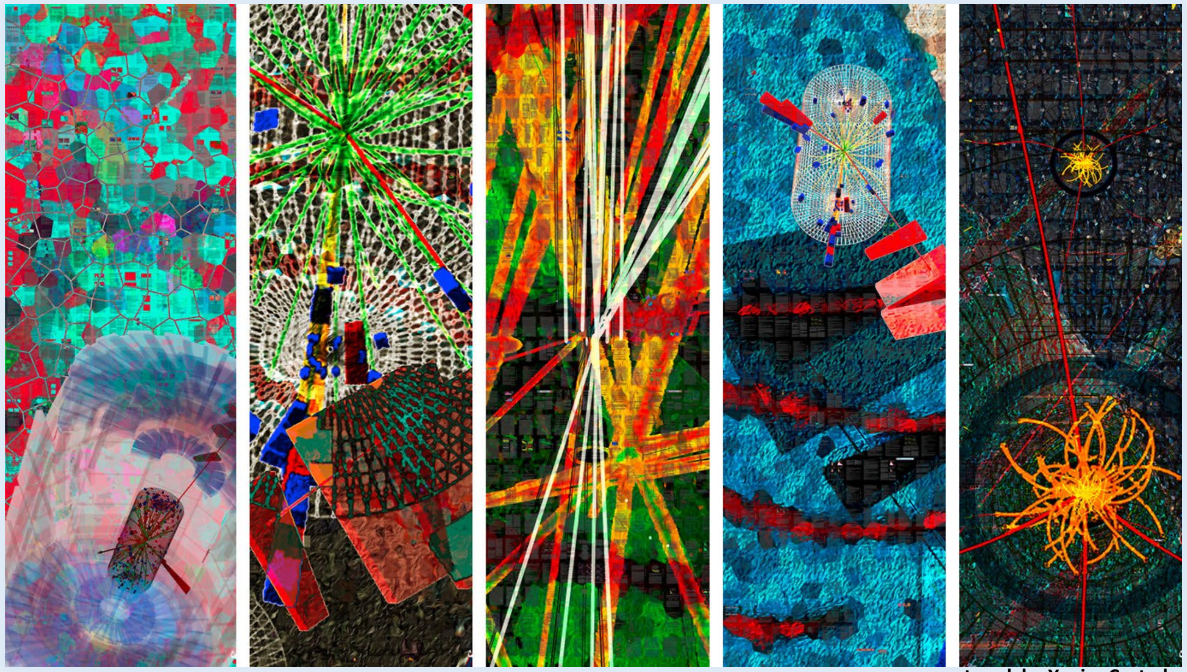
Spanish contribution the upgrades of the LHC experiments for the HL-LHC

IMFP-CPAN

Santander, October 2023


artwork by Xavier Cortada

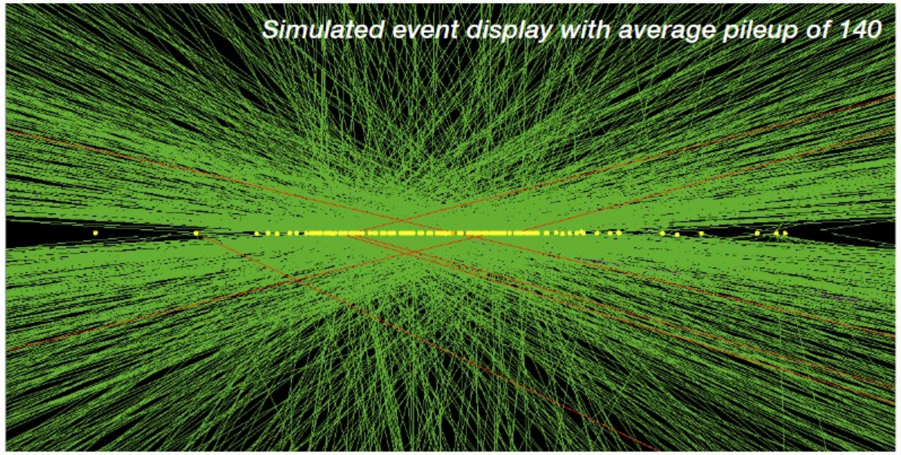
Gervasio Gómez - IFCA

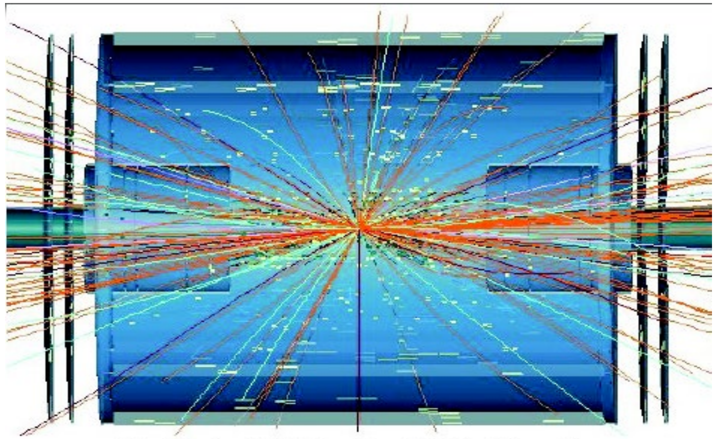
Thank you to the people who provided material for this talk:

Carlos Lacasta, Fernando Martínez, Sebastián Grinstein, Ignacio Redondo, Eduardo Picatoste, Abraham Gallas, Pablo Martínez, Iván Vila

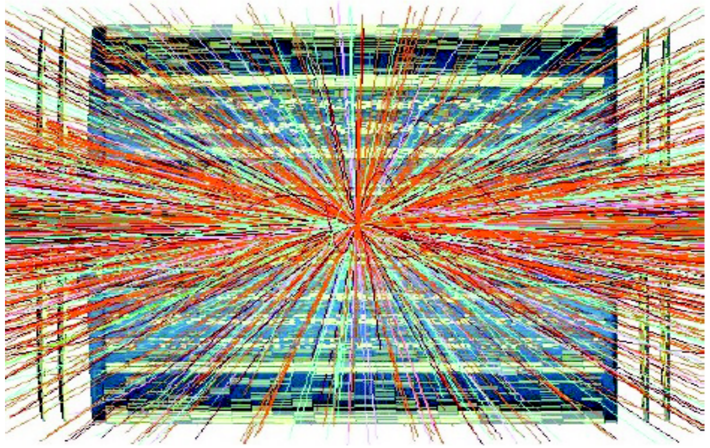
HL-LHC Upgrade

- High Luminosity upgrade of the LHC accelerator
  - Provide ~ x10 increase in luminosity w.r.t LHC design value
  - Larger datasets → increase potential for discoveries after 2029
  - Physics motivation covered in other talks
- Challenging operational environment requires major detector upgrades
  - From 20 to 200 collisions per beam crossing; track multiplicity from ~700 to 10.000
  - Radiation tolerant detectors and electronics to cope with unprecedented fluences
  - Increased granularity to cope with large occupancy and track multiplicity (large pileup)
- Spain contributes to the upgrades of ATLAS, CMS and LHCb



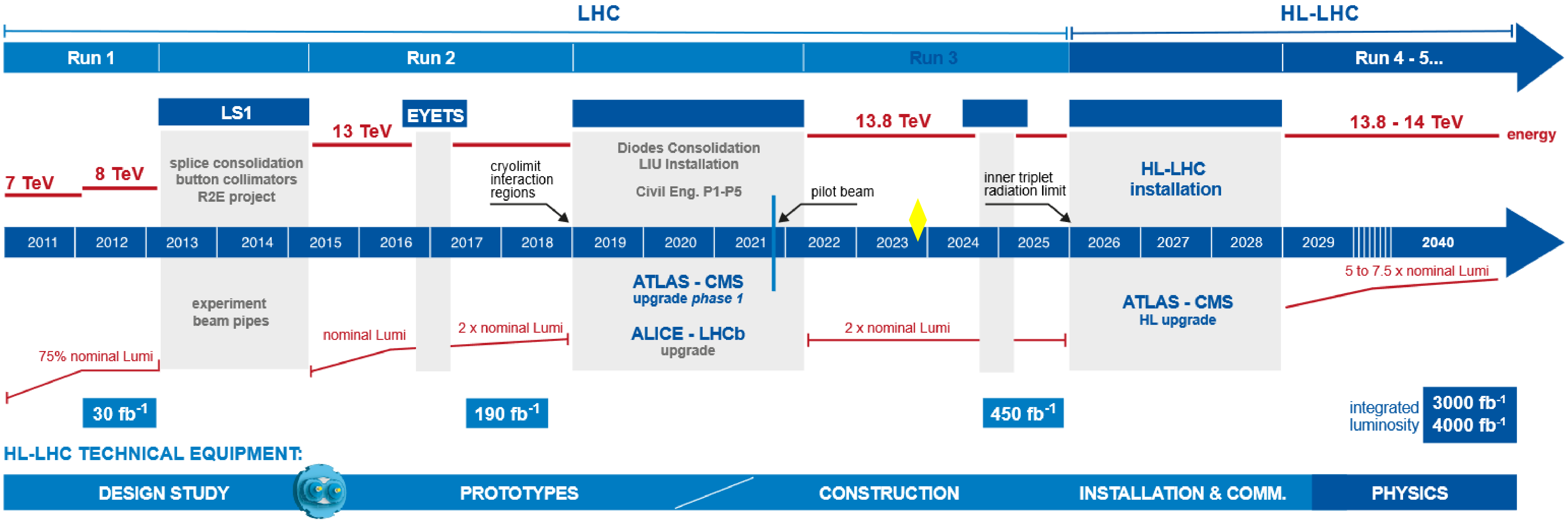


LHC in 2011: 1×10^{33} 1/cm^{2}s



HL-LHC: 5×10^{34} 1/cm^{2}s

HL-LHC schedule



Instantaneous luminosity increased to **5 – 7.5 ×10^{34} cm^{-2}s^{-1}**

Integrated luminosity of **250 fb^{-1}/year**

Expected **3000-4000 fb^{-1}** 12 years after the upgrade.

Very high pile up: **~140-200**

you are here

The Spanish Team

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ICCUB

ATLAS EXPERIMENT

- TileCal
- ITk-strips
- ITk-pixels
- HGTD

CMS

- Muon DT
- L1 trigger
- HGCAL
- IT pixels
- MTD-ETL

LHCb

- ECAL
- VELO
- SciFi/Tk

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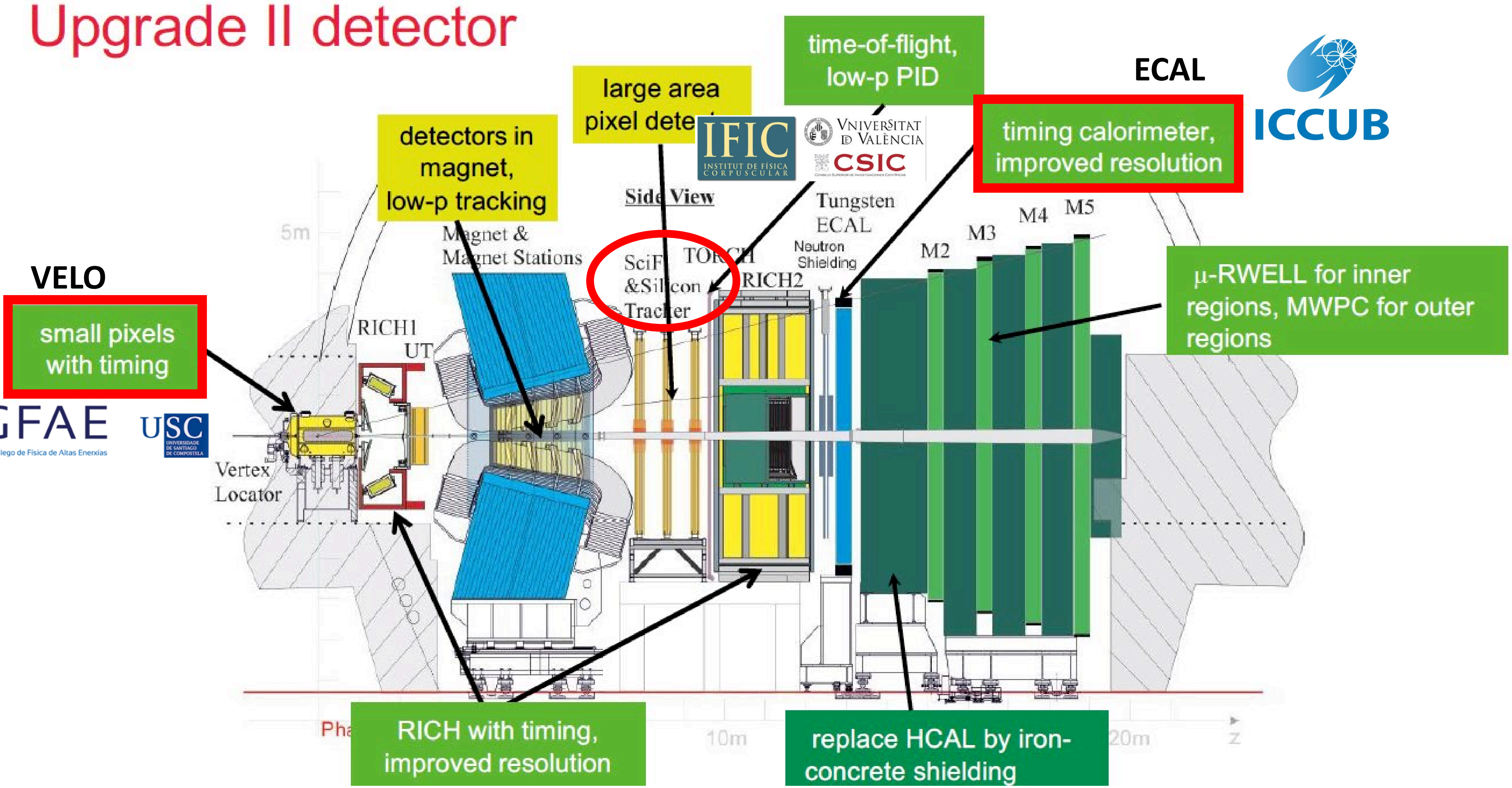
LHCb Upgrade II



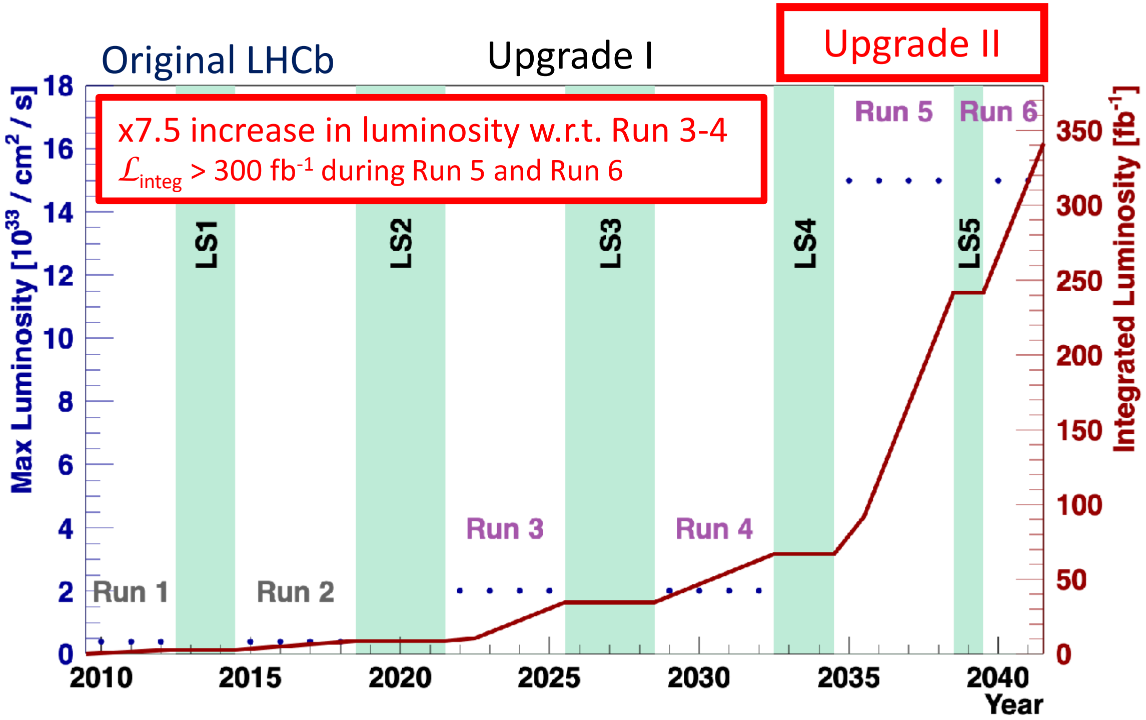
Note: no time to cover upgrade I activities reported in previous years: SciFi, Trigger

Motivation

Upgrade I will not saturate precision in many key observables: a further upgrade is necessary to fully realise the flavour-physics potential of the HL-LHC.

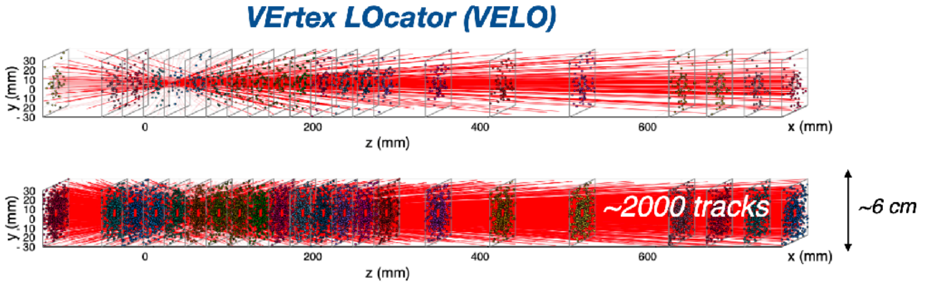
The performance of **Upgrade II** must equal or surpass that of **Upgrade I**, with:

Pile-up reaching values of 40
200 Tb/s of data
Charged particle densities up to $1x10^{12}$ / cm^2



Run 3: pile-up ~5

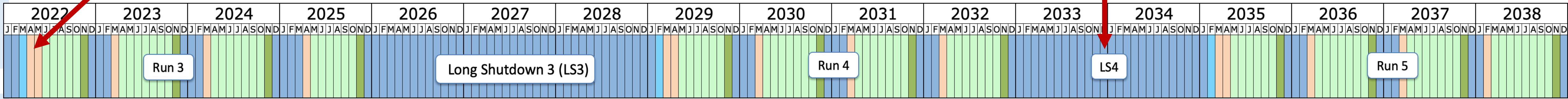
Upgrade II: pile-up ~40



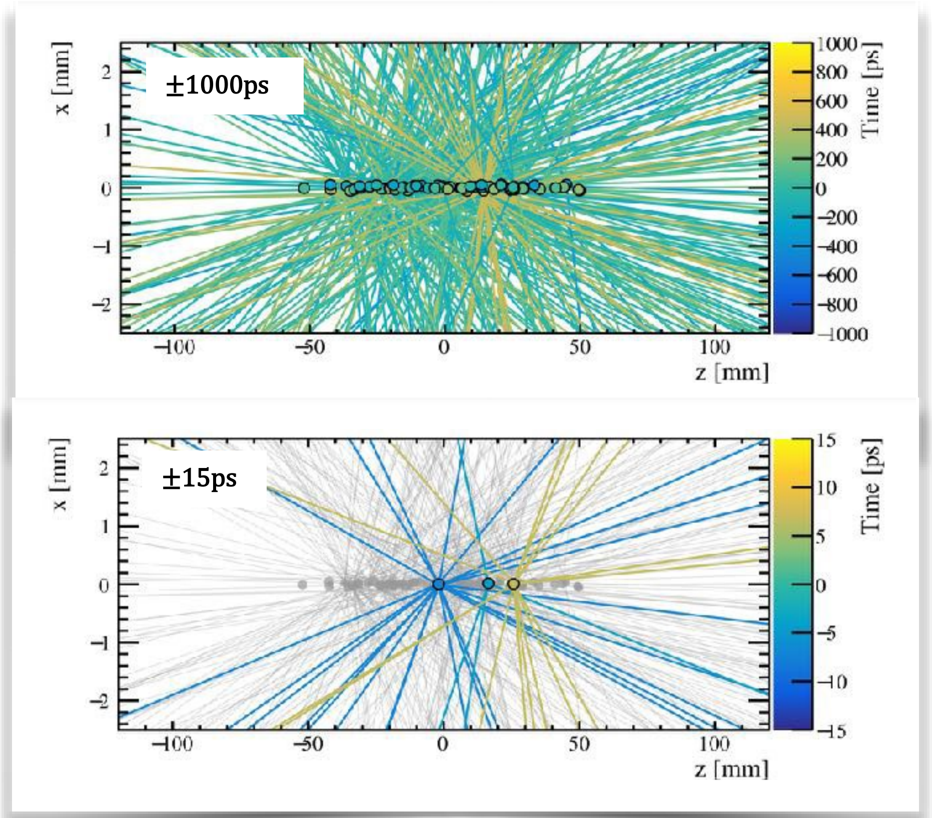
This is the **intensity frontier!** New, lightweight technologies with **high granularity, fast-timing, radiation hardness** and innovative data processing all necessary to go to $\mathcal{L}_{peak} \sim 1.5x10^{34}$ $cm^{-2}s^{-1}$

Upgrade I installation finished

Ramping up developments for Upgrade II to be installed in LS4 (~2033)

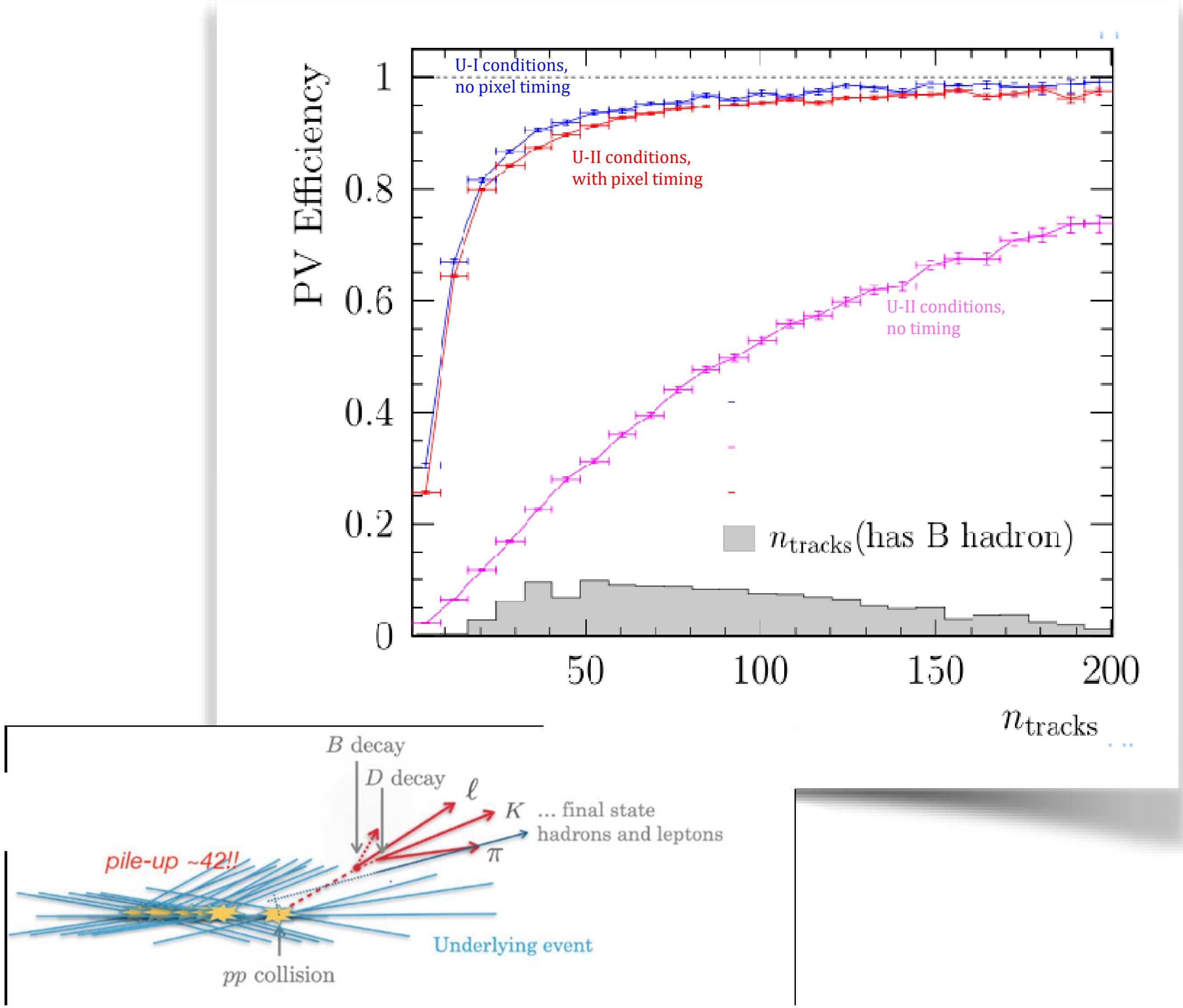


VELO II: the importance of timing



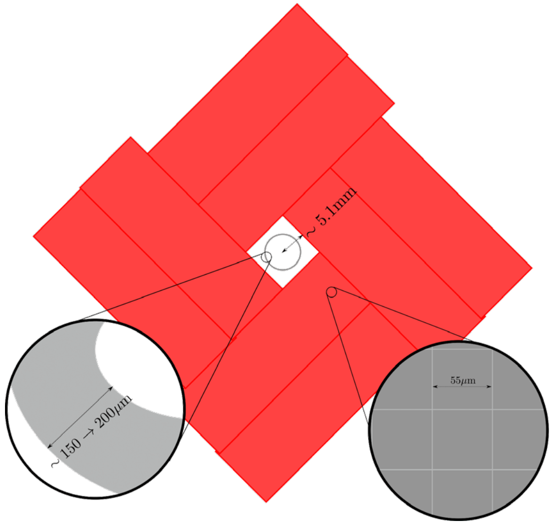
Higher pile-up → PV separation from Upgrade I (4.2 mm) reduced to **1.5 mm** in **Upgrade II** along the beam line.

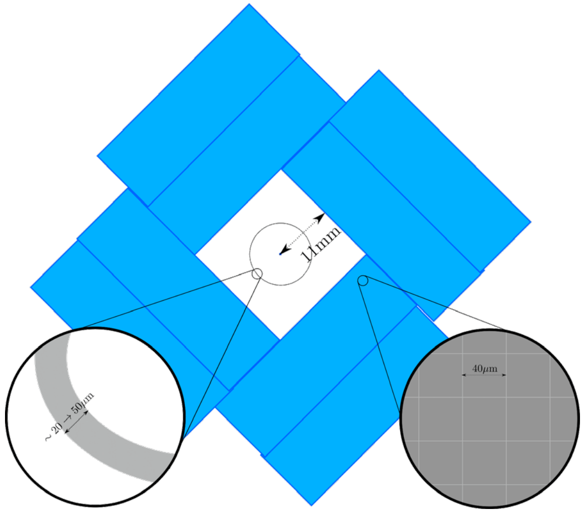
- Proton bunches overlap for a finite time (RMS ~ **180 ps**): in 1 ns window many overlapping collisions
- Increasing the resolution to **20 ps** only a few collisions and corresponding tracks remain



PV efficiency and IP resolutions will yield ~same signal selection performance IF timing resolution of 20 ps/track is achieved.

Upgrade II VELO layout scenarios





The innermost radius of the VELO is a key driving parameter for the physics performance and the detector technological requirements. Consider two limit scenarios (anything in between can be an option), keeping the performance at Upgrade I levels.

