The upgrade program of LHCb

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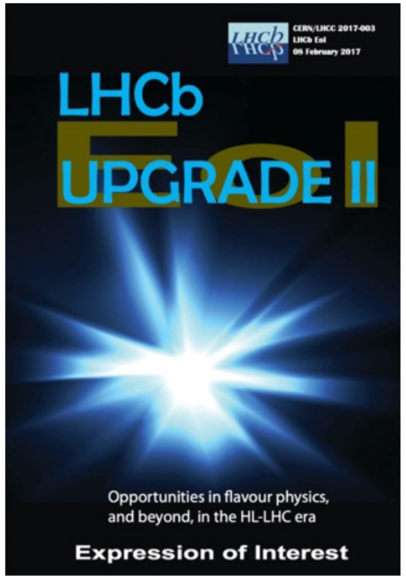
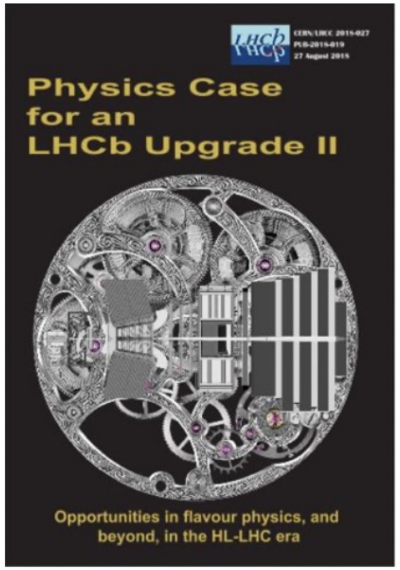
Expression of Interest



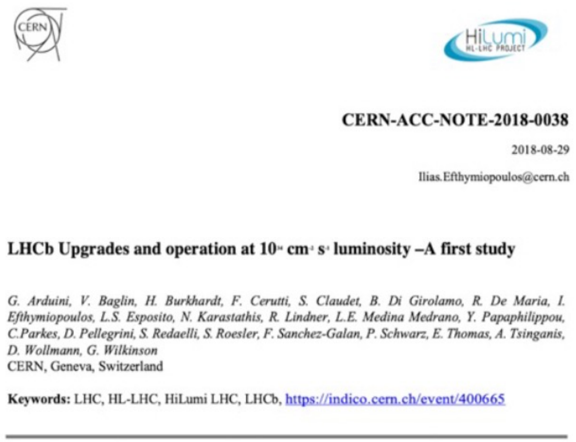
[LHCC-2017-003]

Physics case



[LHCC-2018-027]

Accelerator study



CERN-ACC-NOTE-2018-0038

2018-08-29

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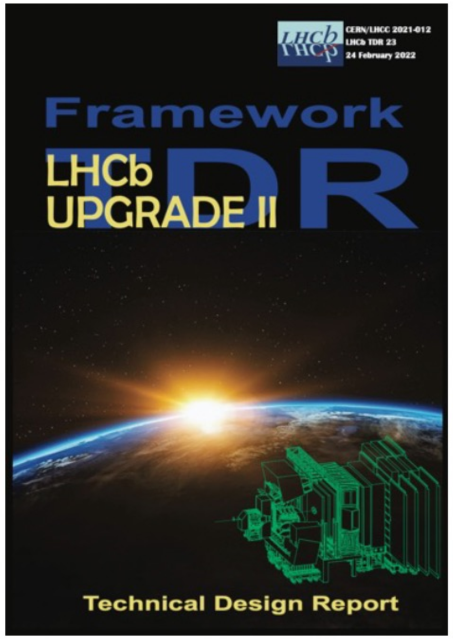
LHCb Upgrades and operation at 10 cm s luminosity –A first study

G. Arduini, V. Baglin, H. Burkhardt, F. Cerutti, S. Claudet, B. Di Girolamo, R. De Maria, I. Efthymiopoulos, L.S. Esposito, N. Karastathis, R. Lindner, L.E. Medina Medrano, Y. Papaphilippou, C.Parkes, D. Pellegrini, S. Redaelli, S. Roesler, F. Sanchez-Galan, P. Schwarz, E. Thomas, A. Tsinganis, D. Wollmann, G. Wilkinson
CERN, Geneva, Switzerland

Keywords: LHC, HL-LHC, HiLumi LHC, LHCb, https://indico.cern.ch/event/400665

[CERN-ACC-2018-038]



[LHCC-2021-012]

CERN Research Board September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

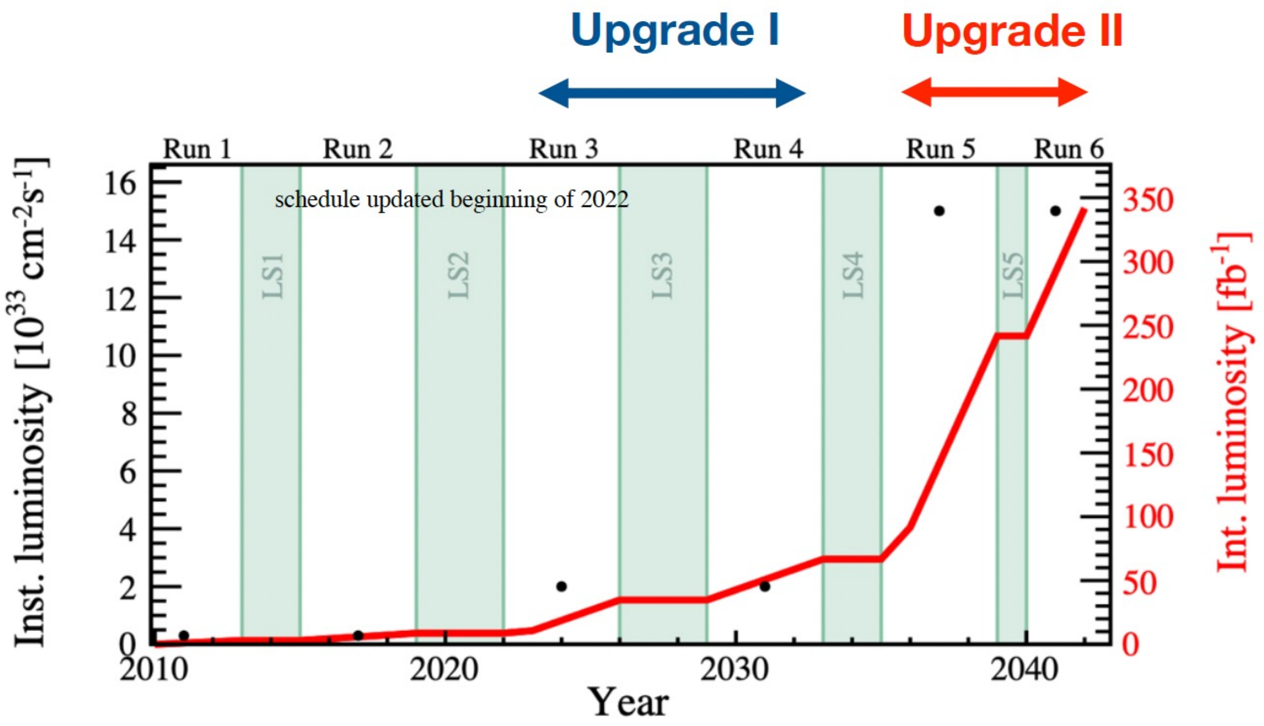
Approved March 2022
R&D programme, scoping document to be prepared followed by sub-system TDRs

[European Strategy Update 2020] ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

- Physics programme limited by detector, NOT by LHC
- Hence, clear case for an ambitious plan of upgrades

Upgrade II

- *L_{peak} = 1.5x10^{34} cm^{-2} s^{-1}*
- *L_{int} = ~300 fb^{-1} during Run 5 & 6, Install in LS4 (2033)*
- *Some smaller detector consolidation and enhancements in LS3 (2026)*

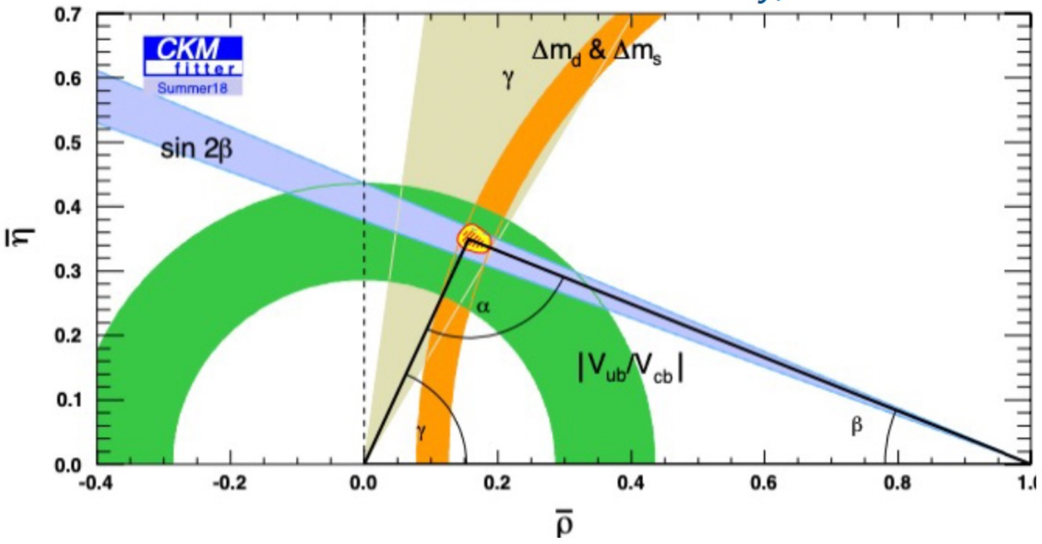


- *Potentially the only general purpose flavour physics facility in world on this timescale*

