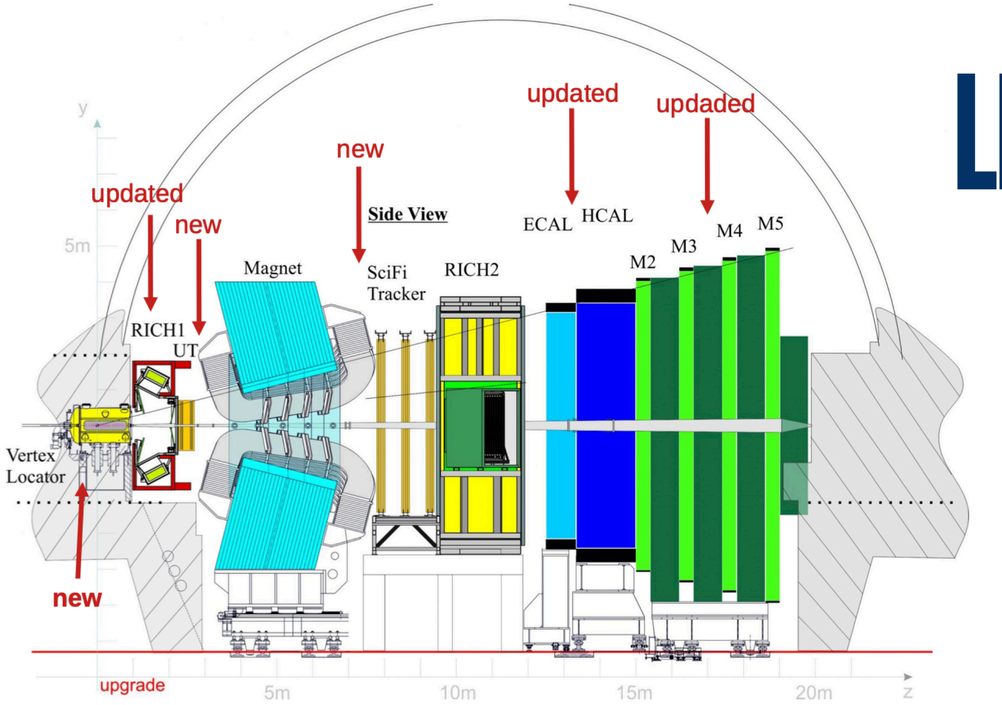
# LHCB VELO

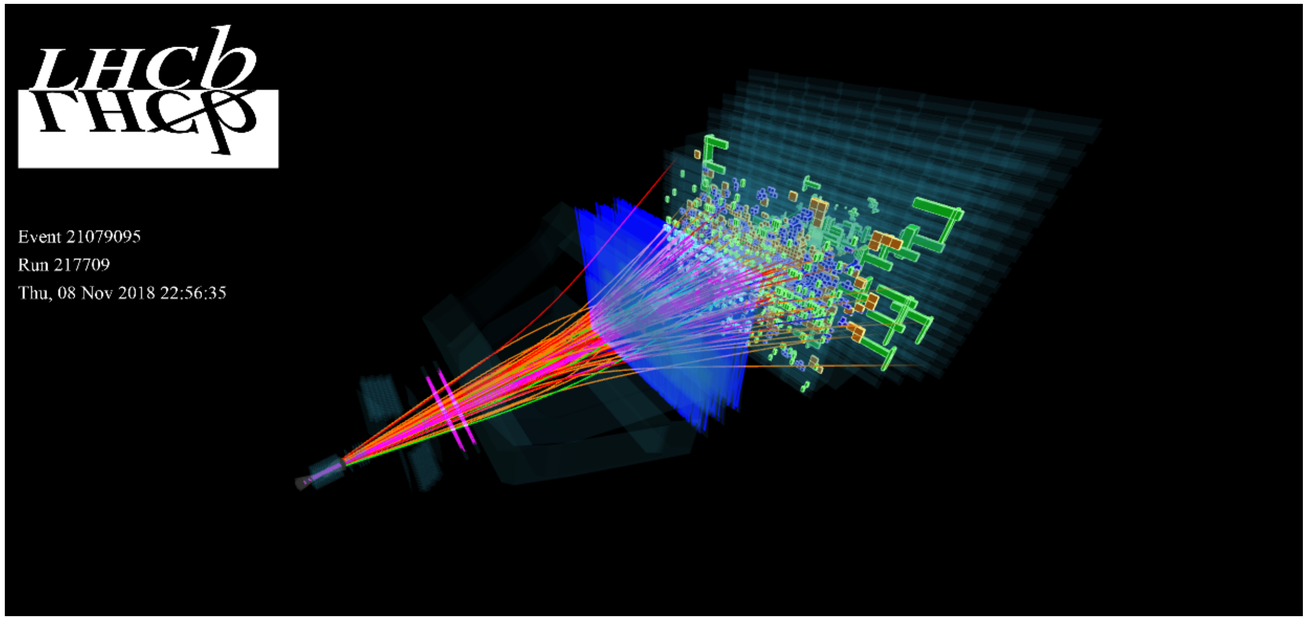
## Present experiences and future upgrades




