Upgrade of the LHCb tracking system: some French-biased perspectives

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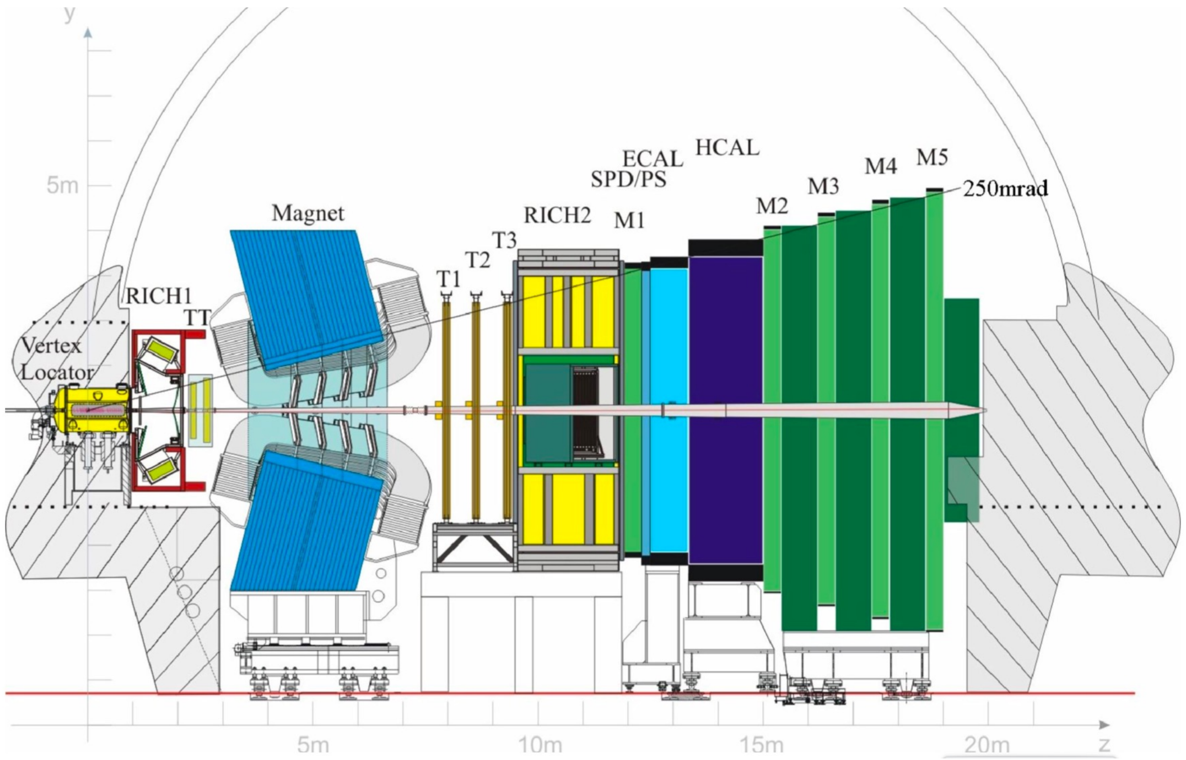
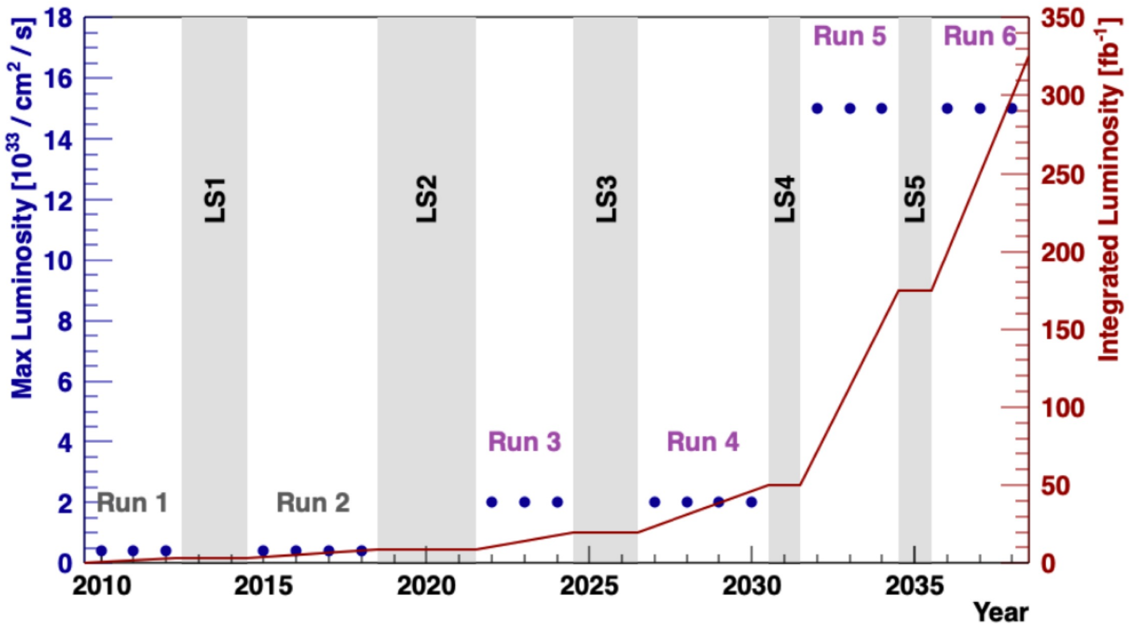
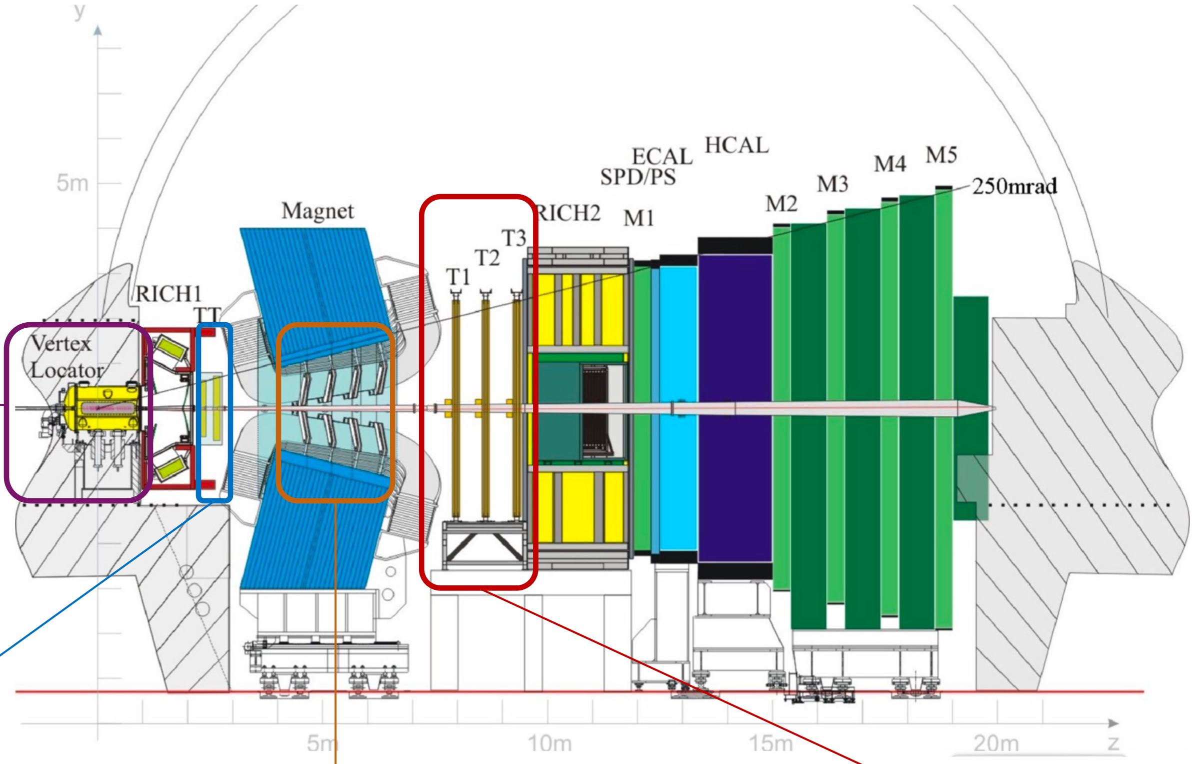
The LHCb Upgrade 2

- An ambitious program implying the upgrade of almost all detectors
- Structured in two phases
  - Consolidation and enhancement phase in LS3 (formerly called Upgrade Ib): no luminosity change (baseline)
  - Main installation phase in LS4 (the so-called U2): luminosity increase
- Detailed in a Framework-TDR being completed in the coming months (for LHCC November session)