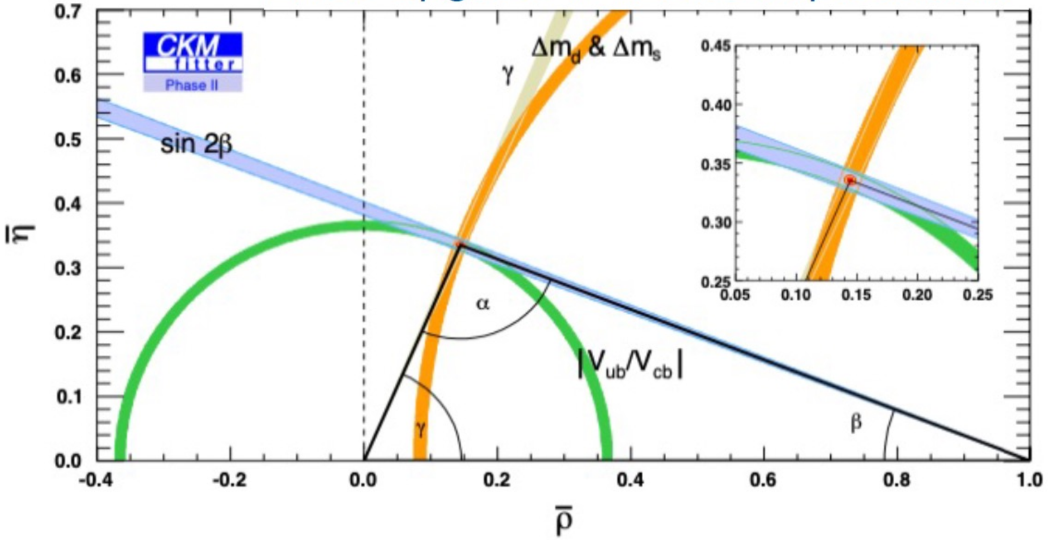
Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests				
γ ($B \to DK$, *etc.*)	4° [9,10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda^0_b \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [29,30]	3%	2%	1%
$a^d_{\rm sl}$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a^s_{\rm sl}$ ($B^0_s \to D^-_s\mu^+\nu_\mu$)	33×10^{-4} [35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm				
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5} [5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5} [38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K^0_s\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69% [40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—	—	—	0.2
$A^{(2)}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$A^{\rm Im}_{\rm T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [53]	0.148	0.097	0.038
Lepton Universality Tests				
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044 [12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12 [61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026 [62,64]	0.007	0.005	0.002

Framework TDR, LHCb-TDR-023

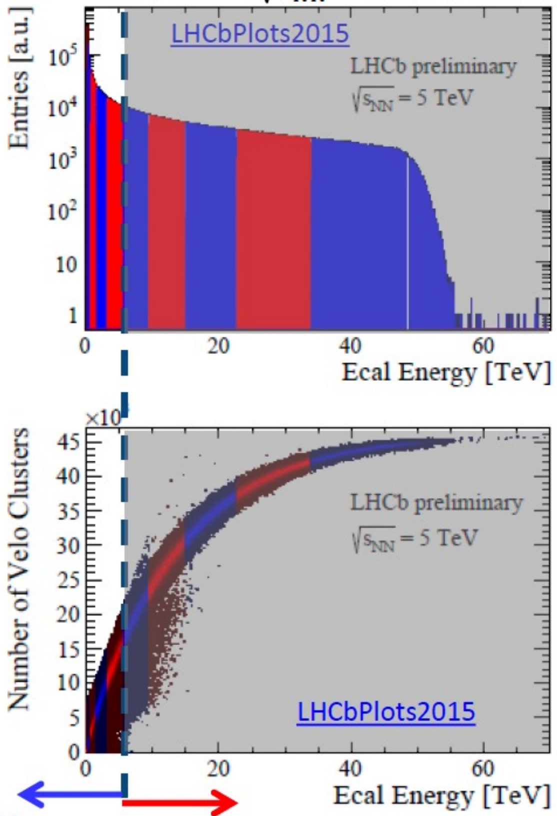
LHCb only, end of 2018



LHCb Upgrade II + LQCD improvement



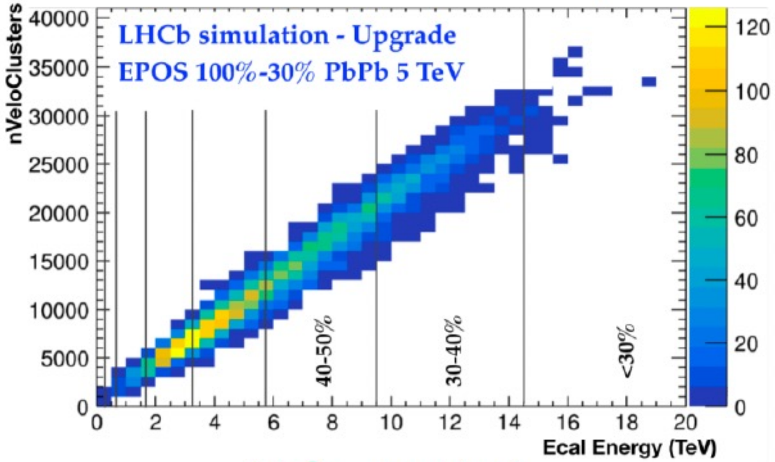
Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV – 2015 data



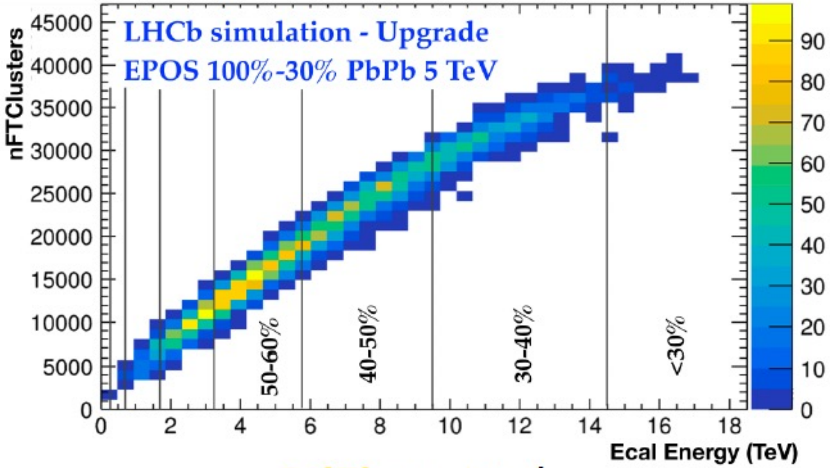
50% less central

50% most central

(B. Audurier LHCb-INT-2020-004)

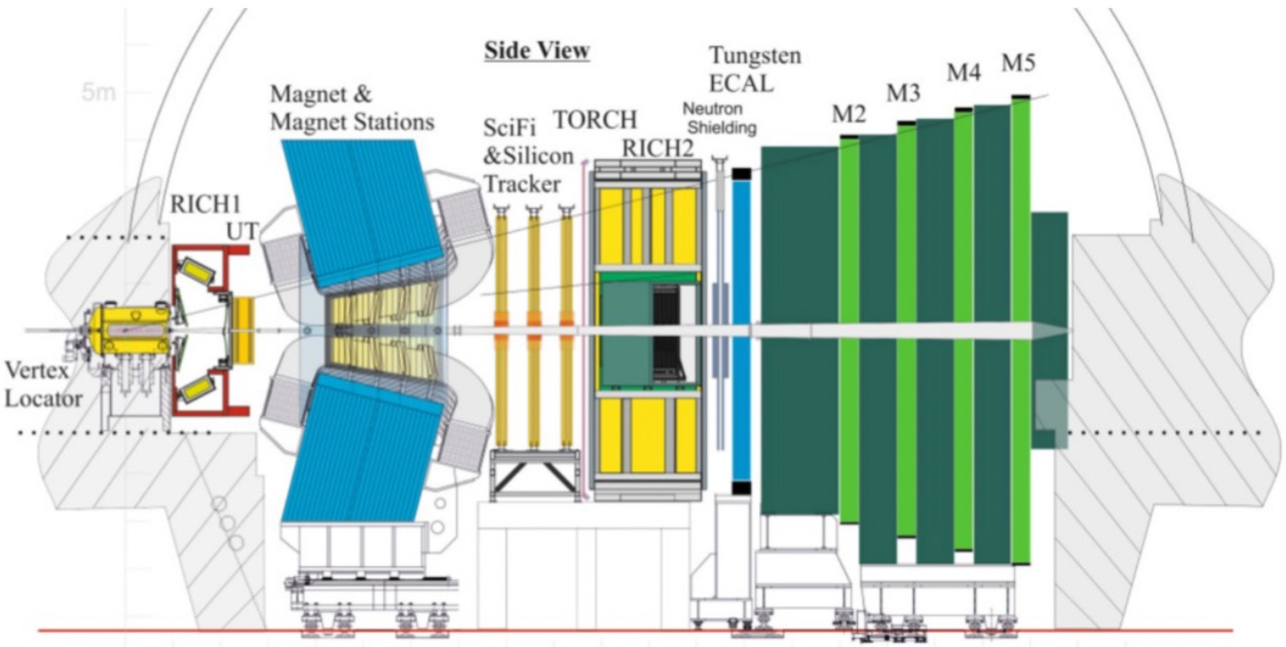


Velo .vs. Ecal



SciFi .vs. Ecal

Targeting same performance as in Run 3, but with pile-up ~40!



