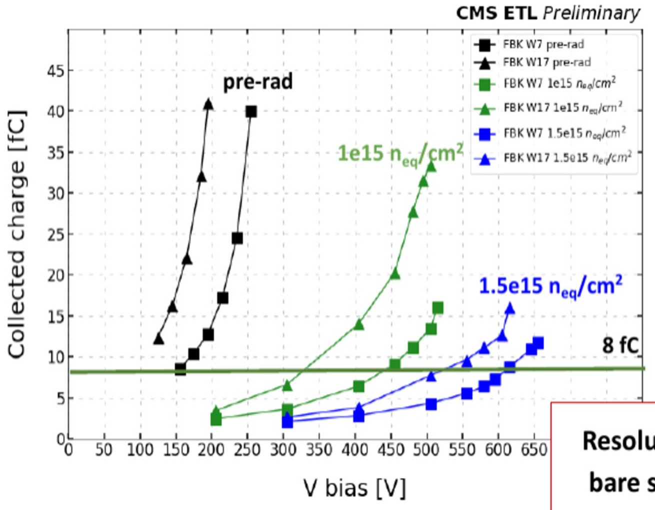
(12% of surface will reach higher fluences than 1×10^{15} 1MeV n_{eq}/cm^2)

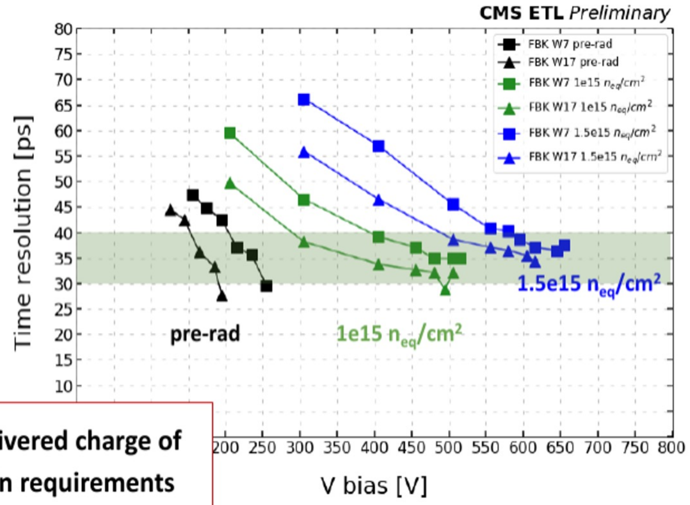
ETL low-gain avalanche silicon diode (LGAD) sensors

LGAD sensor:

- size optimised by occupancy and matched to read-out electronics
- 50 µm-thick, 16×16 pads array with 1.3×1.3 mm^2 pads
- Low leakage current to limit power consumption and noise
- Large and uniform signals: >8 fC pre-radiation, >5 fC after highest irradiation point
- Minimized "no-gain" area needed to isolate pads: inter-pad distance < 50 µm

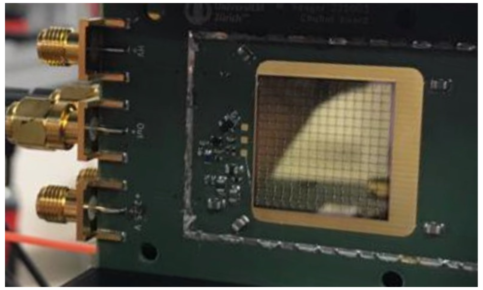


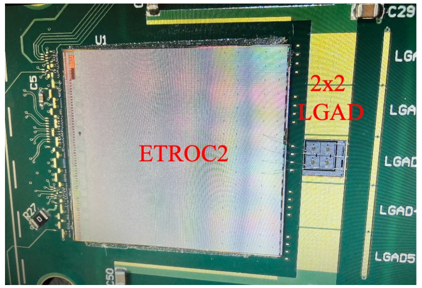




Resolution and delivered charge of bare sensors within requirements

ETL sensor (55 um thick) characterization with beta-source after irradiation meet timing and radiation hardness requirements





Test beam verification of LGAD sensor bump-bonded to low noise + fast rise time ASIC will start in September

Infrastructure

The big numbers

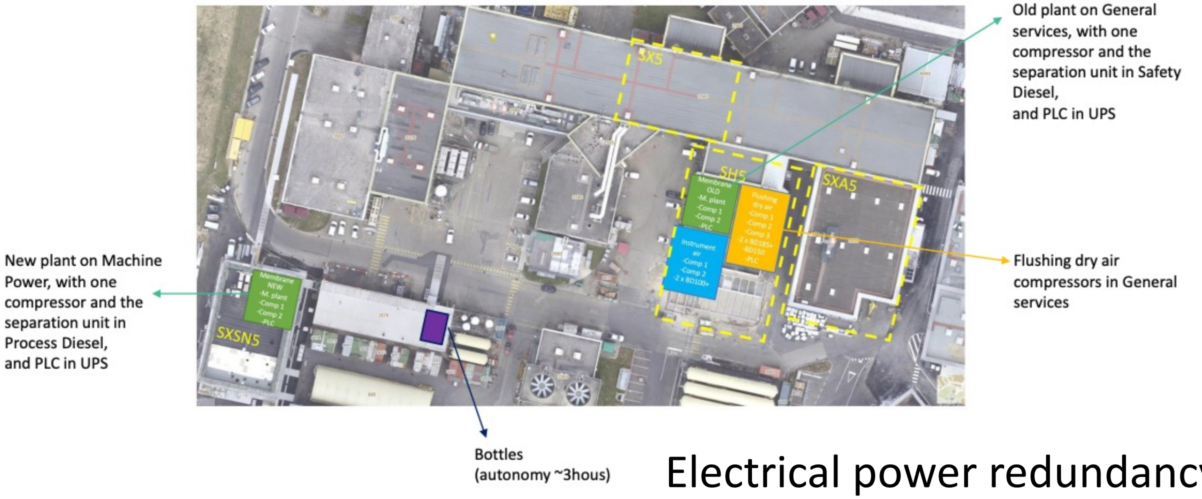
Cooling power evolution (ref: https://edms.cern.ch/document/1751282/5)

- Detector racks: from 600 kW to 1500 kW
- Water cooled detectors: remains constant (few more Muon chambers, higher power density on other systems like B-CAL)
- Cold detectors (sub-zero): from 120 kW (Tracker & Preshower) to (ref. https://edms.cern.ch/document/2043333/4) 550 kW (= 750 kW @ primary system)
- DAQ system: from 1 MW to 2.5 MW (Run3) to potentially up to 5 MW at end of Hi-Lumi operation

Electrical power evolution (ref. https://edms.cern.ch/document/2741045/2)

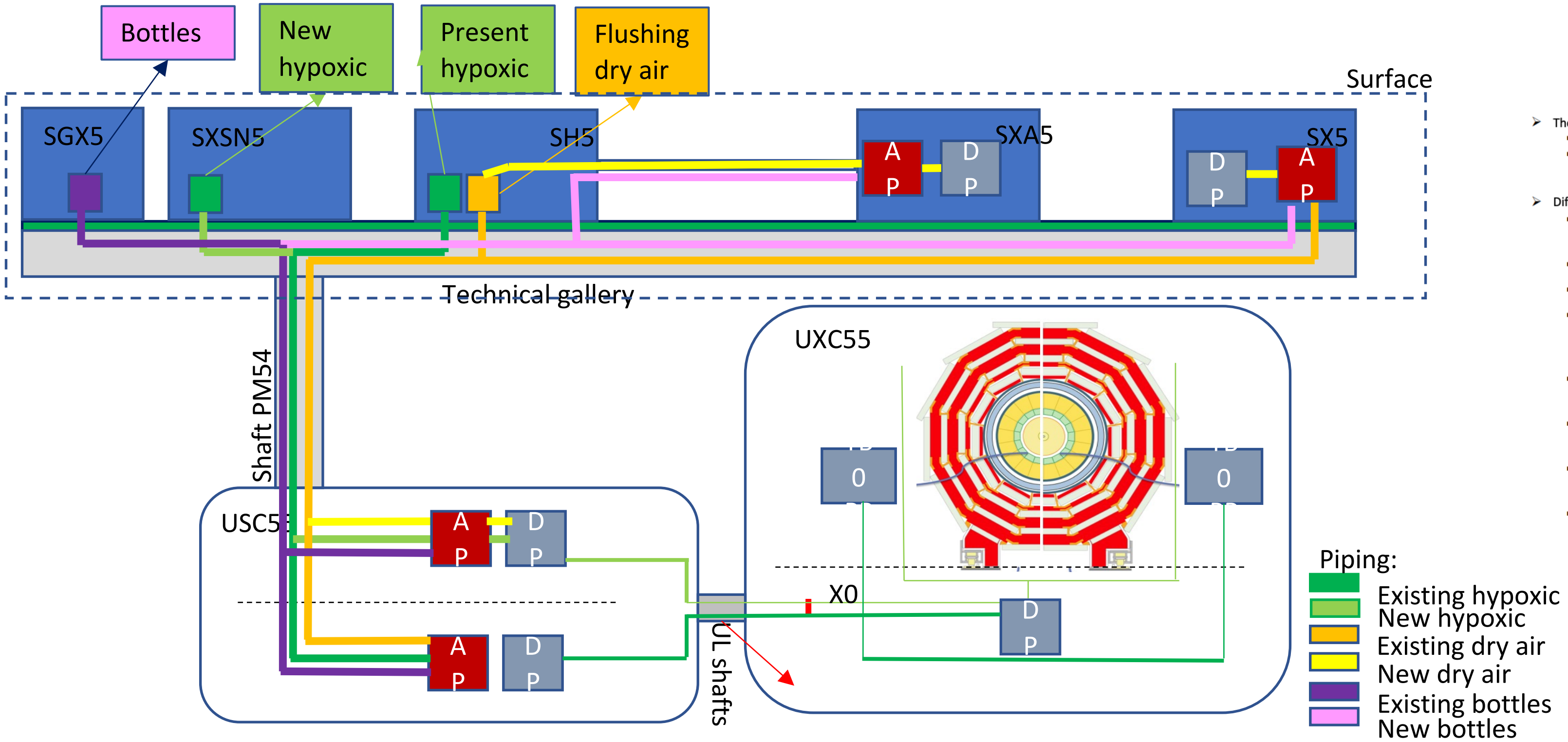
- Detector power increase to 2 MW from max 1.5 MW
- Electrical power supply for CO_2 cooling (with primary & ancillaries) about 2.5 MW
- New Diesel generator to supply secured power for uninterruptable processes (on top of safety systems)

Dry gases for detector inert atmosphere

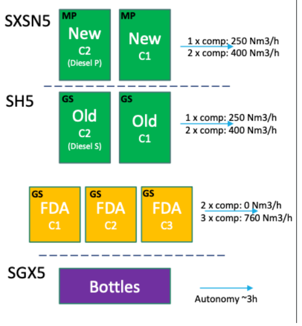


Electrical power redundancy

Dry gas distribution overview



- The gas production system is designed so:
  - One (out of two) hypoxic air plant with two compressors running can supply the full detector needs
  - Three dry compressors from dry air network can supply the full cooling infrastructure plus full detector needs
- Different operation scenarios:
  - Nominal: one hypoxic plant running with two compressors delivers full flow, the other in standby, swap periodically.
  - Machine power failure: old plant working with both compressors.
  - General services failure: new plant working with both compressors.
  - General blackout: each plant has one compressor in a Diesel network. Both compressors can run simultaneously to deliver full flow, or only one to deliver half of nominal flow.
  - Old plant maintenance/failure (including PLC failure): new plant working with both compressors.
  - New plant maintenance/failure (including PLC failure): old plant working with both compressors.
  - Both plants maintenance/failure (including PLC failure): swap to flushing dry air in USC (low pressure failure).
  - Bottles: none of the rest are available (very short autonomy!)



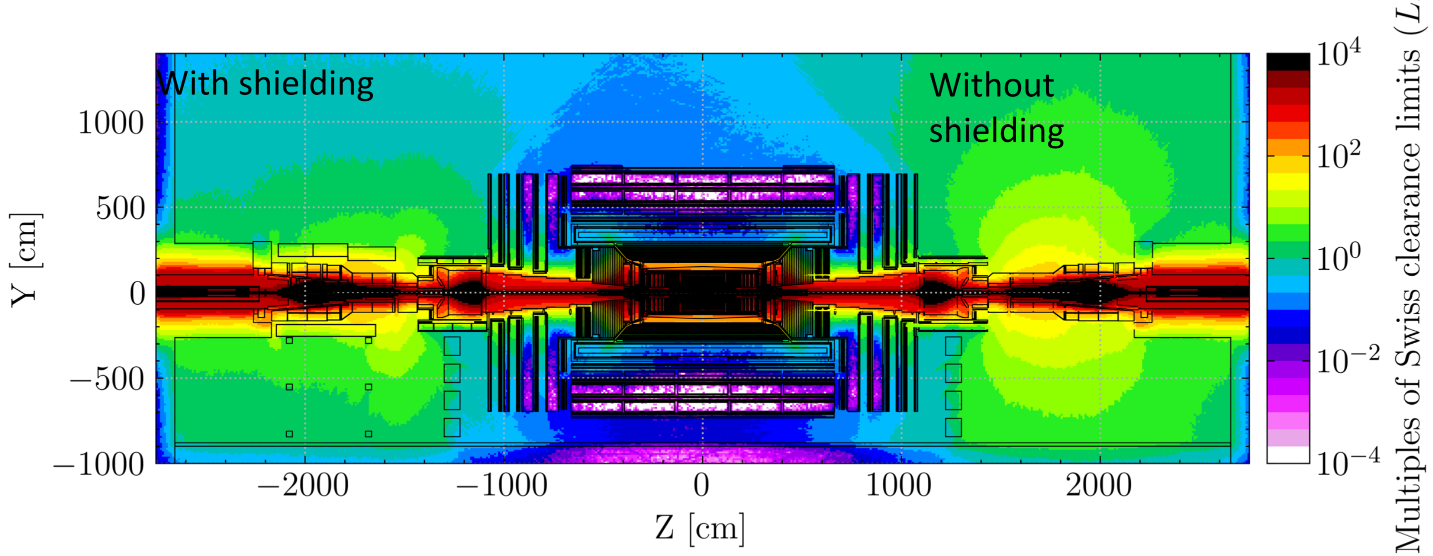
Equipment redundancy

CMS New forward Shielding for activation and neutron reduction

Two-fold goals

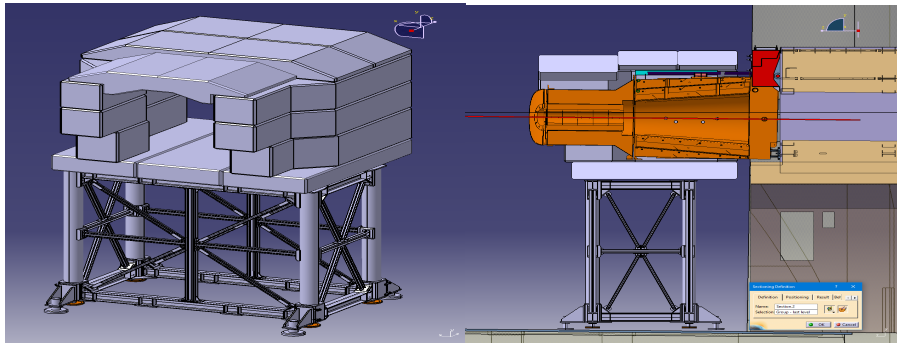
- Limit the activation of steel structures
  - $Fe^{54} + n \rightarrow Mn^{54} + p$

    Mn^{54} is a gamma emitter with half-life of 312 days.
  - Mn^{54} presence in the cavern steel structures makes any destructive intervention very complicated from a procedural point of view.
- Reduce background in muons chambers to increase overall chamber longevity



FLUKA simulation of the expected activation levels for steel (worst case) at 4 months in Long Shutdown 3

- installation assumed in one side of the CMS cavern only;
- Vertical projection over the full UXC5;



240 tons of additional shielding material (90% concrete – 10% steel) per cavern end

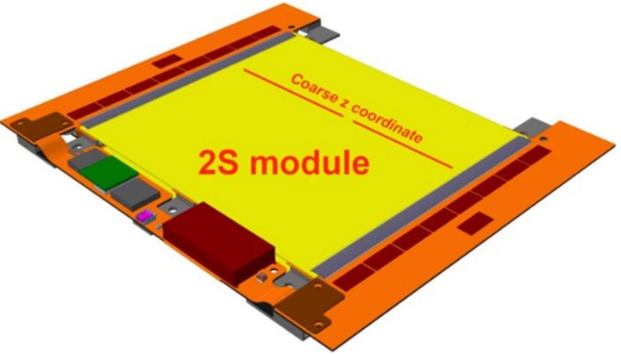
Assembly test of unfilled blocks

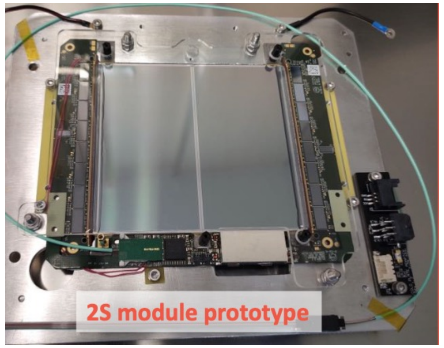
180m³ concrete poured

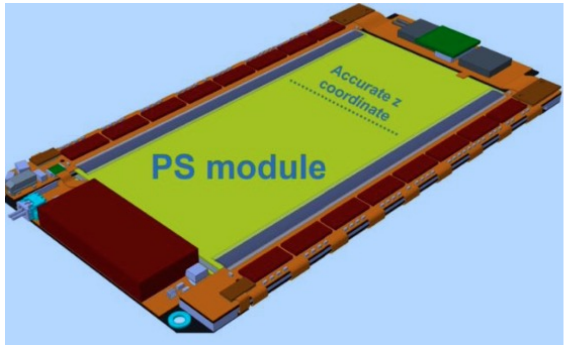
D. Bozzato PhD Thesis. 2023. doi:10.5445/IR/1000159308

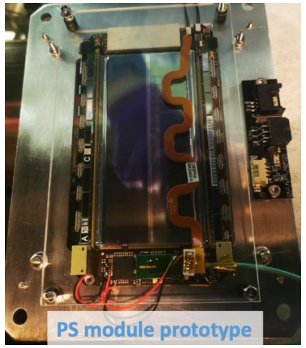
p_T modules concept

Modules provide p_T discrimination in front-end electronics







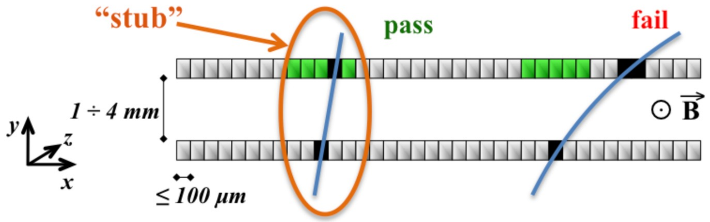


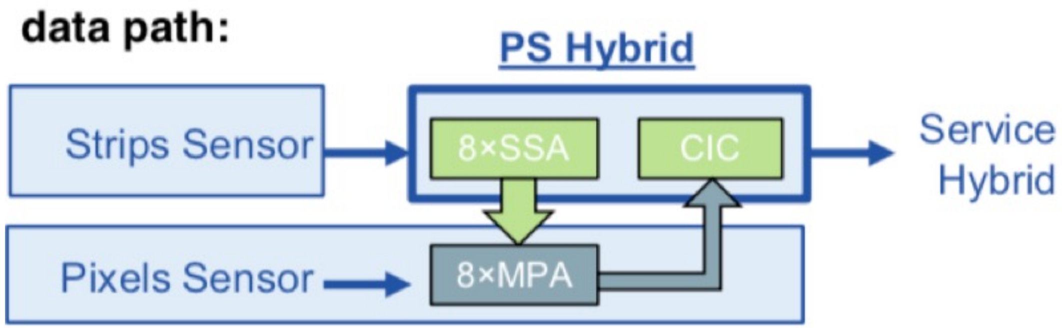
"strip-strip" - 2S modules

- Sensor dimension are 10cm x 10cm
  - two column of 1016 strips
- 2 micro strip sensors with 5cm x 90µm strips
- 2 different spacing : 1.8mm & 4mm

"pixel-strip" - PS Modules

- Top sensor (towards IP): 2.5cm x 100µm strips
- Bottom sensor :1.5mm x 100µm pixels
- 3 different spacing: 1.6 mm ; 2.6 mm and 4 mm





CMS New forward Shielding

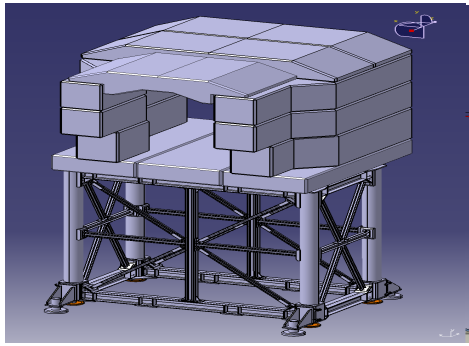
240 tons of additional shielding material (90% concrete – 10% steel) per cavern end

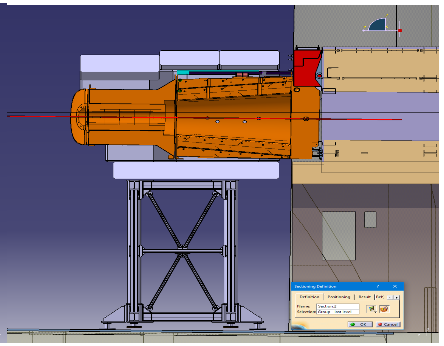
Two-fold goals

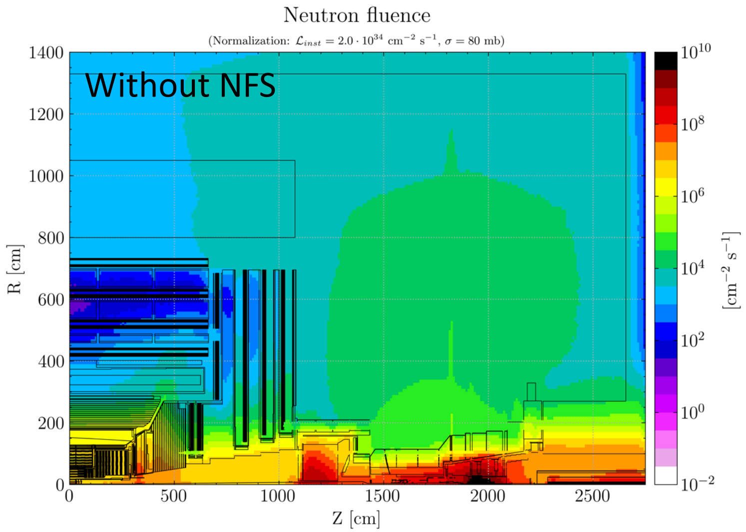
- Limit the activation of steel structures
  - $Fe^{54} + n \rightarrow Mn^{54} + p$

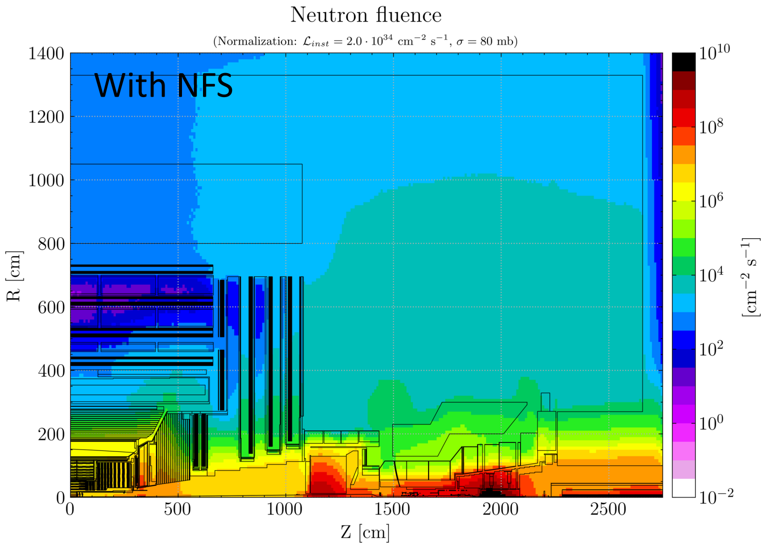
    Mn^{54} is a gamma emitter with half-life of 312 days.
  - Mn^{54} presence in the cavern steel structures makes any destructive intervention very complicated from a procedural point of view.
- Reduce background in muons chambers to increase overall chamber longevity

