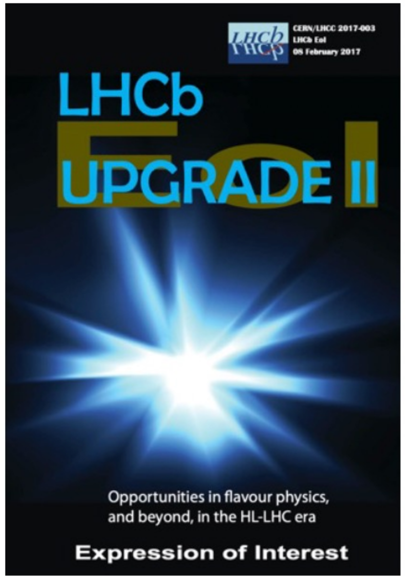
The upgrade program of LHCb

Stefano Matthias Panebianco
CEA – Université Paris Saclay

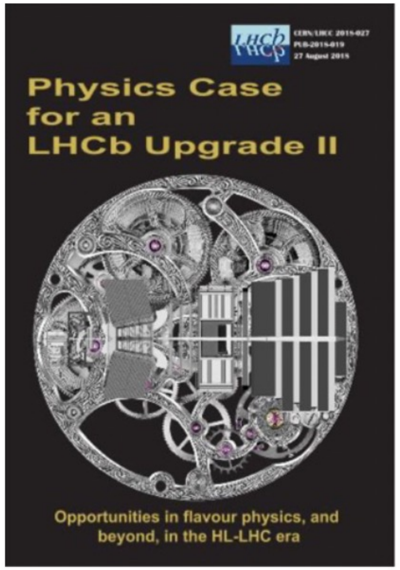
An extremely biased (French/QGP oriented) view… with a lot of stolen material

Expression of Interest



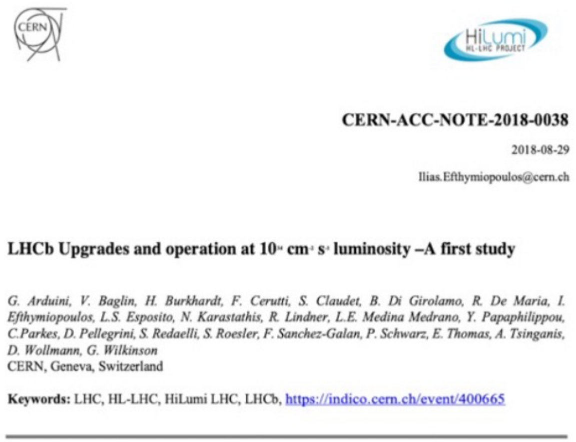
LHCC-2017-003

Physics case



LHCC-2018-027

Accelerator study


CERN-ACC-NOTE-2018-0038

2018-08-29

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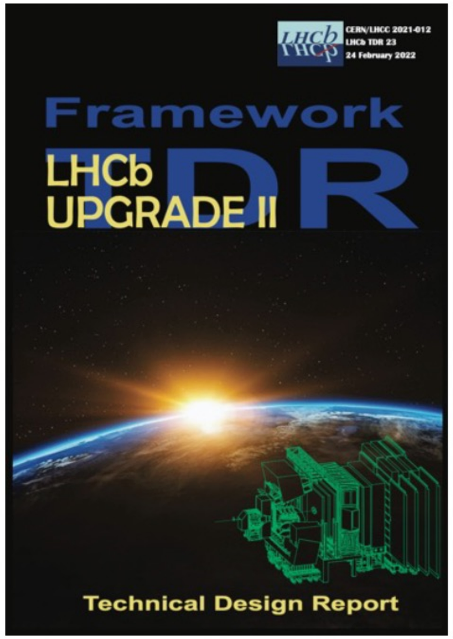
LHCb Upgrades and operation at 10 cm s luminosity –A first study

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."

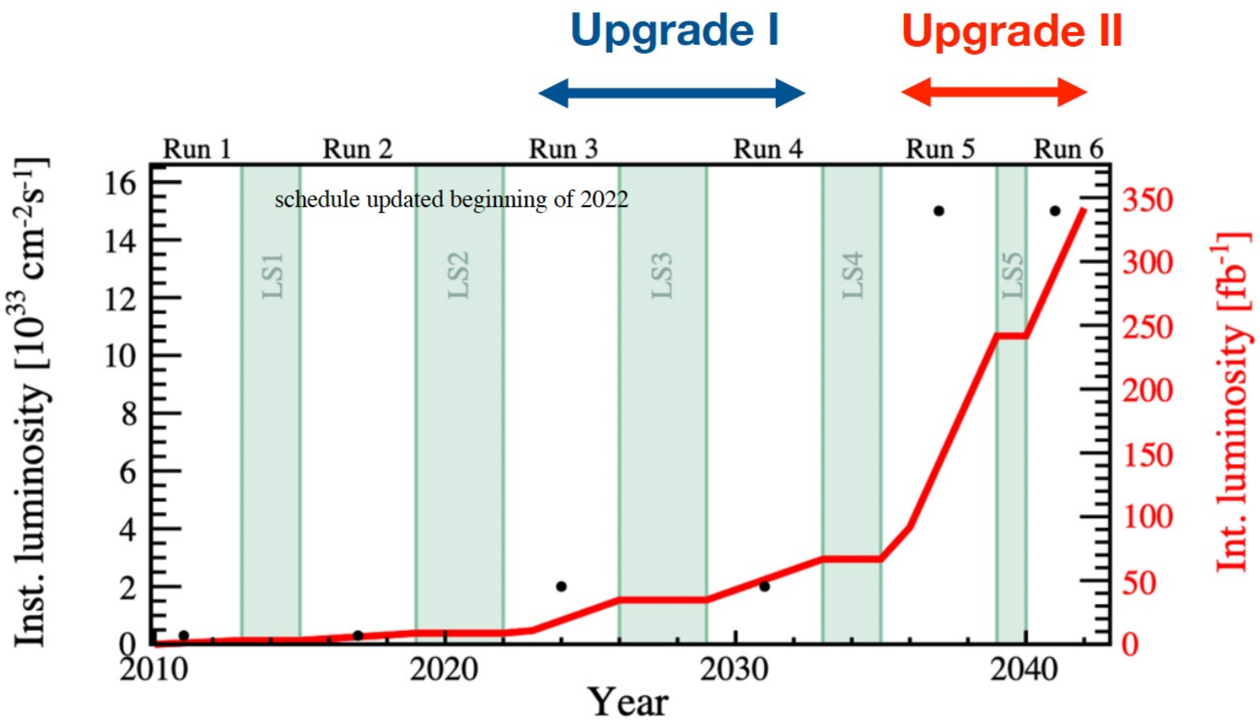
European Strategy Update 2020 ***"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited"***

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

- 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)*

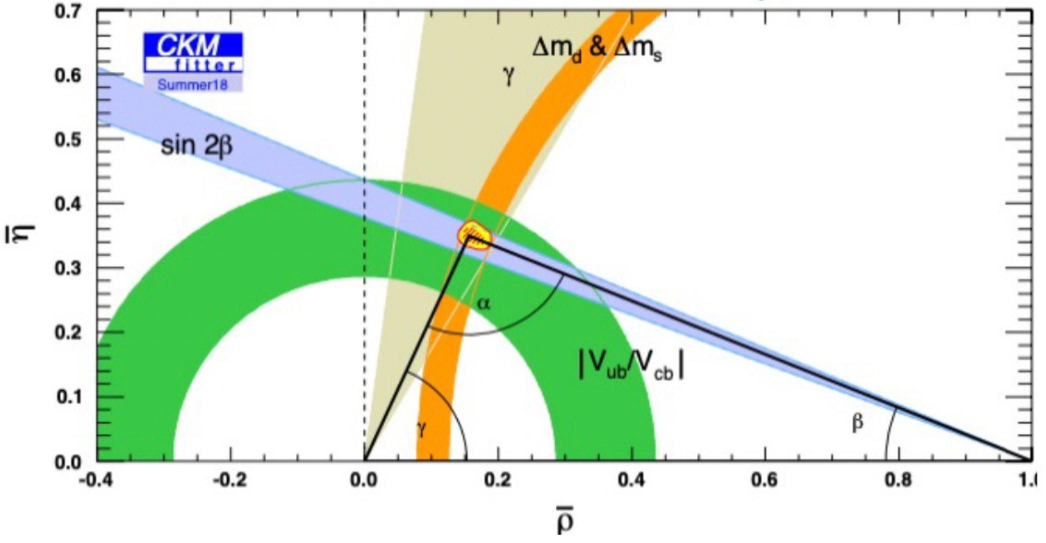


- *Potentially the only general purpose flavour physics facility in world on this timescale*

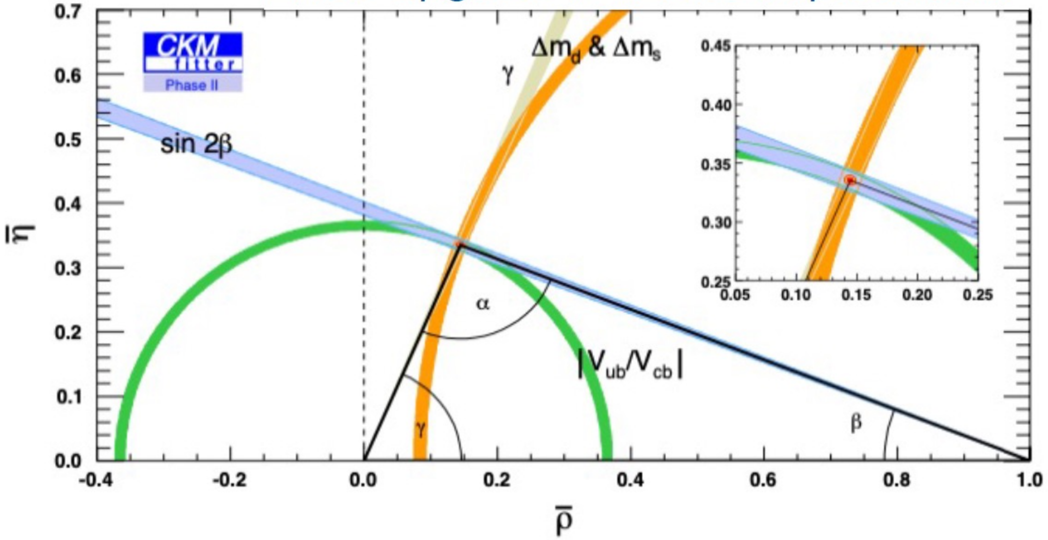
Observable	Current LHCb (up to 9 fb^{-1})	Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests				
γ ($B \to DK$, *etc.*)	$4°$ [9, 10]	$1.5°$	$1°$	$0.35°$
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad [8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6% [29, 30]	3%	2%	1%
$a_{\rm sl}^d$ ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4} [34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
$a_{\rm sl}^s$ ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	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 ($D^0 \to K_S^0\pi^+\pi^-$)	18×10^{-5} [37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays				
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69% [40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—	—	—	0.2
$A_{\rm T}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$A_{\rm T}^{\rm Im}$ ($B^0 \to K^{*0}e^+e^-$)	0.10 [52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$ [51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32 [51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [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

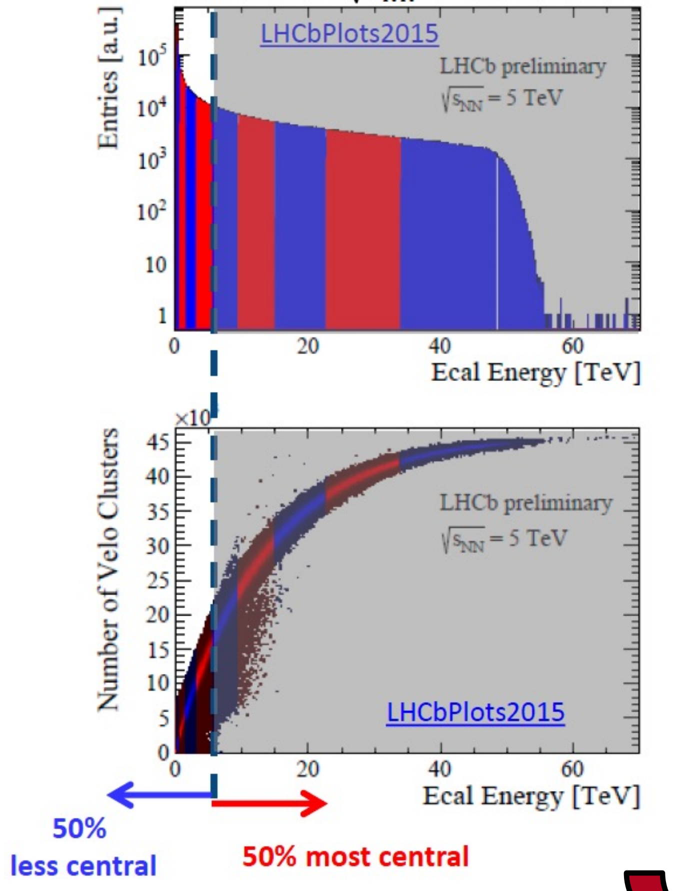
LHCb only, end of 2018



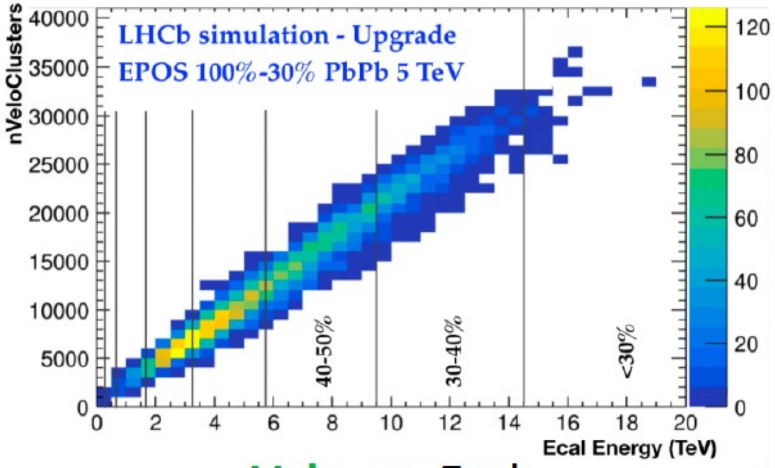
LHCb Upgrade II + LQCD improvement



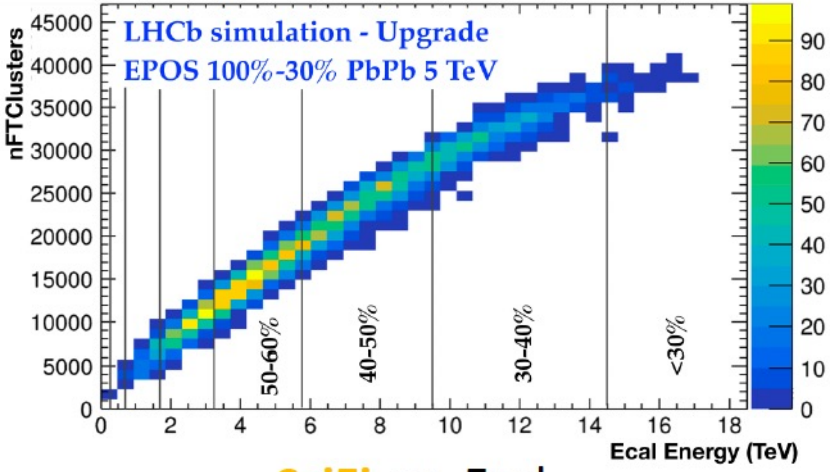
Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 5 TeV – 2015 data