Same spectrometer footprint, innovative technology for detector and data processing

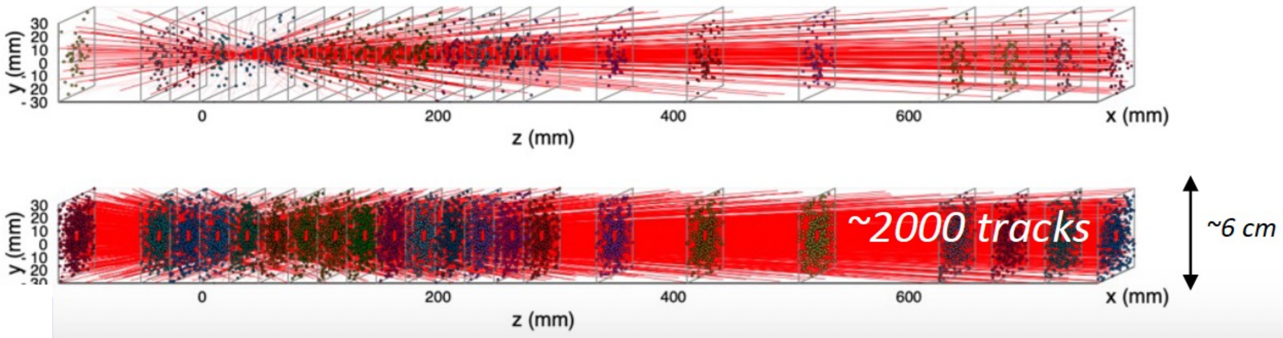
Key ingredients:

- granularity
- fast timing (few tens of ps)
- radiation hardness

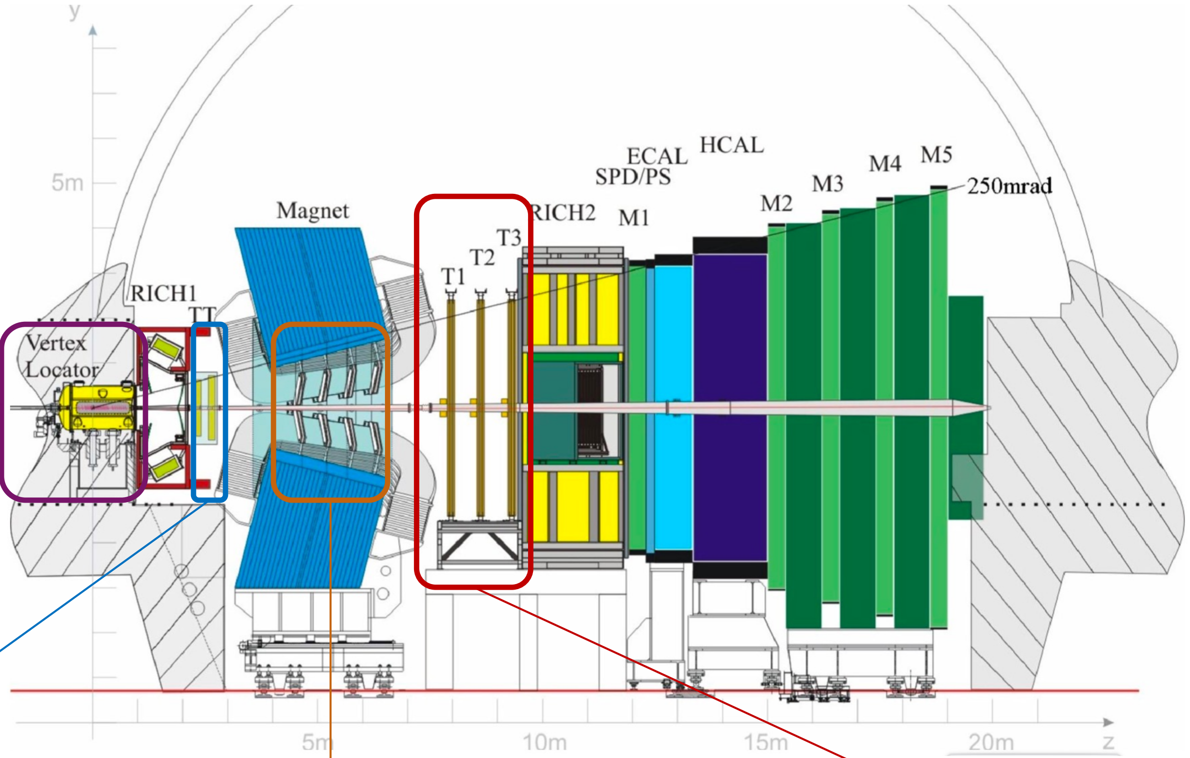
VErtex LOcator (VELO)

Run 3: pile-up ~6

Upgrade II: pile-up ~42



THE TRACKING SYSTEM UPGRADE

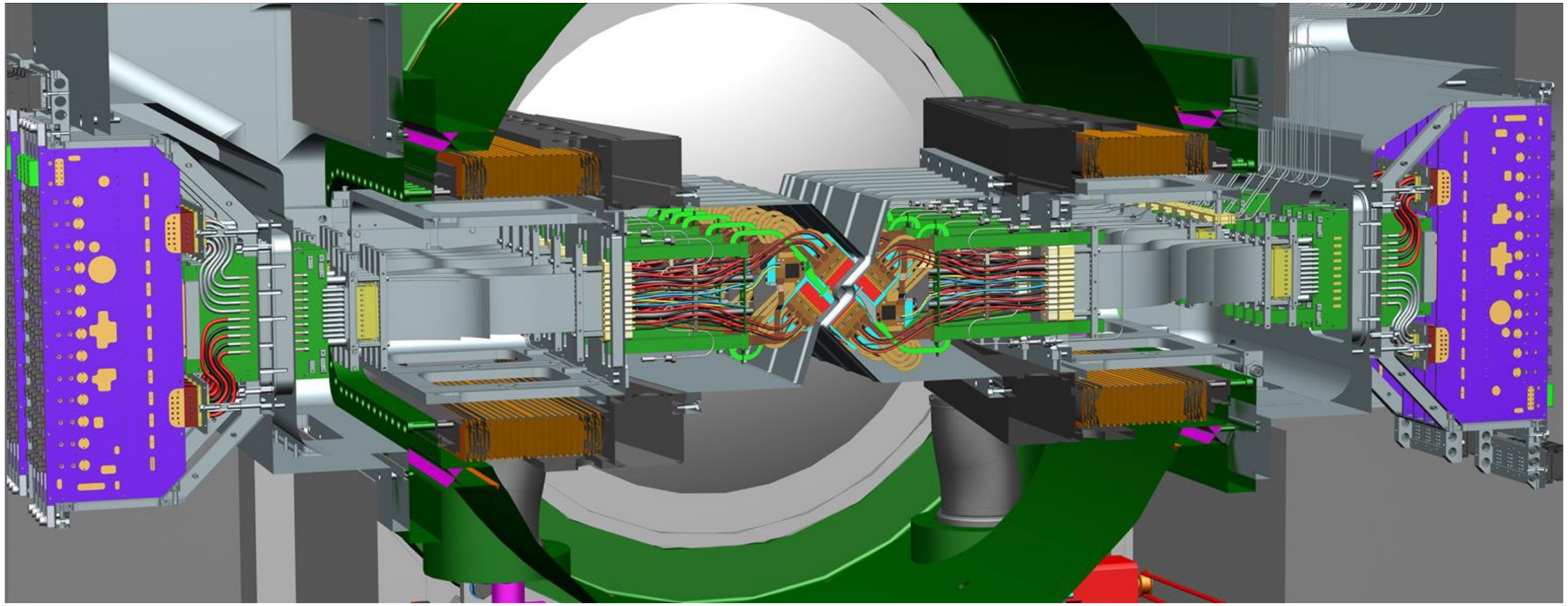


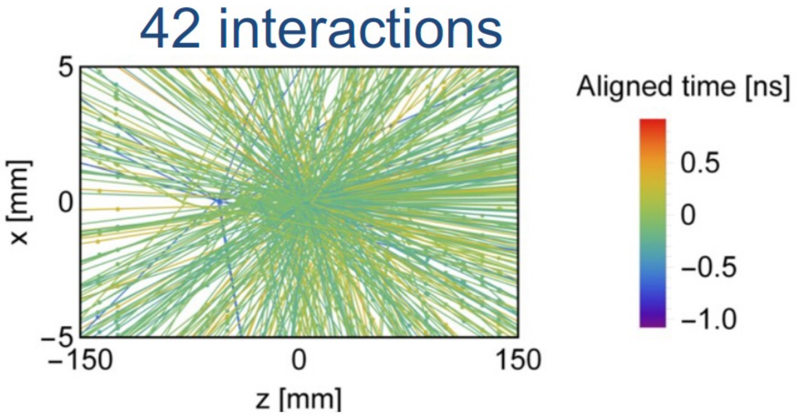
VELO
Pixel with timing

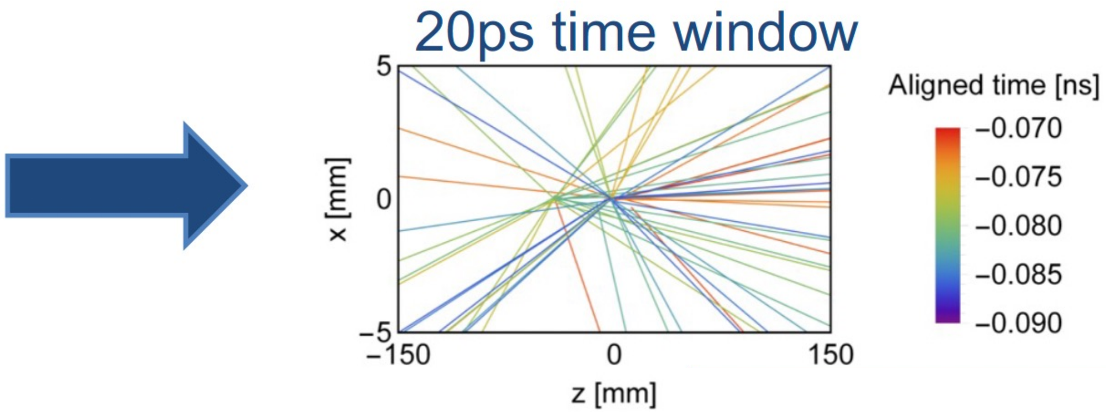
Upstream Tracker
From strip to CMOS

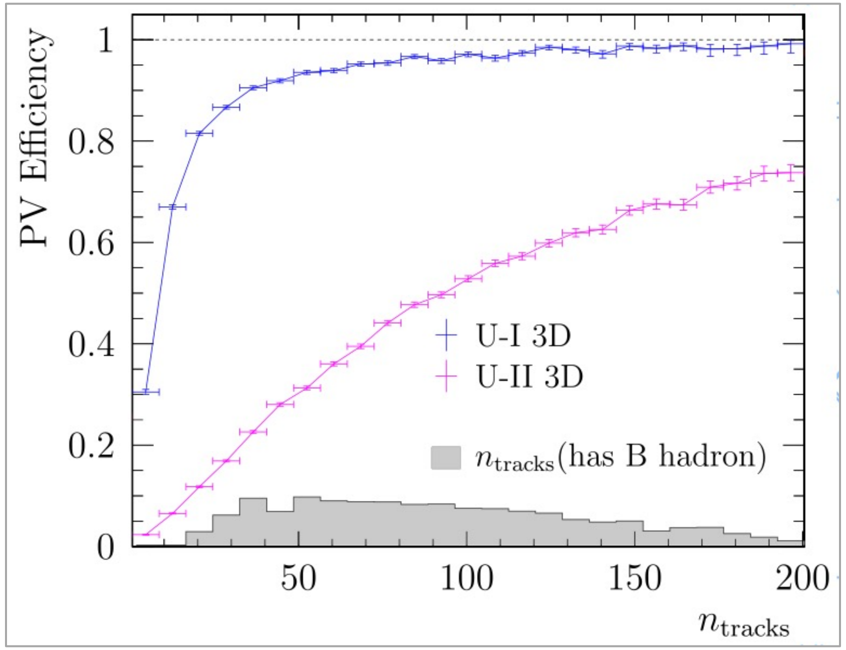
Magnet stations
Tracking on magnet sides

