STAMPS

a Scalable Testbench for Advance detector Modules and Pixel Sensors

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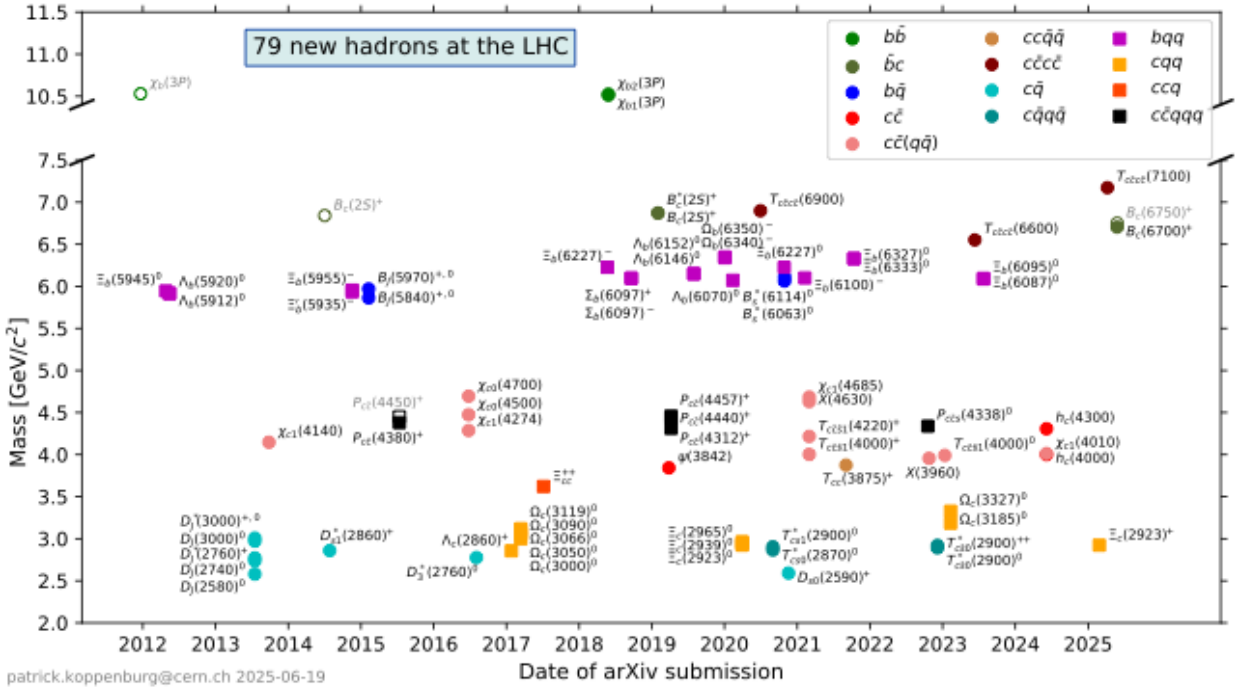
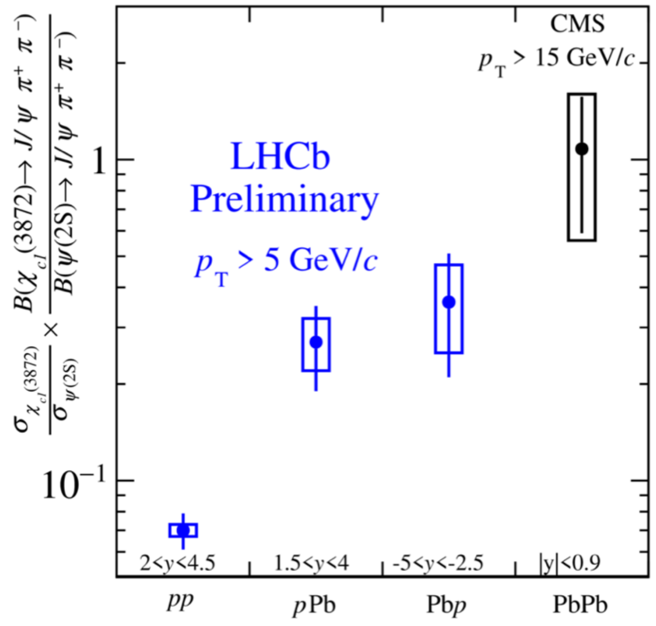
Hadron physics at the LHCb experiment

- Rich physics program in pp and AA, pA collisions systems
- Hadron discovery machine : **79 new hadrons** at the LHC of which **70 discovered at LHCb**!
- Hadrons states studied in different colliding systems



LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC.

PRL 132 (2024) 242301



Exotic hadron $\chi_{c1}(3872)$ experience different dynamics in the nuclear medium

The LHCb upgrades timelines

Lumi $4 \times 10^{32}\,\text{cm}^{2}\text{s}^{-1}$

Lumi $20 \times 10^{32}\,\text{cm}^{2}\text{s}^{-1}$ (x5)

Done

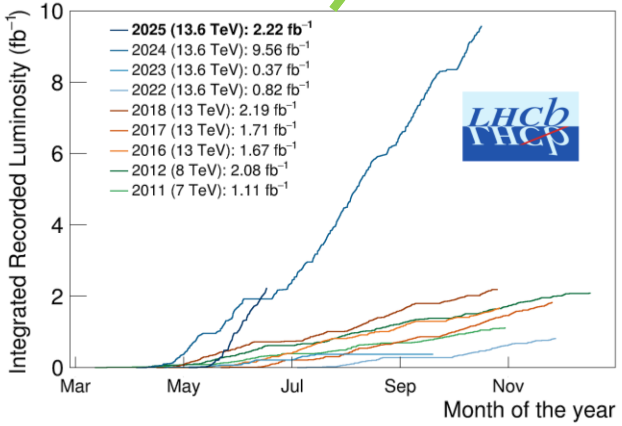
Run 1
2011 - 2012

Run 2
2015 - 2018

LHC LS2
2018 - 2022

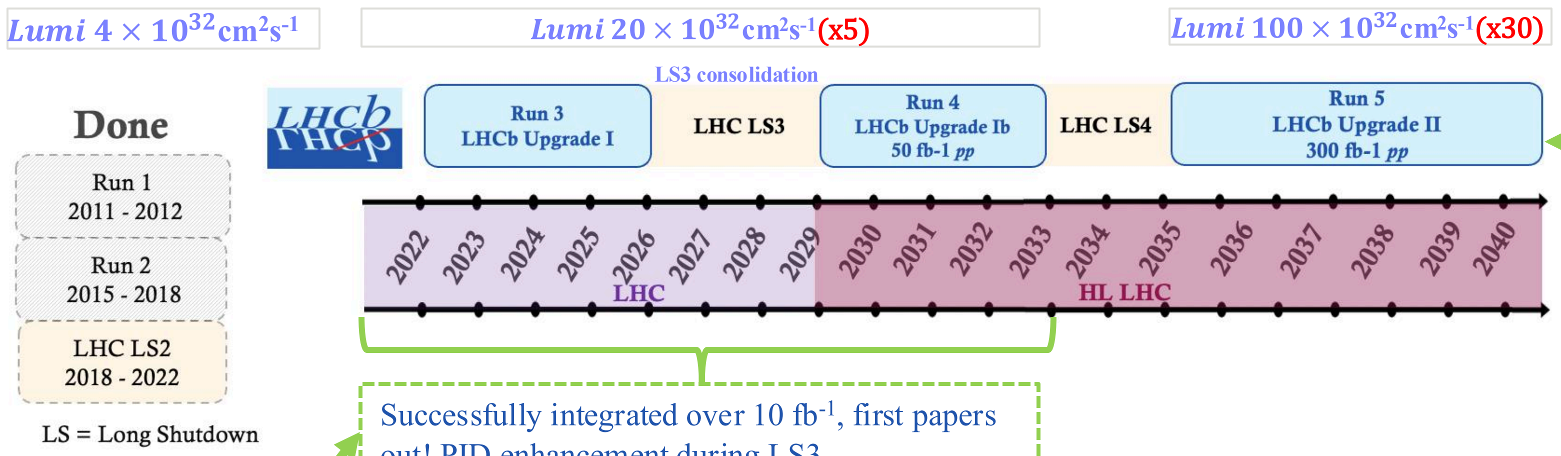
LS = Long Shutdown

Successfully integrated over 10 fb^{-1}, first papers out! PID enhancement during LS3.



The LHCb upgrades timelines

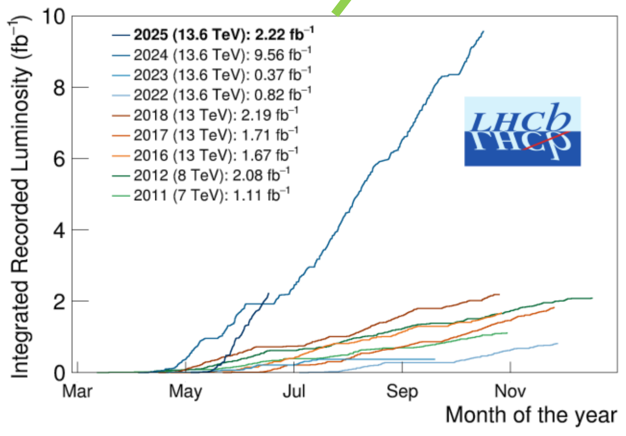
- Most of the observables in heavy flavour dominated by statistical uncertainties at the end of Run 4
- New detector proposed for LHCb during Run 5 : goal 300 fb^{-1} at the end of the LHC and exploit the full potential of HL-LHC for heavy flavor physics

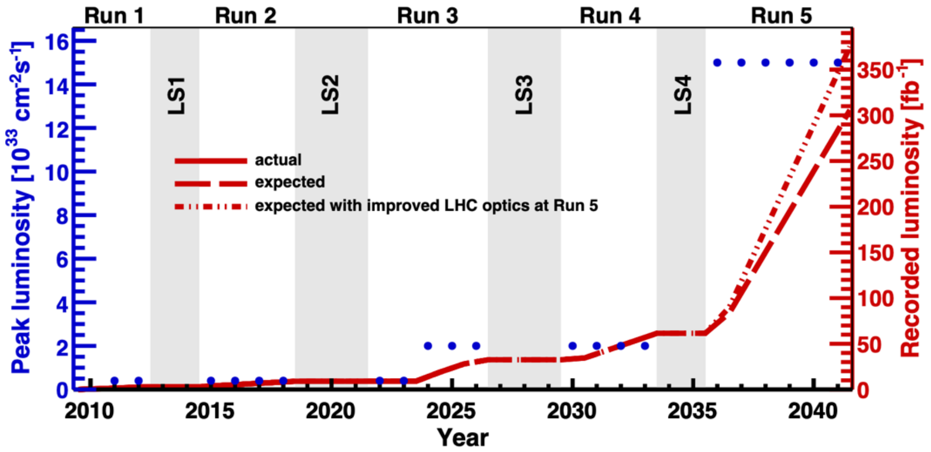


Successfully integrated over 10 fb^{-1}, first papers out! PID enhancement during LS3.