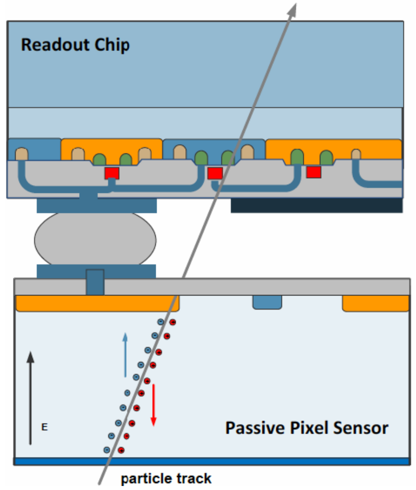
Scenario A (S_A):

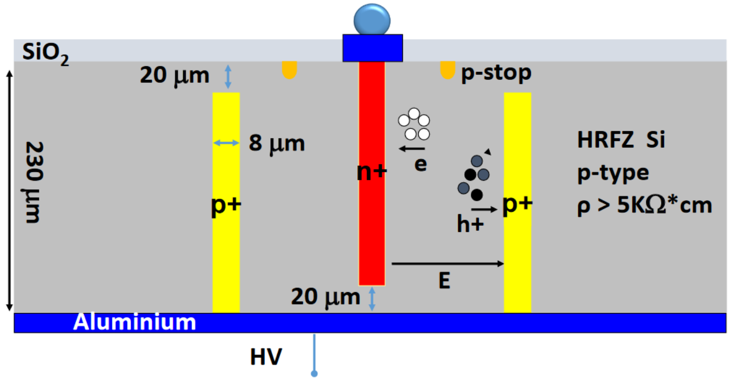
- **Innermost radius** is kept at **5.1 mm**, sensor layout same as Upgrade I
- ASIC needs to deal with a factor **~7.5 times higher hit rate** than the VELO Upgrade I ASIC (plus timing)
- Huge radiation dose means regular **detector replacements** likely needed

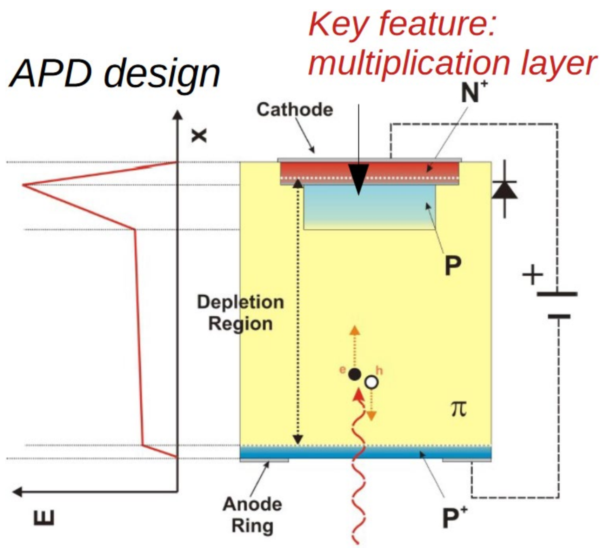
Scenario B (S_B):

- **Radius** relaxed to **12.5 mm**, cluster occupancies match those of Upgrade I
- Increased distance to the collision point requires significantly **better hit resolution**
- Material before the second hit needs to be reduced dramatically → requires:
    - Lighter RF foil, improvements in sensors, ASIC, and substrate materials, major mechanical redesign

U-II VELO sensor technologies







Planar sensors: (Used in **Upgrade I**)

Time resolution achievable with low thickness → short collection times → more uniform weighting field

High fluence → lower collected charge

Signal proportional to thickness: Faster → thinner → less signal → FE challenge

Not clear timing goals achievable while maintaining signal/noise

3D sensors:

Good radiation resistance 3D geometry also benefits timing performance (small column to column distance)

Signal proportional to thickness

Time resolutions ~20 ps with trench electrodes

Inefficient volumes at the columns (challenge high geometrical efficiency at small pitch)

Low Gain Avalanche Detector (LGAD):

Thin high field layer → Excellent timing performance

Gain structure is placed in the sensor itself →Good gain at small thickness

Time resolutions range from 20 to 40 ps

Gain degradation at high fluences

Non-uniform irradiation → difficult to tune sensor gain w/o breakdown

U-II VELO ASICs

Sensor R&D is closely matched to the ASIC development

Upgrade I based on **VeloPix** ASIC (130nm, from Medipix family). A new generation chip - Timepix4 has timing capability

Upgrade II requirements much more demanding still but could draw on similar concepts: **PicoPix++** (28nm)

TIMESPOT demonstrator chips (Timespot0 and Timespot1) implemented in 28 nm CMOS are also promising: 55 μm pitch, optimised for 3D-trench sensors

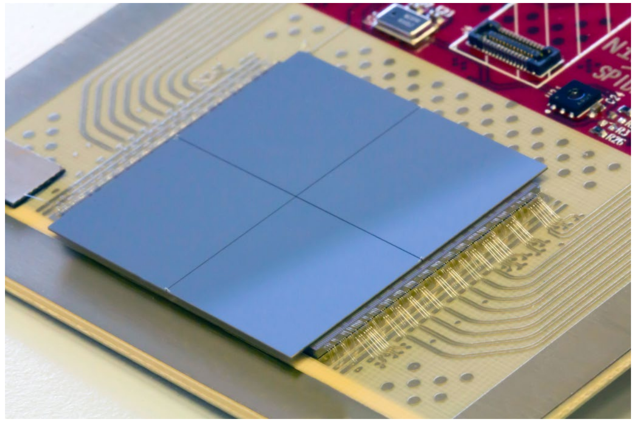
	VeloPix (2016)	Timepix4 (2019)	PicoPix++ (2025)
Technology	130 nm	65 nm	28 nm
Pixel Size	55 x 55 μm	55 x 55 μm	42/55 x 42/55 μm
Pixel arrangement	3-side buttable 256 x 256	4-side buttable 512 x 448	4-side buttable 256 x 256
Sensitive area	1.98 cm²	6.94 cm²	1.98 cm²
Event Packet	24 bit	64-bit	32-bit
Max rate	~400 Mhits/cm²/s	178.8 Mhits/cm²/s	~4000 Mhits/cm²/s
Best time resolution	25 ns	~200ps	~30 ps
Readout bandwidth	19.2 Gb/s	≤81.92 Gb/s	~250 Gb/s

Smaller pitch at larger r to maintain U-I resolution → Pixel pitch

Dose beyond current technical limits: needs replacement → TID lifetime

Innermost r: ~64 tracks per bx & 3.8 Ghits/s requires large b.w. → Bandwidth

Requirement	scenario S_A	scenario S_B
Pixel pitch [μm]	≤55	≤42
Matrix size	256×256	335×335
Time resolution RMS [ps]	≤ 30	≤ 30
Loss of hits [%]	≤ 1	≤ 1
TID lifetime [MGy]	> 24	> 3
ToT resolution/range [bits]	6	8
Max latency, BXID range [bits]	9	9
Power budget [W/cm²]	1.5	1.5
Power per pixel [μW]	23	14
Threshold level [e⁻]	≤ 500	≤ 500
Pixel rate hottest pixel [kHz]	> 350	> 40
Max discharge time [ns]	< 29	< 250
Bandwidth per ASIC of 2 cm² [Gb/s]	> 250	> 94

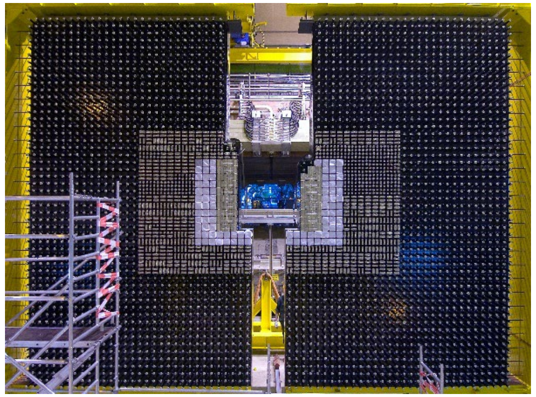


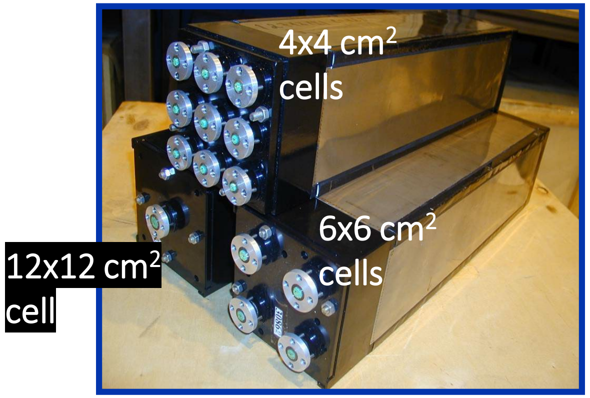
Timepix4 (65nm, Medipix4 collaboration, 2019)

LHCb ECAL Upgrade

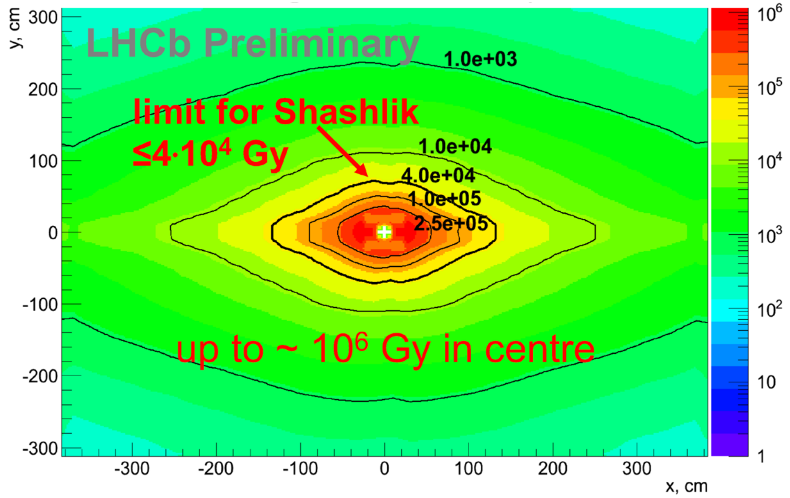
Current LHCb ECAL:

- Optimised for π^0 and γ reconstruction in the few GeV to 100 GeV region at 2×10^{32} cm^{-2}s^{-1}
- Shashlik technology: 4x4 / 6x6 / 12x12 cm^2 cell size
- Radiation hard up to 40 kGy
- Energy resolution: $\sigma(E) / E \approx 10\% / \sqrt{E} \oplus 1\%$
- Large array (8 x 7 m^2) with 3312 modules and 6016 channels





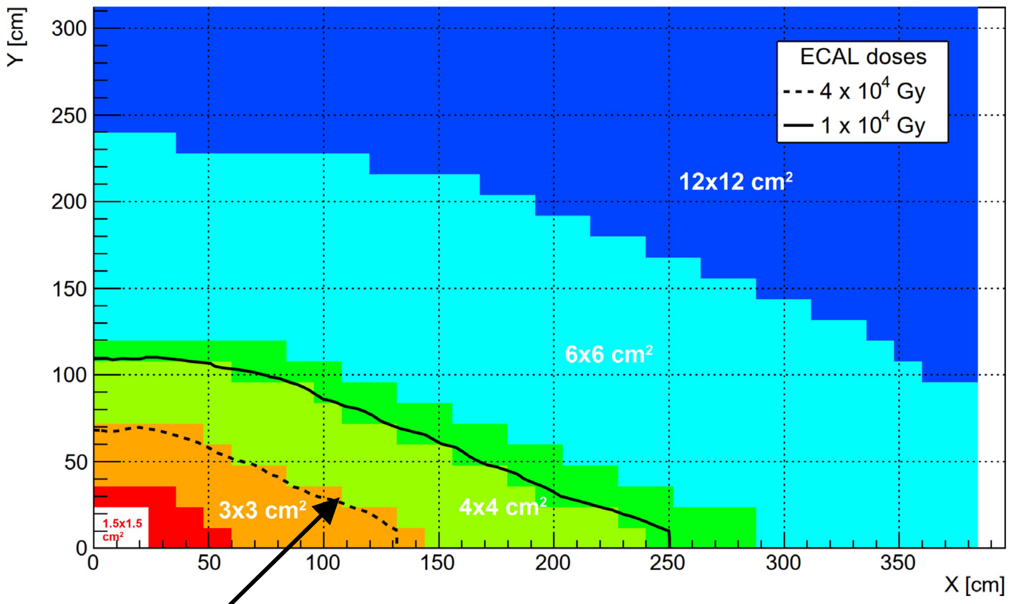
Accumulated radiation dose [Gy] after 300 fb^{-1}



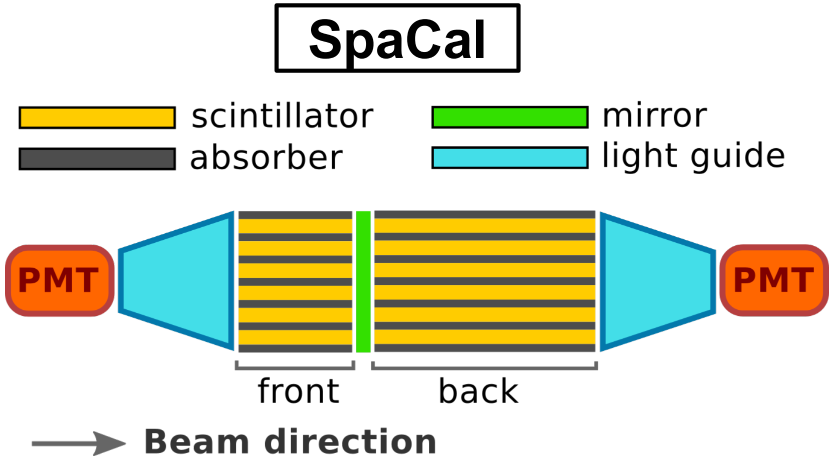
Requirements for the Upgrade II: operation at L = 1-2 x 10^{34} cm^{-2}s^{-1}

- Sustain radiation doses up to 1 MGy and ≤ $6 \cdot 10^{15}$cm^{-2} for 1MeV neq/cm^2 at 300 fb^{-1}
- Keep at least current energy resolution
- Pile-up mitigation crucial
  - → Timing capabilities with O(10) ps precision, preferably directly in the calorimeter modules
  - → Increased granularity in the central region with denser absorber
- Respect outer dimensions of the current modules: 12x12 cm^2

Technologies for the ECAL Upgrade



Radiation limit of current Shashlik technology



SpaCal technology for inner region:

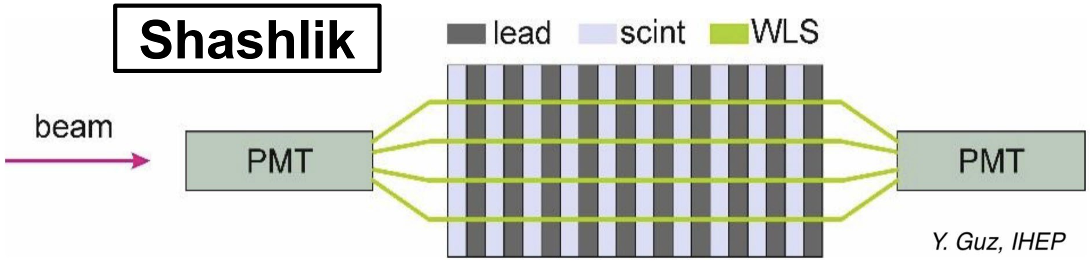
- Innermost modules with scintillating crystal fibres and W absorber
  - → Development of radiation-hard scintillating crystals
  - → 1.5x1.5 cm^2 cell size
- 40-200 kGy region with scintillating plastic fibres and Pb absorber
  - → Need radiation-tolerant organic scintillators
  - → 3x3 cm^2 cell size

Shashlik technology:

- About 3300 new Shashlik modules with improved timing capability and double-sided readout
  - → Possible cost optimization by refurbishing ≈2000 existing modules with fast new WLS fibres, adding ≈1300 new modules with required cell sizes

LS3 enhancement:

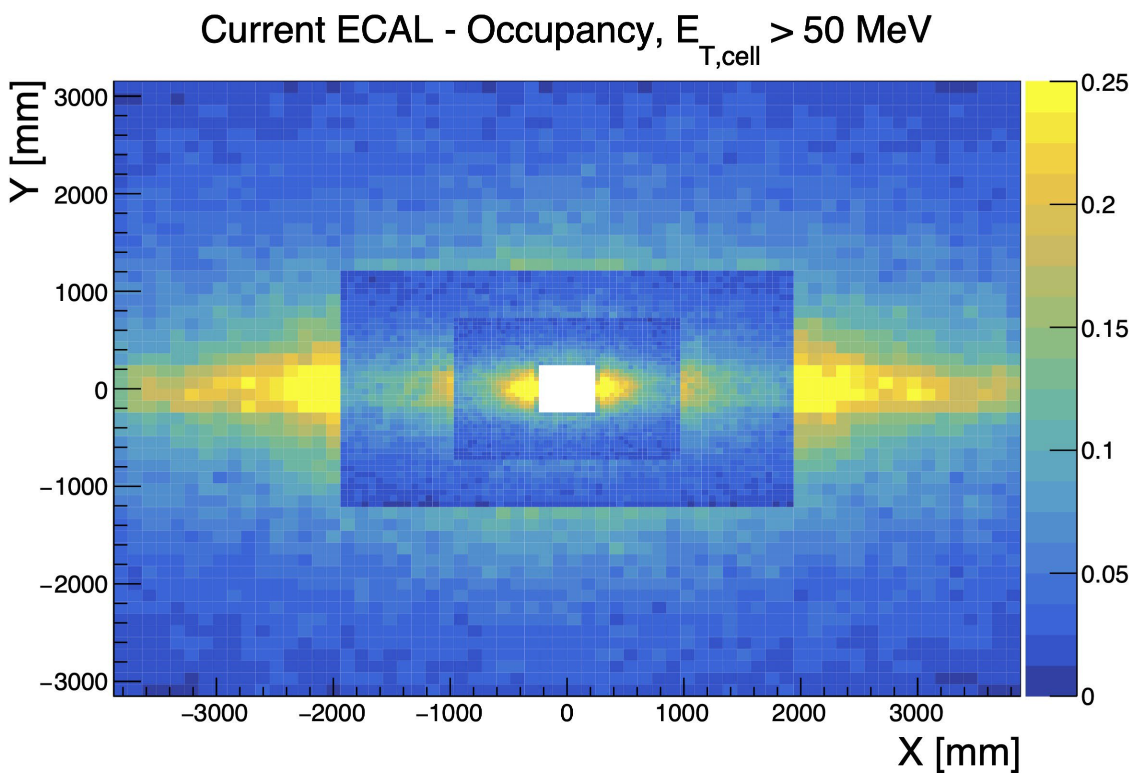
- SpaCal with W absorber for innermost modules equipped with scintillating plastic fibres for 2x2 cm^2 cell size, single-sided readout
- All SpaCal modules tiled by 3°+3° → see later



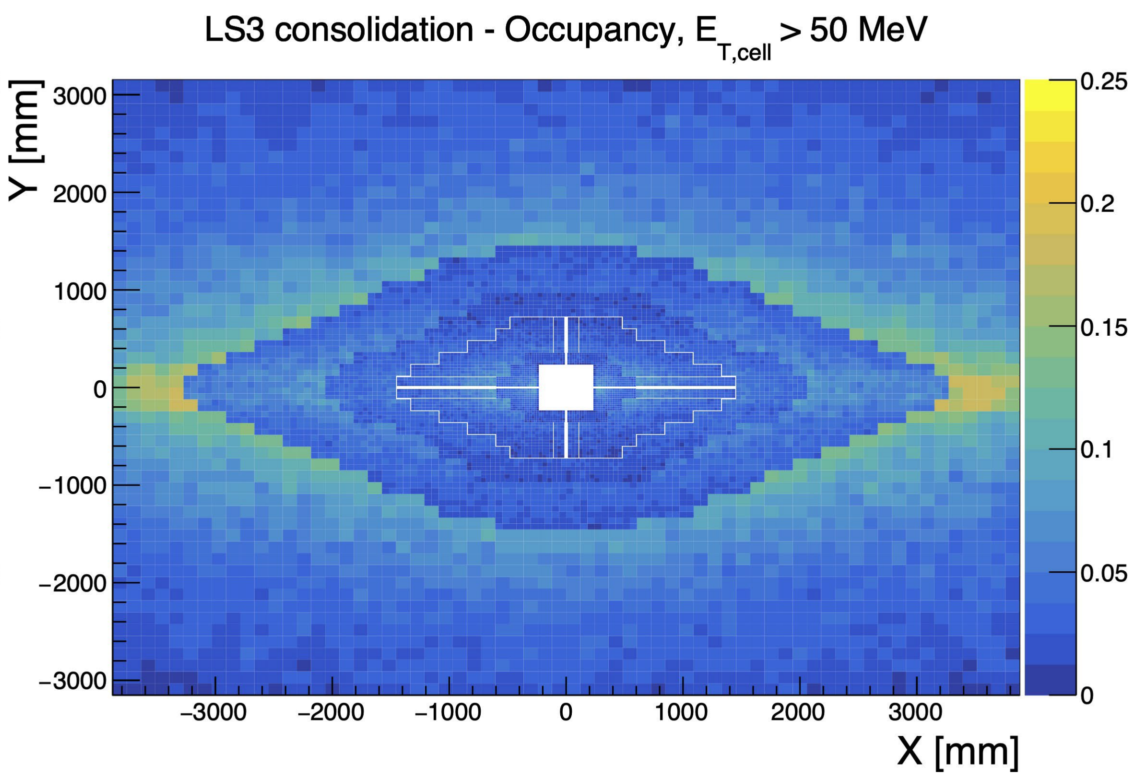
LS3 ECAL: impact of improved granularity

Occupancies from detailed simulation with assumed luminosity: $L = 2 \times 10^{33}\ cm^{-2}s^{-1}$

Current ECAL:



With LS3 enhancement:



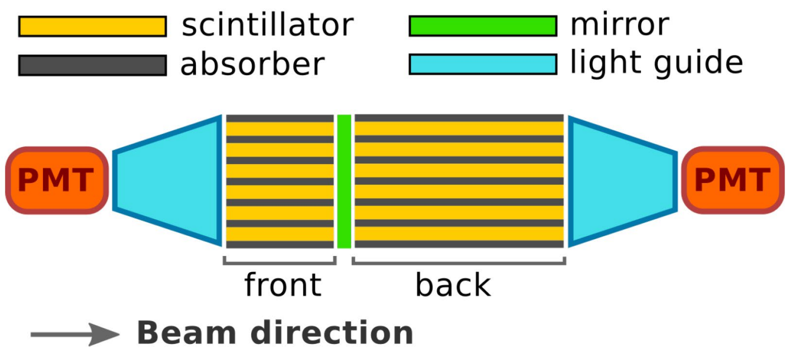
Sizeable occupancy in large regions before LS3 enhancement (challenge for neutral pion reconstruction)

Occupancy map after LS3 enhancement reasonably flat

Also: contribution to Real Time Analysis and ECAL reconstruction

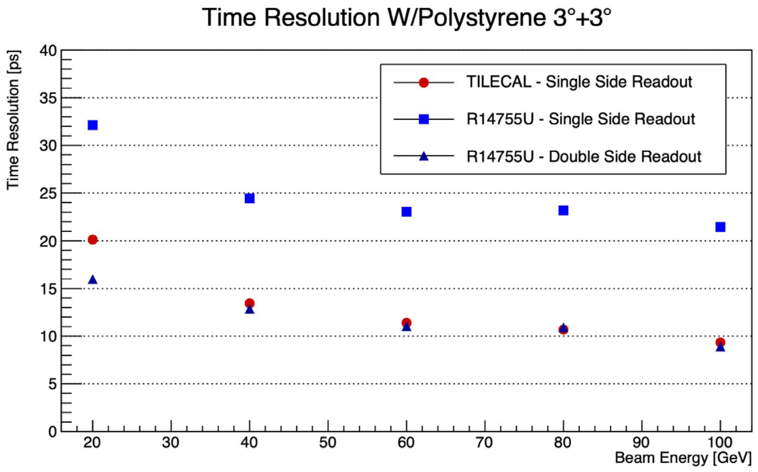
ECAL Prototypes for the Upgrade

- SpaCal-W prototype module
  - Pure tungsten absorber with 19 g/cm^3
  - garnet crystal fibers
  - 9 cells of 1.5x1.5 cm^2 (RM ≈ 1.45 cm)
  - 4+10 cm long (7+18 X_0)
  - Reflective mirror between sections

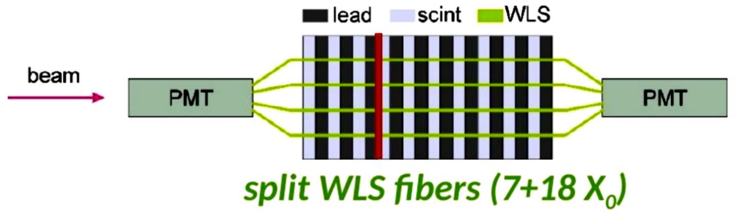


PMT Studies in backup

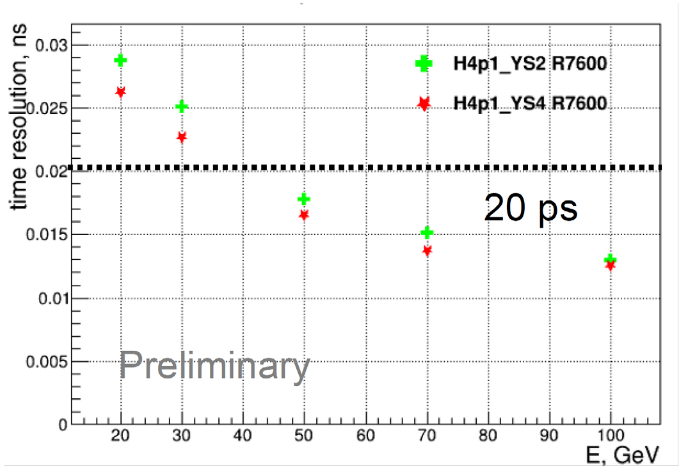
- SpaCal-Pb prototype module
  - Pb absorber + polystyrene fibers
  - 9 cells of 3x3 cm^2 (RM ~ 3 cm)
  - 8+21 cm long (7+18 X_0)
  - Reflective mirror between sections
  - Kuraray SCSF-78 fibres (1mm)



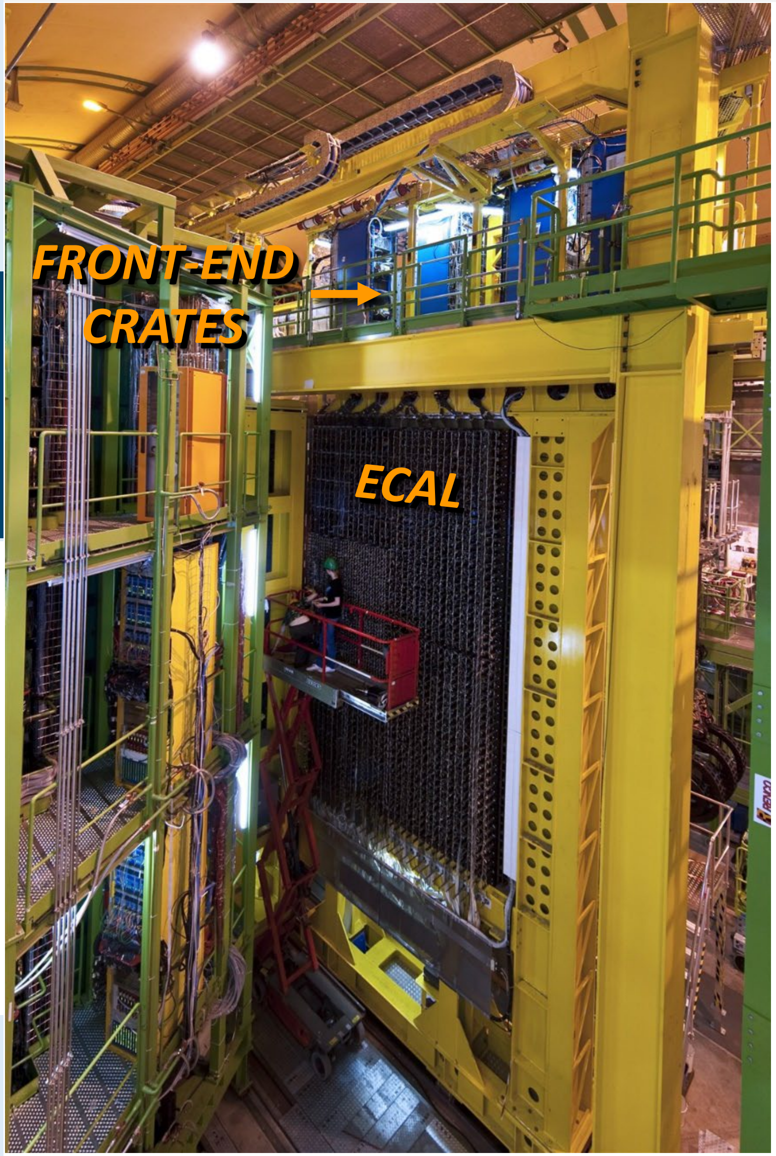
- Shashlik prototype
  - in outer part of ECAL and provide timing information
  - Split WLS fibers (7+18 X0, mirrored fiber ends)
  - Kuraray WLS YS2 and YS4

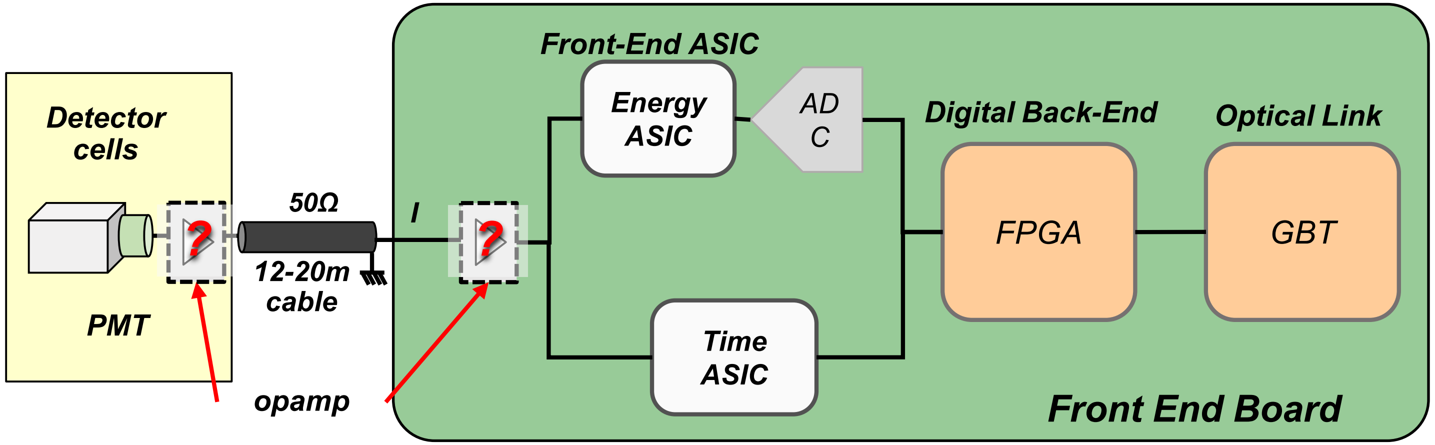


Double-sided readout (CERN SPS 2021



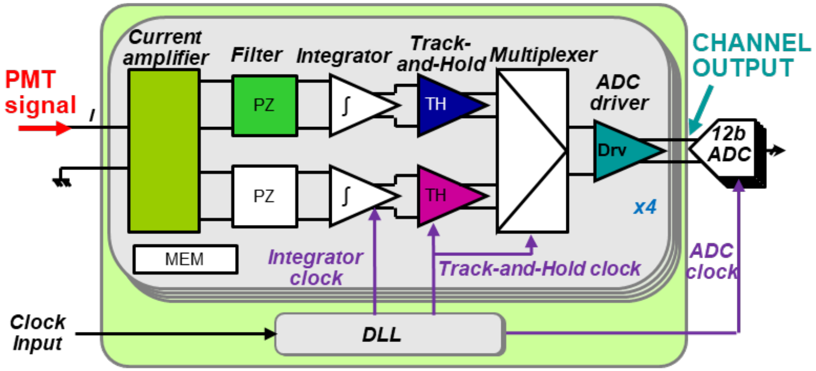
ECAL Readout Electronics





- Photodetectors readout solution follows the same scheme as in current ECAL:
  - Minimal light transport with PMT sensors near modules
  - Electronics in crates on top of the detector (reduced radiation)
  - Connection via analog link (coaxial) up to 20m considered
- ASIC/chipset in TSMC 65nm with separate energy and timing processing paths
- Amplifier + Shaper circuit included on the PMT base or FEB under consideration to compensate cable attenuation, improve SNR, if necessary

Design of energy ASIC analogue processing chain



LHCb SciFi + Silicon Tracker

Tracking Stations for Upgrade II

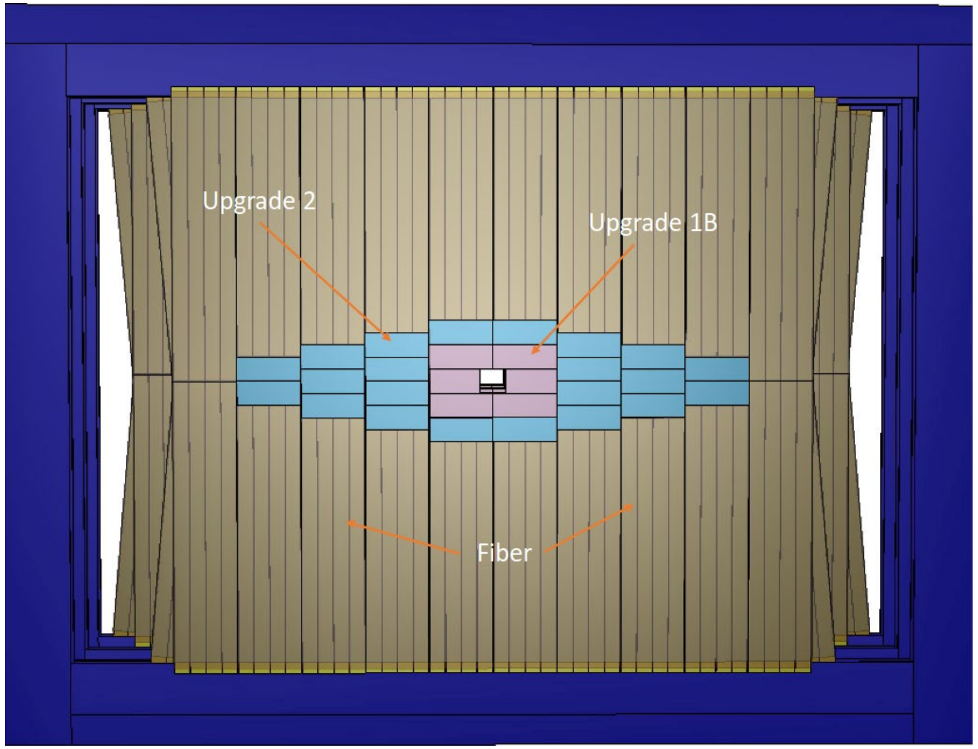
- Extend Si-DMAPS pixels: six 3 m^2 layers (3 double-layer stations)
  - integrated Silicon/SciFi modules to minimize material
  - replacement forced by rad damage

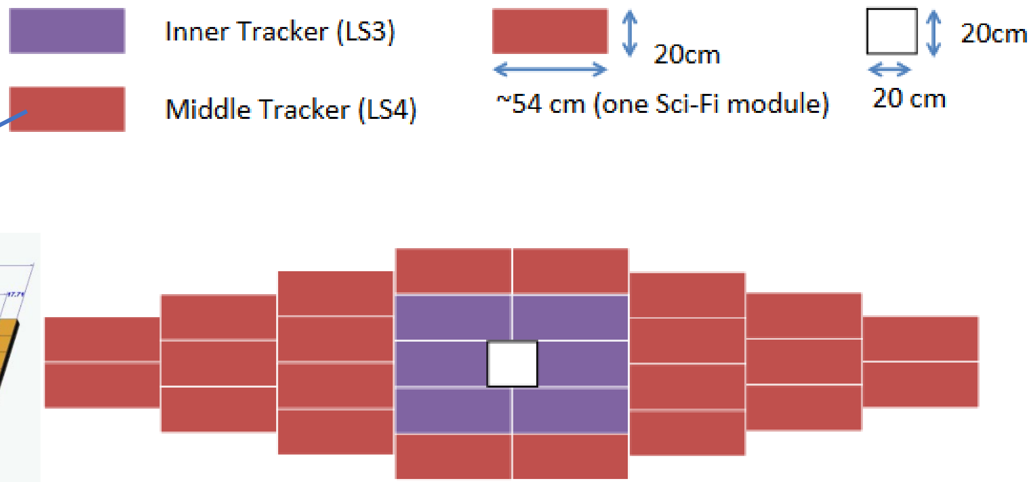
- Cryogenic cooling needed for SiPM readout
  - dark count rate strongly reduced even after full irradiation
  - clustering no longer required for noise rejection.
  - Also: 150-300 mW/cm^2 from DMAPs