THE TRACKING SYSTEM UPGRADE



VELO
Pixel with timing

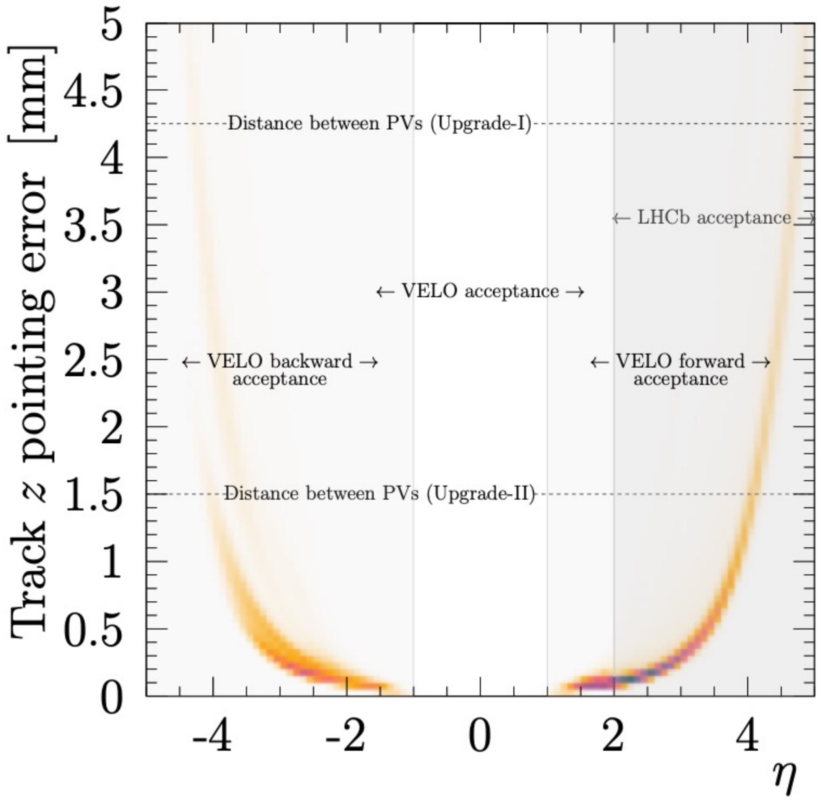
Upstream Tracker
From strip to CMOS

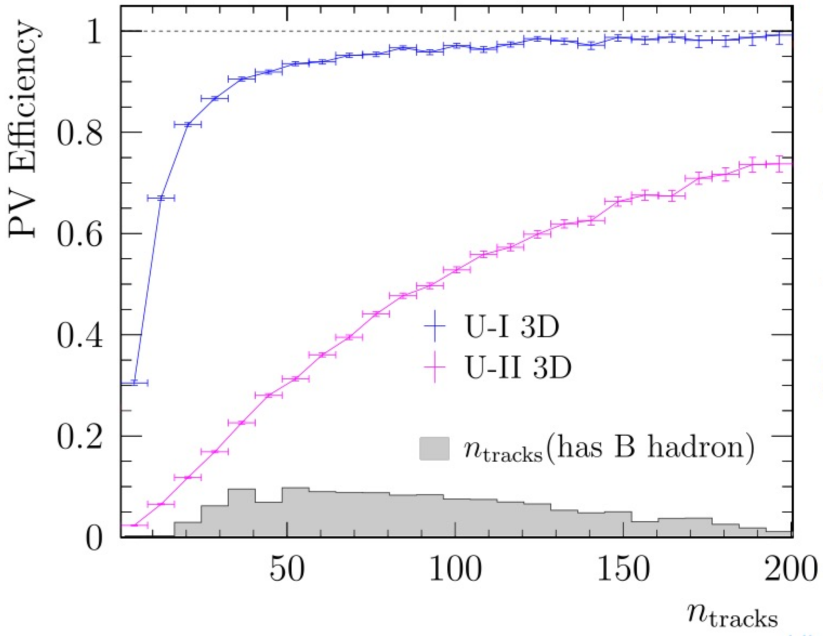
Magnet stations
Tracking on magnet sides

Mighty Tracker
Combine SciFi & CMOS

Vertex Reconstruction @ $\mu \sim 50$

The Phase II Upgrade Challenge



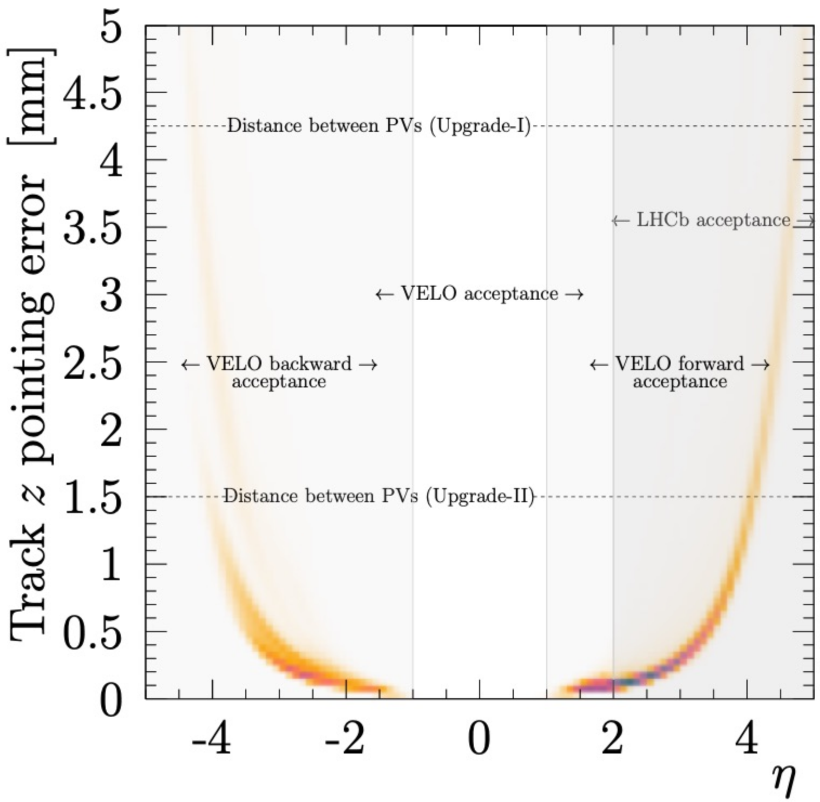


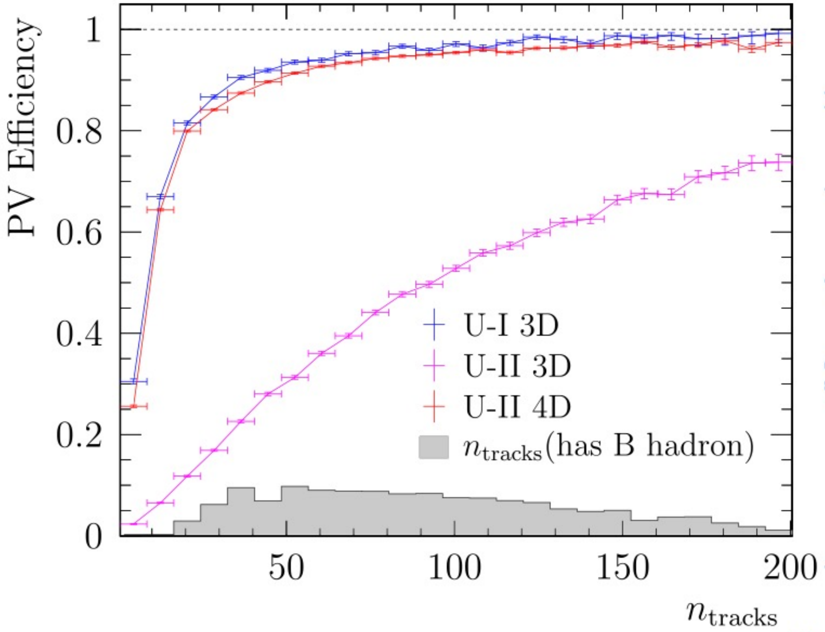
▷ At ∼ 50 interactions / bunch crossing, PV separation is comparable to the per-track pointing resolution to the beam axis (∼ 1 mm) : Reconstruction becomes tough.

Tim Evans

Vertex Reconstruction @ $\mu \sim 50$

The Phase II Upgrade Challenge



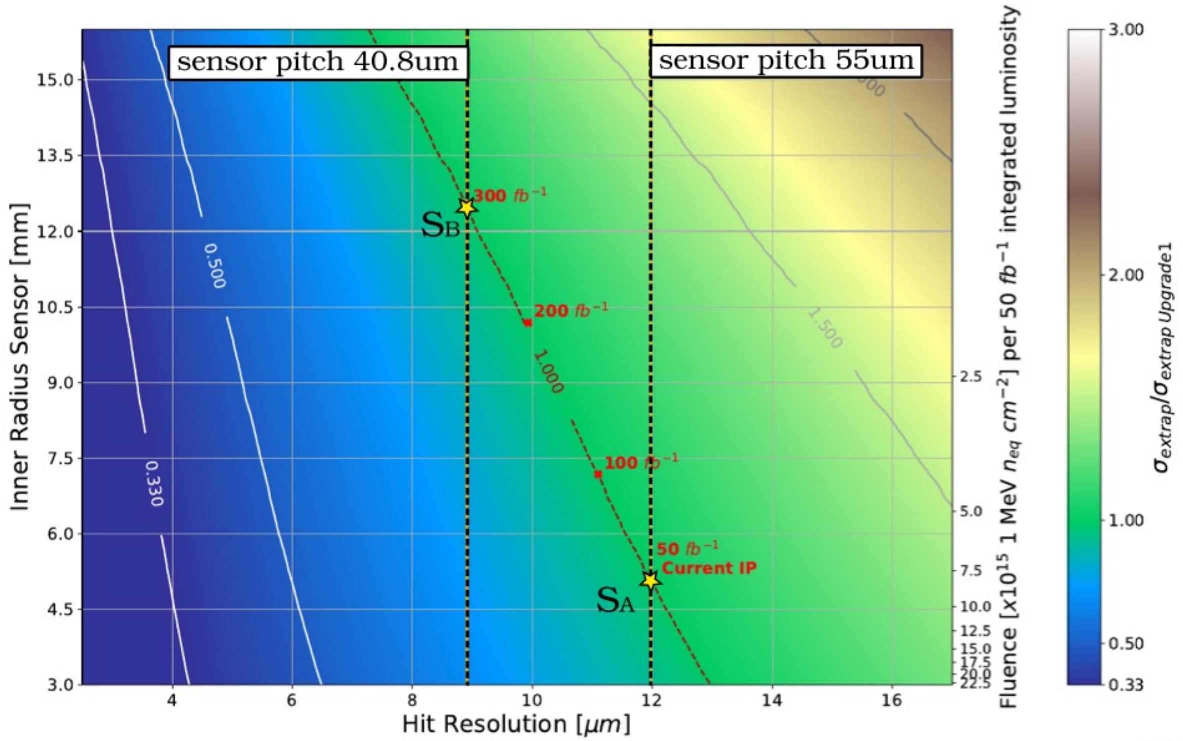


- ▷ At $\sim$ 50 interactions / bunch crossing, PV separation is comparable to the per-track pointing resolution to the beam axis ($\sim$ 1 mm) : Reconstruction becomes tough.
- ▷ Initial studies show adding 50 ps / hit timestamp almost completely recovers the Upgrade-I vertex reconstruction efficiency.

Tim Evans

	VeloPix (2016)	Timepix4 (2018/9)	Picopix? (2024)?
Technology [nm]	130	65	< 65
Pixel Size [μm]	55×55 μm	55×55 μm	55×55 μm?
Pixels	256×256	512×448	256×256?
Area $[cm^2]$	1.98	6.94	1.98
Event packet [bit]	24	64	64?
Max. Rate $[10^6 Hits/cm^2/s]$	~ 400	~ 180	~ 4000?
Time resolution (TDC)	25 ns	200 ps	$20 - 50$ ps?
Readout bandwidth [Gb/s]	19.2	≤ 81.92	~ 500?