Next challenge: cope with **higher inst. luminosity** while keeping same performance as previous runs:

- Increase granularity
- Add timing measurement (resolutions up to 10-50 ps)
- Radiation hardness (up to 10^{16} n_{eq}/cm^2)
- Data rate: 200 Tbit/s
- Cope with high heavy ions multiplicities

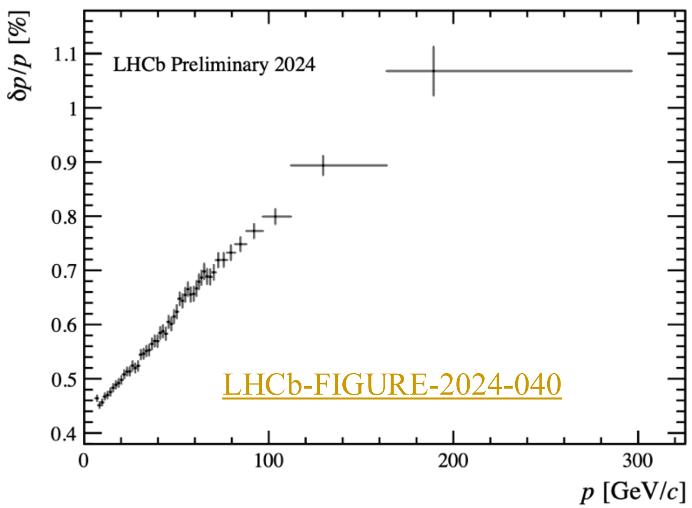


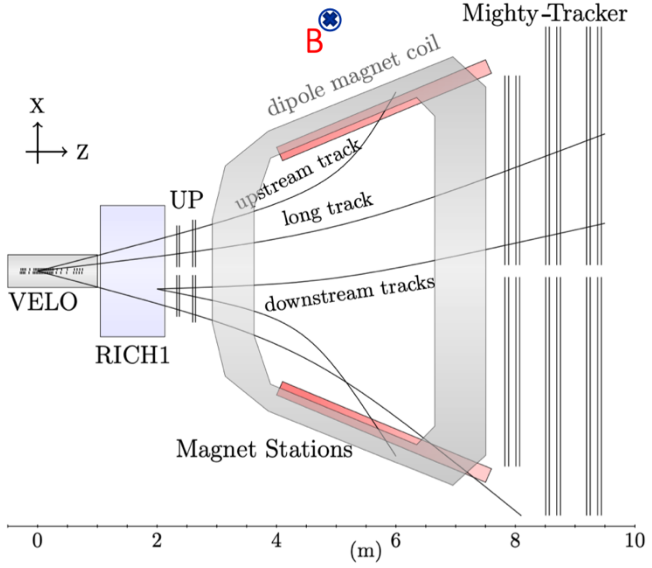


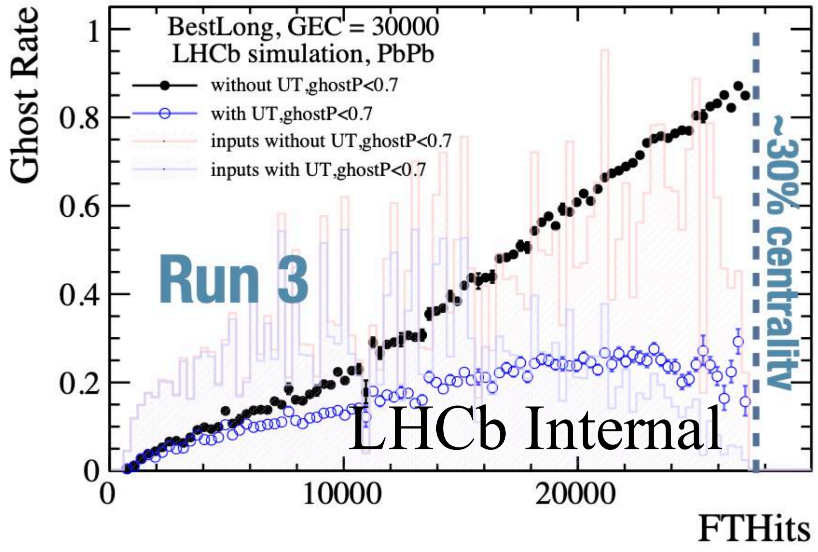
Tracking detectors upgrades

- LHCb must keep its excellent momentum resolution (essential for hadron physics program)
- Tracking algorithms: combination of different track segments coming from different subdetectors
- In high pile-up and high multiplicity environment → fake tracks (ghosts) : rate increases with multiplicity

from 0.5% up to 1.1% (up to a momentum of 200 GeV)







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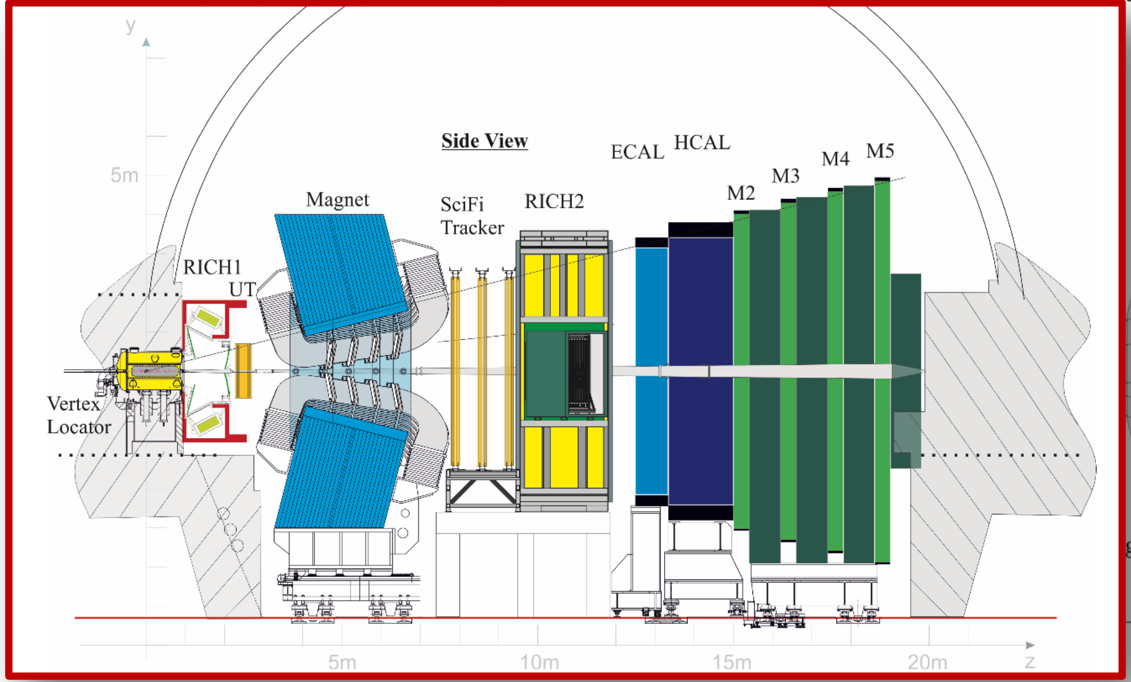

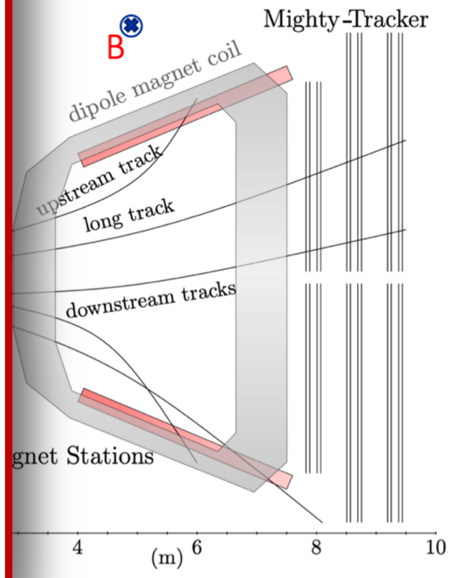

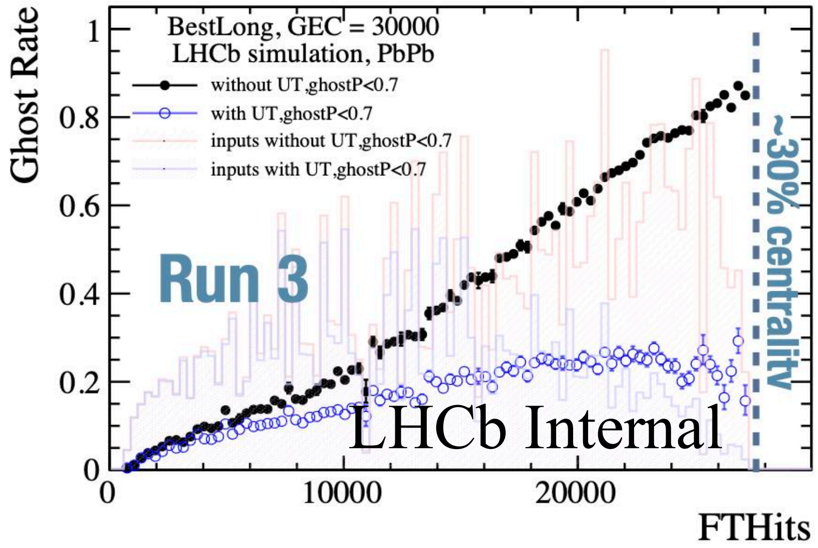

- LHCb **Upgrade I** tracking system:
  - VELO:Vertex LOcator, Pixelated hybrid silicon
  - Upstream Tracker: silicon micro-strip
  - SciFi Tracker: scintillating fibers + SiPMs

Tracking detectors upgrades

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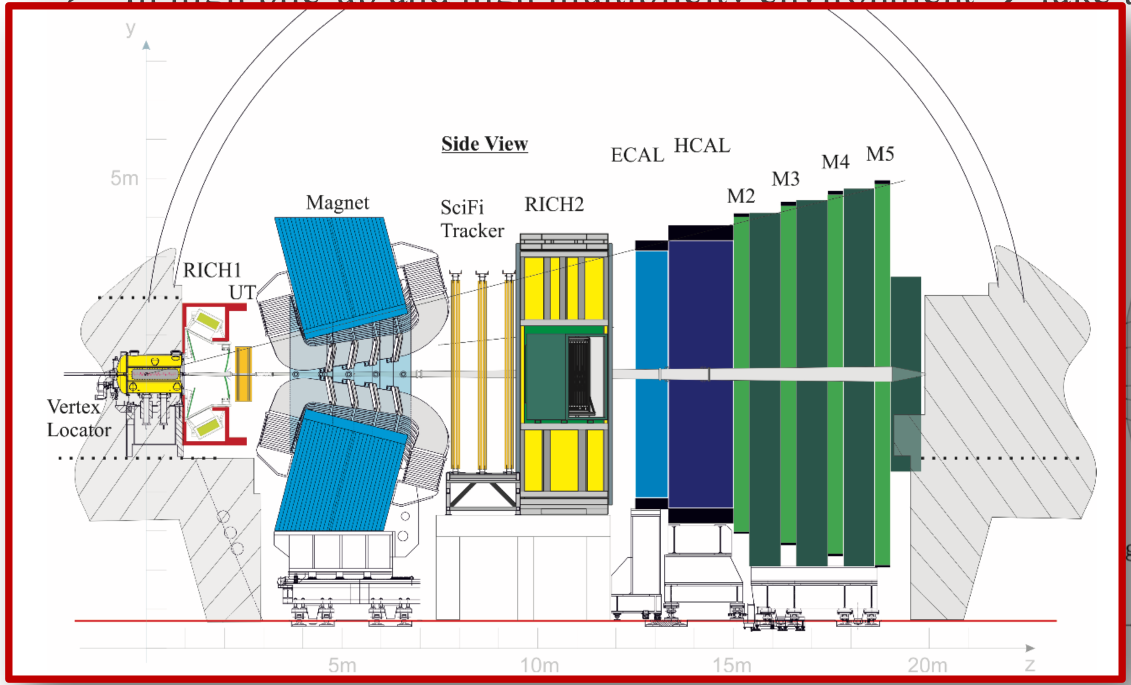