Mighty Tracker
Combine SciFi & CMOS

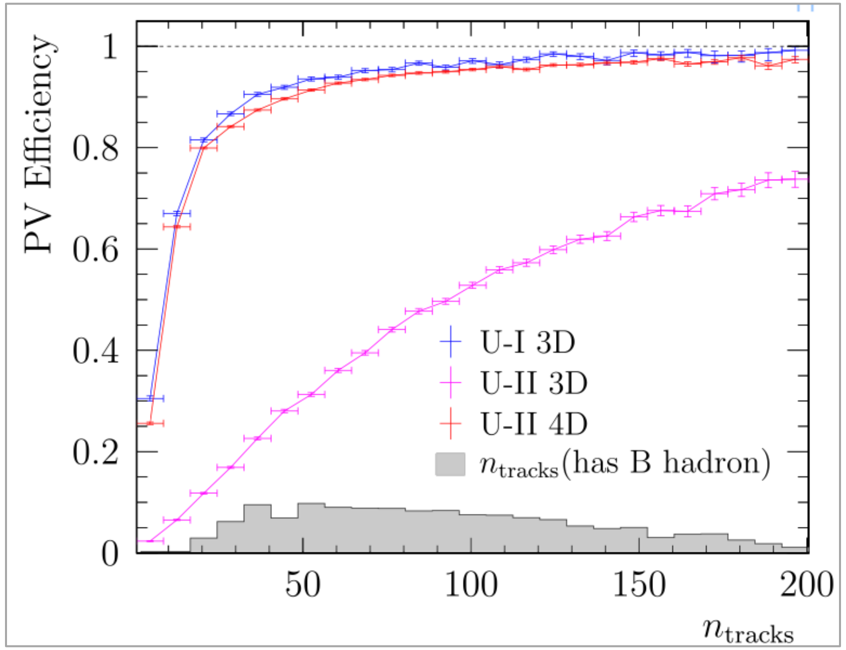


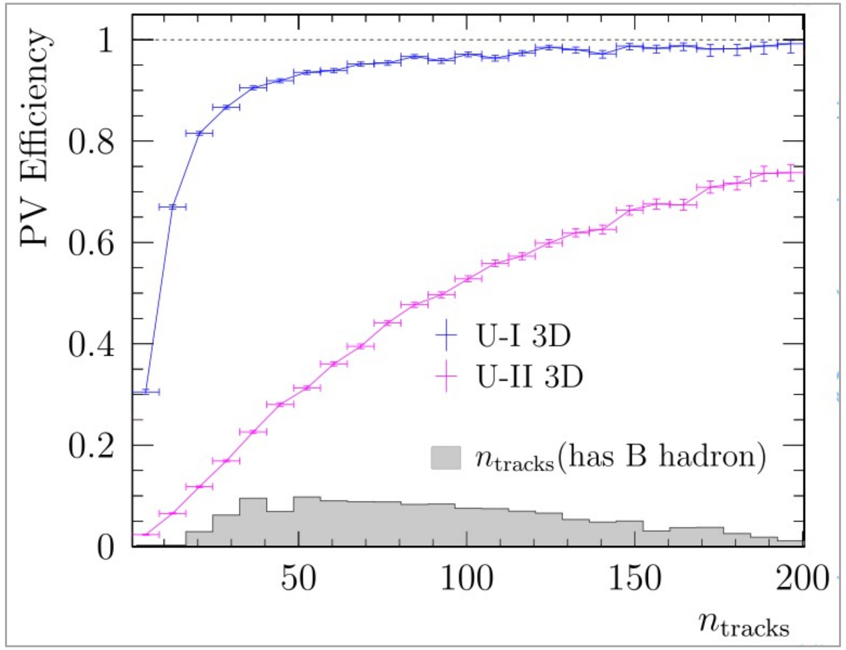

42 interactions
x [mm]
z [mm]
5
0
−5
−150
0
150
Aligned time [ns]
0.5
0
−0.5
−1.0


20ps time window
x [mm]
z [mm]
5
0
−5
−150
0
150
Aligned time [ns]
−0.070
−0.075
−0.080
−0.085
−0.090

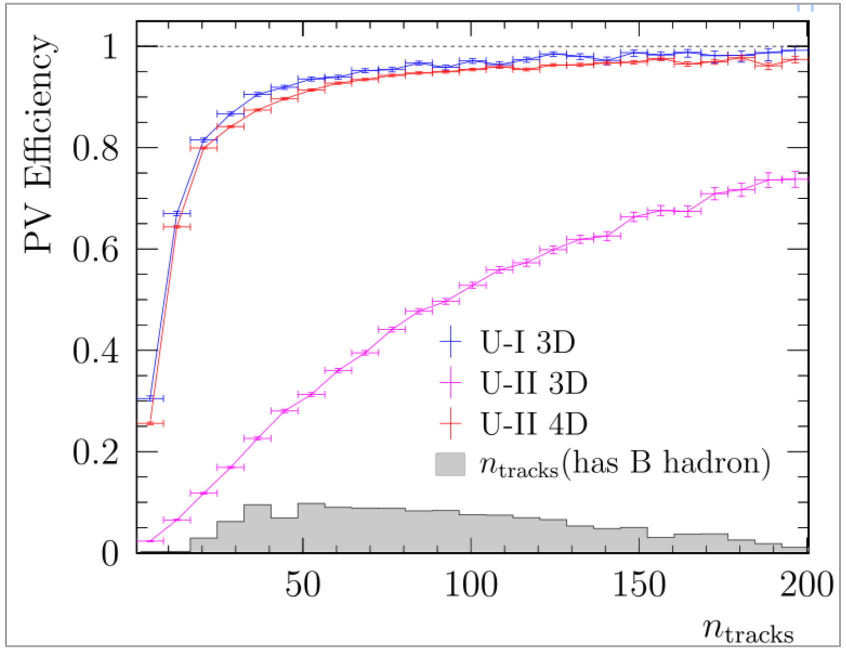

PV Efficiency
1
0.8
0.6
0.4
0.2
0
50
100
150
200
n_{tracks}
U-I 3D
U-II 3D
n_{tracks}(has B hadron)

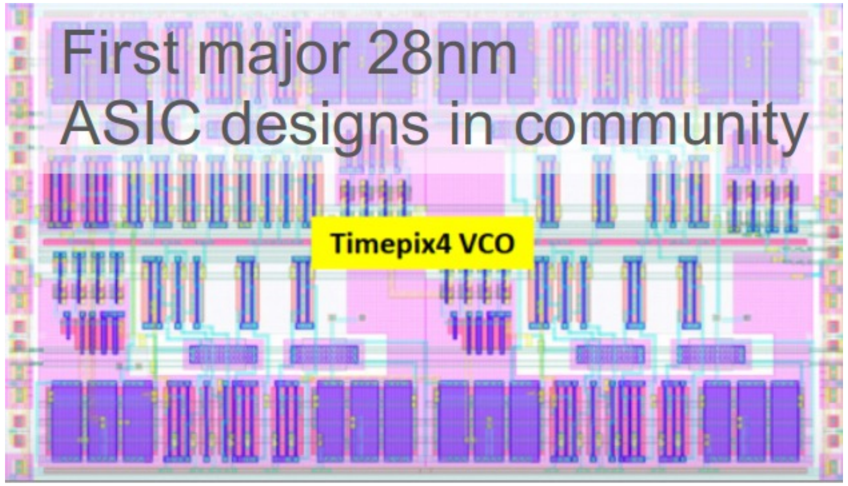
Add 4D!

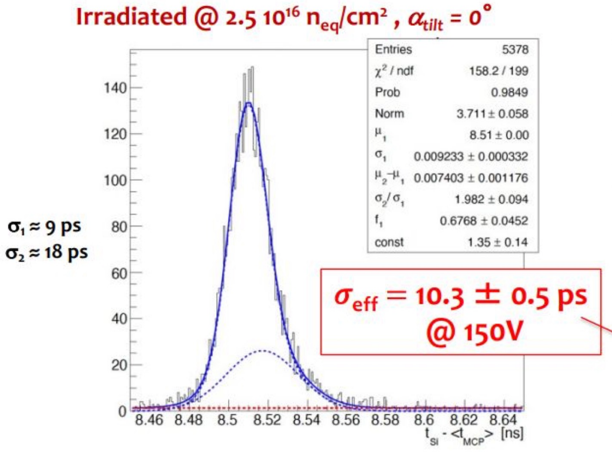

PV Efficiency
1
0.8
0.6
0.4
0.2
0
50
100
150
200
n_{tracks}
U-I 3D
U-II 3D
U-II 4D
n_{tracks}(has B hadron)

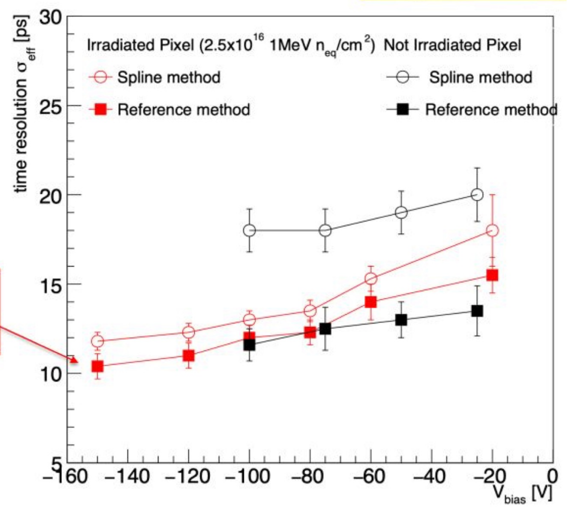


Add 1D!