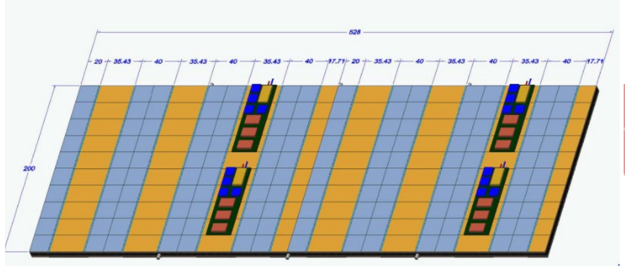
- Add ~ 1.5 ns resolution timestamp?
  - lower combinatorics reconstruction
  - requires new front-end electronics

- **PACIFIC 2.0: SiPM readout ASIC for the SciFi/Tracker**

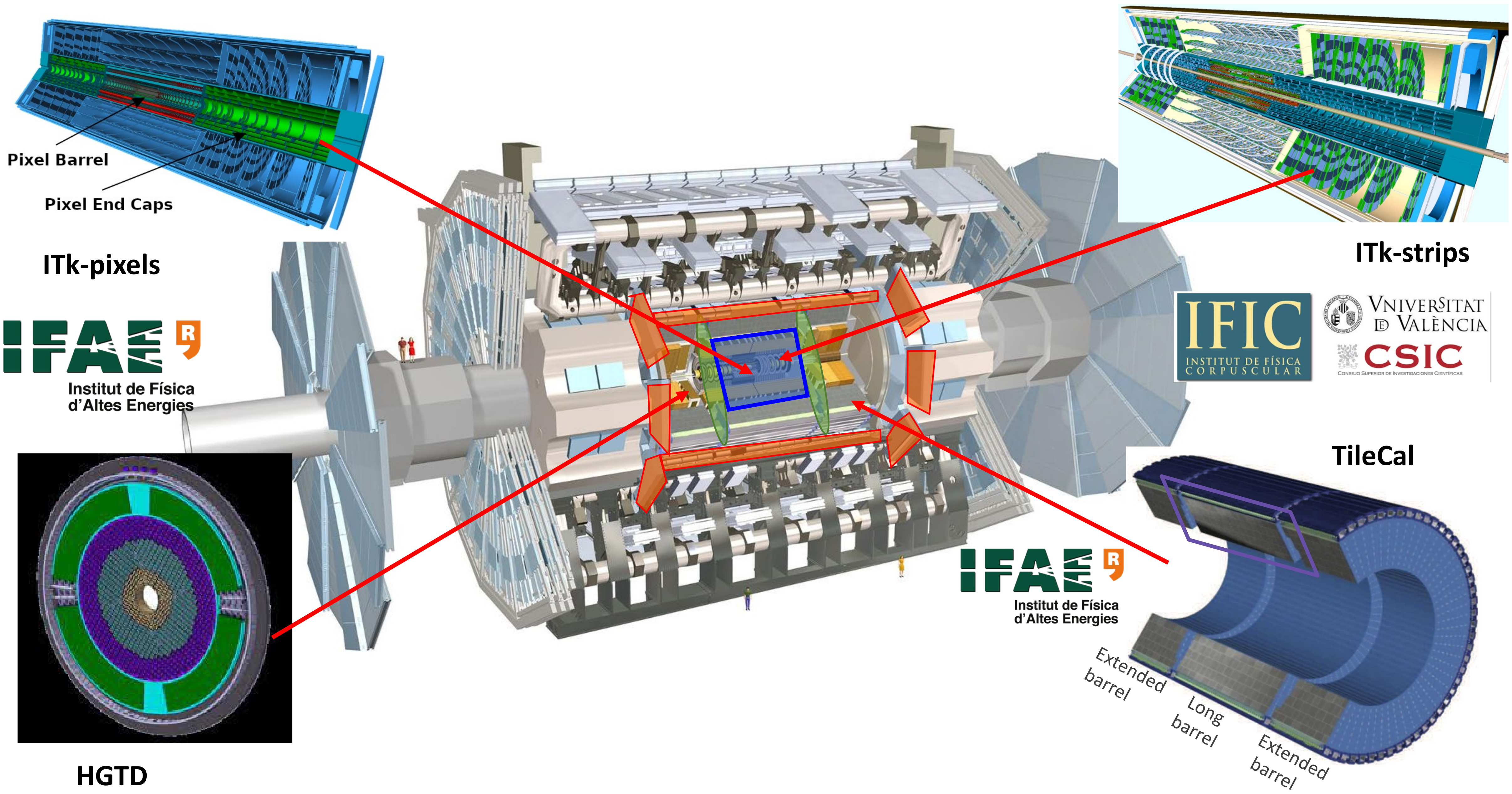
(profit from experience in PACIFICr5 development)







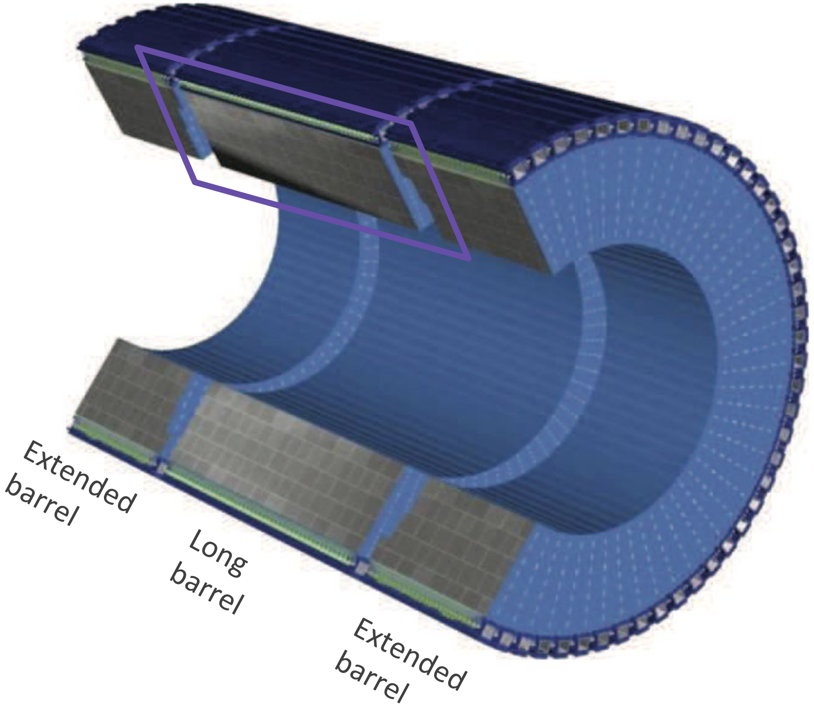
ATLAS Upgrade

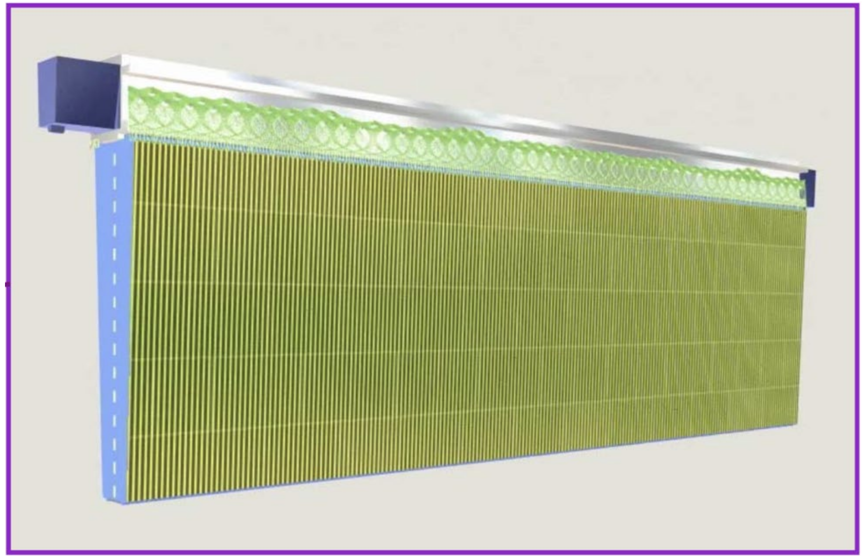


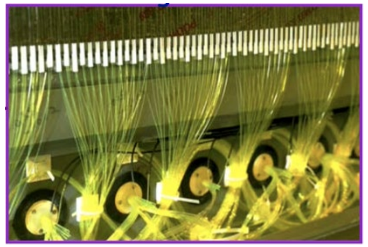
ATLAS TileCal

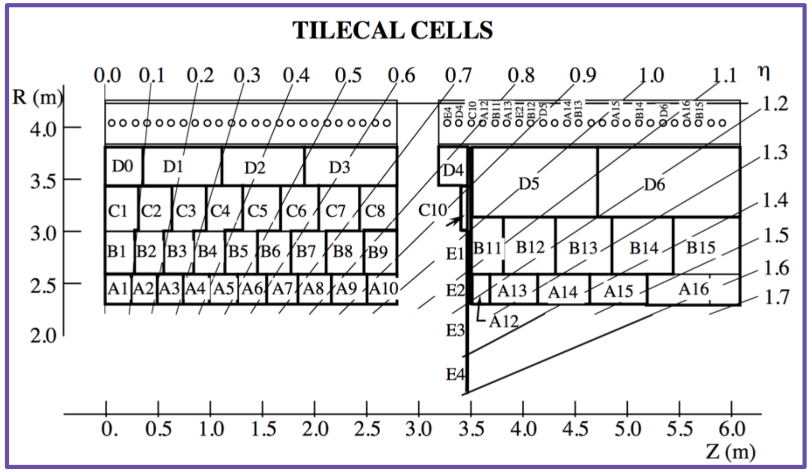
Tile Calorimeter is the central section of the hadronic calorimeter of ATLAS ($|\eta| < 1.72$). It is a sampling calorimeter made of steel plates and plastic scintillator tiles. It has ~ 10.000 channels

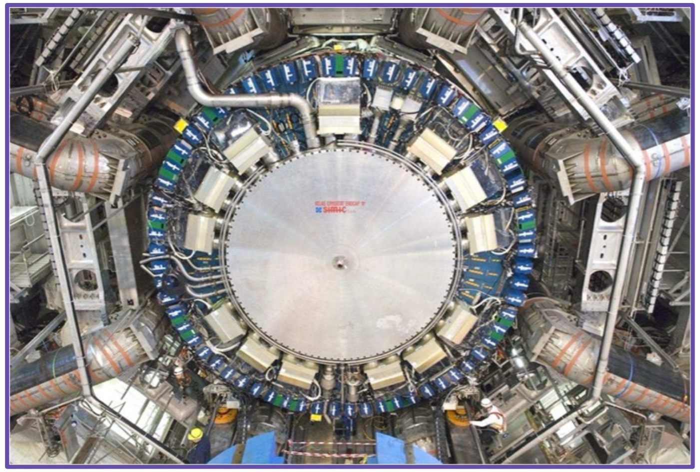
Measures energy of hadrons, jets, τ-leptons and ETmiss







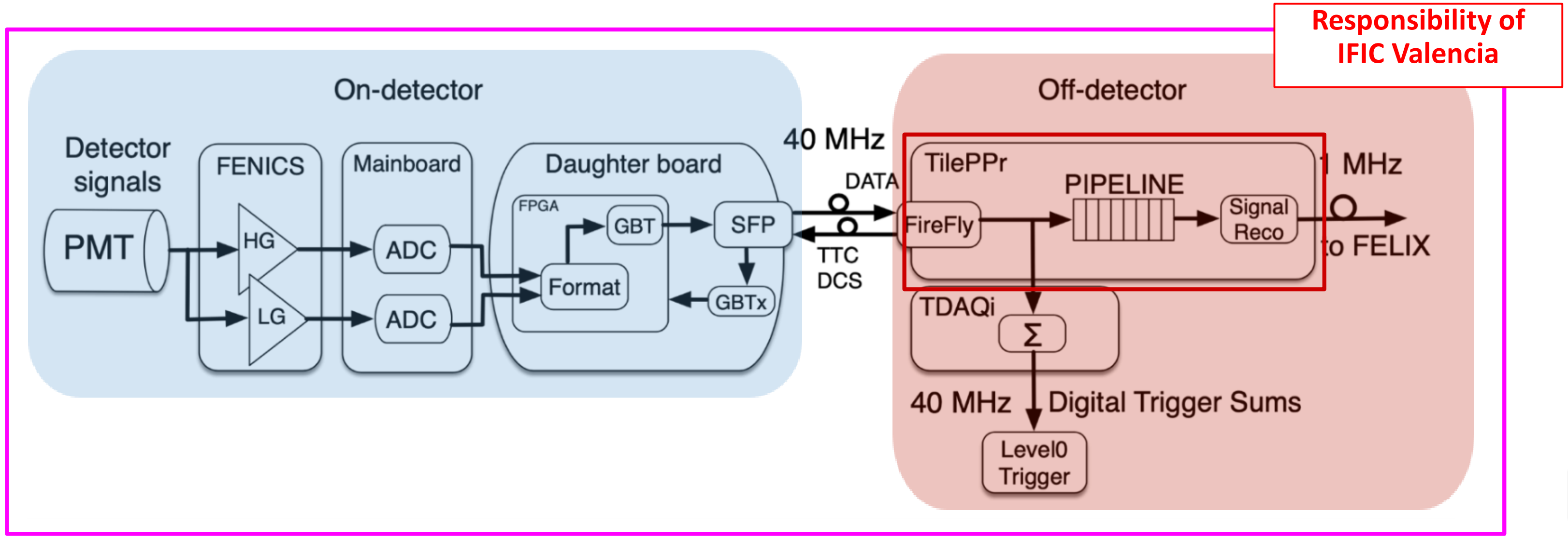


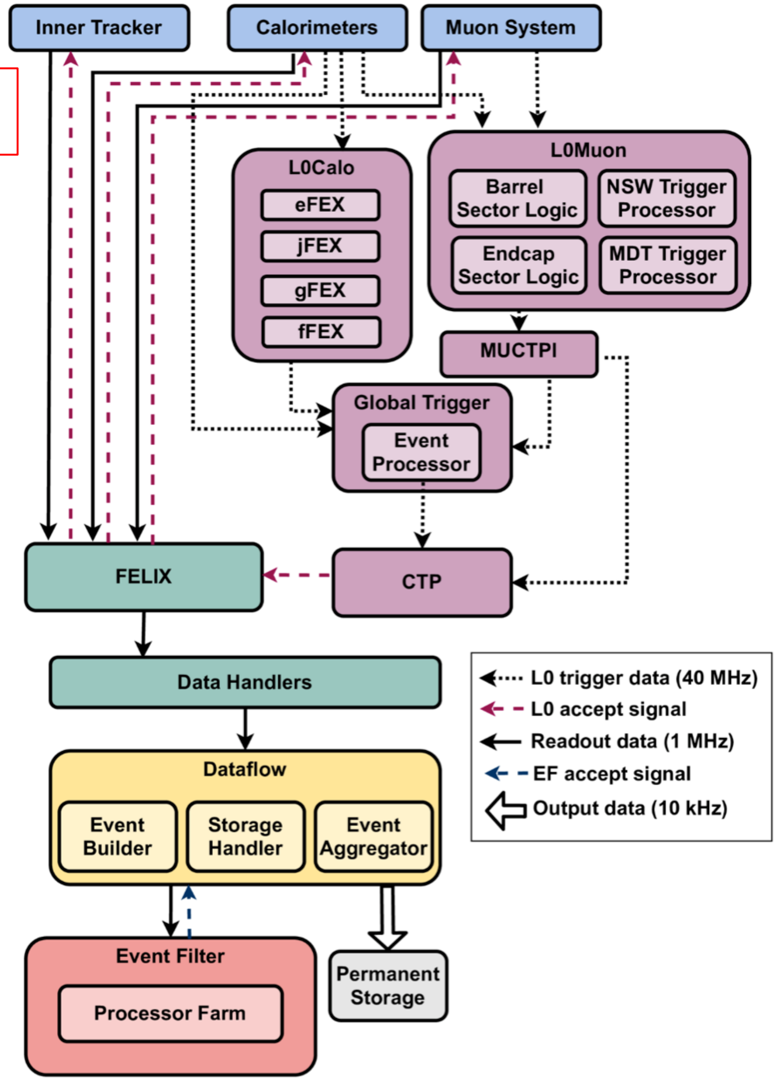


IFIC and **IFAE** involved in TileCal since its beginning and working on its development and operation

TileCal Pre-Processor (TilePPr)

TileCal PreProcessor (TilePPr): is the interface between the “on-detector electronics” and the trigger & data acquisition system, **40 MHz** (40 MHz x 1 Mb event size = **40 Tb/s**)





TilePPr will reconstruct the energy at 40 MHz for the Level0 Trigger at the HL-LHC
(Read-Out Driver reconstructed the energy at 100 kHz for the HLT in Run 1-3)

Memorandum of Understanding (MoU) signed by the Ministry in 2018 established that the IFIC group is responsible for the design, preproduction and production of the **76%** of the TilePPr modules.

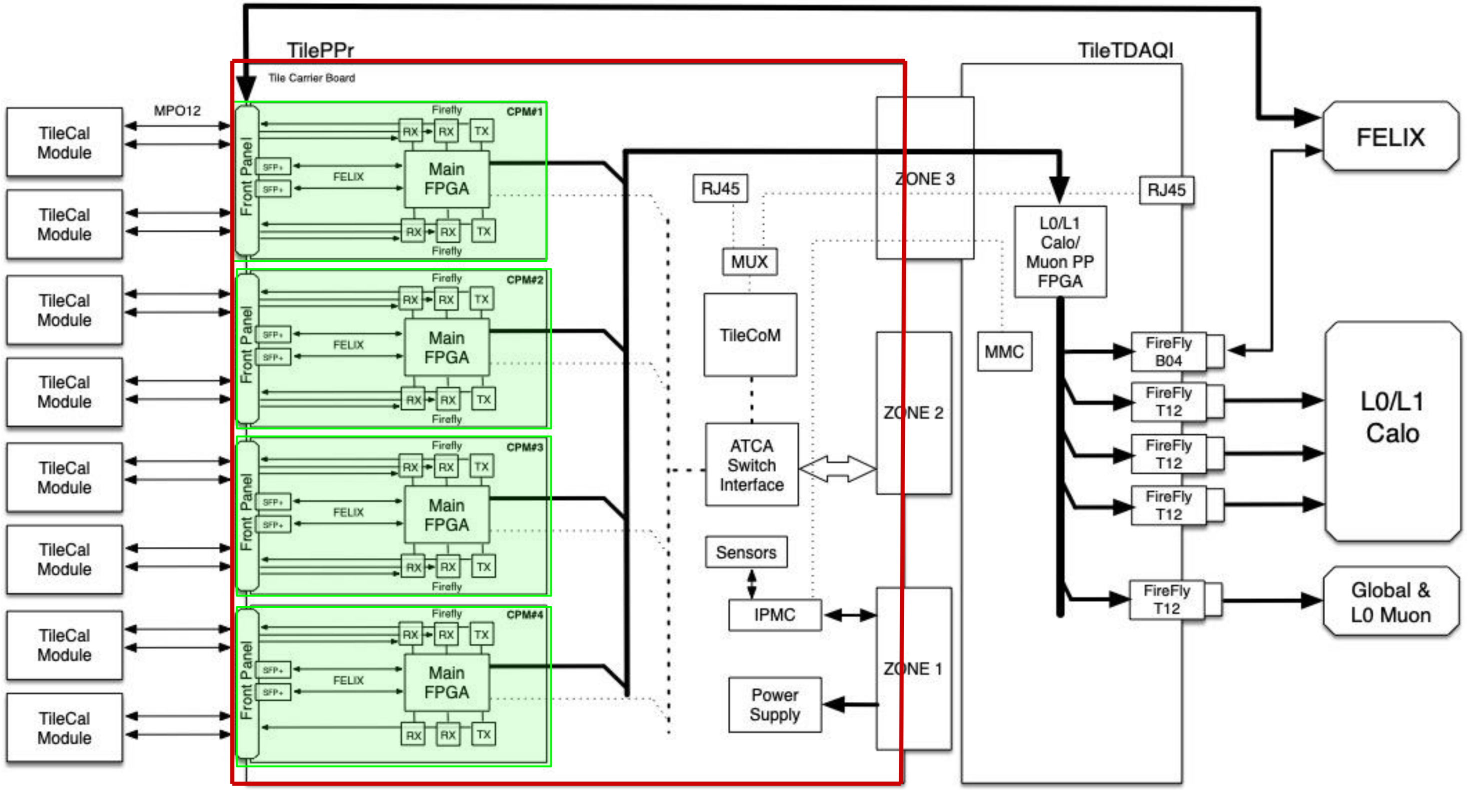
A. Valero Tile Calorimeter Phase-II Upgrade **Deputy Project Leader** (2018-2019) and overall editor of the Technical Design Report of the ATLAS TileCal Phase-II upgrade.

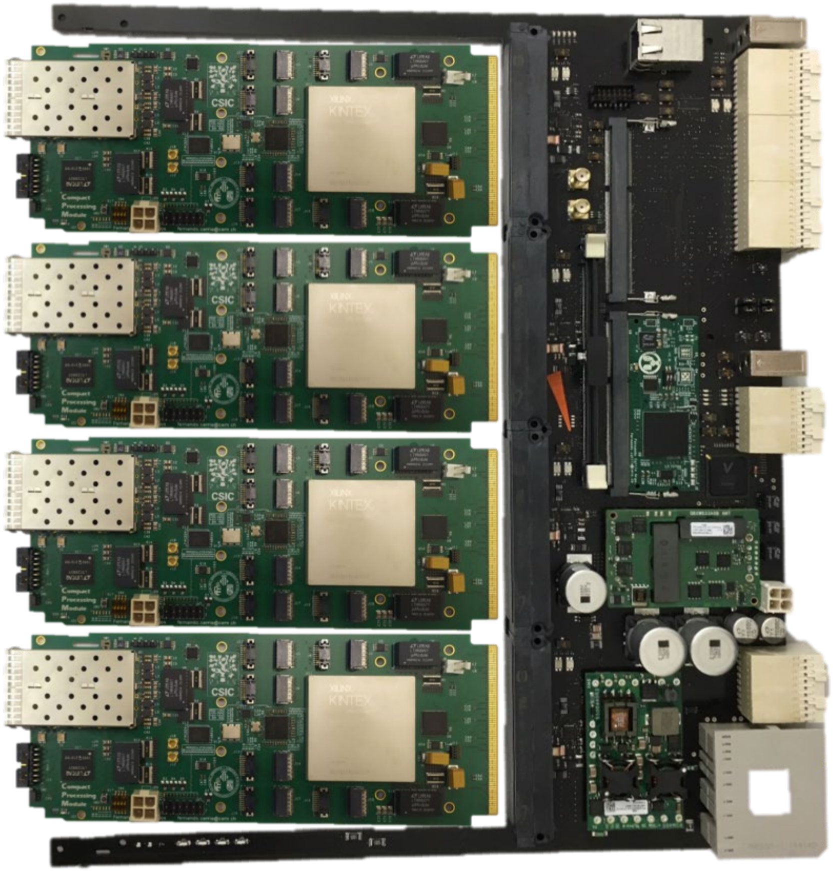
F. Carrio Tile Calorimeter Phase-II Upgrade Deputy Project Leader since 01/01/2023.

TileCal off-detector electronics

A total of **32** PPrs are needed to read the Tile Calorimeter. Each PPr module is formed by:

- 1 ATCA Carrier board
- 4 CPMs (Compact Processing Modules)

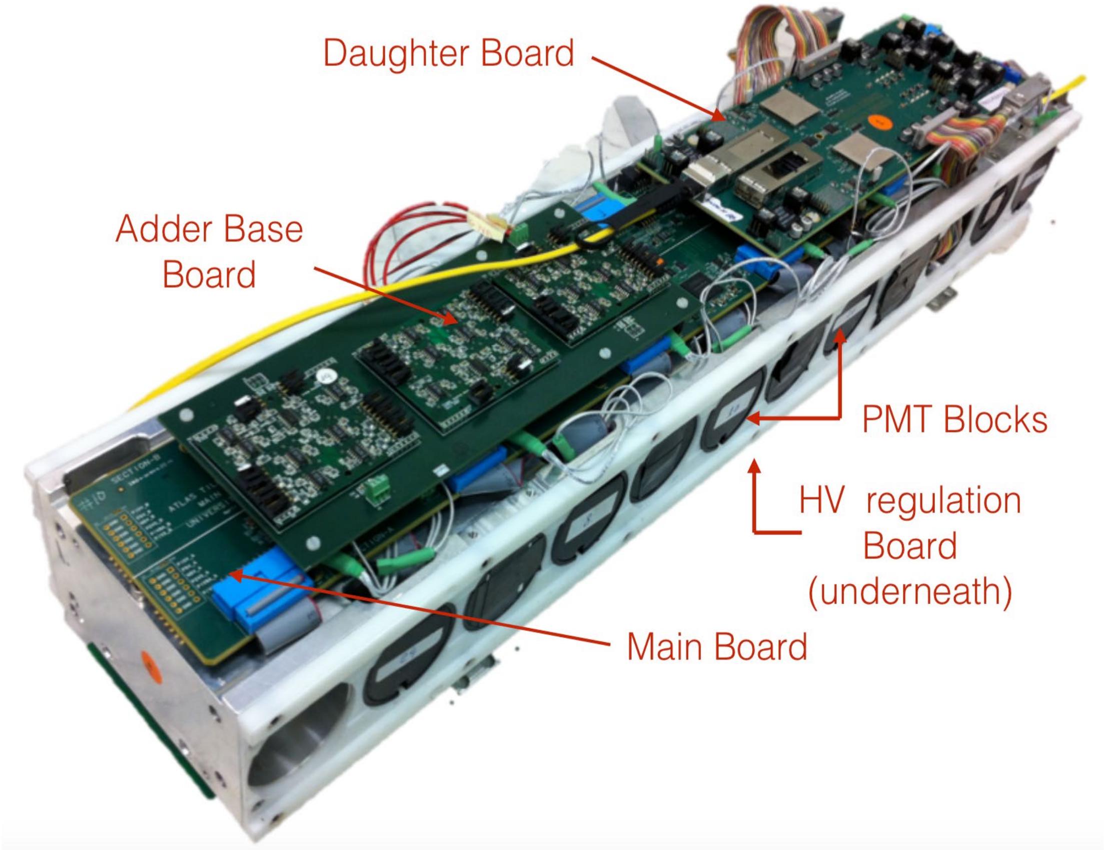




Details of CPMs and Mezzanine ATCA carrier boards in backup

TileCal MiniDrawers

- Mechanical housing of TileCal front-end electronics (**mini-drawers**) proposed and designed by IFAE



- Production of 40% mini-drawers in-house
- Completed **on-time** and delivered to CERN

Other TileCal Activities:

- Implementation of the Tile-based luminosity measurement to Run 4
- Investigation of possible fine granularity readout for the TileCal latest stages of HL-LHC

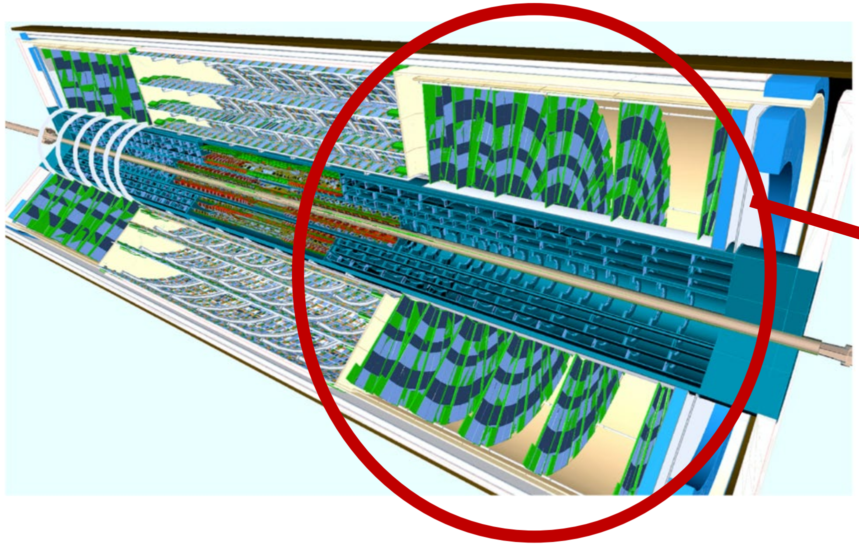
ITk Strips

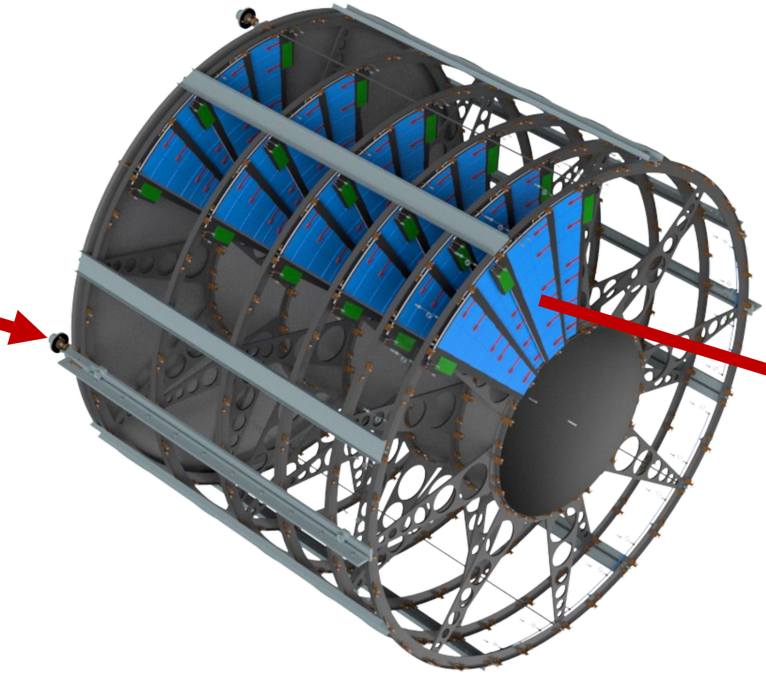
The ITk is ATLAS's inner tracker in charge of reconstructing the traces of the particles generated in the collisions.

IFIC-Valencia works in the ITk-Strip **endcap**.

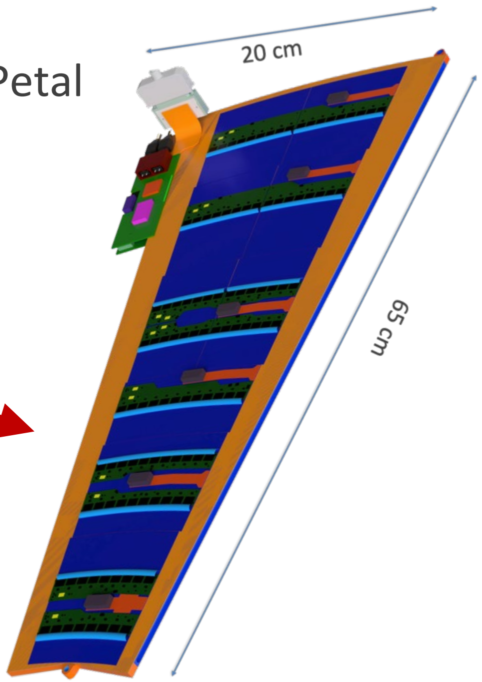
- Each endcap has 6 disks.
- Each disc has 32 wedge-shaped carbon fiber supports (petals).
- Each petal houses 18 sensors, 9 on each side.