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

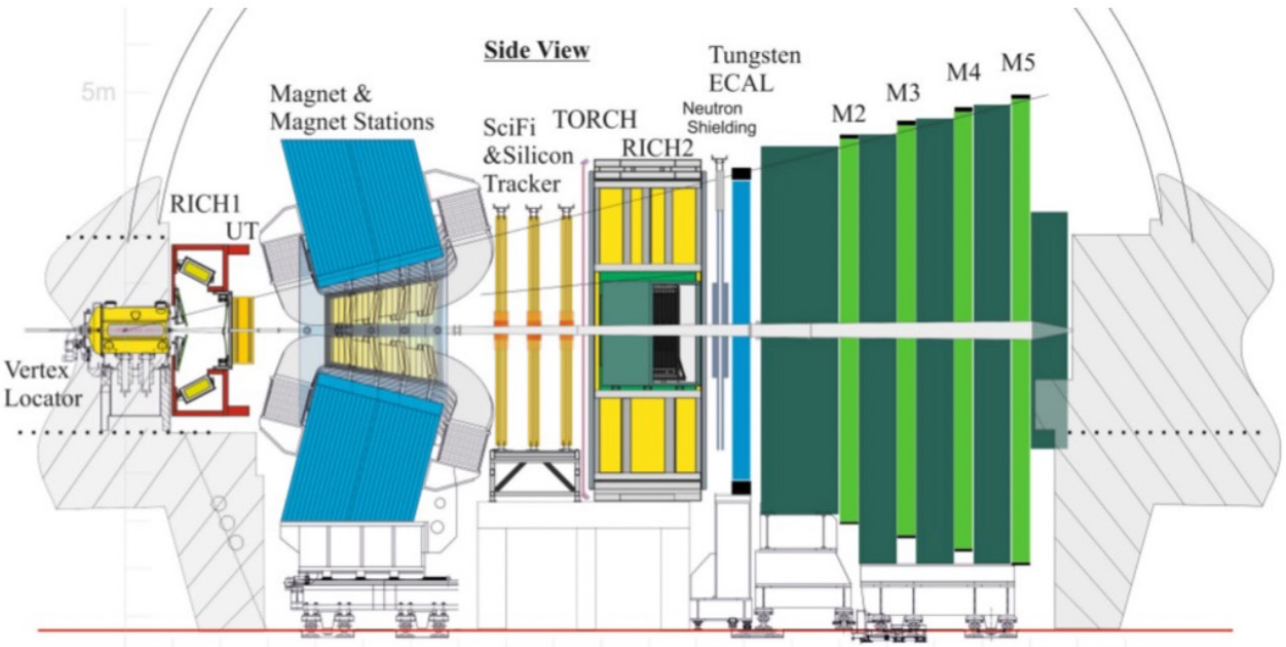


Velo .vs. Ecal



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

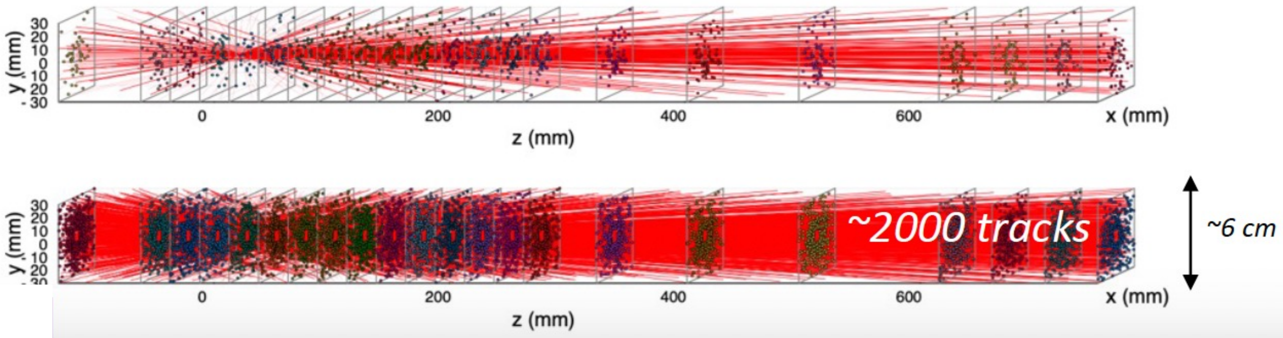
Key ingredients:

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

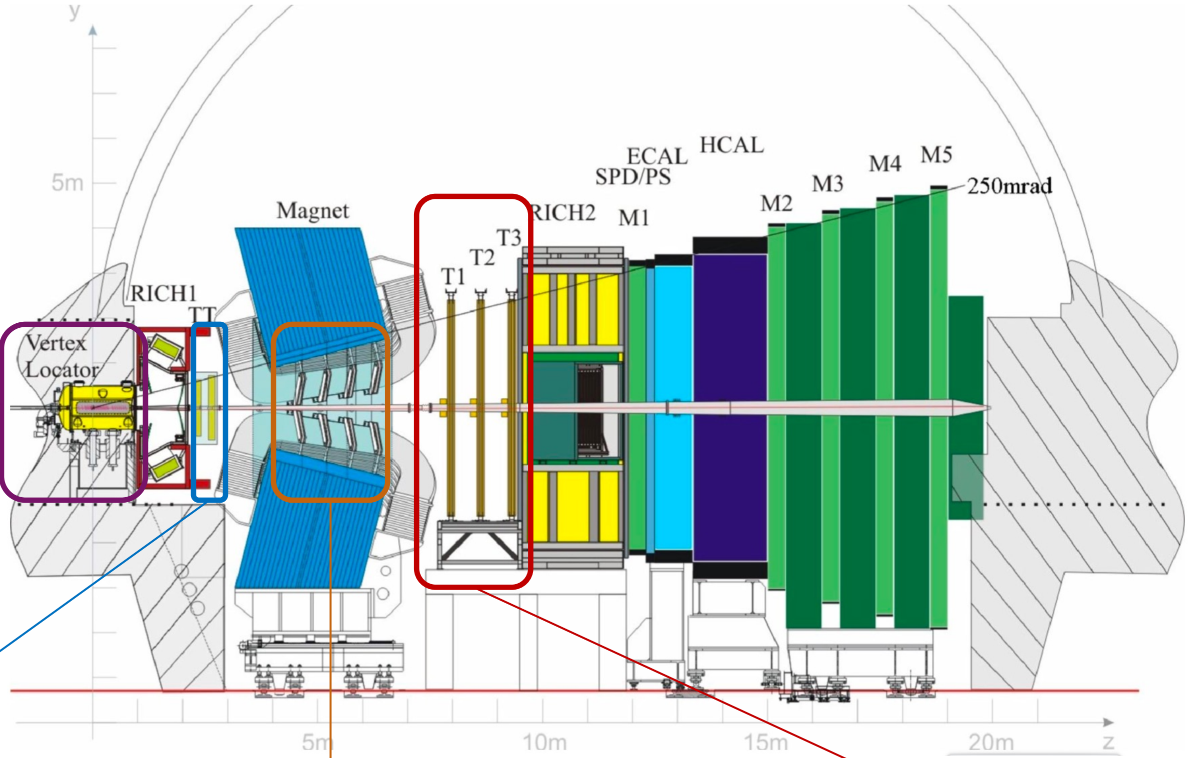
VErtex LOcator (VELO)

Run 3: pile-up ~6

Upgrade II: pile-up ~42



THE TRACKING SYSTEM UPGRADE



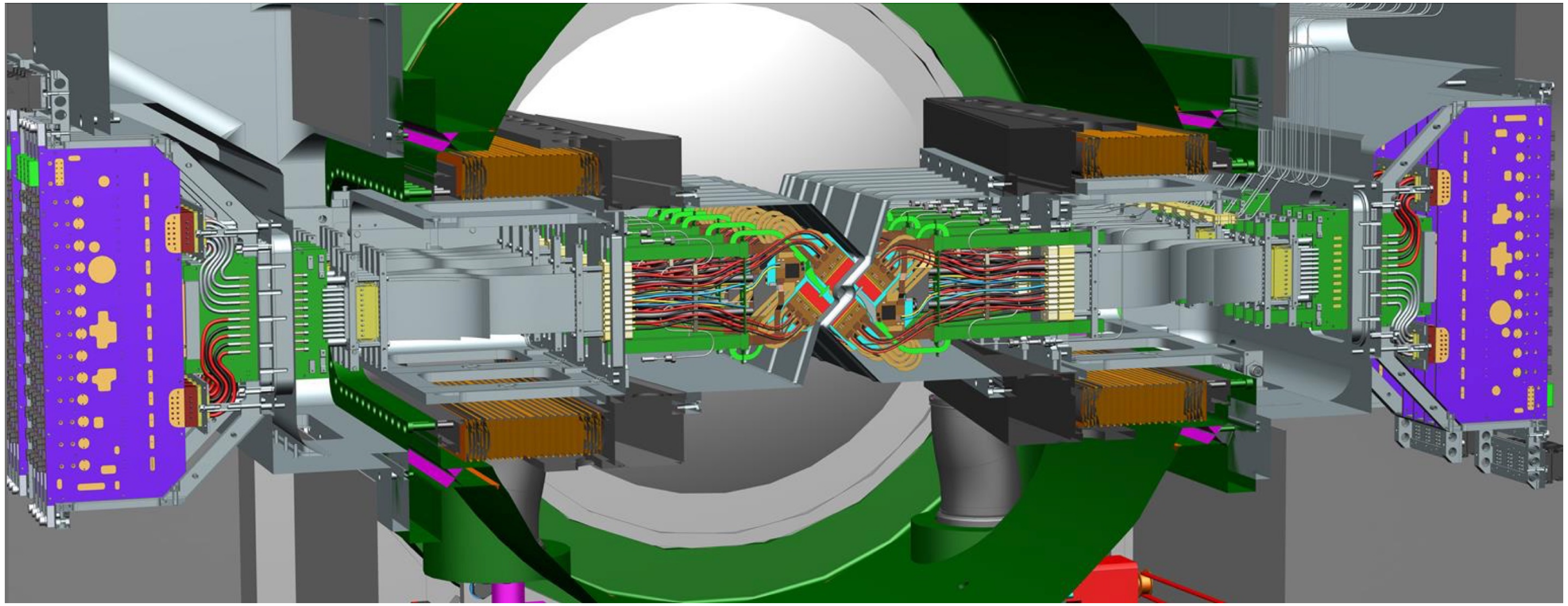
VELO
Pixel with timing

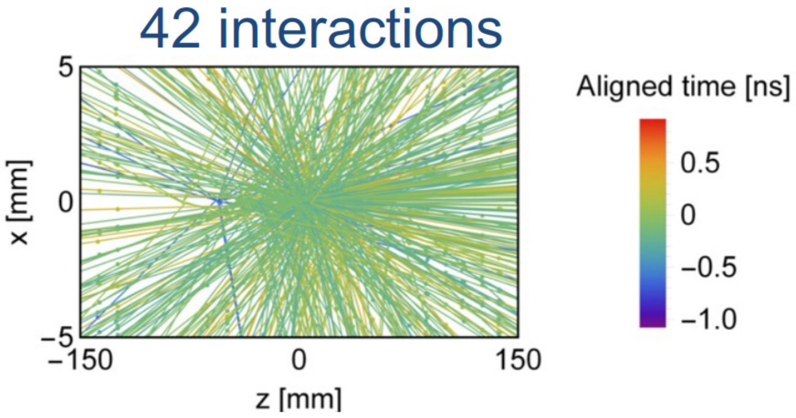
Upstream Tracker
From strip to CMOS

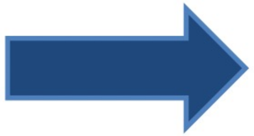
Magnet stations
Tracking on magnet sides

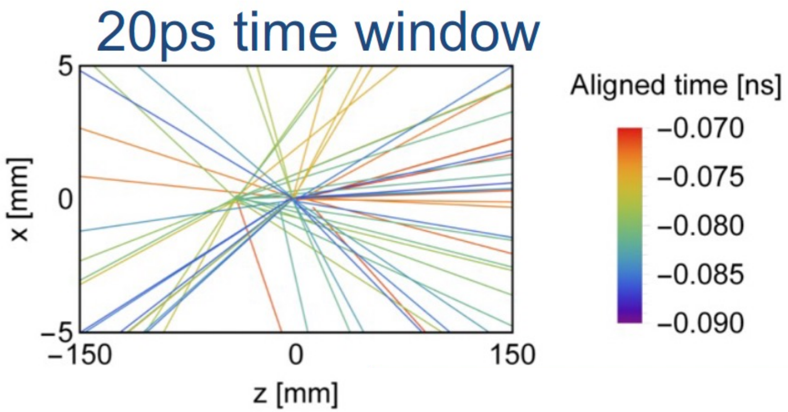
Mighty Tracker
Combine SciFi & CMOS

VELO

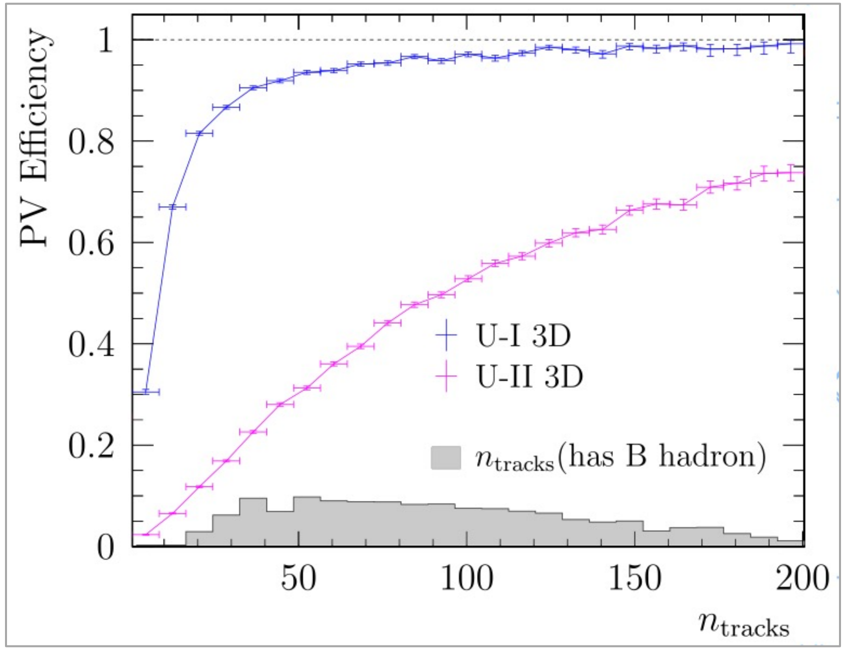



42 interactions
Aligned time [ns]
0.5
0
−0.5
−1.0
x [mm]
5
0
−5
−150
0
150
z [mm]

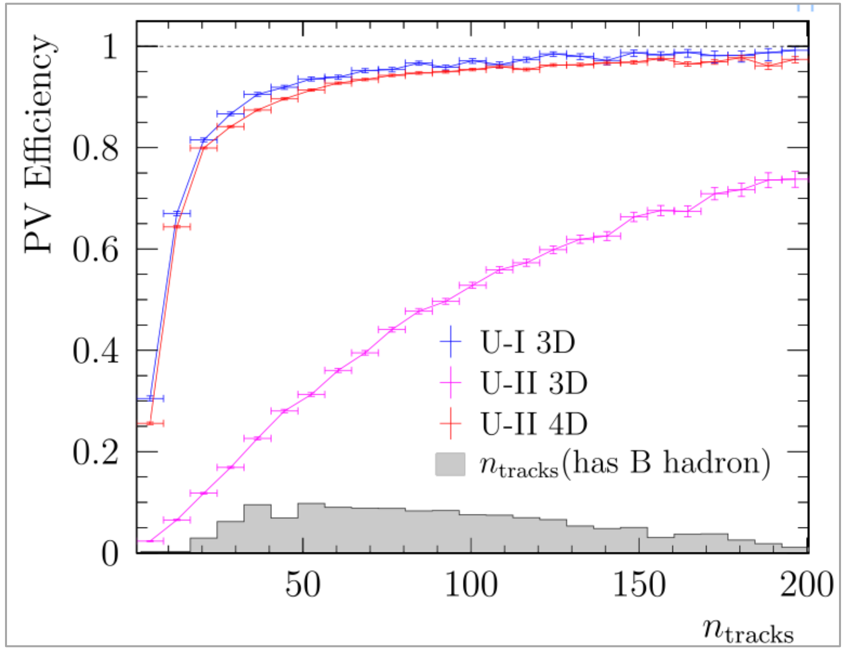


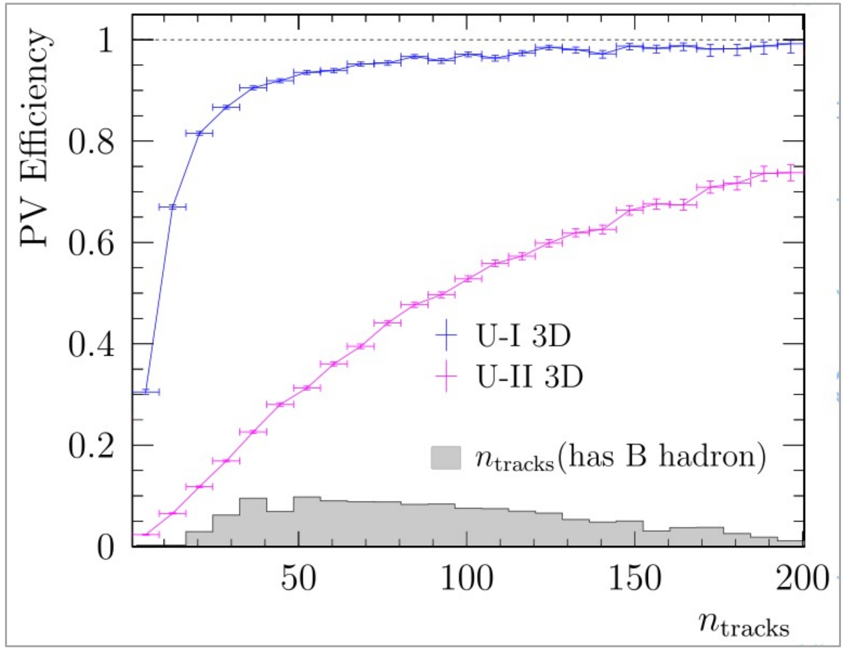

20ps time window
Aligned time [ns]
−0.070
−0.075
−0.080
−0.085
−0.090
x [mm]
5
0
−5
−150
0
150
z [mm]