Push the limits of Frontend ASIC



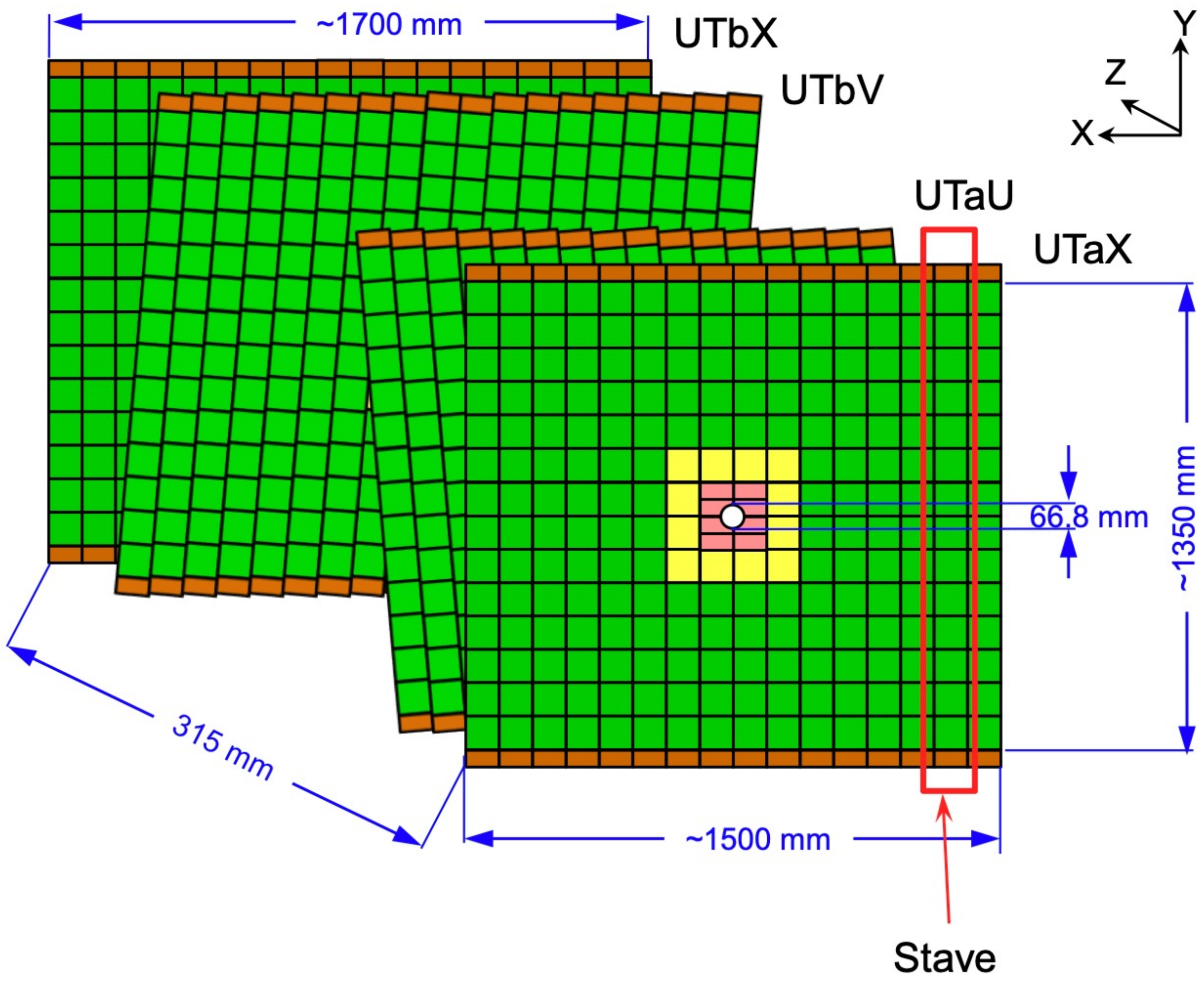
Limit the radiation damage (10^{16} 1 $MeVn_{eq}/cm^2$/year)

- Optimize position, pitch and material
- Several scenarios under study
- The most critical point seems to be the foil

Sensor	A	B	C	D
Type	p-in-n	n-in-p	n-in-p	n-in-p
Thickness(μm)	320	250	250	250
Pitch (μm)	187.5	93.5	93.5	93.5
Length (mm)	~100	~100	~50	~50
Strips/sensor	512	1024	1024	1024
SALTs/sensor	4	8	8	8
Numbers	888	48	16	16

- Four planes of silicon strip detectors, readout ASICs at sensor proximity.
- Higher segmentations near the center. Max occupancy ~ 1.4%.
- Stave structure: modules on 2 sides for overlapping, readout at 2 ends.
- In total 68 staves, 968 sensors, 4192 ASICs.

The present UT upgrade



The UT upgrade – From strips…

pp collisions

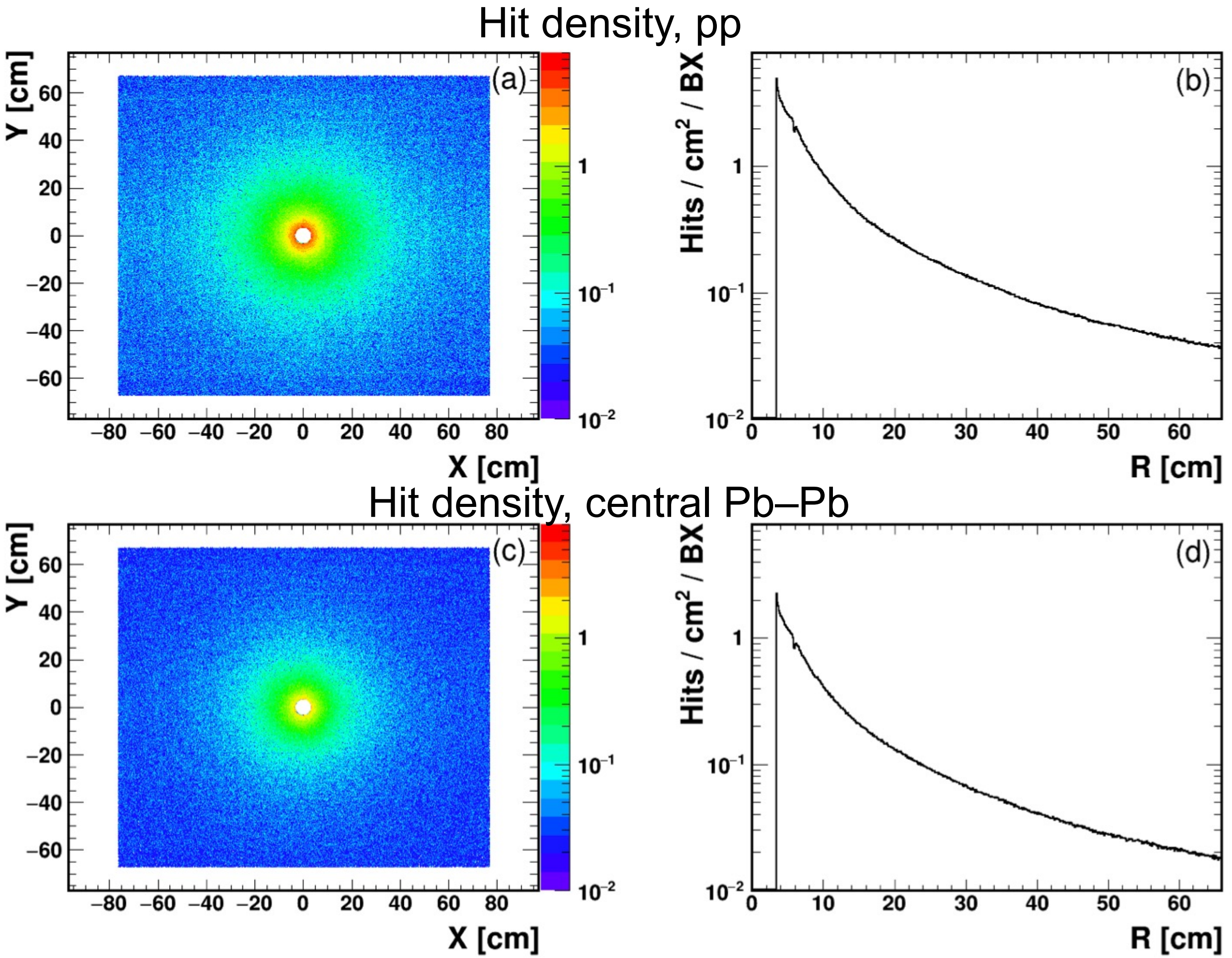
- Instantaneous Luminosity 2×10^{34} cm^{-2}s^{-1}
  - 67% of BX have beam-beam collisions
  - O(10) tracks per pp collision
  - Average hit rate in UT: 5.9 hits/cm^2/BX$_{coll}$

Pb–Pb collisions

- Instantaneous Luminosity up to 10^{28} cm^{-2}s^{-1}
  - Pile-up: negligible
  - O(1000) tracks per central Pb–Pb collision
  - Average hit rate in UT: 2.9 hits/cm^2/BX$_{coll}$
  - Maximum hit rate in UT: 52.5 hits/cm^2

Lighter ion collisions

- Allow larger integrated luminosity
  - Still no significant pile-up (except O–O)
  - Smaller track densit than Pb–Pb



UT is key to connect VELO and MIT track segments

UT is essential for Upstream and Downstream tracks

Possibility of standalone UT track segment

- Will likely require three UT stations
- Could improve and speed-up track matching
- Could provide momentum estimation

Need of timing is being studied

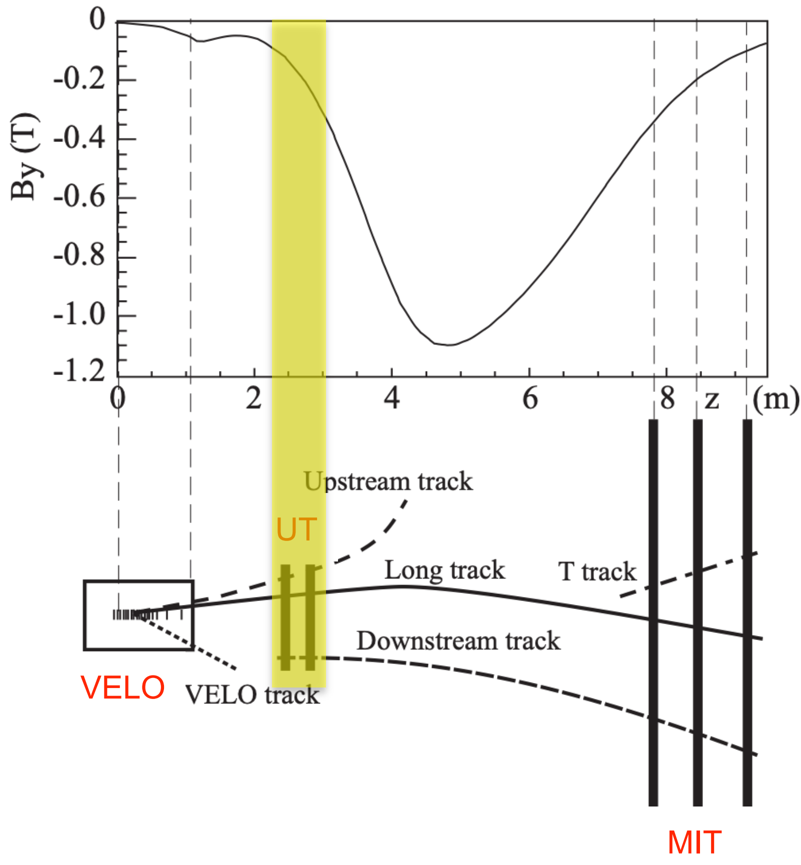
- Minimum requirement: BX identification, few ns time resolution
- Tracking: e.g. background rejection, sub-ns time resolution