Inner Tracker system

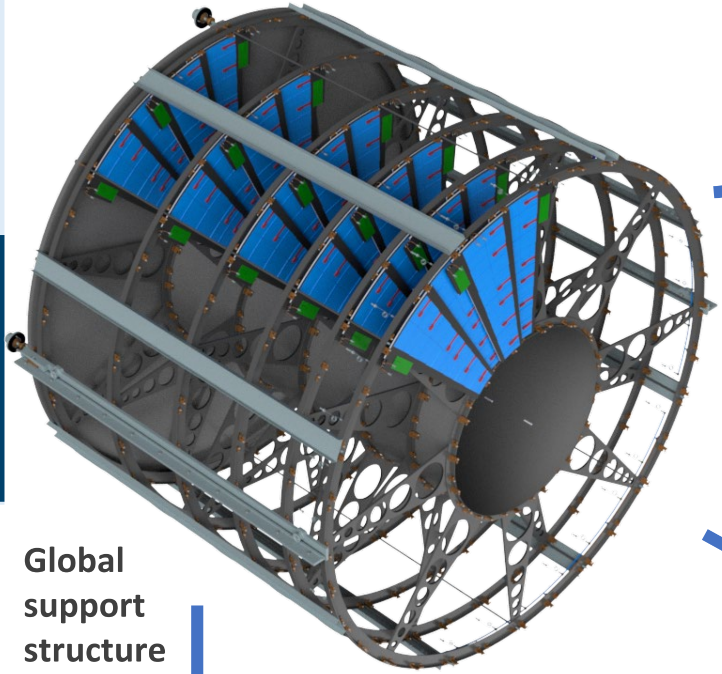




Petal

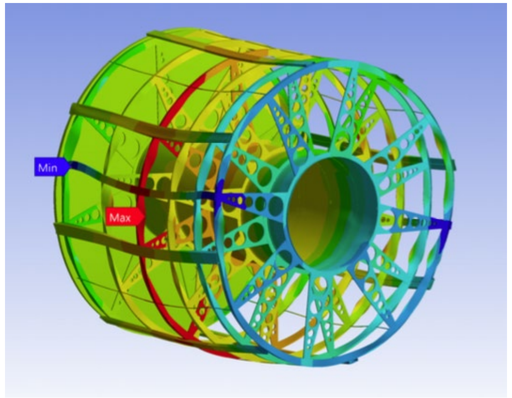


ITk Strip activities

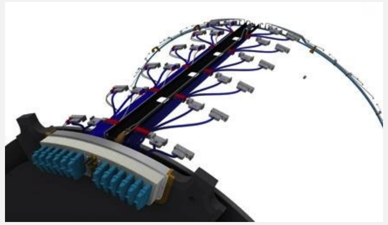


Global support structure

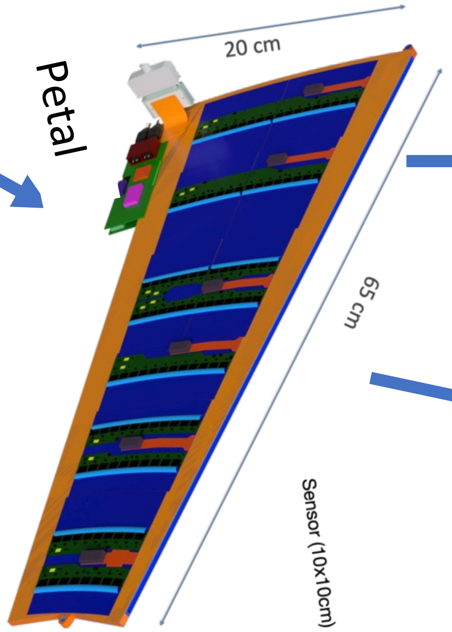
FEA simulations



Services

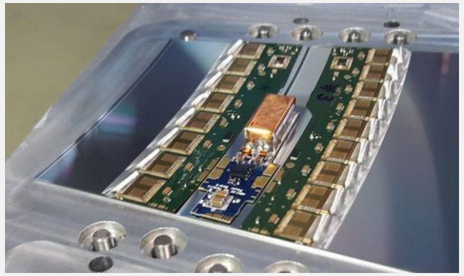


Petal



Petal loading

Modules

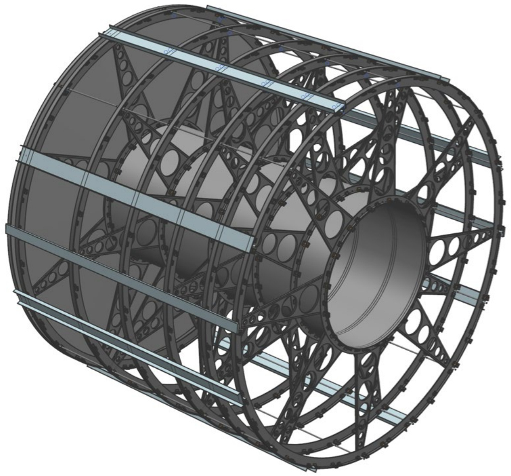


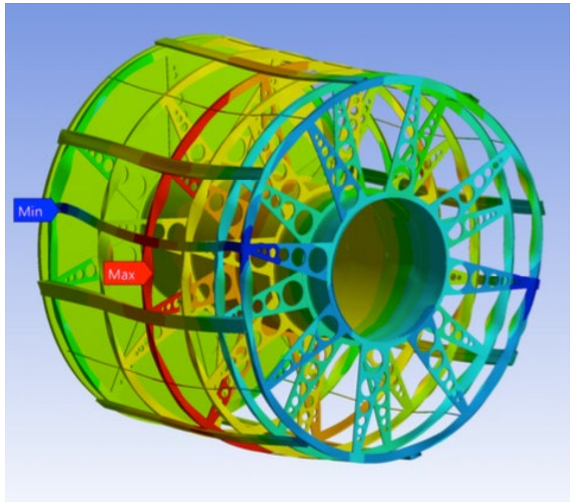
Cores
+
Bus tapes

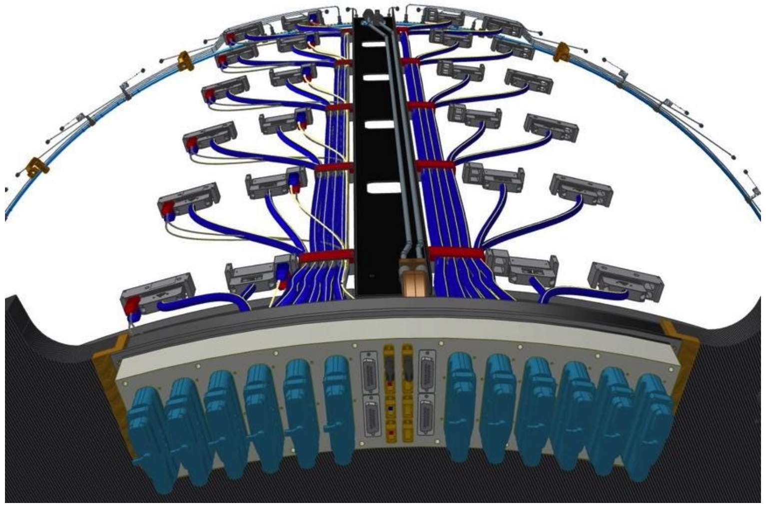
Posts of responsibility

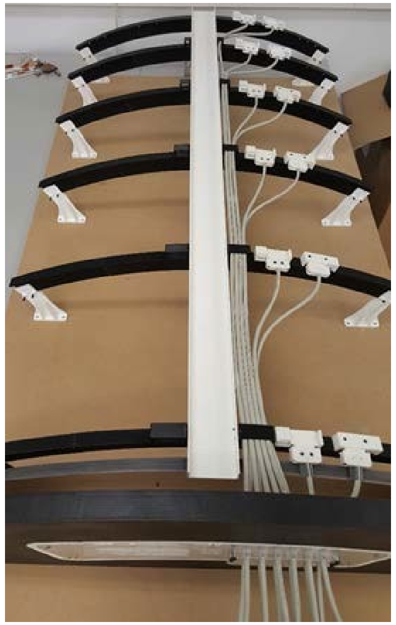
- **C. Lacasta** was Deputy ITk-strips Project Leader. Now Cores Activity Coordinator
- **P. Bernabeu** is Services Activity Coordinator
- **C. Solaz** is deputy Production Manager in charge of Part-flow and Logistics

Global Support & Services









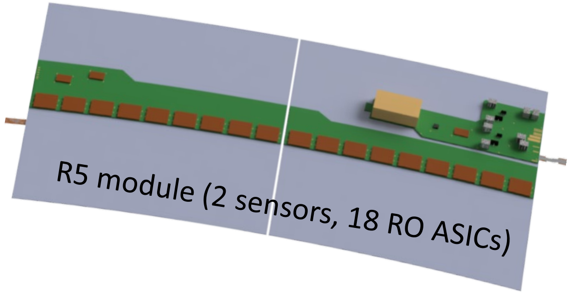
Designed the global support structure and petal fixation to the structure together with NIKHEF and DESY

Finite Element Analysis (FEA) to optimize the structural stability of the system.

- Design of the service module bringing power, control signals and cooling to the petals.
- Service patch panel in the structural bulkhead to connect to services beyond the ITk volume.
- Design of customized cables and connectors for both detector and off-detector connections.

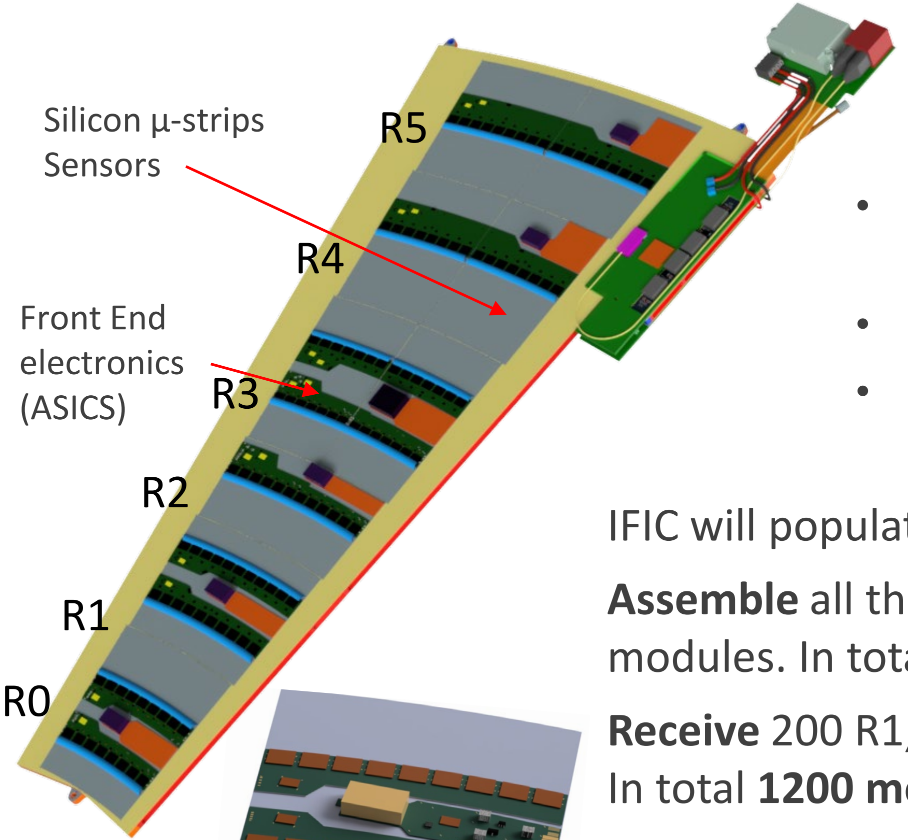
Assemble and test the **16 service modules** and install them in the EC mechanical structures

Petals & Modules

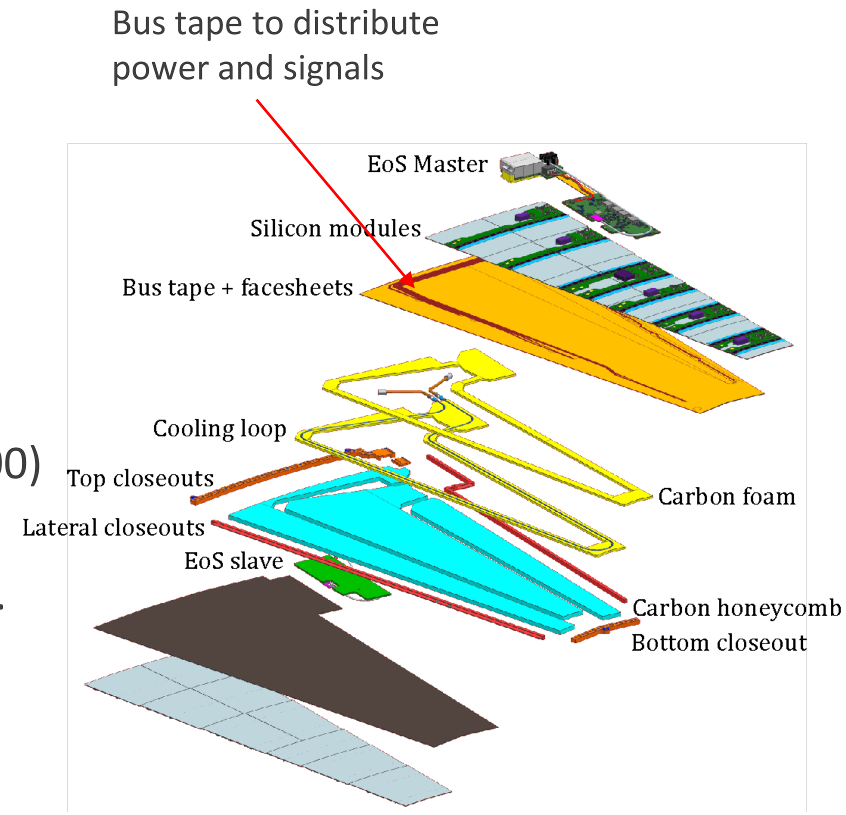


Sensors are glued on local supports (**Petals**). This is the building block of the EC system. It is a carbon fibre sandwich with integrated cooling and electronics.

Double sided object with **18 sensors**, 70cm height, 10-20cm width



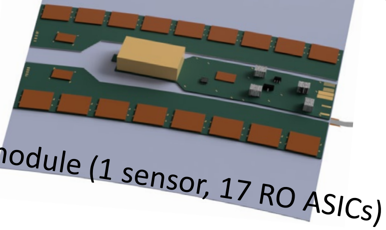
- Each petal has six rings of sensors. One sensor shape per ring.
- 3 upper radius rings have 2 sensors.
- In total, 18 modules, 9 on each side



IFIC will populate 100 petals:

Assemble all the required R0 (200) and R5 (2x200) modules. In total **600 modules**.

Receive 200 R1, 200 R2, 2x200 R3 and 2x200 R4. In total **1200 modules.**

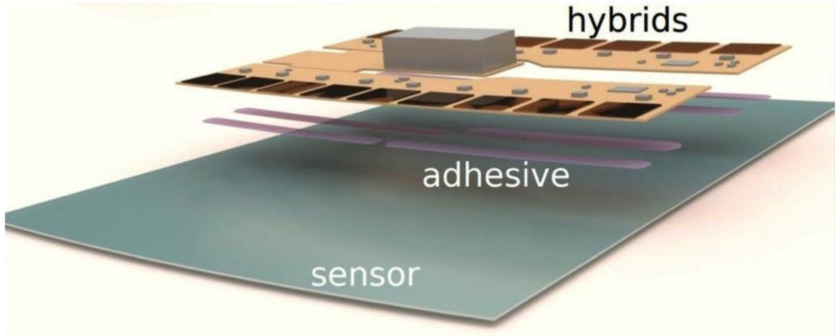


Module Assembly

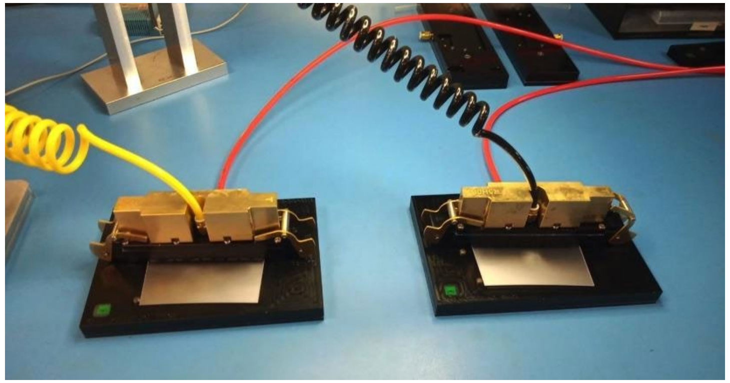
High precission assembly

Requires quite some infrastructure and parts coming from other sites in the collaboration

Parts need to be positioned within 10 µm



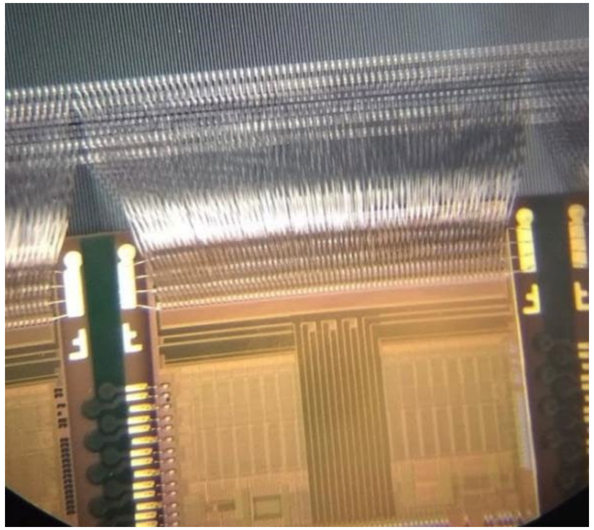
Glue thickness controlled to the **10 µm** level to ensure thermal path and control stray capacitances.

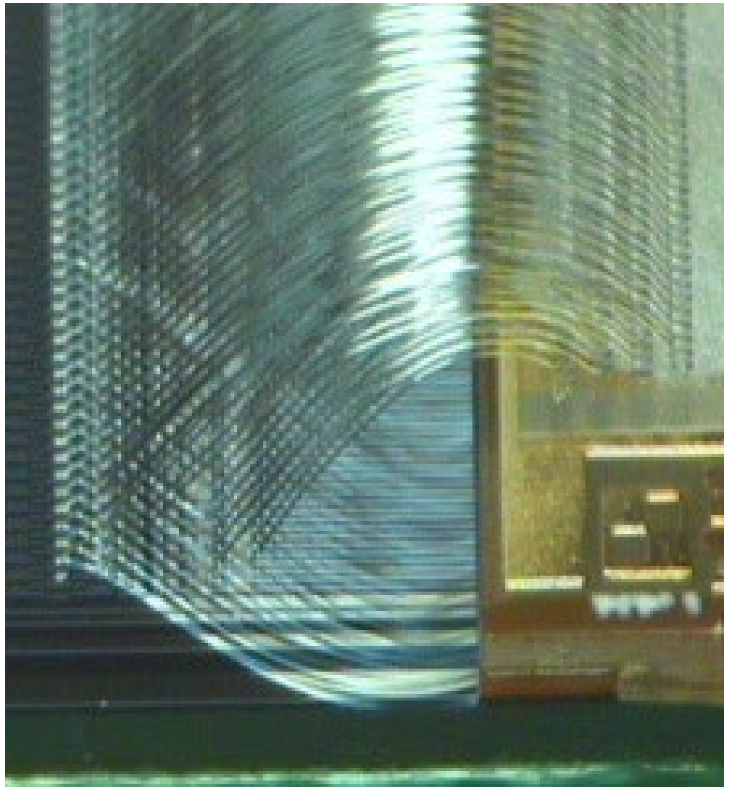


Wire bonding R/O ASICs to sensors is the lengthiest part of the process.

256 bonds/chip in 4 rows and approx. 1.4 m of wire.

Bond 7000 chips, close to **1.8 million wirebonds** and about **10 km of wire**.





4 row wire-bonding

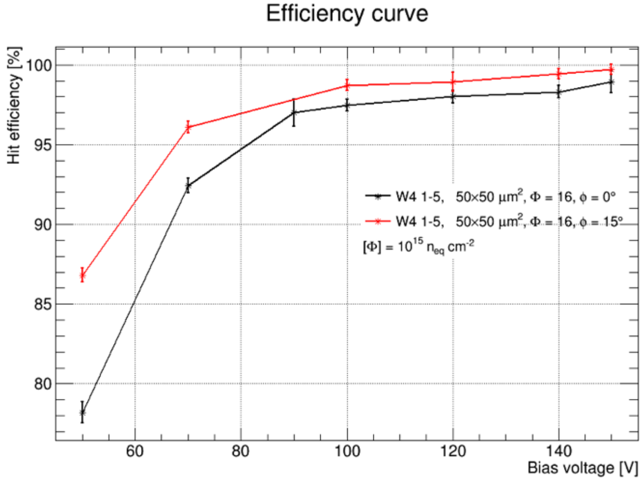
Different tooling for different modules. Gluing of hybrid to sensor has to be well under control.

Apart from assembly, we do thermal cycles for their QC

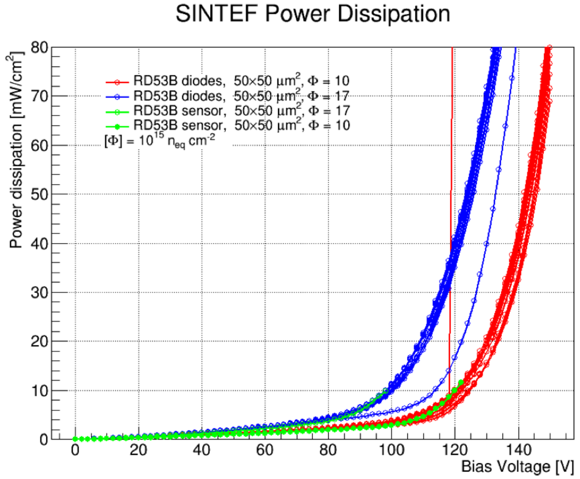
System tests, Petal QA/QC, Petal loading in backup

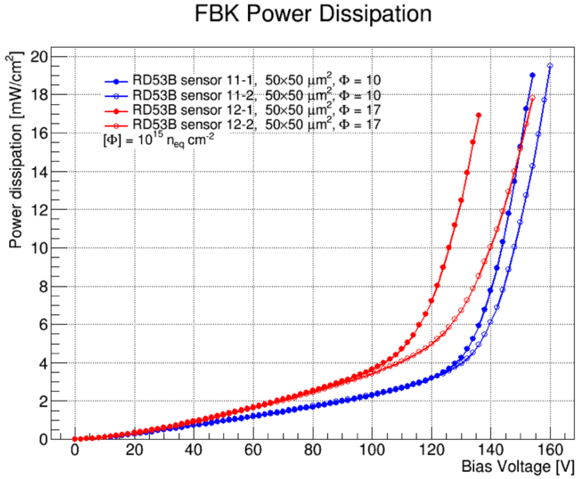
ITk Pixels: 3D sensor activities

- **Sensors for innermost pixel layer of ITk**
  - Radiation hardness up to ~1.7E16 neq/cm2 (replace inner layer once, due to ASIC)
  - Evaluation of ATLAS pre-production sensors from different vendors at IFAE/CNM
- In parallel we continue exploring the **limits of the 3D sensor technology**
  - Further irradiations and beam tests using CNM sensors from MS and R&D runs
  - Characterization for applications beyond HL-LHC (4D tracking, extreme radiation, ...)

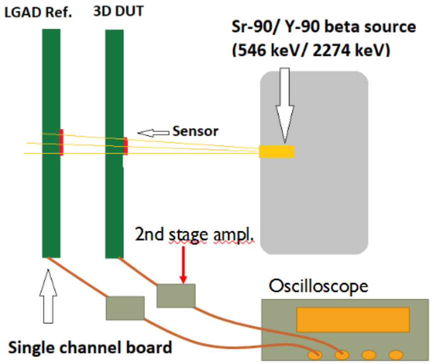


Beam test results of MS modules with CNM sensors





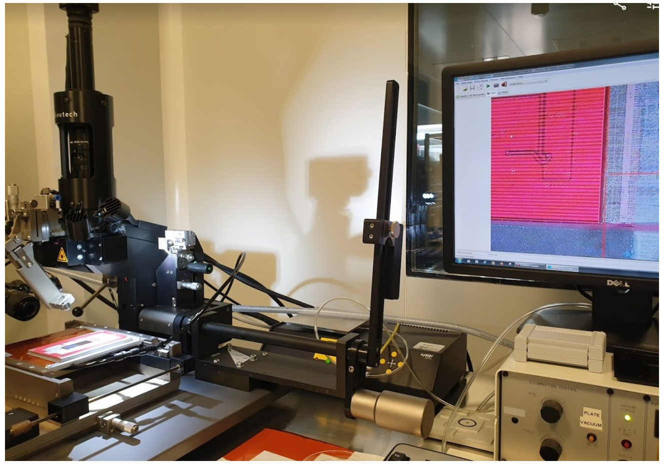
ATLAS pre-production sensors measured at IFAE/CNM



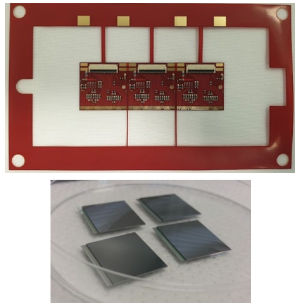
Also: studies of 3D sensors for timing (AIDAInnova), reaching ~30 ps resolution

ITk Pixel module assembly

- IFAE will assemble ~200 **3D modules/triplets for the innermost pixel layer** of ATLAS (whole L0 production)
  - Builds on the experience of IBL and AFP
- Multi-stage **qualification process,** schedule:
  - Dummy silicon and process/tooling qualification ✓
  - RD53A (planar) module qualification/testing ✓
  - ITkPixV1.1 module qualification/testing and pre-production
    - "Pre-production" Q4 2023
  - Full production (assembly and testing) with final chips
    - Q1 2024 – Q1 2026

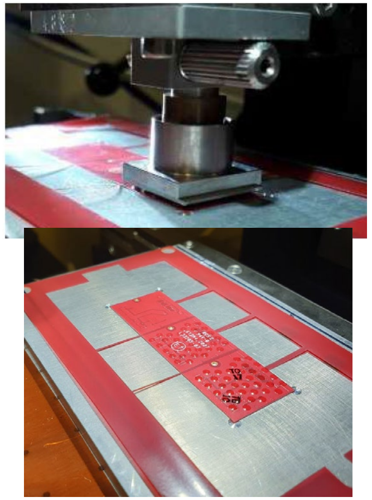


Pick and place machine (5um placing precision)

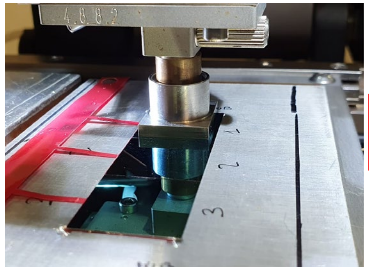


Bare module and flex

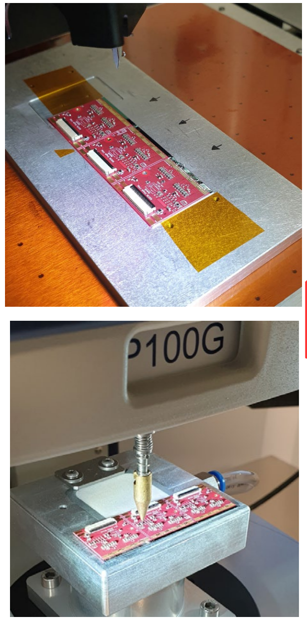
Initial metrology



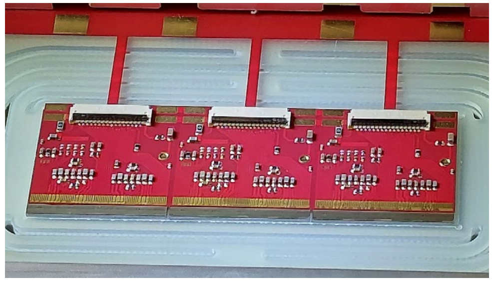
Glue deposition



Placing and glue drying



Wire-bonding & Pull-test

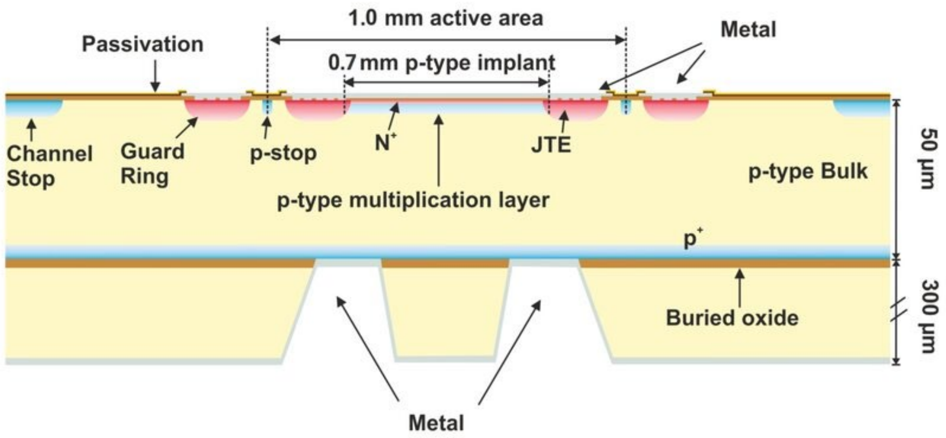


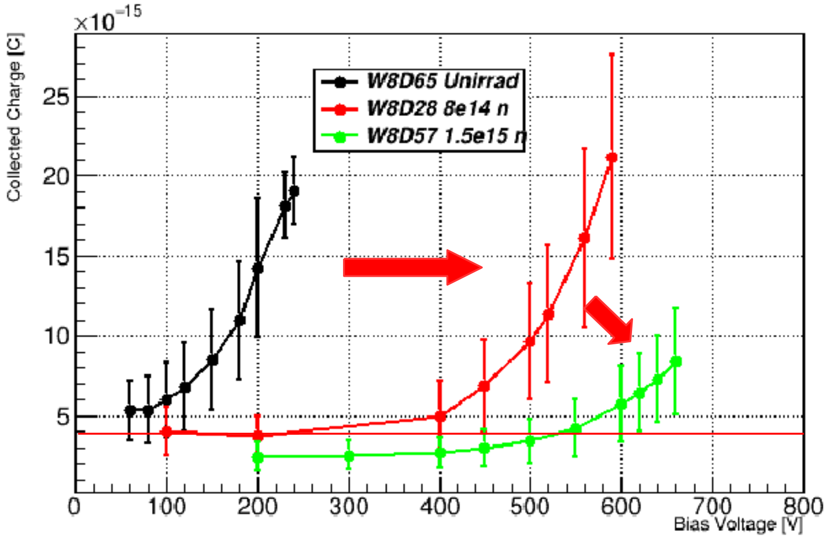
RD53A Triplet

~25 triplets already produced and tested

HGTD: sensor development

- **LGAD** sensors for HGTD required to provide Q=4fC after 2.5E15neq/cm2
- Studied performance of sensors in beam tests and lab
- CNM invented LGAD technology **but** operation of its sensors **after** irradiation bias remains a challenge



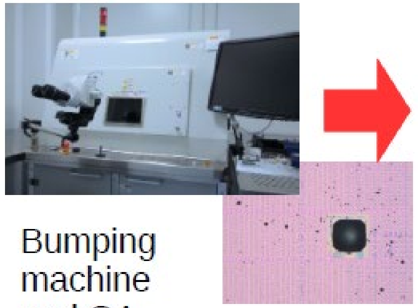


CNM LGAD technology	c-factor [cm²]
Boron	9.69×10^{-16}
Boron with carbon	9.33×10^{-16}
Si-Si no carbon	7.26×10^{-16}
EPI no carbon	8.53×10^{-16}
EPI carbon	4.9×10^{-16}
Si-Si carbon (being tested)	$(3.4\text{-}4)\times10^{-16}$ (TBC)

Tried different technologies including C diffusion in gain layer for improved radiation tolerance

HGTD Hybridization

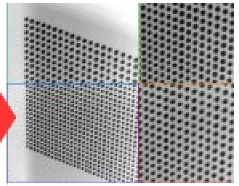
- Leading **module assembly** activities
  - Most complicated step: bump-bonding, done in-house at IFAE
  - HGTD Prototypes already bump-bonded at IFAE: 2x2, 5x5 and full size 15x15
    - IFAE also produces first ETROC1&2 hybrids (for CMS)
  - Successful full size ALTIROC2 hybridization for HGTD demonstrator program