VELO

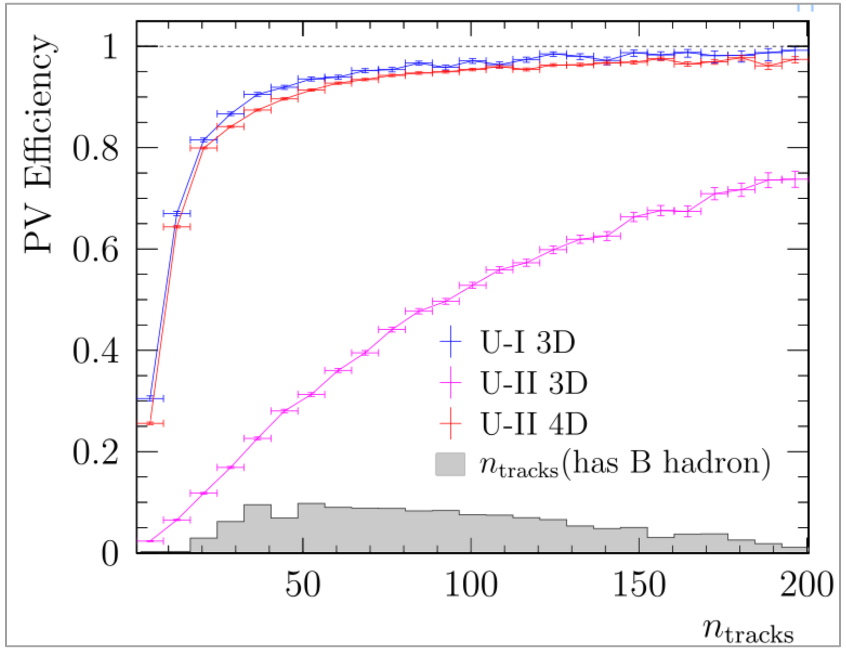

PV Efficiency
U-I 3D
U-II 3D
n_{tracks}(has B hadron)
n_{tracks}

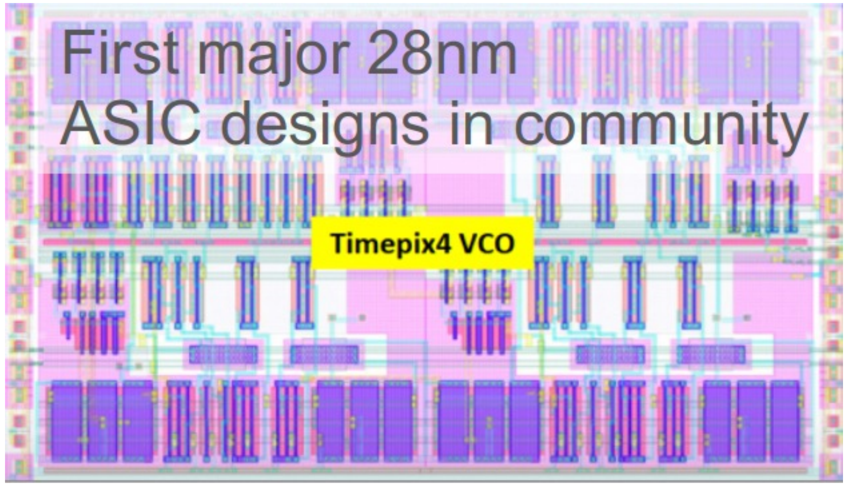
Add 4D!

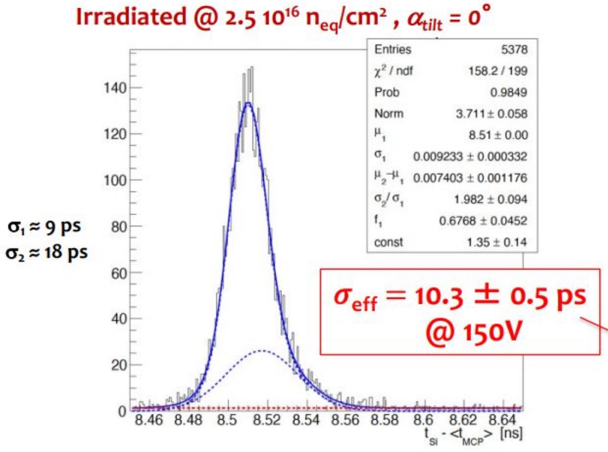

PV Efficiency
U-I 3D
U-II 3D
U-II 4D
n_{tracks}(has B hadron)
n_{tracks}

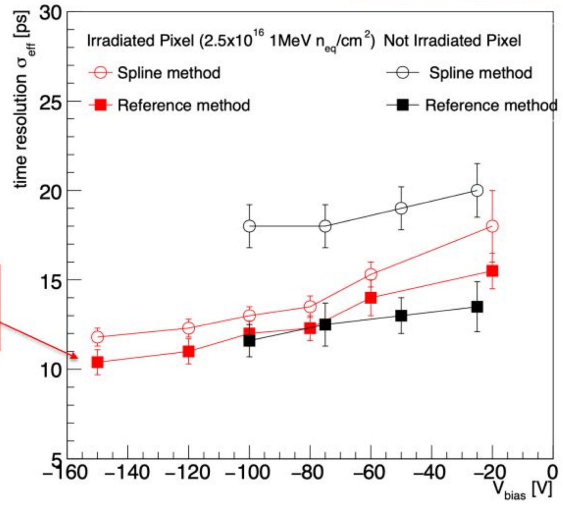


Add 1D!

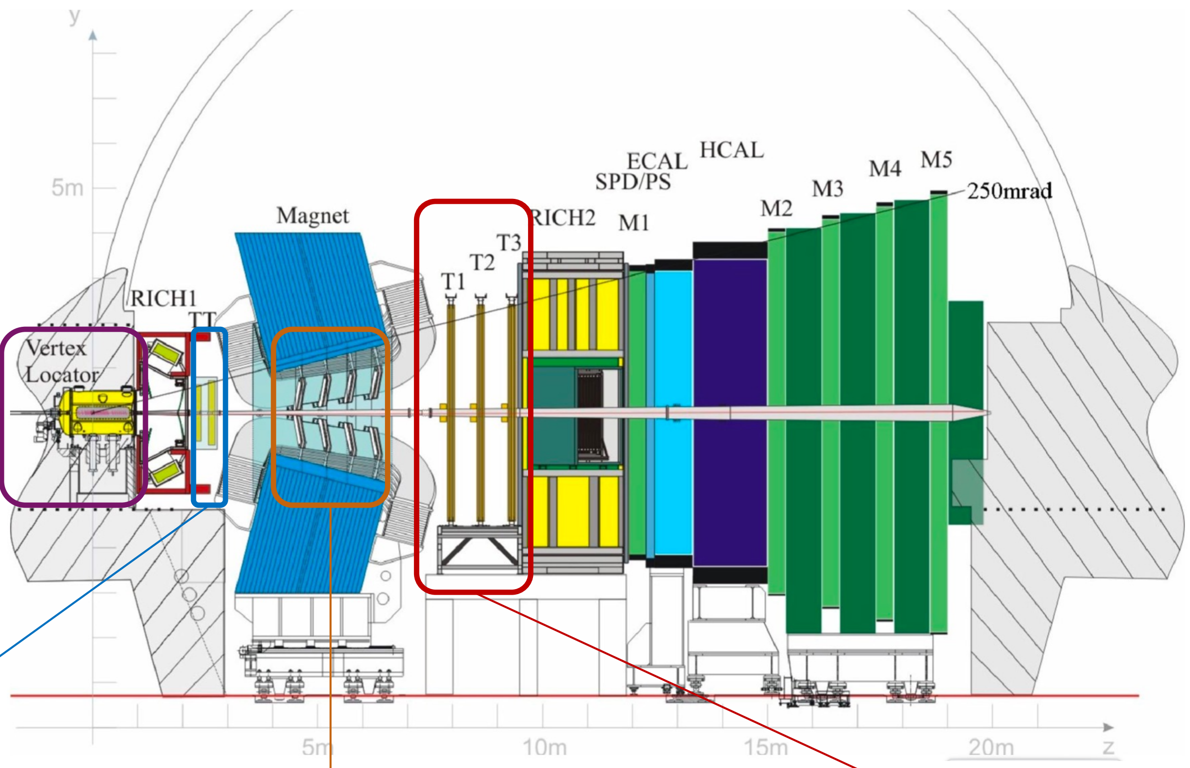








Pre-irradiation performance is already recovered at $\Delta V_{bias} \approx$ 10-15 V



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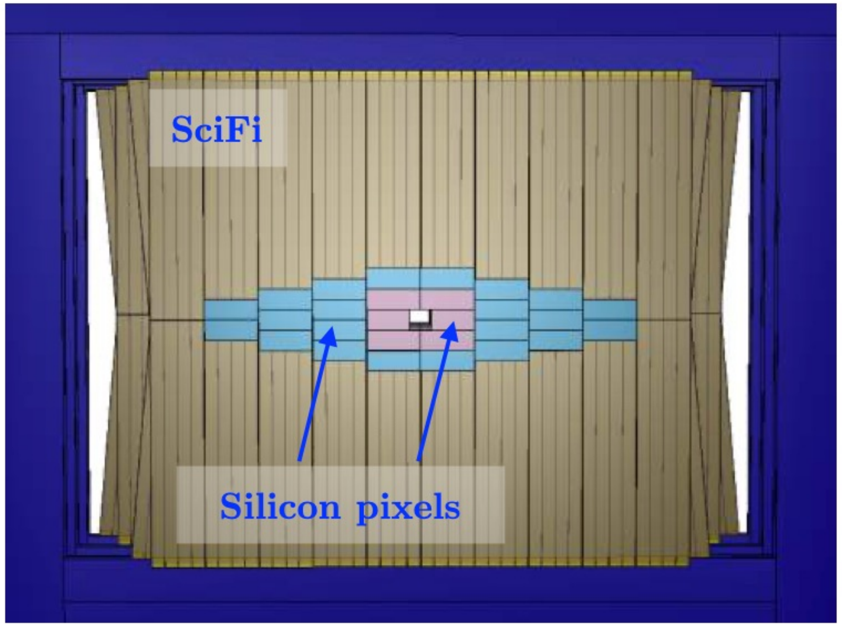
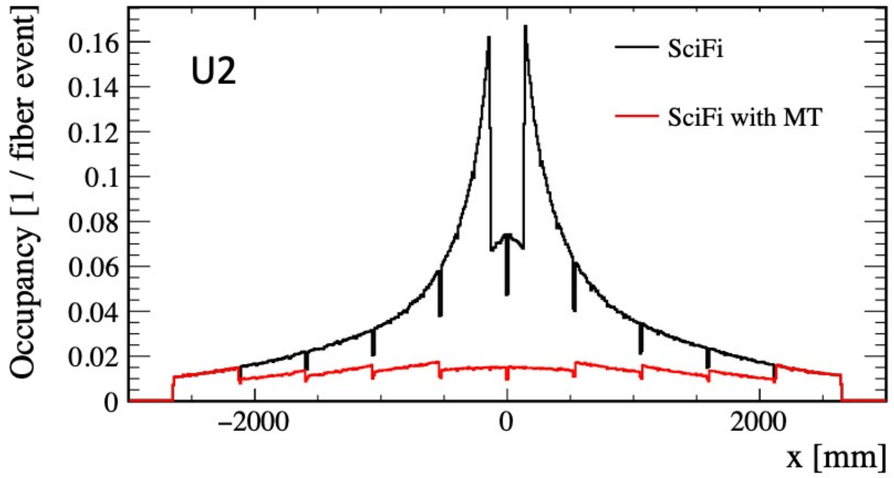
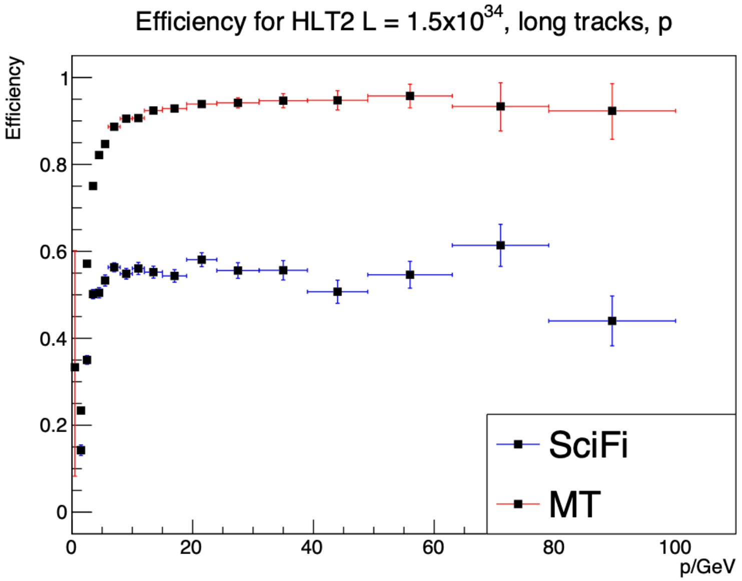
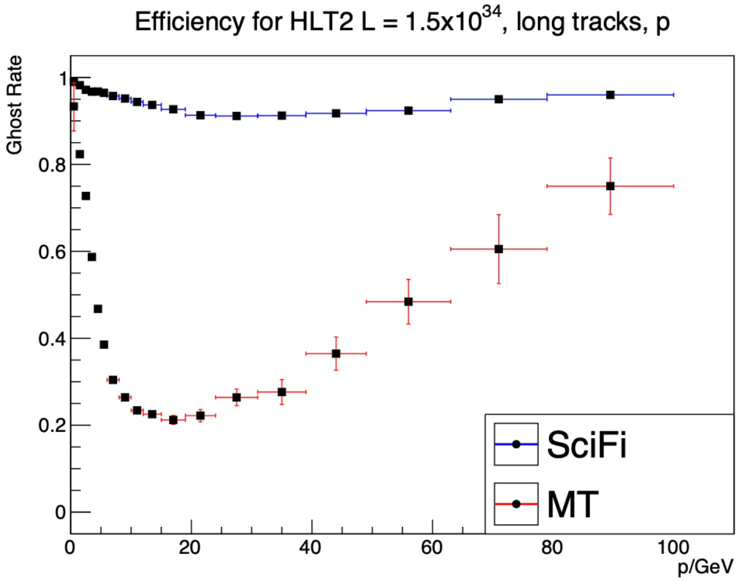
Mighty tracker