Being built, first-end installation planned for 2024









Assembly test of unfilled blocks

180m^3 concrete poured

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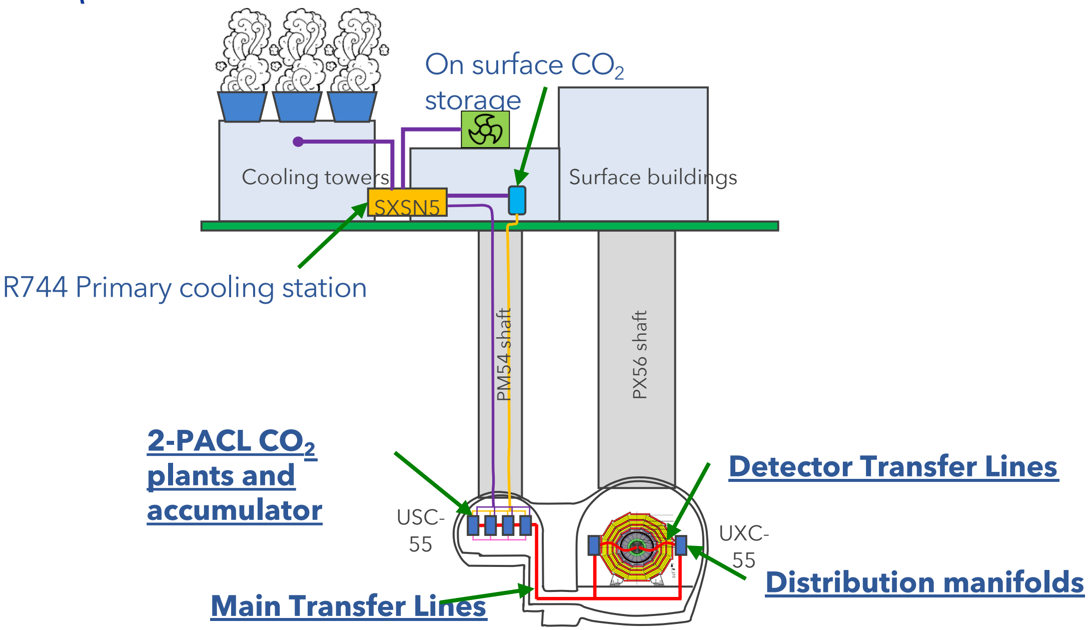
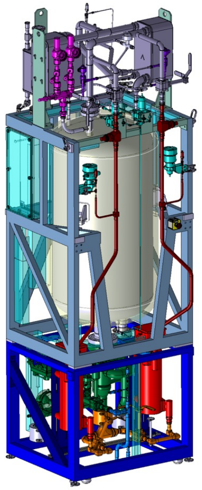
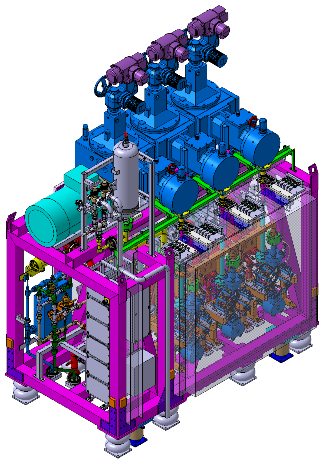
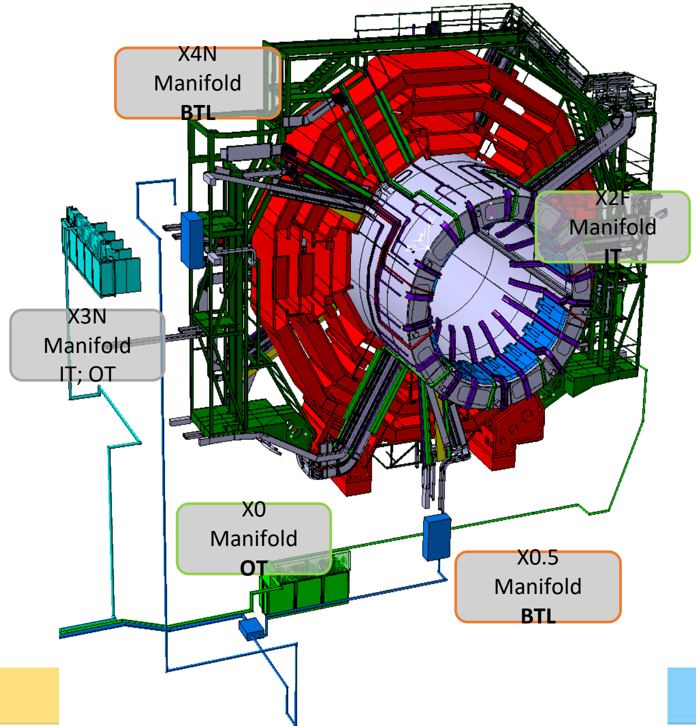
CO_2 evaporative cooling @ CMS

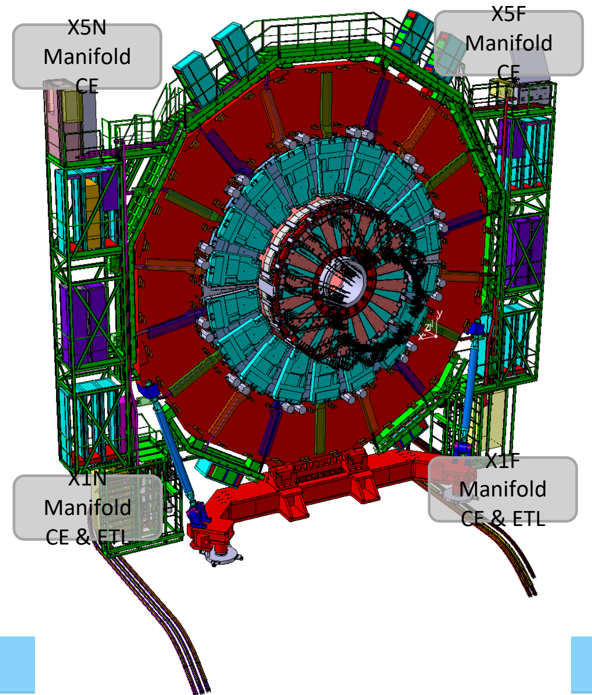


- Serves Tracker, HGCAL, MTD detectors with coolant temperatures down to -35 C
- Substitute C6F14 and R404a with liquid CO_2 (on detector pumped loops) and R744 (primary system)
- High reliability, complex system: design for high pressure (100 bar), low temperature
- Vacuum insulation for all transfer lines, to cope with stringent quality and space requirements

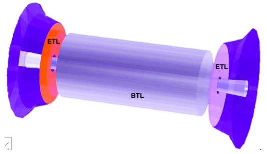






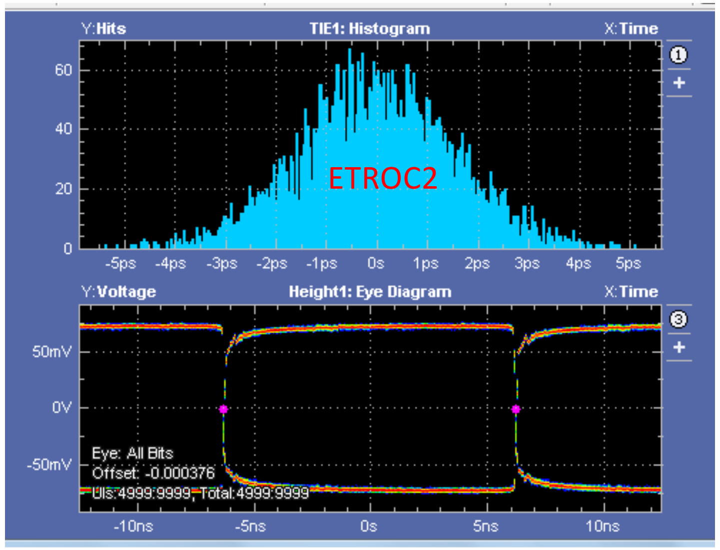


MTD – Endcap Timing Detector – ETROC2

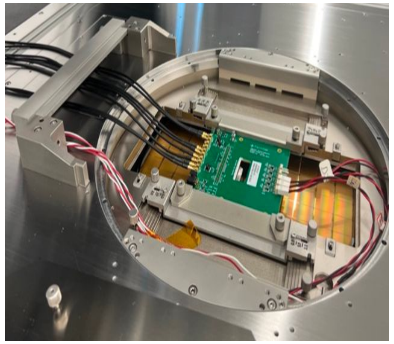


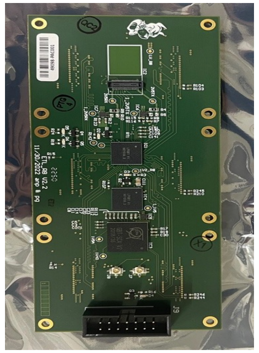
ETL ETROC2 (TSMC 65 nm) ASIC tests ongoing

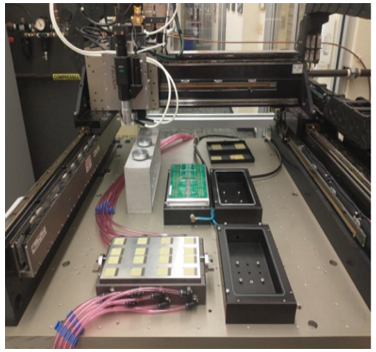
- PLL locks, I2C communication for chip configuration successful, fast communication established
  - Measured random (rms) **jitter** of 40 MHz TDC clock from PLL in ETROC2 < 2ps
  - Demonstrated charge injection all the way to the output of ETROC2 and received data unpacked correctly in FPGA, using fast command interface.
- System tests have started
  - Successful I2C communication and R/W configuration registers with single bare ETROC2 PCB & prototype readout board (**middle**)
  - ETROC2 integrated into test beam setup previously used with ETROC1 (**right**)



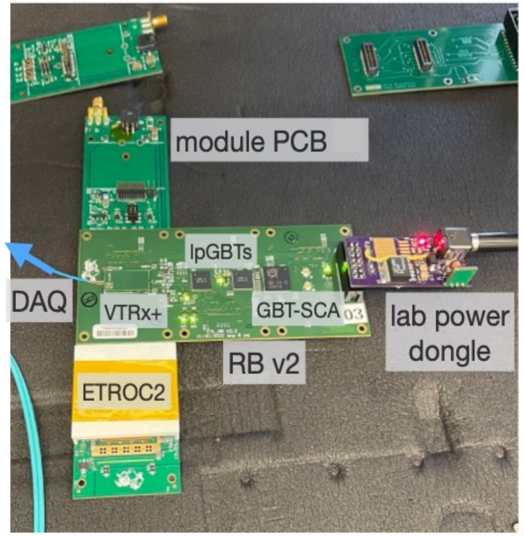
Validation of LGAD + ETROC2 based prototypes – ongoing
Final ETROC3 pre-production ASIC for 2024

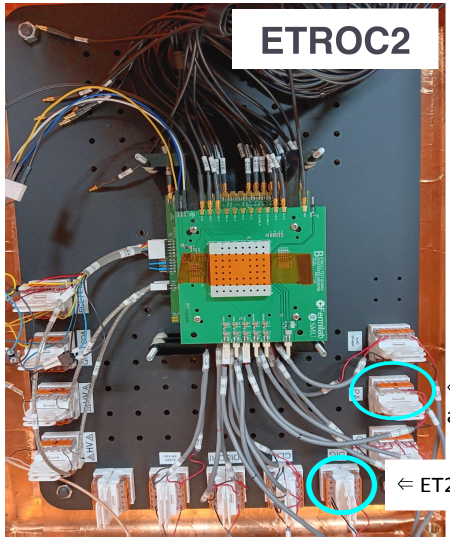






Readout board and module assembly demonstrated
9 k modules (1 or 2 sensors)





General context

- Radioactivity is induced in detector and infrastructure components by prompt radiation as a consequence of the operation of high-energy accelerators and collider experiments. Irradiation conditions at the LHC experiments will become harsher with increasing luminosity making the assessment of induced radioactivity a pressing need.
- While the activation of the inner detector components cannot be avoided, the activation outside of HEP detectors can be mitigated and should be kept to levels as low as reasonably achievable (ALARA principle).
- With the only exception of the visitor platform that can normally be declassified after a certain cooling time during shutdown periods, the CMS experimental cavern (UXC55) is classified as a radiation area: any material leaving a radiation area must be subject on a control measurement that depends on the expected activation levels.
- Activation in the CMS cavern constrains maintenance, particularly in all the areas not in the shadow of the yoke :
  - stainless steel (type 304L) and iron are the most activated materials;
  - ^{54}Mn ($T_{1/2}$ = 312.5 d) is the main driver;
  - this was clearly shown in FLUKA simulations and confirmed by LS2 RP residual dose rate surveys and gamma spectroscopy measurements.
- The CMS Technical coordination investigated the reinforcement of the existing forward shield with two-fold purpose: reduction of activation in the infrastructures at the periphery of CMS and reduction of background radiation for the Muon Drift Tubes;

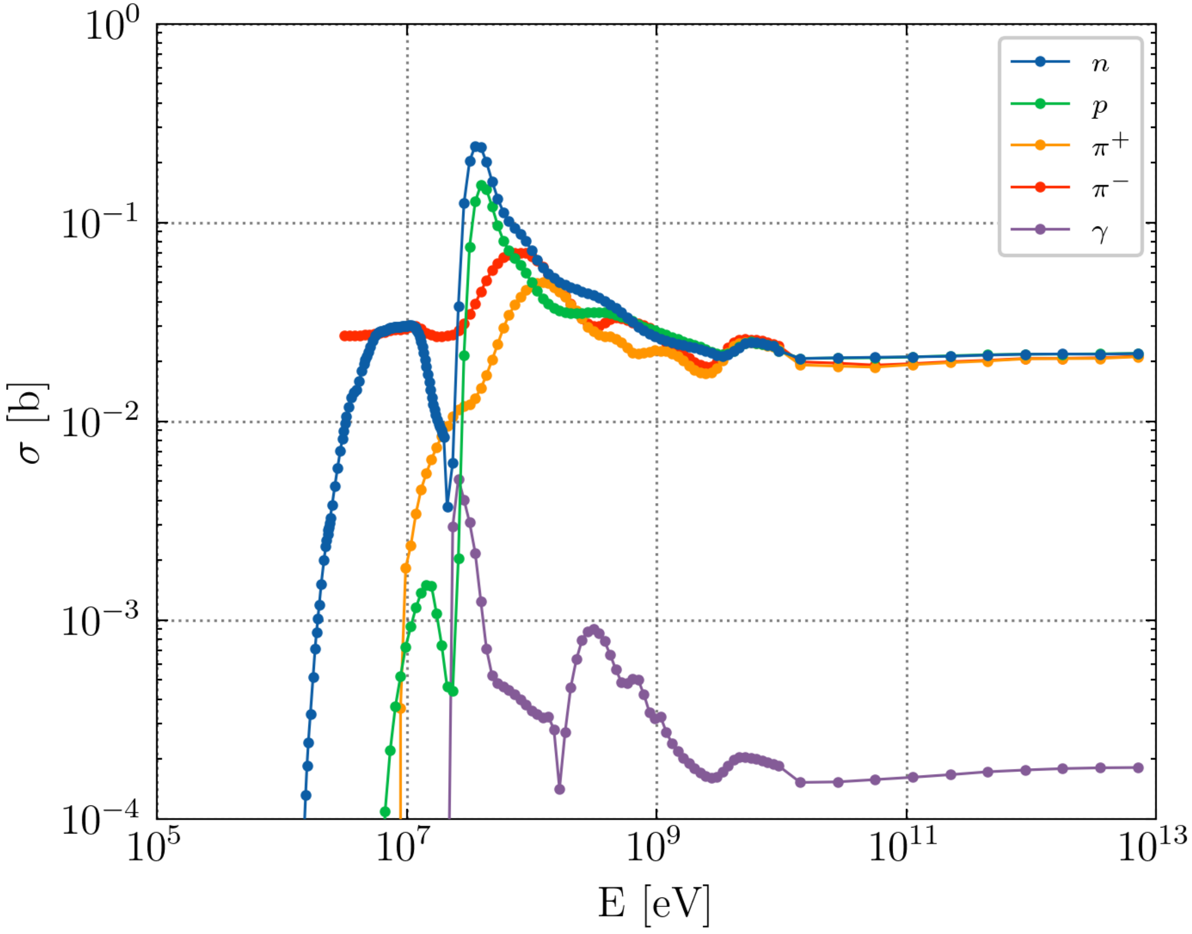
General context

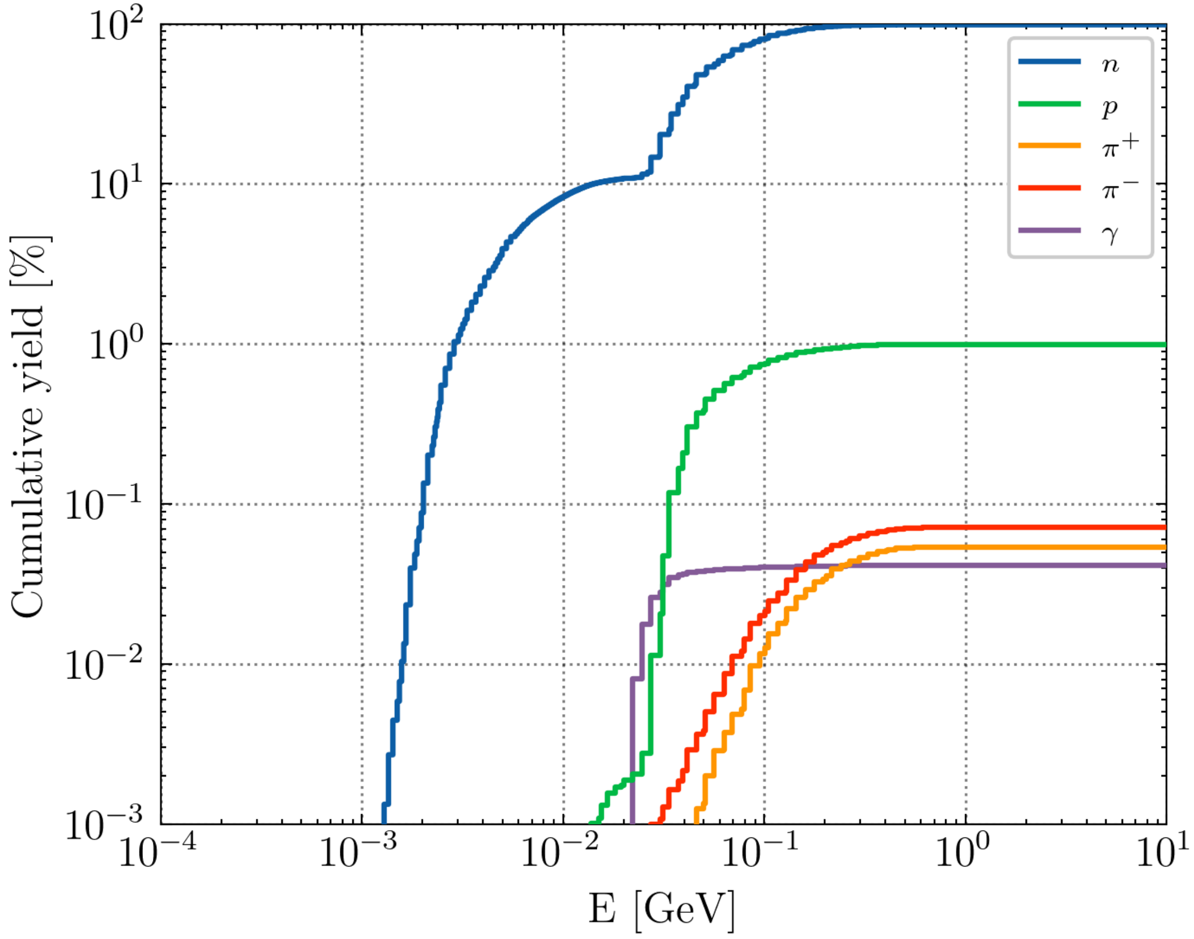
- FLUKA simulations were performed in iteration with CMS engineers to optimize the shield design: the expected activation levels in the UXC5 infrastructures were estimated with the fluence conversion coefficients code.
- The fluence conversion coefficients method is based on the idea that radiological hazard factors can often be expressed as a weighted sum of radionuclide mass-specific activities with radionuclide-specific weights. Coefficients are pre-computed and applied online during Monte Carlo transport calculations.
- Important premise on CERN and Swiss Radiation Protection rules:
  - a material containing a mixture of radionuclides can be cleared from regulatory control if the following condition (among others) is met:

$$\boldsymbol{LL = \sum_{b=1}^{N_R} \frac{A_b}{LL_b} < 1.0}$$

  - **This defines the Multiples of clearance limits $\boldsymbol{LL}$** (sometimes quoted as sum of LL fractions). A_b are the radionuclide specific activities in Bq/g and LL_b the clearance limits in Bq/g.
  - The condition on the LL is the most constraining one.
  - The 70% of the Multiples of (Swiss) clearance limits at the CMS periphery is due to ^{54}Mn alone (^{54}Mn has a clearance limit of 0.1 Bq/g)!

^{54}Mn production issue

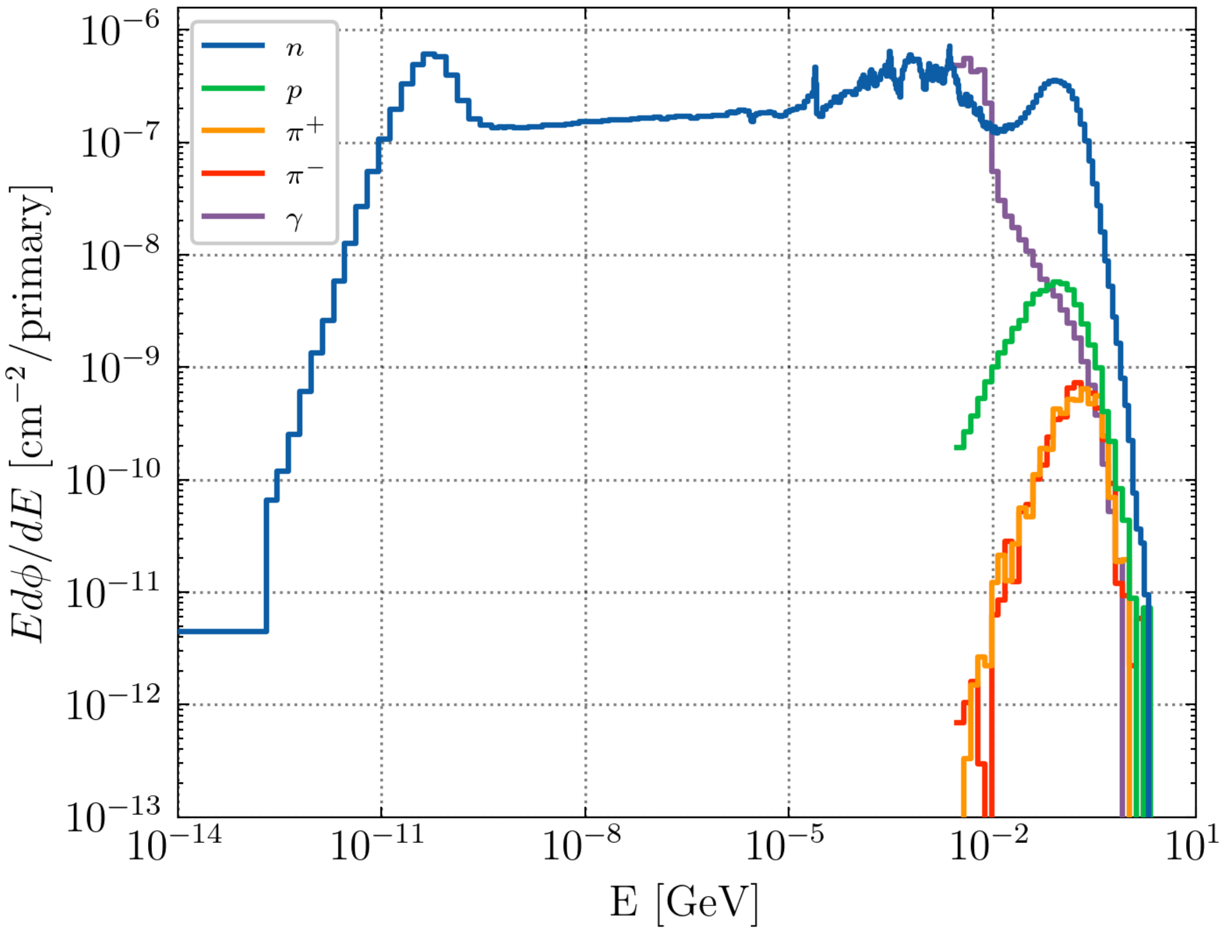




Left: FLUKA estimation of the ^{54}Mn production cross sections from natural iron for the particle species dominating the activation processes at the UXC5 periphery .

Right: ^{54}Mn cumulative production yield (convolution of production cross section with particle fluence energy spectra) from natural iron for the particle species dominating the activation processes at the UXC5 periphery. The vast majority of ^{54}Mn comes from neutrons between 20 MeV and 100 MeV.