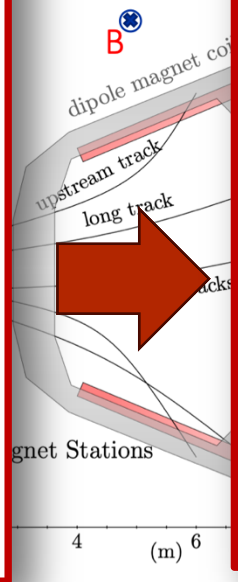

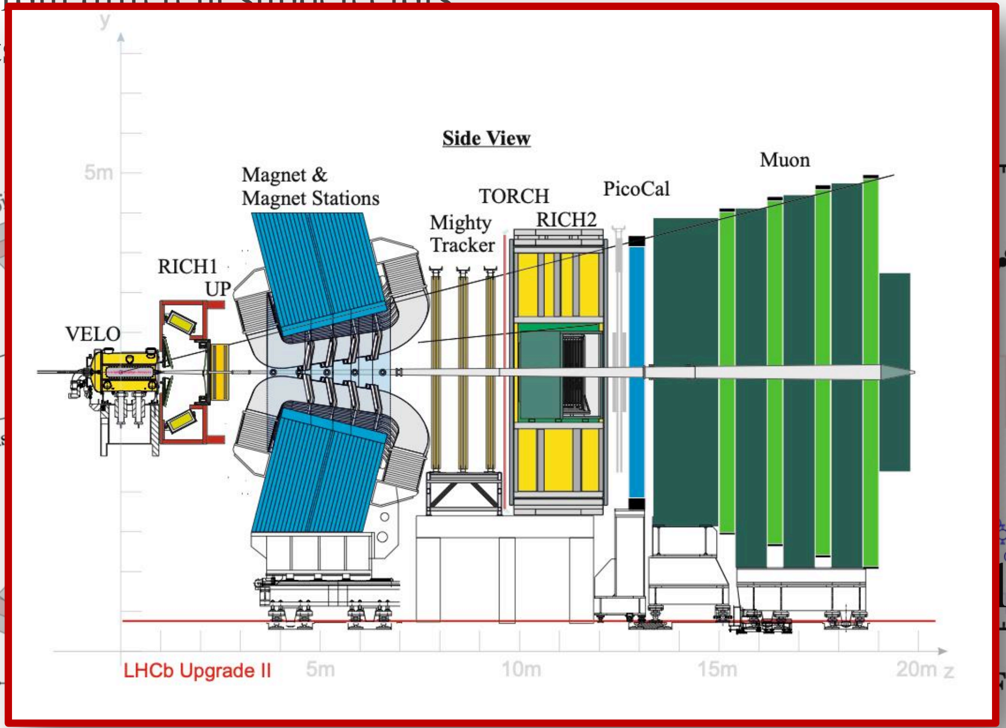

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  - o VELO:Vertex LOcator, Pixelated hybrid silicon
  - o Upstream Tracker: silicon micro-strip
  - o SciFi Tracker: scintillating fibers + SiPMs

- ➢ LHCb **Upgrade II** tracking system:
  - o VELO: pixels with timing
  - o Upstream Pixel: **MAPS**
  - o Mighty+SciFi Tracker**: MAPS**+ fibers + microlenses SiPMs

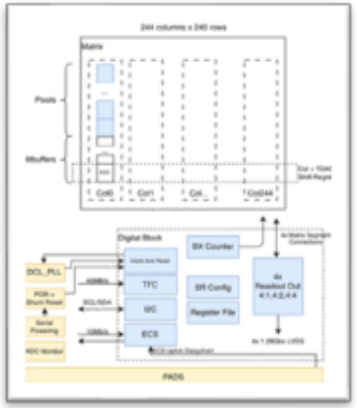
Candidates MAPS for tracking detectors

- **MAPS (Monolithic Active Pixels Sensors)** : promising candidate for tracking systems in future high energy physics experiments
- High spatial resolution (a few μm), good timing resolution (a few ns for bunch tagging), low material budget and well-controlled power consumption and radiation hardness
- New R&D(s) on-going : **new sensors to be tested extensively**

MightyPix: AMS 180 nm process

- based on knowledge of previous HV-CMOS sensors, ATLASPix and MuPix
- Submission of the full matrix soon

JINST 19 C04045



RadPix: LF 150 nm

- LF foundry, similar design to MP

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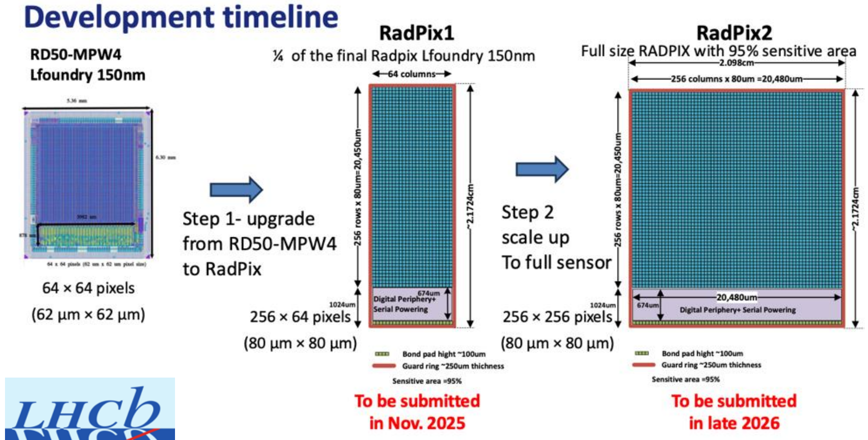
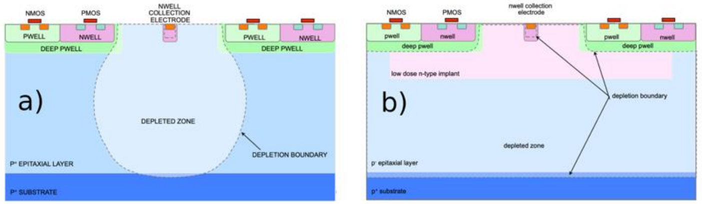
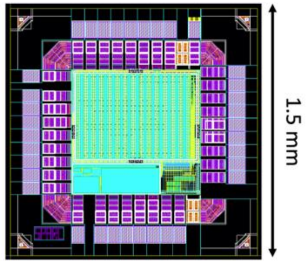


Versatile : TPSCo 65 nm

- LV candidate, developed within DRD3





JINST 19 (2024) 02, C02033
10.1109/TNS.2023.3299333

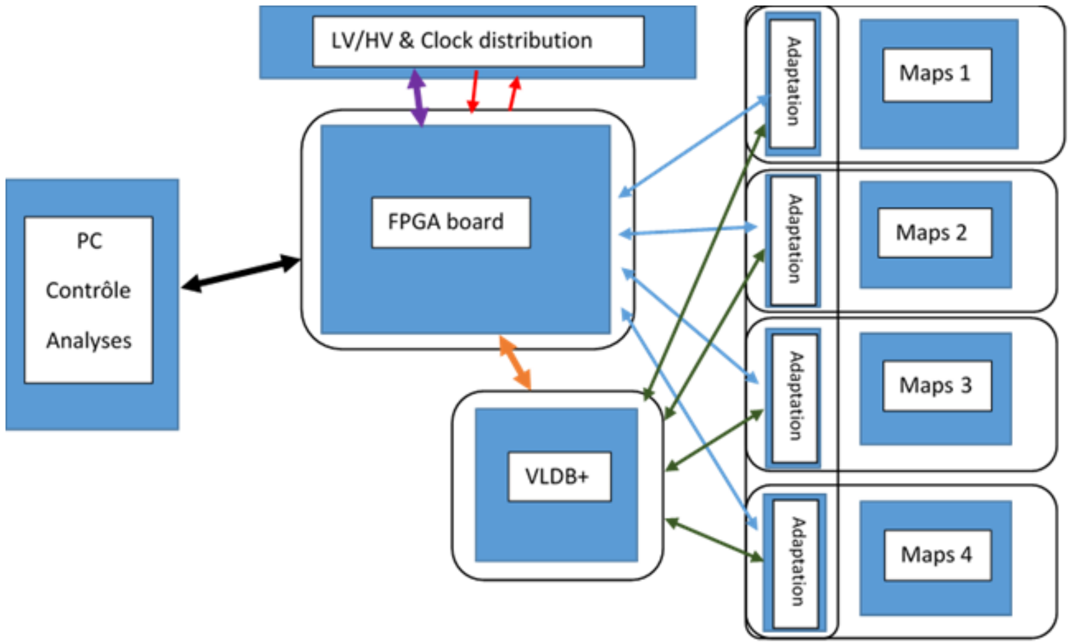
In general, many new developments of MAPS technologies, all new sensors need to be tested

Testing of MAPS sensors

Fundamental to test new candidates in an unbiased way.
Testing procedure can be standardized with a **scalable testbench.**

Goal: build a scalable testbench for streamlined testing of MAPS candidates

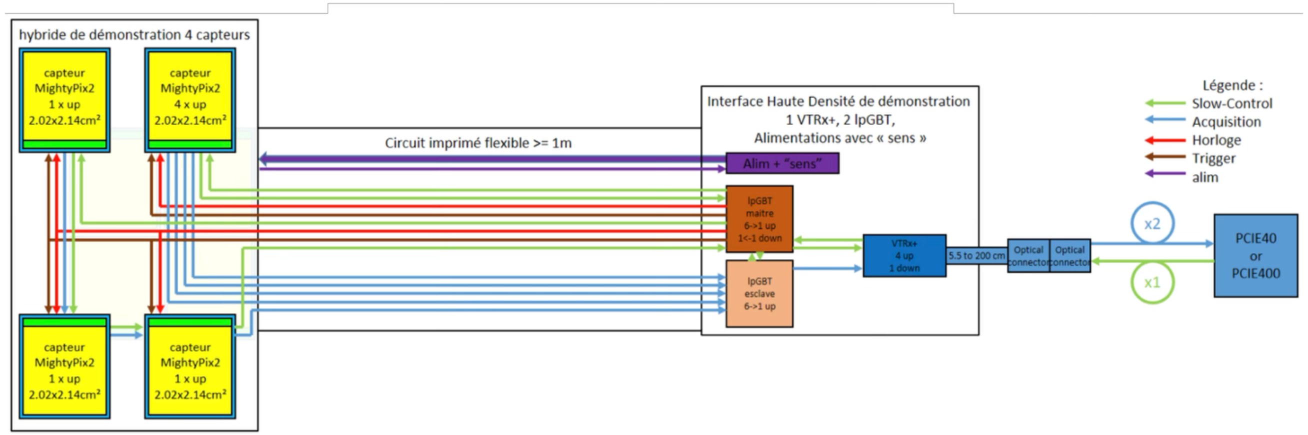
- What are the functionalities to test:
  - measurement of general functionalities (analog and digital part, IV curves etc..)
  - performances (with laser, radioactive sources, testbeam)
  - irradiation effects NIEL, TID, SEE
- General setup
  - **Xilinx FPGA Board (commercial):**
    - handles control and data acquisition
    - MAPS sensors connected via a carrier board
    - In phase 2: include the VLDB+ board for high-speed optical data transmission
  - **Candidate MAPS Boards:**
    - customized board for each sensor may be needed since each may have unique power and communication needs.
  - **Interface Board:**
    - Bridges the FPGA and MAPS boards, ensuring signal and connection compatibility. Design depends on MAPS specifications.
  - **Acquisition & Analysis PC:** Receives FPGA data via Ethernet. Runs software for data capture, analysis, and real-time visualization.