CEPC WORKSHOP - 23/10/2026 - VINICIUS FRANCO LIMA (UFRJ)

# LHCB AND VELO




LHCb is a single-arm forward spectrometer focused in measuring CP-violation and rare decays using b and c hadrons

Detectors aim at delivering excellent momentum resolution and particle identification capabilities

High precision track and vertex reconstruction is fundamental to reach physics goals

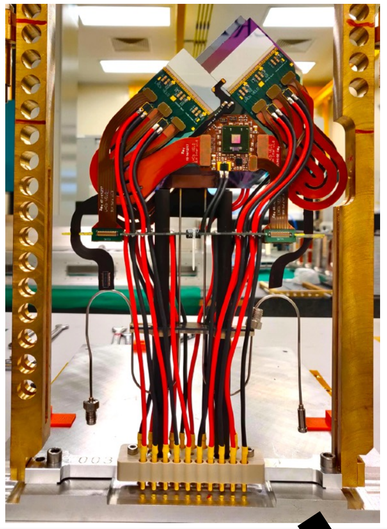

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# VELO

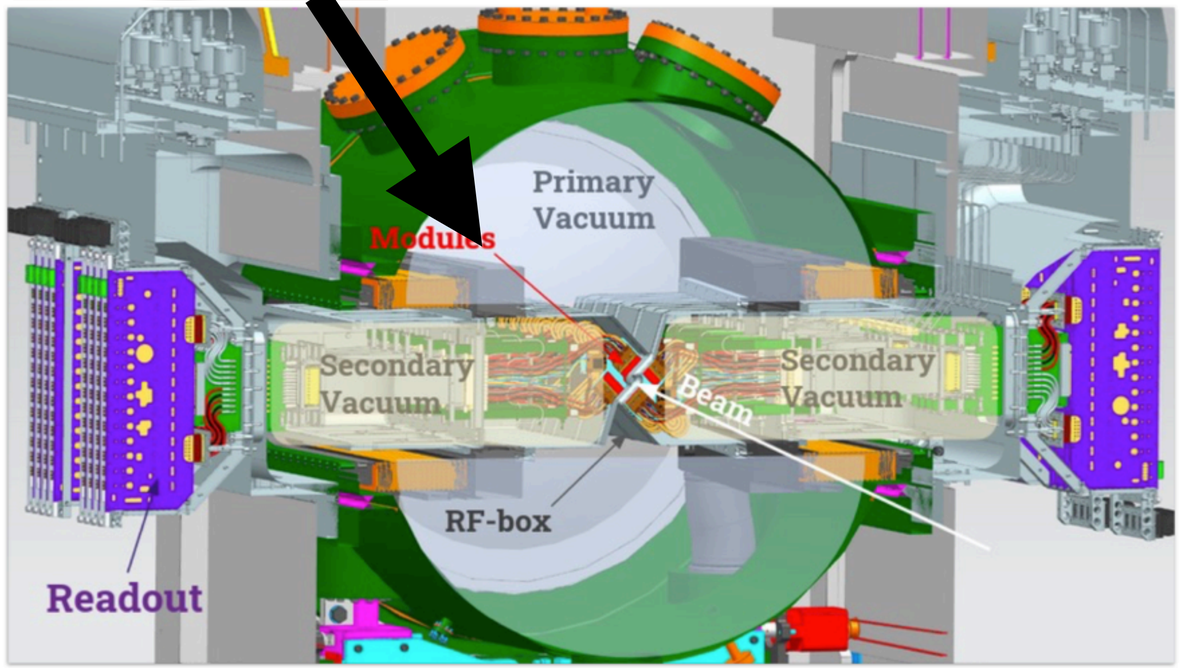
The Vertex Locator (VELO) is responsible for vertexing and track reconstruction around the interaction region in LHCb