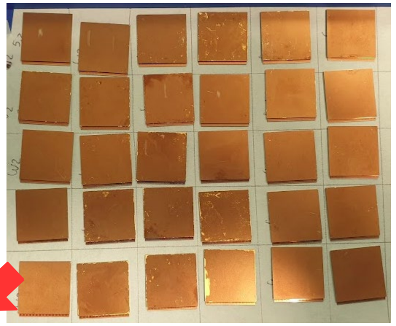
Bumping machine and QA

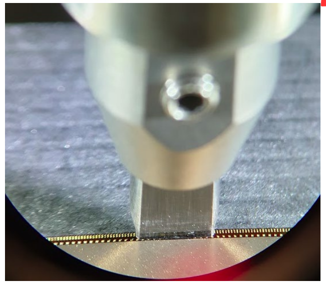
Reflow

Flip-chip/bump-bonding

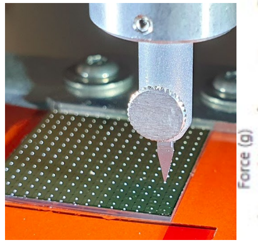


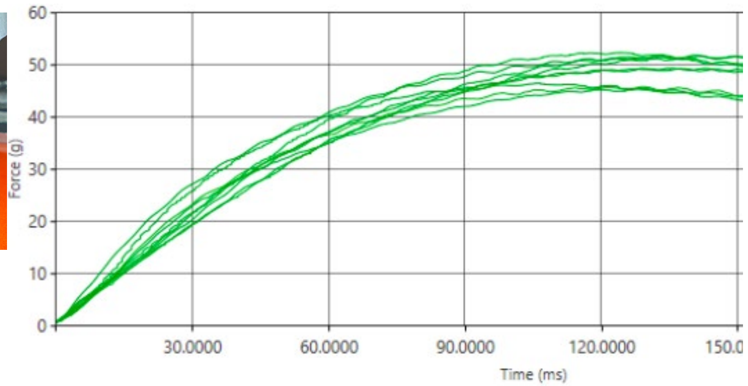
X-ray inspection (QA)





- Hybrid shear test
- **> 50 N** ✓
- Consistent with bump shear





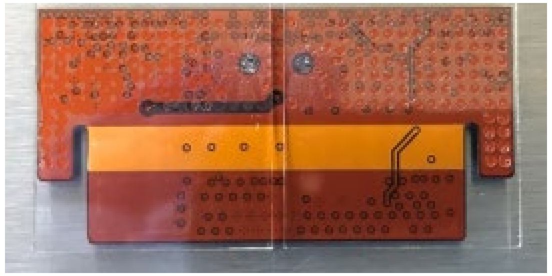
Bump quality check with shear tests at IFAE ✓

IFAE in good position to make significant contribution to HGTD construction

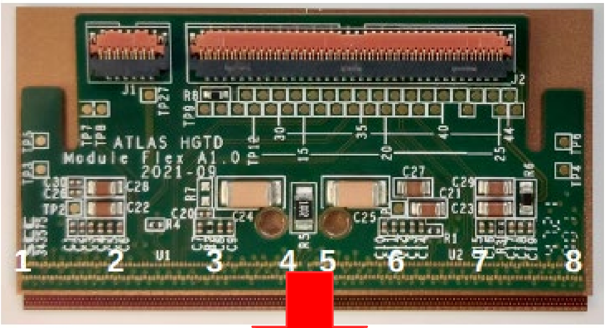
Note: pre-production Q2 2024

HGTD Module Assembly

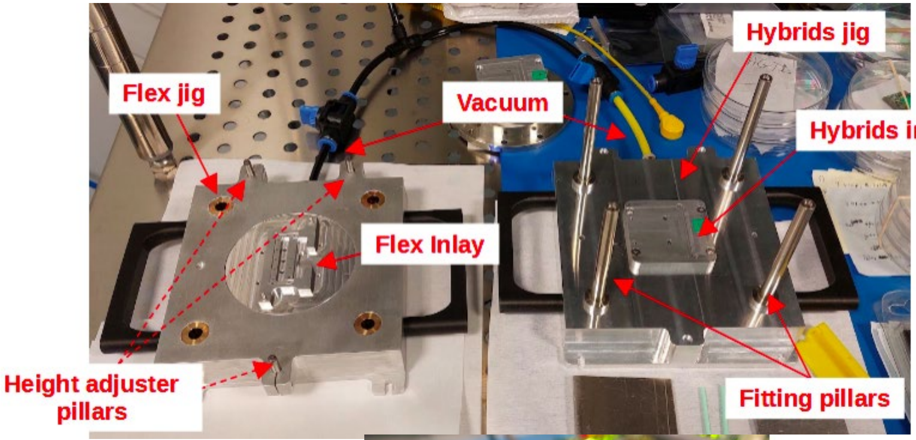
- IFAE will assemble ~1000 HGTD **modules** (10%)
  - Builds on the experience of IBL, AFP and ITk
- Multi-stage **qualification process**
  - Production of modules for the demonstrator ✓
    - More than **20 modules fabricated and delivered**
  - Pre-production Q2 2024, production 2025

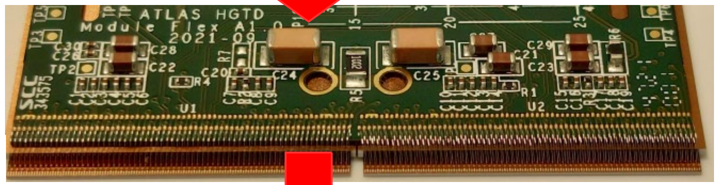


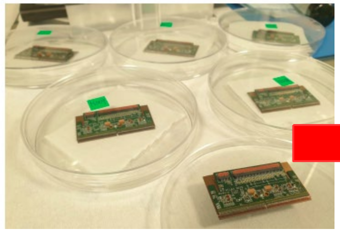
Glue distribution check with glass dummies



Metrology:
Thickness
Flatness
Gap
Glue weight
Etc...

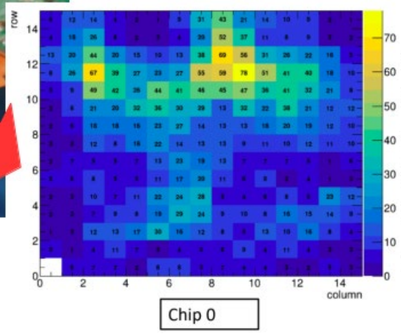




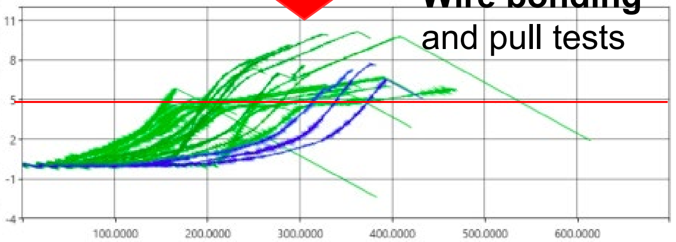


Full verification of hybrid connectivity on **all** sensor/process flavors

Sr-90 Test



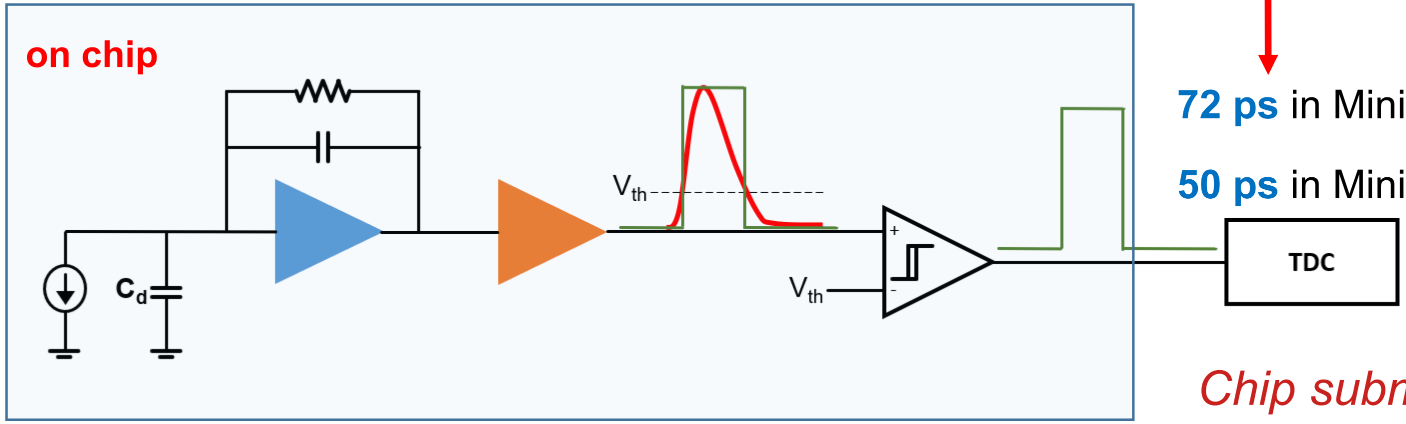
Wire bonding and pull tests



HGTD R&D: DMAPS

- Following IFAE work on **H35demo** (ATLAS upgrade) and **TaichuPix** (CEPC) investigating **DMAPS for timing** (replacement of inner layers if HGTD)
- IFAE joined effort by IRFU (CACTUS reached >100 ps time resolution, and Mini-Cactus ~60 ps)
  - **Mini-Cactus-v2** is an improved version of Mini-CACTUS:
    - Large collecting electrode pixels (1 x 1 and 1 x 05 mm^2)
    - **2 new pre-amp architectures to improve the jitter**
    - New discriminator with hysteresis
    - TDC and TW compensation off-chip

$$\sigma_{hit}^2 = \sigma_{Landau}^2 + \sigma_{jitter}^2 + \sigma_{TW}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

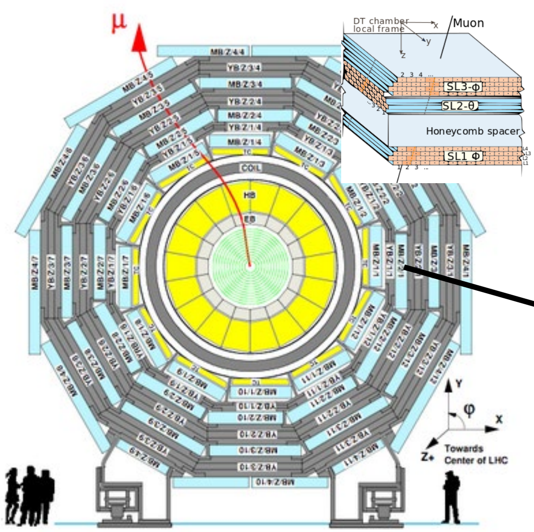


72 ps in Mini-CACTUS (simul.)

50 ps in Mini-CACTUS V2 (simul.)

Chip submitted June 2023

CMS Upgrade



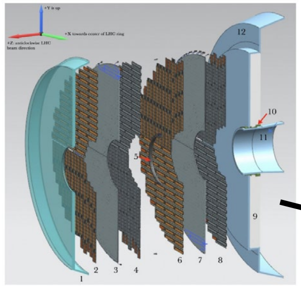
μ DTs + L1 Trigger

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

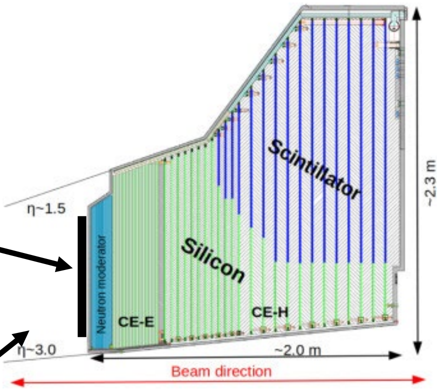
UAM
Universidad Autónoma de Madrid

Universidad de Oviedo

ITAINNOVA
CNM
Centro Nacional de Microelectrónica
IMB
UC Universidad de Cantabria
IFCA Instituto de Física de Cantabria
CSIC



ETL



HGCal

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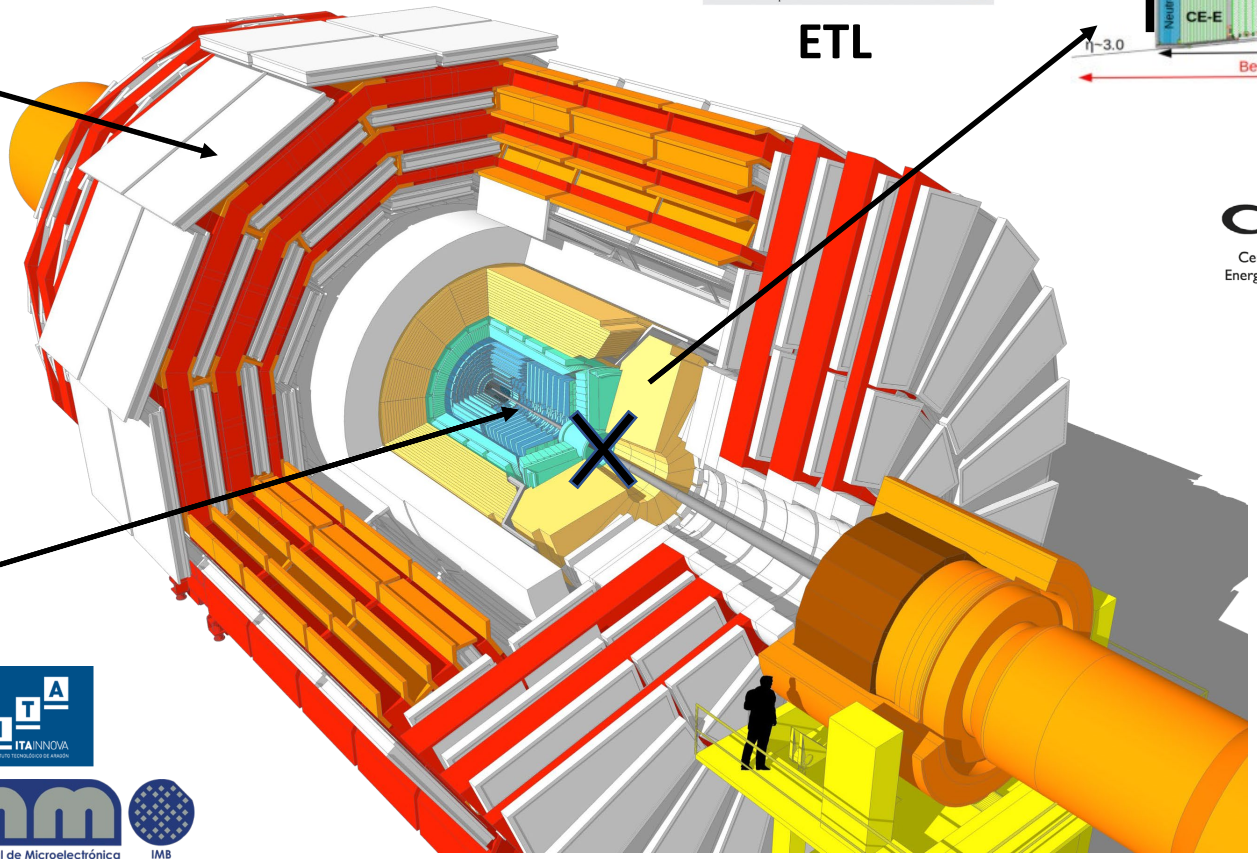
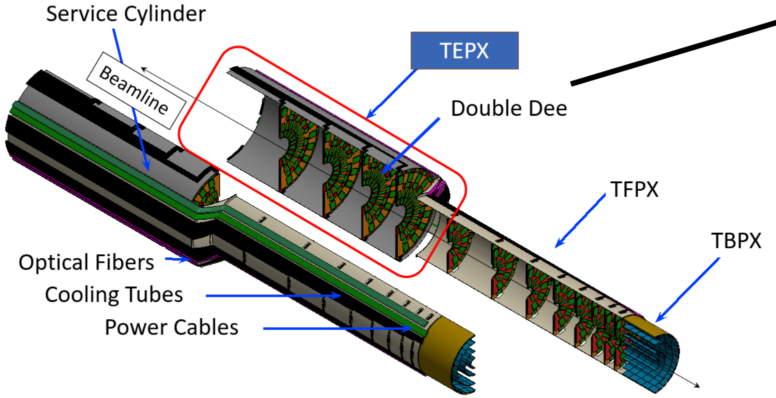
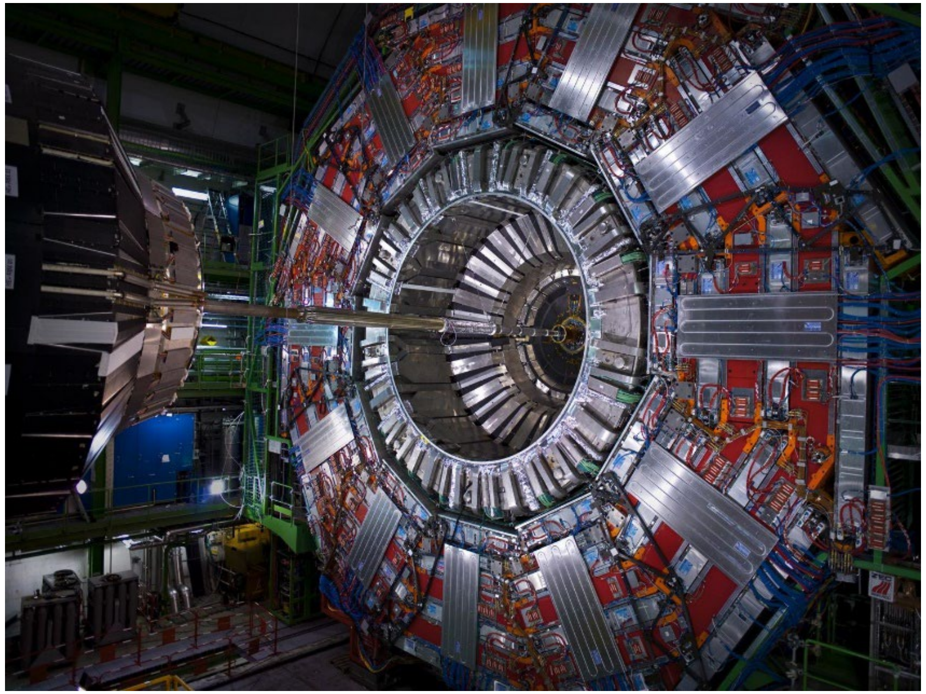


Inner Tracker

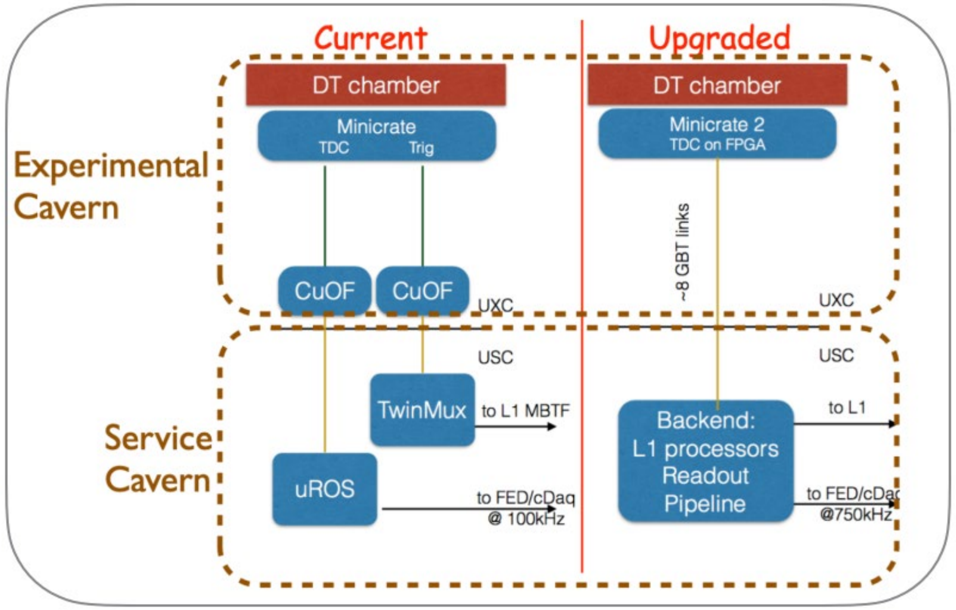


ITAINNOVA
CNM
Centro Nacional de Microelectrónica
IMB
UC Universidad de Cantabria
IFCA Instituto de Física de Cantabria
CSIC

CMS Muon Drift Tubes



- 250 CMS DT gas chambers instrument the barrel region of the return yoke providing superb Muon identification, reconstruction and triggering over > 40% of CMS Volume. CIEMAT is significant collaborator of DT (~1/4) since CMS construction.
- In HL-LHC: chambers remain, but full electronics system is replaced to match CMS operating conditions.
- Electronics have been redesigned with a new architecture with the goal to enable offline reconstruction precision and methods to the L1 t (HW) trigger.



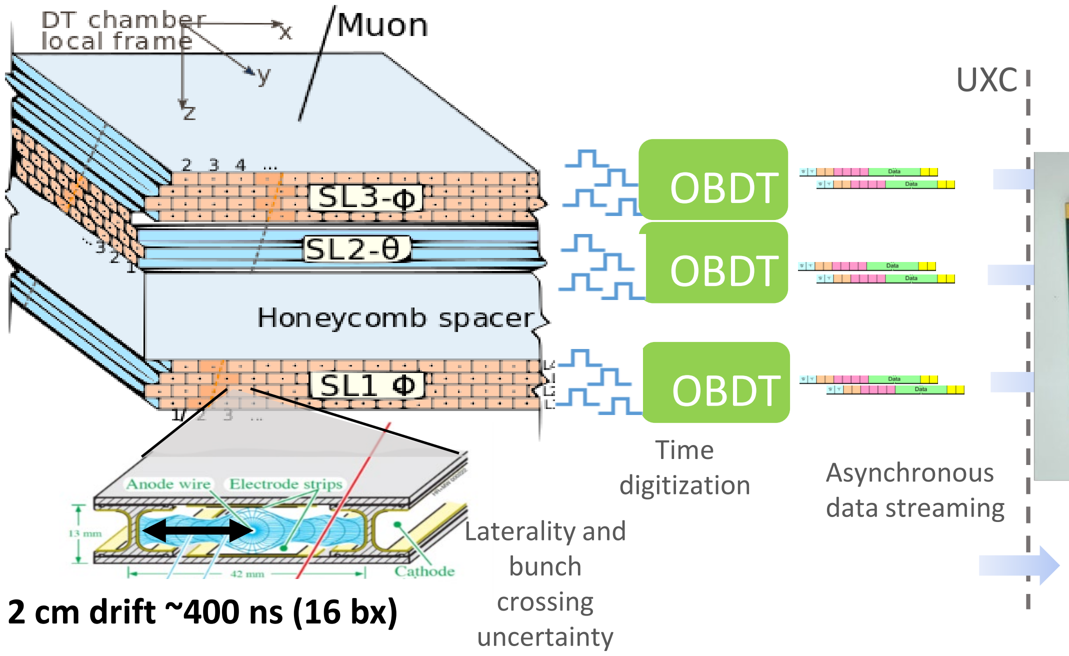
- Present system relies on filtered data through copper links to get the data out of the chambers.
- Profiting from rad hard optical link technologies, all hits are shipped to the backend where Trigger Primitives and Readout Event matching will be now produced by powerful FPGAs without radiation constrains.
- System started in production status after internal review (ESR, May 22).

- CIEMAT has lead Phase 1 upgrades and Phase 2 since conception from different positions (Project Leader, Upgrade, TDR editor…). Presently C.F. Bedoya DT Upgrade Coordinator.
- Spain committed to 26 % of the DT Upgrade Core Cost.

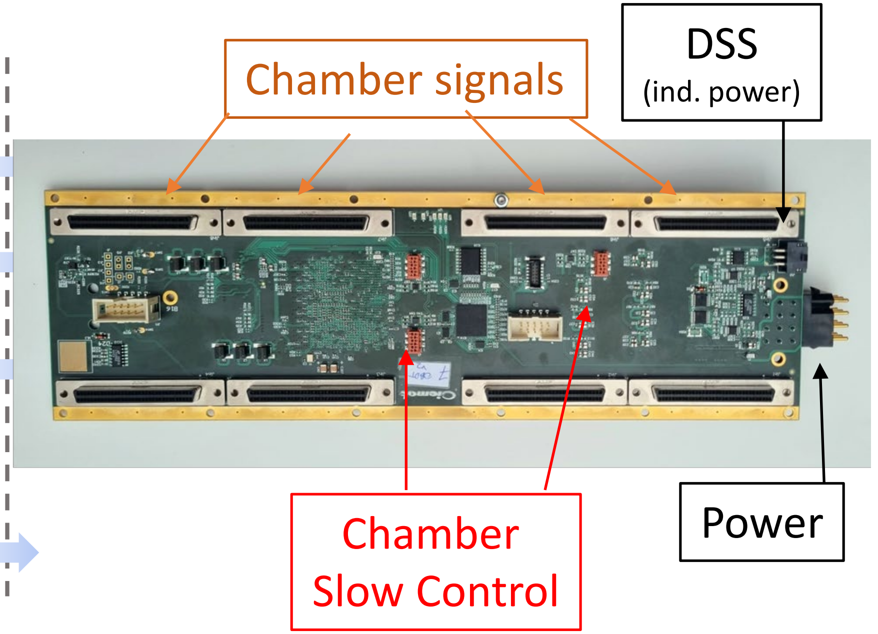
CSIC Consejo Superior de Investigaciones Científicas
IFCA Instituto de Física de Cantabria
UC Universidad de Cantabria

DT FE electronics design & functionality

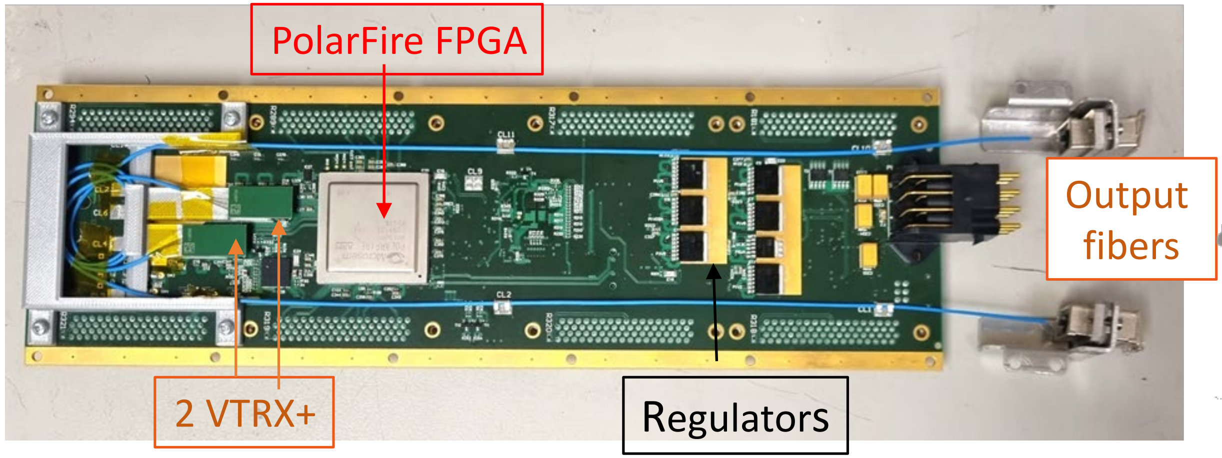
- The Frontend system digitize the LVDS hit times coming from the chambers in rad hard PolarFire Microsemi FPGA which can instrument > 200 channels with a precision of 0.8 ns, enough for the DT chamber precision.
- There will be ~1000 such boards of two kinds: ϕ and θ. As the θ SuperLayer chamber connectors are deep in the yoke and cables cannot be replaced without extracting the chambers , a specific board has been designed by CIEMAT to serve the legacy cables.
- It also needs to provide slow control to legacy chamber systems as : i) inside-chamber analogue electronics ii) pressure sensing iii) alignment hw iv) a time calibration system (developed with RTWH Aachen). It is protected by an onboard safety system based on temperature and power sensing, complemented by a humidity sensor monitoring (cooling leaks in CMS happen regularly).
- After several prototype cycles, final revision ongoing before full production is launched (**220 boards**).



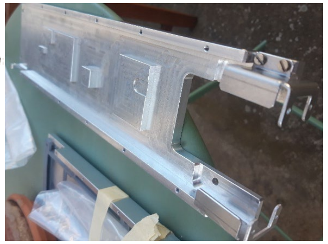
2 cm drift ~400 ns (16 bx)



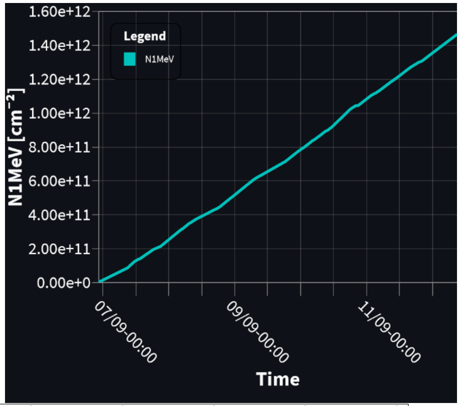
OBDT-θ production and testing



Assembly in Aluminum frame which acts as thermal interface and as mechanical and electro-magnetic shield, being ready for field deployment after careful QA tests.

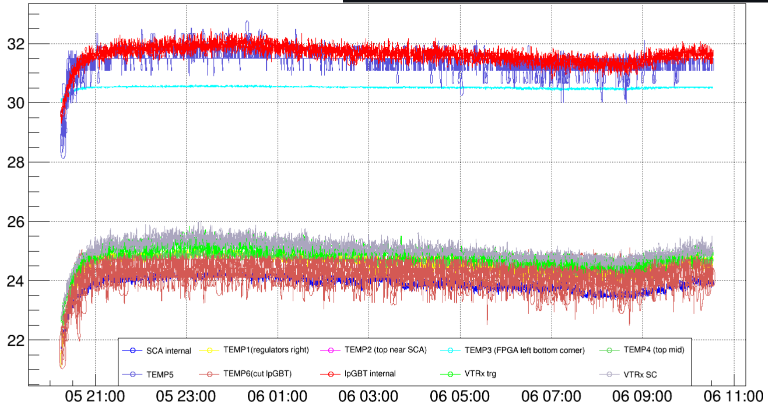


- Several thermal fillers tested for thermal behavior and for irradiation degradation at CIEMAT's Co60 "Nayade" facility
- Optimal thermal interface and low power consumption allows operation <40 C when in normal operating conditions as in CMS (water -cooled). In the lab we have routinely operated stably without cooling when inside the frame.



- Previous irradiation of OBDTv1 (GBTx) prototype at CERN CHARM facility and OBDTv2 phi in medical accelerator➔ MicroSemi PolarFire can be used with intended functionality for the required fluences.
- This September irradiated present OBDTθ (lpGBT) prototype:
- No intervention was required until reaching a dose equivalent to **20x HL-LHC**.

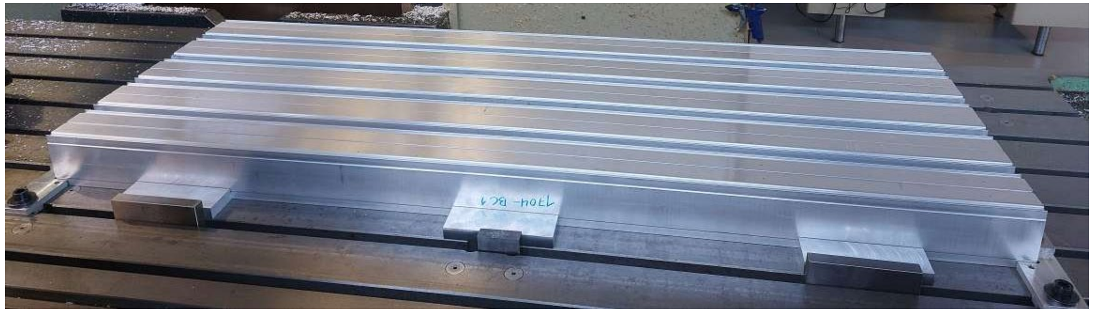
OBDT



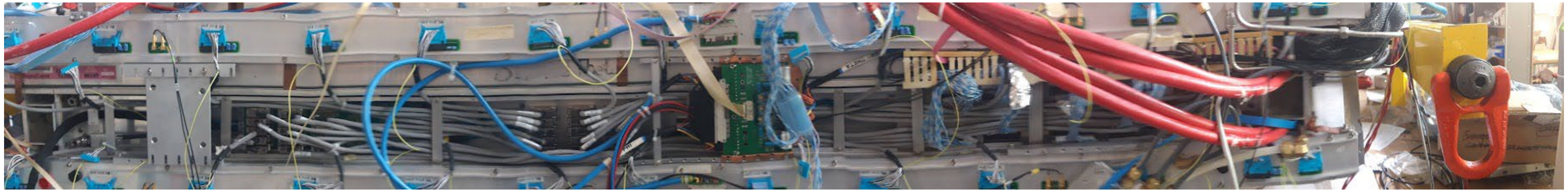
- Full production will suffer accelerated aging "burn-in" test in an oven @ 70 C, setup being prepared @ CIEMAT

DT Minicrates

- Phase 2 Minicrate design inherits from legacy Minicrate: avoid integration problems in the chamber by keeping design, modify only inside of the profile for optimal cooling.
- Instrumentation of the 250 chambers requires several (**11**) types of minicrates. CIEMAT produces and mechanizes all the Minicrate profiles and the OBDTθ frames.