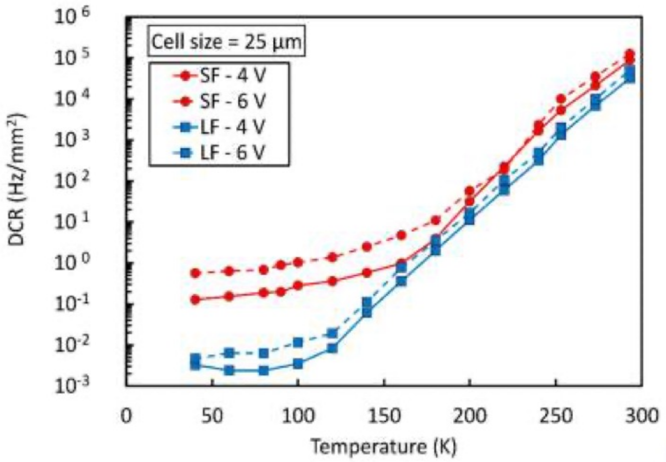




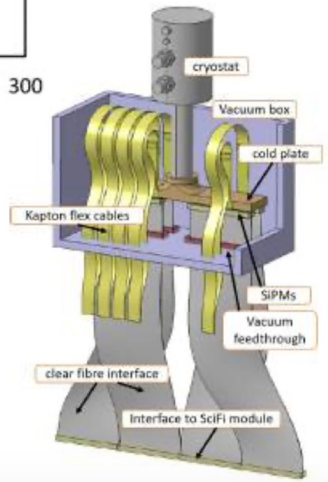
SciFi Enhancements

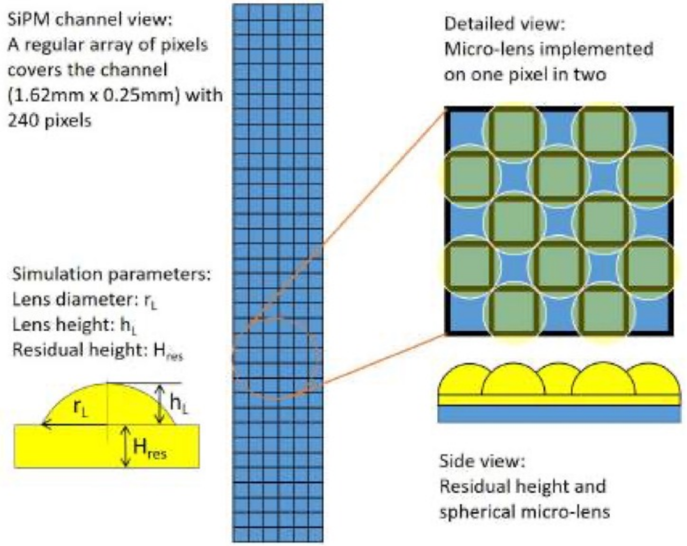
Major improvement seen cryogenic cooling to allow to run below -120 °C

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

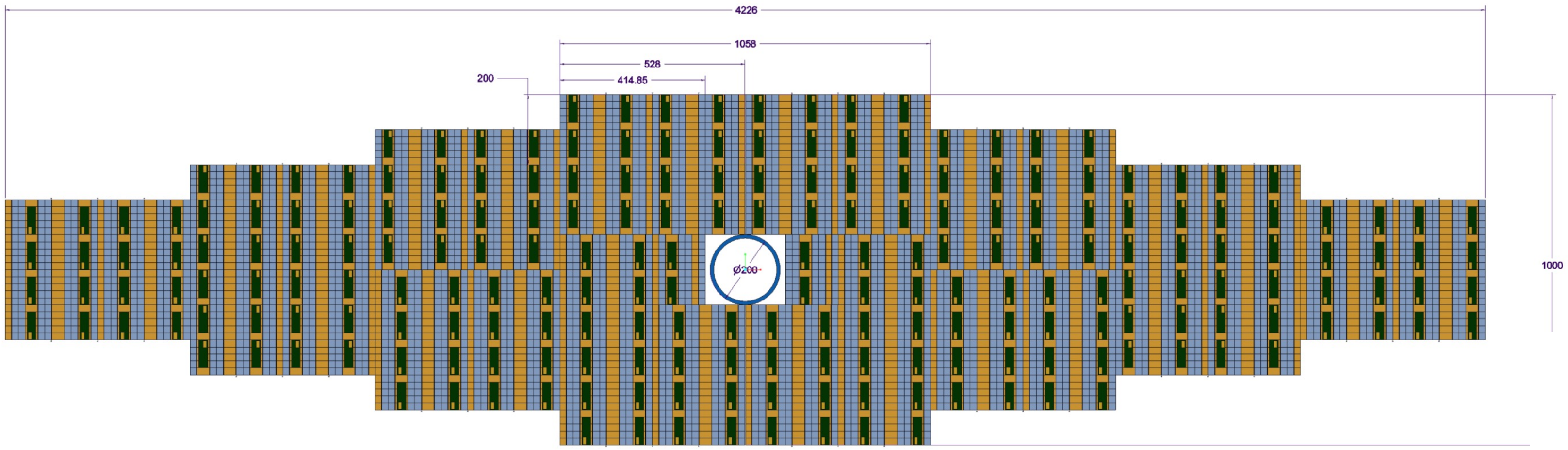


Additional interface
~ 16 % loss in light





Better SiPMs and micro-lensing should compensate for light loss



One Layer $3m^2$
2 Layers per station
6 Layers in total

HV-CMOS

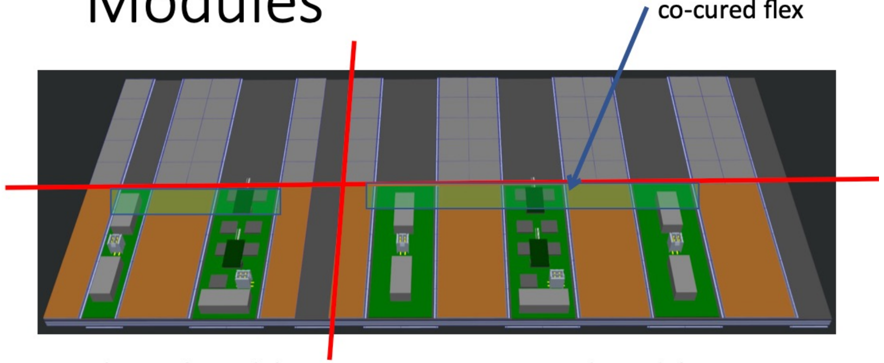
- One of the main drivers of the project is the size of the silicon area
- MAPS chips are limited to ~$2x2\ cm^2$ (foundry)
- The most critical points are:
  - In Time **Efficiency**
  - **Power** Consumption
  - **Radiation** Tolerance

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	6×10^{14} 1 MeV n_{eq}/cm^2
Power consumption	< 150 mW/cm^2
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)

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

Problems with MightyPix1

- There was a mistake in the MP1 design
- New I2C interface and the well tested shift register interfered
- One load signal not connected (Bias block)
- Sadly the simulation tested after config block
- An error message was overlooked

- Things happen. We will now concentrate on what to do!

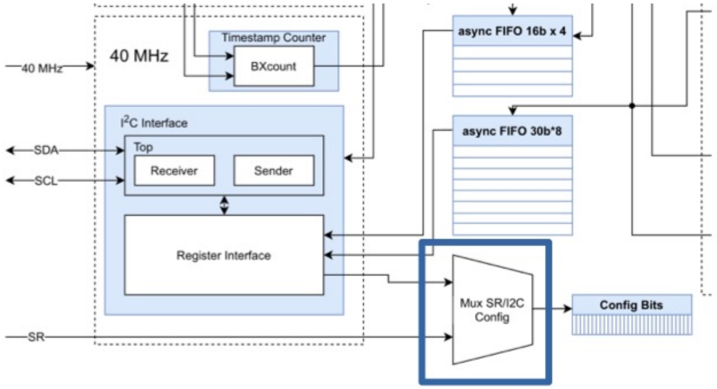
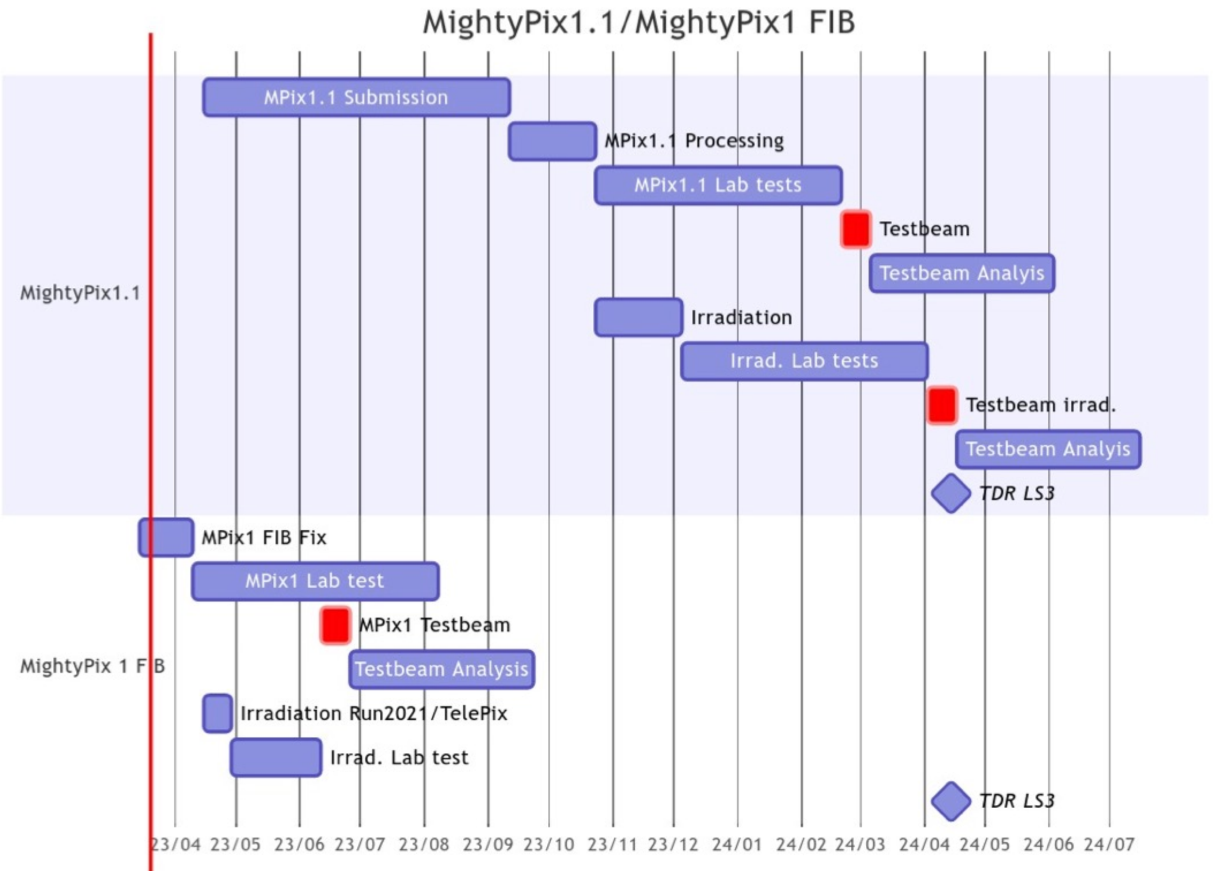


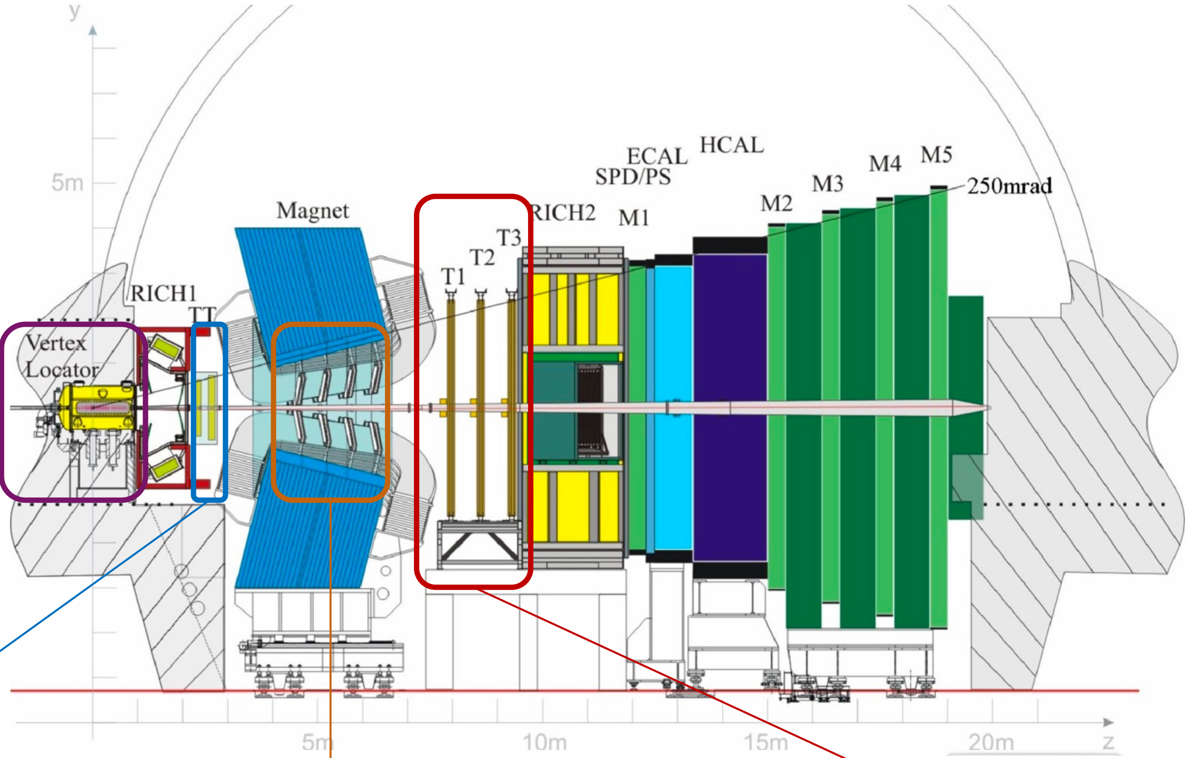
Table B.2: 36 IDACs

DAC	Bits	Default
Q0	1:0	0
Qon	3:0	4'b0101
BLRes	5:0	6'd5
VNCompFine	5:0	6'd1
VN	5:0	6'd20
VNFB	5:0	6'd5
VNRegC	5:0	6'd1
VNDel	5:0	6'd10
VPBigFine	5:0	6'd20
VPDAC	5:0	0
VN	5:0	0
VNFoll2	5:0	6'd20
VNFB2	5:0	0
VPLoad2	5:0	0
VPVCO	5:0	6'd7
VNVCO	5:0	6'd15
VPDelDclMux	5:0	6'd30
VNDelDclMux	5:0	6'd30
VPDelDcl	5:0	6'd30
VNDelDcl	5:0	6'd30
VPDelPreEmp	5:0	6'd30
VNDelPreEmp	5:0	6'd30
VPDcl	5:0	6'd30
VNDcl	5:0	6'd30
VNLVDS	5:0	6'd10
VNLVDSDel	5:0	6'd10
VPPump	5:0	6'd5
VNCPc	5:0	6'd5
VNVCOc	5:0	6'd10
VPRegCasc	5:0	0
VPSmallFine	5:0	6'd20
VNComp	5:0	6'd30
VPFoll	5:0	6'd30
VPBiasRec	5:0	6'd5
VNBiasRec	5:0	6'd5

Resubmission

- KIT offered to resubmit a fixed MightyPix1.1
- Consider using repaired sensors (Focused Ion Beam FIB)
- Maybe wafer scale or more FIB is possible





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UT

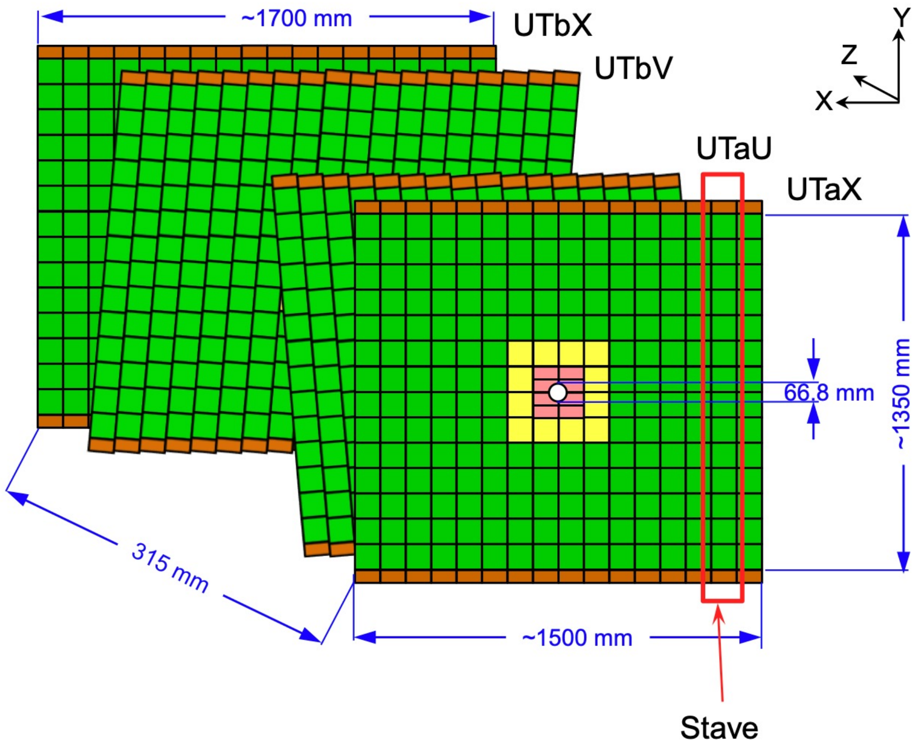
- Project in very early stage
- Proto-collaboration including labs from China and France