Need to handle high-occupancy of most central Pb–Pb collisions

Solution: replace the Si strips with CMOS MAPS

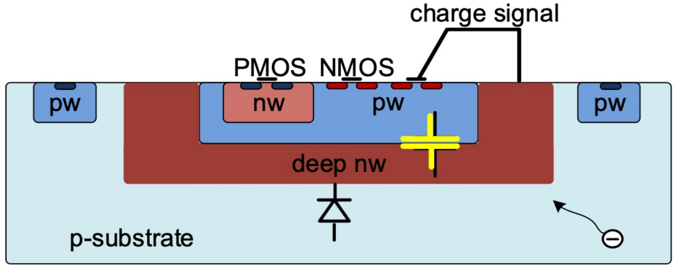
Large interest within the French HI community and beyond…

- LLR, LPNHE, Irfu, Subatech,…
- Several labs in China

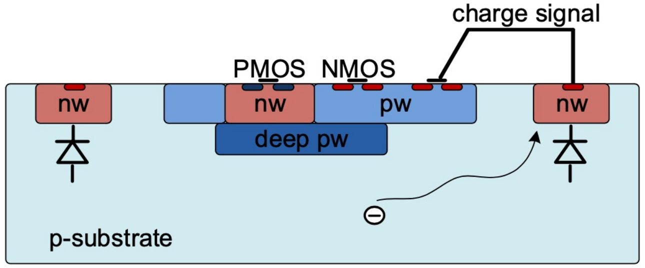


THE UT UPGRADE – FROM STRIPS… TO PIXELS

Two main CMOS options under development



Large collection electrode



Small collection electrode

- Typical pixel size: 50 x 150 μm^2
- Circuitry inside the collection well (requires high field: HV-CMOS)
- High radiation hardness
- Higher noise (high capacitance)
- Higher power consumption
- Possible cross-talk (digital to sensor)
- Presently developed under AMS-180 (MuPix, ATLASPix) and LF-150 technologies (Monopix2)

- Typical pixel size: 30 x 30 μm^2
- Circuitry outside the collection well (requires low/moderate field: LV-CMOS)
- High radiation hardness thanks to process modification (increase of depletion zone)
- Lower noise (low capacitance)
- Lower power consumption
- Less sensitive to cross-talk
- Presently developed under TJ-180 (Monopix2, MALTA2)

Main advantages

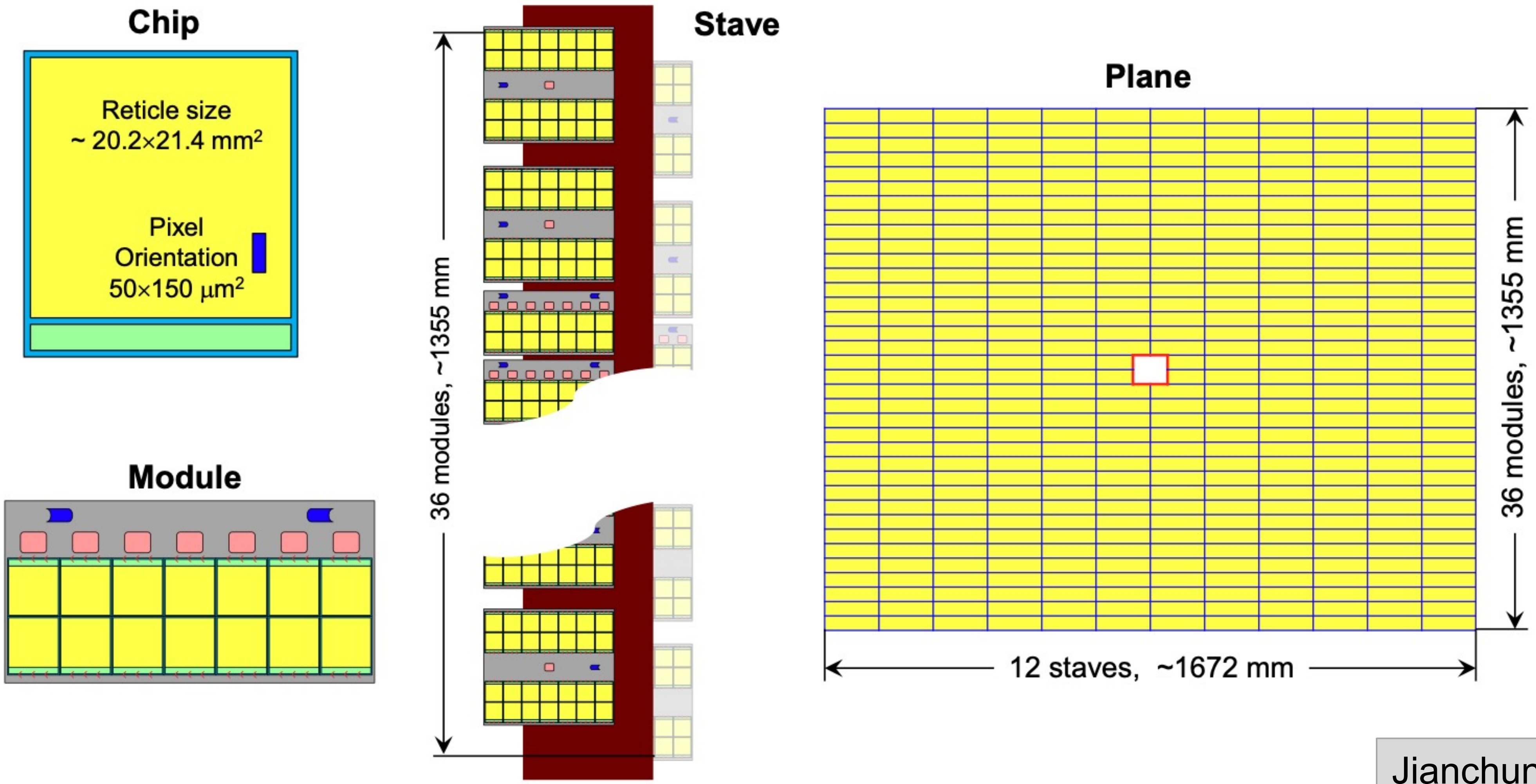
- Excellent space resolution
- Low budget
- Good radiation hardness
- High integration in monolithic technology

Main challenges

- Readout architecture for very high hit rate
- Provide high radiation tolerance
- Improve time resolution (eventually to sub-ns range)
- Keep low power consumption

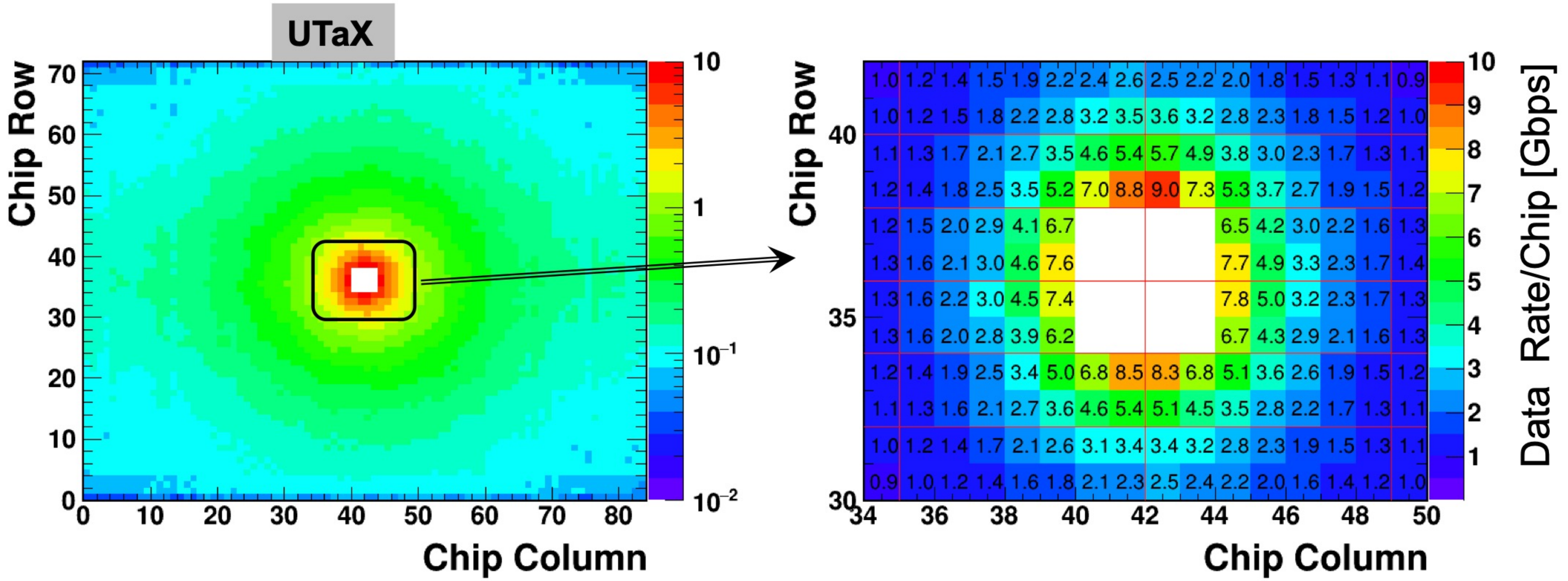
Final choice on MAPS technology will be based on refined and consolidated detector specifications

A possible setup, very preliminary



Jianchun Wang

THE UT UPGRADE – IMAGINE A SETUP



- Use minimal 28 bits per pixel hit.
- The whole UT throughput is 6.8 Tbps.
- The hottest chip ~9.0 Gbps, which needs at least 8 links of 1.28 Gbps/link.