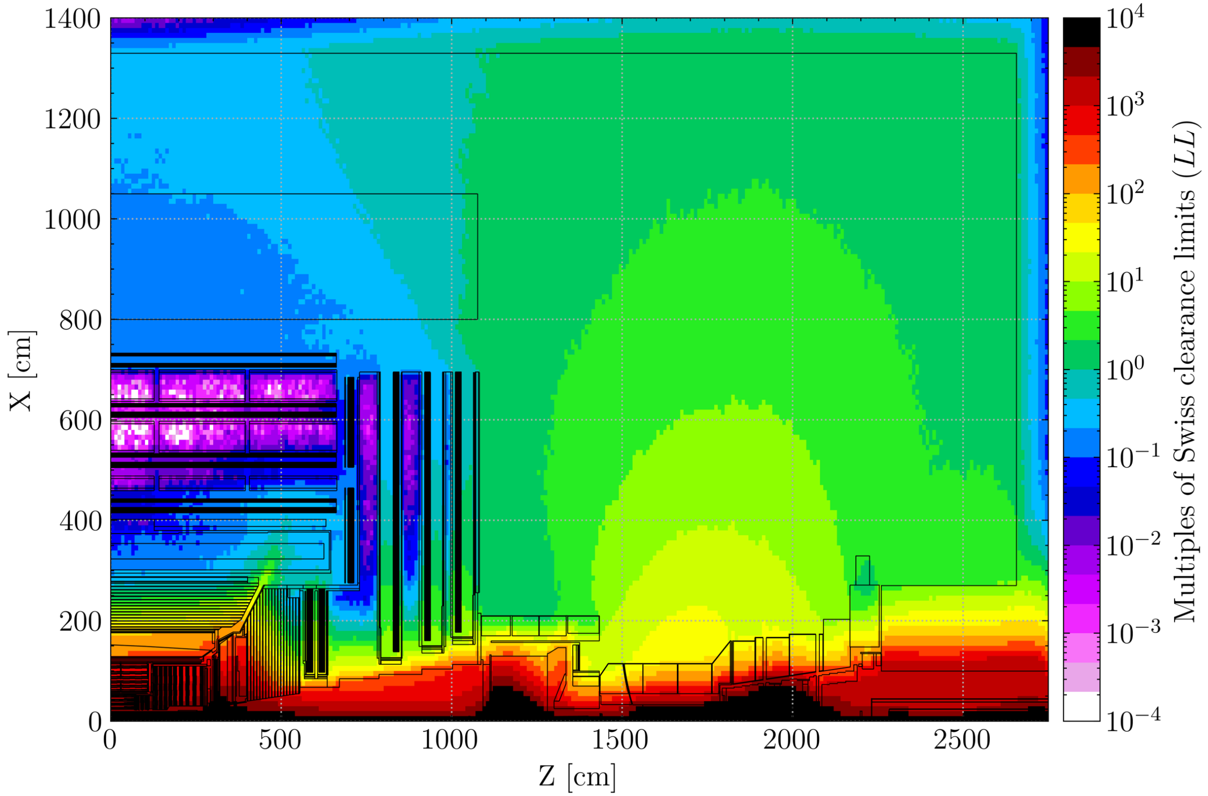
Particle fluence energy spectra at the UXC5 periphery



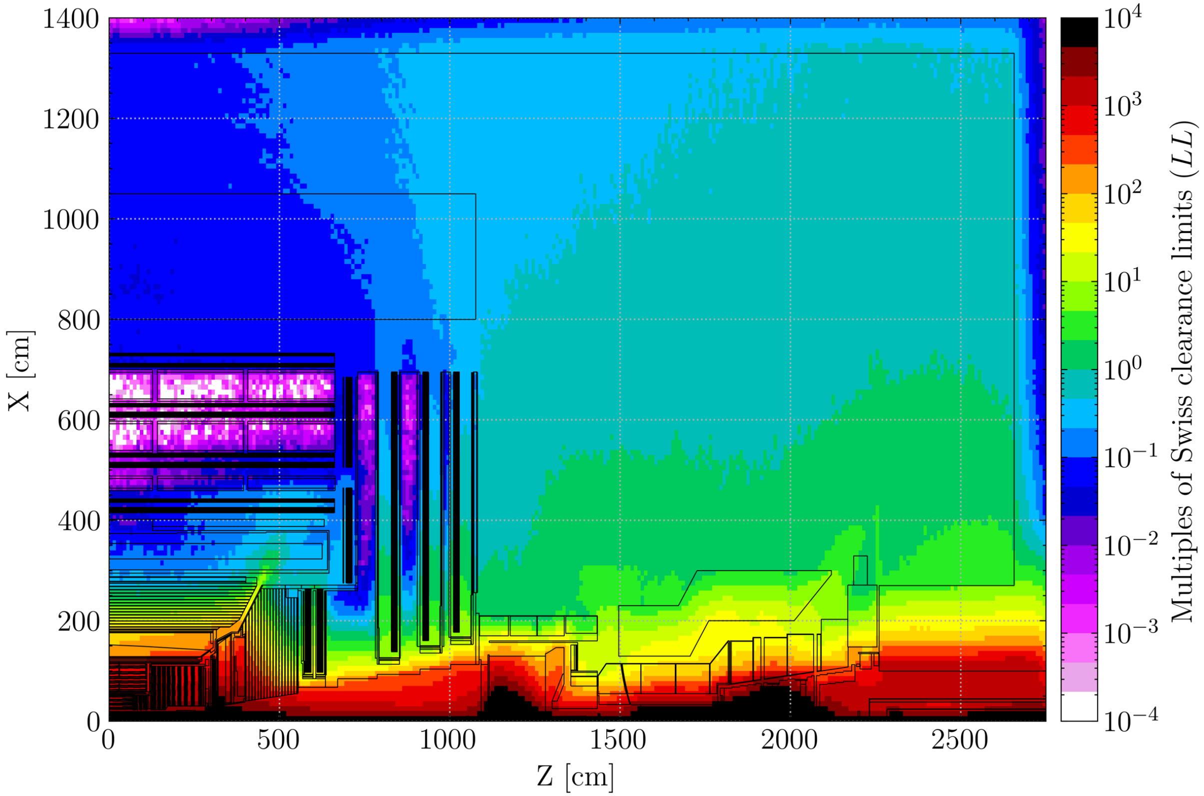
FLUKA simulation of the particle fluence energy spectra at the UXC5 periphery .

Preliminary design studies for the CMS New Forward Shield

Without the shield

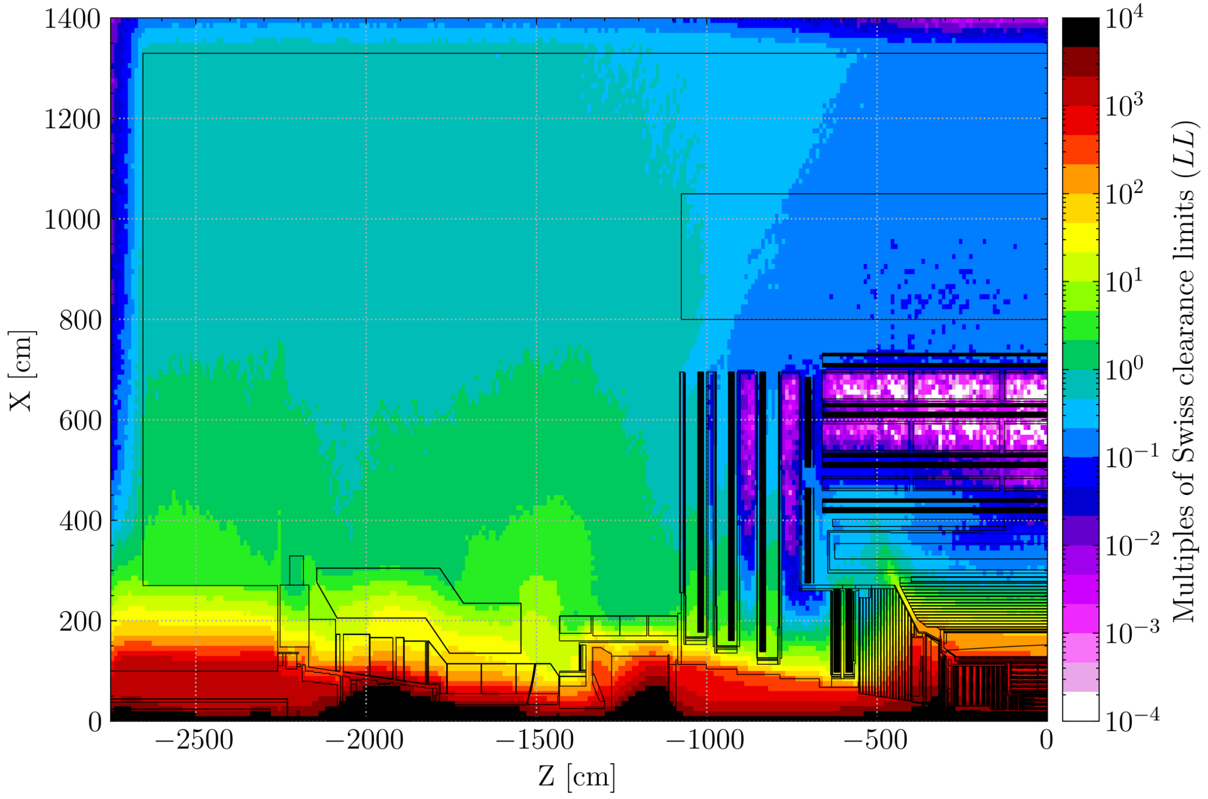


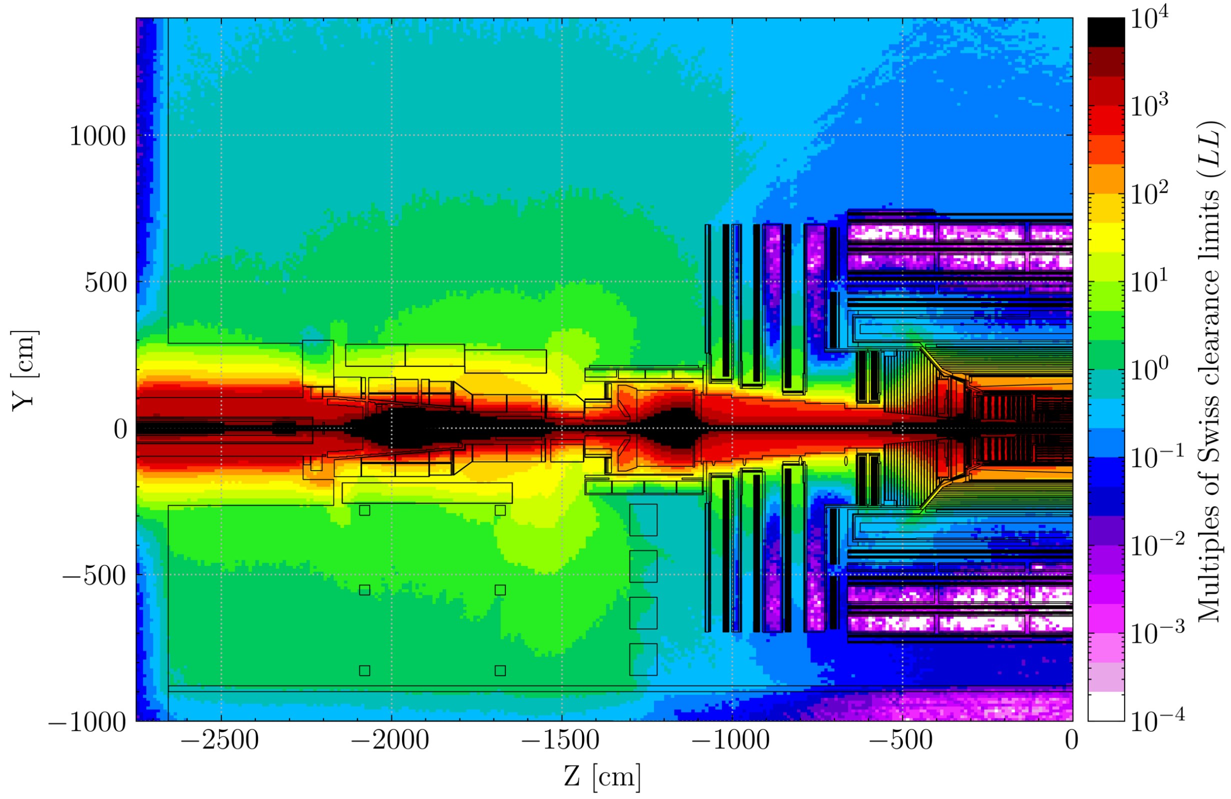
With the shield



- FLUKA simulation of the expected activation levels for steel (worst case) at 4 months in Long Shutdown 3
  - expected reduction of activation levels in the cavern infrastructures (radial distance from beam axis > 8 m) of a factor up to 4 (notice the significant shift of the boundary at which LL=1);
  - calculations performed with the fluence conversion coefficients method;

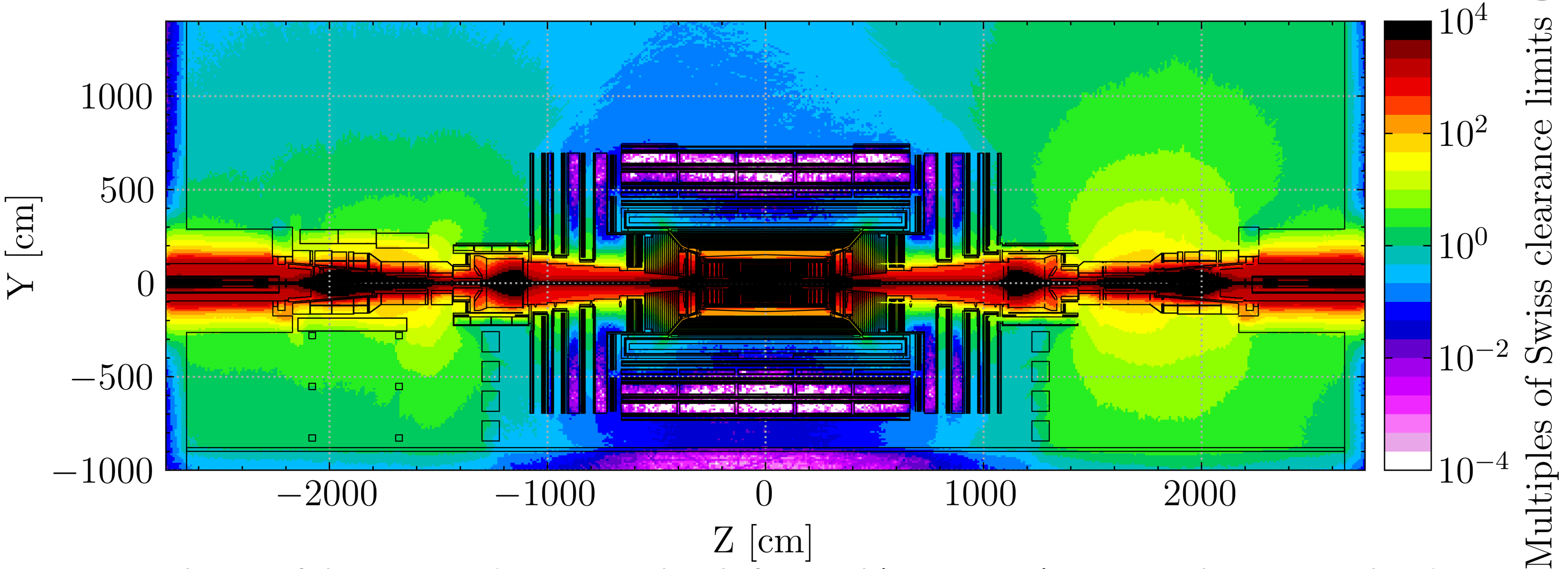
Simulations for the final CMS New Forward Shield design





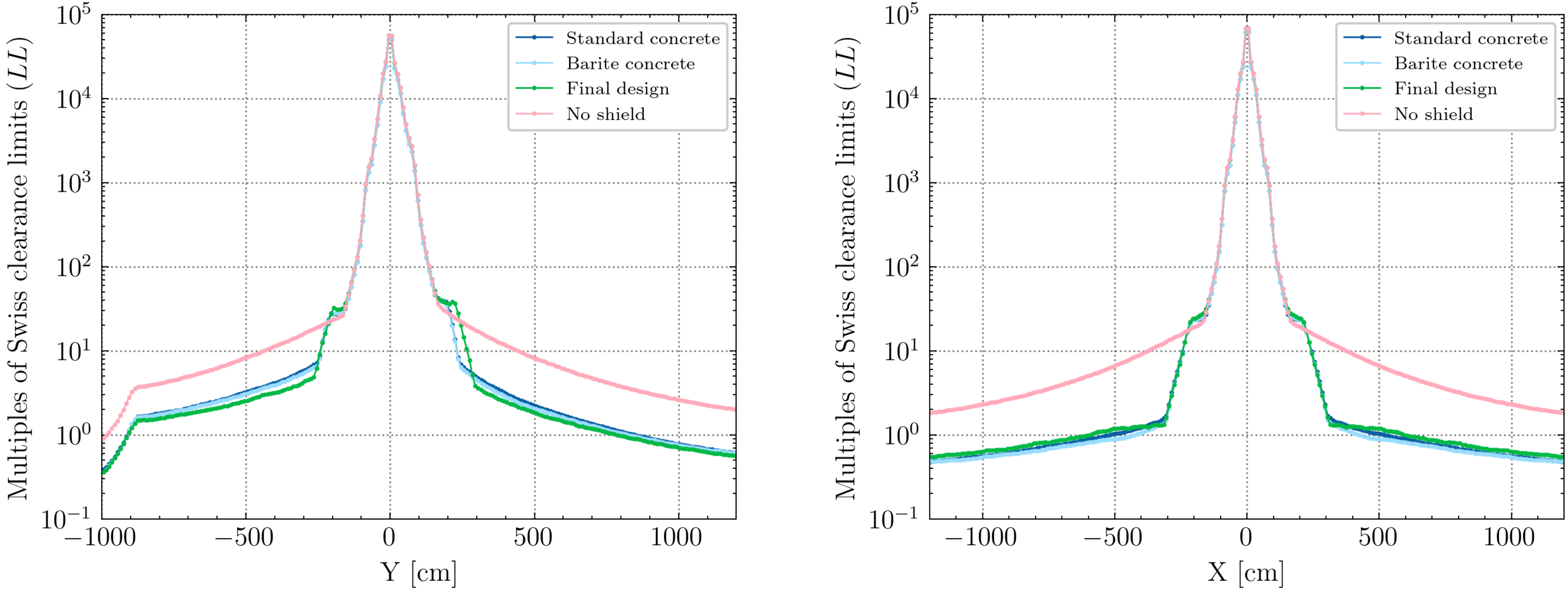
- FLUKA simulation of the expected activation levels for steel (worst case) at 4 months in Long Shutdown 3
  - installation assumed in one side of the CMS cavern only;
  - calculations performed with the fluence conversion coefficients method;
  - horizontal and vertical projections (close-up);

Simulations for the final CMS New Forward Shield design



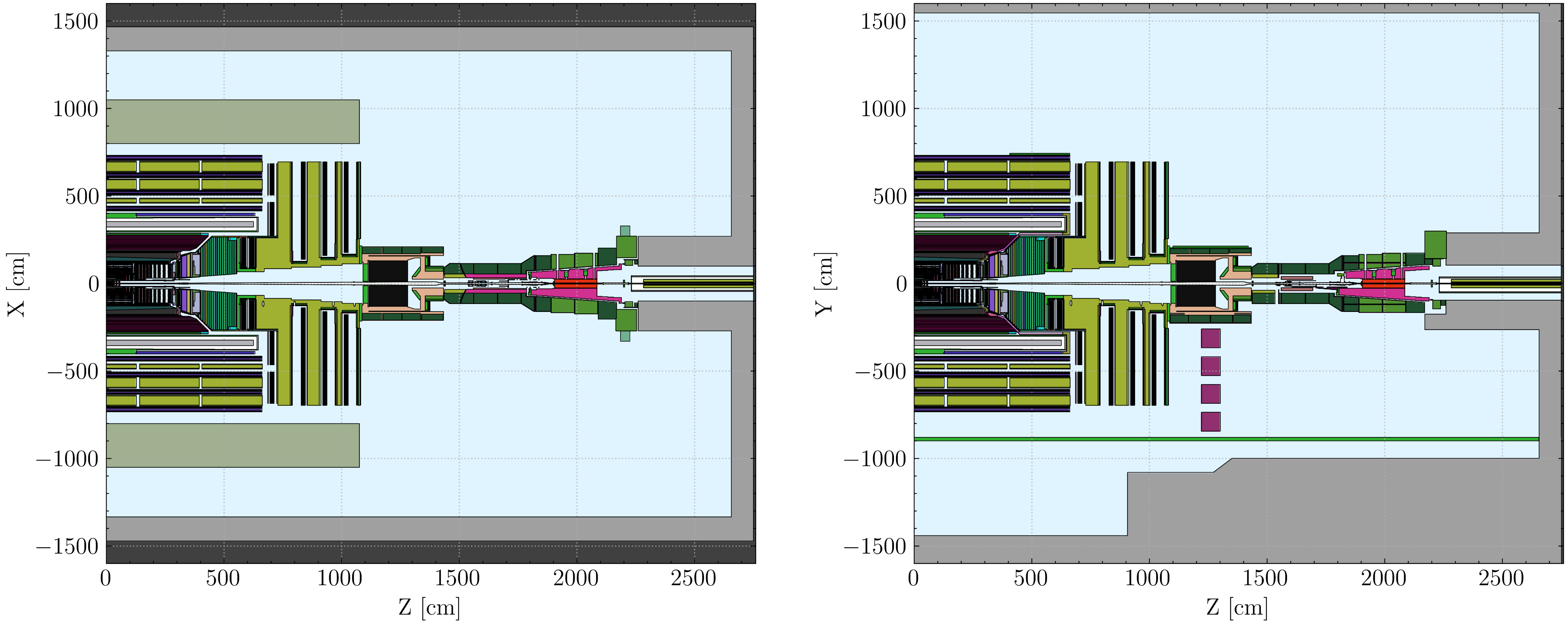
- FLUKA simulation of the expected activation levels for steel (worst case) at 4 months in Long Shutdown 3
  - installation assumed in one side of the CMS cavern only;
  - calculations performed with the fluence conversion coefficients method;
  - Vertical projection over the full UXC5;

Comparison of the shielding effectiveness

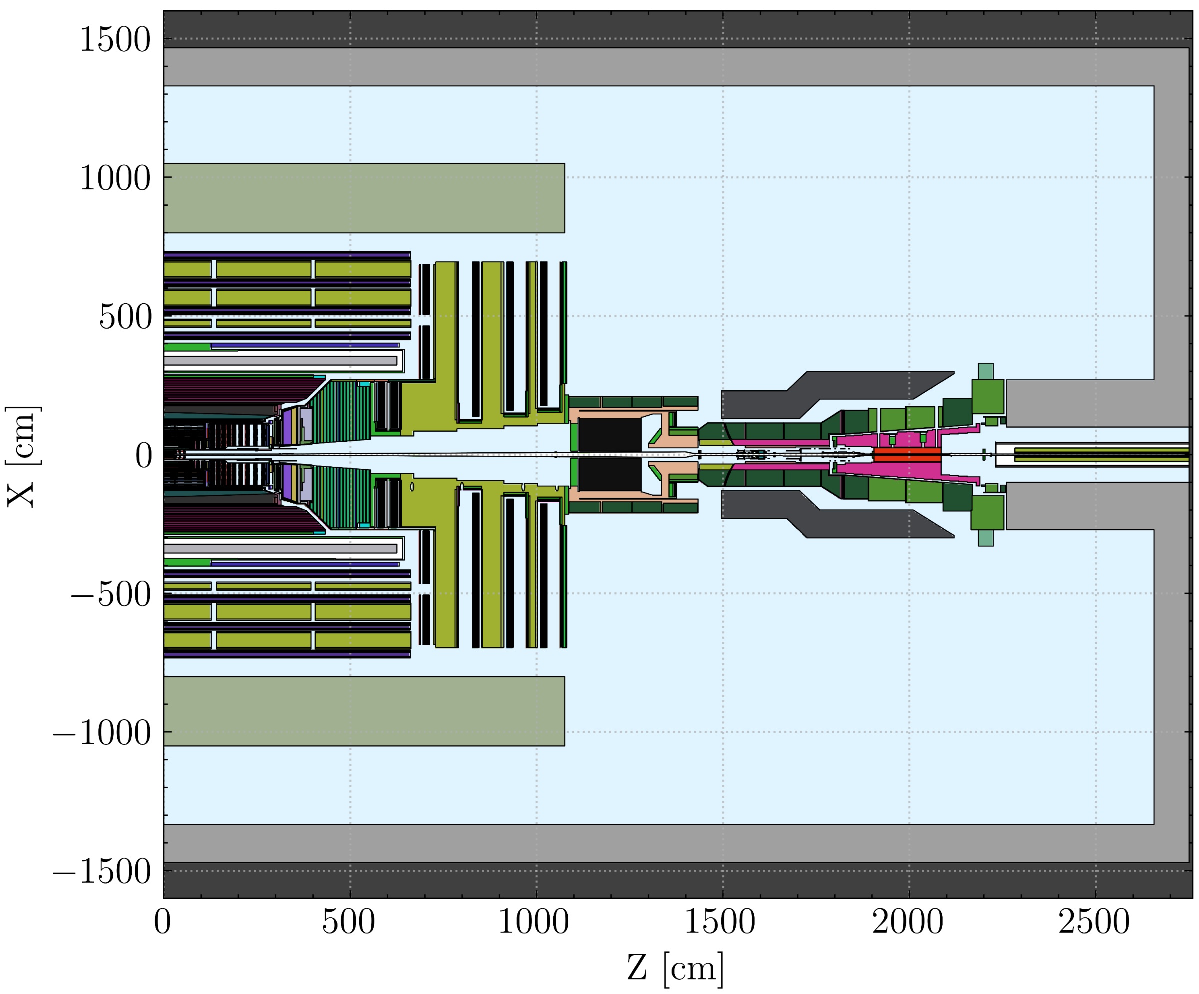


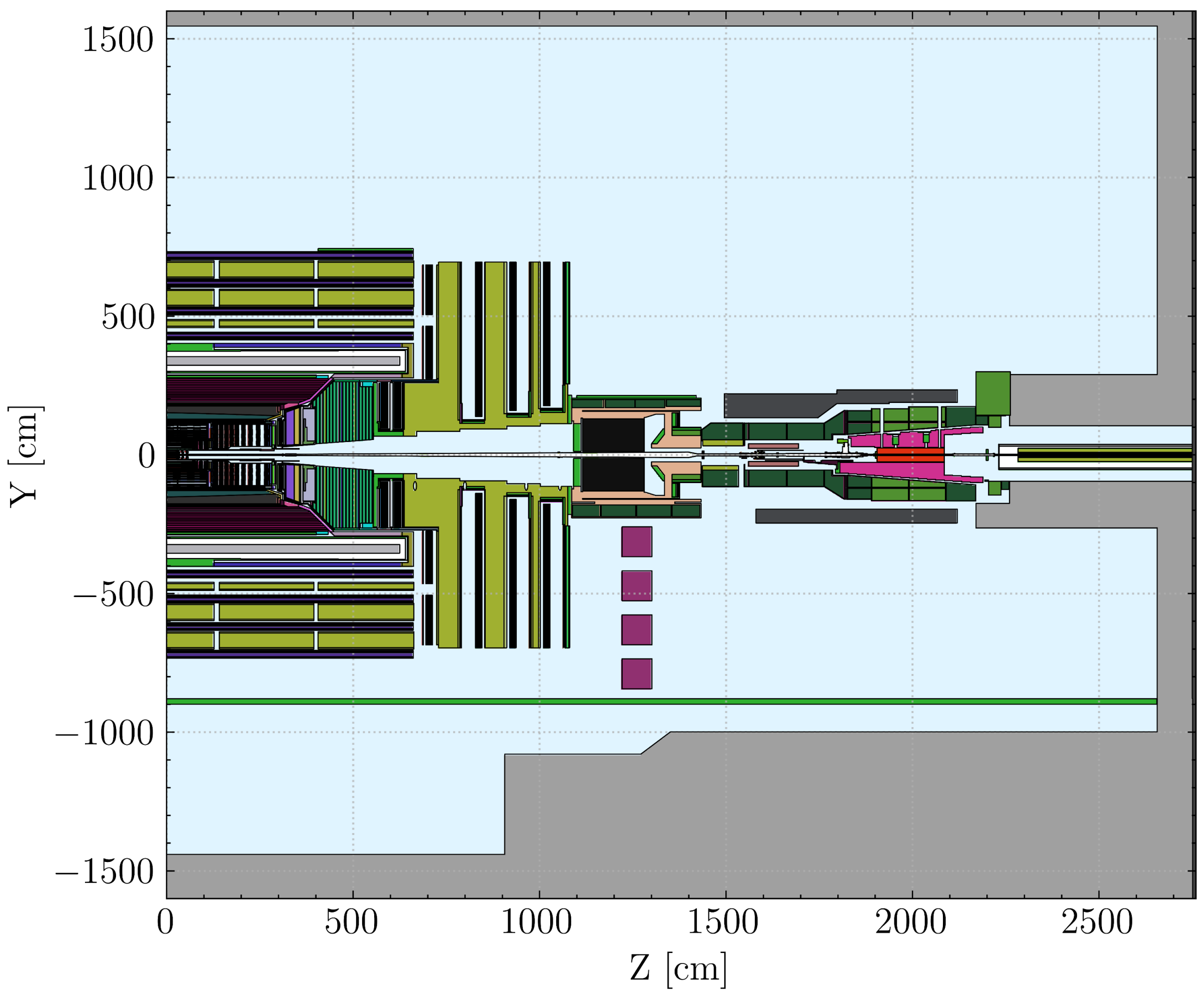
- FLUKA simulation of the expected activation levels for steel (worst case) at 4 months in Long Shutdown 3
  - Comparison of various shielding designs
  - Standard concrete most cost-effective solution
  - Effectiveness of the final design is optimized in the vertical direction, comparable in horizontal one