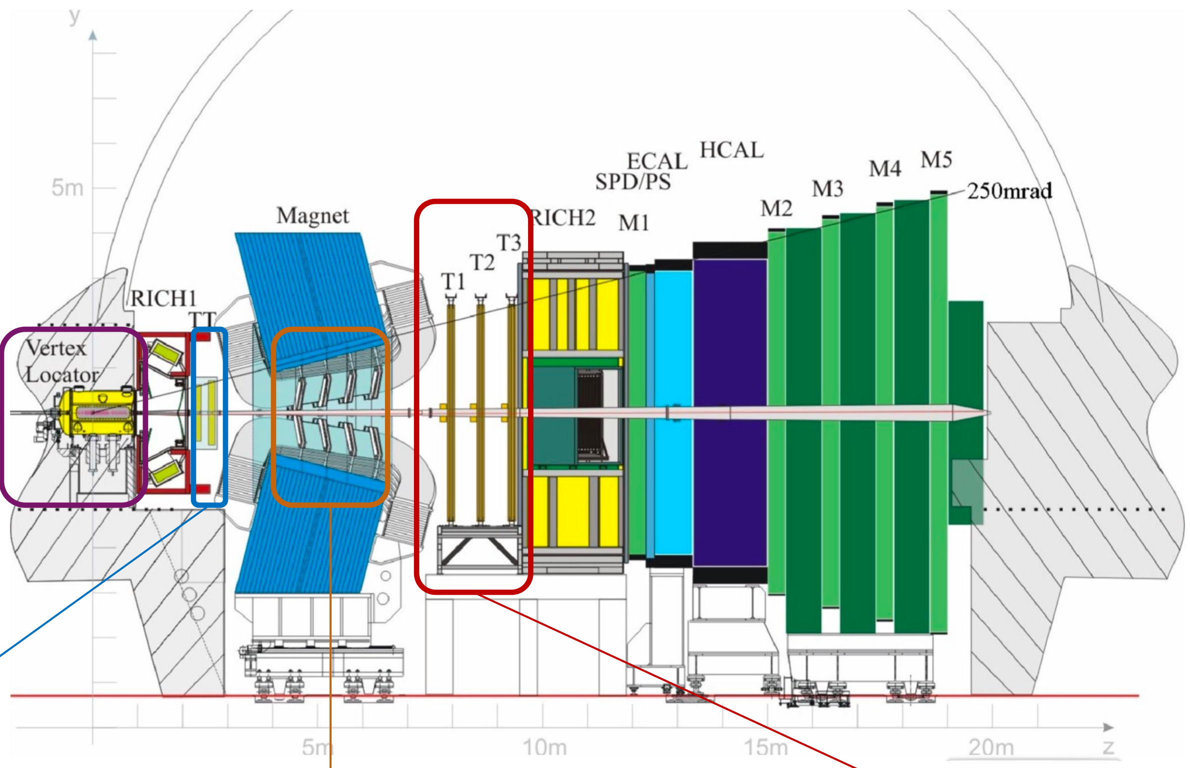








Pre-irradiation performance is already recovered at $\Delta V_{bias} \approx$ 10-15 V



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Pixel with timing

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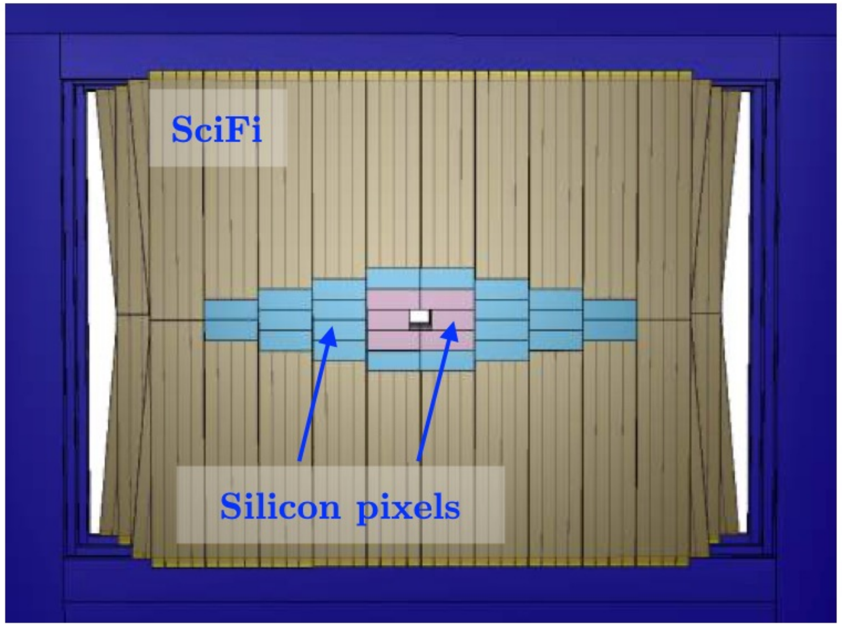
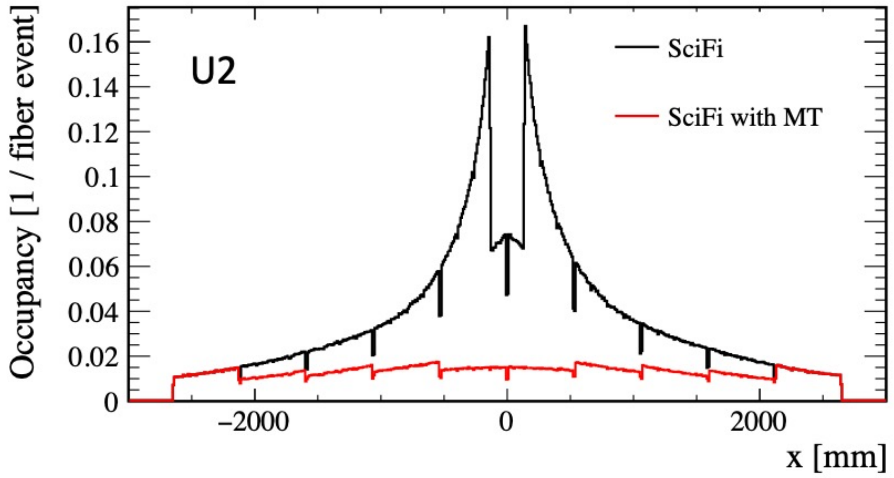
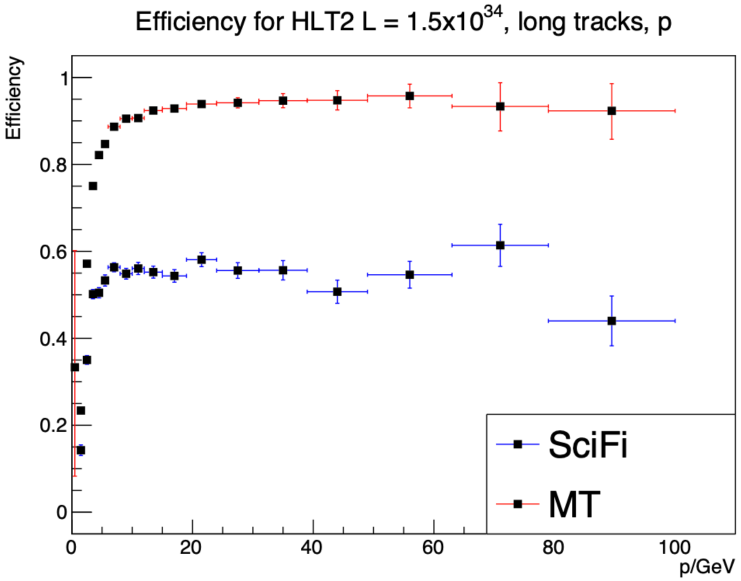
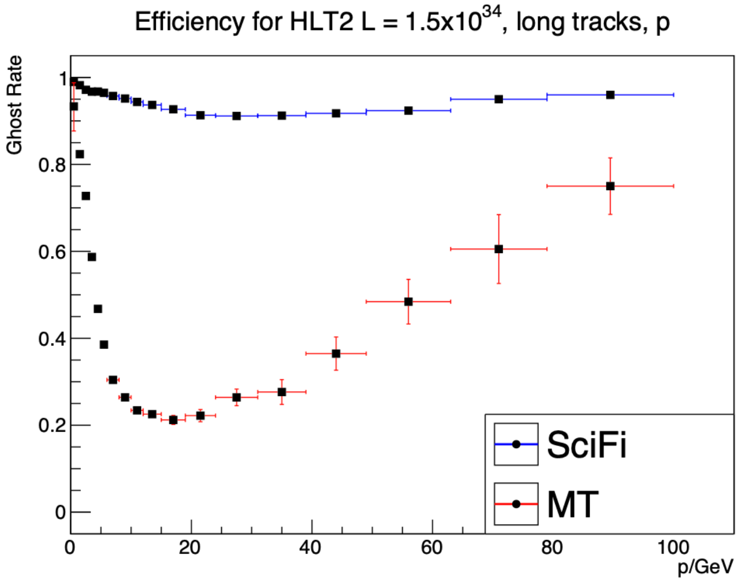
Mighty tracker