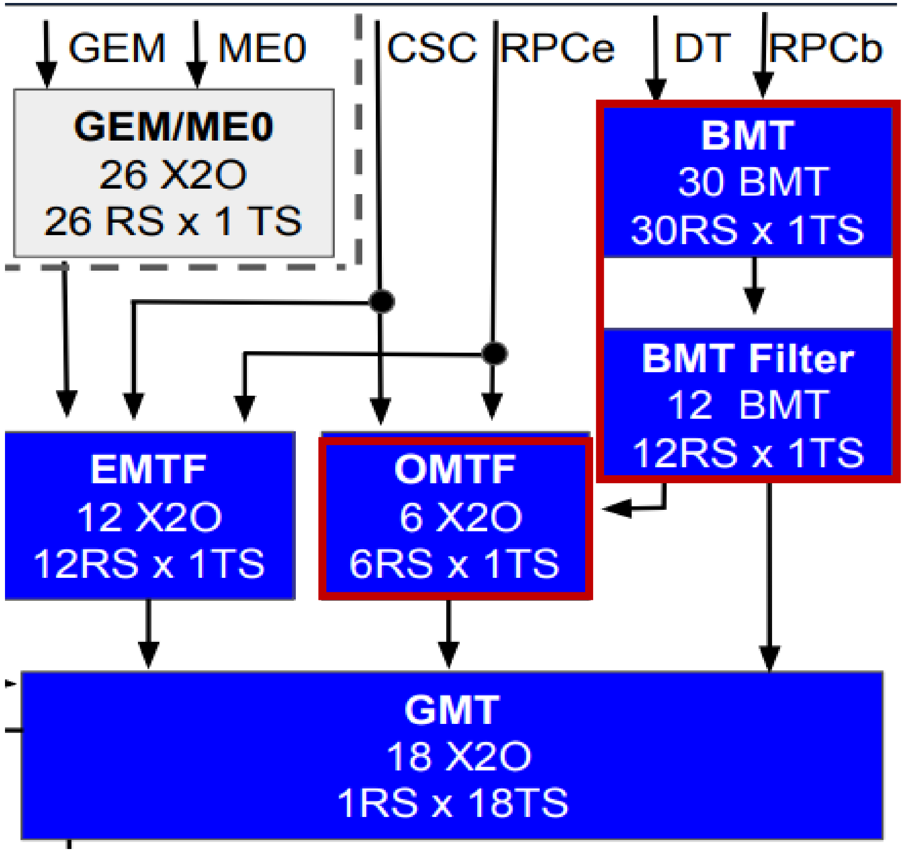
- Mechanical and cabling verification of the MB1 minicrate design in a MB1 chamber with realistic services and phase 2 cables at P5 surface:

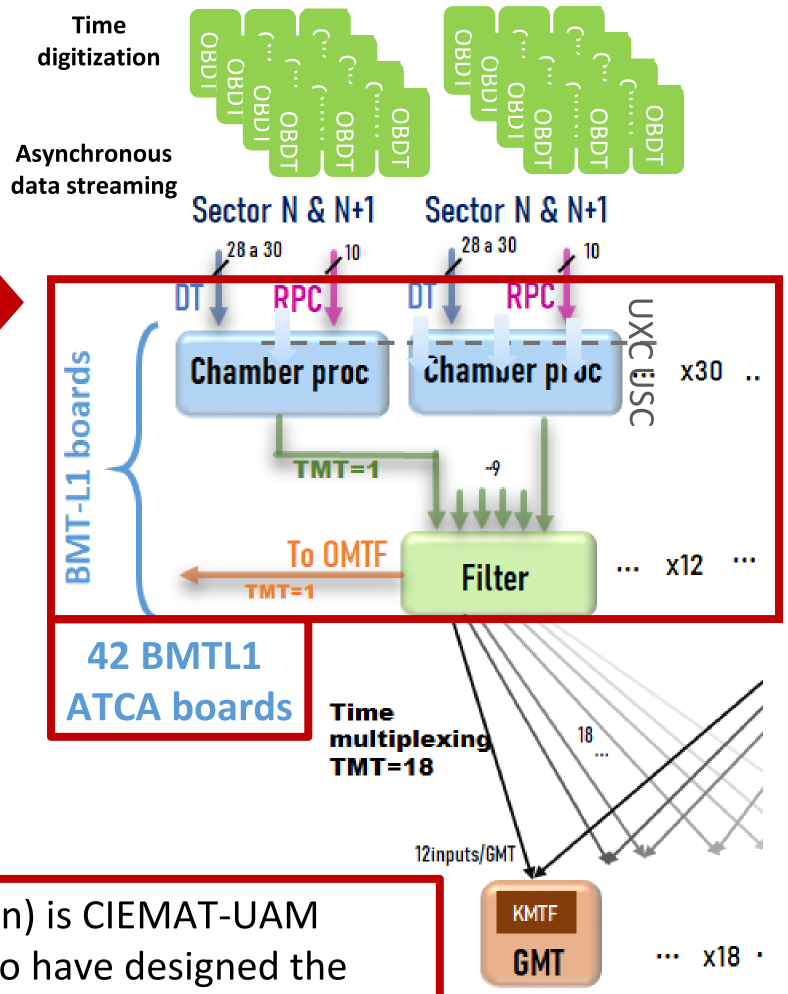


- CIEMAT getting ready to i) produce OBDTθ frames, ii) assemble all OBDTθ boards into frames, iii) qualify them testing all functionality and iv) assemble MB2 minicrates (adding OBDTϕ produced by INFN).
- All minicrates should be at CERN before installation access is allowed by CMS, ½ year after LS3 start.

Muon L1-Trigger Upgrade

UAM participated in L1T already during CMS construction CIEMAT and U. Oviedo joined later as a result of Phase1. C.F.Bedoya is L1T Resource Manger, S. Folgeras L1T DPG coordinator.





- **BMTL1** (OBDT data backend and trigger primitive generation) is CIEMAT-UAM responsibility in collaboration with U. Ioannina, Greece, who have designed the ATCA board.
- Uni. Oviedo is responsible of **OMTF** with Polish collaborators and based on X20 board (UCLA) and has SW responsibilities in BMTL1.

L1-trig: Analytical Method (AM) Algorithm

- Analytical Method developed by CIEMAT-UAM to implement analytical solutions for reconstructing the DT trigger primitives for Phase 2. It exploits the maximum resolution achievable by the DT chambers, bringing the hardware system closer to the offline performance capabilities.
- **Close collaboration between CIEMAT-UAM and Uni.Oviedo**
- To be complemented by BMTL1 Filter time coincidences across Muon Stations for rate control, confirmation
- AM is implemented in FW and there is a **perfect emulator-FW agreement** (time, slope, position).

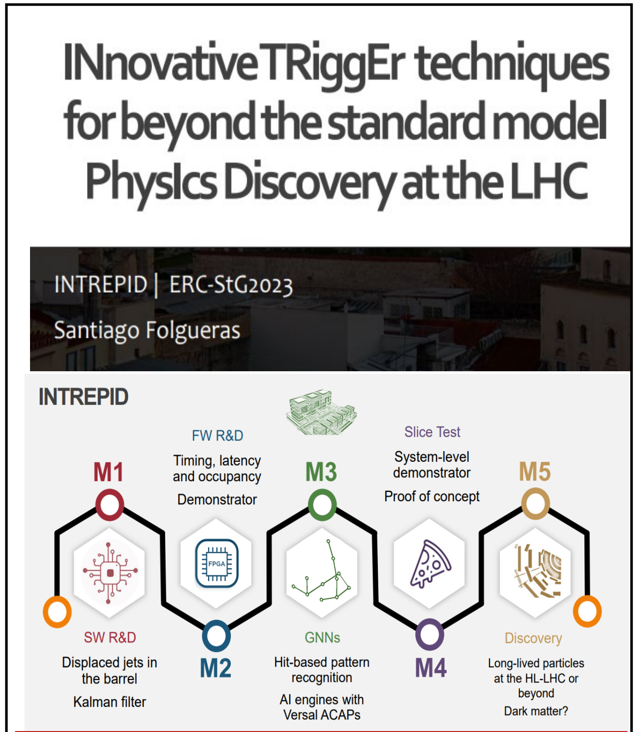
AM performance during collisions:

FE: 13 **OBDTV1 (GBT) in YB+2 S12**
Backend : Phase 1 HW (TM7)
Fully integrated in CMS (power, TCDS, DAQ, CMSSW)
Extensively operated in GR during LS2 and Run3 & calibrated, delivering **superb performance**

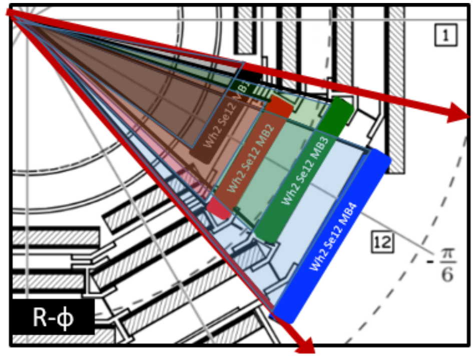
Demonstrated new DT BMTL1 Phase 2 architecture

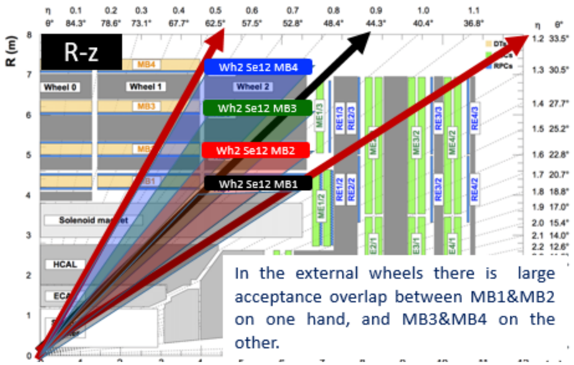
2023: update demonstrator with **9 OBDTv2 (lpGBT) prototypes** in neighbouring sector and backend prototypes (**BMTL1 ATCA board** & Slow Control), which have already operated during collisions.

2024: continue updating the Slice Test@ P5 as it provides ideal field testing



Recent 5-y **ECR grant!** Focus on displaced signature searches at OMTF&BMTL1. Advanced platforms.





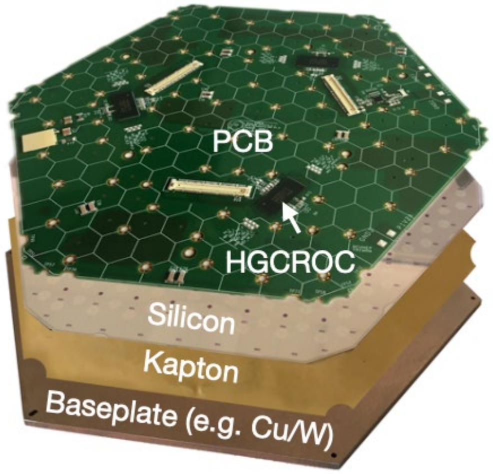
Next: BMTL1 & OMTF boards (X20) will be integrated in L1T 904 integration facilty in preparation for final CMS internal review, which is expected soon.

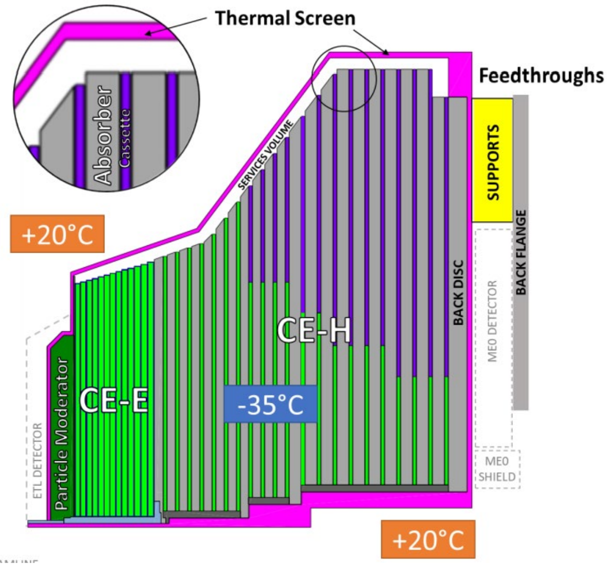
HGCal

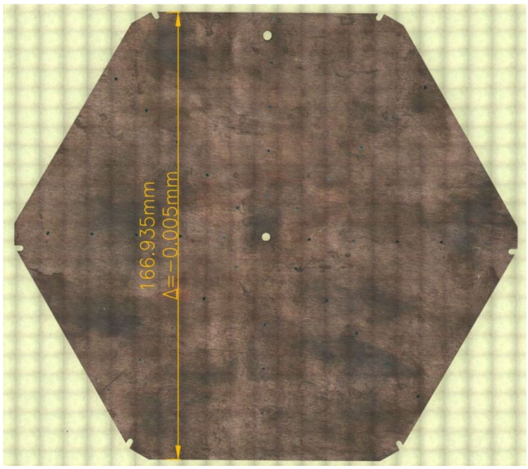
Radiation degradation and physics potential of having good reconstruction in the forward rapidity region:

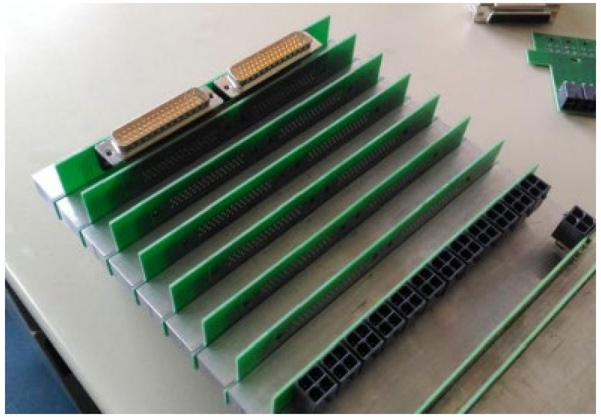
replace endcap ECAL/HCAL with high granularity calorimetry techniques pioneered by CALICE for ILC.

CE-E & inner CE-H use **Si sensors**, outer CE-H scintillator plastic as sampling material.









Since October 2022 CIEMAT, among others, has answered the call from CMS Upgrade management to help HGCAL (after Ukraine invasion):

- Trials of cutting CuW baseplates (23 pieces): heatsink &interface of the Si modules. Building specific tools, measuring the results and establishing a process according to specs. Also investigated its density homogeneity using industrial radiography tools available at CIEMAT.
- Limited participation in commissioning activities at CERN (participation in SPS testbeam of HGCAL modules)
- Designed and produced the first prototypes of HV and LV thermal screen feedthroughs, used to pass the thermal screen PRR. Boards are simple but strict conditions due to harsh environmental conditions (radiation, magnetic field, cryo)

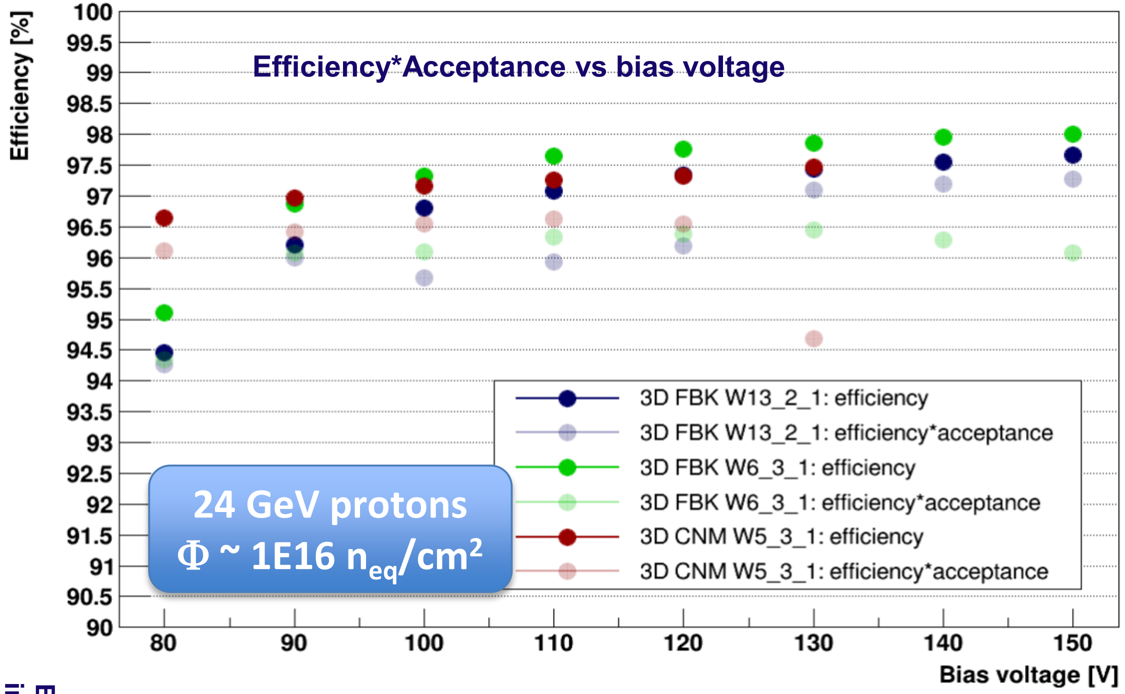
CMS Inner Tracker Upgrade: 3D pixel activities

- Characterization of 3D sensor radiation tolerance in TB campaigns
- **IT TBPX L1 to be implemented with 3D 25x100 μm pixel sensors**

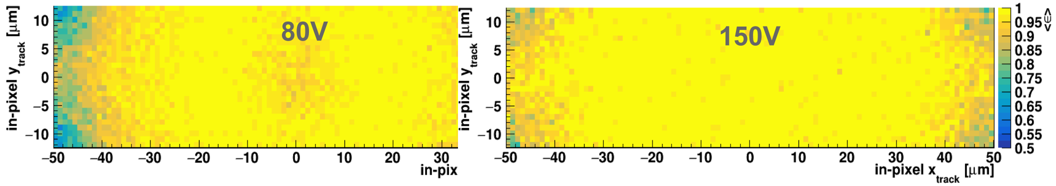
Efficiency at normal incidence: higher than 97% for all the modules after full depletion.

- Modules tuned to average thresholds of 1000e- at T≃-30º
- The **efficiency plateau starts at around 90V**

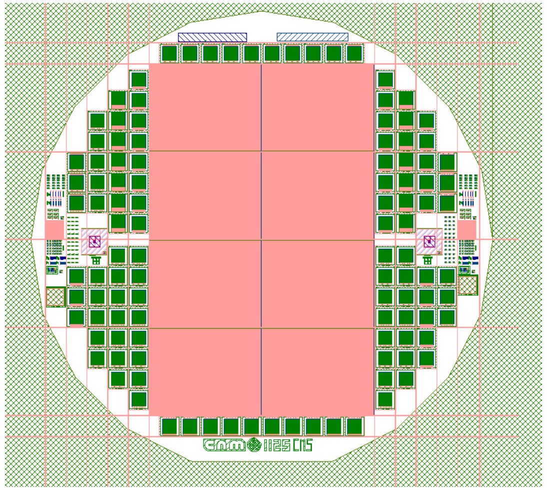
→ operation range: around 40V for CNM and 50V for FBK modules.

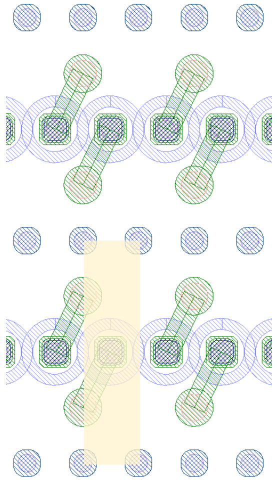


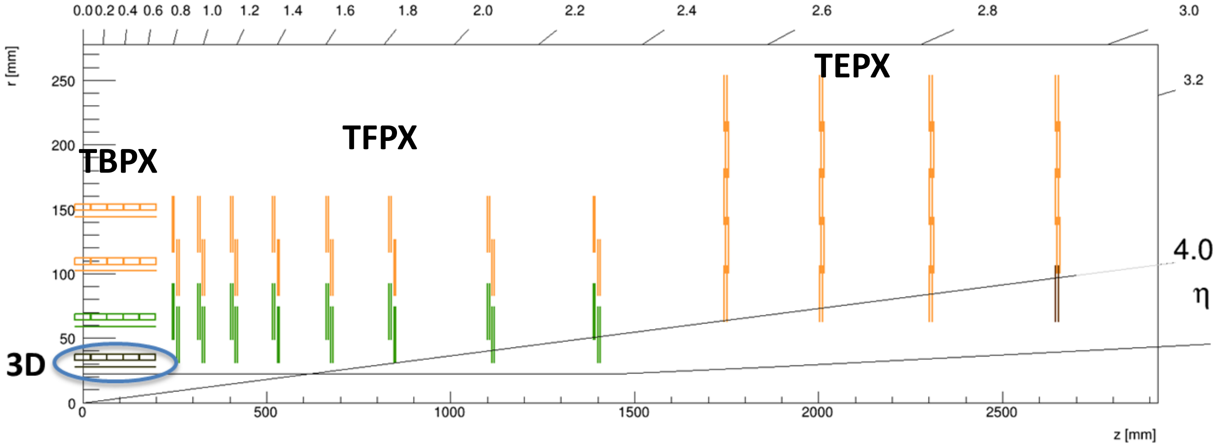
Efficiency map in the pixel cell



CNM: 100 mm SiSi wafers (150+200 μm)
8 CROC singles 25x100 (p-stop)







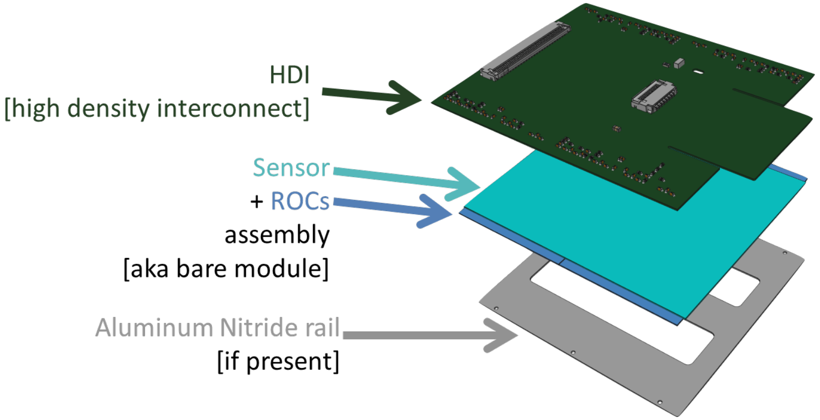
Runs 4+5 TBPX L1: Fluence 1.9E16 1 MeV n_{eq} & TID 1.0 Grad

IFCA coordinates IT sensor group since 2018

CMS IT modules

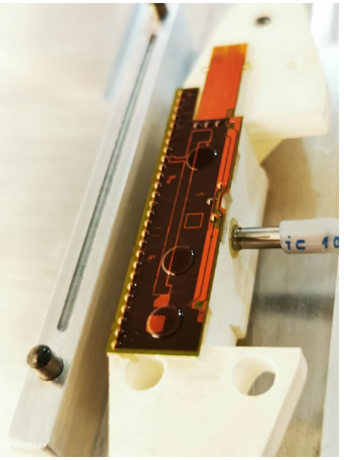
IFCA aims to assemble:

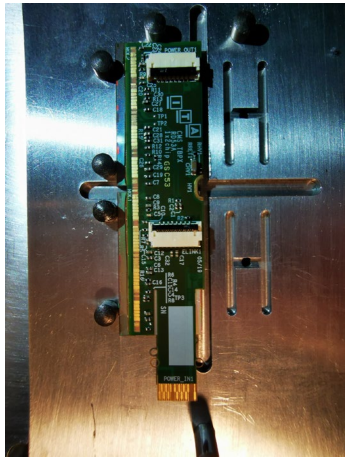
- ~ 50 **TBPX L1 1x2 modules** (half of TBPX L1): ITAINNOVA 1x2 HDI, 2 1x1 3D sensors
- ~ **300 TEPX 2x2 modules** (planar sensors)
- (TFPX mostly a USA project)



TBPX 1x2 3D:
Glue deposition via stencil
Micrometric precision positioning via jigs

TEPX 2x2:
Glue deposition via stamp
Micrometric precision using robot

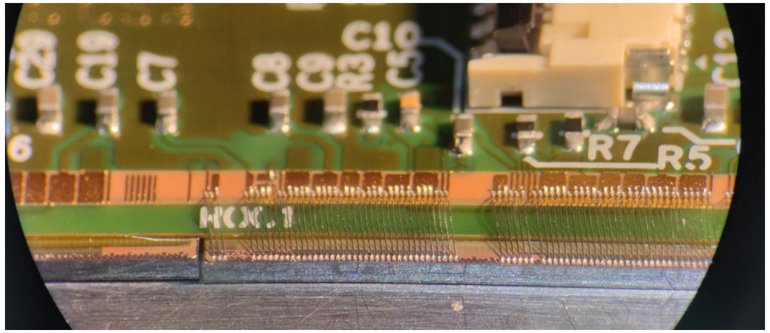


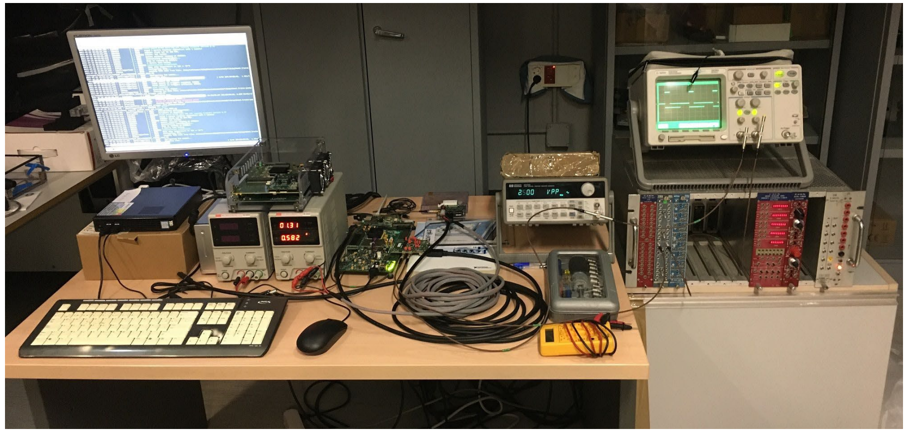


Module QC

- Pull tests on dedicated wire bond pads
- Thermal cycles in climate chamber
- CMS DAQ readout: Ph2_ACF for system tests
- X-ray tests for pixel hit map

Wire bonding: ~200 wire bonds / ASIC





FE, HDI, EMC, Serial Power

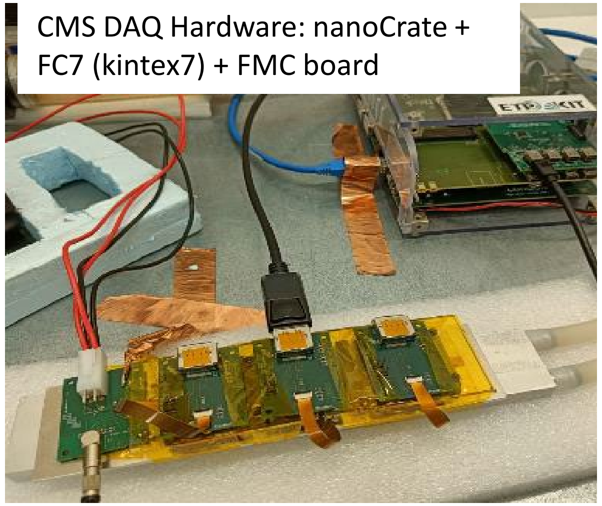
CROC simulation models & ETROC testing (ASICs)

CMS Pixel & ETL System prototyping - Electronics & DAQ

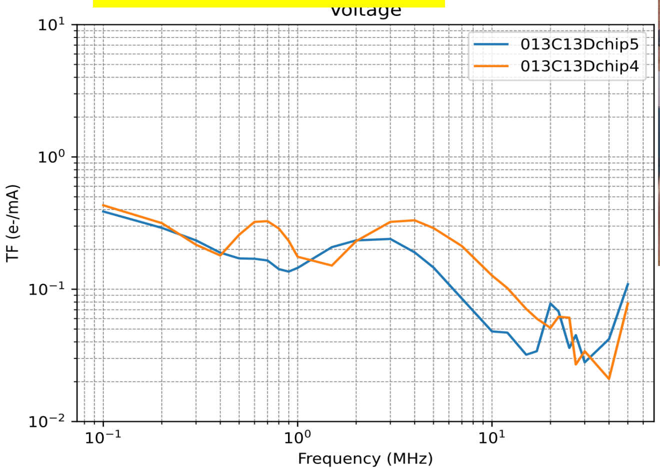
Serial powering

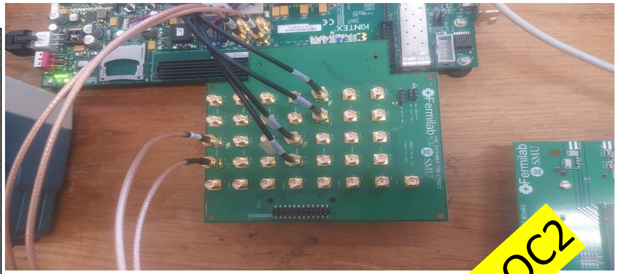
Hardware, gate-ware and firmware for ASIC/DAQ comm. and control.