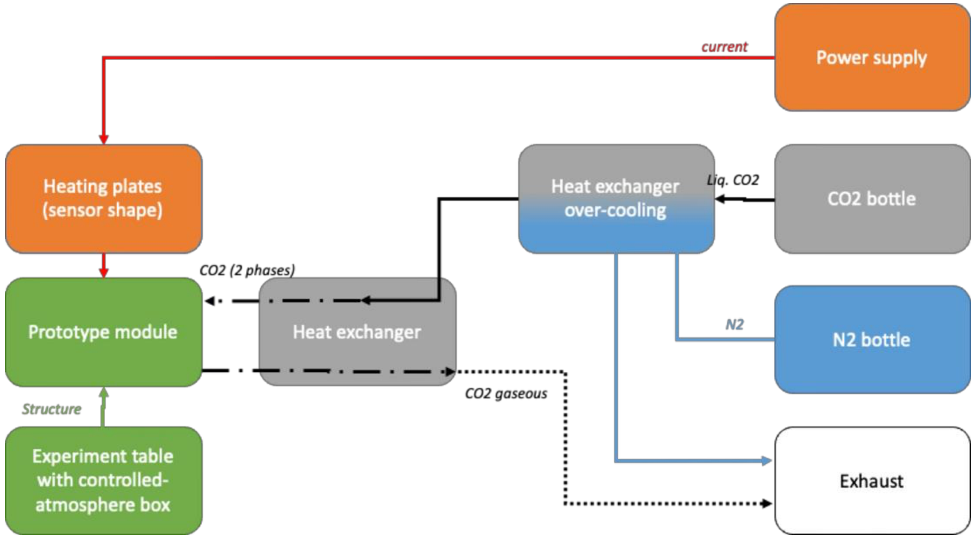
- To be extended to multi-chip operations and prototyping of hybrids and QA procedures

Module development

- **Modules:** groups of MAPS integrated on a hybrid flex and connected to key components (lpGBT, VTRX+) and optical links Need to carry out tests on power distribution, chain operation, and the effects of cooling.
- **Objective 1:** demonstrate the feasibility to operate maps chains (daisy chain) and to manage a high density of data, control and power lines via development of module prototypes



- **Objective 2:**
  - Sensors need to be cooled (at around -10°C)
  - Development of cooling solutions needed: proposal to use CO_2 bi-phase cooling
  - Need to demonstrate the capacity to dissipate the power (~300 mW/cm^2) along the ~1m module



Project summary

Multiple sensor designs are currently **under evaluation**, and **systematic testing is needed** to determine which candidates meet the necessary performance specifications

Objectives:

1. **to develop versatile test benches to evaluate MAPS sensors.**
2. **to demonstrate the feasibility of operating MAPS chains with efficient cooling via the development of module prototypes**.

Key points:

1. Robust and adaptable to all types of next-generation sensors with minimal modifications
2. Support both single-sensor (i.e. test bench) and multi-sensor chains (i.e. modules)
3. Including portability for irradiation campaigns
4. Should be easily usable :
    1. Enable **remote control** to ensure **accessibility for users both online and offline** for wider use
    2. Production of a detailed documentation
    3. Regular workshops to **train early-career researchers** and generally all users in the setup and operation of the test bench platform

Conclusions on STAMPS

Short-term R&D to build a scalable test bench for MAPS

- Deliverables:
  1. Testbench prototype with software applications for users
  2. Module demonstrator with first studies data transmission, powering and cooling performance

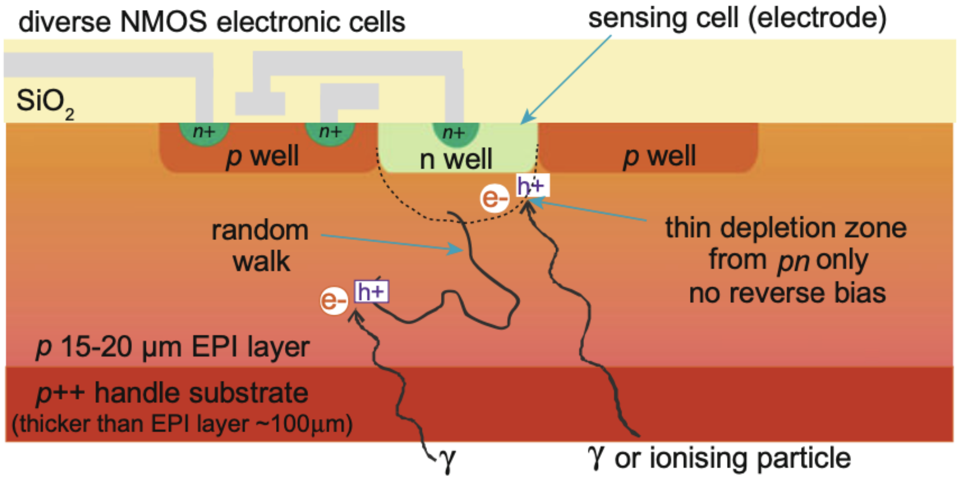
The results obtained will be reported through peer-reviewed instrumentation journals (JINST) and international conferences (Vienna conference)

- Request: ~600kEuros
  - 2 postdocs of 3 years : 480 kEuros
  - 100 kEuros for testbench of sensors and modules prototyping, including testbeam time
  - 30 kEuros for workshops organization and travelling costs

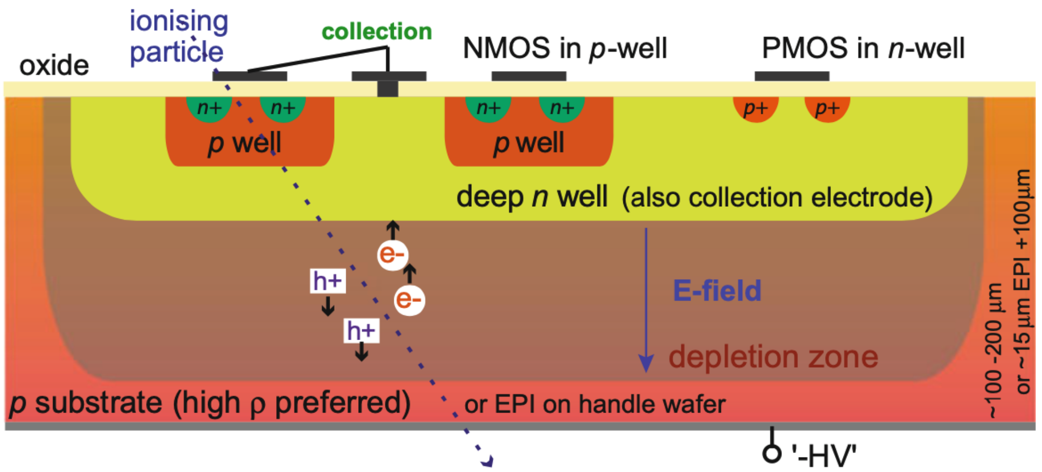
- **Final remarks:**
  - **Need to build expertise in this area and training the next generation of physicists** and engineers : critical to maintaining leadership and continuity in tracking detector development over the long term
  - The project is a collaboration of three French labs: LLR, CEA-Irfu and Subatech
  - Other collaborations can be envisaged with LHCb institutes in Europe: Germany or UK
  - Open to collaboration with other proposals on pixel sensors or tracking detectors for hadrons developments

BACKUP

MAPS sensors: low vs high voltage



$$w \sim \sqrt{\rho \cdot V}$$



Small collection electrode – LV CMOS

- Readout electronics outside the collection well
- Require **low field**
- Small depletion zone, outside that charges collected by **diffusion** (slow)
- High radiation hardness thanks to process modification (high reisistivity to have larger depletion zones)
- *Low* capacitance (small collection electrode)
  - Lower noise (even if diffucion is slow, S/N good)
  - Lower power