- R&D is only starting and the main technological choices are still open
- Could certainly benefit from synergy with the Mighty Tracker project
- Next major milestones:
  - Scoping document: September 2024
  - TDR: end of 2025

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$_{coll}$

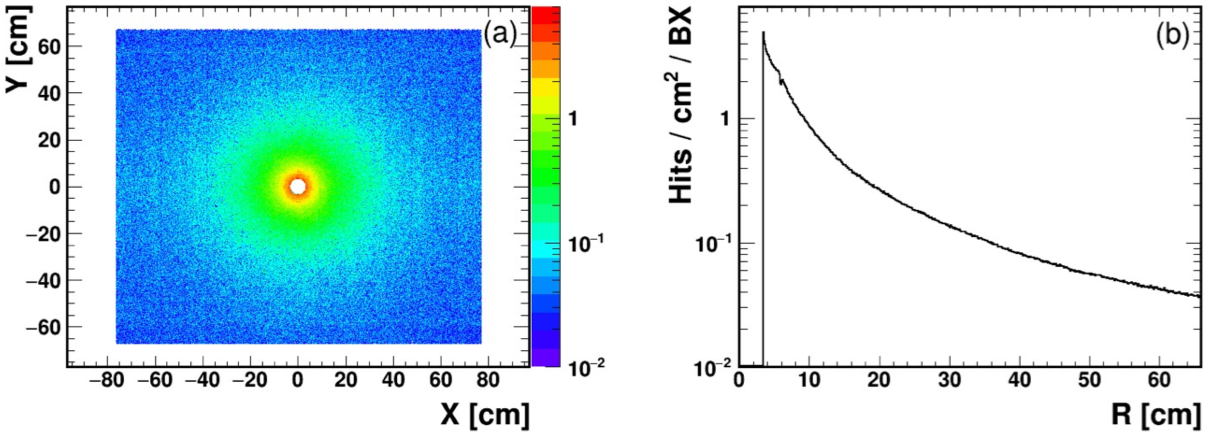
Pb–Pb collisions

- 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

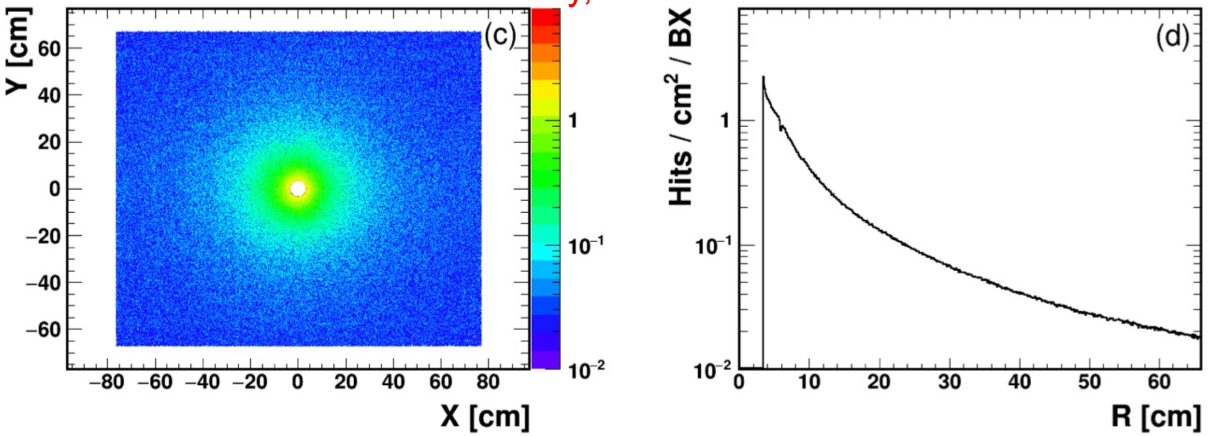
Lighter ion collisions

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

Hit density, pp



Hit density, central 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

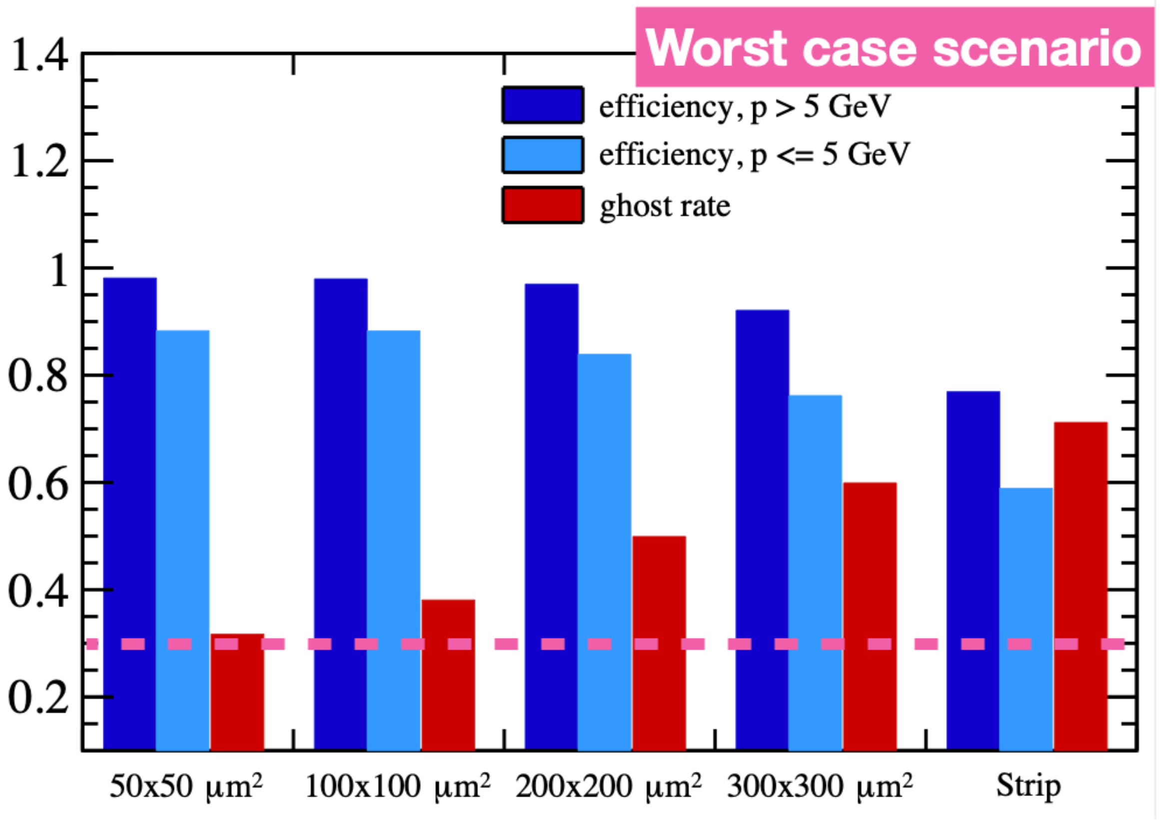
Characteristics	Specification
Hit rate in hot event and region	160 MHz / cm^2 pp (~52.5 hits / cm^2 / BX for Pb/Pb)
Time resolution	O(1 ns) for BX tagging
Pixel size	O(30×30 μm^2)
Power consumption	O(100-300 mW/cm^2)
Radiation dose for 350 fb^{-1}	3×10^{15} 1-MeV n_{eq}/cm^2, 240 Mrad

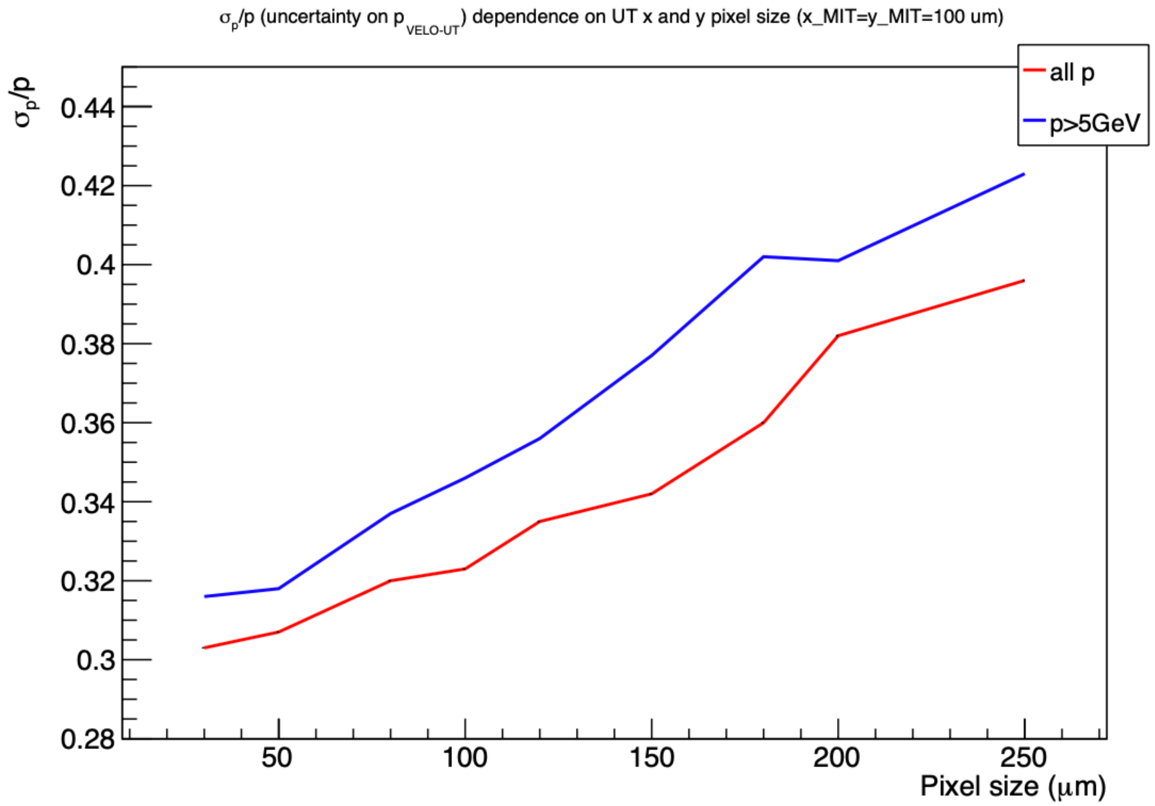
Close to ATLAS CMOS outer layer specifications

PIXEL SIZE

A lot of requirements to be consolidated

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





Investigation of CMOS technologies

https://indico.cern.ch/event/1285479/contributions/5417480/attachments/2651634/4591280/2023-05-23_Migthy-UT_CMOS.pdf

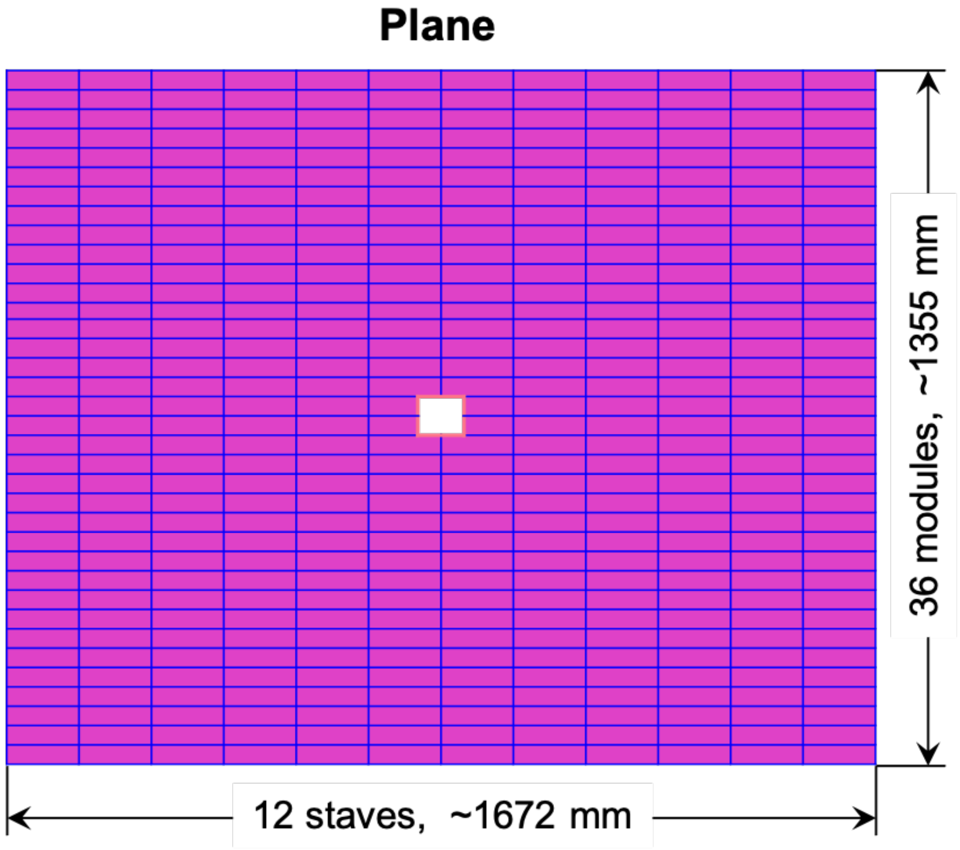
- **MightyPix (AMS180nm)**
  Most advanced sensor : almost full functionality prototype
  Designed specifically for LHCb (readout)
  With the present demonstrated specs: not fully suitable for UT (readout rate, radiation dose)
  Interest in China to participate to the qualification and tests

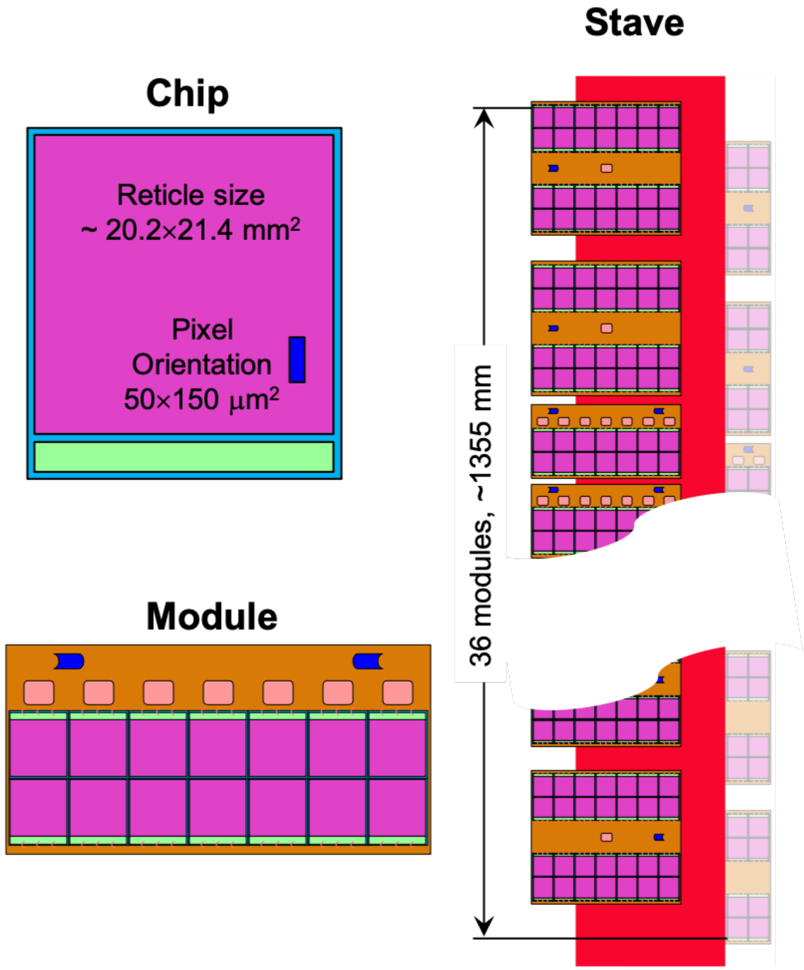
- **MALTA family (TJ180nm)**
  Pixel size : $36.4 \times 33\ \mu m^2$
  98% "in-time" tagged data from test-beam without ToT (= less data to be sent - tbd)
  Proven 3×10^{15} 1-MeV n_{eq}/cm^2, 100 Mrad @ -20°C
  Malta 2 (2021): enlarged transistors for lower noise and higher gain
  Malta 3 (ongoing design): on-chip time tagging, serial output, daisy chain readout
  Strong interest from developers to include UT specifications
  Irfu participated to the chip qualification, LLR is joining the effort