BXID	Column	Row
12b (0-3563)	9b (≤399)	7b (≤127)

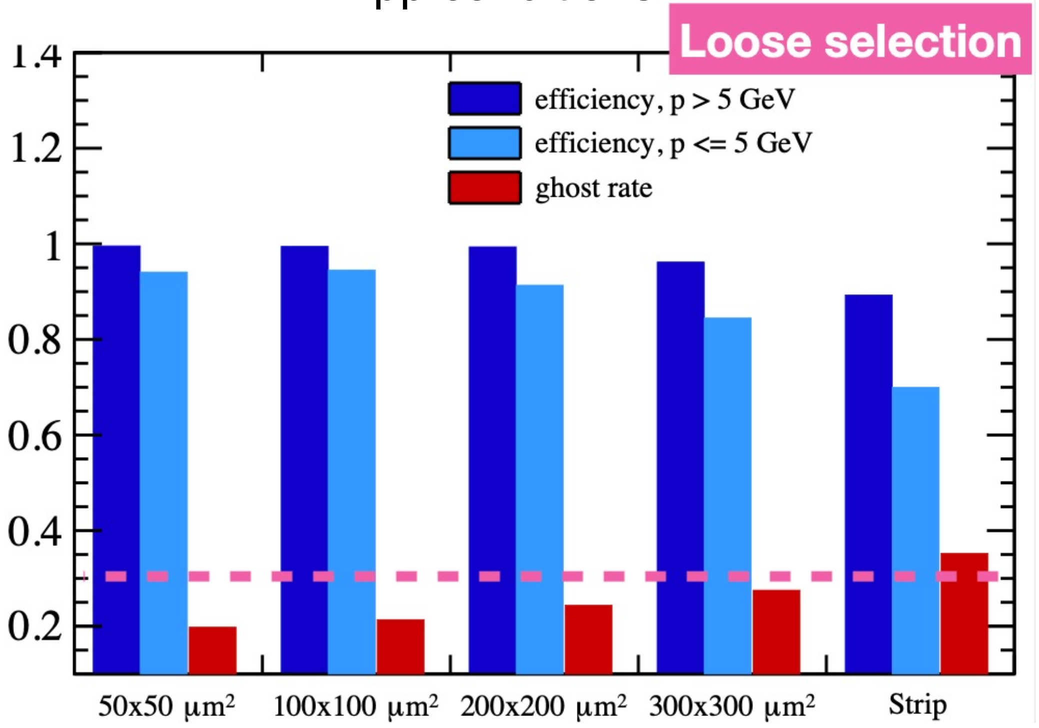
Jianchun Wang

Characteristics	LV-CMOS	HV-CMOS
Chip size	3.5×3.5 cm^2	2.0×2.0 cm^2
Pixel size	30×30 μm^2	50×150 μm^2
Chip thickness	100 μm	
Position resolution	5–10 μm	15, 40 μm
Time resolution	O(1 ns)	
Power consumption	100–300 mW/cm^2	
Data rate per chip	Up to 30 Gb/s	Up to 9 Gb/s
Radiation dose	3×10^{15} n$_{eq}$/cm^2, and 240 Mrad TID	

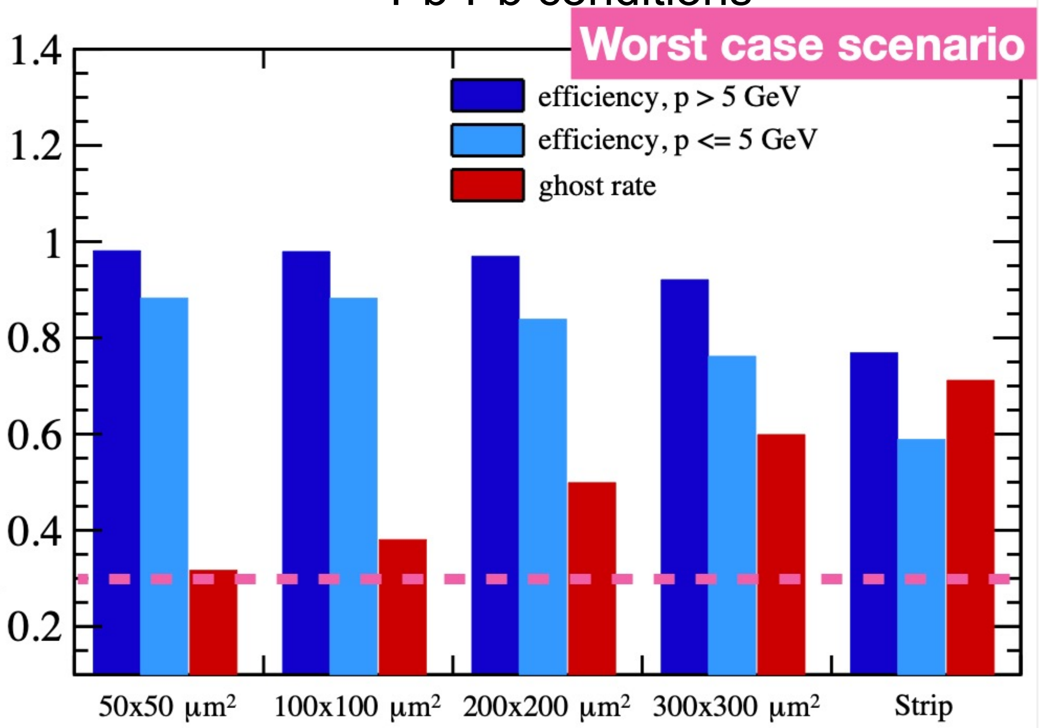
UT standalone performances (Cristina Agapopoulou)

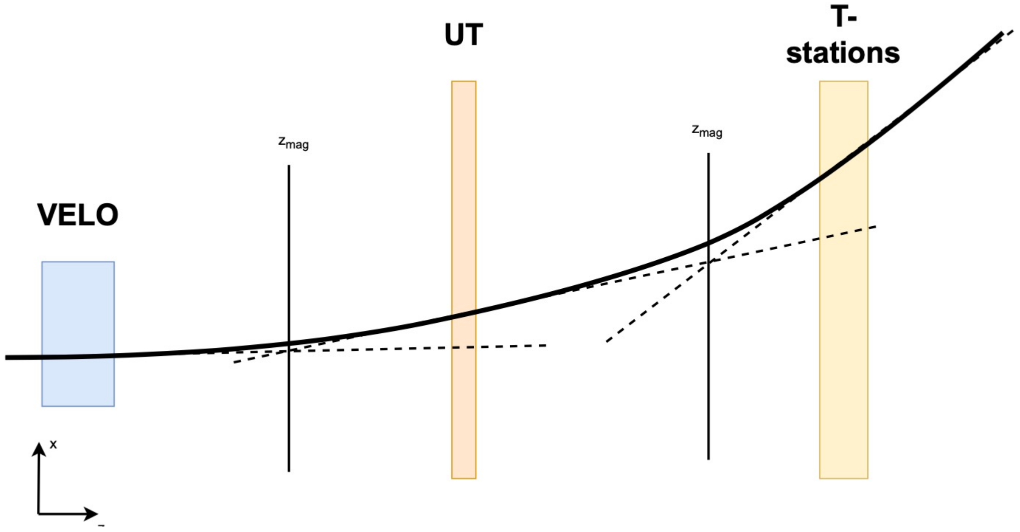
- Small pixels required to reduce ghost rate (especially in Pb-Pb) and improve efficiency at low momentum
- Similar efficiency achievable in pp and Pb-Pb