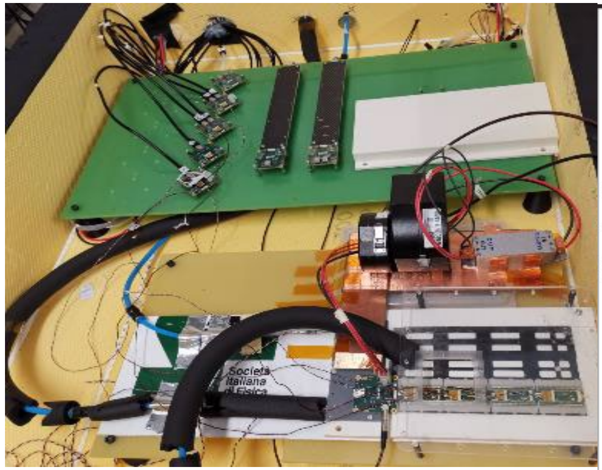
<u>3D – RD53A based</u> Serial Powering protoype (3 modules) – TF test at ITAINNOVA

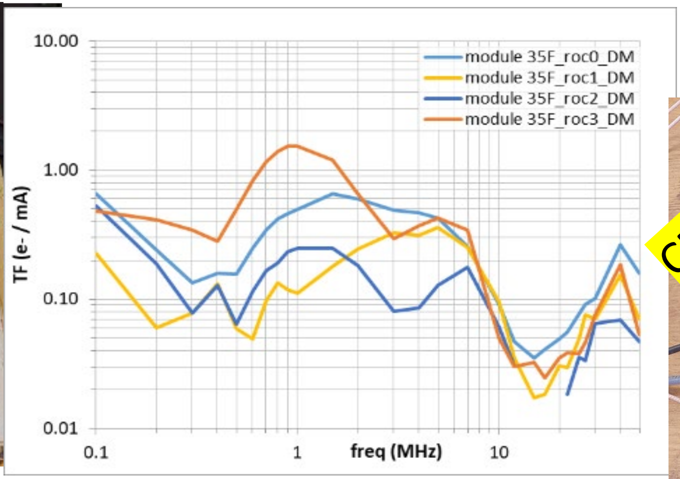


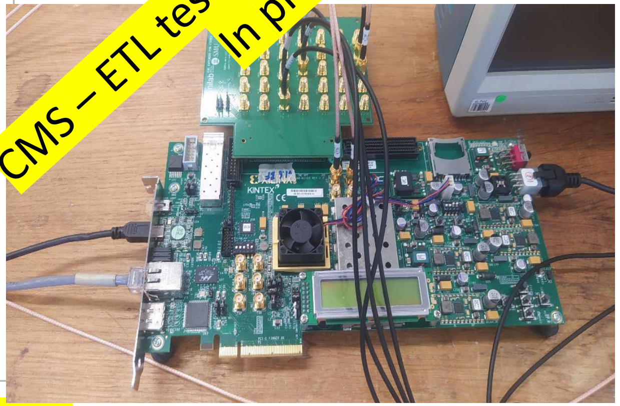
CMS DAQ Hardware: nanoCrate + FC7 (kintex7) + FMC board









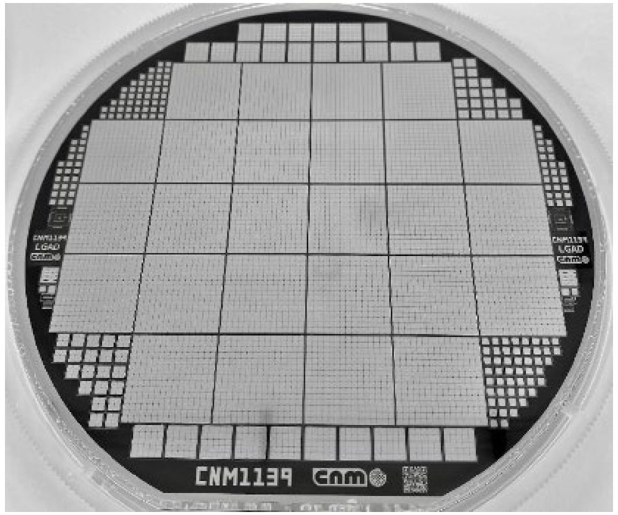


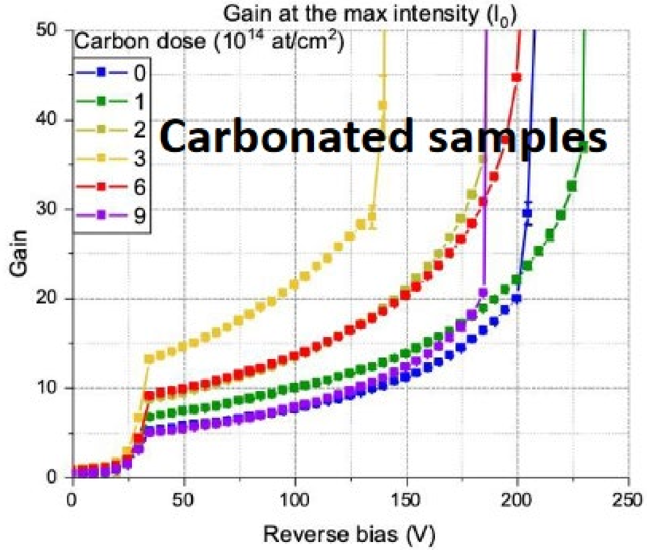
CMS – ETL test set-up based on ETROC2
In preparation

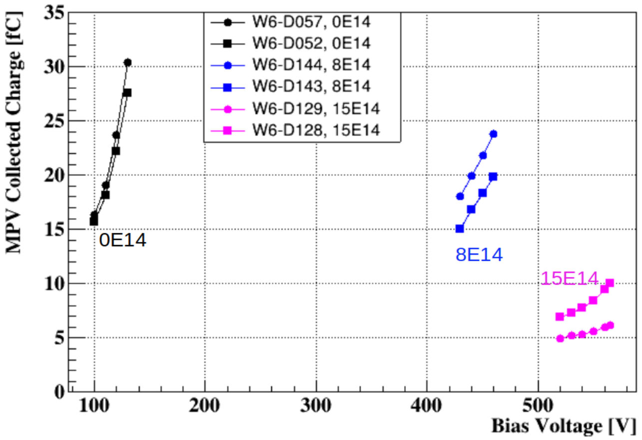
<u>Plannar – RD53A based</u> Serial Powering protoype (3 modules) – TF test at CERN (CMS TK Facility)

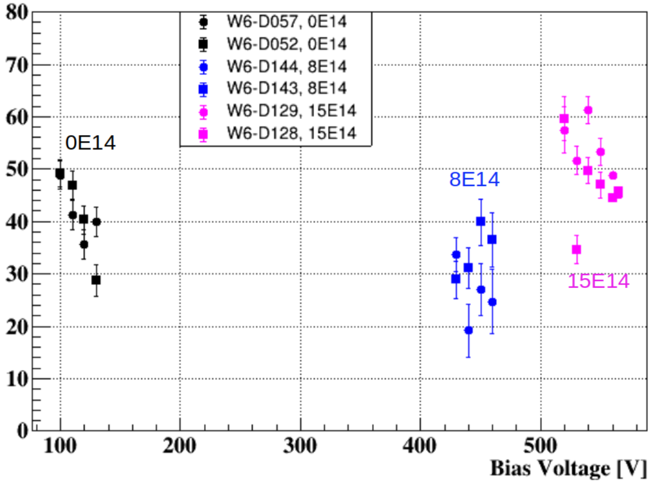
CMS ETL: LGAD sensor R&D

- New batch of carbonated LGAD matching final sensor specifications for ETL manufactured at **IMB-CNM**
- Full characterization carried out with Radioactive source and SPS test beam at CERN
- Optimization of the Carbon dose to improve the radiation tolerance.
- First deep junction batch still under manufacturing
- Complies with the ration tolerance requirements for the ETL





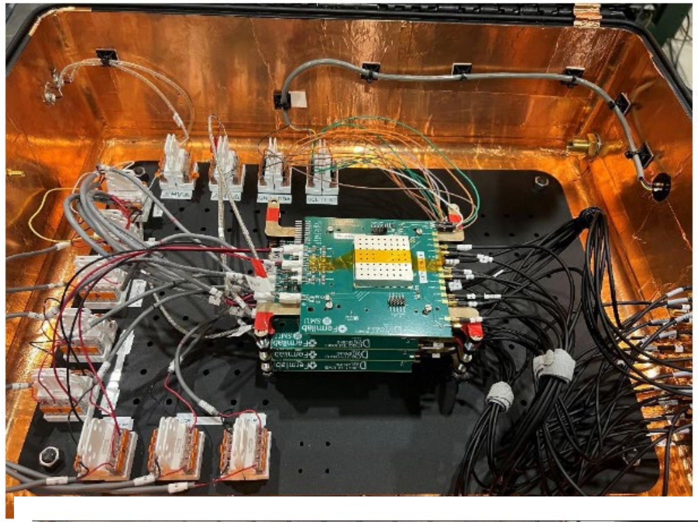




ETL-ETROC2

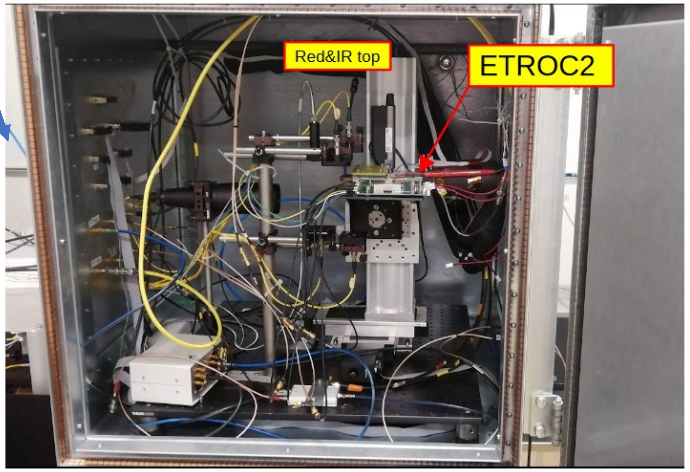
- **Major project milestone** : First version of a full fledged readout ASIC (ETROC2) arrived in March.
- Bump bonding (IMB-CNM and Baretek) of first batch ETROC2 batch to 16x16 LGAD prototype sensors completed in August
- Very low noise levels present, overcoming previous ETROC version major issue.
- Test beam at the CERN North Area and laser testing at CERN SSD laser facility carried out in the second half of September

Fully self contained, self referential sensor+ETROC2 stack system at SPS TB. Three sensor layers with accompanying master clock board and FPGA DAQ.

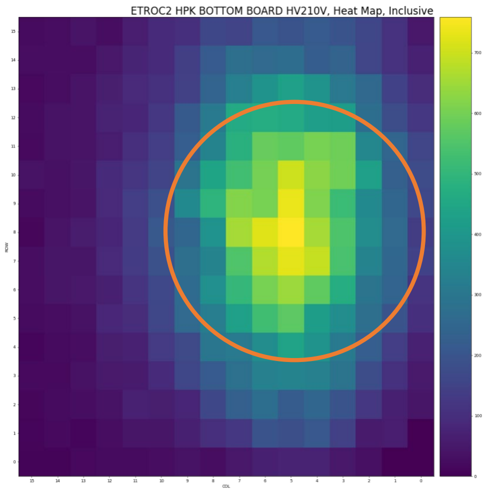


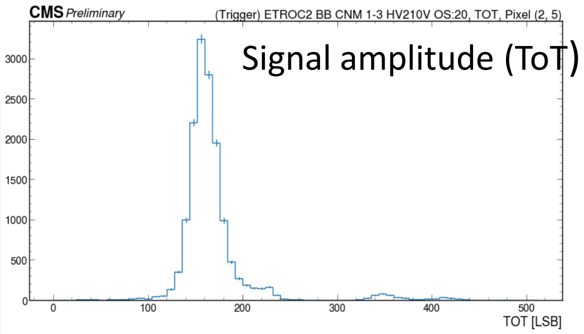
Fully functional ETROC2+sensor assembly (SSD laser facility) for dedicated jitter studies and ETROC2 performance

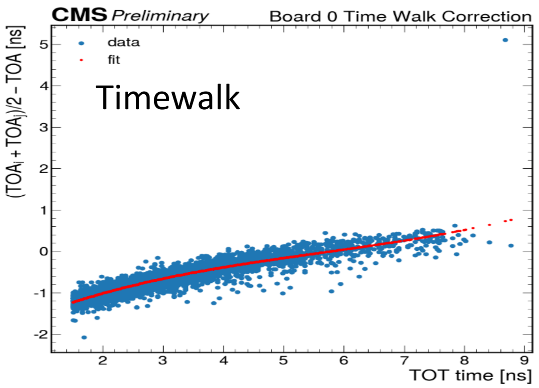
- Very promising out-the-box performance: SPS beam profiling and track correlation observed.
- Preliminary determination of the ETROC2 assembly jitter using the laser: < 30 ps.



beamspot

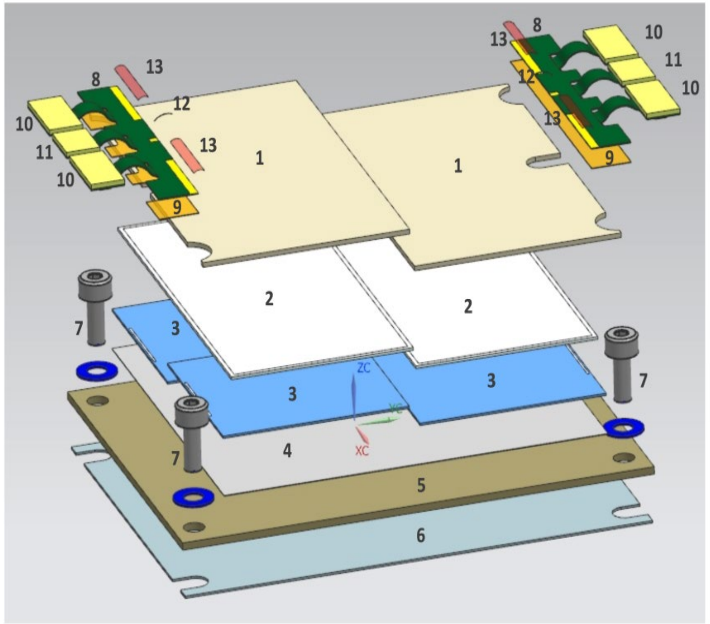


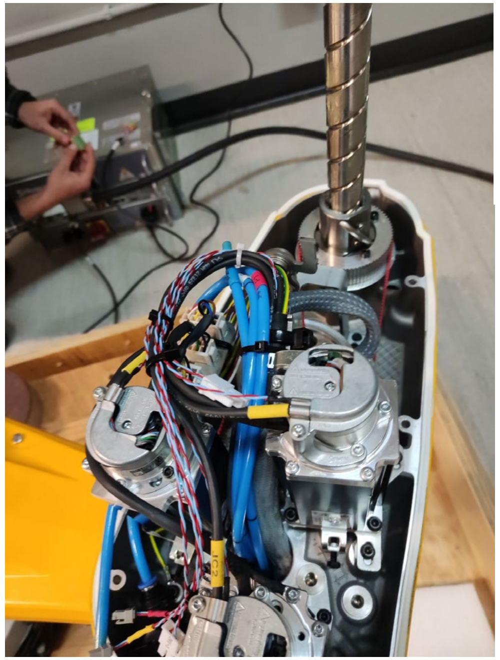


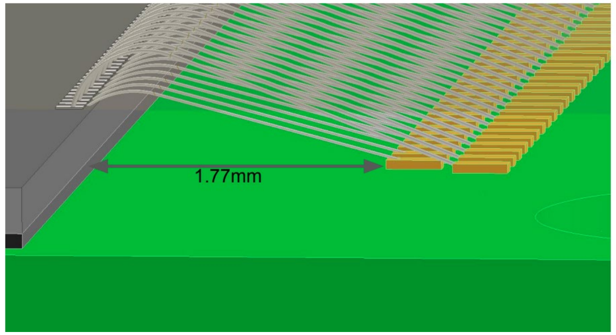


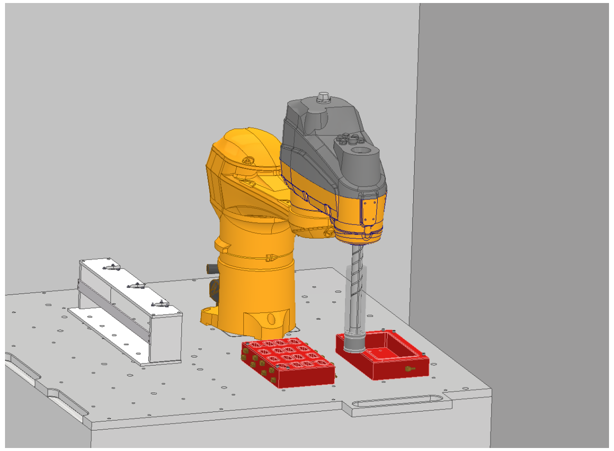
ETL Module Assembly

- Assembly of about 900 (~10%) Endcap Timing Layer modules at IFCA
- Automated procedure based on a SCARA ROBOT to ensure precision
- First test assemblies expected by the end of the year (currently commissioning of the setup)
- Workflow established in collaboration with other sites (Nebraska, Fermilab and Torino)
- Wire bonding and testing of modules performed on-site



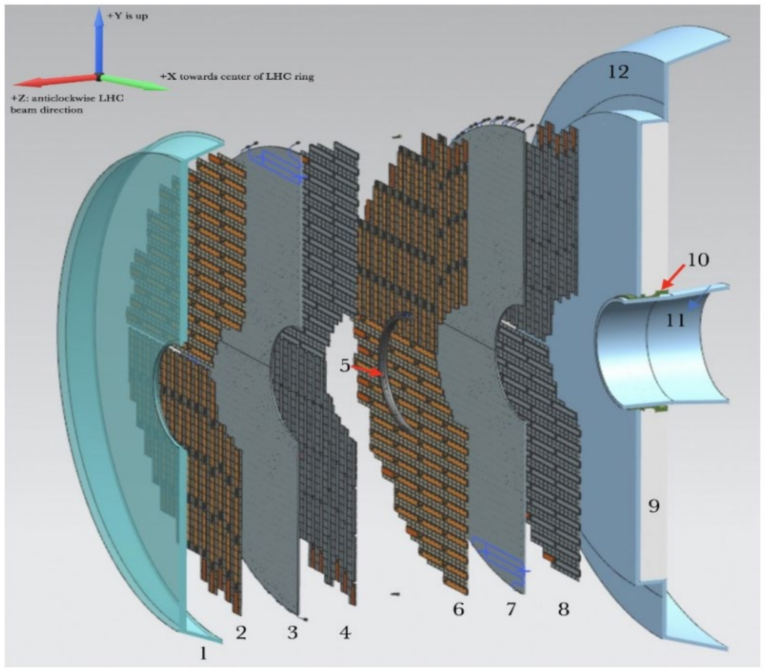


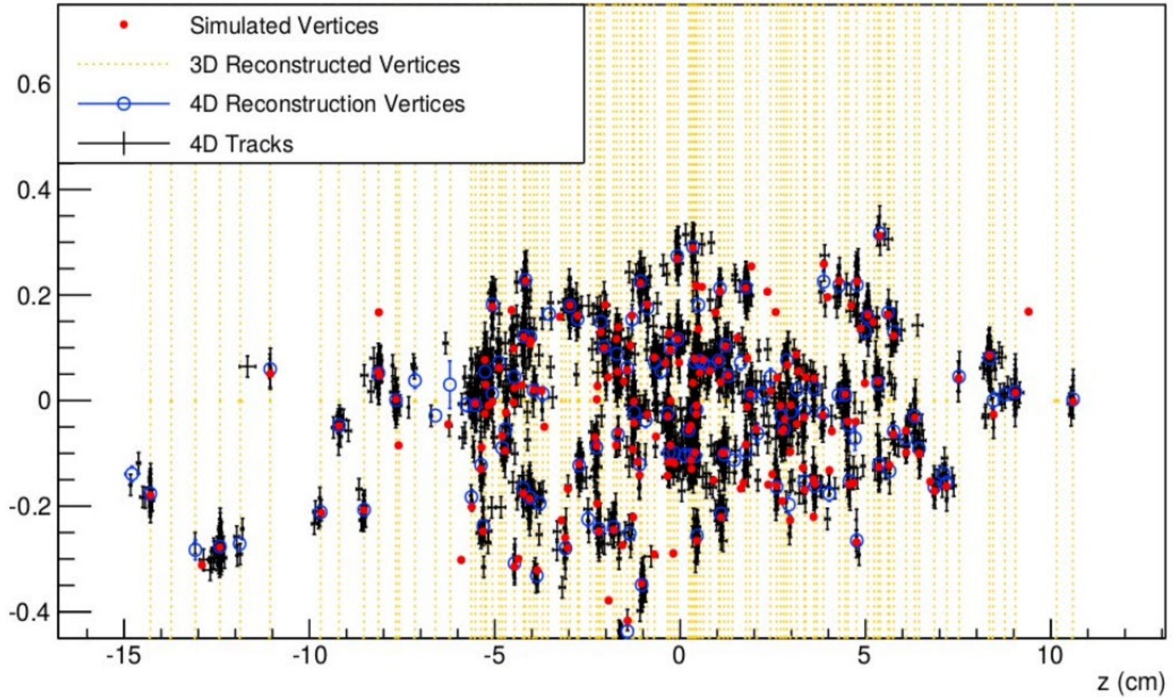




MTD Geometry and Reconstruction

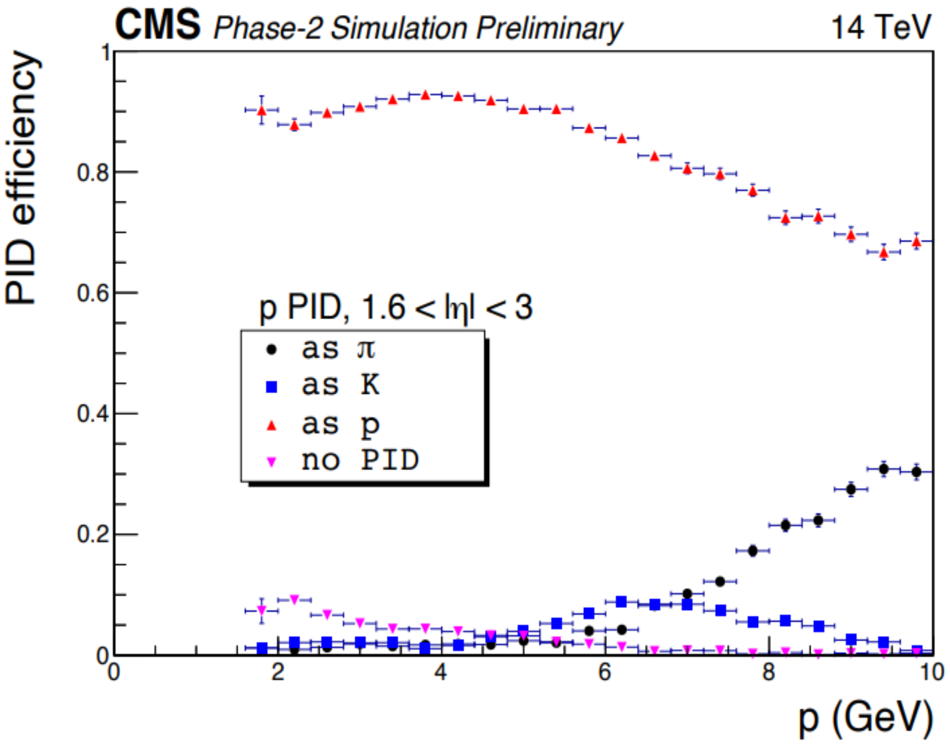
- In charge of the Data Performance Group of the MTD:
  - Implementation and optimization of the detector geometry in CMSSW
  - Digitization and detector response (new ETL response model in progress)
  - Local reconstruction, 4D global reconstruction and 4D vertex building
- Calibration procedures and initial alignment plans starting to be deployed

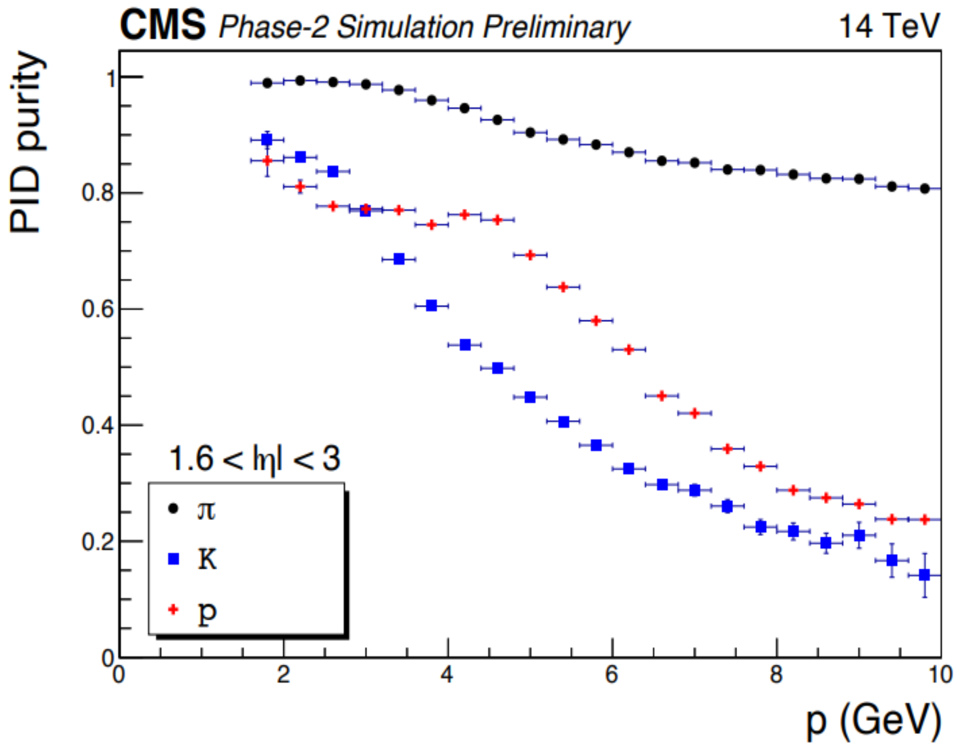




Update of the MTD Physics Case

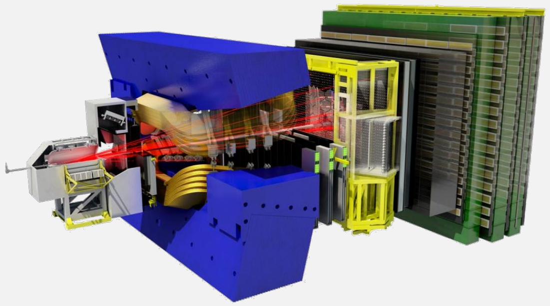
- New physics cases studied in the last couple of years
- Extension of searches for long-lived particles decaying into displaced jets
- Use of timing information to estimate Particle ID (Time-Of-Flight-based Particle ID)
- Strong impact on B physics analysis as it improves the particle tagging performances



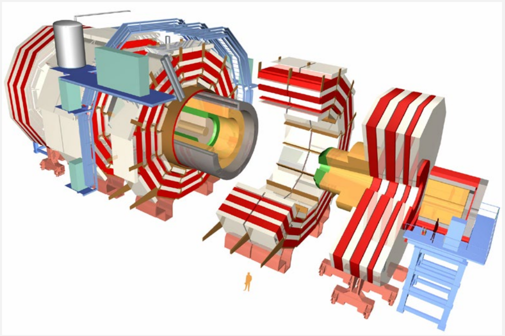


Getting Ready for HL-LHC era!

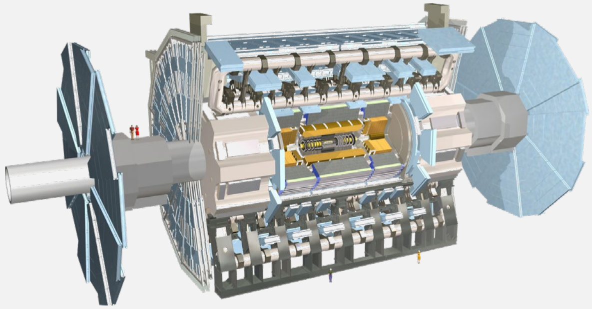
LHCb



CMS



ATLAS



Exciting Physics Ahead

THANK YOU for your Attention

(the following slides were placed as backup due to lack of time)

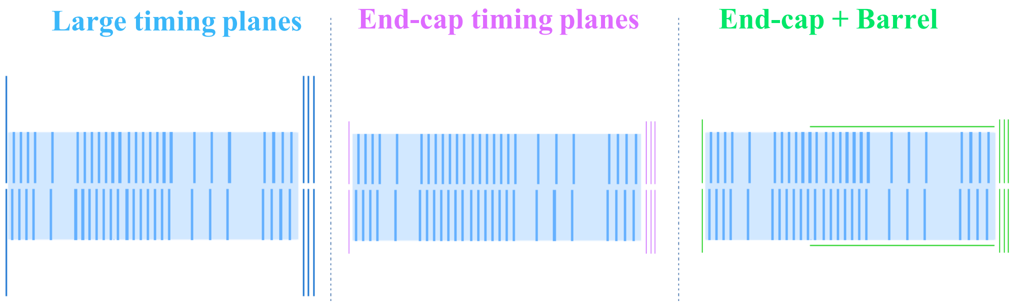
LHCb Timing Options

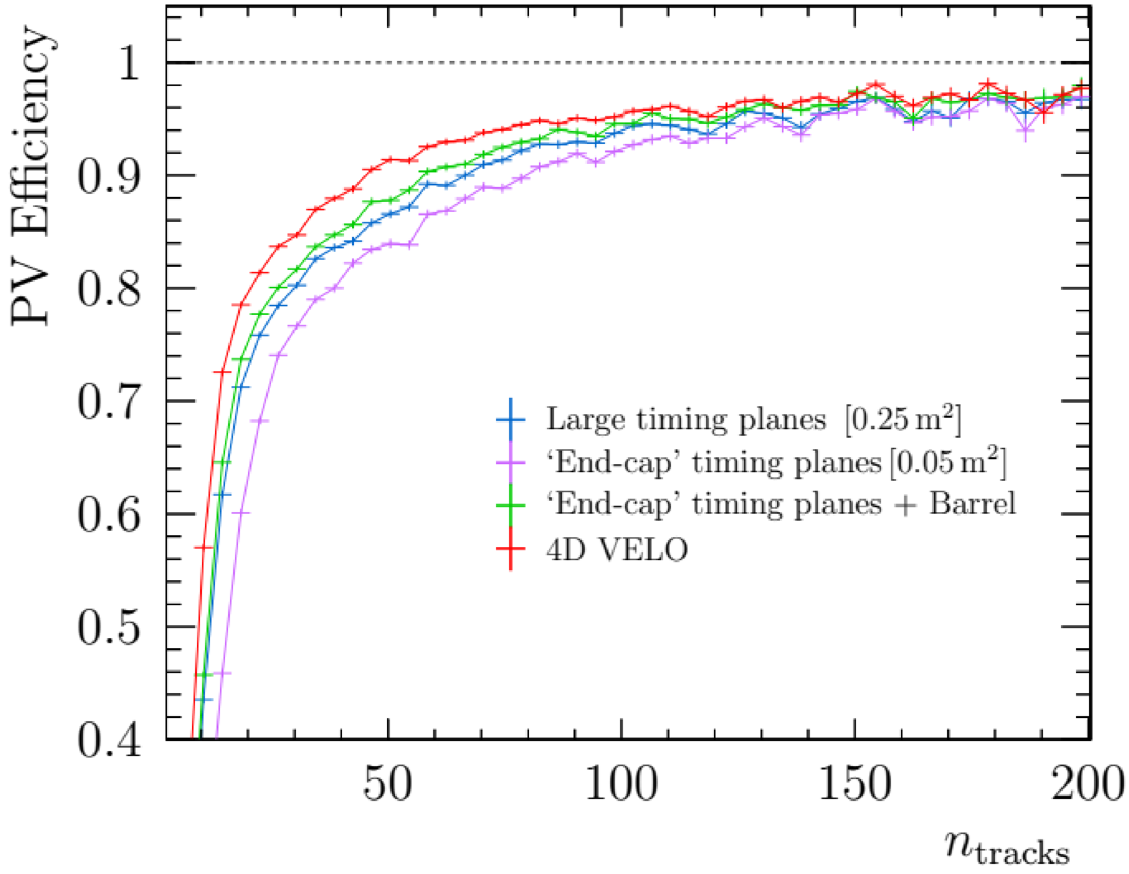
Dedicated timing planes

- Greater distance to luminous region → less radiation damage, smaller pitch
- Three segmented timing layers required to provide independent timestamps
- Single measurements need at least 25 ps resolution
- Much larger detector area, constraints in material budget and a higher price tag

Full 4D Tracking: Precise timing in every hit

- Requires individual hit resolution of < 50 ps
- Better efficiency in pattern recognition and vertex reconstruction
- Reduction of ghost track rate
- **Full 4D tracking is strongly preferred!**