- **DPTS (TJ65nm)**
  Large development group at CERN involved for ALICE ITS3
  Proven working after 1×10^{15} 1-MeV n_{eq}/cm^2 @ room temperature
  Test vehicle for digital asynchronous readout
  Working point ~ 99% efficiency at acceptable fake-hit rate
  Strong interest from Irfu (and IPHC) to submit in ER2 (mid 2024)

A lot of requirements to be consolidated

- **Pixel size**
- **Chip size, detector position, number of planes**
  - Dead areas (keep below 1%) → efficiency
  - Tracking performances
  - Data rate (also depending on the readout scheme)





- Similar layout for small pixel or large pixel CMOS solutions
- The UT system consists of 4 (or 3) planes

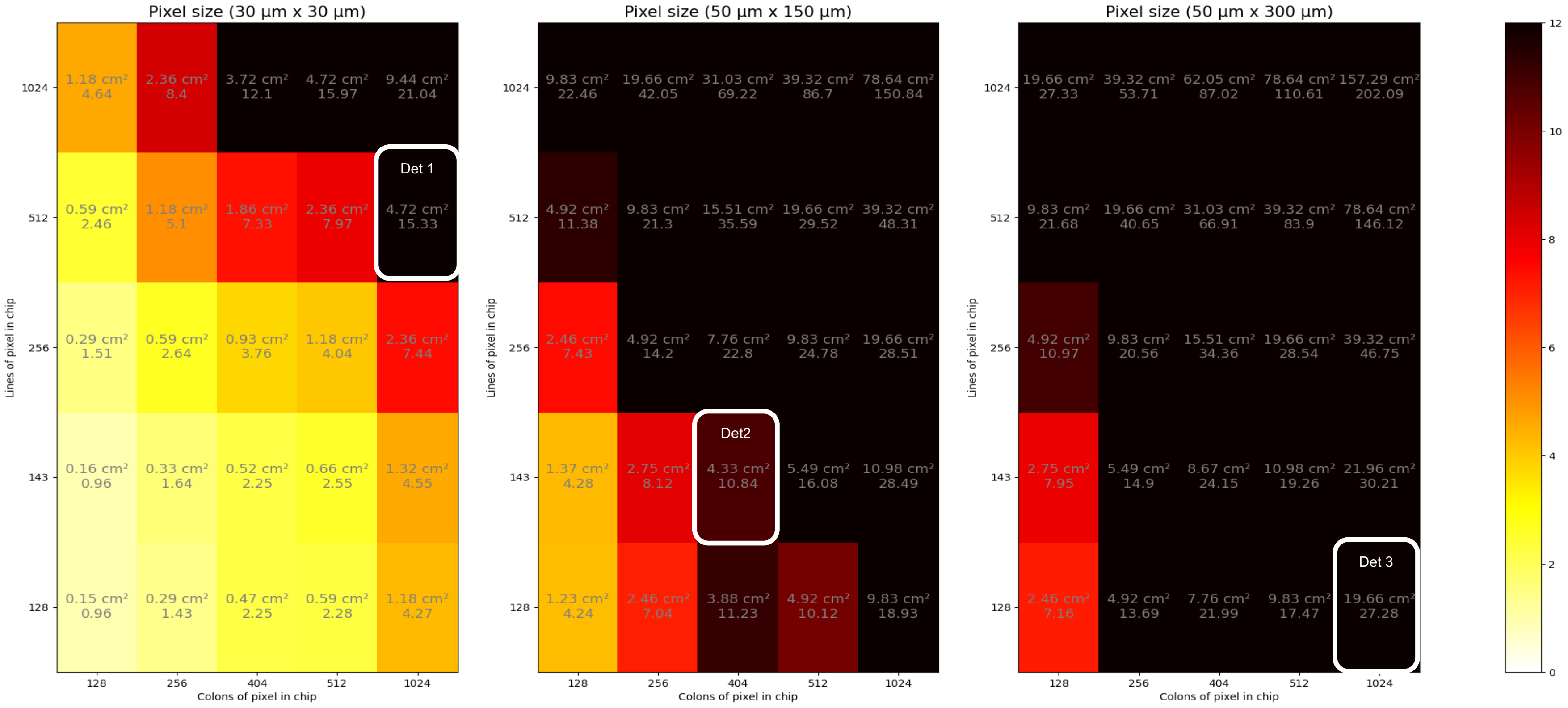
DATA RATE

A lot of requirements to be consolidated

- **Pixel size**
- **Chip size, detector position, number of planes**
    - Dead areas (keep below 1%) → efficiency
    - Tracking performances
    - Data rate (also depending on the readout scheme)

Det	Pixel size	Bits per hit	Chip area	Data rate of the hottest chip
1	30 µm x 30 µm	31	4,72 cm²	15,3 Gbit/s
2	50 µm x 150 µm	29	4,23 cm²	10,8 Gbit/s
3	50 µm x 300 µm	29	19,66 cm²	27,2 Gbit/s

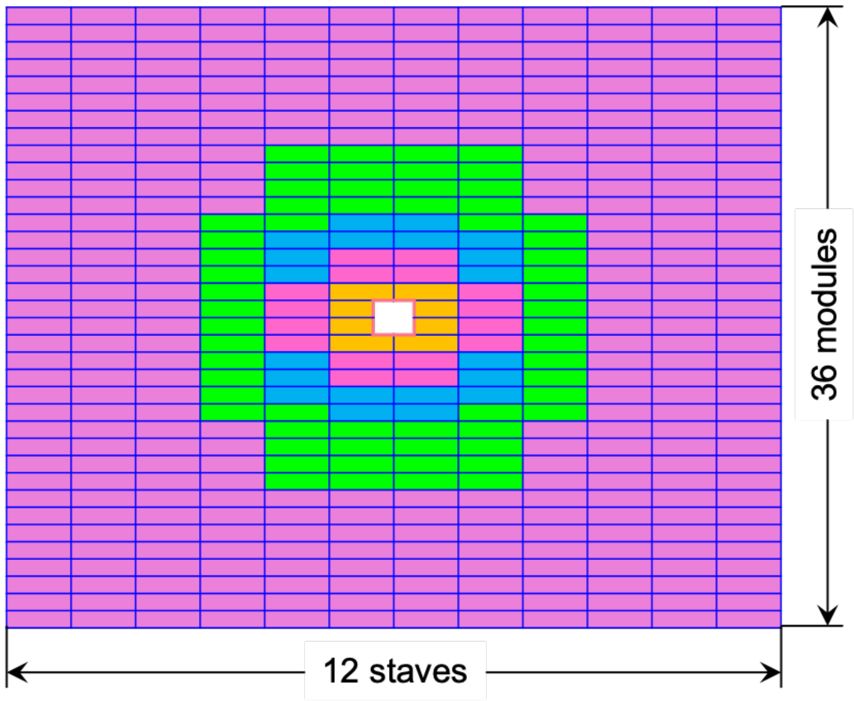
Data rate [Gbit/s] of the hottest chip for different configuration of detectors



A lot of requirements to be consolidated

- **Pixel size**
- **Chip size, detector position, number of planes**
  - Dead areas (keep below 1%) → efficiency
  - Tracking performances
  - Data rate (also depending on the readout scheme)

A box corresponds a 7×2-Chip module



1888 lpGBTs (data)
1312 lpGBTs (control)
1312 VTRx+
4512 Optical fibers

Ring	5	4	3	2	1	All
e-links / chip	1	1	1	1-3	2-7	
Gbps / e-link	0.32	0.64	1.28	1.28	1.28	
lpGBT / module	0.5	1	2	7	14/10	
Num of modules	1312	240	80	64	32	1728
Num of data lpGBTs	656	240	160	448	384	1888
Num of ctrl lpGBTs	656	240	80	192	144	1312

Dual-module (for lpGBT efficiency) ↑ (Ring 5)

The configuration will be further optimized with sensor chip development and better simulation studies.

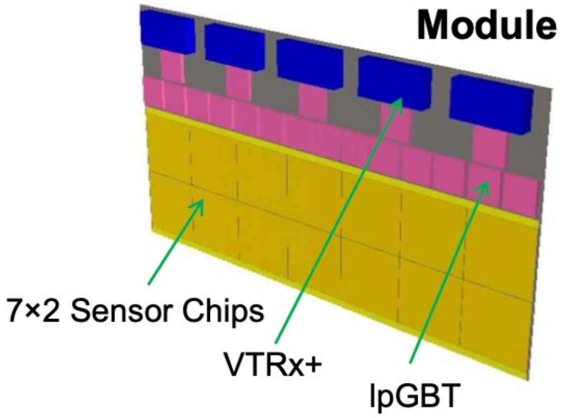
A lot of requirements to be consolidated

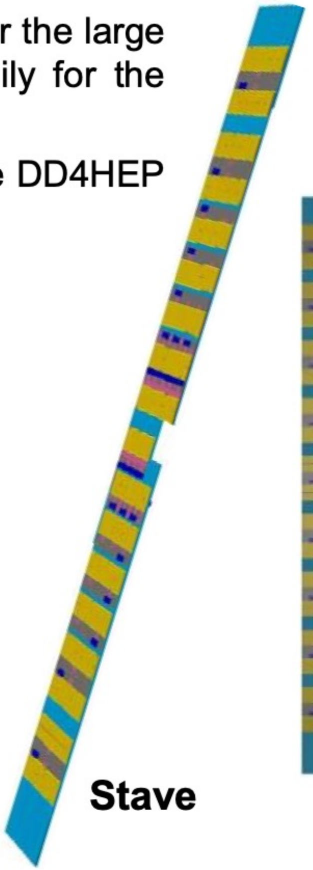
- **Pixel size**
- **Chip size, detector position, number of planes**
- **Chip thickness and global material budget**
  - Position (→ momentum) resolution, multiple scattering

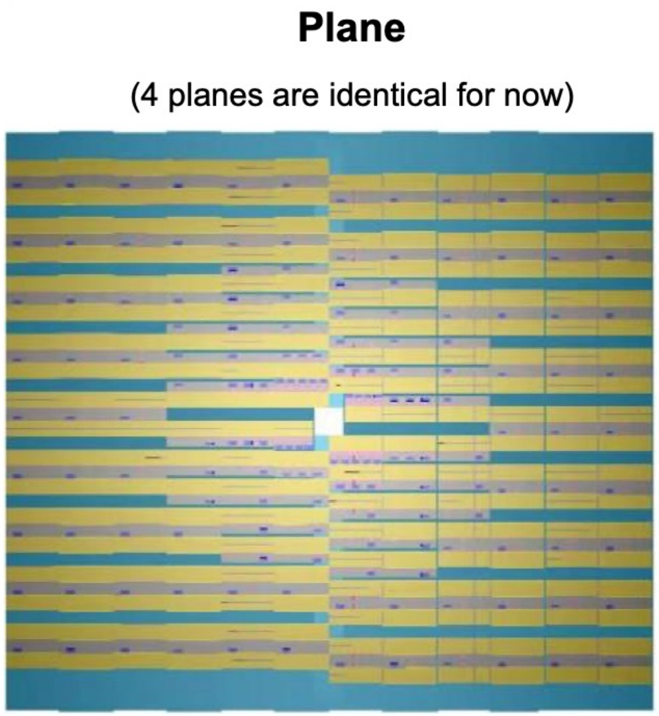
https://indico.icc.ub.edu/event/163/contributions/1626/attachments/663/1321/LHCbU2_WS2023_UT.pdf

- Detector description has been developed for the large electrode solution. It can be modified easily for the small electrode solution.
- It was initially created based on DDDB. The DD4HEP version now has been well debugged.

Extremely crowded for the inner modules







THE MATERIAL BUDGET

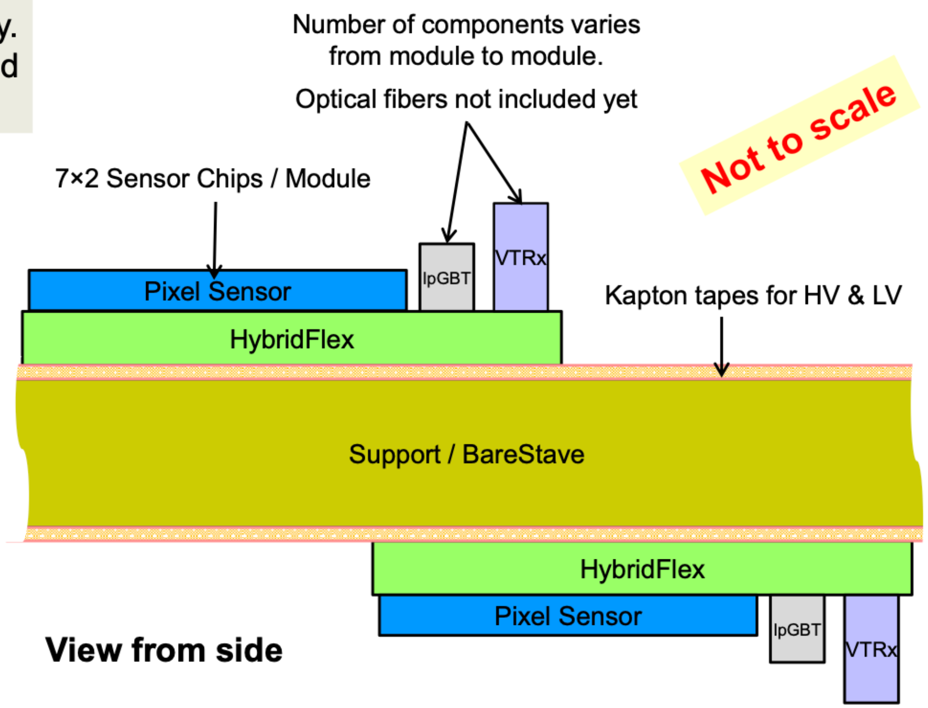
A lot of requirements to be consolidated

- **Pixel size**
- **Chip size, detector position, number of planes**
- **Chip thickness and global material budget**
  - Position (→ momentum) resolution, multiple scattering

https://indico.icc.ub.edu/event/163/contributions/1626/attachments/663/1321/LHCbU2_WS2023_UT.pdf

Sizes and materials are preliminary. More precise values will be used when available.