pp conditions



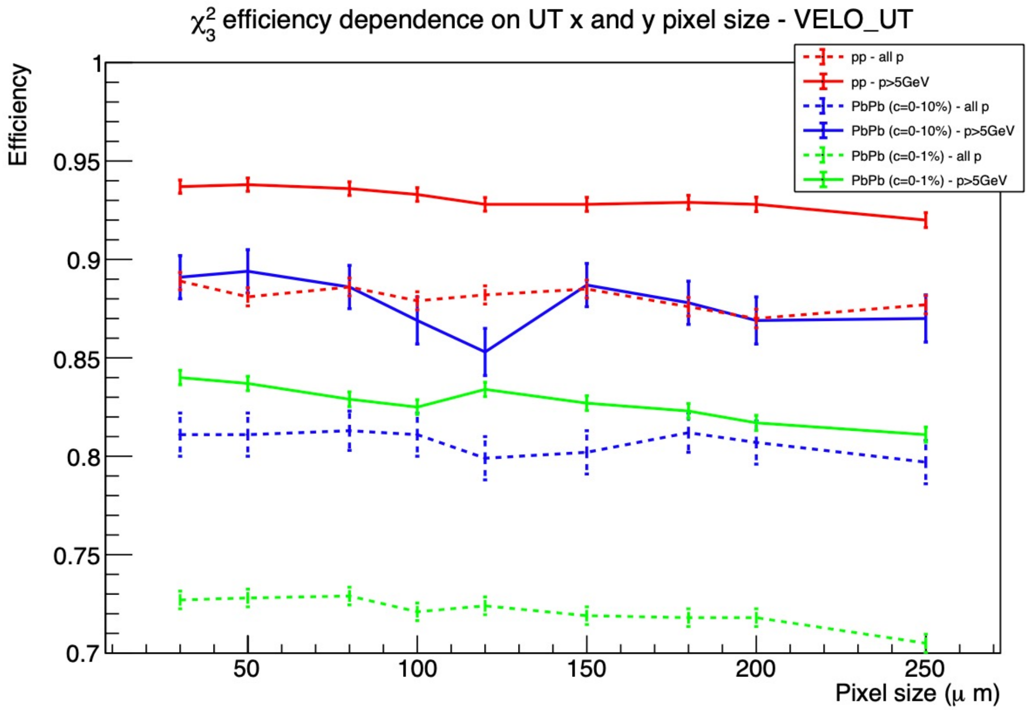
Pb-Pb conditions

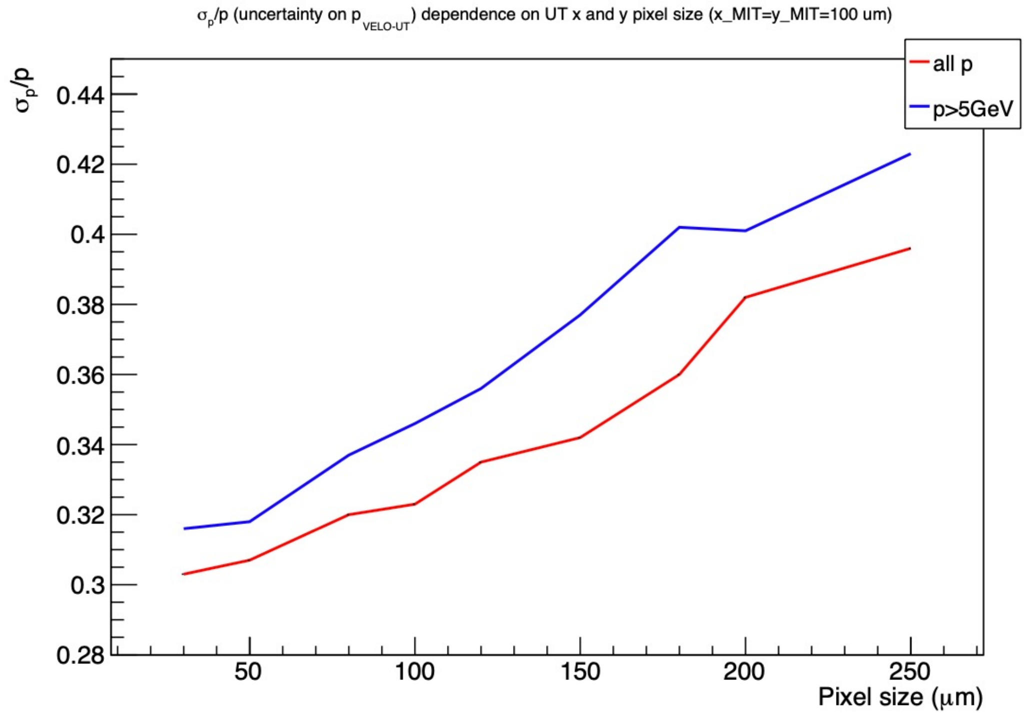


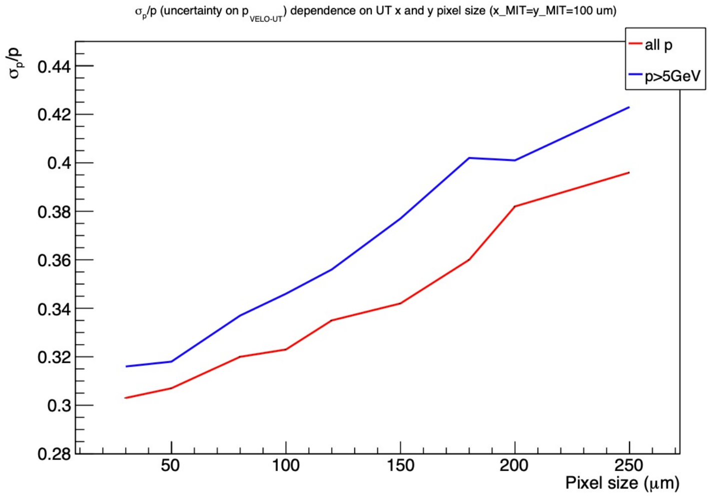


Matching studies (B. Audurier, G. Legras, M. Winn)

- All very preliminary!!!!
- Efficiency in most central Pb-Pb can be kept reasonably high, even at low momentum
- Impact of pixel size negligible on efficiency but essential for momentum resolution

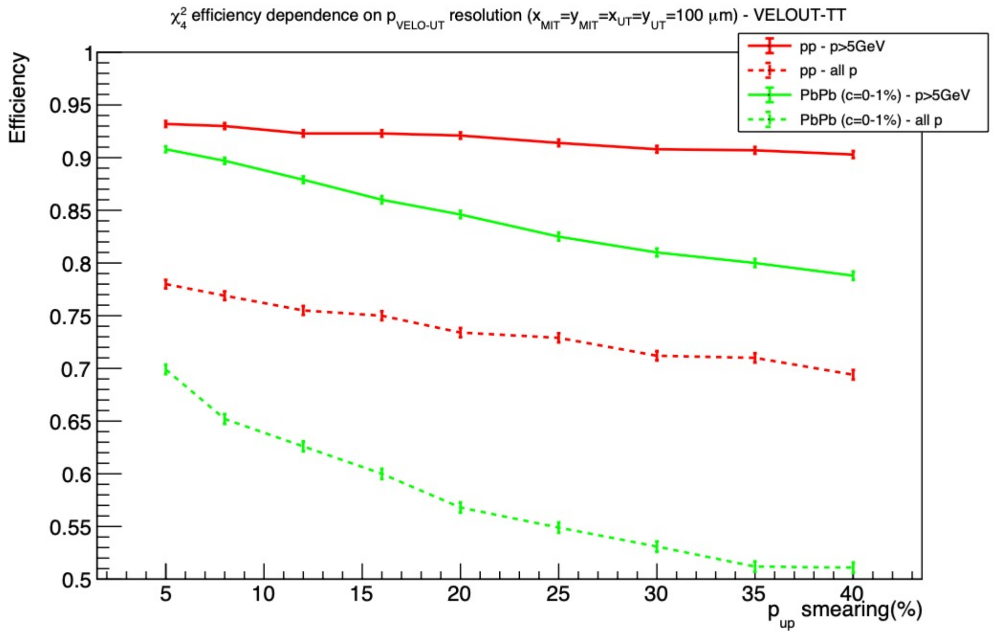




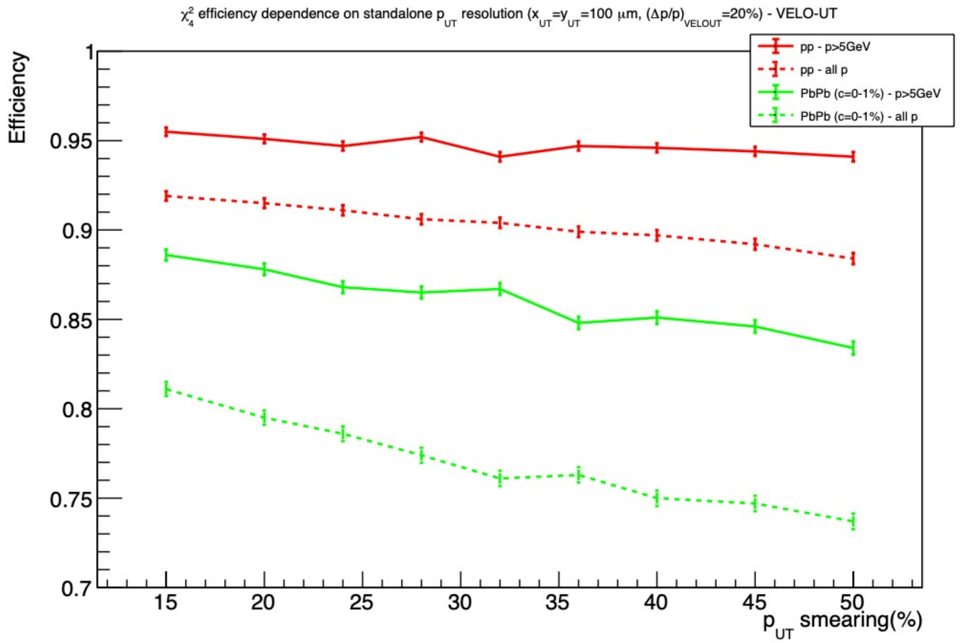


Matching studies (B. Audurier, G. Legras, M. Winn)

- All very preliminary!!!!
- Efficiency in most central Pb-Pb can be kept reasonably high, even at low momentum
- Impact of pixel size negligible on efficiency but essential for momentum resolution
- Momentum resolution sensibly increase the efficiency



VELO+UT

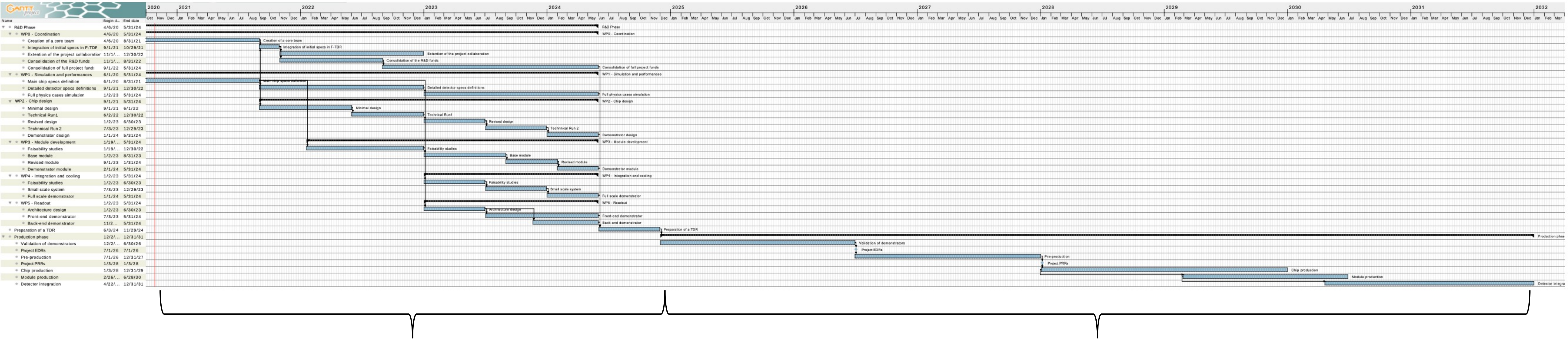


UT standalone

The UT upgrade – What's next

- Preliminary studies and performances included in the F-TDR
- Proto-collaboration being consolidated (high impact of French labs)
- In the ~3 years to come
  - Consolidate the performance studies and apply them to the largest set of physics cases (quantify projections)
  - Start the R&D on the CMOS with a preliminary design (LV/HV?) to qualify under beam test
  - Implement a technical solution of the mechanical setup (power distribution and cooling) and the readout scheme
  - Complete the R&D by a Technical Design Report (together with a detailed cost/funding assessment)
  - Attract new labs (within and eventually from outside LHCb)

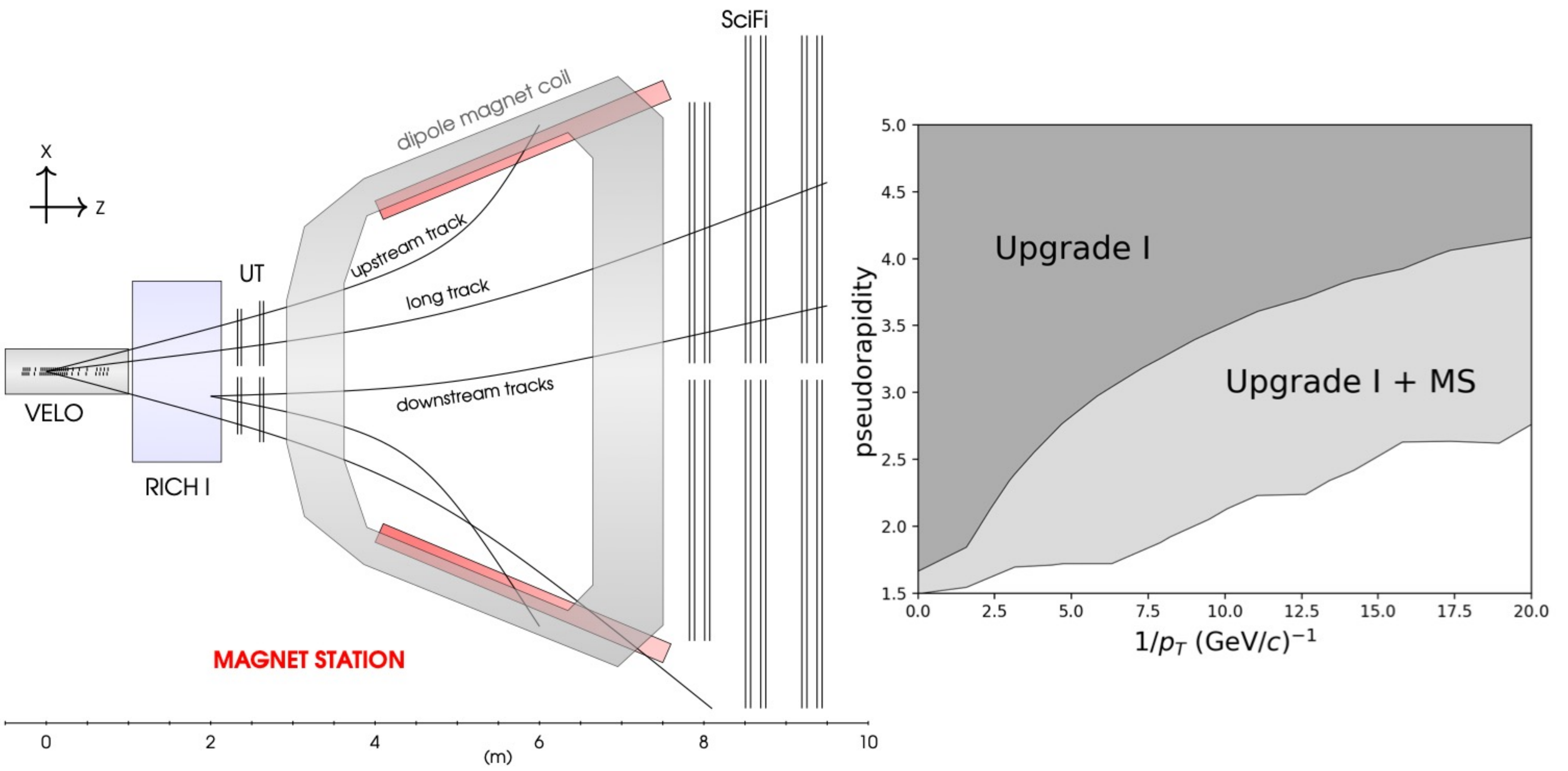
2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031