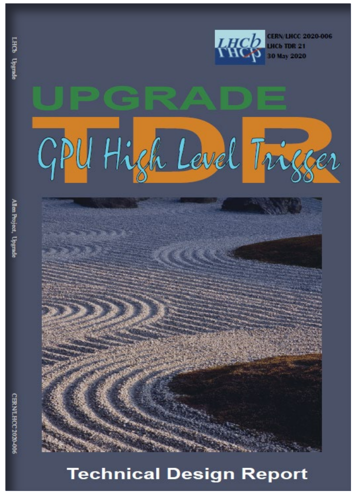


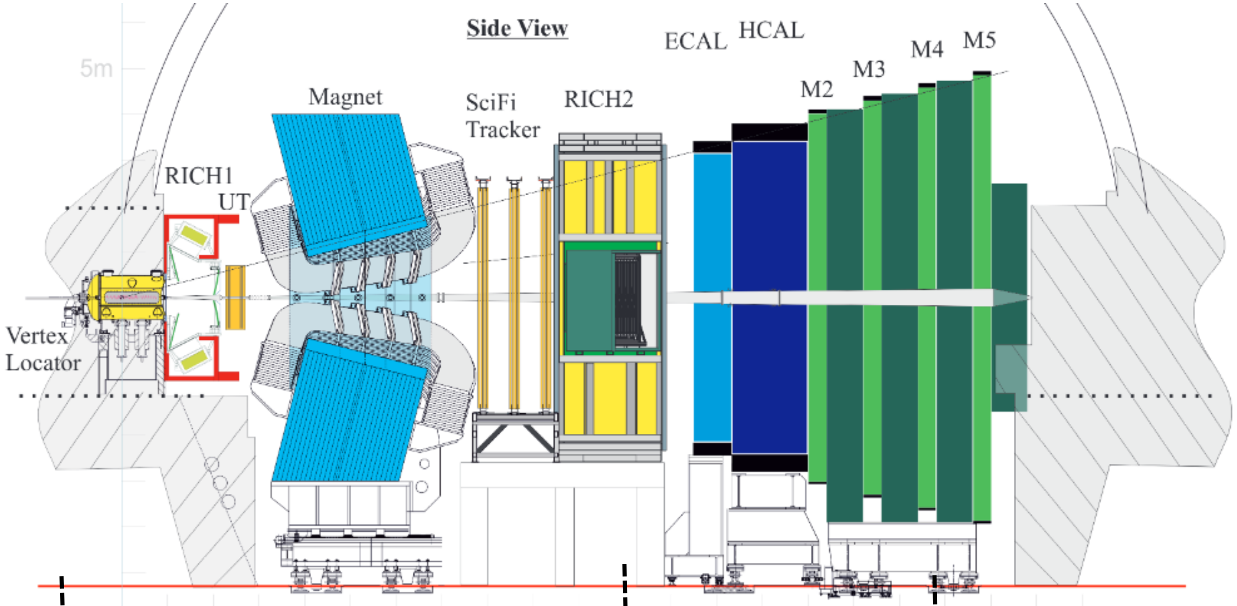


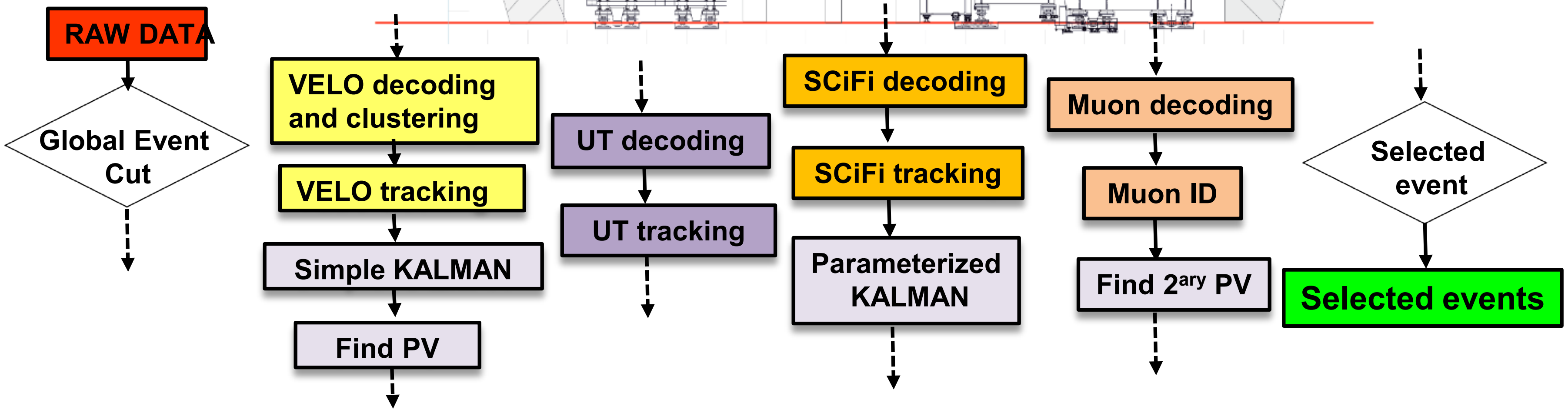
LHCb Trigger

- No L0 hardware trigger for Run3 → full detector read-out at 30 MHz → fast reconstruction
- Detector data received by O(500) FPGAs and built into events in the Event Building servers
- Full HLT1 on Real Time with GPUs → **O(200) Nvidia RTX A5000**

Now also contributing to RETINA FPGA-based trigger for Run 5



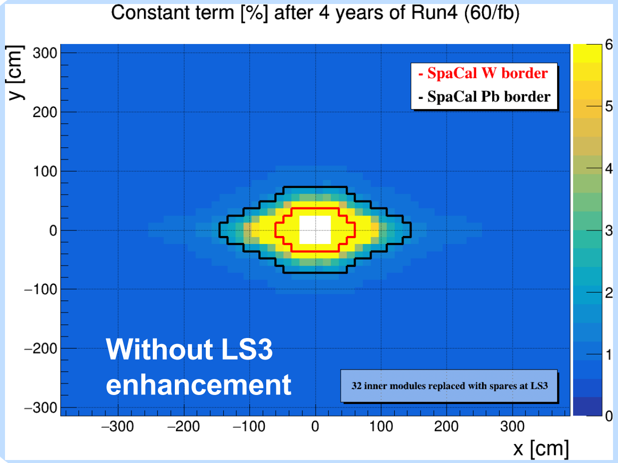




ECAL Upgrade Strategy

Run 3 in 2022-2025:

- Run with unmodified ECAL Shashlik modules at L = 2 x 10^{33} $cm^{-2}s^{-1}$ (new 40 MHz readout)

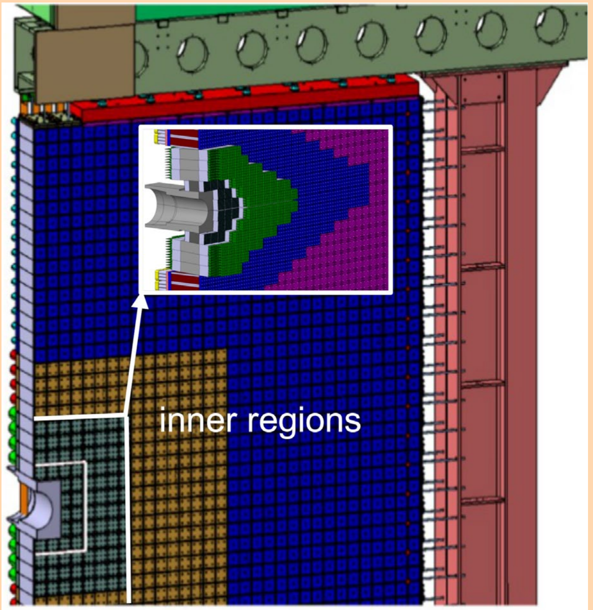


LS3 enhancement in 2026-2028:

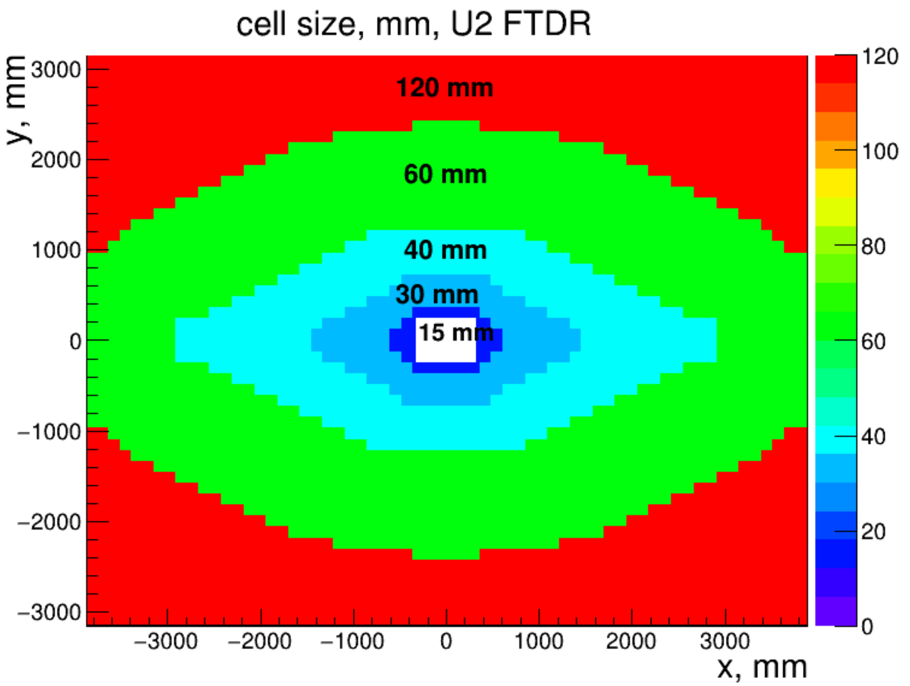
- Introduce single-section rad. tolerant SpaCal (2x2 and 3x3 cm^2 cells) in inner regions and rebuilt ECAL in rhombic shape to improve performance at L = 2(4) x 10^{33} $cm^{-2}s^{-1}$
  - → **32** SpaCal-W & **144** SpaCal-Pb modules with plastic fibres compliant with Upgrade II conditions
  - → Option to include timing information with single-sided readout to inner regions

LS4 Upgrade II in 2033/2034:

- Introduce double-section radiation hard SpaCal (1.5x1.5 & 3x3 cm2 cells) and improve timing of Shashlik modules for a luminosity of up to L = 1.5 x 1034 cm−2s−1
  - → Innermost SpaCal-W modules equipped with **crystal fibres**
  - → Include **timing** information and double-sided readout to full ECAL for pile-up mitigation



PMT requirements and studies

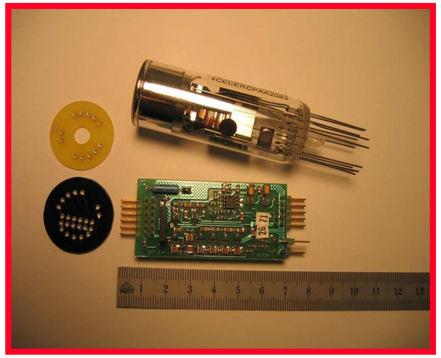


Cell size	Technology	High G (Imax lim.)	Low G (Imax lim.)
15 mm	SPACAL W	4k	1k
30 mm	SPACAL Pb	4k	500
40, 60, 120 mm	Shashlik	100k	11k

Study gain and time resolution uniformity over photo-cathode and for different bias and light conditions for different PMTs

- Different detector zones, different needs (gain, aging, geometry, radiation hardness)
  - Inner part: SPACAL-W/Pb for high radiation doses
  - Outer zone: Shashlik with lower radiation doses
- Stringent geometry in the innermost zone (15 mm)
- Aging is an important limit
  - Total integrated charge ≥ 10^3 C (to be confirmed)
- Time resolution ≤ 20 ps
- Non-linearity ≤ 2%
- The PMT should withstand doses ≤ 1 Mgy

R7899-20 (ECAL/HCAL)

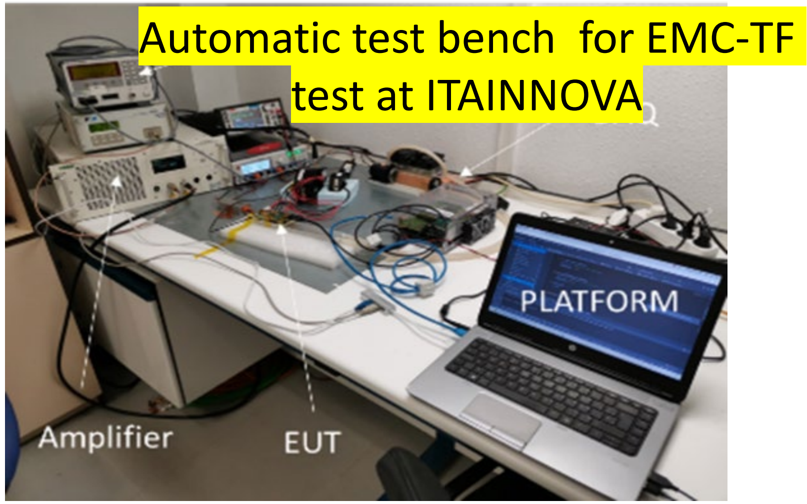


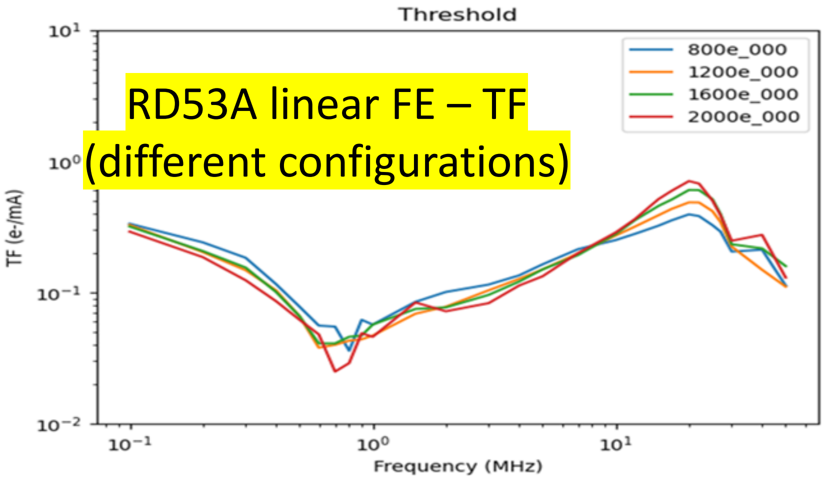
R11187 (TILECAL), R7600U-100

R14755U-100

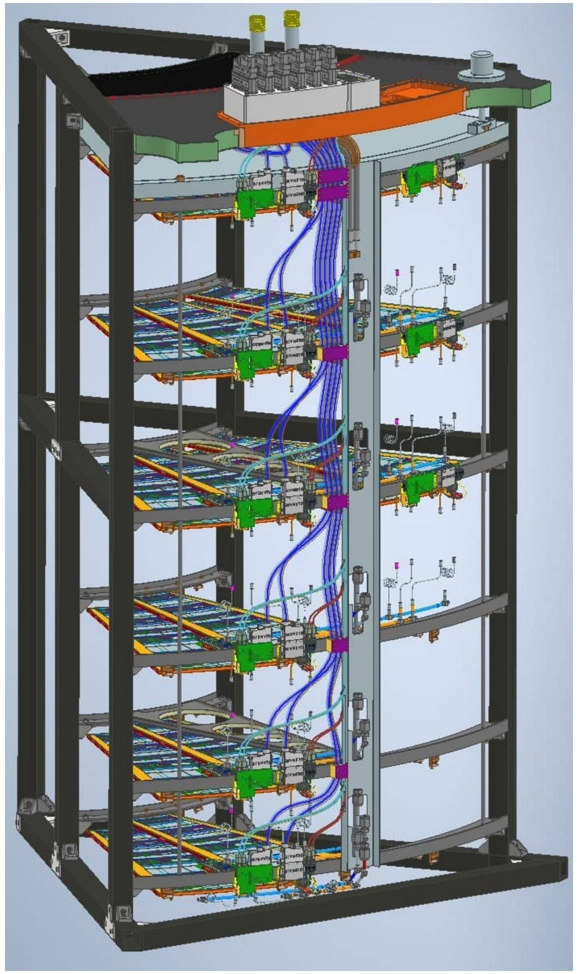
ITAInnova R&D activities and services associated to HL-LHC

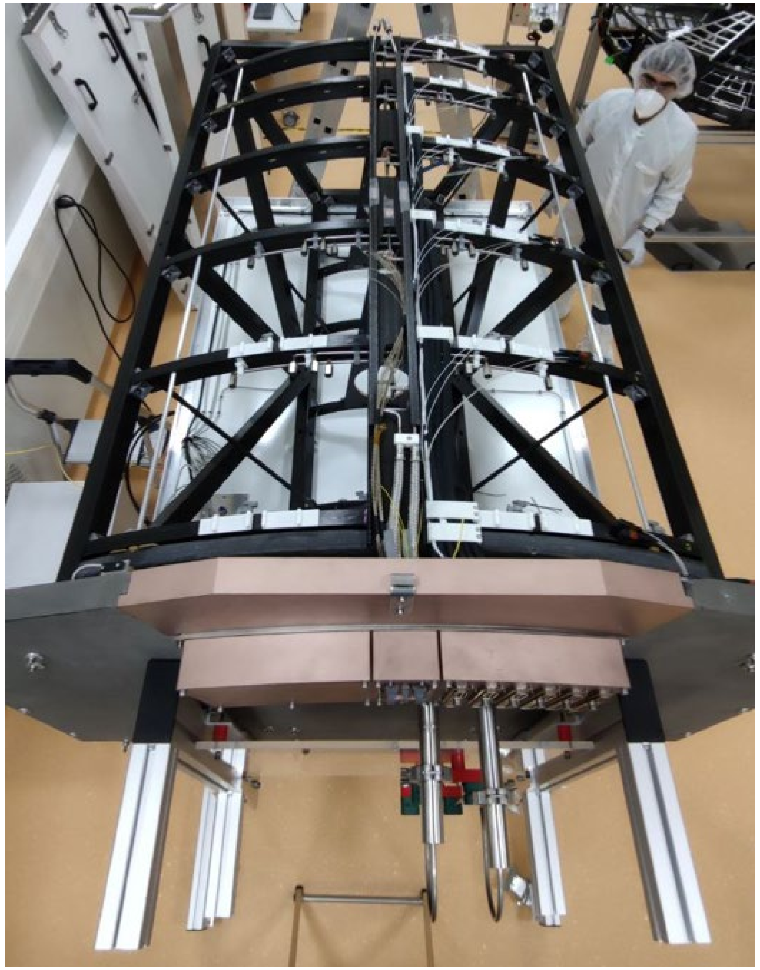
- GaN based DC-DC converter design for serial powering applications (**GaNCAP4CMS**)
- Design and development new systems for noise control for physics detectors:
  - A portable test bench to perform EMC conducted emission test of DC-DC in irradiation facilities
  - An automatic EMC test bench to measure the noise TF of physics detectors.
- ITAINNOVA is Tech. Assistance facility for EMI detector characterizations





ATLAS ITk-strips System Tests





Patch Panel installed at DESY (October 2022)

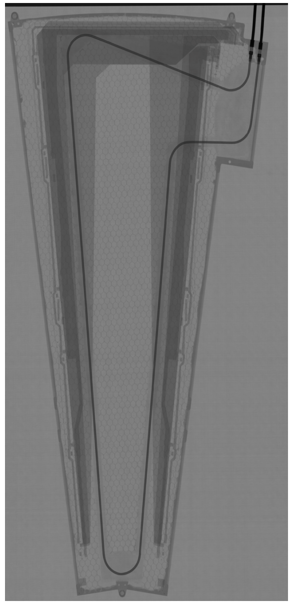
- Designed the mechanical structure for a system tests setup that will be operated first at DESY and later at CERN
  - The setup will operate more than one petal at a time and will serve to test several aspects of the system
- Participate in the preparation and operation of such system

CSIC Consejo Superior de Investigaciones Científicas
IFCA Instituto de Física de Cantabria
UC Universidad de Cantabria

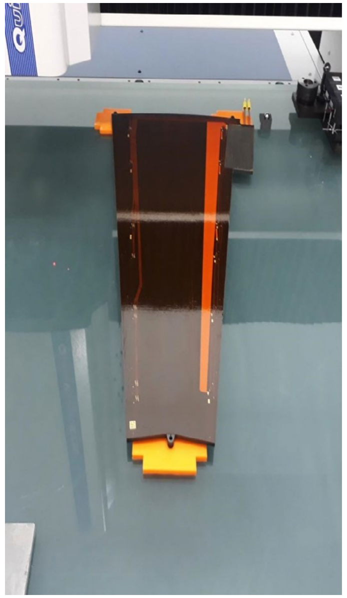
ATLAS ITk Petal QA&QC + Bustapes

QC of **200** core petals during production phase

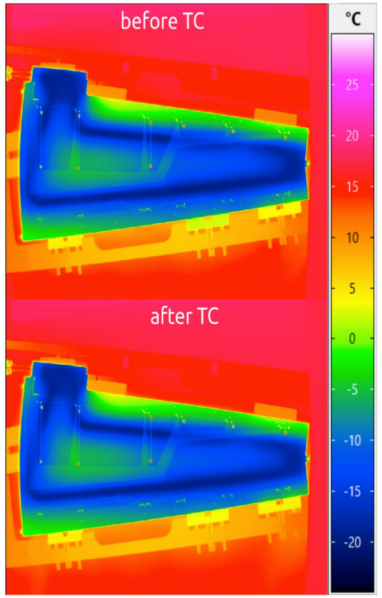
X-ray scan



Metrology

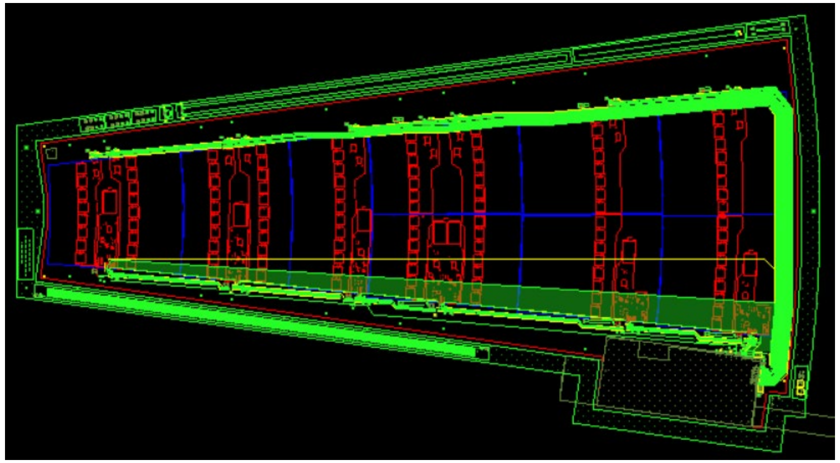


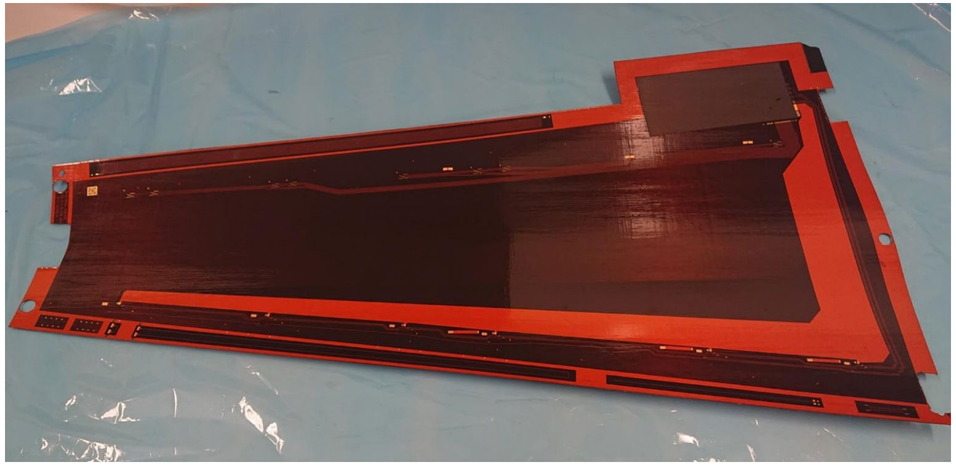
Thermal cycling + IR image



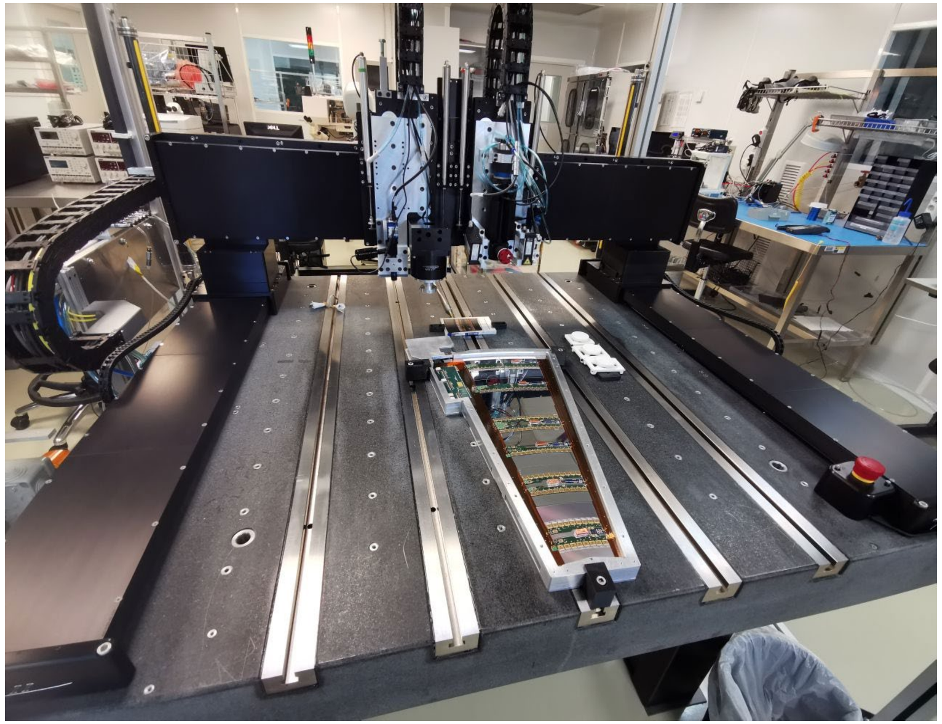
The different signals and voltages get to the modules via the traces on a polyimide tape (**bustape**) which is co-cured with the carbon fiber pre-pregs that make the petal facing, where modules are glued onto.

Those tapes where designed by **Fernando Carrió** and **Pepe Bernabeu** (front and back) and are fabricated in Slovenia





Petal Loading



”Populate” **100 petals** (we build 600 of the 1800 modules needed).
We do it with a “very-large” pick-and-place machine that:

- Dispenses the glue on the petal
- Positions the module with 20 µm precision
- Does the final metrology

Fully loaded petals have to be bonded, electrically tested and operated at -35 ^{O}C. We do this with CO_2 cooling

CMS IT fluence scenarios & sensor requirements

- Revised and consolidated radiation levels for qualification of different options and final choices
  - Adopt coherently the "ultimate scenario" with 4000 fb^{-1} delivered at the end of the HL-LHC program

	RUN 4		RUN 5		RUN 6		Run 4+5		Run 4+5+6	
	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad	1E16 1 MeV n_eq	Grad
BPIX L1	0.73	0.40	1.16	0.63	1.63	0.89	1.88	1.03	3.51	1.91
BPIX L2	0.20	0.11	0.31	0.18	0.44	0.25	0.51	0.29	0.94	0.55
FPIX R1	0.48	0.31	0.77	0.50	1.08	0.70	1.25	0.81	2.34	1.50
FPIX R2	0.23	0.17	0.36	0.27	0.51	0.38	0.59	0.44	1.11	0.82

  - Operating BPIX L1 (and FPIX R1) during the entire high-luminosity program does not appear realistic
    - Independently of the sensor technology choice
    - The whole HL-LHC program in the ultimate scenario would result in a fluence of 3.5E16 1 MeV n_{eq} and a dose of 1.9 Grad for the inner modules of TBPX L1
  - **Adopt as baseline scenario a replacement in LS5, and define the fluence and dose to reach LS5 (in the ultimate scenario) as the benchmark to evaluate all the technology and design options**
    - **Fluence 1.9E16 1 MeV n_{eq}, dose of 1.0 Grad**

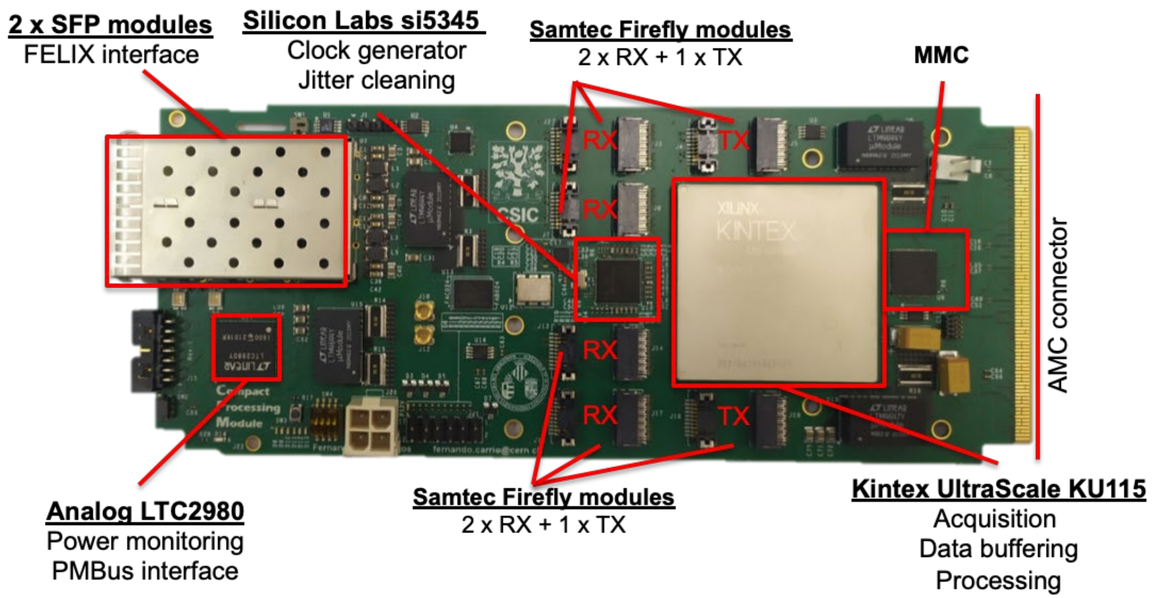
For 3D at 1.5E16, require Ileak< 150 mA/cm2, Power < 30 mW/cm2 at Vop at T= -25C with Vop < 200V

Compact Processing Modules (CPM)

- Single AMC board:
  - 6 Samtec Firefly modules (4 RX + 2 TX)
  - 14 channels through AMC connector
  - 2 SFP modules
  - Xilinx Kintex Ultrascale KU115 FPGA

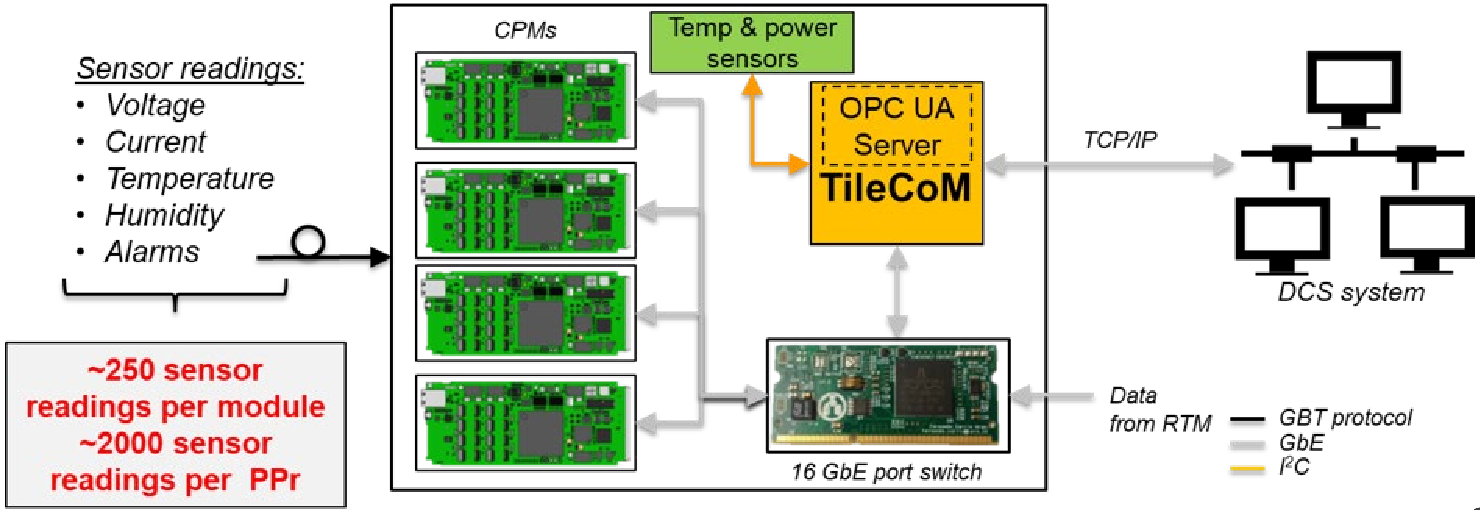
- Firmware organized with HDL-on-GIT (HOG):
  - Firmware reproducibility guaranteed and traceability of files
  - First version of signal reconstruction firmware produced

- 5 CPM v2 produced Q4 2021
- 2 CPM v2.1 produced in Q3 2022



Carrier Mezzanine Boards

- Mezzanine designs as compact, replaceable and upgradeable solutions
- TileCoM - Computer on Module
  - Xilinx Zynq UltraScale+ XCZU2CG + 512 MB DDR4
  - DDR4 SODIMM-240 pin form factor
  - Main functionalities
    - Remote programming of all on-detector and off-detector electronics
    - Interface with the ATLAS TDAQ system for detector configuration
    - OPC servers to provide monitoring data to the ATLAS Detector Control System
- 16 GbE ports switch module
  - Unmanaged Ethernet Switch chip Broadcom BCM5396
  - DDR3 SODIMM-204 pin form factor



Carrier + CPM + DAQ integration tests ongoing