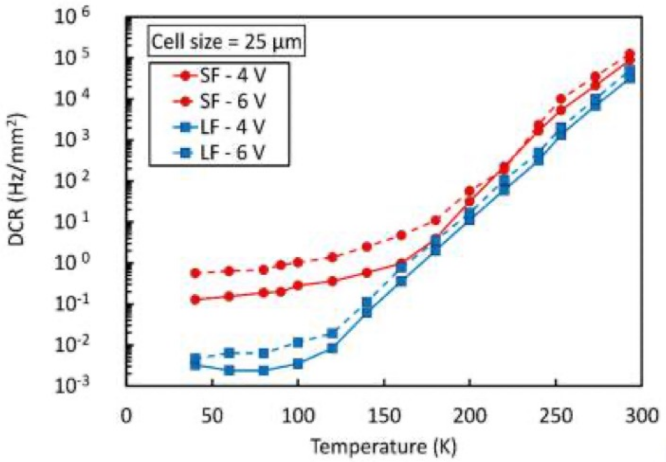


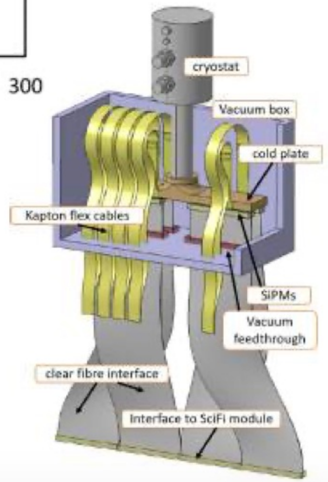


SciFi Enhancements

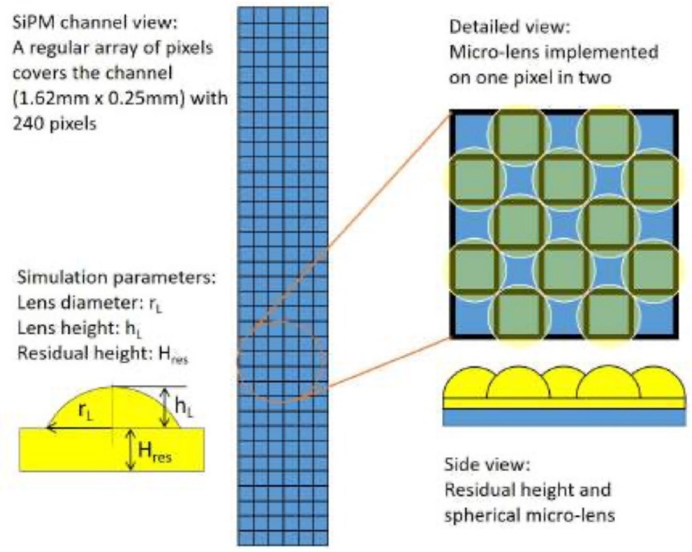
Major improvement seen cryogenic cooling to allow to run below -120 °C

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

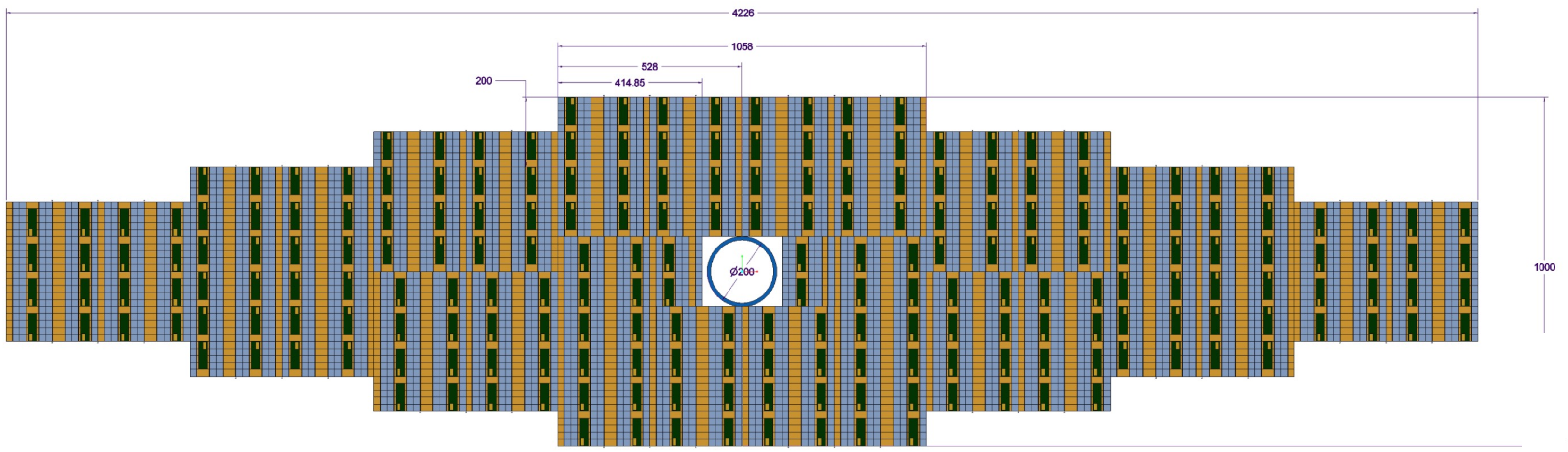




Additional interface
~ 16 % loss in light

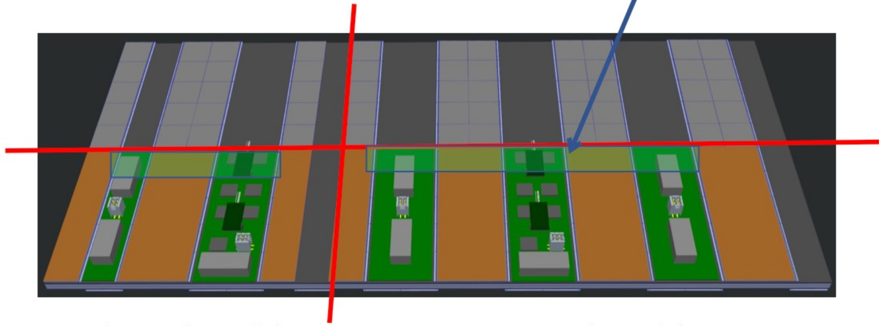


Better SiPMs and micro-lensing should compensate for light loss



One Layer 3m²
2 Layers per station
6 Layers in total

Modules



- One layer consists of 4 sub-modules
- 28 modules per layer (2 short)
- One sub-module is a electrical unit
- Build chip-modules to save space
- Co-cured service flex for power/signal distribution

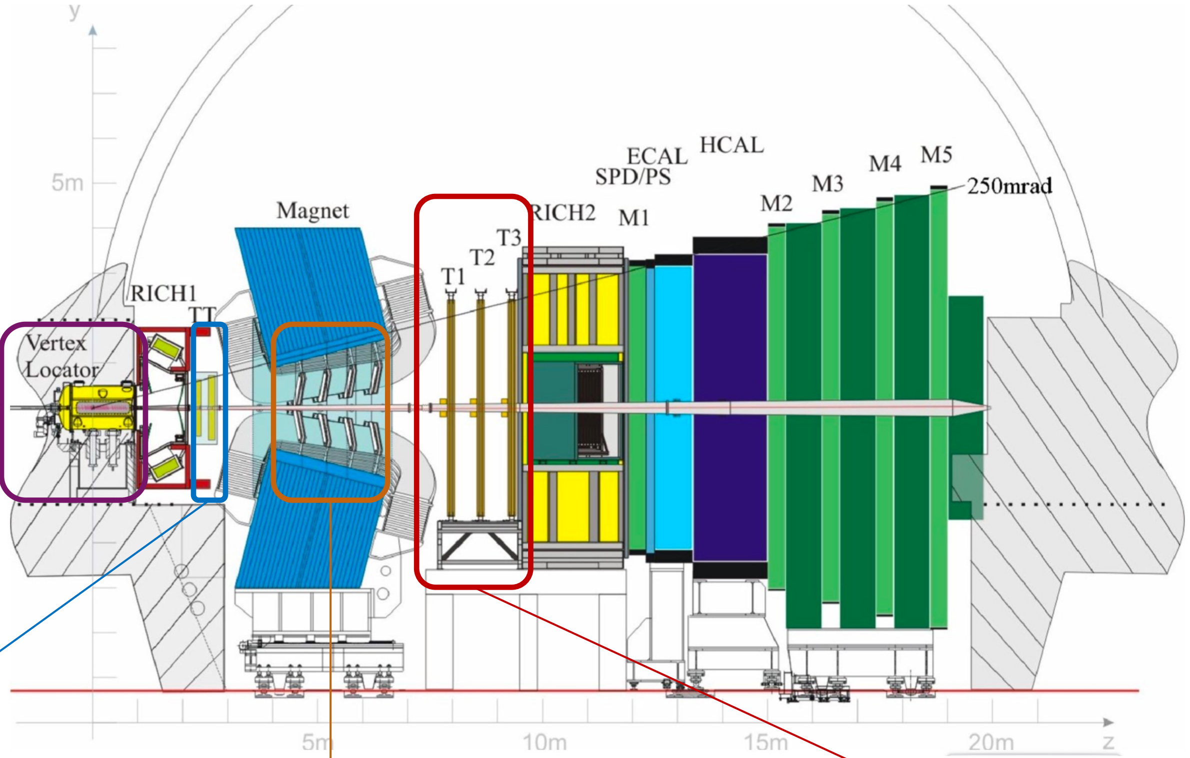
HV-CMOS

- One of the main drivers of the project is the size of the silicon area
- MAPS chips are limited to ~2x2 cm² (foundry)
- The most critical points are:
  - In Time **Efficiency**
  - **Power** Consumption
  - **Radiation** Tolerance

Pixel size	< 100 µm x 300 µm
In-time efficiency	> 99% within 25 ns window
Timing resolution	~ 3 ns within 25 ns window
Radiation tolerance	6 x 10^{14} 1 MeV n_{eq}/cm^2
Power consumption	< 150 mW/cm²
Data transmission	4 links of 1.28 Gb/s each
Compatibility with the LHCb readout system	

LHCb-INT-2019-007, 2019

Layout for MightyPix1 (1/4 of full size)



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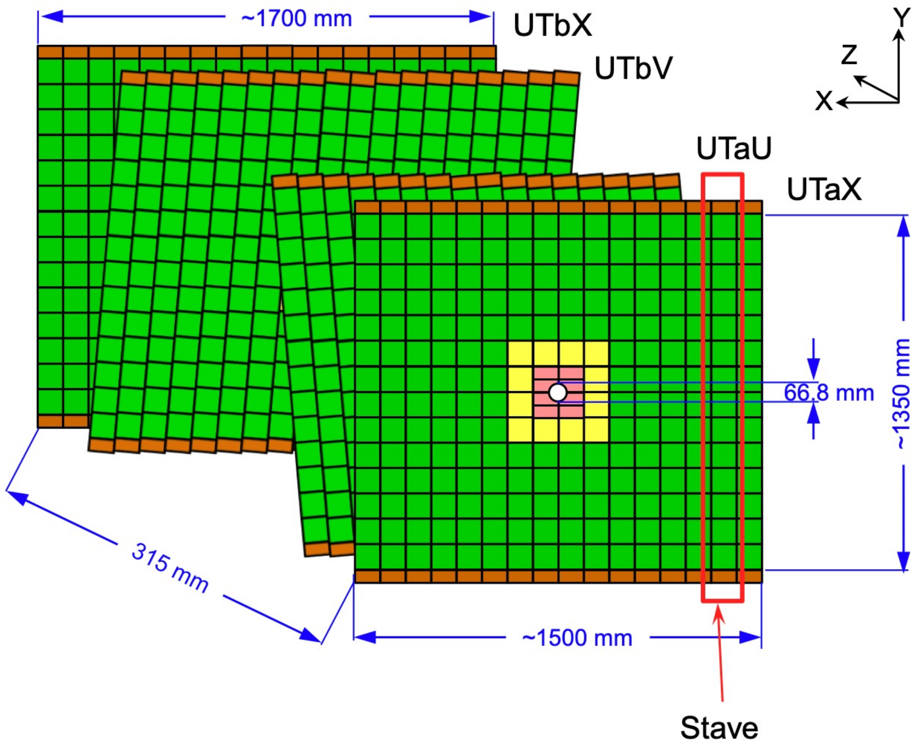
From the present UT...