52 Modules mounted on 2 movable halves that close around the beam to a nominal distance of 5.1mm

Designed to maintain high efficiency even after collecting 50fb$^{-1}$



X 52





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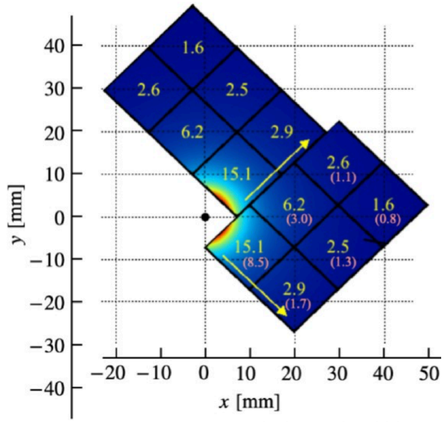
# VELO UPGRADE I

Readout with VeloPix ASIC; 65k 55x55 um pixels, triggerless readout.

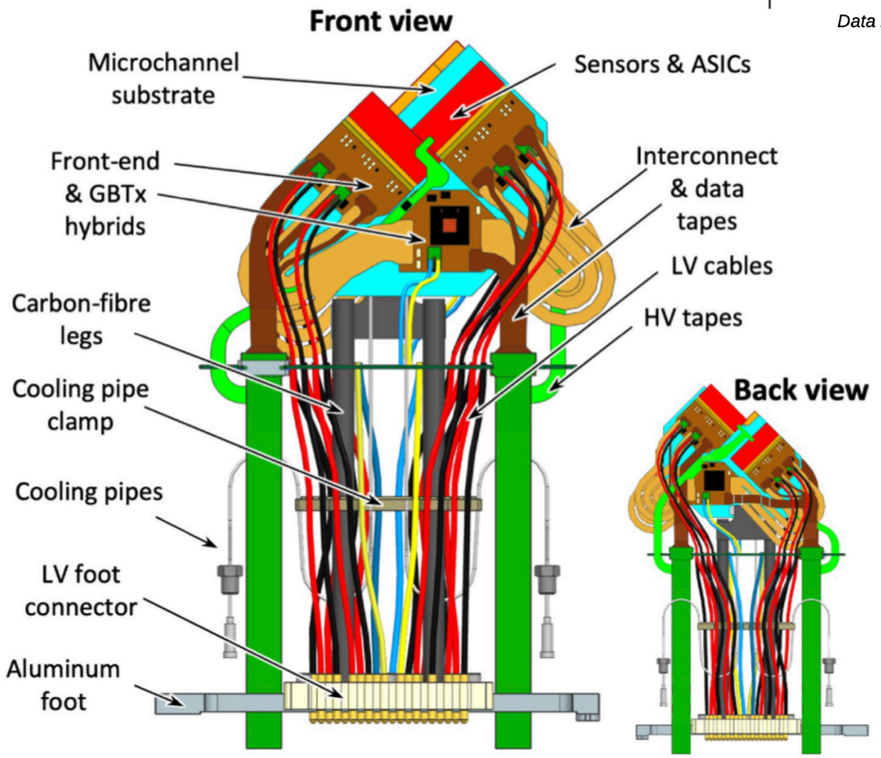
Up to 15.1 Gbit/s in the hottest ASIC

Microchannel substrates to deliver evaporative CO2 cooling.