CMS Run 3 FLUKA simulation geometry: no shielding



CMS Run 3 FLUKA simulation geometry: preliminary studies





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  - S. Roesler. Radiological Control of Material from CERN's Radiation Areas. Tech. rep. CERN EDMS record 942171.
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- **Fluence conversion coefficients method and applications**
  - R. Froeschl. A method for radiological characterization based on fluence conversion coefficients. In: J. Phys.: Conf. Ser. 1046.1 (2018), p. 012006. doi:10.1088/1742-6596/1046/1/012006.
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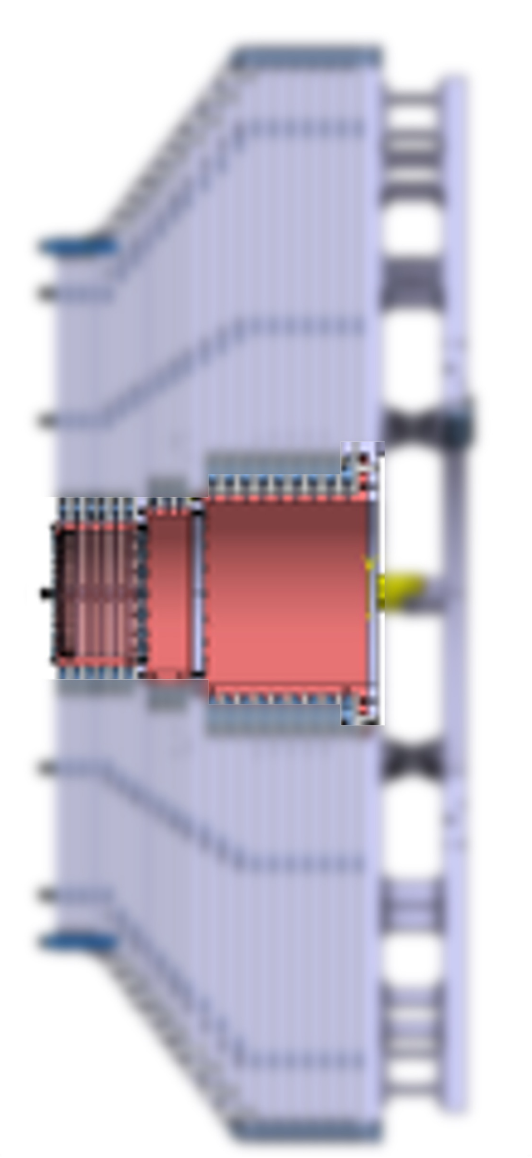
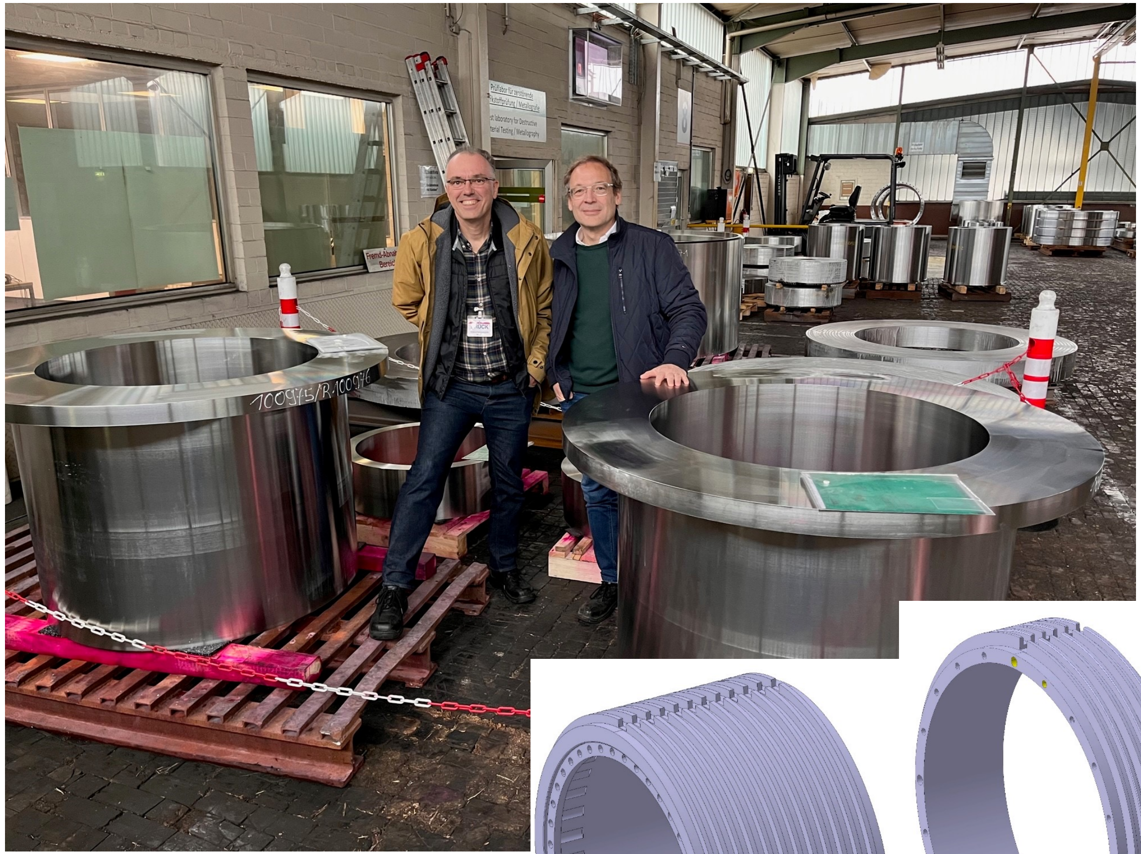
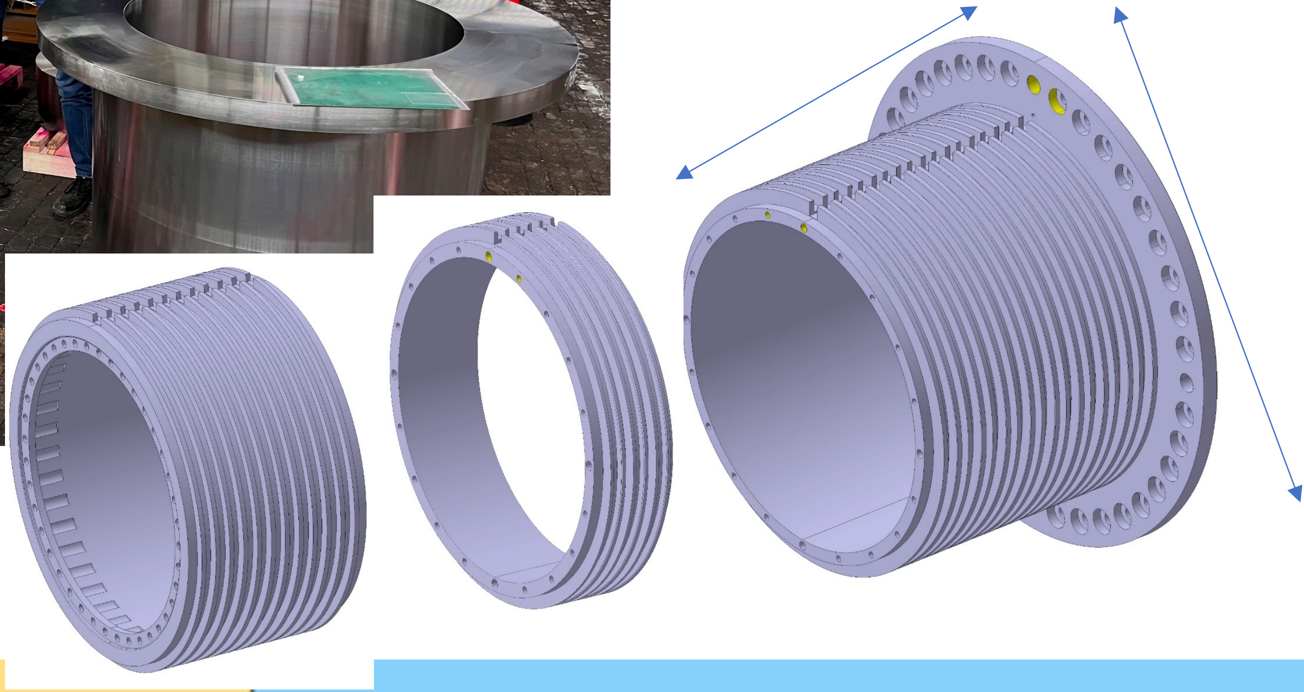
  - D. Bozzato. Monte Carlo simulations and benchmarks for the radiological characterization of the LHC experiments. PhD Thesis. Karlsruher Institut für Technologie (KIT), 2023. doi:10.5445/IR/1000159308.

Selected HGCAL (heavy) Mechanics Highlights



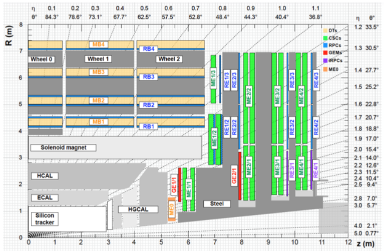
- Ring forged inner cylinders in HMC-3 Pakistan for final machining.





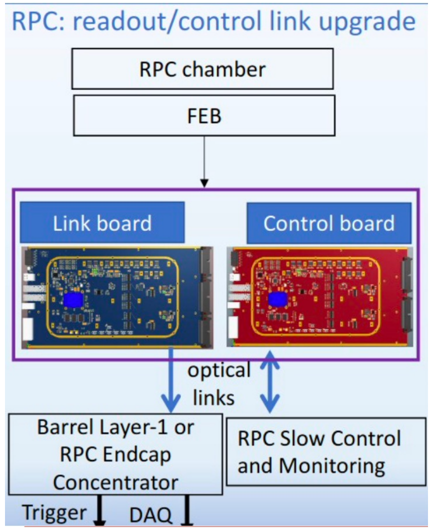
RPC services installed for upgrade systems

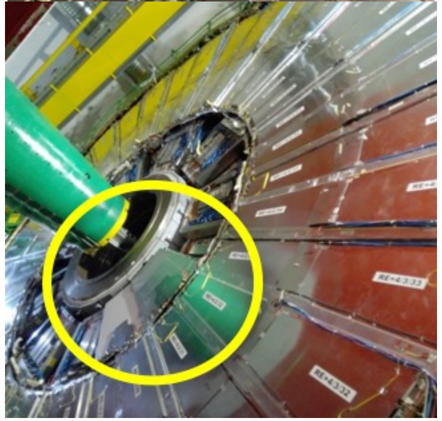
Backup



Upgrade the readout “link system” of all RPC chambers

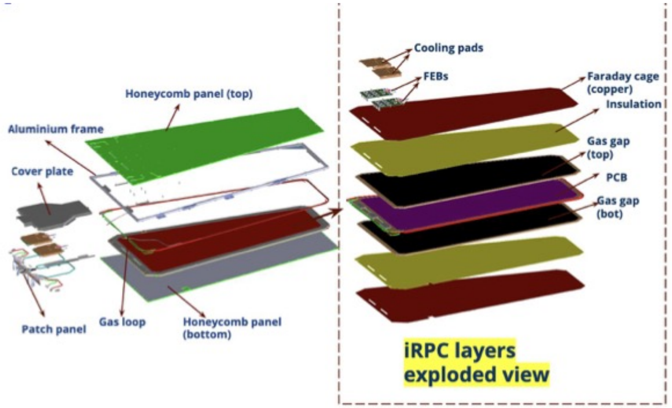
- Improves trigger hit resolution from 25 ns to 1.5 ns
- 1376 link boards, 216 control boards





iRE3/1 and iRE4/1

- New RPC chamber design
- Provides redundancy in already instrumented forward region
- Electronics adapted to exploit chambers intrinsic < ns time resolution



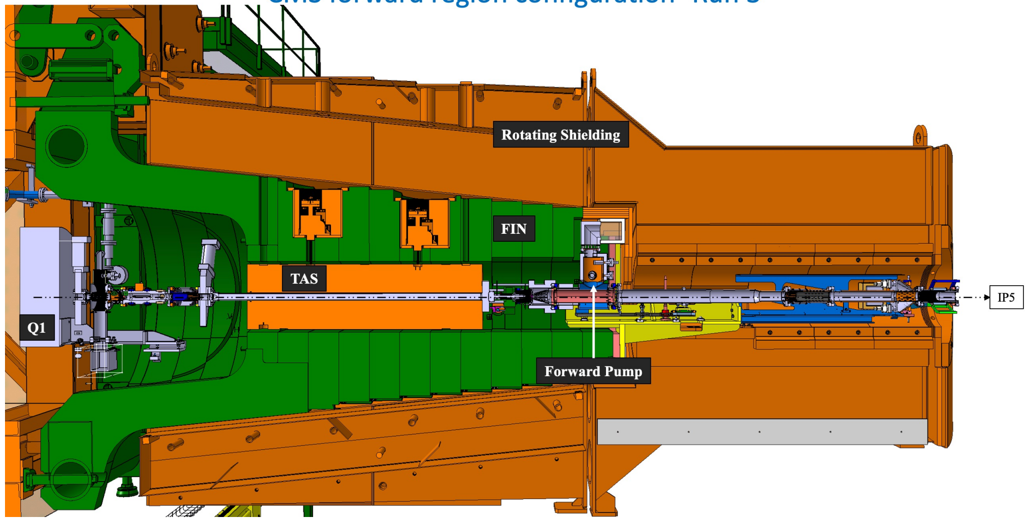
1 chamber ≈ 1.6 x 1.2 m² trapezoidal shape

	iRPC	RPC
High Pressure Laminate thickness	1.4 mm	2 mm
Num. of Gas Gap	2	2
Gas Gap thickness	1.4 mm	2 mm
Resistivity (Ωcm)	0.9 - 3 x 10^{10}	1 - 6 x 10^{10}
Charge threshold	< 50 fC	150 fC
space resolution (eta)	1.5 cm	20-28 cm
space resolution (phi) strip pitch driven	0.3-0.6 cm	0.8-1.9 cm
Intrinsic time resolution	0.5 ns	1.5 ns