- The UT detector in phase-I upgrade (P1UG) consists of 4 planes of silicon strips. The design was optimized for a peak luminosity of $L=2\times10^{33}$ $cm^{-2}s^{-1}$ (max occupancy of 1.4%) and can handle a data rate of $\times1.5$ higher

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



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… to a high luminosity concept

pp collisions

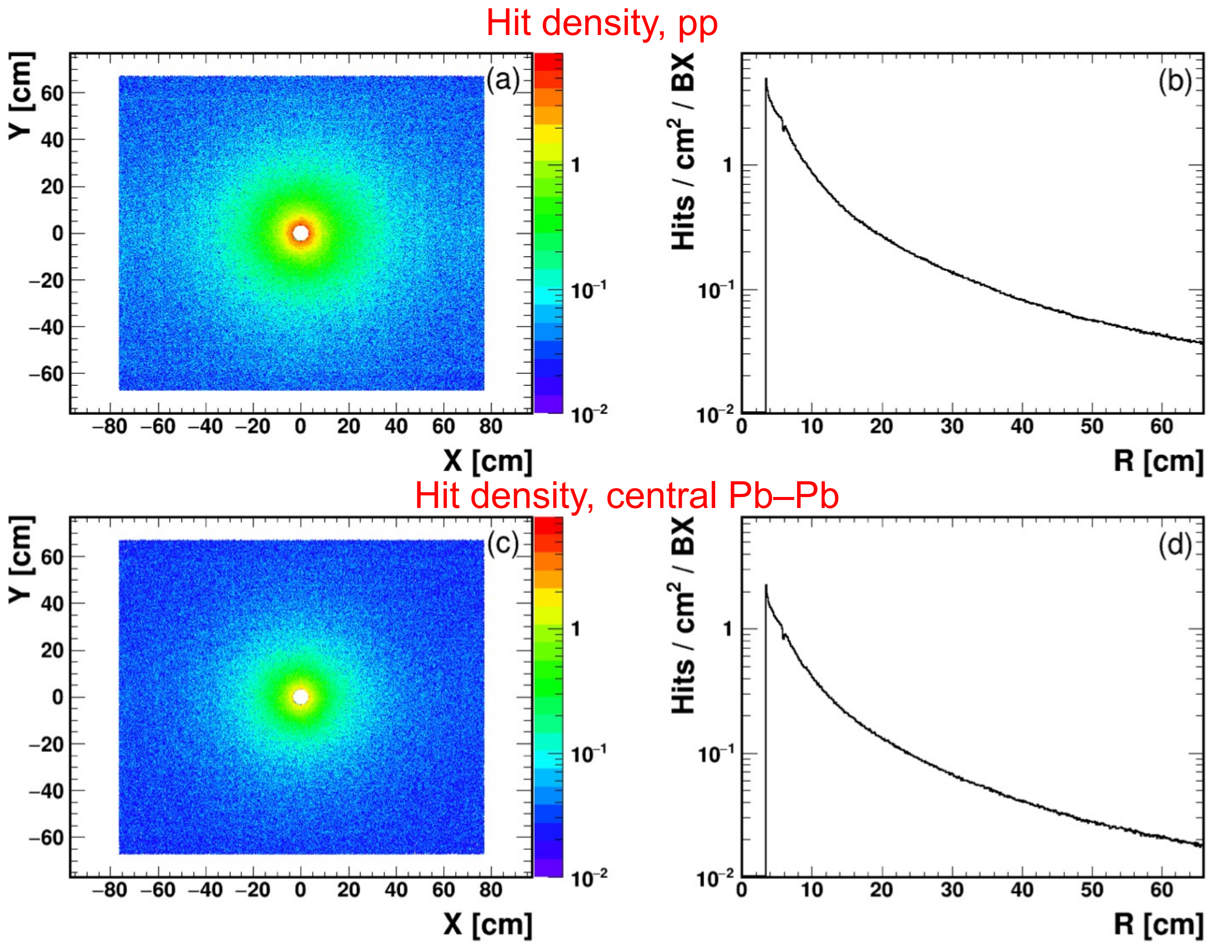
- Instantaneous luminosity 2×10^{34} cm^{-2}s^{-1}
  - 67% of BX have beam-beam collisions
  - O(10) tracks per pp collision
  - Average hit rate in UT: 5.9 hits/cm^2/BX$_{coll}$

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 density than Pb–Pb



Preliminary specifications

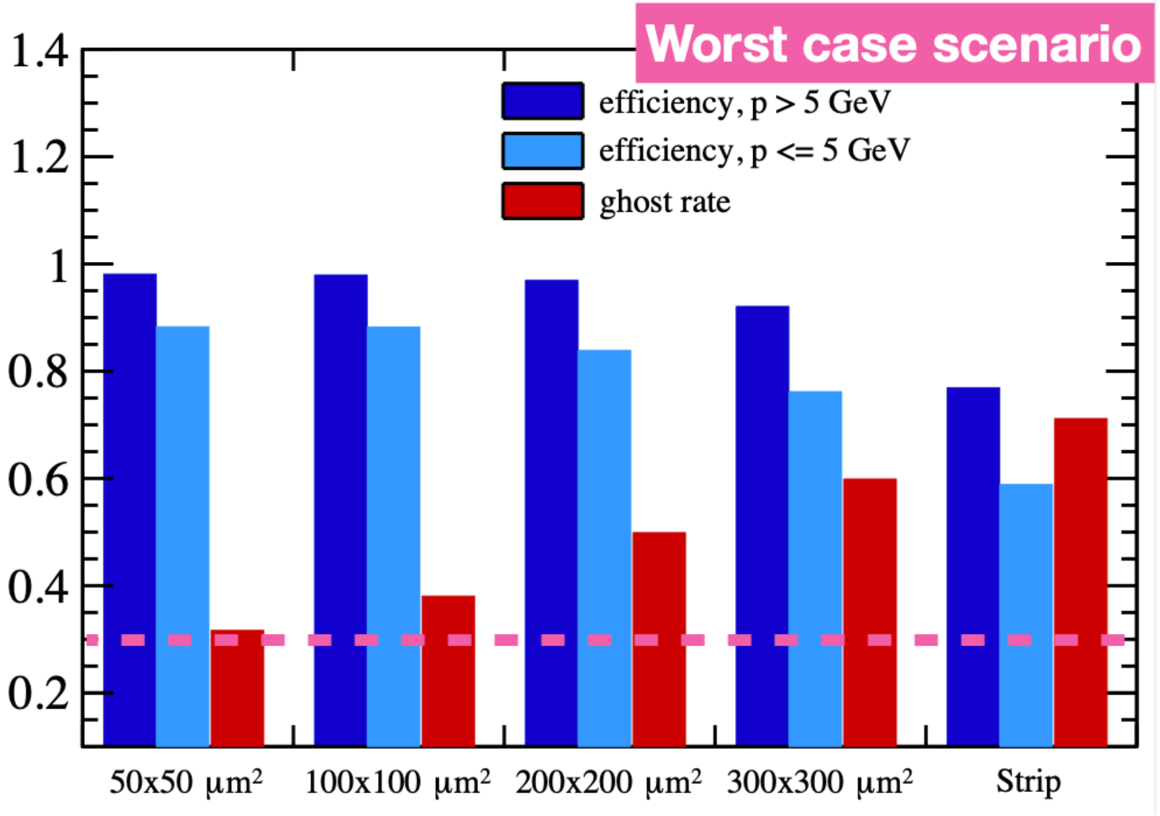
- Concept presented within the F-TDR: well received by the LHCC
- First tentative list of specifications
- To be further consolidated and detailed: work in progress

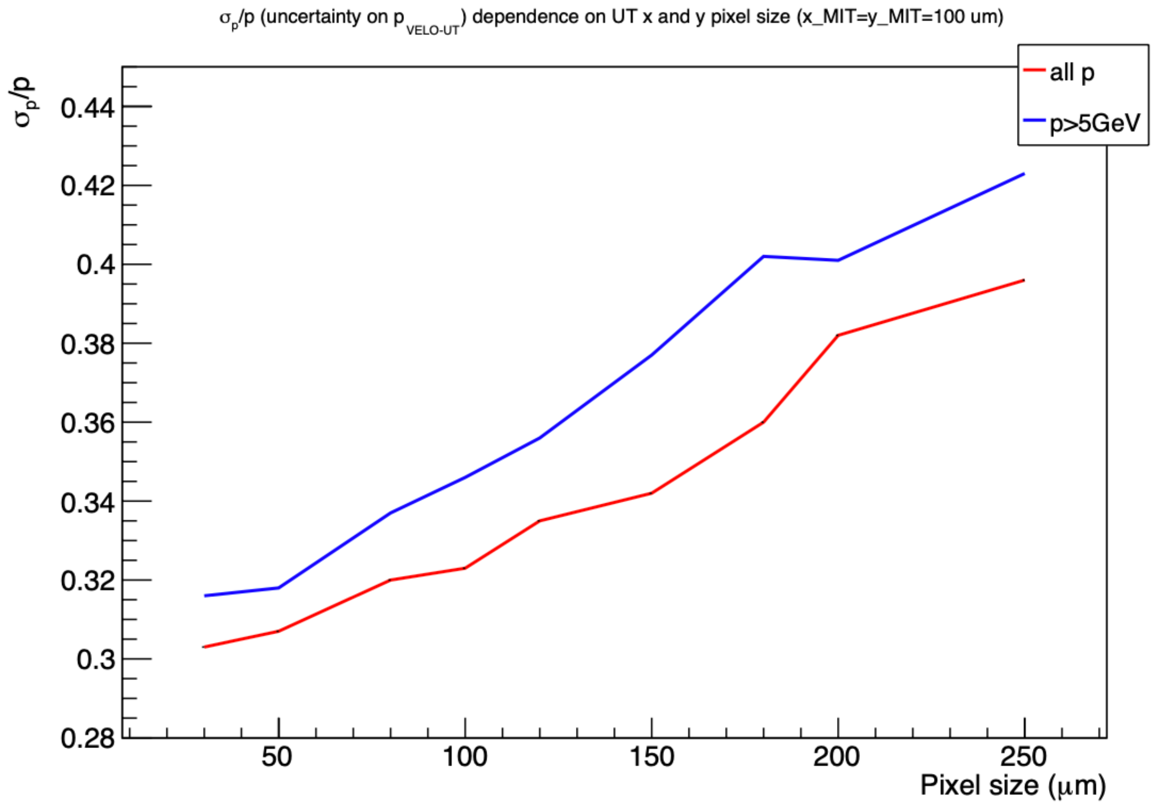
Characteristics	Specification
Hit rate in hot event and region	160 MHz / cm^2 pp (~52.5 hits / cm^2 / BX for Pb/Pb)
Time resolution	O(1 ns) for BX tagging
Pixel size	O($30\times30\ \mu m^2$)
Power consumption	O(100-300 mW/cm^2)
Radiation dose for 350 fb^{-1}	3×10^{15} 1-MeV n_{eq}/cm^2, 240 Mrad