R&D phase

Pre+production phase

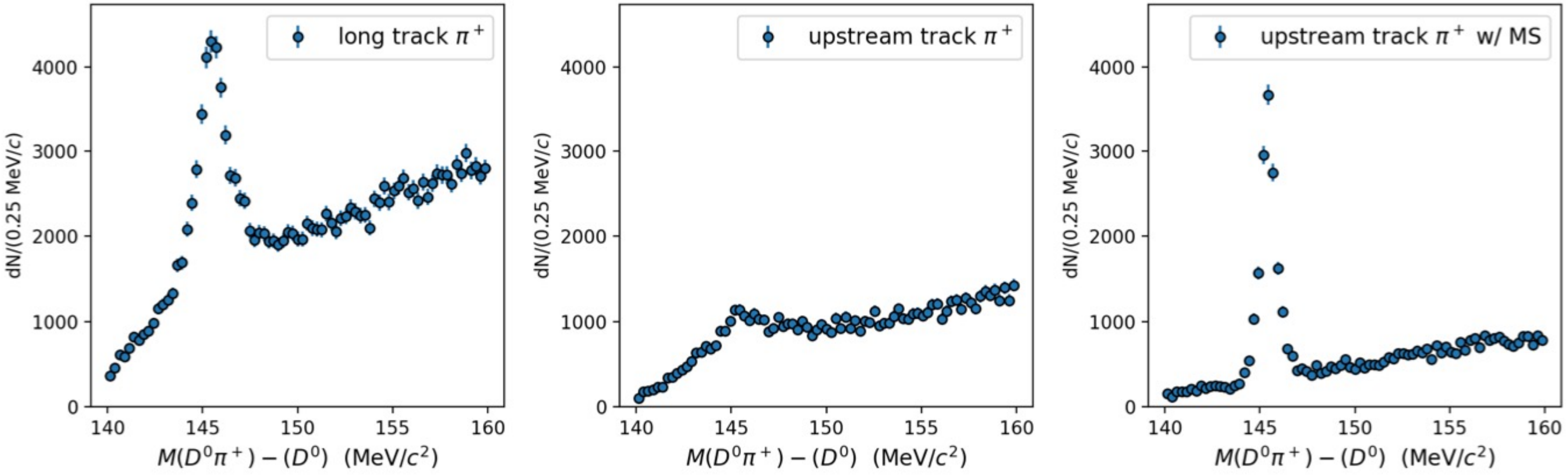
The Magnet stations



- provides high precision tracking for an extended momentum and pseudorapidity region
- help reconstruct tracks at the outer edges of the SciFi

Cesar Luiz da Silva

The Magnet stations



- VELO+UT tracks can be taken for granted for Physics analysis ?
- new study with Run 2 simulation using $p_T < 1$ GeV/c $D^{*+} \to D^0\pi$ decays
  - Pbp simulation: PYTHIA+EPOS with $\sim$ 15 binary pp collisions
  - the pion can be a long or upstream track
- almost no peak is seen for Upstream tracks
- if the pion track information is replaced by its true 4-momentum smeared in $\delta p/p = 1\%$ (twice the momentum resolution of the MS), a sharp peak is observed
- MS allows momentum resolution improvement and ghost track rejection
- zero p_T D^+ and D^{*+} are at reach with the Magnet Trackinh Station

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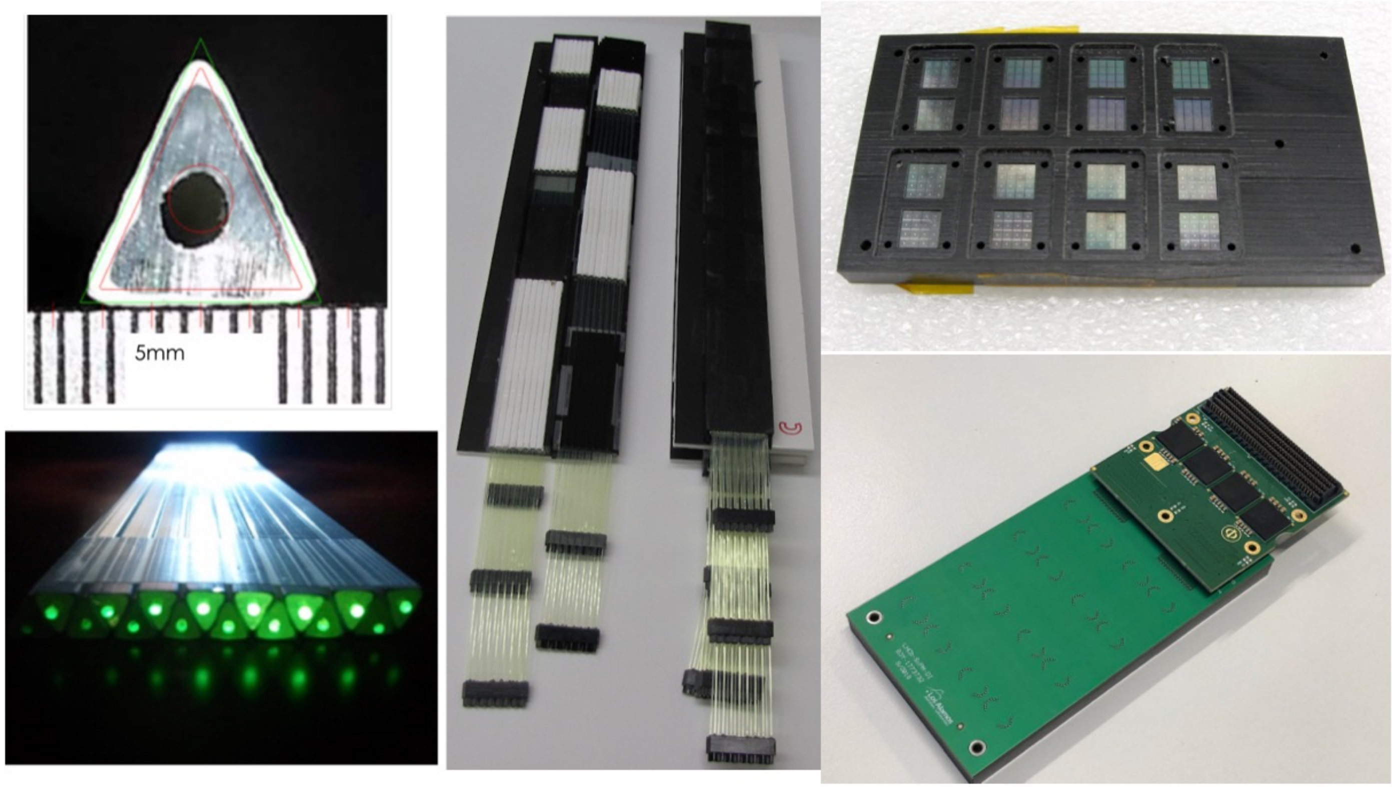
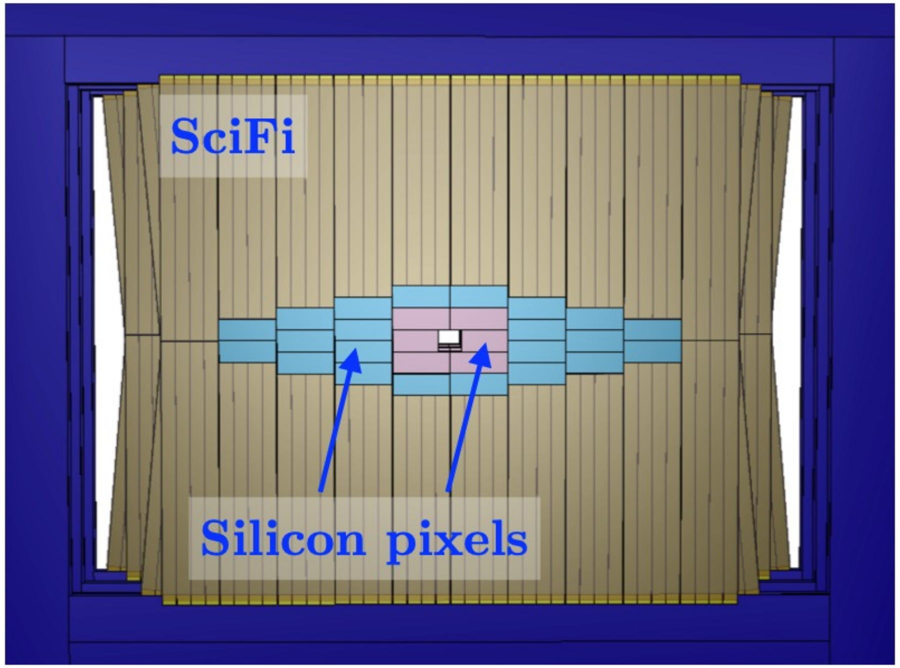
The Magnet stations