Expected fluence of $8 \times 10^{15}$ 1 MeV $n_{eq}$ / $cm^2$, after 50 $fb^{-1}$



*Data rate per pixel ASIC in Gbit/s*





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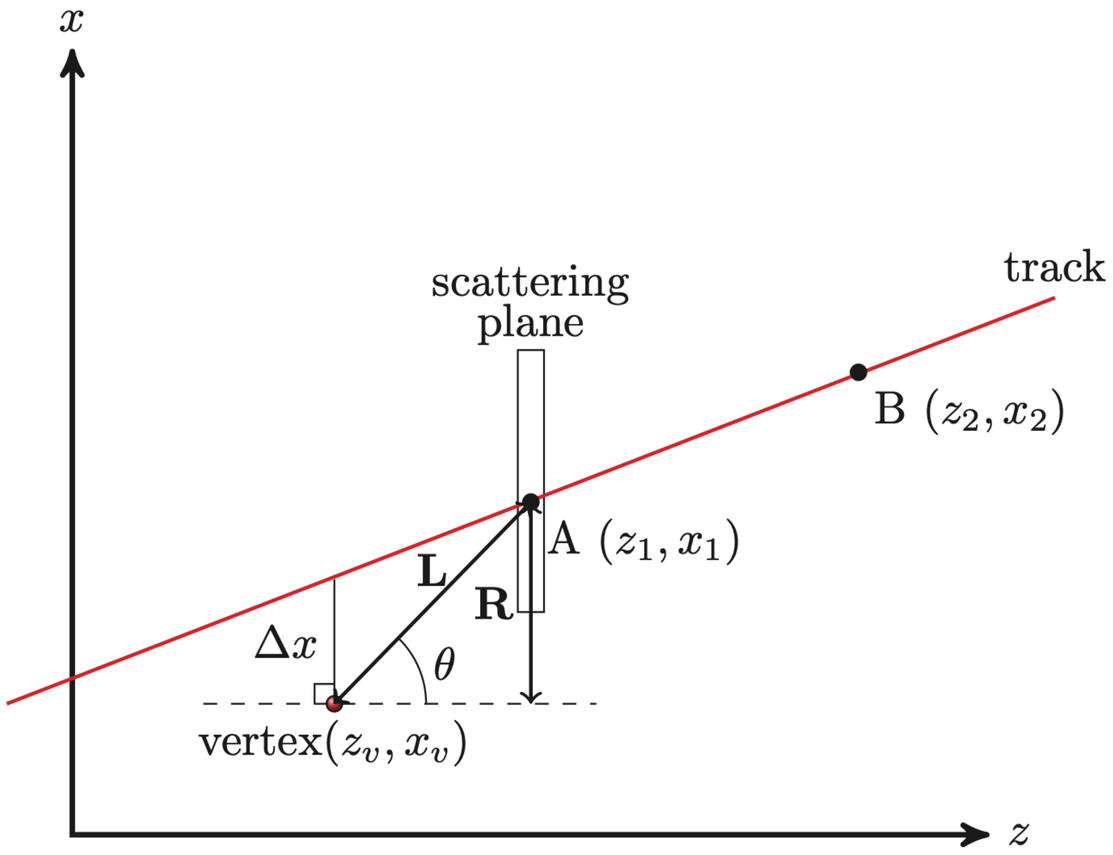
# INTERMEZZO: IP RESOLUTION

**Impact Parameter (IP) is a very important discriminant variable in the LHCb physics program**

$$\sigma^2_{\Delta x} = \underbrace{\frac{\sigma_0^2}{(z_2 - z_1)^2}\left[(z_2 - z_v)^2 + (z_1 - z_v)^2\right]}_{\text{resolution term}} + \underbrace{\theta_0^2 (z_1 - z_v)^2}_{\text{MCS term}}$$

$$\theta_0 = \frac{13.6\ \text{MeV}}{p\,\beta\,c}\, q\,\sqrt{\text{x}/X_0}\,\left[1 + 0.038\,\ln(\text{x}/X_0)\right]$$

$$\sigma^2_{\Delta x} = \frac{\sigma_0^2}{(z_2 - z_1)^2}\left[(z_1 - z_v)^2 + (z_2 - z_v)^2\right] + \frac{R^2}{p_T^2}\left(\frac{13.6\ \text{MeV}}{\beta\,c}\, q\,\sqrt{\text{x}/X_0}\,\left[1 + 0.038\,\ln(\text{x}/X_0)\right]\right)^2$$




Tsopelas, P.