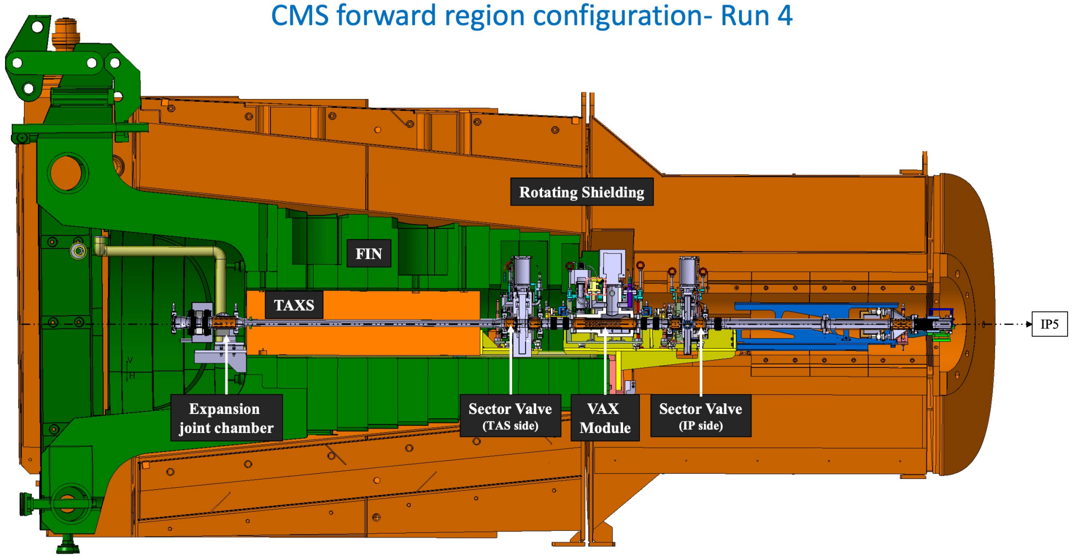
RPC: Resistive Plate Chamber

Upgrades to the TAS region

CMS forward region configuration- Run 3



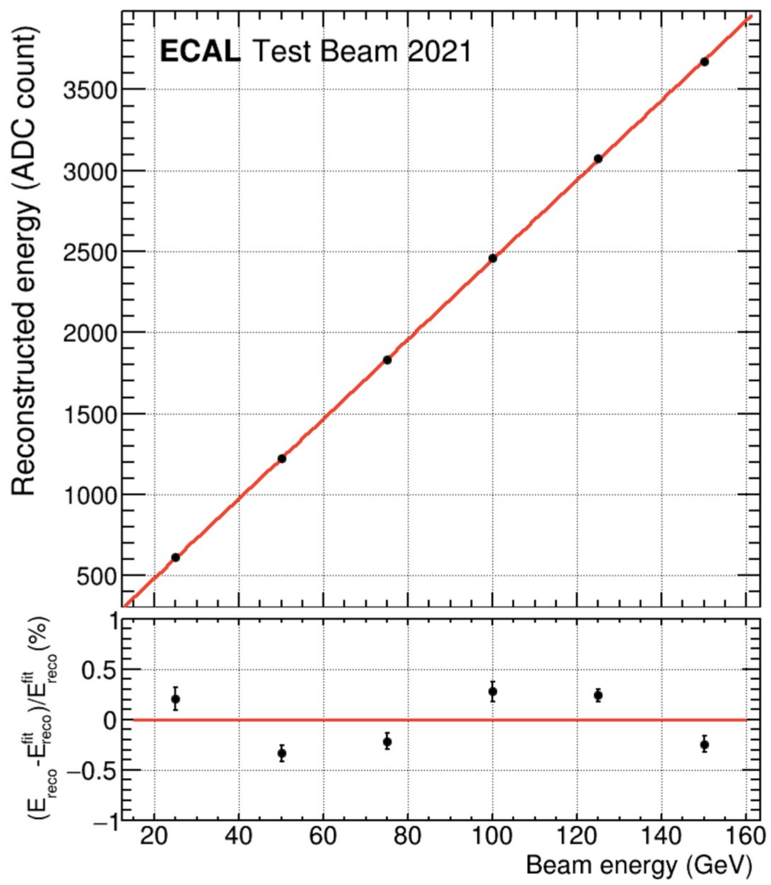
CMS forward region configuration- Run 4



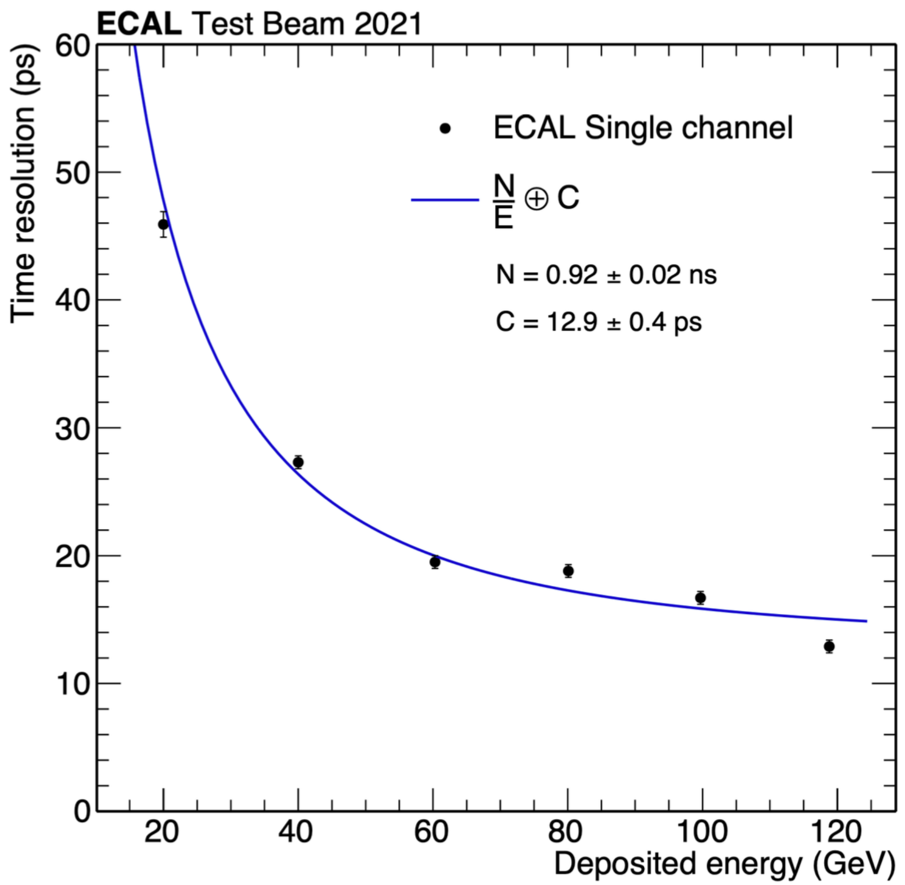
BCAL/ECAL

CMS Phase-2 Calorimeter performance

Energy linearity



Timing resolution

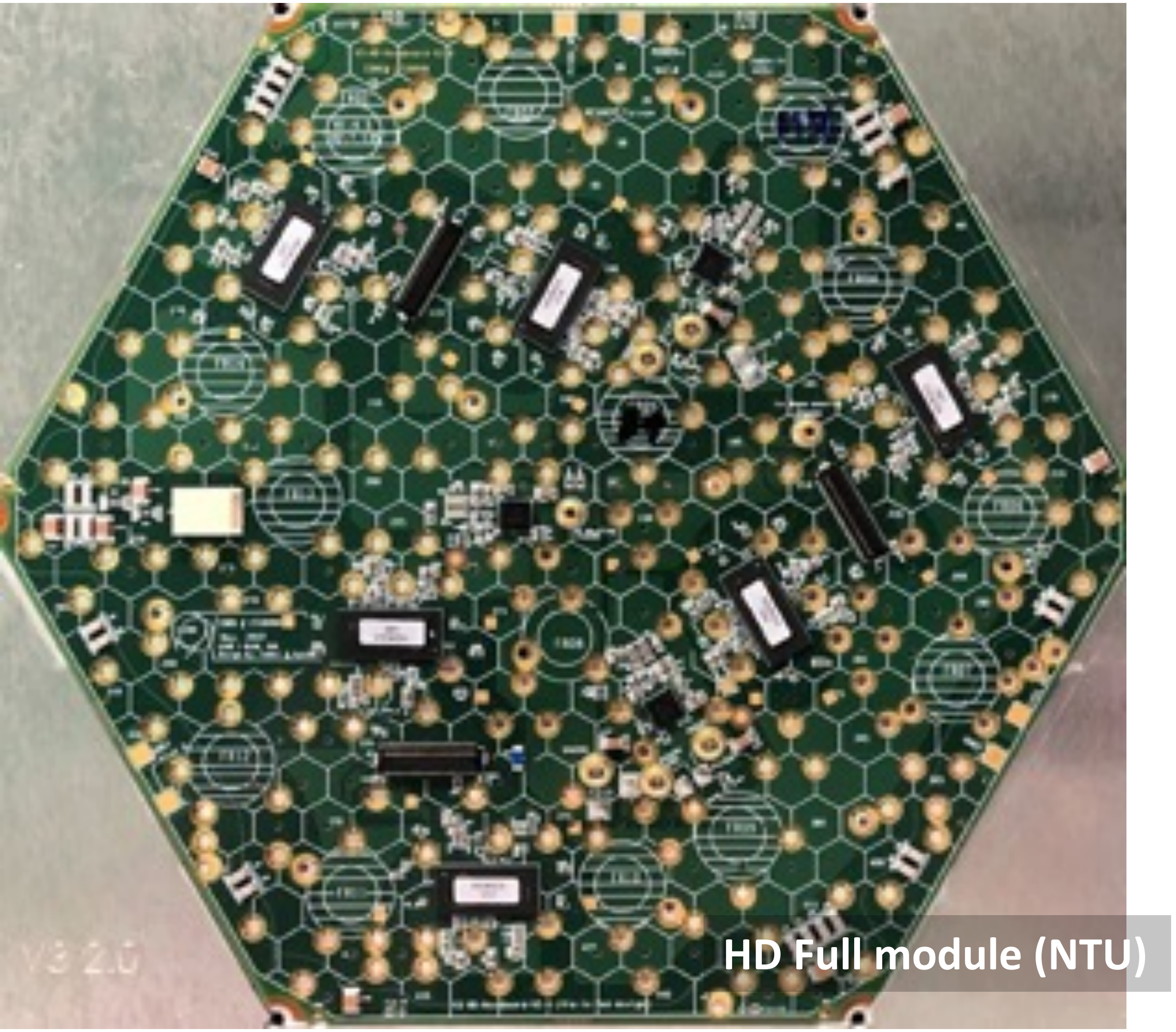


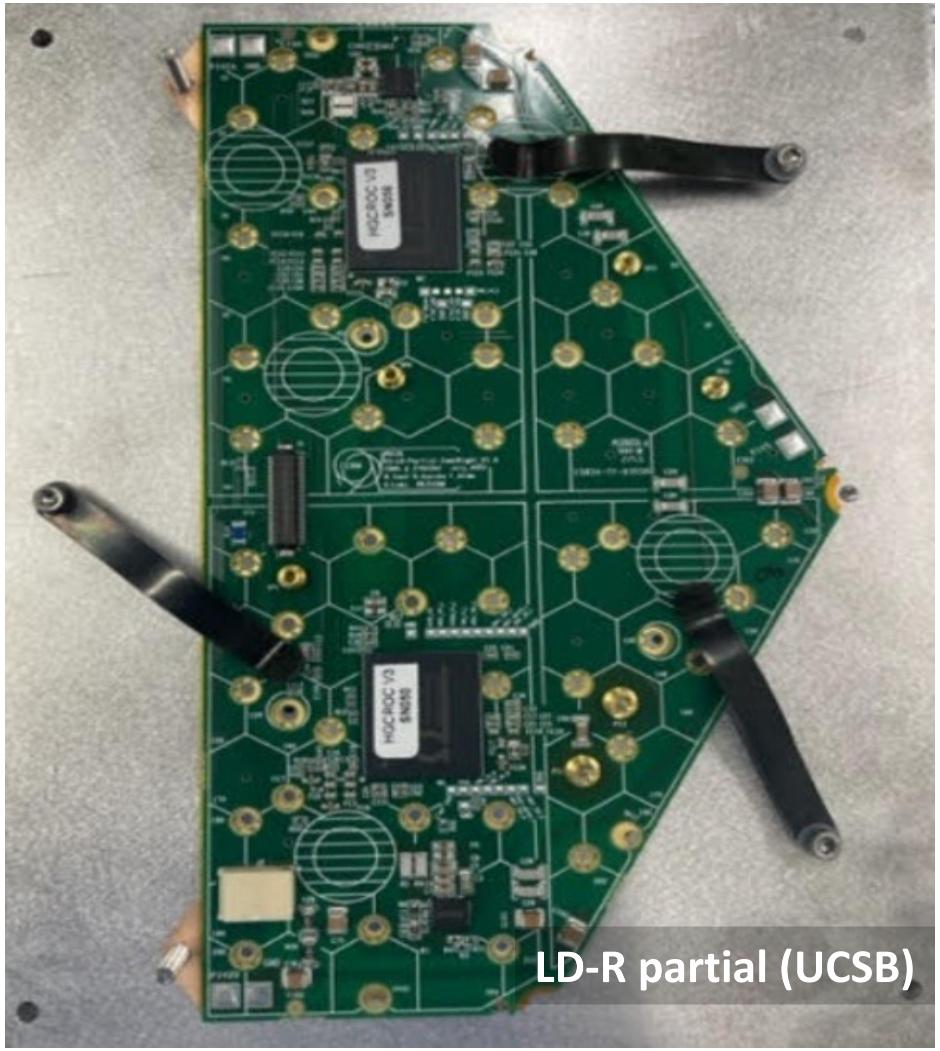
ECAL Supermodules – photo from 2006 – to be multiplied in LS3

Multiply by 2 and realize at P5

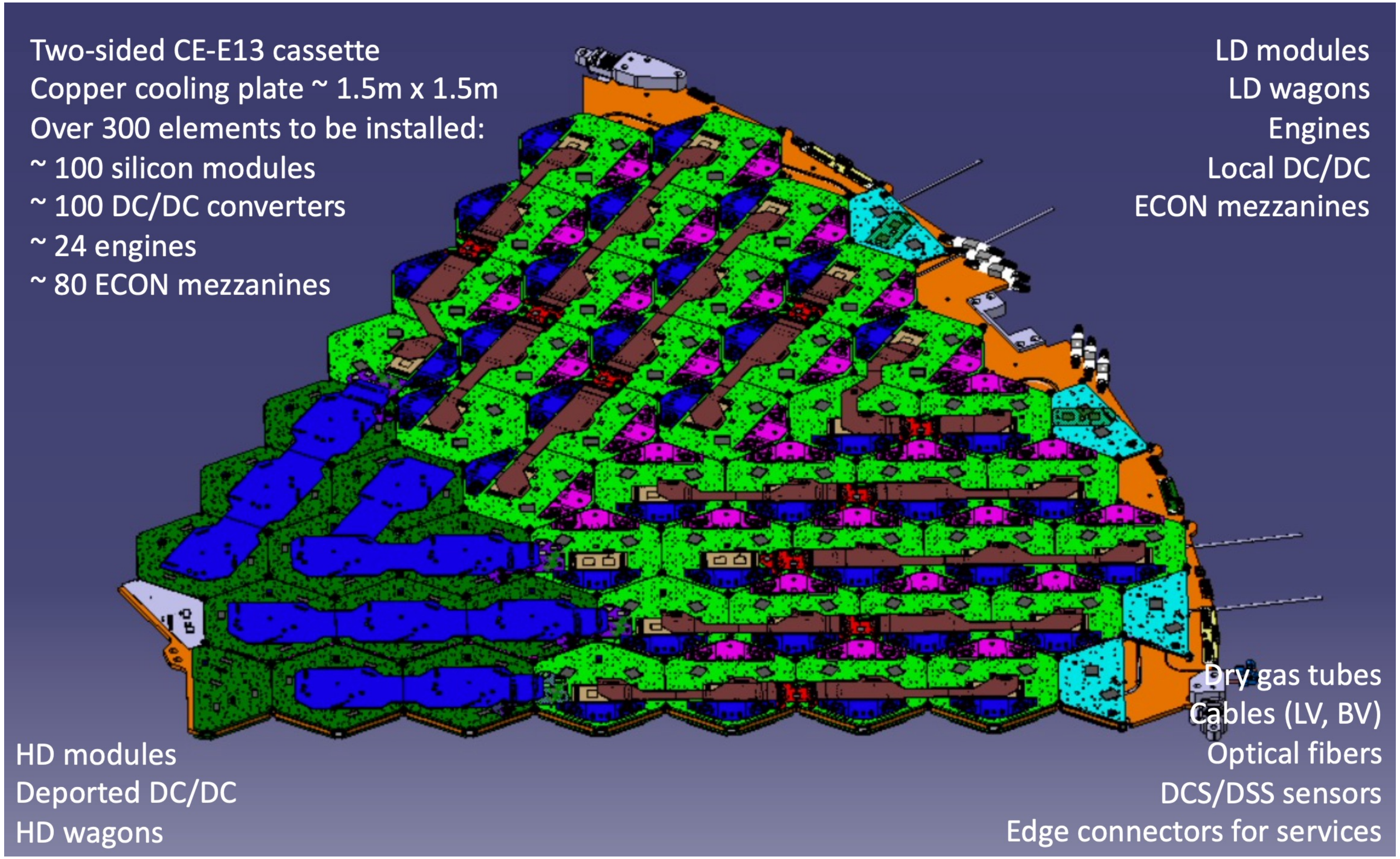
HGCAL

Examples of a high-density (HD) full module & a low-density right (LD-R) partial module





Example HGCAL CE-E cassette



HGCAL mechanics

From Physics requirements
--> Technical choices

Compactness and density, high X_0 / λ (27.7/8.5)

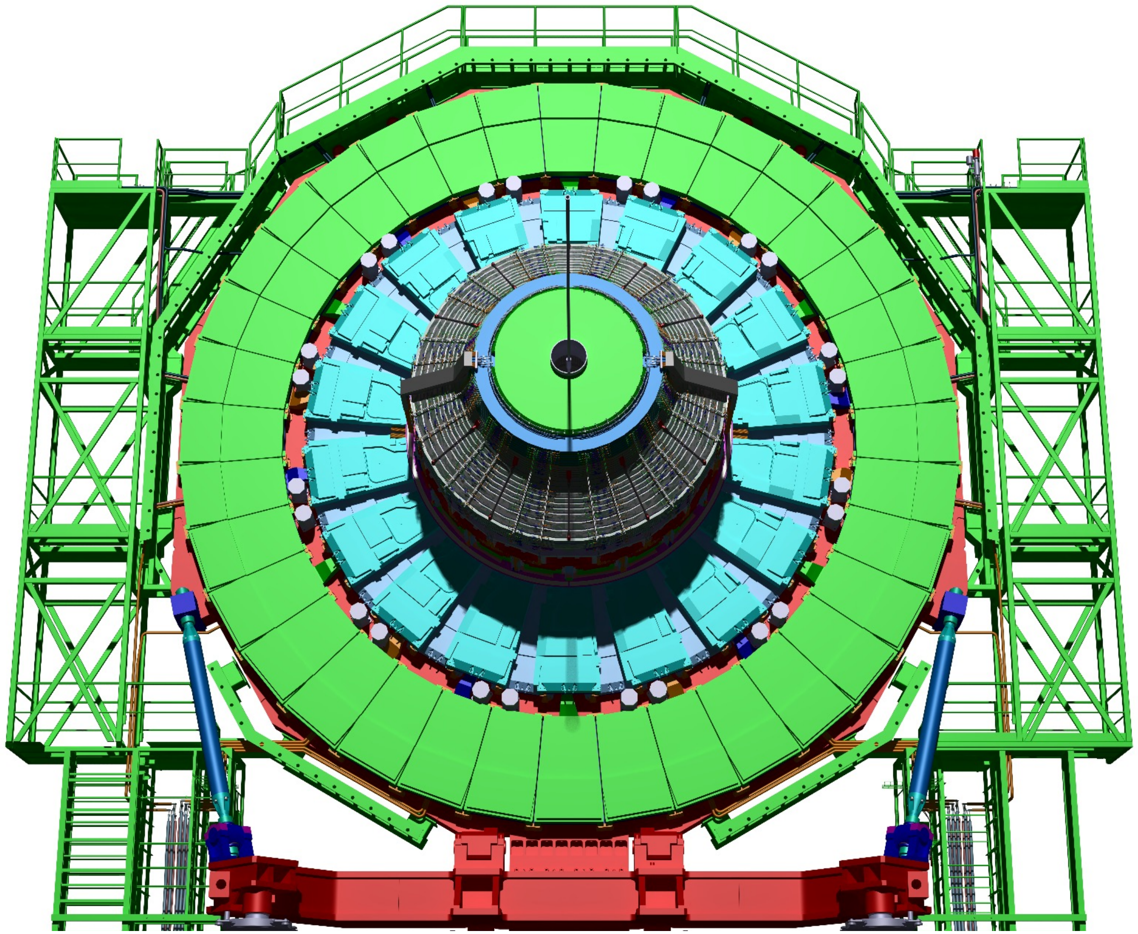
Minimal perturbation of silicon tiling

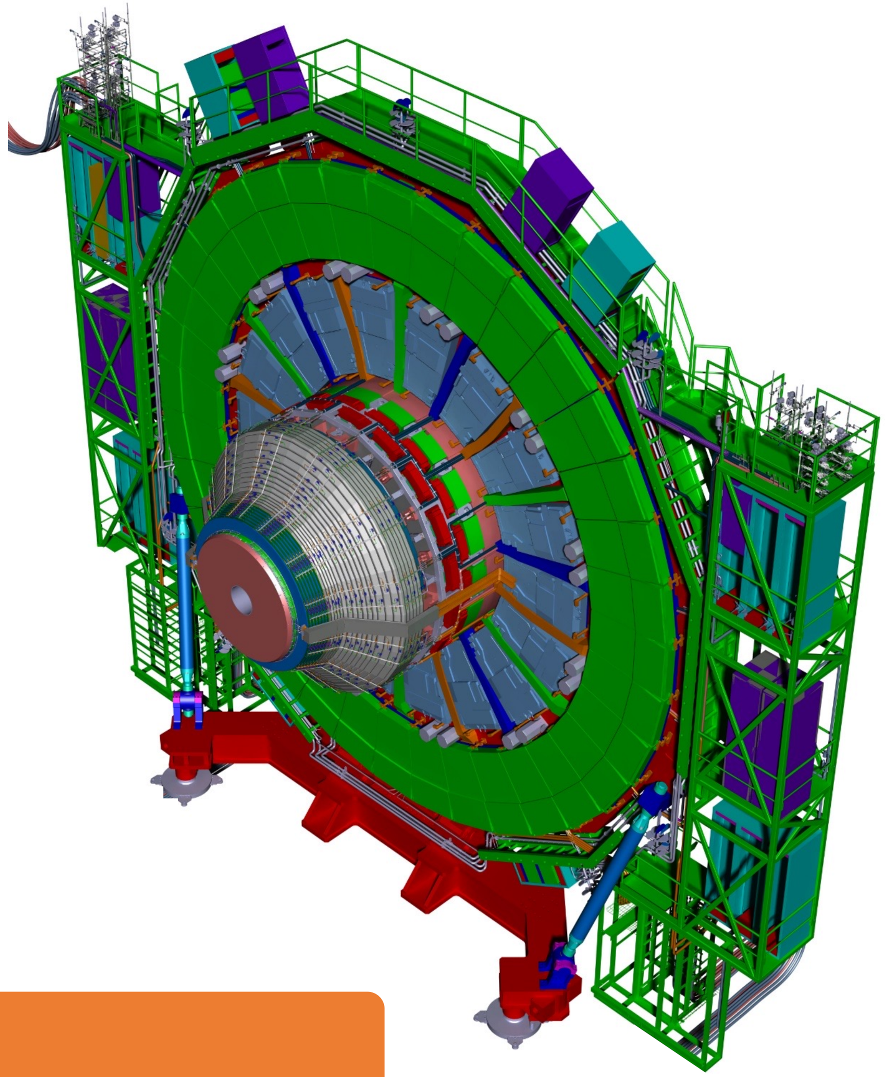
- **Absorber:** Brass or SS → SS (price + mechanics+HSE)
- **Cassettes:** Copper (physics and conductivity)
- Intermed. Wedges: Titanium grade 4 (strength, flexibility, conduction)
- Bolting: High strength stainless steel bolts BUMAX (physics, mechanics)
- High loaded wedges and pins: Inconel (mechanics)

working temperature -35°C

High conductivity and density for cassettes

Looking forward to realising HGCAL





Please enjoy this very helpful video;

https://www.youtube.com/watch?v=BrPQTGGlK08

K. Rapacz et al, 4 minutes long

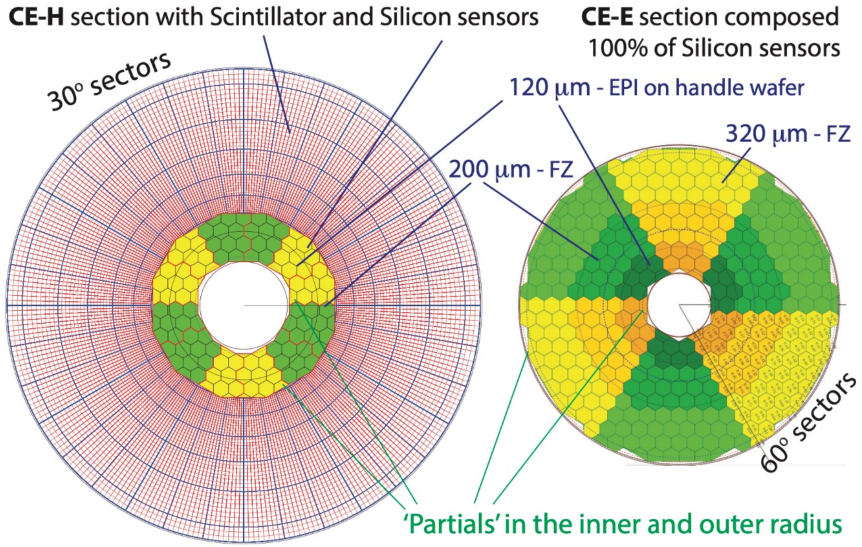
S/N optimizations for final HGCAL silicon layout

HGCAL considers three thicknesses (120, 200, 300 µm) and two densities (LD,HD)

Driven by expected exposure to non-ionizing radiation (up to > $1.5 \times 10^{16} n/cm^{2}$)

driven by limiting the cell capacitance (also correlated with higher particle density in the regions with high fluence)

Thickness [µm]	S = MIP_{eq} [ke^{-}/µm] (PDG-based)	Density	Typ. cell area [cm^2]	C [pF]	V_{dep} [V]
120	67	HD	0.56	48	42
200	70	HD	0.56	24	120
		LD	1.26	67	
300	73	LD	1.26	45	263



Experimental irradiation measurements used as data driven input model of S/N over full life of HGCAL in all cell locations in all layers

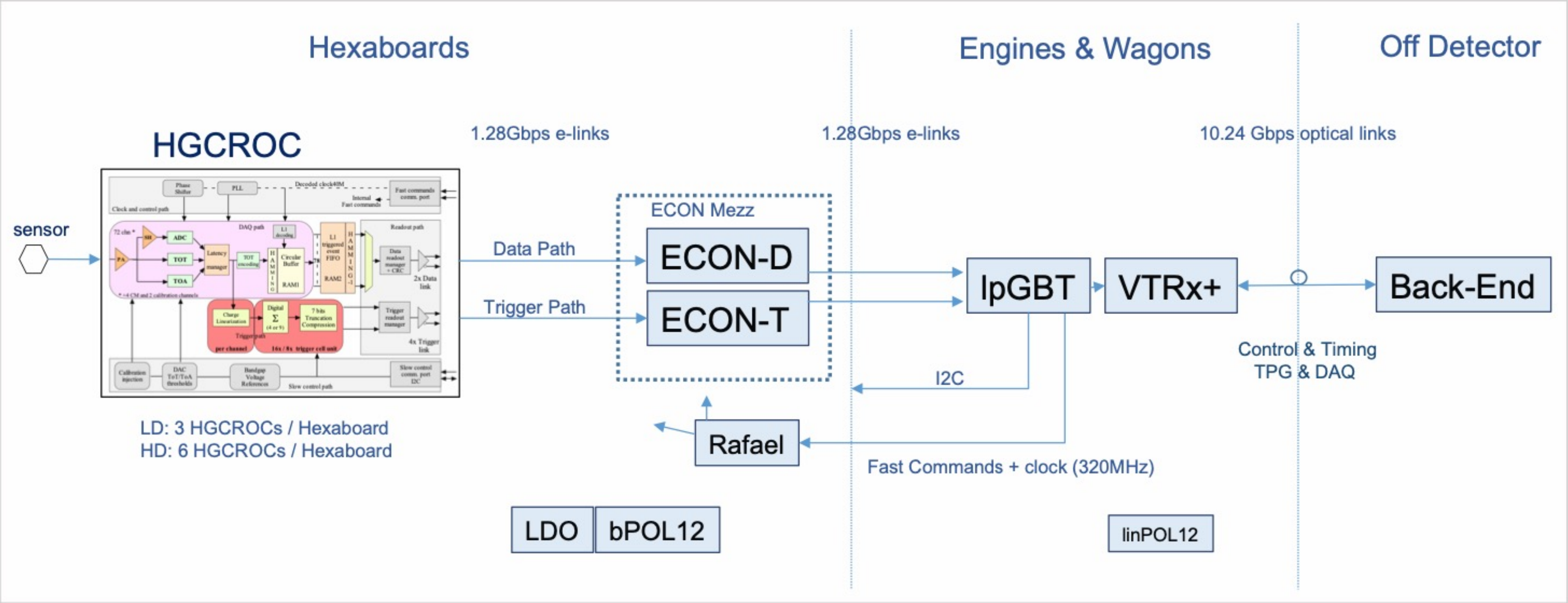
Model considers:

- sensors signals evolution (for all types), sensor leakage current, thermal contact and expected annealing behavior.
- full electronics-chain noise contributions

Pre-production 300 um LD sensors already started – largest volume

Production readiness review for high density and partial sensor imminent with corresponding refined layout of sensor boundaries optimized for S/N

HGCAL electronics and data flow



ASIC developments: HGCROC, ECON-T/D, LDO & Rafael

Generic components: lpGBT, VTRx+, DCDCs

These are hosted on pcbs: Hexaboards, Engines & Wagons (CE-E/H) & Tileboards (CE-H)

Note: The figure above is for the Si region.
The scintillator region is very similar. It uses a different version of HGCROC ie. HGC2ROCv3 and also uses the SCA for Slow Control and ALDO for SiPM biasing.