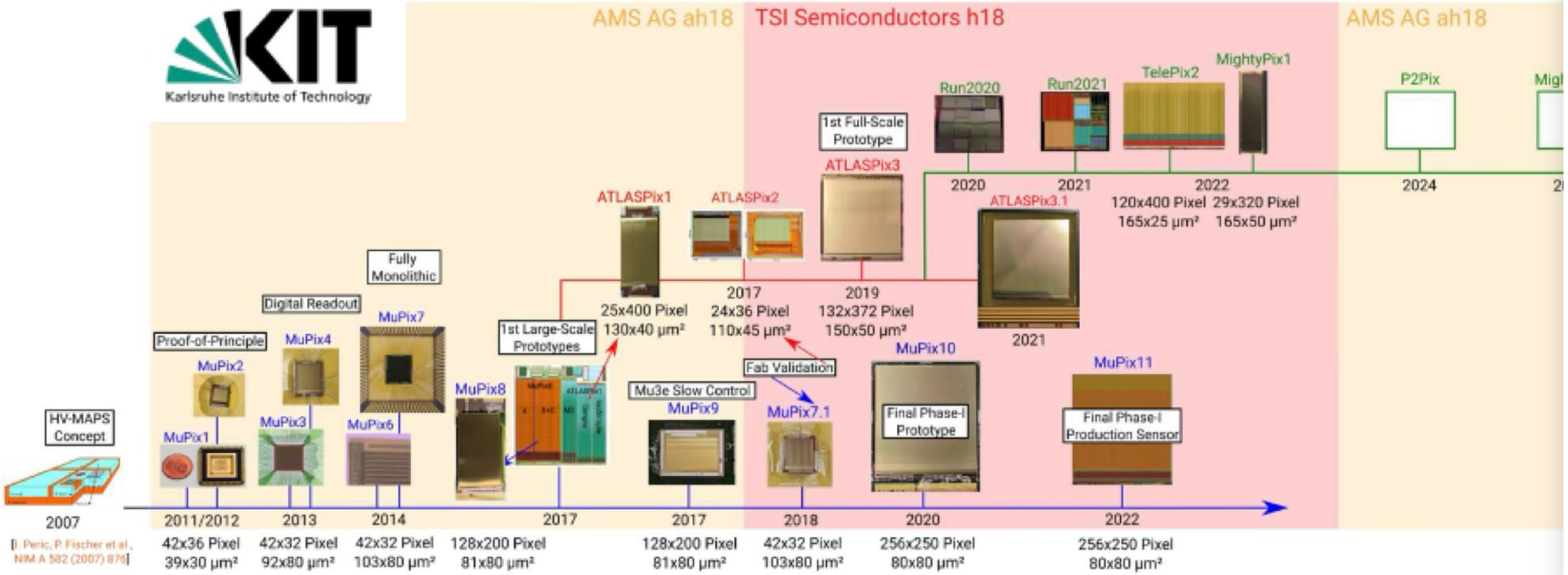
"TPSCo 65nm (Strasbourg)", Malta

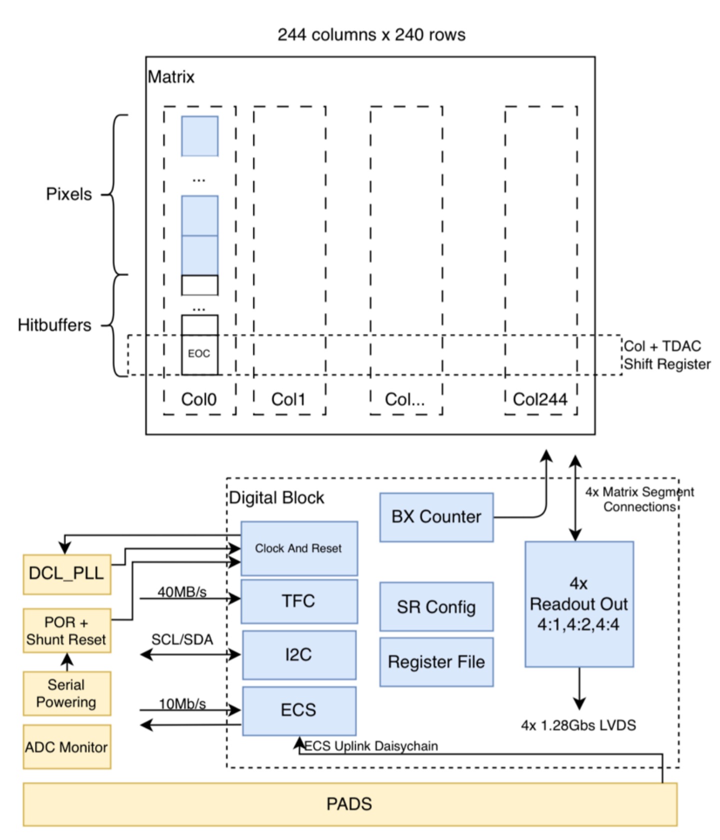
Large collection electrode – HV CMOS

- Readout electronics inside the collection well
- High voltages can be applied
- High radiation hardness thanks to HV substrate biaisng, few hundreds V
- *High* capacitance
  - Higher noise
  - Higher power

MigthyPix (Karlsruhe), RadPix(Liverpool), COFFEE(IHEP)

MightyPix: 180 nm – HV CMOS





MightyPix2:

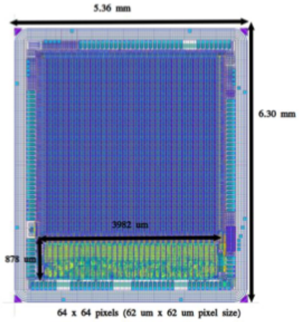
- Chip size: **2 cm × 1.66 cm**
- Pixel size: **84 µm × 84 µm** (identical to P2Pix)
- 2 output mode
  - – Long: 41-bit hit data word
  - – Short: 30-bit hit data word (high-rate mode, 4 data links with 5-bit column address)
- Radiation hardness : NIEL: $3\text{x}10^{14} n_{eq}/cm^2$ and TID: 40MRad

- Periphery
  - – **4 data links (max. 1.28 Gbit/s)**
  - – Slow control (serial powering & ECS compatible)
  - – Timing and Fast Control (TFC)
  - – Gearbox + asynchronous FIFO for improved rate
- EOC: End of Column Buffer handling data transfer from Hitbuffers to Digital Readout.
  →each column reads 480 rows

RadPix: 150 nm

Development timeline

RD50-MPW4
Lfoundry 150nm



64 × 64 pixels

(62 µm × 62 µm)

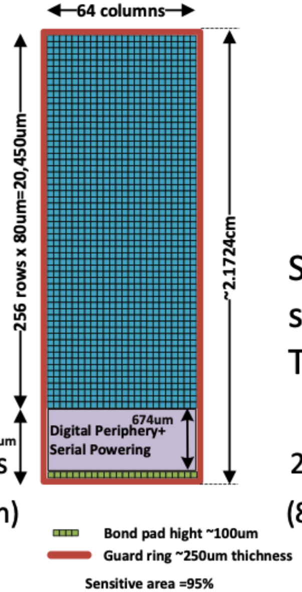
By Eva Vilella

Received in early 2024

Step 1- upgrade from RD50-MPW4 to RadPix

RadPix1

¼ of the final Radpix Lfoundry 150nm



256 × 64 pixels

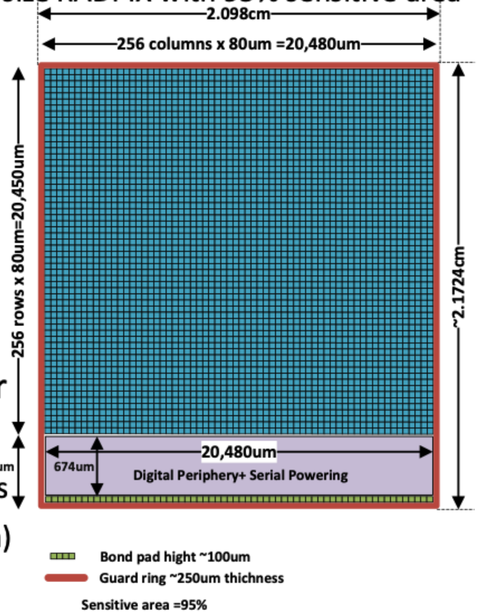
(80 µm × 80 µm)

To be submitted in Nov. 2025

Step 2
scale up
To full sensor

RadPix2

Full size RADPIX with 95% sensitive area



256 × 256 pixels

(80 µm × 80 µm)

To be submitted in late 2026

- Same property as MightyPix but different foundry (LF foundry)
- Submission Q1 2026

RadPix1

- Chip size: ¼ **of final chip 0.5 cm × 2 cm**
- Pixel size: **80 µm × 80 µm**
- Power consumption optimisation (< 9.6 µW/pixel to meet 150 mW/cm^2 requirement, with 99% in-time efficiency)
- 1 × 35-bit hit data word (in progress)

Periphery (of RadPix1)

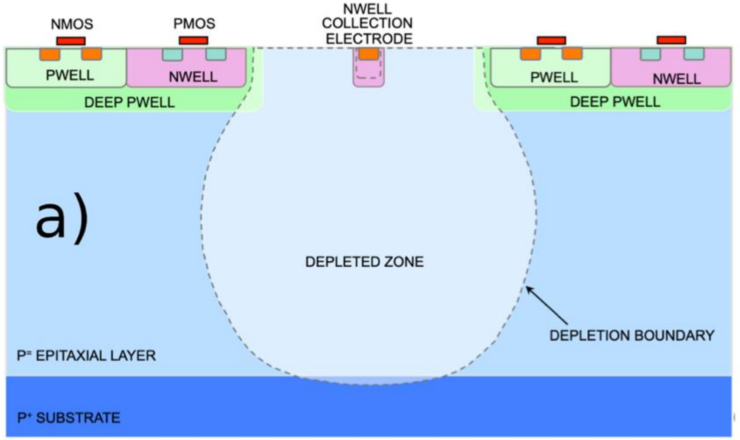
- 1 data link (max. 1.28 Gbit/s)
- Slow control (I2C protocol for convenience)
- Timing and Fast Control (TFC)
- Serial powering, Power-on-Reset

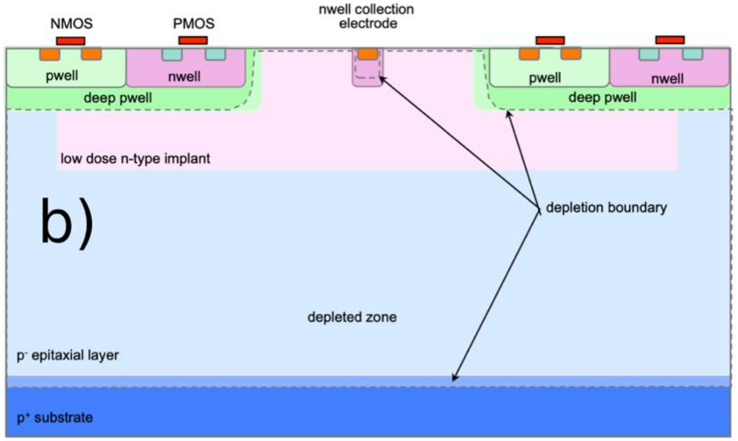
Data rate: expect 8.4 Gbps→need 7 links at 1.28 Gbs
→ can be reduced by sharing BXID information

TPSCO: 65nm – LV-CMOS

➢ LV CMOS with new process:

JINST 20 C01019





Standard Process

- Features an n-well collection electrode with circuitry is isolated by a deep p-well.
- **Depletion region has balloon shape** from the n-well to the p+ substrate.
- Epitaxial layer depth ~10 µm; lateral regions remain undepleted.

Charge collection:

- Diffusion-dominated.
- Slow and prone to charge trapping.
- High charge sharing between pixels.

Modified-with-Gap Process

- Adds a **deep low-dose n-type implant below** CMOS circuitry including gaps at pixel edges
- **Depletion region extends laterally as** the gaps allows for electric field development
- The lateral electric field induces **drift-dominated charge** collection

- **Charge collection:**
  - Drift-dominated, even at edges.
  - Faster and less affected by charge sharing.

Planning for MightyPix2 testing

- MightyPix2 main candidate for both MP and UP, expected **by the end of the year**
- Preparation of the testing procedures:
  1. build a test setup as general as possible**, compatible with all the sensor candi**dates
  2. easily movable for **test beams**

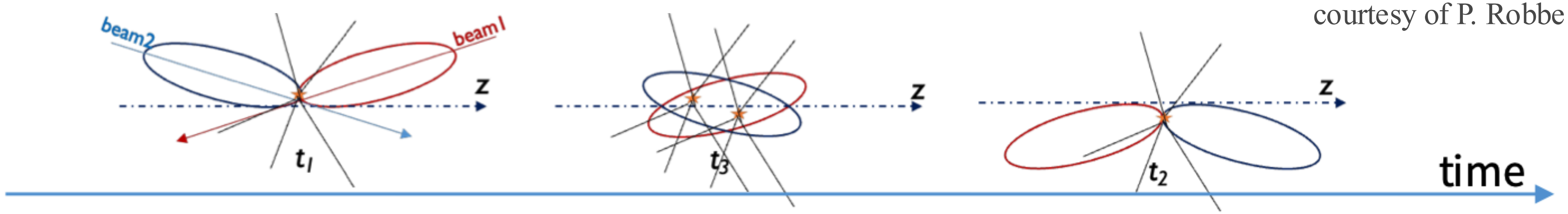
○ **General functionality** • IV, VV & CV curves • analog pixel • digital (periphery & pixel) ○ **Performance tests using radioactive sources, laser and testbeam** • DAC setting optimisation • Time resolution vs power • In-time efficiency • Hit rate capability	○ **Irradiation effects** ○ NIEL • Neutrons, protons ○ TID • Low dose (~1MRad) • full dose (~40MRad) ○ Single event effects • SEE ○ **Interfaces** • TFC, ECS • Data Link quality	○ **Multi chip operation** ○ Serial powering ○ Daisy chaining ○ **Prototyping for hybrids, modules** ○ **Development of QA procedures** ○ **LHCb compatibility** ○ LpGBT ○ MiniDAQ

Slide by Sebastian Bachmann

Upgrade II of LHCb

- Same geometry for the detector with innovative technologies for sub-detectors and data processing
- Main elements:
  - Increase granularity
  - Add timing measurement (resolutions up to 10-50 ps, in VELO, RICH/TORCH, ECAL)
  - Radiation hardness (up to 10^{16} n_{eq}/cm^2)
  - Data rate: 200 Tbit/s
- Time spread of pp interaction region ~200 ps (t_2-t_1): measurement of time of particles with ~10 ps precision to distinguish different pile-up interactions in the same bunch crossing.

courtesy of P. Robbe



For Heavy Ion collisions:
- No or very small pile-up: time measurement does not help
- Contrary to pp, one interaction can have a wide range of multiplicity depending on the system (proton-Helium vs PbPb) and on the centrality (overlap of the two colliding ions):
  - From less than 1 pp interaction to up to 360 pp interactions for the most central PbPb collisions.
  - A pile-up of 40 pp interactions corresponds to 40% centrality in PbPb.