(Unit: mm)	Thickness	W×L
Pixel Sensor	0.200	20.2 × 21.4
IpGBT	1.250	9 × 9
VTRx+	4.000	10 × 20
HybridFlex	0.300	142 × 75
Kapton Tape	0.100	142 × full
BareStave	4.000	142 × full



A lot of requirements to be consolidated

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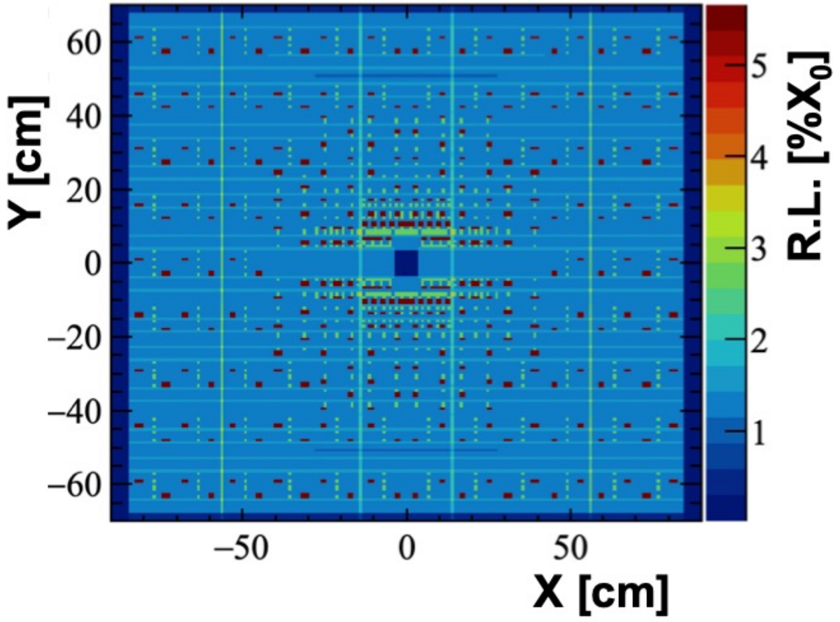
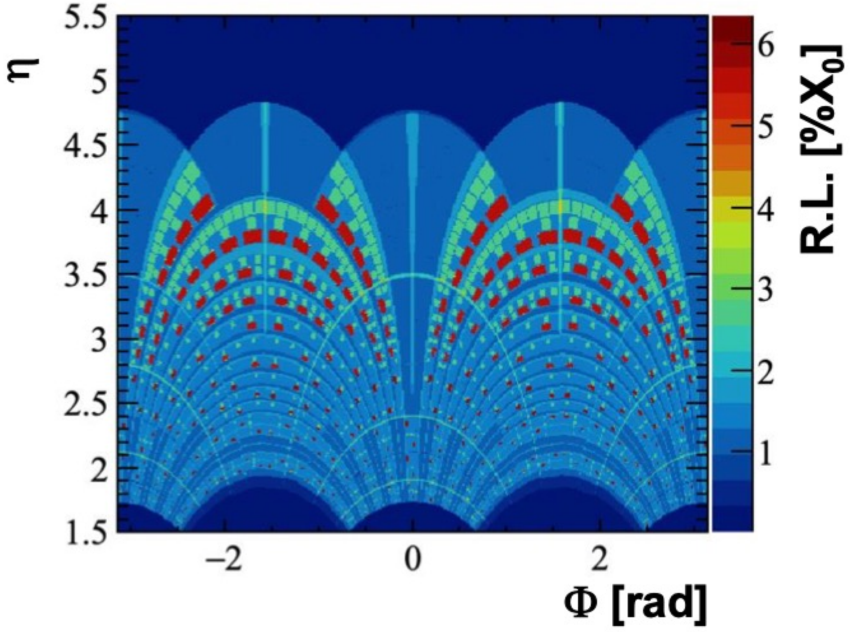
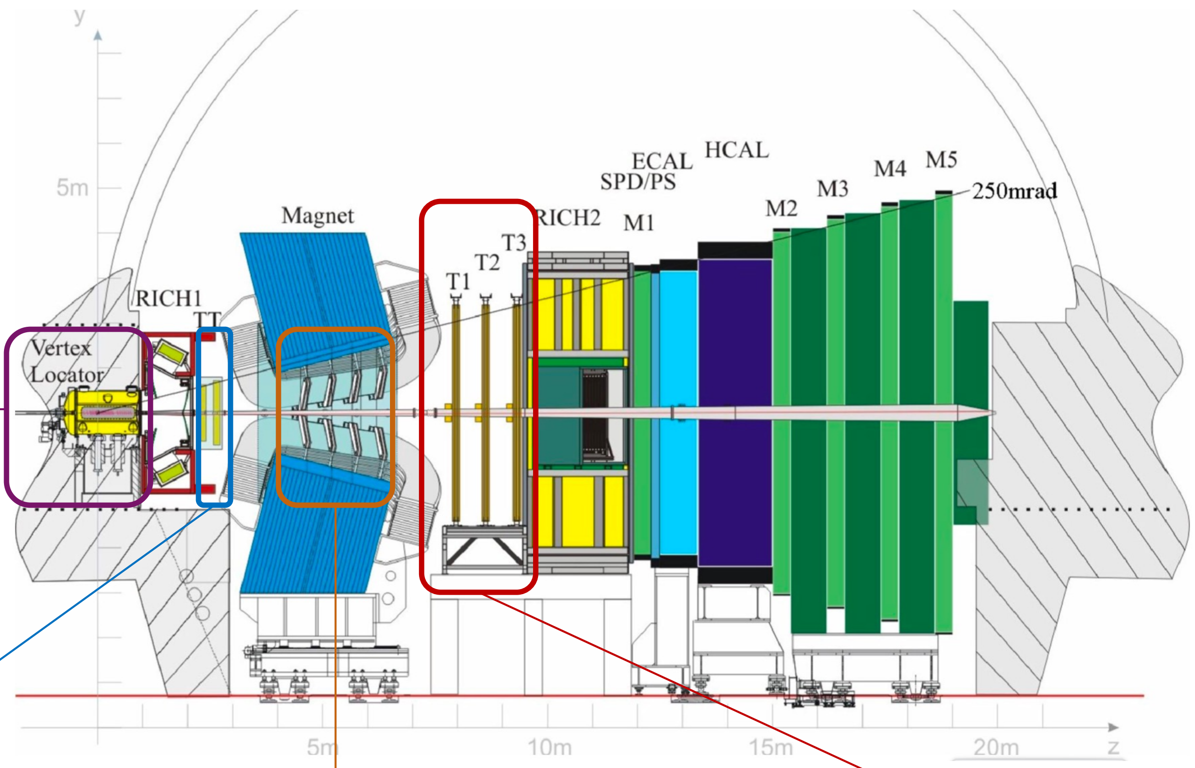




The Tracking System upgrade



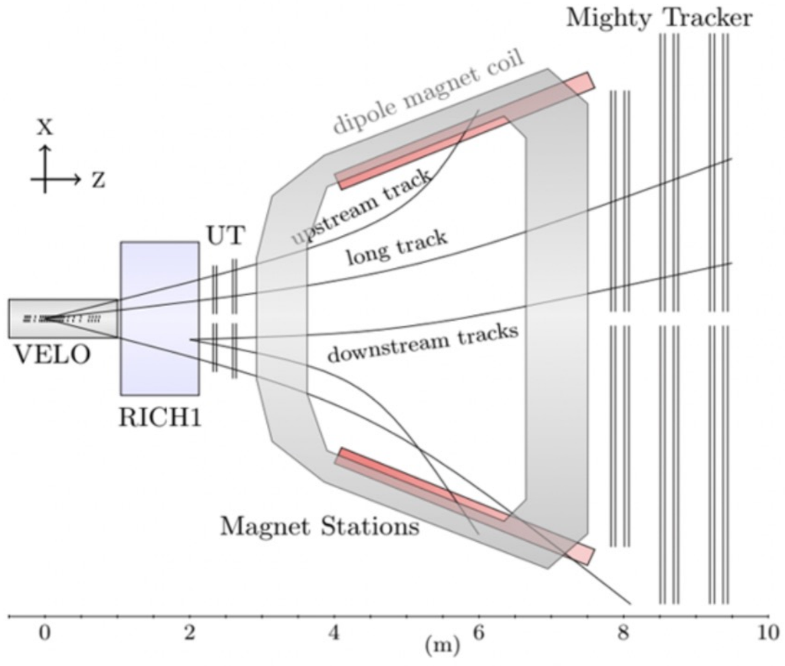
VELO
Pixel with timing

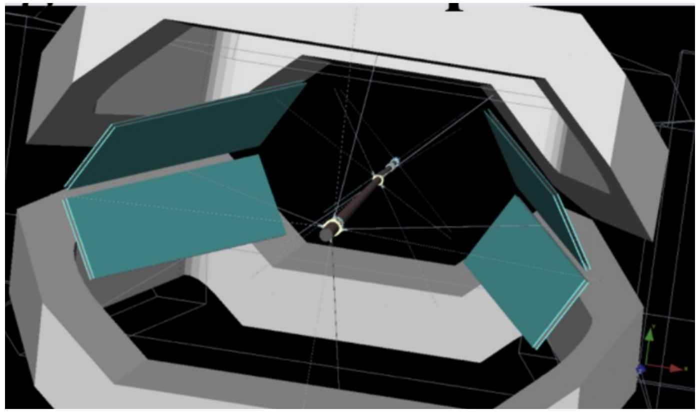
Upstream Tracker
From strip to CMOS

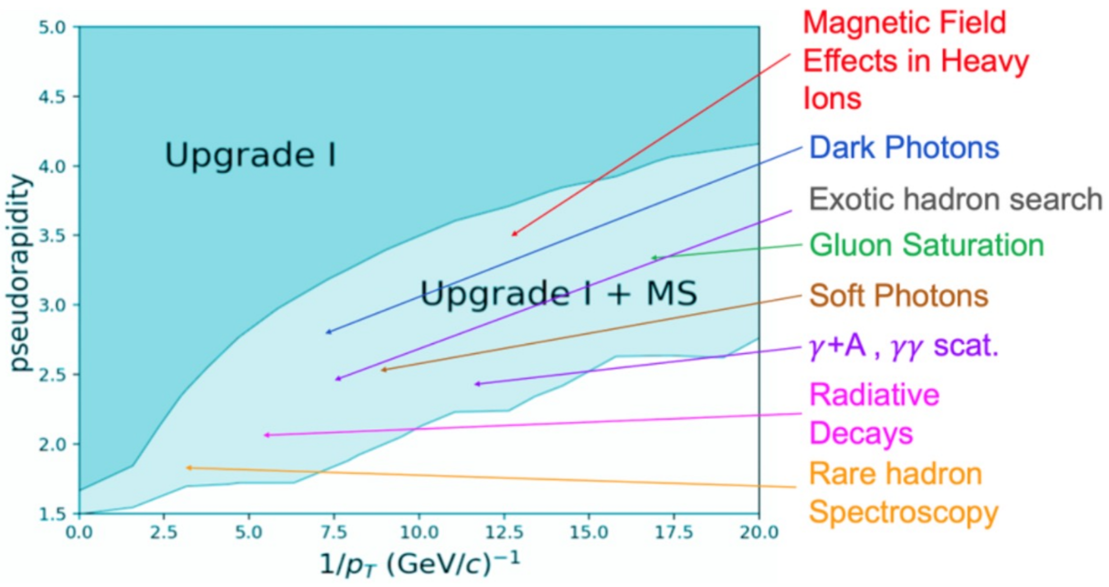
Magnet stations
Tracking on magnet sides

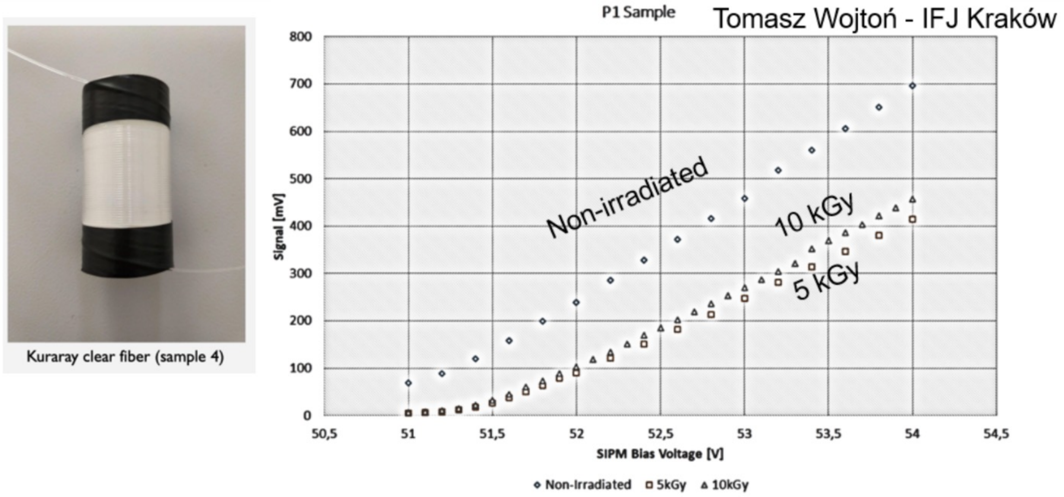
Mighty Tracker
Combine SciFi & CMOS

MAGNET STATIONS









- 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.

Cost and descoping

LHCC-2021-012

Approved March 2022

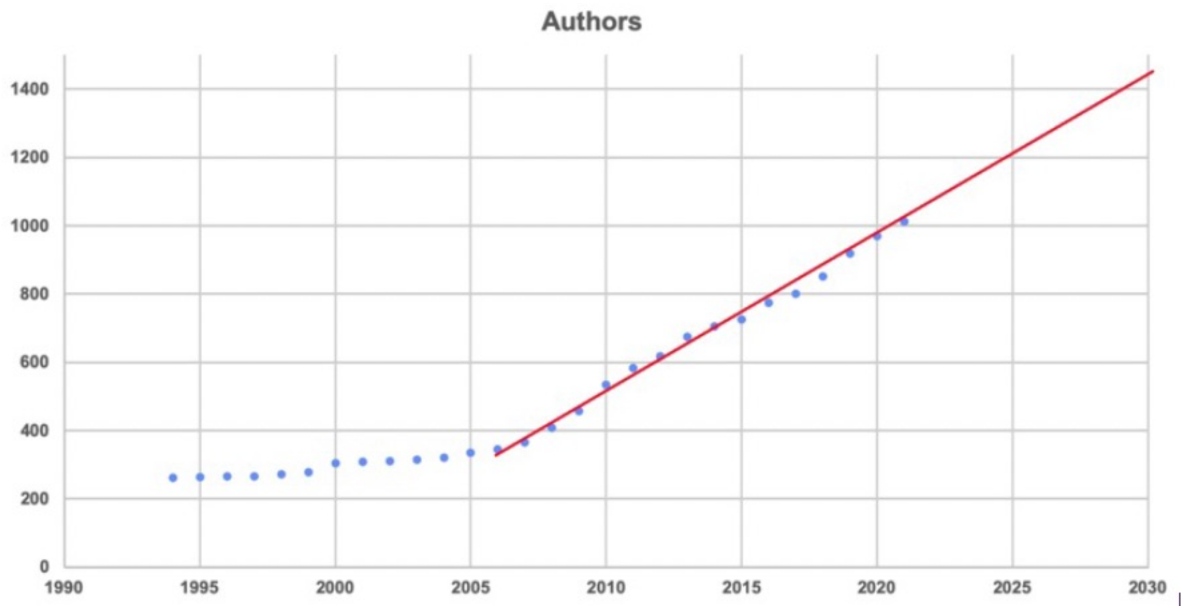
- *Detector design and technology options*
- *R&D program and schedule*
- *Cost for baseline, options for descoping*
- *National interests*

Detector	Baseline (kCHF)
VELO	14800
UT	8900
Magnet Stations	2300
MT-SciFi	22400
MT-CMOS	19500
RICH	15600
TORCH	9900
ECAL	34800
Muon	7100
RTA	17400
Online	8900
Infrastructure	13500
Total	175100

Detector	Countries involved
VELO	BR, CERN, ES, FR, IT, NL, PL, RU, SE, UK
UT	CN, FR
Magnet Stations	PL, US
Mighty Tracker (SciFi + MAPS)	BR, CH, DE, ES, SE, UK
RICH	CERN, IT, PL, RO, SI, UK
TORCH	CERN, UK, SI
ECAL	AU, CERN, CN, ES, FR, HU, IT, RU, US
Muon	IT, RU
RTA	BR, CERN, CN, DE, ES, FR, IT, NL, PL, RU, UK, US
Online	CERN, FR

COST AND DESCOPING

LOW	MEDIUM	FTDR
~120 MCHF	~150 MCHF	~175 MCHF
conservative	*optimistic, but not completely unrealistic*	*clearly above what can be achieved by present collaboration*
all FTDR descopes	*some FTDR descopes*	*full FTDR option*



Next step: SCOPING DOCUMENT

Estimated cost scenarios (baseline and descoped) with analysis of physics performances, person-power and funding profiles, project organisation and milestones, list of TDRs and project schedule