Courtesy P. Aspell

Frontend ASICs for HGCAL

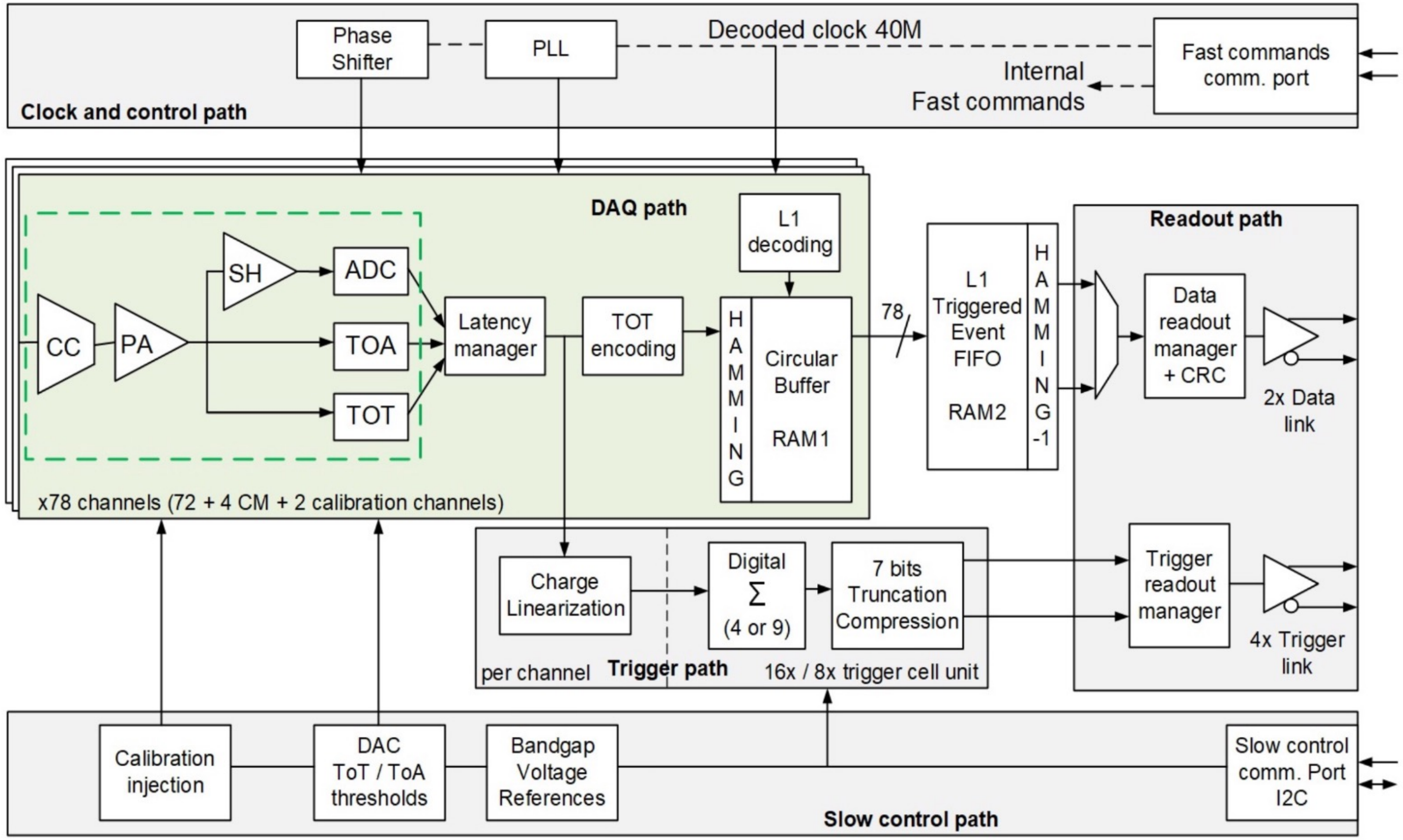
HGROC (TSMC130 nm) Submitted for Engineering run by OMEGA; intended to be the production chip

HGCROC:
- Covers full dynamic range of HGCAL, for both silicon and SiPM-on-tile with small adaptations

Analogue architecture:
- Programmable pre-amplifier gain
- ADC for small values: 10-bit 40 MHz SAR
- TOT TDC after preamplifier saturates: 12-bit, 50ps LSB
- Timing: TOA TDC 10-bit and 25ps LSB

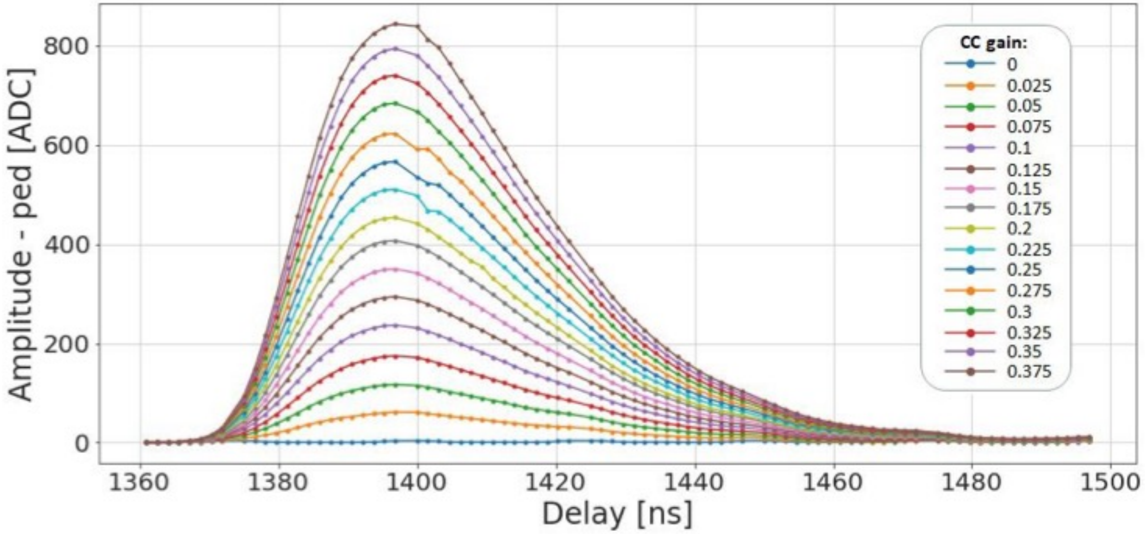
Outputs 1.28 Gb/s:
- Trigger primitive data: Sum of 4 (9) channels, linearization, compression to 7-bit floating point
- DAQ event data: 12.5 μs latency buffer (500-deep) for ADC/TOT/TOA.
- 32-event de-randomizer buffer (750 kHz av. trigger rate).

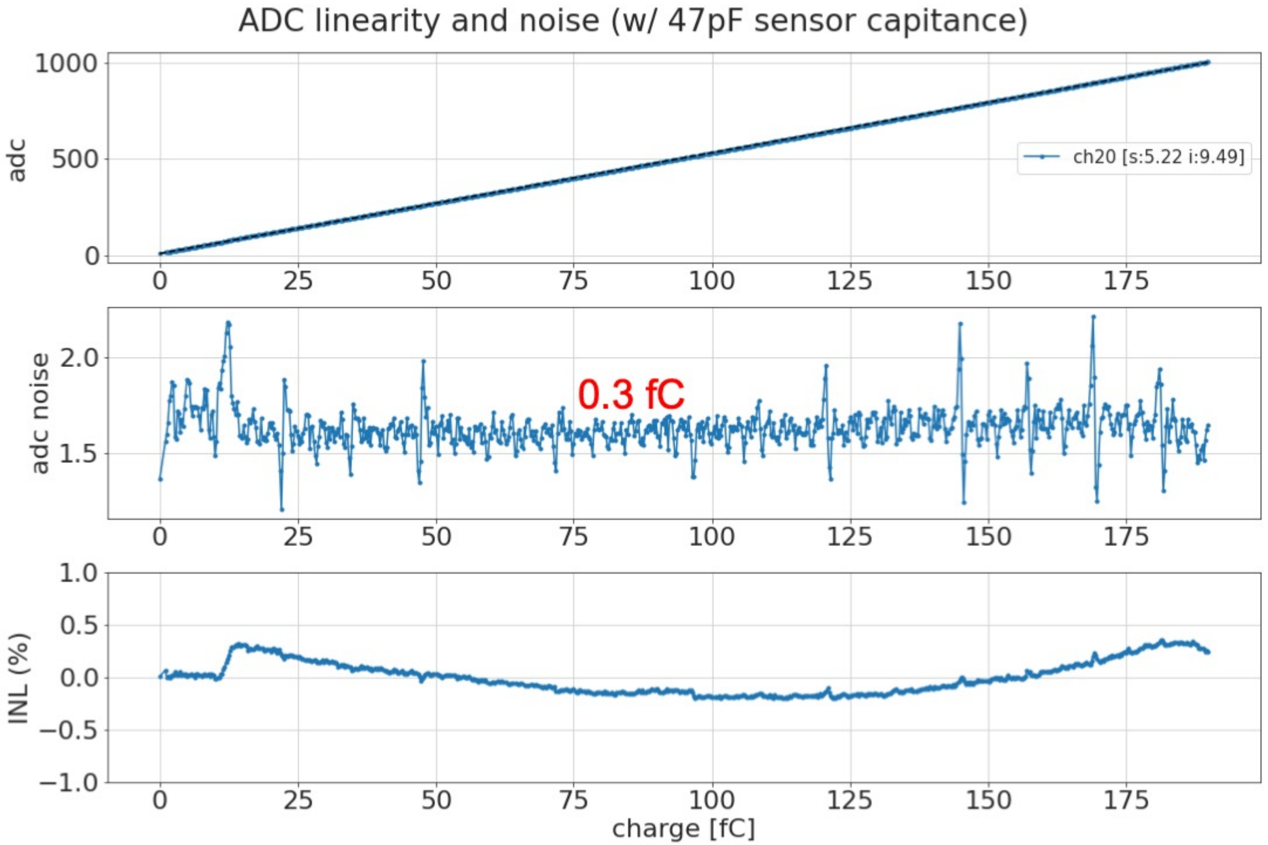
Control:
- Synchronous fast control: 320 MHz (8 bit @ 40 MHz)
- Asynchronous slow control: I2C



Frontend ASICs for HGCAL

HGROC (TSMC130 nm) Submitted for Engineering run by OMEGA; intended to be the production chip





ASIC performance on previously submitted prototypes generally very good and irradiation TID and SEE test complete

ASIC packaging being finalized for HD, LD and SiPM on tile versions

Others Front End ASICs of the CMS HGCAL

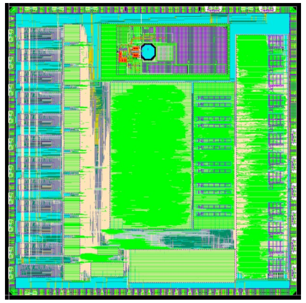
Final FE ASIC prototype submitted for ECON trigger & prototype data transfer ASICs in test

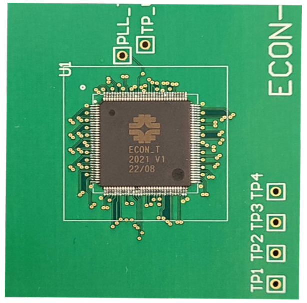
ECON-T: frontend concentrator chip for trigger path, concentrates trigger data via one of 4 trigger algorithms

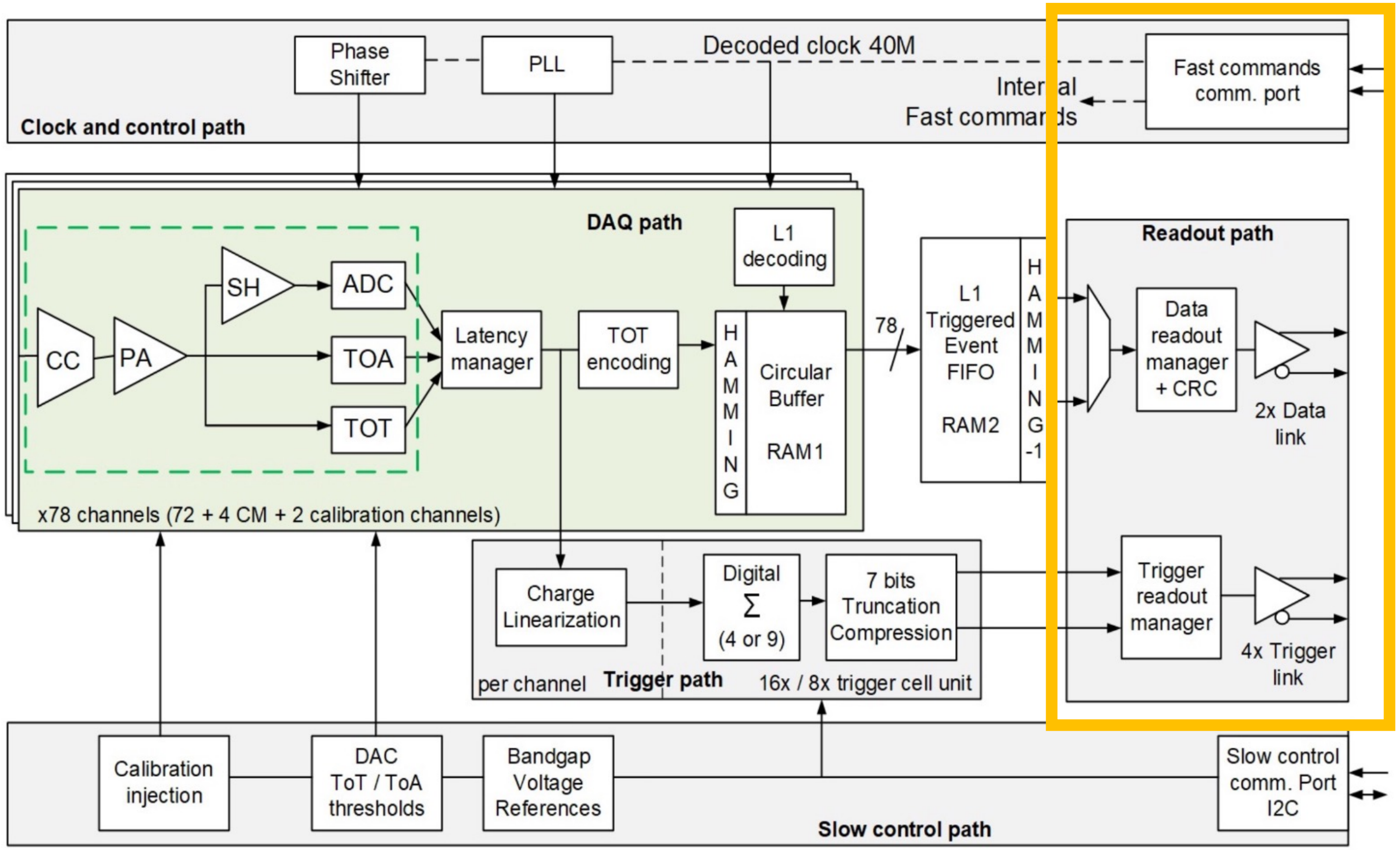
ECON-D: frontend concentrator chip for DAQ path, performs channel alignment and zero suppression after L1 Accept

RAFAEL: clock and fast control fanout, production ASIC submitted

LPGBT: for sending/receiving data/clk/control signals via optical link (and VTRX+)



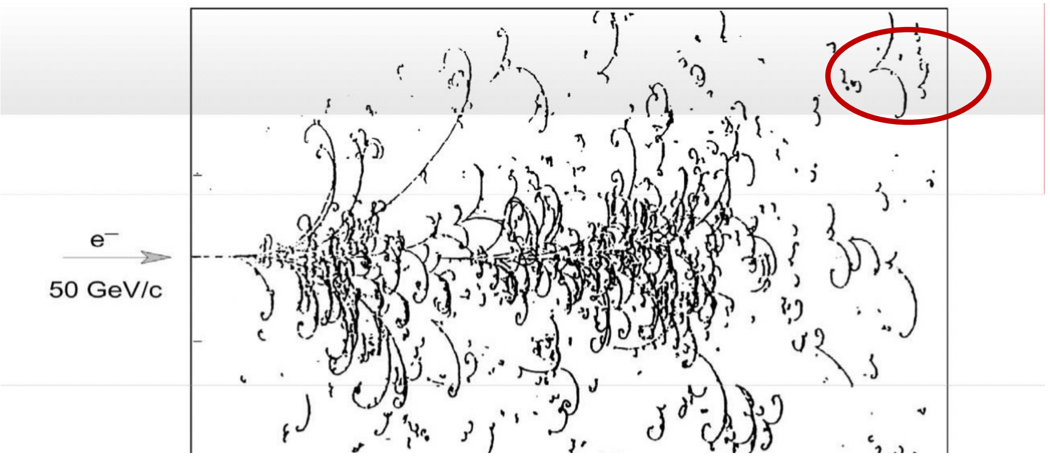




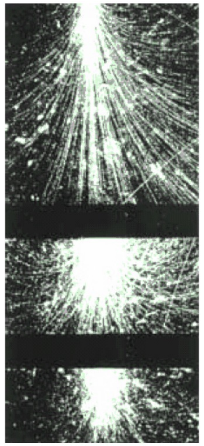
Going Forward by looking backward - Imaging Calorimetry in the endcap

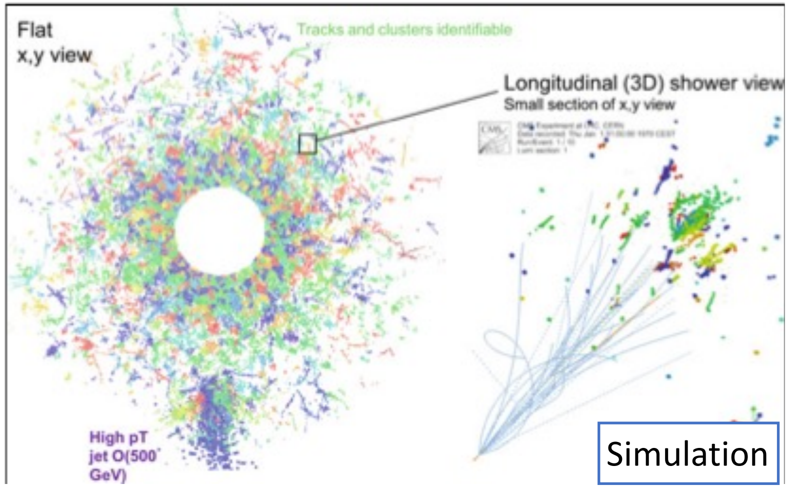
Idea kindly borrowed from D. Barney

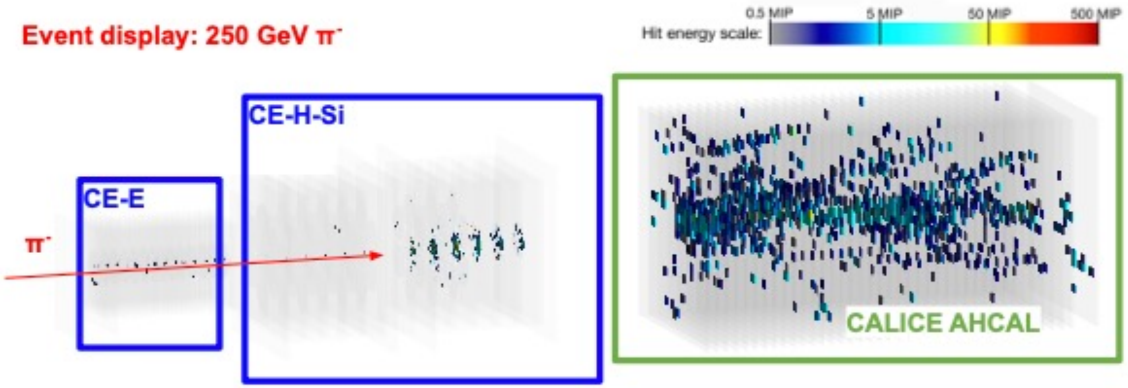
Big European Bubble Chamber
3T; L=3.5m, X_0=34cm



The previous generation of calorimeters could "see" showers! Can we do this again – at 40 MHz and PU=200?



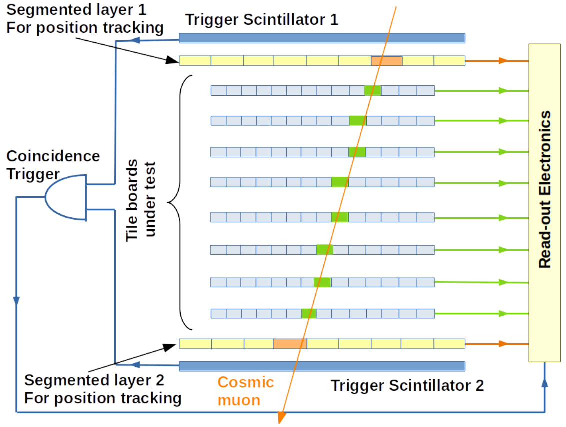




3D topology and $\sigma_t \simeq$ 20 ps for 25 GeV/c electrons (test beam 2018)
Caollaboration CMS silicon layers and CALICE team for SiPM-on-tile

SiPM on tile modules – automation of preparation of parts

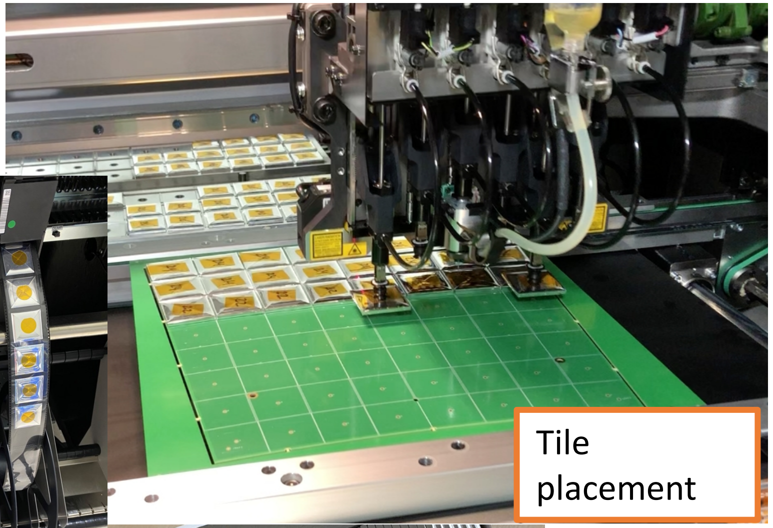
Large detector, 280 000 SiPMs, 280 000 tiles, 3744 pcbs, 3744 assembled tile modules



Cutting table

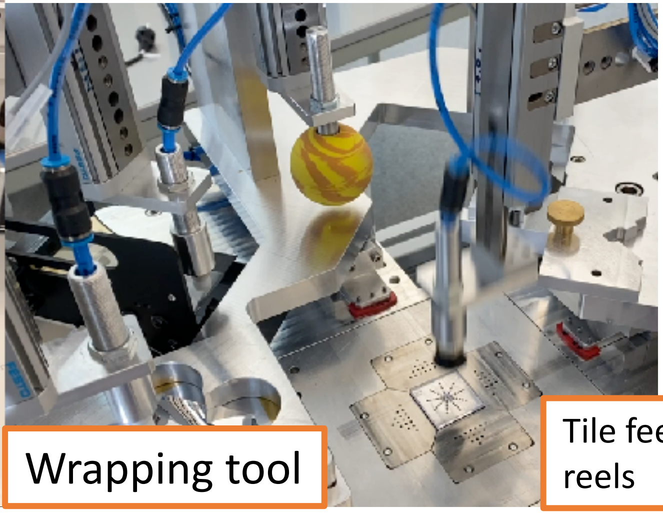
Tile assembly centers use programmable and vision-controlled tile placement

Tile-modules work as stand-alone detectors: first complete test with ionising particles before integration into more complex cassette environment