LHCb Upgrade I

Overall major upgrade, >90 % of detector channels!

Completely new readout system for the full detector

LHCb-DP-2022-002
LHCb-TDR-12

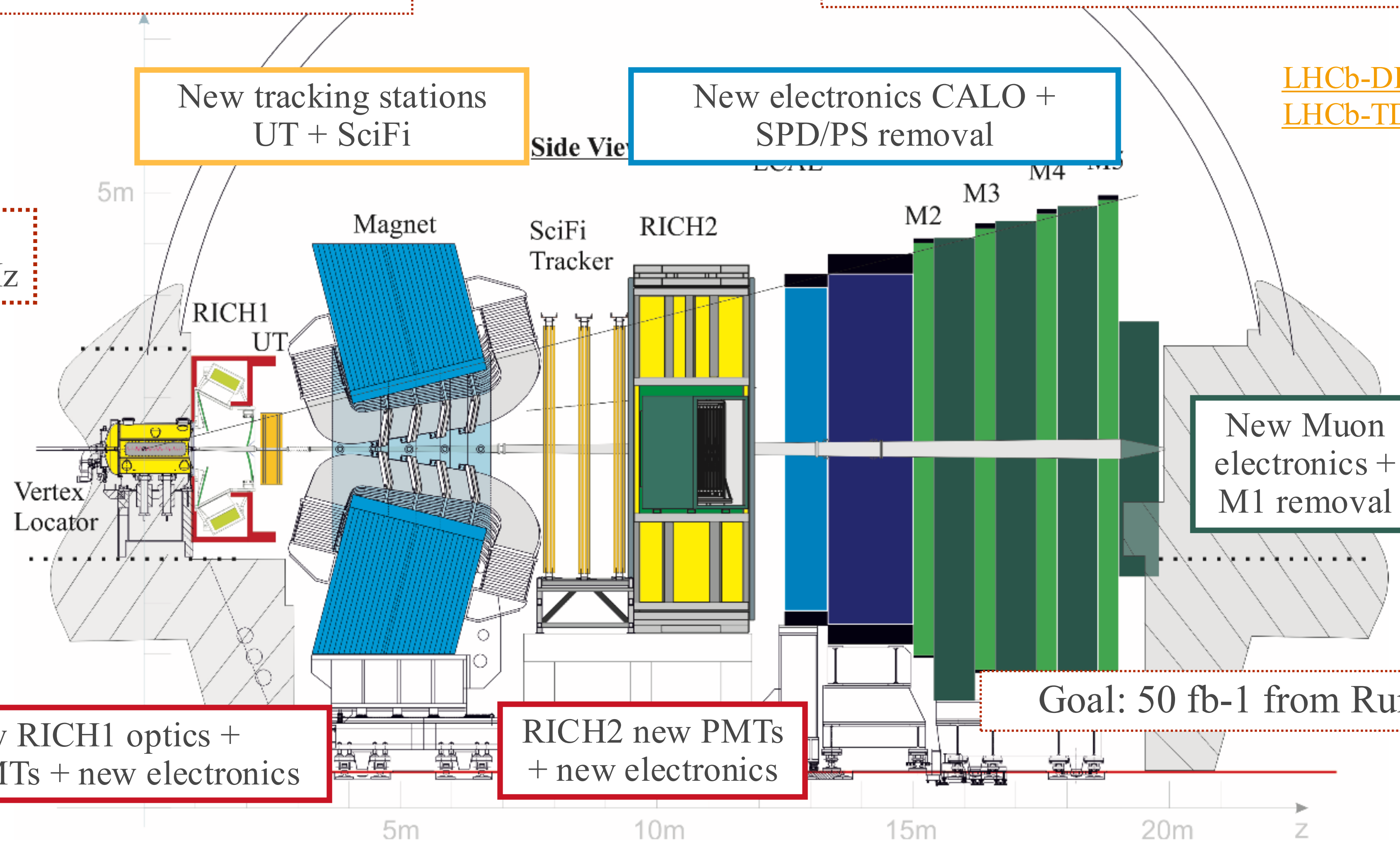
Fully software trigger at 40 MHz

New tracking stations UT + SciFi

New electronics CALO + SPD/PS removal

New pixel VELO

New Muon electronics + M1 removal

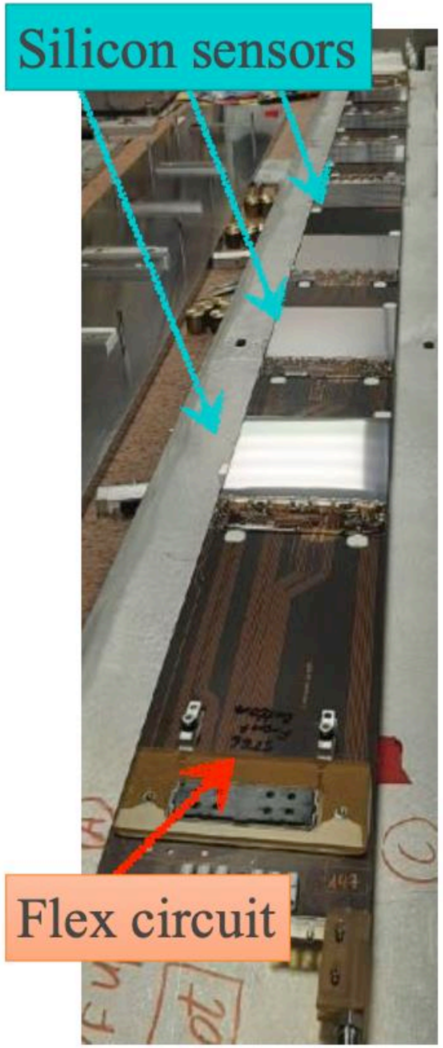


New RICH1 optics + new PMTs + new electronics

RICH2 new PMTs + new electronics

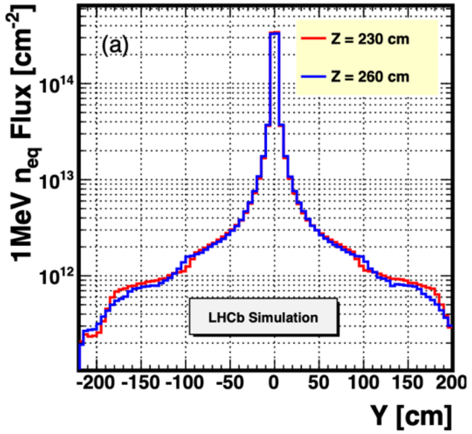
Goal: 50 fb-1 from Run1 to Run 4

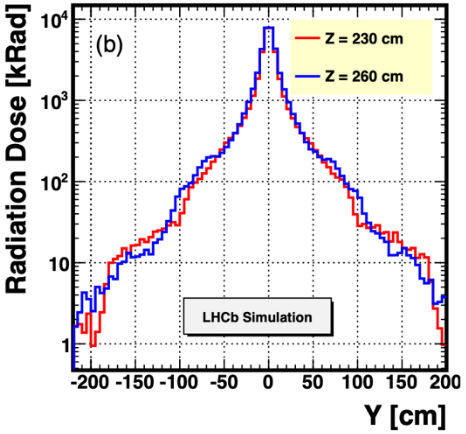
Upgrade I trackers: UT

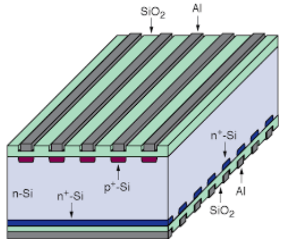


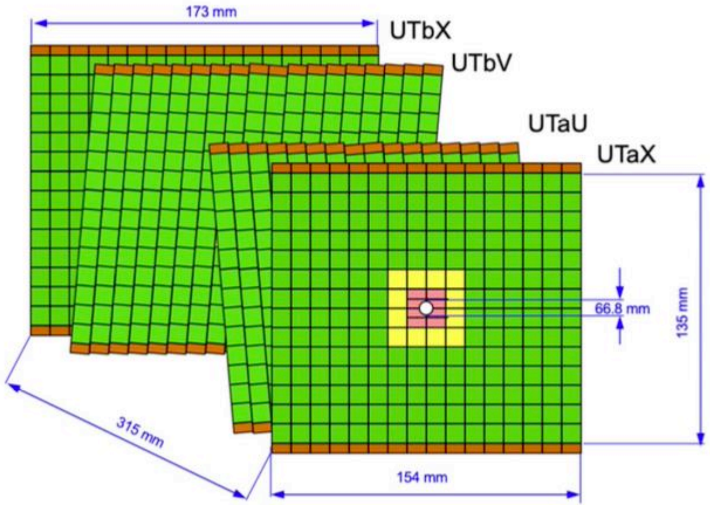
- **Single-sided silicon strip sensors** mounted on either side of staves (vertical strips)
- Four layers upstream the magnet:
  U and V layers provide stereo information
- Partially overlapping in Y direction
- Staves staggered in Z for partial overlap in X direction
- Increasing granularity getting closer to the beam
- ✦ Sensors mounted on staves (both sides) with bi-phase CO2 cooling (<−50 C)

Up to 1 kGy for near detector electronics, 4×10^{14} n_{eq}/cm^2







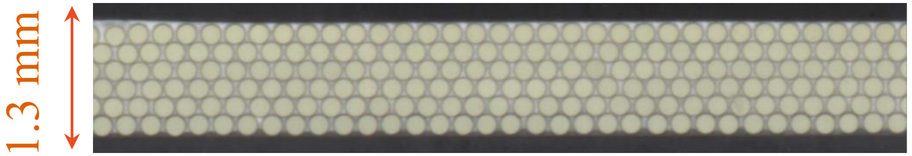


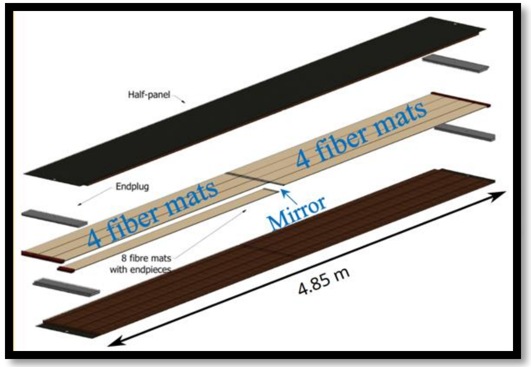
Property	Sensors B,(C,D)	Sensors A
Technology	n^+-in-p	p^+-in-n
Thickness	250 μm	250 μm
Physical dimensions	98 mm X 98 (49) mm	98 mm X 98 mm
Length of read-out strip	98 (49) mm	98 mm
Number of read-out strips	1024	512
Read-Out strip pitch	95 μm	190 μm
Sensor number (needed)	48 (16,16)	888