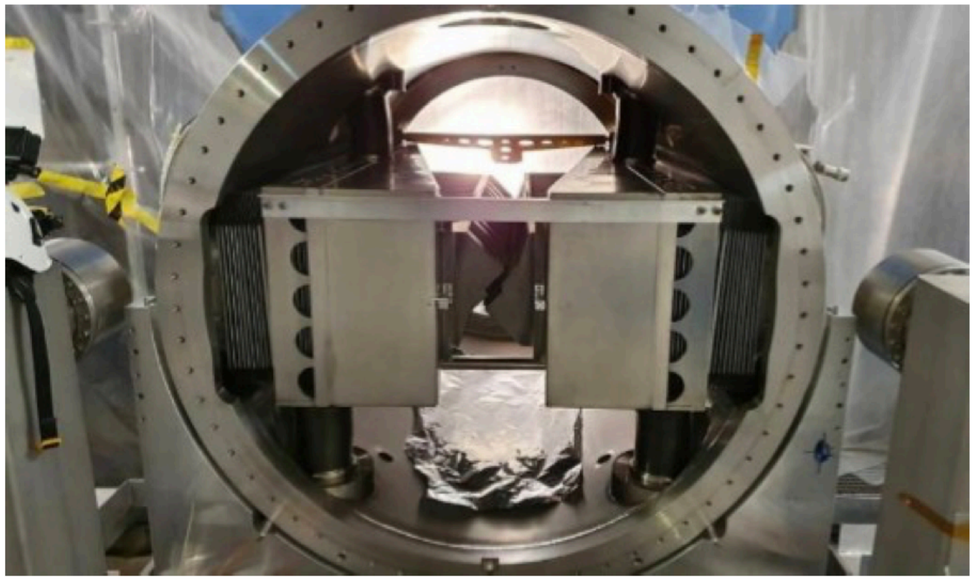
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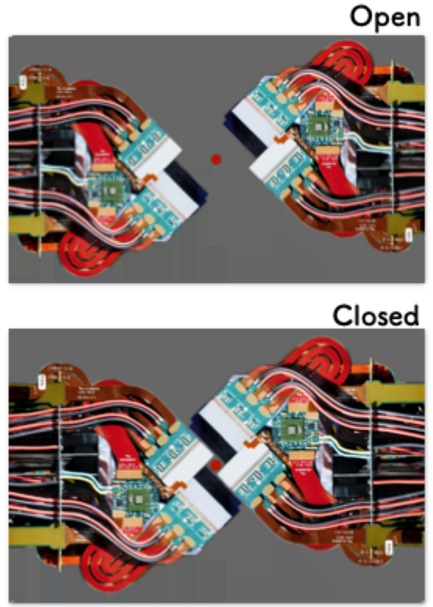
# VELO MOTION SYSTEM