Close to ATLAS CMOS outer layer specifications

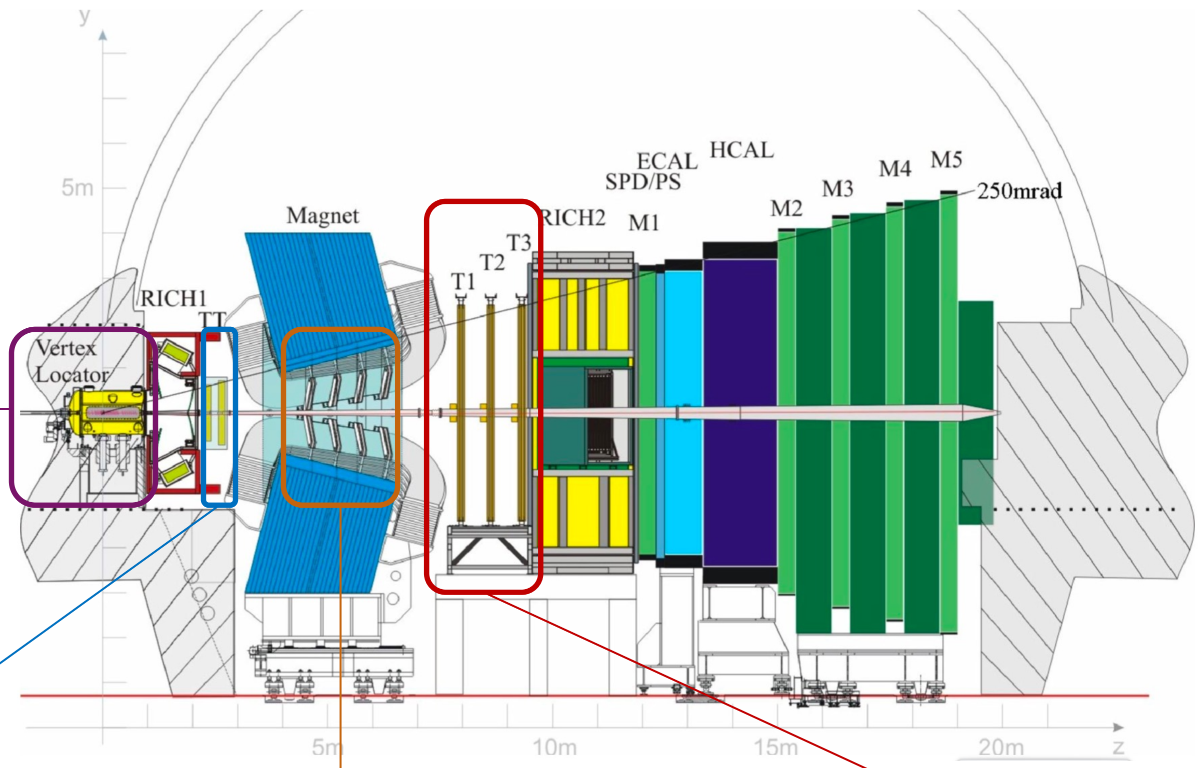
A lot of requirements to be consolidated

- **Pixel size**
    - Occupancy
    - Space (→ momentum) resolution
    - Tracking performances (ghost rate)





THE TRACKING SYSTEM UPGRADE



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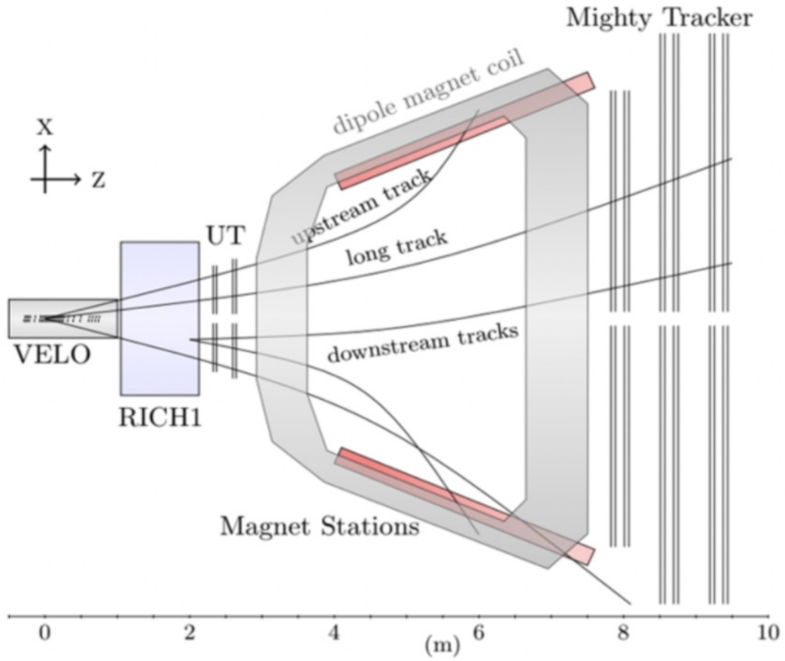
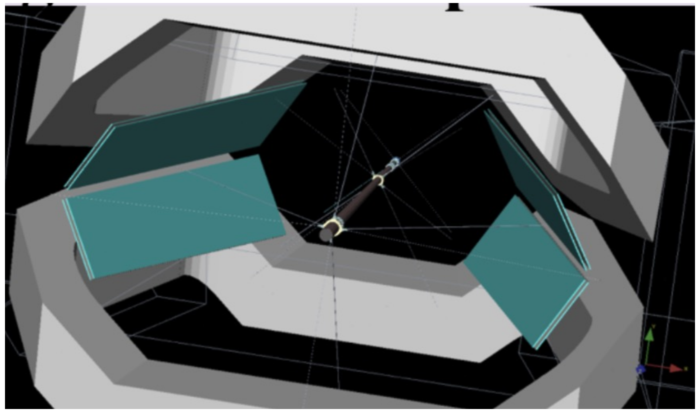
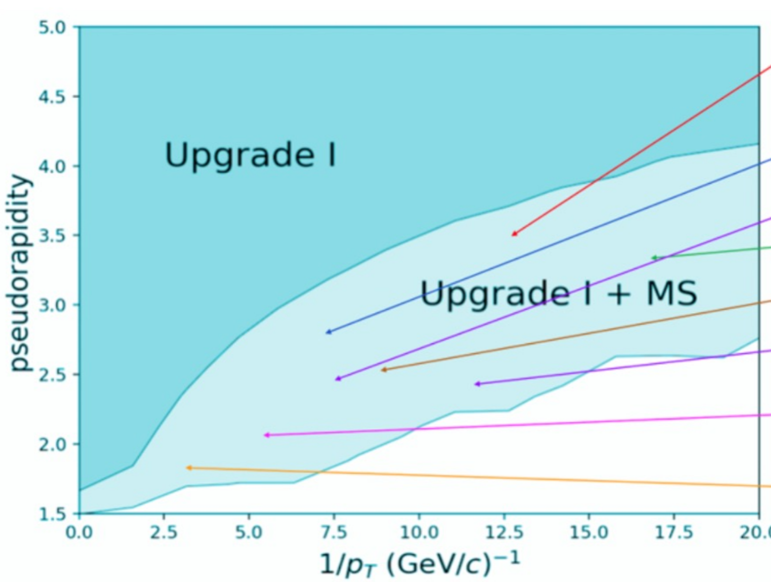
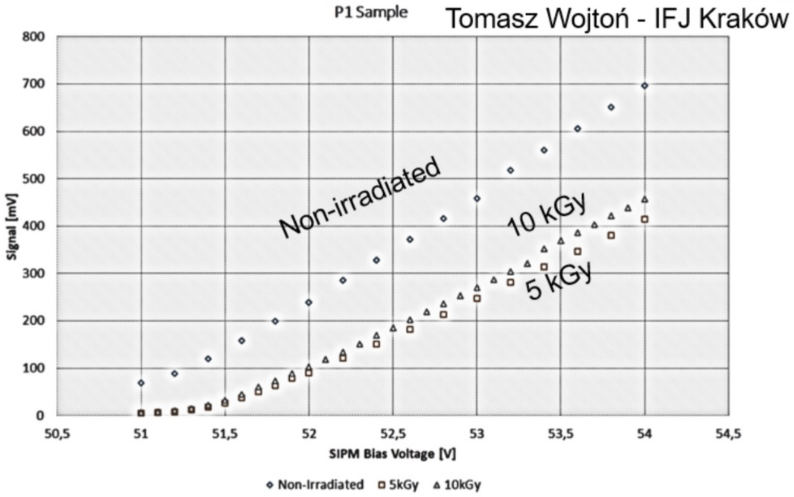







Kuraray clear fiber (sample 4)



- 40% drop in light yield after 10 kGy on covered fibers (P1 sample)
- Expect < 2kGy radiation after 50 fb^{-1} on the clear fibers running on top an bottom of the magnet.
- Panel and fiber ribbon replacement is an option for Run5.