Upgrade I trackers: SciFi

- Scintillating fibers organized in fiber mats

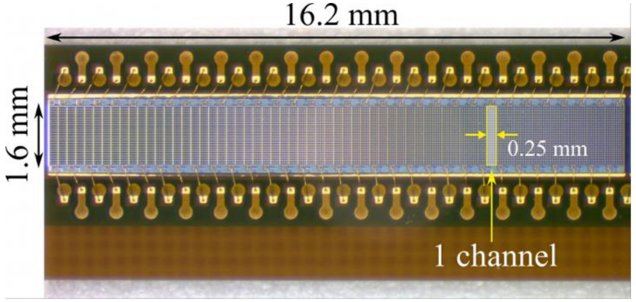
Cross section of a fiber mat

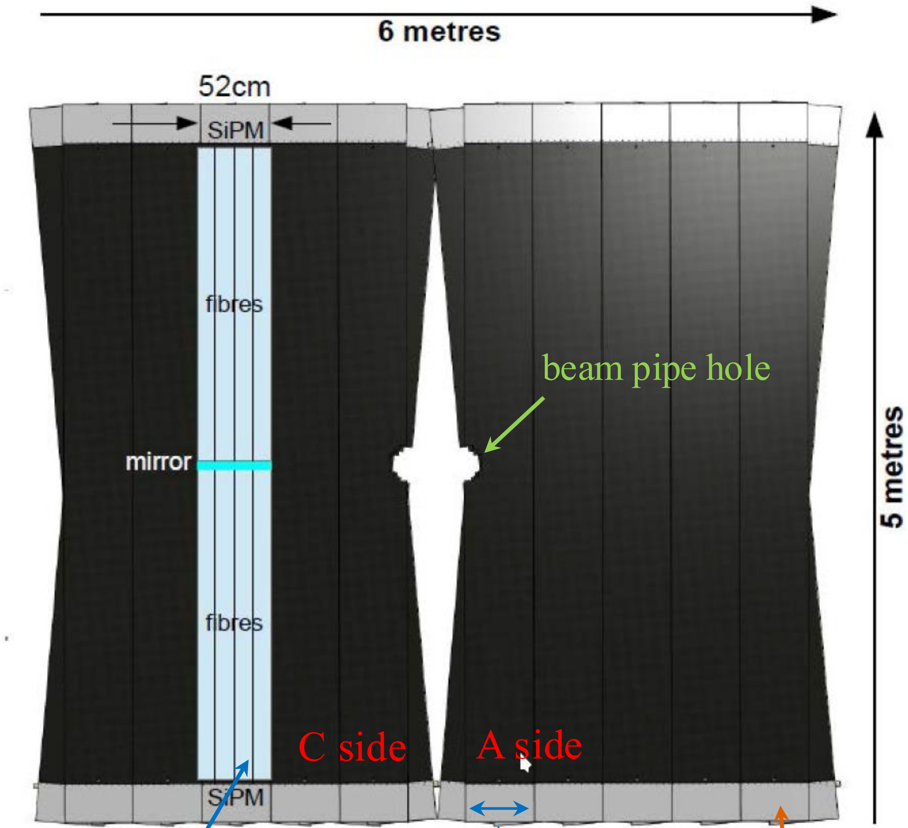




Charge particles in the Fiber
→ Forster transfer + scintillation

- Silicon PhotoMultipliers SiPMs to the detect light





4 layers:
2 in a C frame

4 fiber mats per module

5-6 modules per side

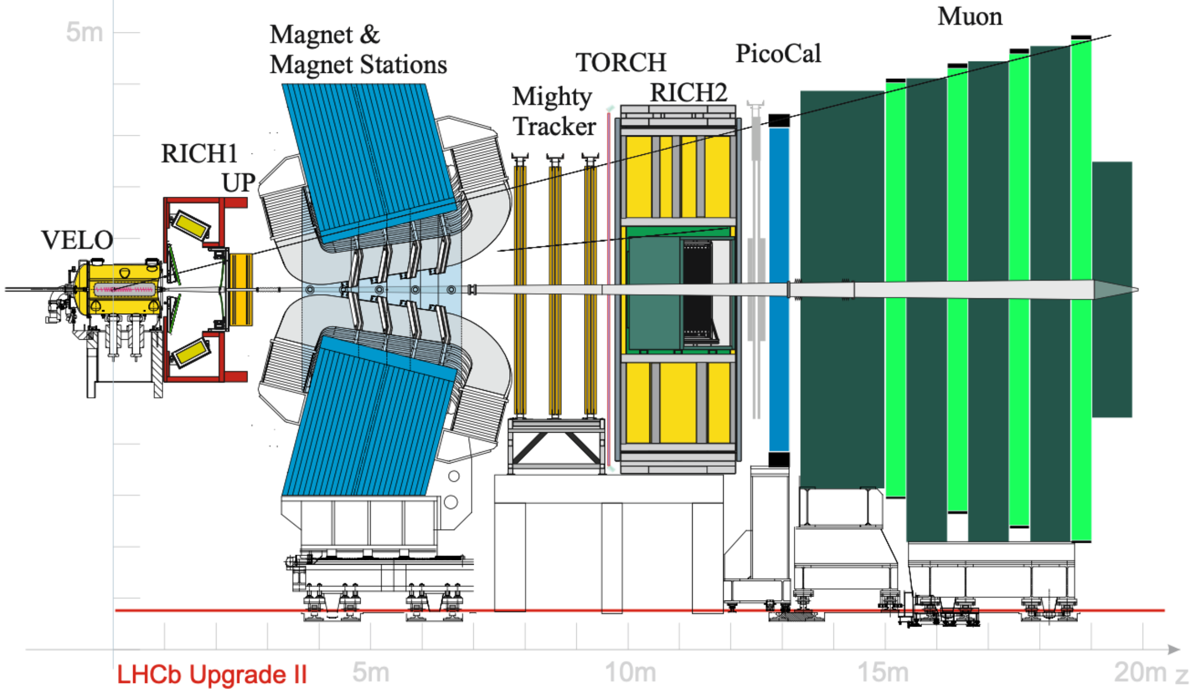
SiPMs and Read-out boxes

Upgrade II

Upgrade II : increase instantaneous luminosity

$\mathit{Lumi}\ \cancel{150}\ 100 \times 10^{32} cm^2 s^{-1}$ **(x40)**

- Increase granularity
- Add **timing** measurement (resolutions up to 10-50 ps, in VELO, RICH/TORCH, ECAL)
- Radiation hardness (up to $10^{16}\ n_{eq}/cm^2$)
- Data rate: 200 Tbit/s



For Heavy Ion collisions:

- No or very small pile-up: time measurement does not help
- Contrary to pp, one interaction can have **a wide range of multiplicity** depending on the **system** (proton-Helium vs PbPb) and on the **centrality**

Tracking: move from fibers and strips to pixels detector necessary to substains high particle rates

Specifications for UP and MT

UP Specification

Parameter	UP Specification
Pixel size in x	$\lesssim 100$ µm
Pixel size in y	$\lesssim 100$ µm
Substrate thickness	< 200 µm
Pixel orientation	central sym.
Max. Particle Rate $= R_{Part}$	74(34) MHz/cm^2
Max. Hit Rate	150 Mhit s^{-}1cm^{-2}
Max. length of data word	32
Overall efficiency	>96%
In-time efficiency	>99% within 25 ns
Noise rate (End of life)	$\lesssim$ 400kHz/ cm^2
Transmission rate	$N \times 1.28$ Gbit/s
NIEL	$3 \times 10^{15} n_{eq}/\mathrm{cm}^2$
TID	240 MRad
Power Consumption	$\lesssim$ 300 mW/ cm^2

MT Specification

Parameter	MP Specification
Pixel size (bending plane)	$\lesssim 100$ µm
Pixel size (non bending plane)	$\lesssim 200$ µm
Substrate thickness	<200 µm
Pixel orientation	x
Max. Particle Rate	17 MHz/cm^2
Max. Hit Rate	34×10^6 s^{-}1cm^{-2}
Max. length of data word	32
Overall efficiency	>96%
In-time efficiency	>99% within 25 ns
Noise rate (End of life)	$\lesssim$ 400kHz/ cm^2
Transmission rate	4 links of 1.28Gbit/s each
NIEL	$3 \times 10^{14} n_{eq}/\mathrm{cm}^2$
TID	40 MRad
Power Consumption	$\lesssim$ 150 mW/ cm^2

For **UI** this was:

- **SF:** 35 kGy near the beam pipe, 6×10^{11} n_{eq}/cm^2 SiPMs
- **UT:** up to 1 kGy for near detector electronics, 4×10^{14} n_{eq}/cm^2

***NIEL – Non-Ionizing Energy Loss** (Effects on sensor, **crystal lattice damage**)
***TID – Total Ionizing Dose** (Effects on MAPS electronics)

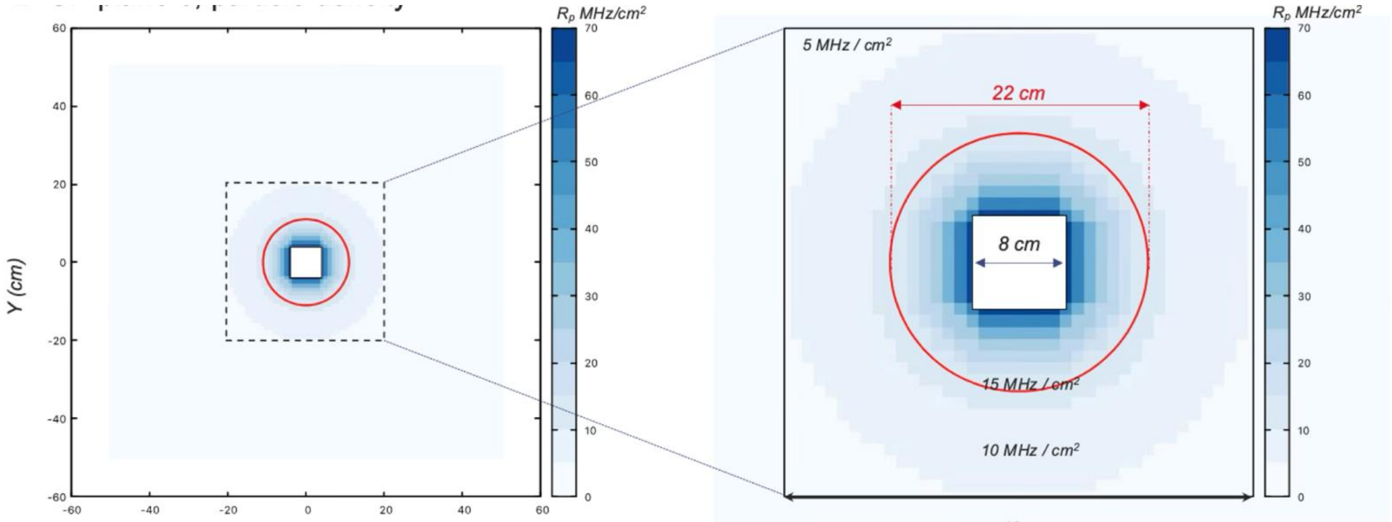
Particle rates in the trackers

➢ UP first layer particle density

Max. Particle Rate $= R_{Part}$	74(34) MHz/cm^2	Max. Particle Rate	17 MHz/cm^2
Max. Hit Rate	150 Mhit s^{-1}cm^{-2}	Max. Hit Rate	34×10^6 s^{-1}cm^{-2}