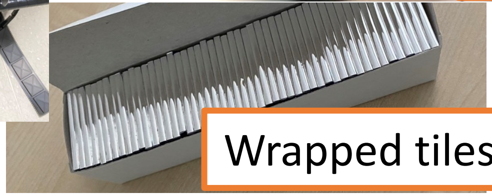
Tile placement

Cutting tool



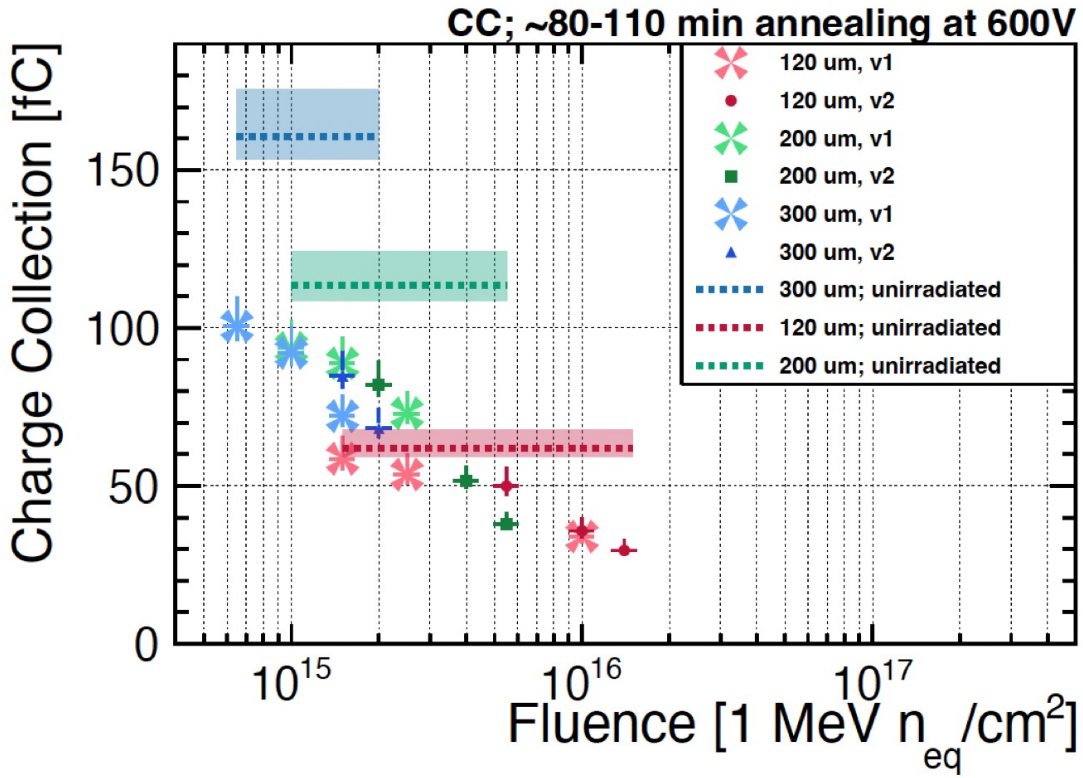
Wrapping tool

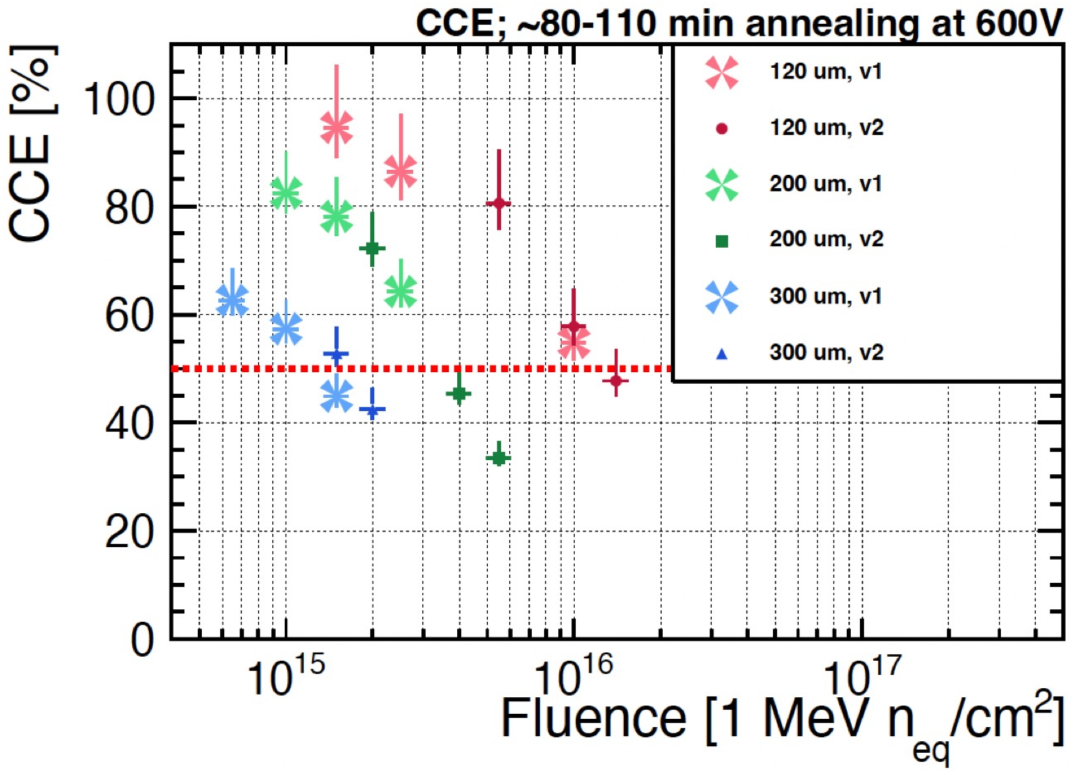
Tile feeder reels



Wrapped tiles

HGCAL sensors – radiation qualification

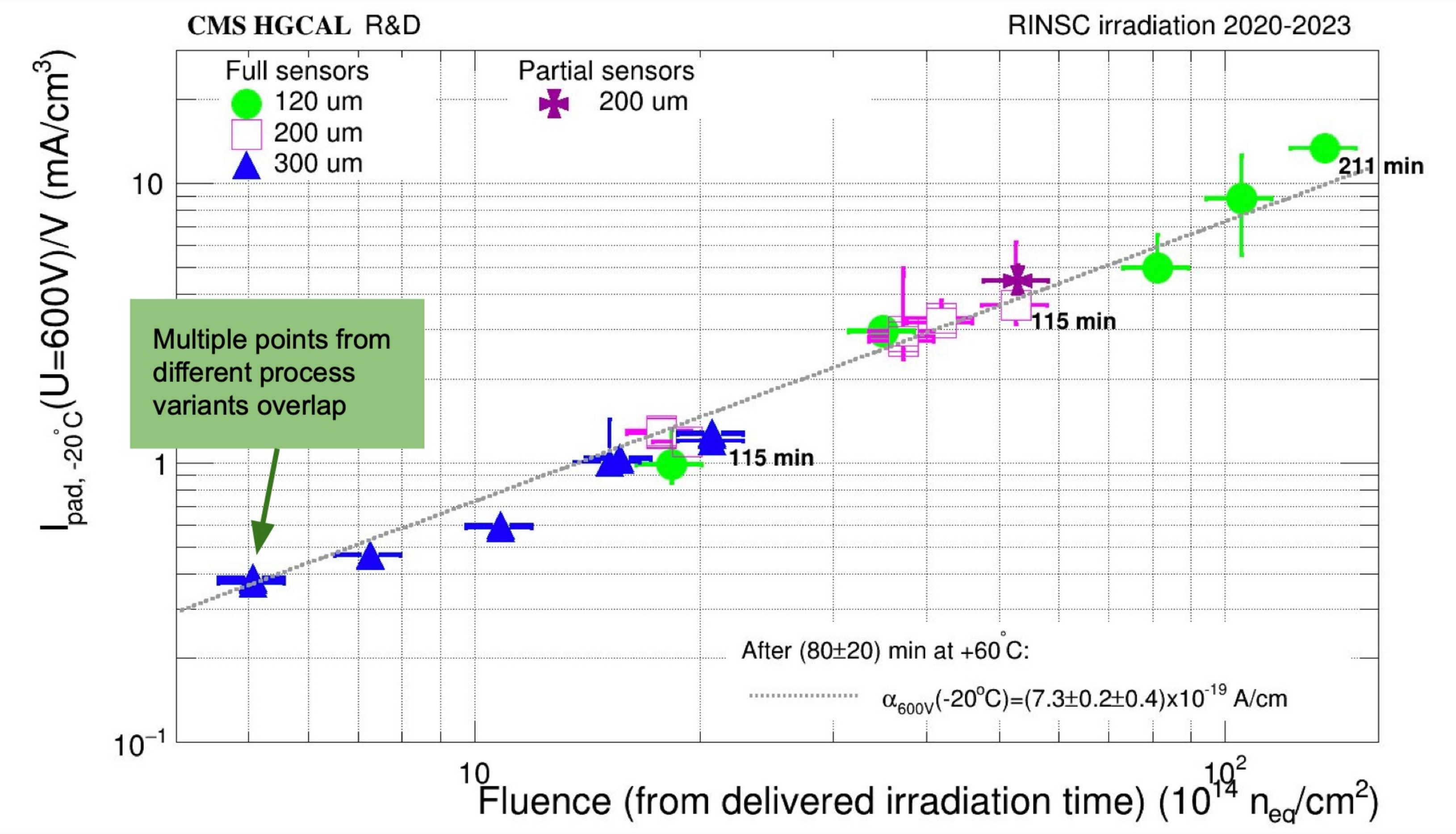




Leena Diehl et al, RD50 Workshop, June 20, 2023

HGCAL 8” silicon sensors – radiation qualification

neutron-irradiated at the novel irradiation facility RINSC up to $1.4 \cdot 10^{16}$ n /cm^2



Use 3 neighboring full cells in the current (fluence ϕ) maximum within a full sensor to estimated current related damage rate α with

$$\frac{I}{V} = \alpha \cdot \phi$$

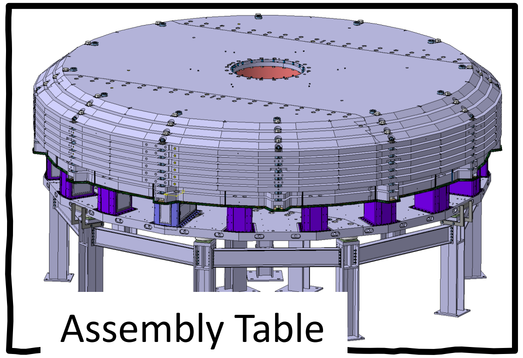
RINSC reactor beam port

Linear leakage current vs fluence as expected

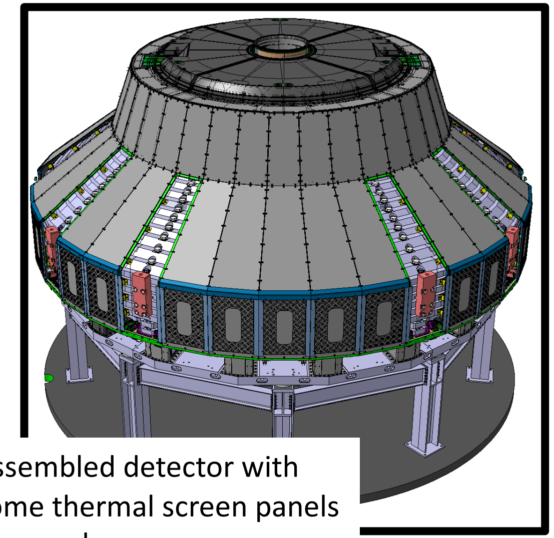
arXiv:2209.10159

Tooling - Detector structural support during assembly and installation on YE1

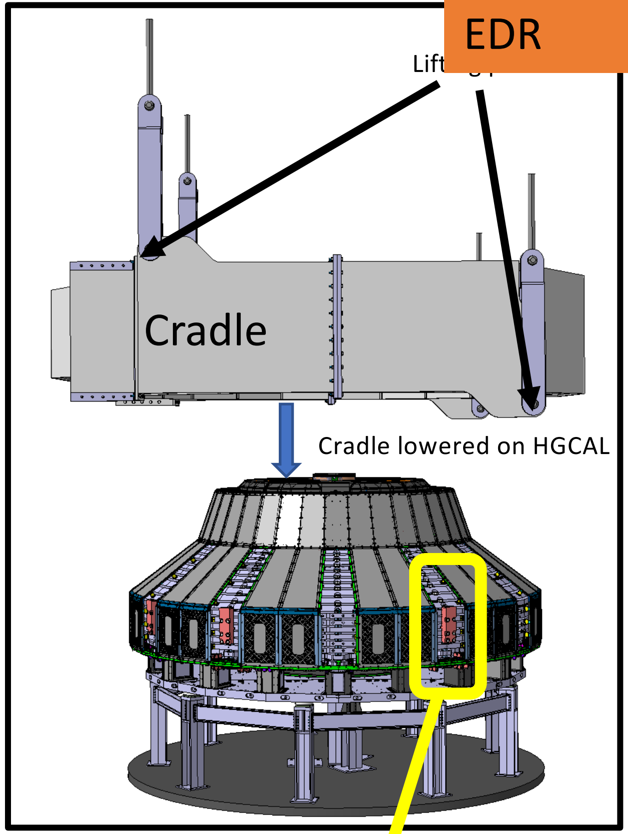
Check if compatible with slides at Tooling C EDR

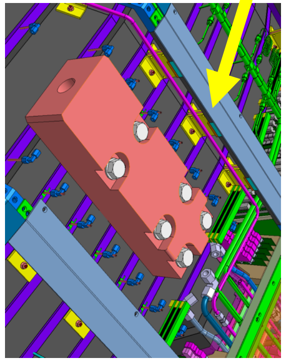

Assembly Table

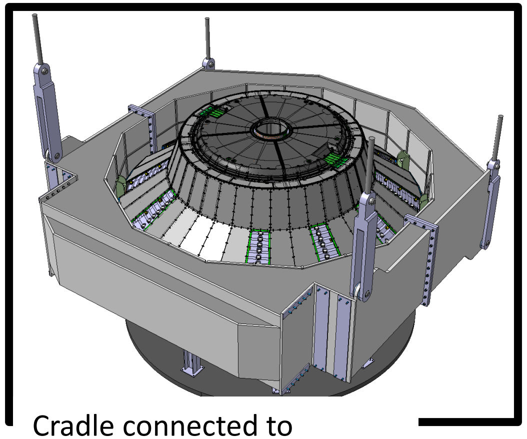
Detector assembly

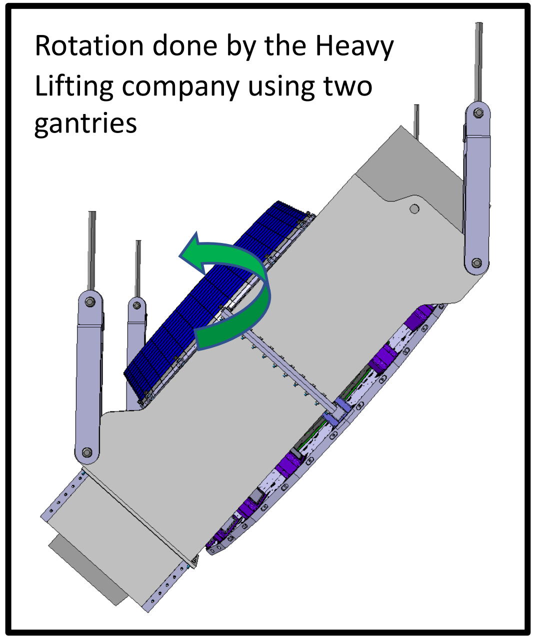

Assembled detector with some thermal screen panels removed .

Detector ready for transport




Cradle interface block

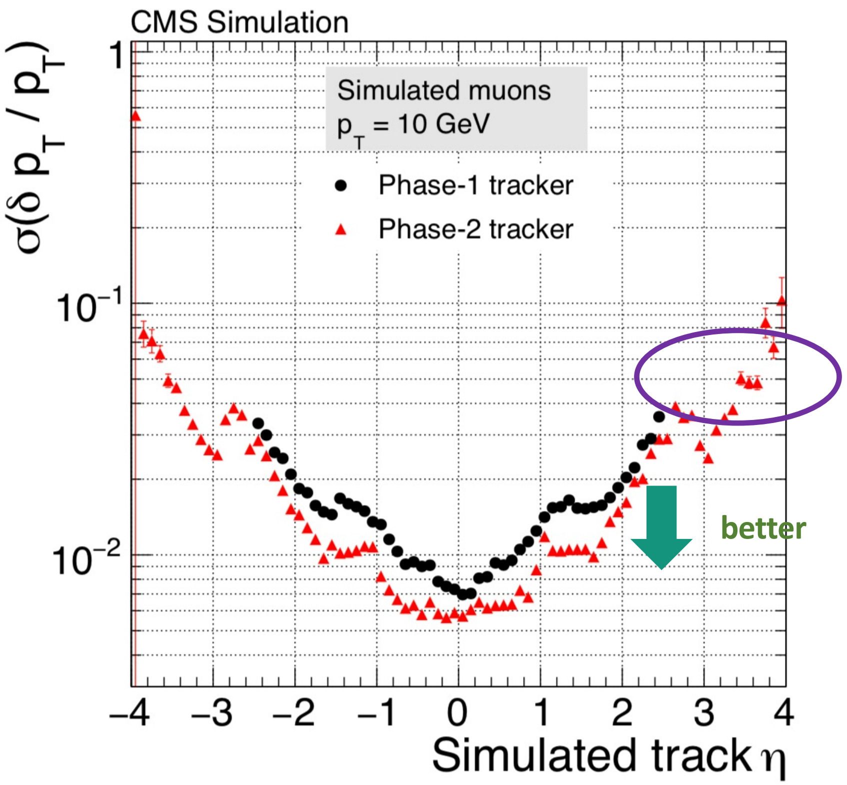

Cradle connected to assembled HGCAL


Rotation done by the Heavy Lifting company using two gantries

Performance

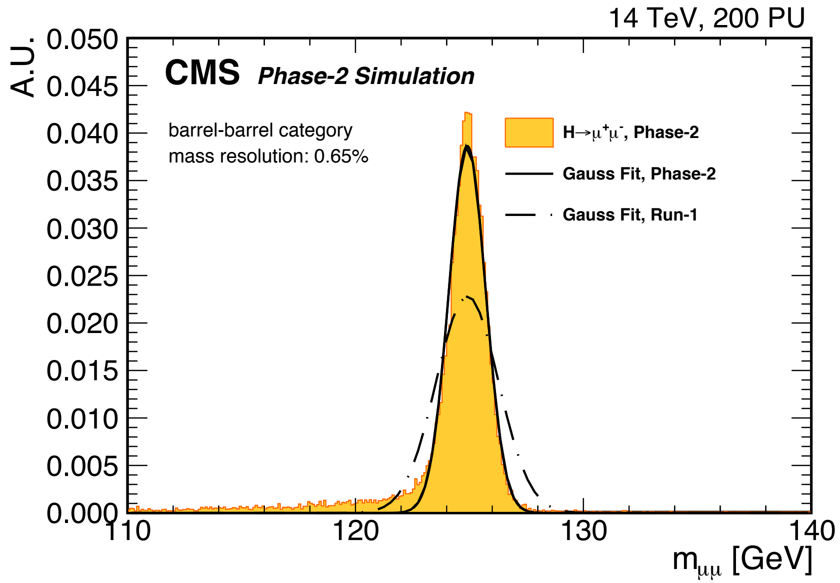
Tracker-2 Performance

p_T resolution



***H → μμ*: coupling to muons**

- 65% improvement on $m_{\mu\mu}$ in barrel-barrel category (0.65% mass resolution)
- 5% coupling precision possible with 3000fb^{-1}



- More precise tracking parameters
  - **Largely due to reduced material budget, thus less multiple scattering**
- Extended coverage, allowing e.g. better forward jet reconstruction
  - **Helps PU-mitigation, VBF, di-Higgs**

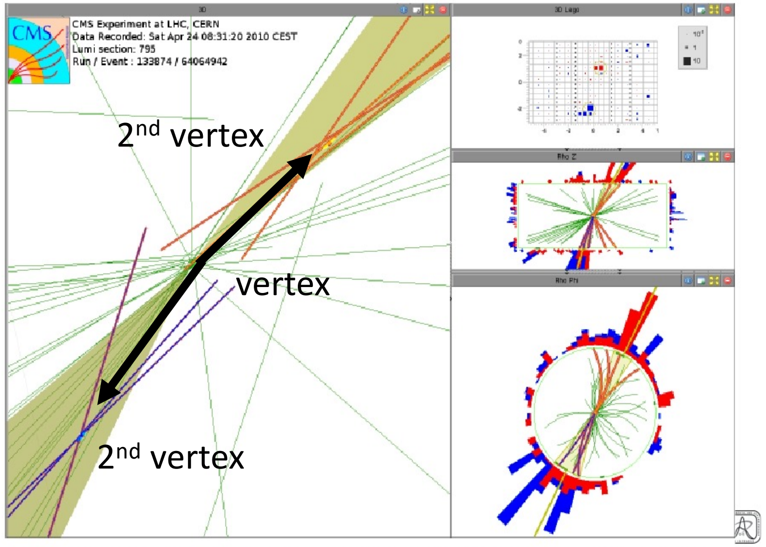
See FTR-21-006 for latest analysis

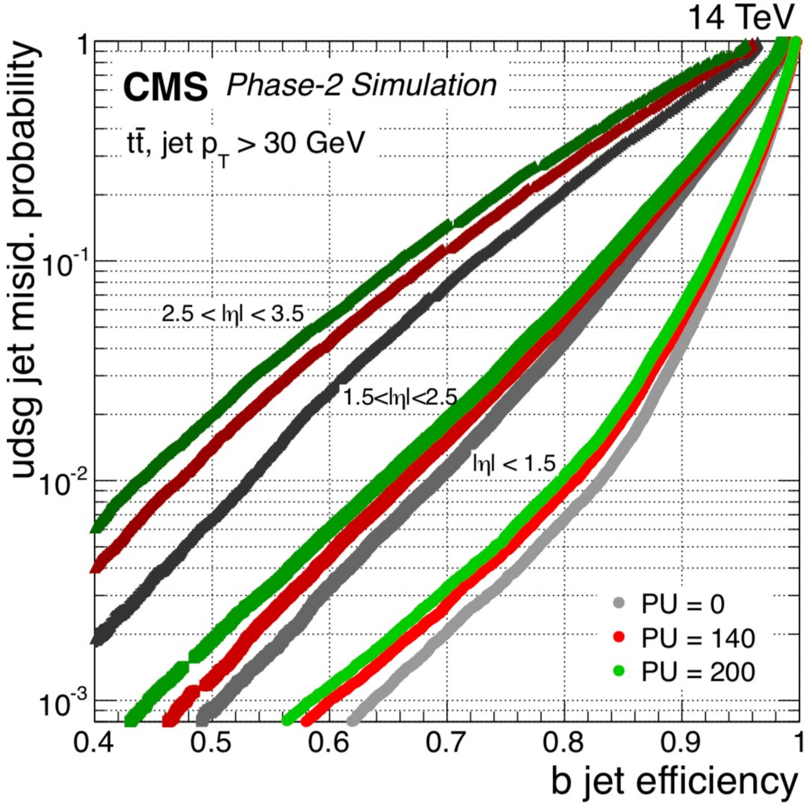
Yes, it is a *b*-quark

Better btagging

Due to excellent pixel detector

- High resolution, very high granularity
- Timing detector improves further





***b*-lifetime defines pathlength**

pathlength identifies ***b*-quark**

Di-Higgs Production in the $HH \rightarrow bbbb$ ***decay channel***

- +8% acceptance
- +50-70% efficiency of of 4 *b*-Quarks-tagging at 200 pile-up

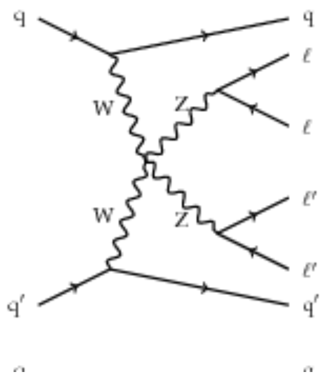
Pixel at small radius(r~3cm) and small Pixels (25x100μm^2)

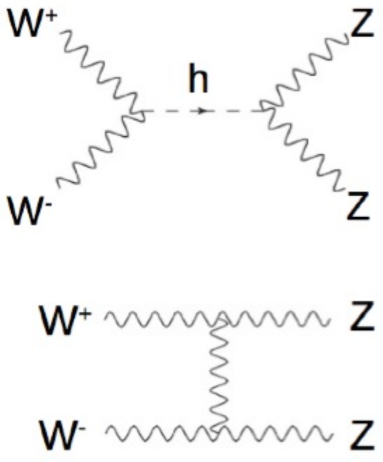
– excellent *b*-tagging

CERN-LHCC-2017-009 CMS-TDR-17-001

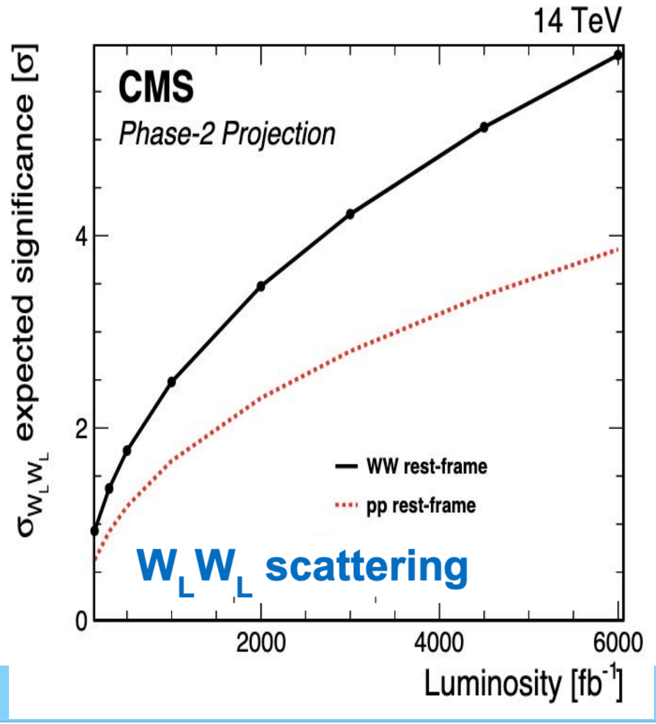
Vector Boson Fusion VBF - Scattering VBS

- The longitudinal W scattering is one of the essential probes of Higgs mechanism
  - The Higgs unitarizes W_L scattering that otherwise would be divergent.
- Deviation = new physics
- VBF - Distinctive signature:
  (forward jets from initial state quarks)
  → **forward region/extension crucial**
  - **CMS is doing this with big verve**
    - **Pixel, Muons, Calorimeter, Timing**



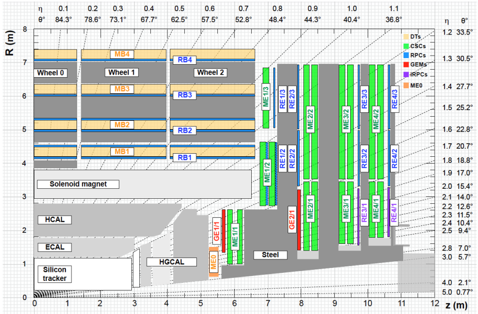


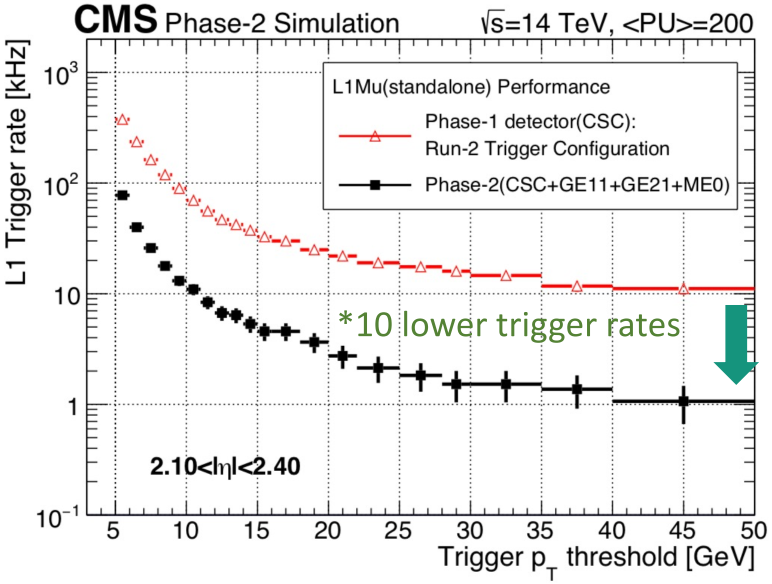
$V_L V_L \rightarrow V_L V_L$ discovery significance up to 2.75σ (combining WWjj+WZjj)



CMS PAS FTR-22-001

new Muon system
improved rate and timing capabilities

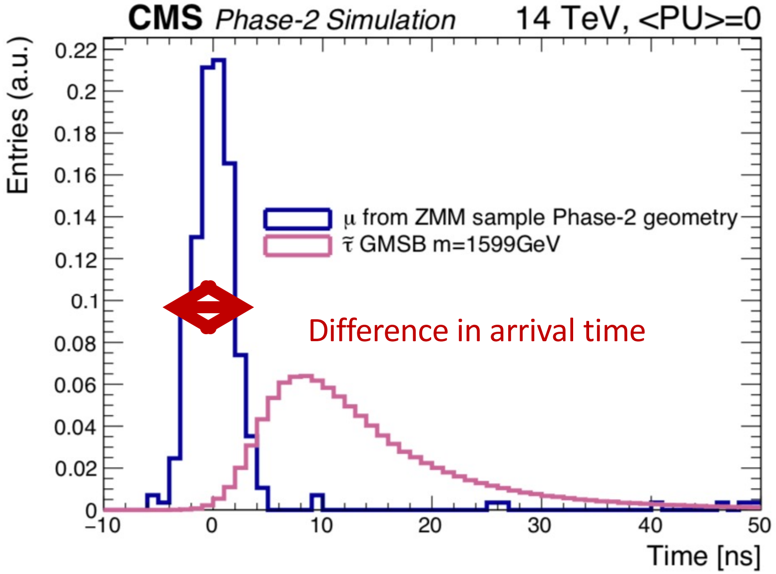




- Rates, efficiencies, precision
  ➔ much better, more flexible trigger
- Allows trigger on displaced tracks
  - No vertex constraint
  - New physics!?!?