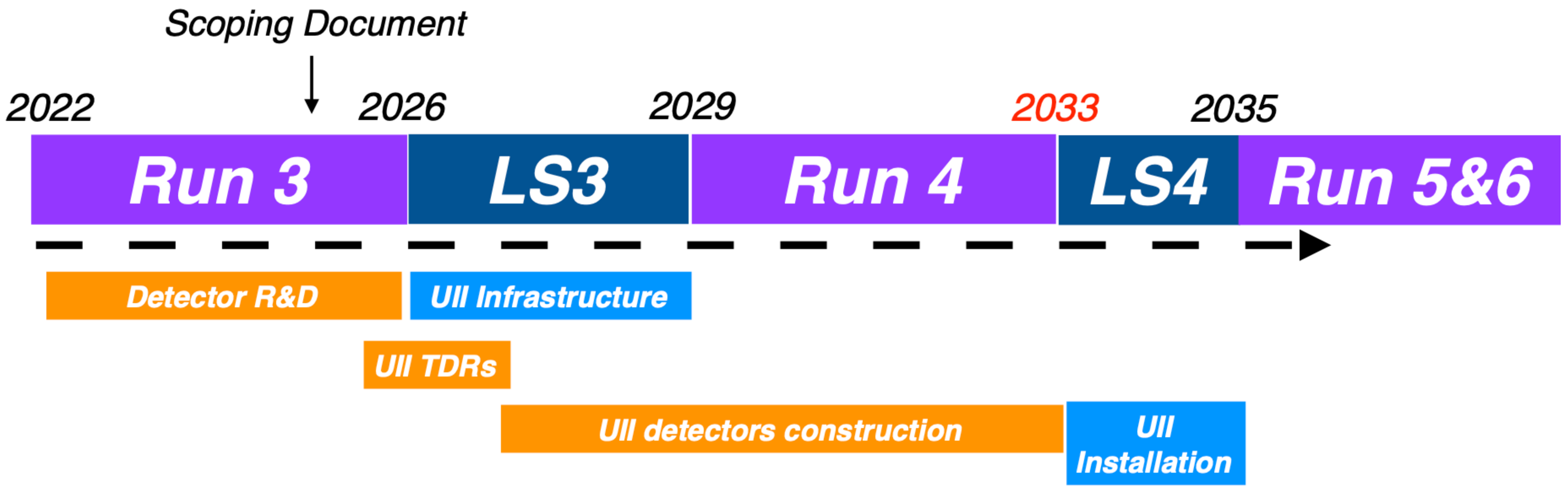
LHCC: "Some elements of this have been fulfilled by LHCb with FTDR"

Need to complement with more detailed plans on the descoping option, and with a matrix of participations (person-power and funds) discussed with the funding agencies

This is needed before proceeding with sub-detector TDRs

Target is to produce the Scoping Document within 2024

PLANNING



Constraints on Upgrade II plans

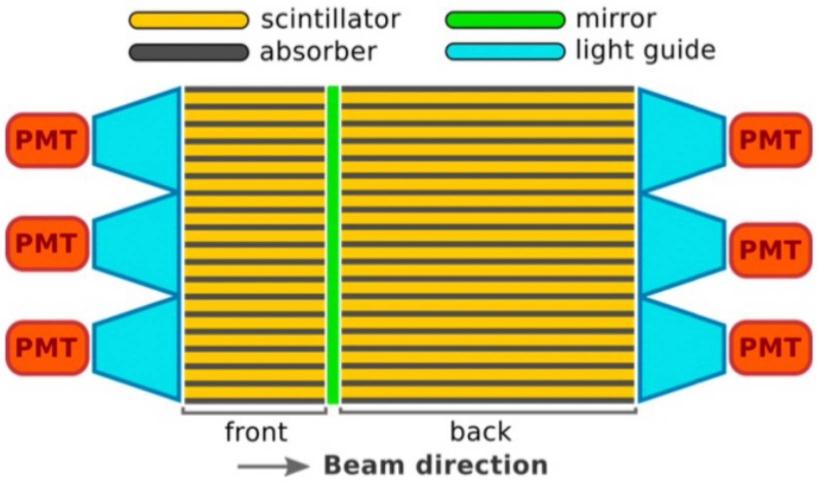
- All detector components fully ready at beginning of LS4, in 2033
- LS4 duration of 2 years will be fully needed for Upgrade II installation

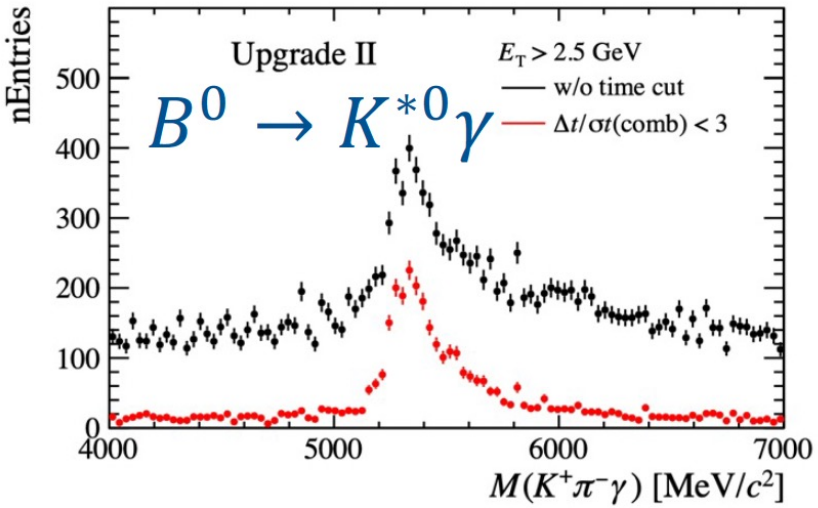
→ Start detector element construction during LS3

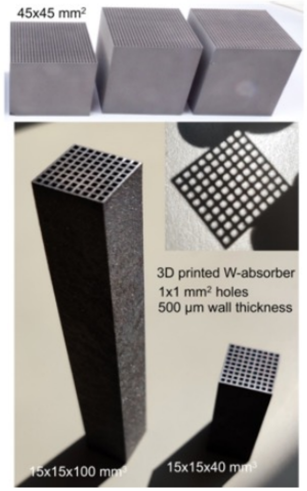
→ Anticipate some LHCb detector infrastructure work to LS3

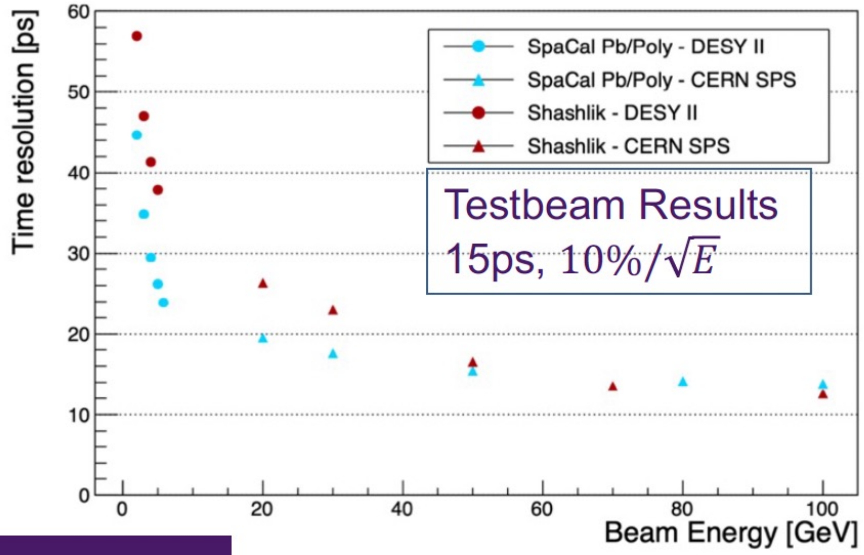
5D Calorimetry: Precision timing

- Goal: achieve energy resolution and reconstruction eff. ~ to Run1&2
  - pile-up, radiation up to 1MGy
- Requires: granularity, precision timing
- Different technologies in different regions
- Crystal fibres R&D for highest fluence regions
- Extensive R&D



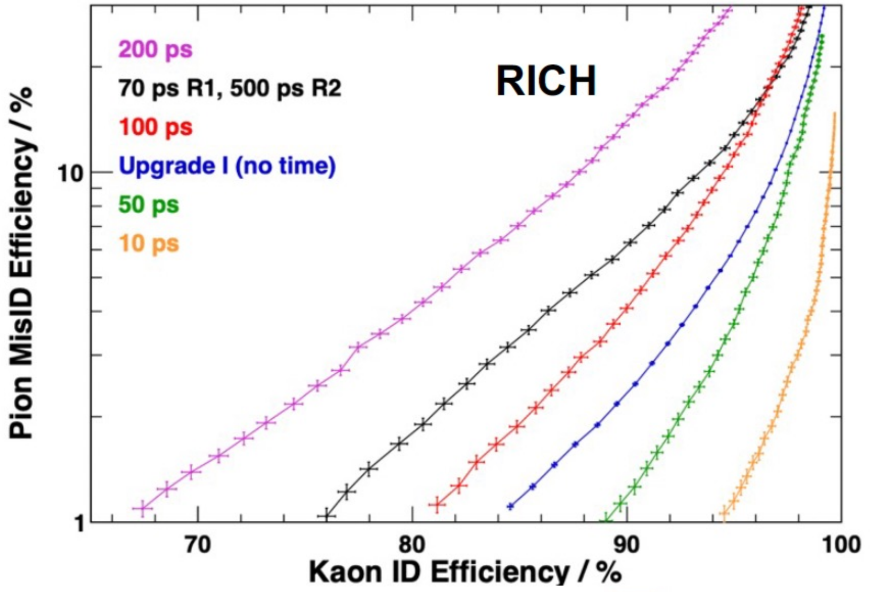


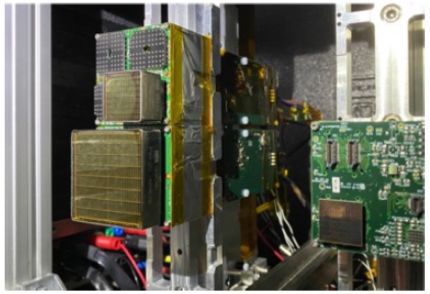


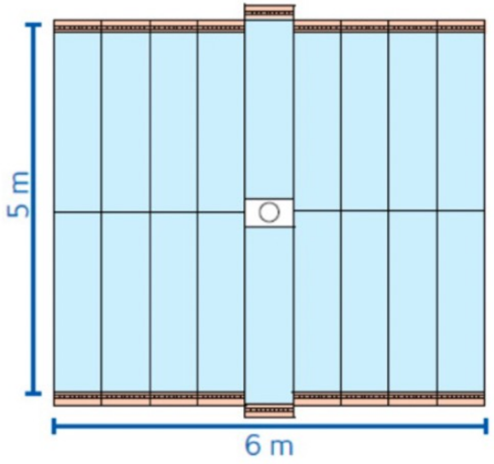


Particle ID: π/K/p – RICH & TORCH with Timing

- Hadron particle identification key to LHCb unique physics capabilities
- RICH 1 & 2 geometry maintained
- Time of flight TORCH system
  - Cover wide momentum range
- In both systems precision timing is crucial for Upgrade II performance
- RICH: Time-stamping each photon with a resolution of few tens of ps
- TORCH: 10-15 ps time resolution per track
- Synergy on electronics readout

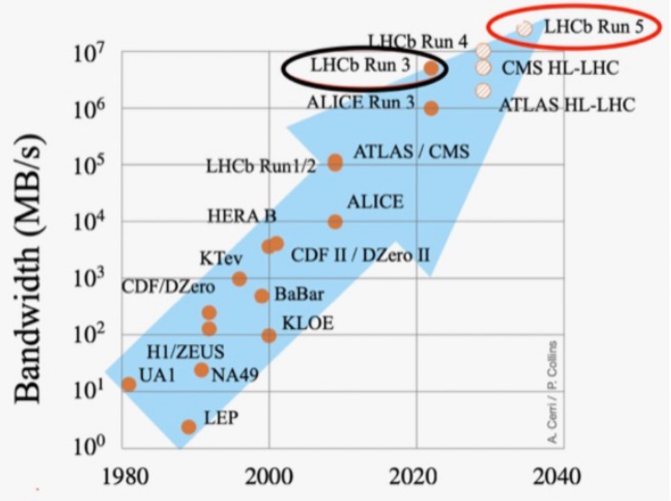




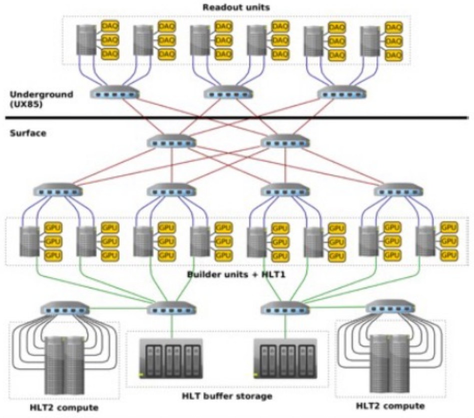


Online & Offline

LHCb Upgrade II data throughput: 200 Tb/s

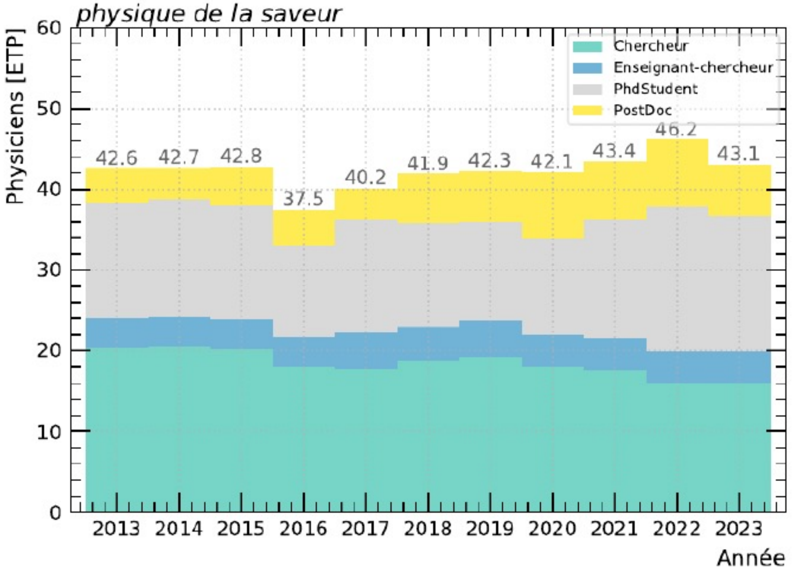


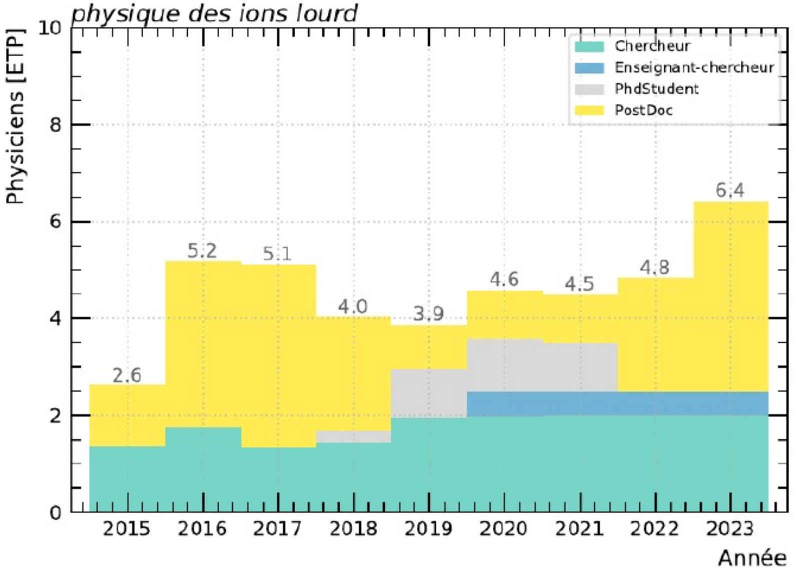
Event-builder architecture



- Novel trigger system for Upgrade I
  - Fully software trigger
  - HLT1 based on GPUs
- Similar concept planned for Upgrade II
- But at 200Tb/s!
  - Further exploitation of hybrid architectures: CPU, GPU, FPGA…
- Offline computing requirements are significant
  - Upgrade I model not sustainable
  - LHCb Upgrade II in Run 5 issues similar to ATLAS & CMS Phase II of Run 4
  - Coordination with WLCG and the HEP Software Foundation on mitigation

- The population of physicists is relatively stable over 10 years:





- The LHCb Upgrade II project attracts newcomers from the ALICE collaboration:
  - SUBATECH, 4 physicists with expertise in the ALICE / MFT detector
  - LPC, 3 physicists have expressed their interest in joining LHCb by LS3
  - IRFU, 3 physicists with expertise in the ALICE / MFT detector. Interested by the R&D of LV CMOS sensors for UT Upgrade II