Particles rate in the UP

$$R_{hits} = R_{part} \times \frac{N_{hits}}{particle}$$



- R_{part}=17 MHz/cm^2 **for MP**
- $\frac{N_{hits}}{particle}$ = depends on cluster size, 1.1-1.2
- and a safety factor (x2)

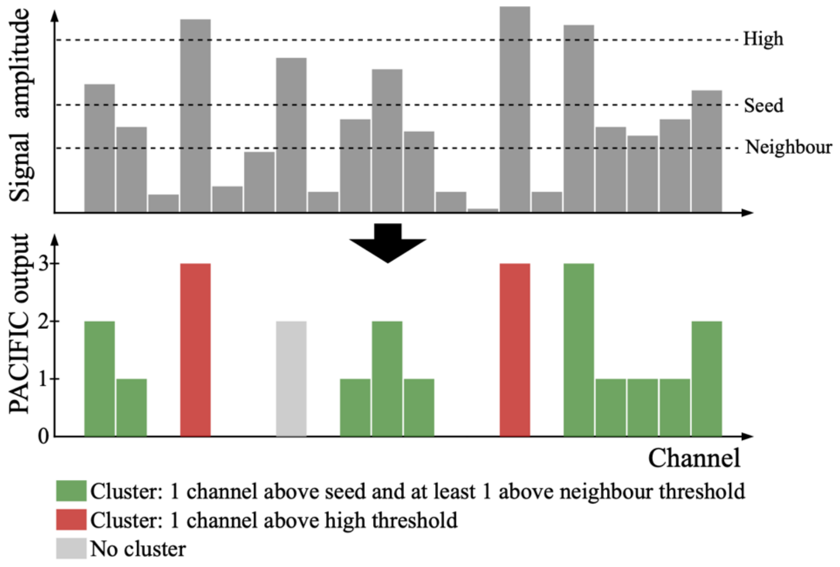
Most of the UP area has a similar particle rate as the Mighty Tracker, except the center
We could use **the same pixel sensor for both the MP and the UP**

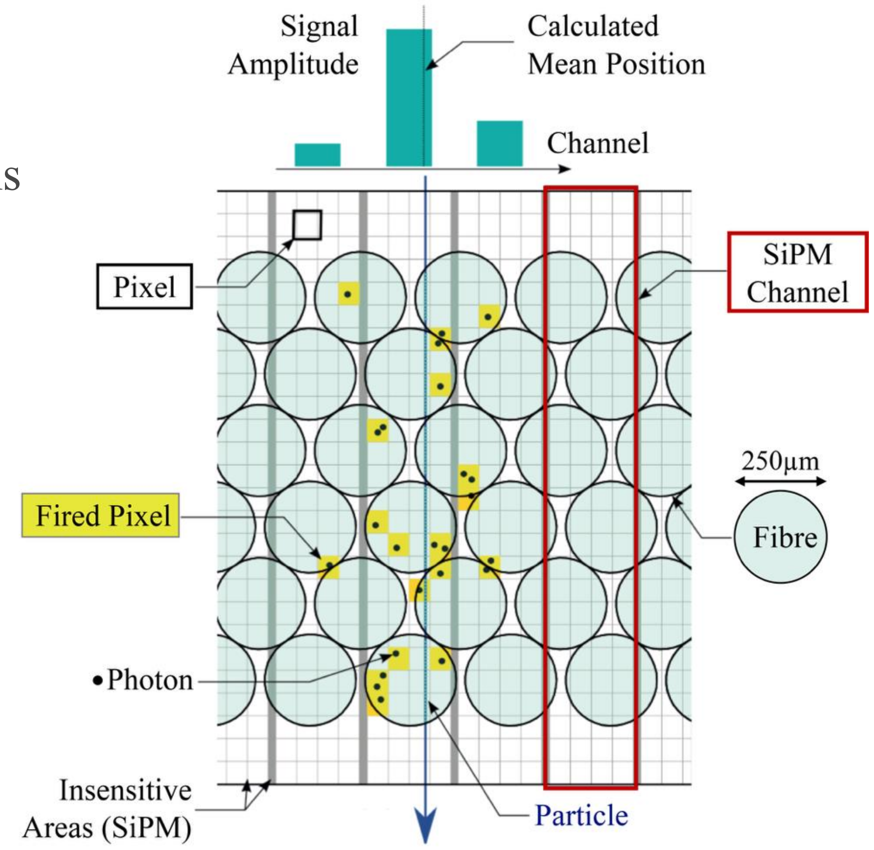
Find a different solution for the central region

1. Leave a hole in the central part → loss in rapidity
2. Cover the central part with another technology

From Fibers to clusters

- Particle deposits energy in several fibers along it's path
- Scintillation photons are transported to SiPM arrays via total reflection
- Amplitude in each channel proportional to the number of detected photons





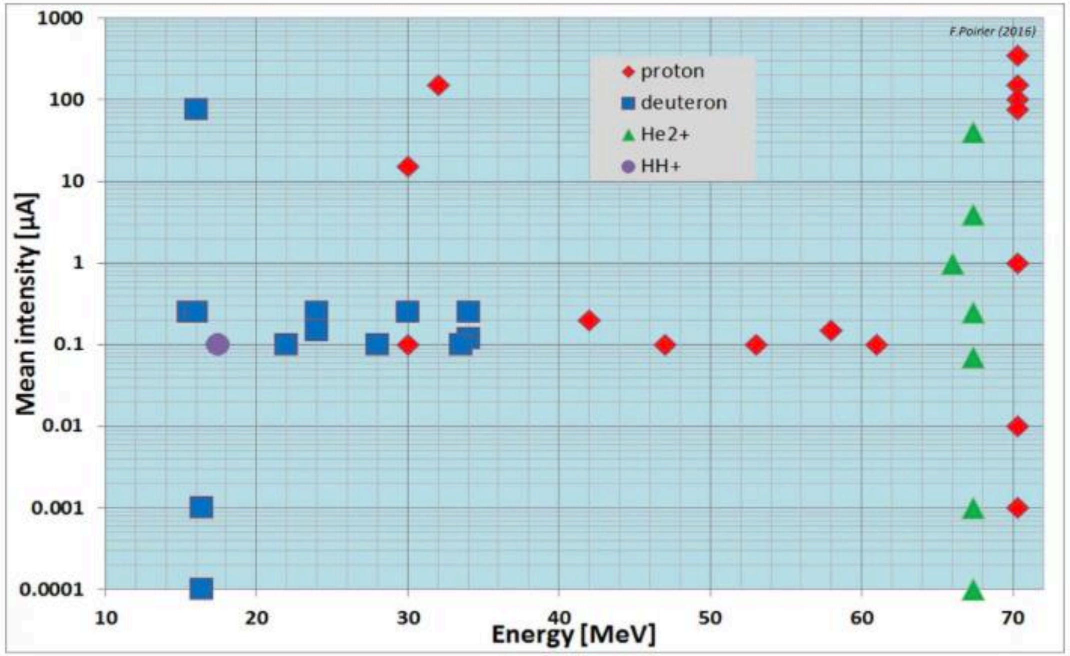
Clustering with 3 thresholds

1. seeding: starting point
2. neighboring: if signal passing seeding, neighbouring channels should pass this th. to form a cluster
3. high: high single channel signal is a cluster by its own

Barycenter reconstructed using weighted mean.
No per pixel hit information!

Arronax, Nantes, France

- Arronax: facility for medical applications and test beams close to Subatech Nantes
- Cyclotron up to 70 MeV protons
- Can be used to test soft SEUs mainly



Les caractéristiques du cyclotron Arronax

Arronax est un cyclotron isochrone à quatre secteurs. Il est constitué d'un électro-aimant capable de développer un champ magnétique vertical maximum de 1,64 T qui maintient les particules sur des trajectoires spirales dans le plan horizontal.

- Multi-particules : protons (H+), alpha (He2+) et deutons (D+)
- Énergie cinétique : 30-70 MeV protons, 68 MeV alpha
- Intensité : 750 µA protons, 35 µA alpha, 80 µA deutons
- 2 sorties simultanées en protons à énergie et intensité différentes si besoin
- Pulsation des particules
- Cyclotron isochrone à quatre secteurs
- Diamètre extérieur : environ 4 m
- Hauteur : 3,60 m
- Poids : environ 145 tonnes, soit le poids à vide d'un Boeing 777
- Fréquence de fonctionnement : 30,45 MHz avec des cavités RF composées de deux *dees* soumis à une tension de 65 kV

vue à 360°

Louvain, Belgium

- UCLouvain600
- Centre de Recherche du Cyclotron (CRC) - Institut de Physique Nucléaire (UCL-FYNU)
- heavy ion beams (HIF), proton beams (LIF), neutron beams (NIF) and a Cobalt60 source (GIF)

Heavy Ion Facility (HIF)

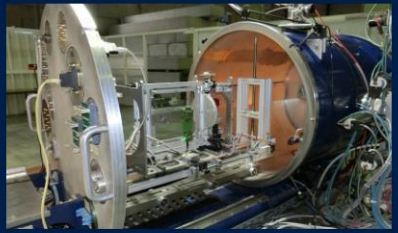
irmp | Louvain-la-Neuve

The Cyclotron Resources Centre offers **a cocktail of 9 ions** with an energy of 9.3 MeV per nucleon which covers a large domain of LET and ranges.

On special request, **a lithium beam** with LET 0.35MeV/(mg/cm²) is also available.

The **irradiations are made under vacuum**.

The frame support is motorized in X, Y, Z direction in order to place the device under test (DUT) in front of the beam. The frame can also be tilted. Interchangeable flanges with different kind of electrical feedthroughs are available. The CRC can also **develop flange with new connectors on request**.



Available particles inside the cocktail

M/Q	Ion	Energy [MeV]	Range [µm]	LET [MeV/(mg/cm²)]
3,25	$^{13}C^{4+}$	131	269.3	1,3
3,14	$^{22}Ne^{7+}$	238	202,0	3,3
3,37	$^{27}Al^{8+}$	250	131,2	5,7
3,27	$^{36}Ar^{11+}$	353	114,0	9,9
3,31	$^{53}Cr^{16+}$	505	105,5	16,1
3,22	$^{58}Ni^{18+}$	582	100,5	20,4
3,35	$^{84}Kr^{25+}$	769	94,2	32,4
3,32	$^{103}Rh^{31+}$	957	87,3	46,1
3,54	$^{124}Xe^{35+}$	995	73,1	62,5