RPC-2 time resolution 1ns (today 25ns)

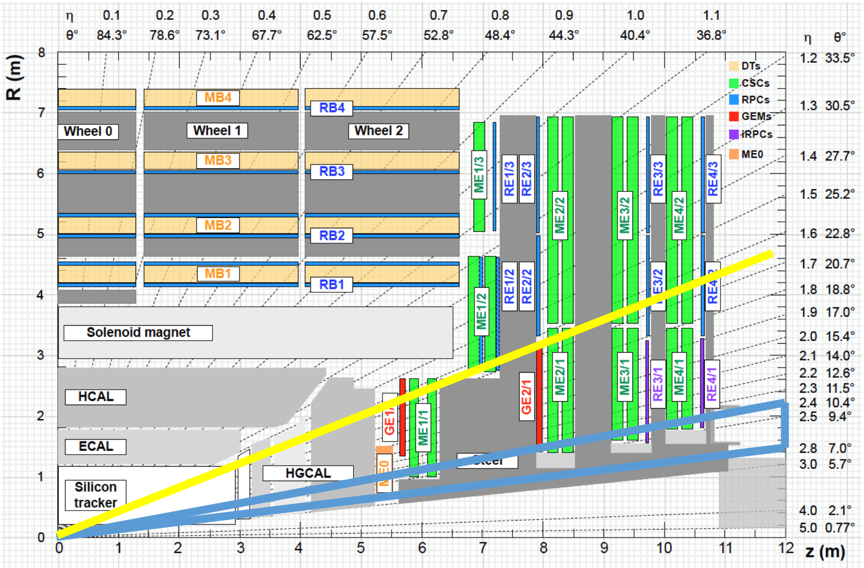
Identify 'slow" Heavy Stable Charged Particle

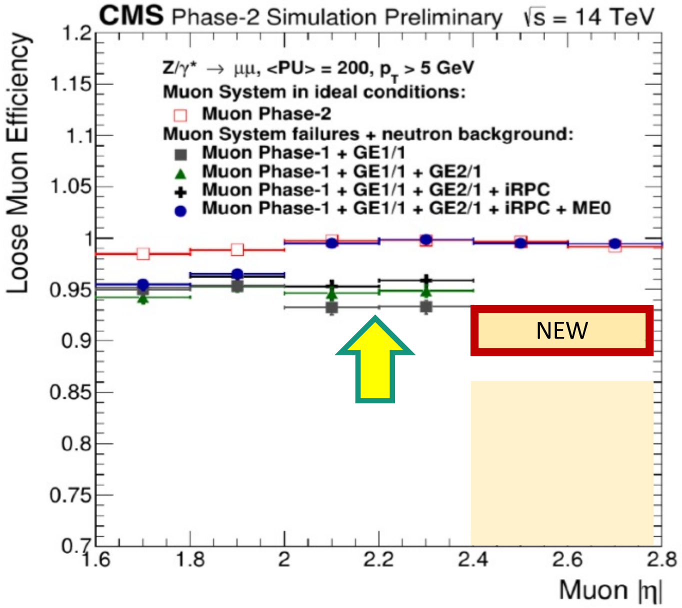


LLP Long Lived particle (NEW)

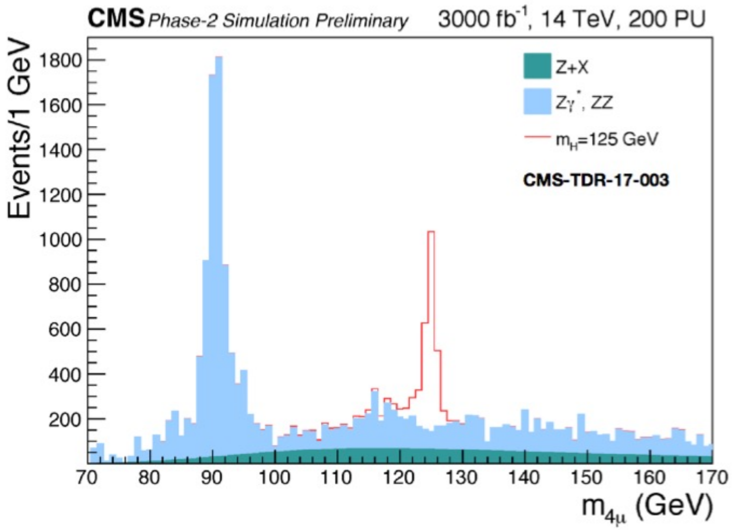
RPC Resistive Plate Chamber – a Muon detector

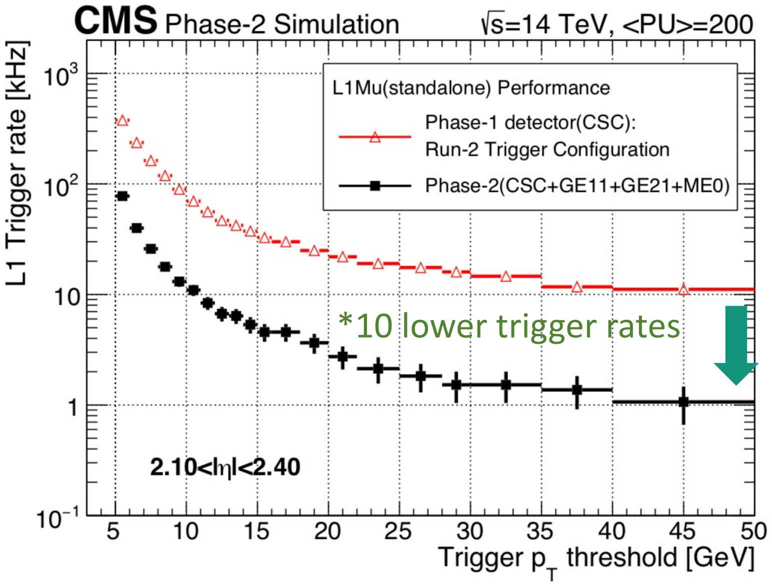
Improved muons performance & acceptance in forward region





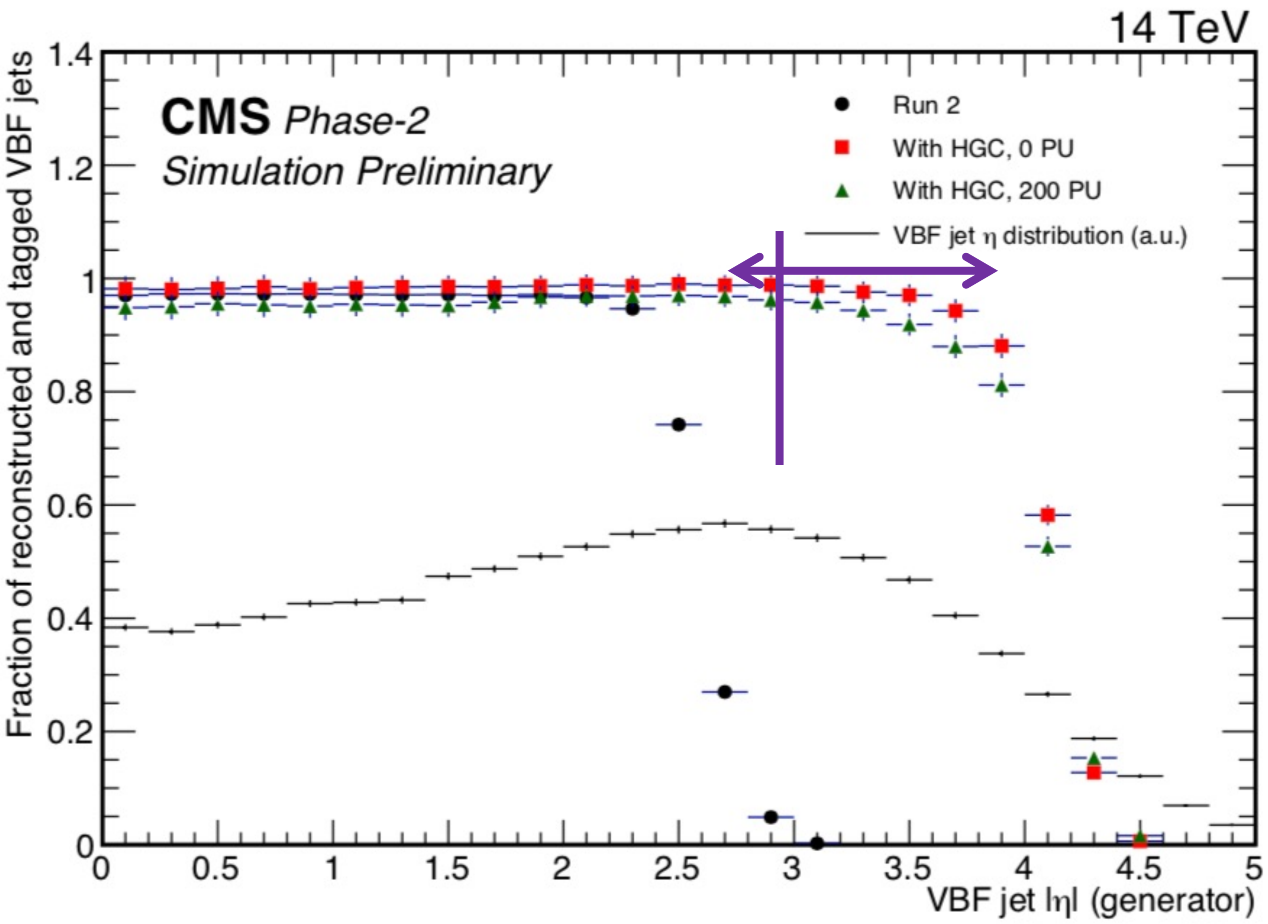
Higgs into 4 leptons:
acceptance increase ~17%

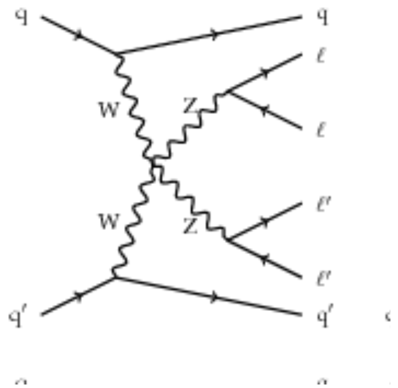




CERN-LHCC-2017-012 CMS-TDR-016

Impact of HGCAL performance & acceptance on Vector Boson Fusion (VBF) jet reconstruction





VBF benefits from forward extension

η Pseudorapidity ~~ angle, forward = large η

CERN-LHCC-2017-023 CMS-TDR-019

CMS Phase-2 Upgrade organization

Upgrade Support Project Office

UTC: Paola Tropea

URM: Andrzej Charkiewicz

Deputy RM with focus on upgrade: Adriana Telesca

UEOC: Magnus Hansen

UPO: Matthias Kasemann, Francesca Cavallari

Upgrade Project Coordinator:
Frank Hartmann
and deputie(s):
Paolo Rumerio
Anne Dabrowski

Cent. Coord. Contacts

- Off./Comp. Coord.*
- PPD Coord.
- Trigger Coord.
- Run Coord.

Cross-System Working Groups

- Electronics and Online Systems*
  UEOC + convener(s)
- Detector Interfaces and Integration*
  UTC + convener(s)

* Joint with Tech. Coord

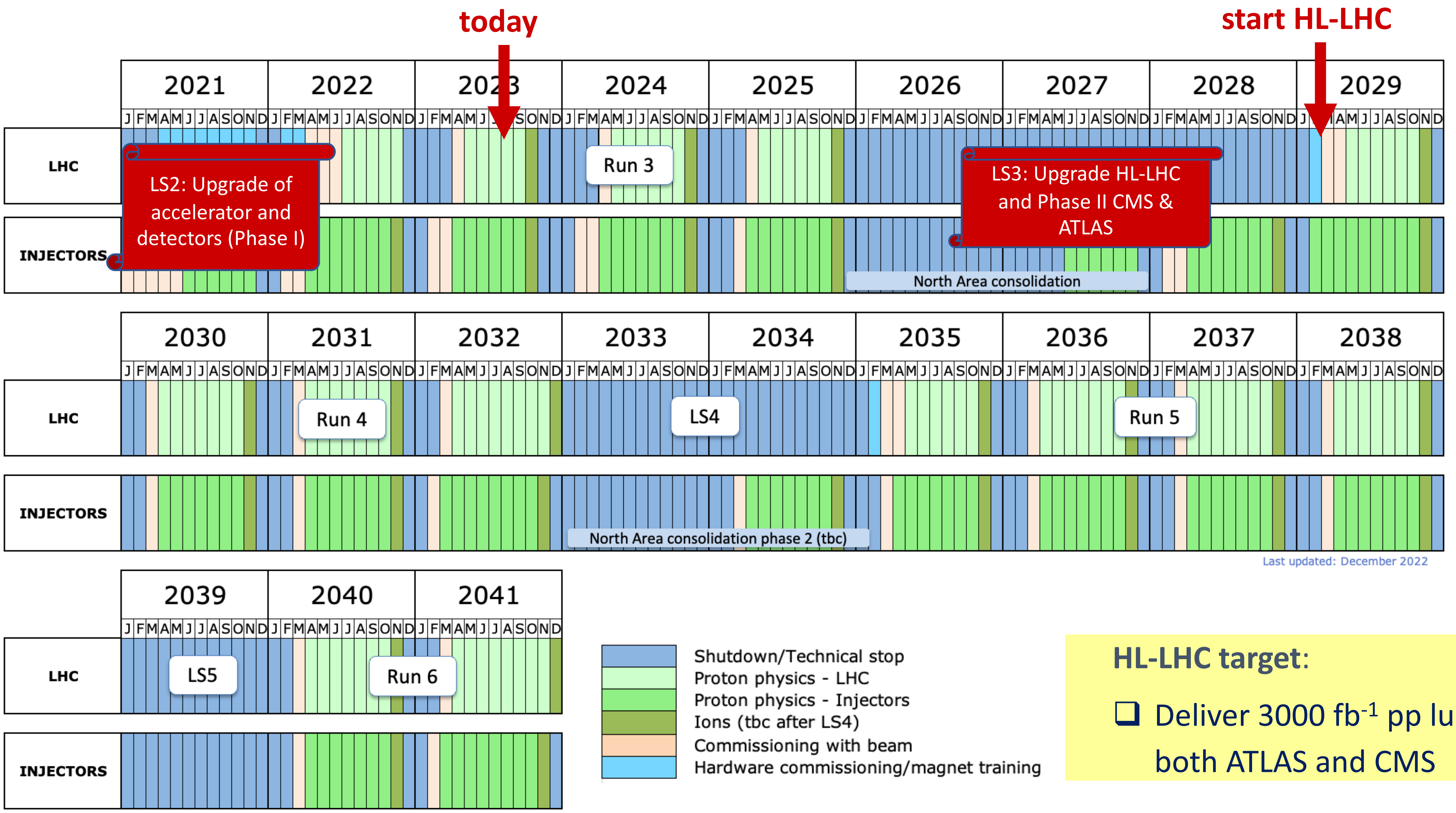
Upgrade Systems
SUC(s); PM (Deputy PM)

- Tracker: Andrea Venturi; Kristian Hahn (NN)
- Barrel Calorimeters: Bob Hirosky; Toyoko Orimoto, (NN)
- Endcap Calorimeter: Karl Gill (Marcello Mannelli, Jeremy Mans)
- Muons: Isabelle de Bruyn; Gabriella Pugliese (NN)
- MIP Timing Det.: Tommaso Tabarelli de Fatis (David Stuart)
- BRIL: Olena Karacheban; David Stickland, Gabriella Pasztor
- L1-Trigger: Michail Bachtis; Alexander Zabi (Michail Bachtis)
- DAQ: Christoph Schwick, Emilio Meschi (Marco Pieri, Christoph Schwick)
  HLT: Soham Bhattacharya, Marco Rovere

Upgrade Steering Group

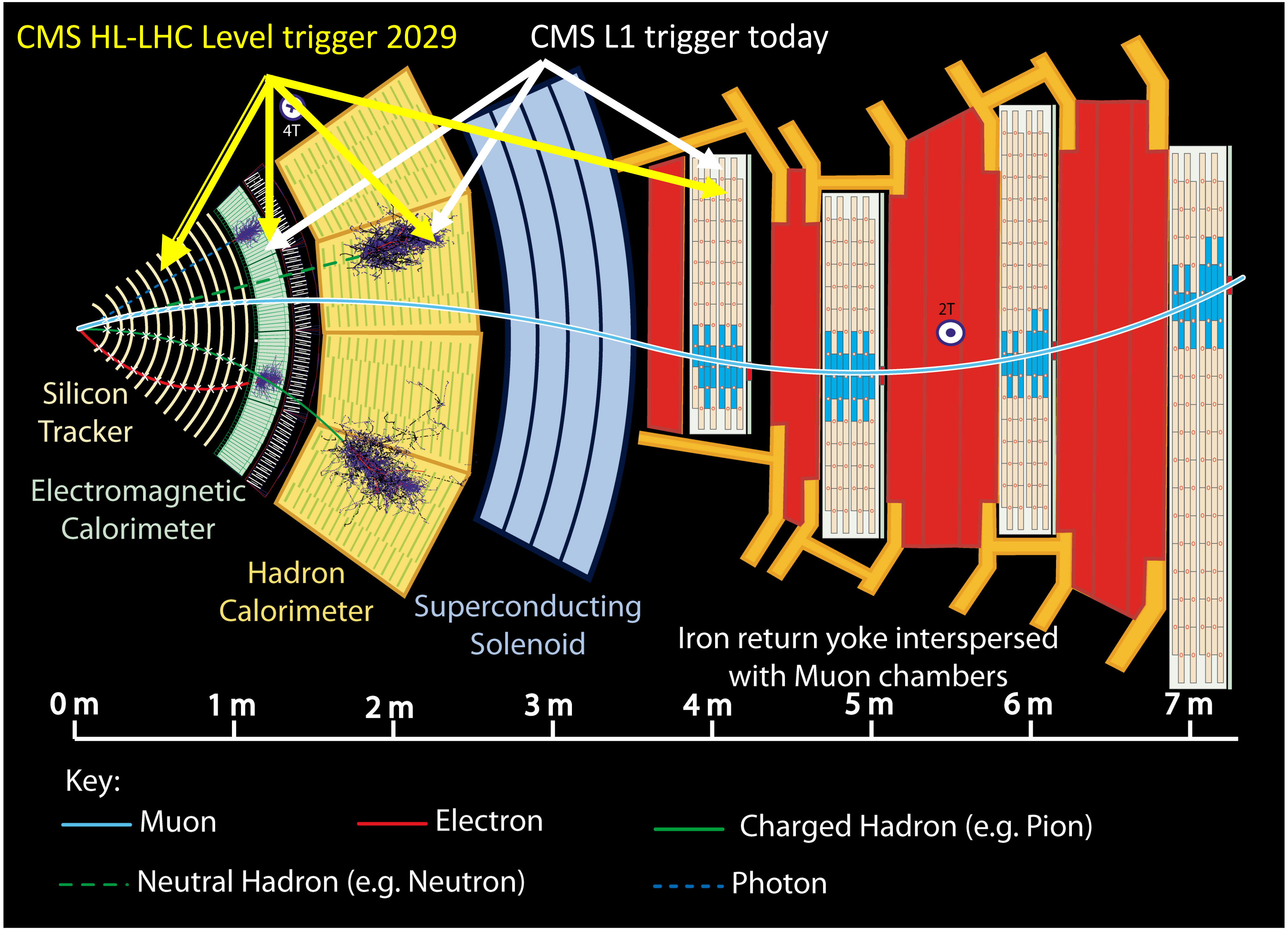
- Upgrade Project Office
- Cross System working groups
- Upgrade Systems
- Central Coordination Contacts

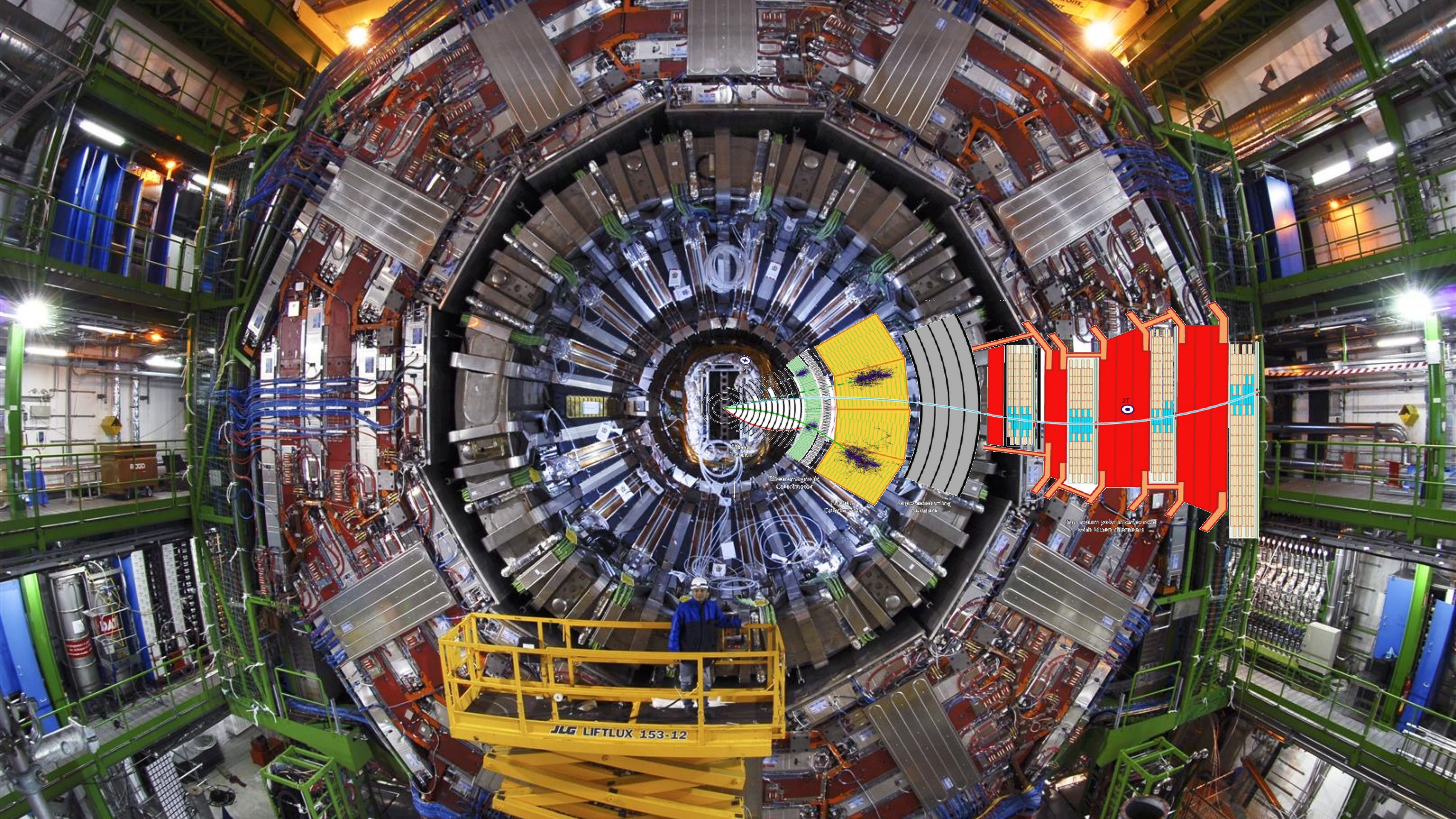
* Phase-2 Offline and Computing Upgrade is with Offline and Computing Coordination



HL-LHC target:

- ❑ Deliver 3000 fb^{-1} pp luminosity to both ATLAS and CMS


CMS HL-LHC Level trigger 2029
CMS L1 trigger today
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
JLG LIFTLUX 153-12

Preliminary HL-LHC optimistic schedule