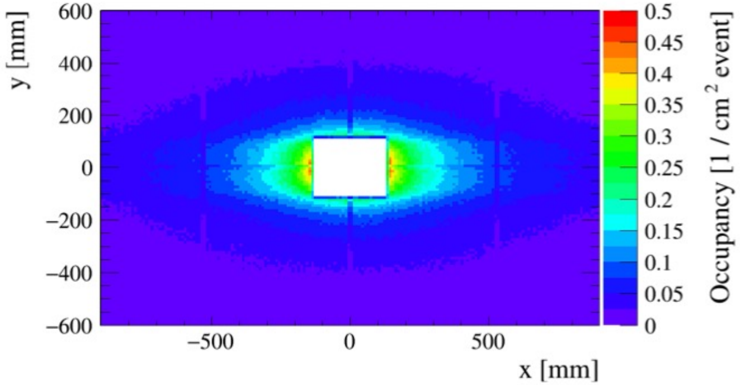


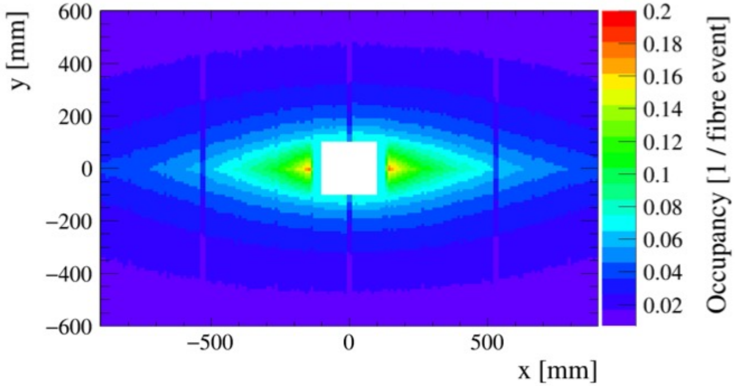
- extruded triangular scintillating bars
- 5% light loss after 1Mrad(10kGy) exposure, more than expected with 50 fb^{-1}
- light collected by a WS and guided through clear fibers to SiPMs located outside the magnet

Cesar Luiz da Silva

- $\int \mathscr{L} = 300\text{fb}^{-1}$ ⇒ significant fibre radiation damage in inner region
- $\mathscr{L}_{\text{inst}} = 1.5\times10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
  ⇒ very high occupancy (up to 20%/fibre/event)
  ⇒ SciFi must be replaced near beam pipe to maintain the same (or better) tracking performance
- Solution: instrument the inner region with a pixel detector, while keeping scintillating fibres in the outer region







Inner + Middle + SciFi Tracker = Mighty Tracker

(Distinguish between Inner and Middle regions because LHCb is exploring the option to install Inner part for Run4)

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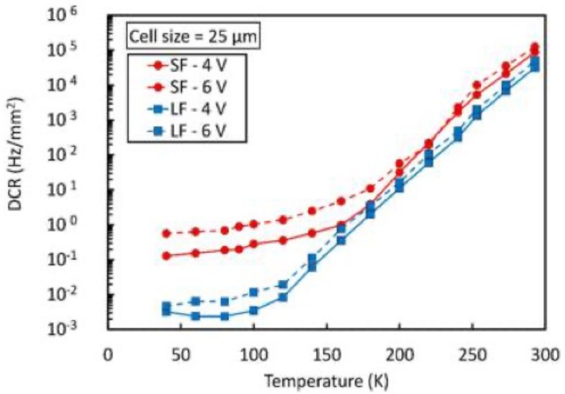
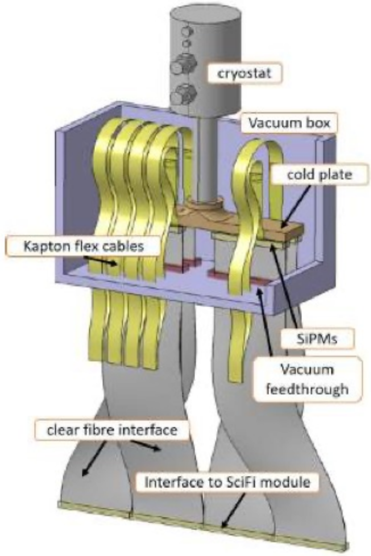
SciFi enhancement

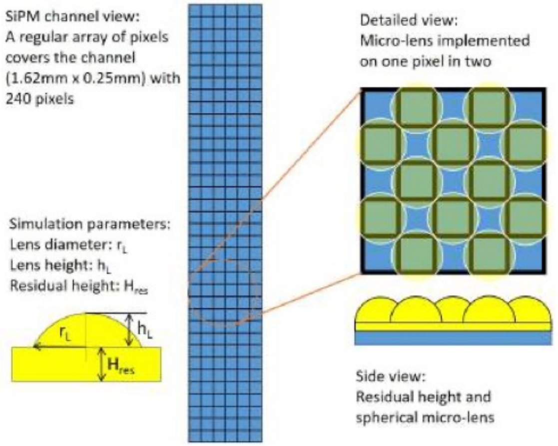
Major improvement seen cryogenic cooling to allow to run below -120 °C

- Essential to maintain reasonable noise rate for SiPMs after irradiation
- Should allow to reduce the cluster thresholds while keeping acceptable dark count rate





Additional interface
~ 16 % loss in light



Can gain back ~ 20 % by microlens.
Geometry packing of SiPMs also improved

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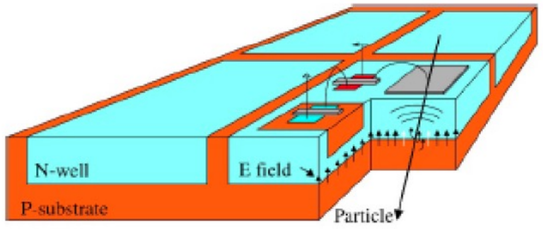
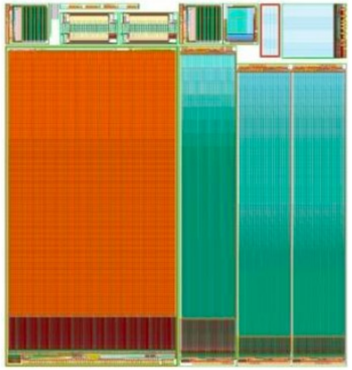
The MightyPix

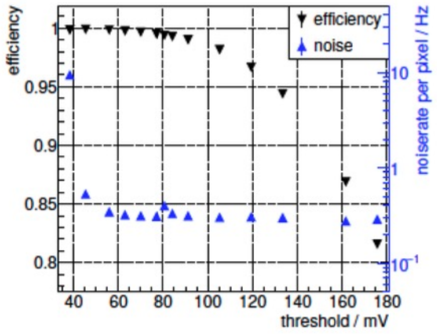


- Monolithic Active Pixel Sensor (MAPS)
- Integrated pixel sensor & chip
on **single** piece of silicon
  - Low-cost commercial process
  - e.g. used for mobile phone cameras
- First radiation hard CMOS tracker at LHC



- Chip based on existing MuPix/ATLASPix
- https://arxiv.org/abs/2002.07253
  - "MightyPix" Specification document in preparation

Parameter	Depleted CMOS Sensors for LHCb
Chip Size	$\sim 2\,\text{cm} \times 2\,\text{cm}$
Sensor Thickness (μm)	200 (ATLASPix3)
Pixel Size (μm)	100×300 (with smaller sizes to be explored)
Time Resolution (ns)	Must be within 25 ns window
Inactive area	$< 5\%$
Power Consumption (W/ cm²)	0.15
Data transmission (Gbps)	4 links of 1.28 Gb/s each, multiplexed to 2 and 1 links
NIEL (TBC)	3×10^{14} (6×10^{14} with safety factor)



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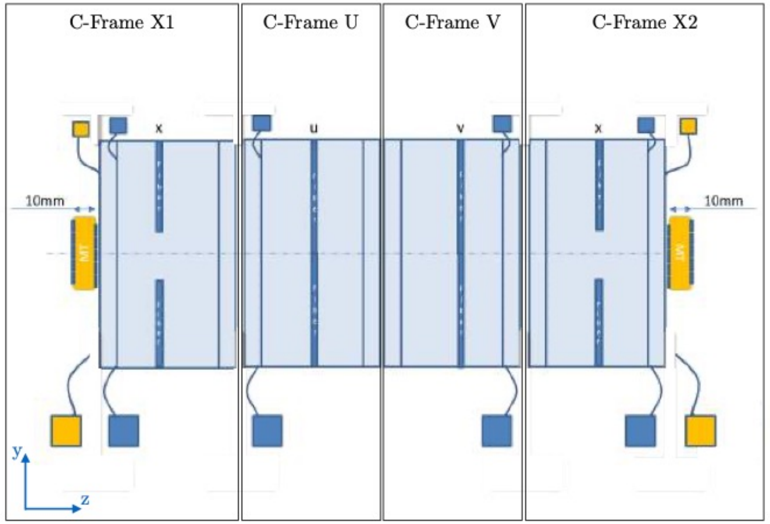
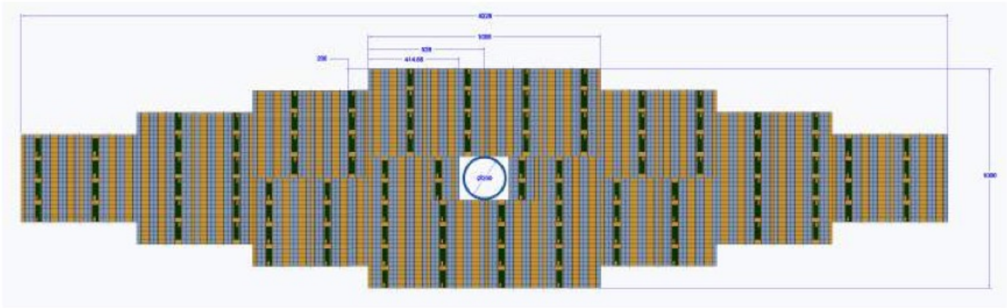
SciFi-CMOS integration

- SciFi layers and station layout similar to Upgrade 1 (modulo cryogenic cooling and mounting of layers on individual C-frames)
- Silicon layer panels (+ services) mounted on front and back of first/last x-layers in each station
- Panels integrated into Airex support box that provides thermal isolation (allowing operation below 0º C)



Alex Bitadze, Trevor Savidge



Services for Silicon run across Fiber acceptance
Care needed with material budget

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Conclusions

- HL-LHC conditions require a major upgrade of all LHCb trackers
- Very important effort in prospecting solutions which use innovative techniques
- Preliminary studies (physics cases, tracking performances, technological solutions) have been made and integrated within the Framework-TDR
- Large interest of several French labs in contributing to the Upstream Tracker upgrade
  - Leading role in performing preliminary studies and accreting a proto-collaboration
  - Ambitious physics program thanks to the complementary role of Mighty Tracker and (eventually) Magnet Stations
  - The R&D program is being started and will gain momentum in the coming 3 years
- Exciting physics and technological developments ahead of us and important occasion to significantly enhance the impact of the French community in the HI program for the Run5 and beyond…