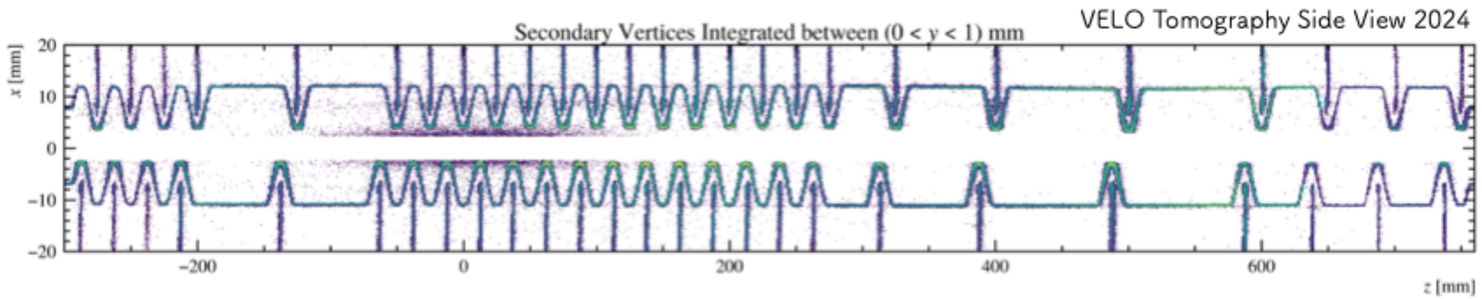
During injection VELO halves need to be moved out by ~5cm to ensure detector safety

Drift in one of the halves observed, access to motion system was extremely restrictited, overclosure procedure developed to correct for it.

0.5mm shims used whilst “tomography” was done to ensure detector position was within margins, removed for 2025!





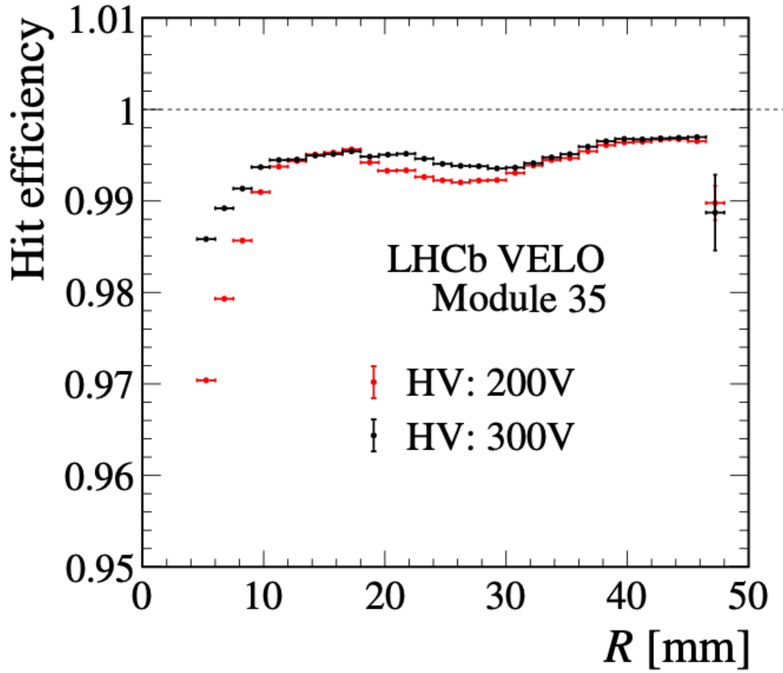


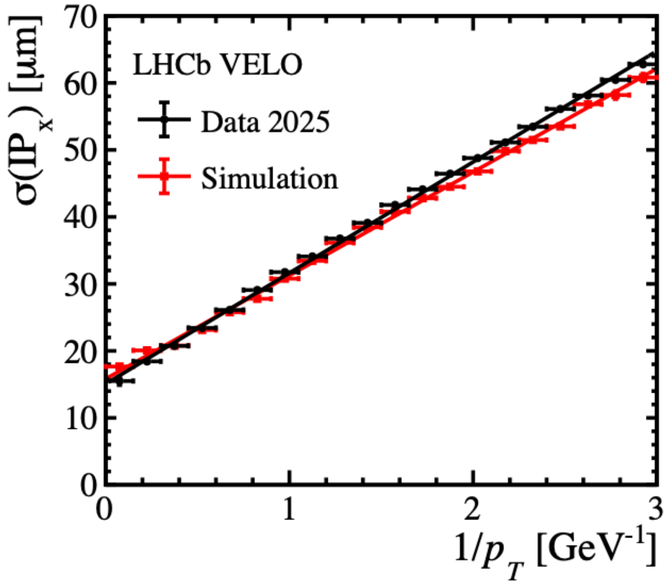
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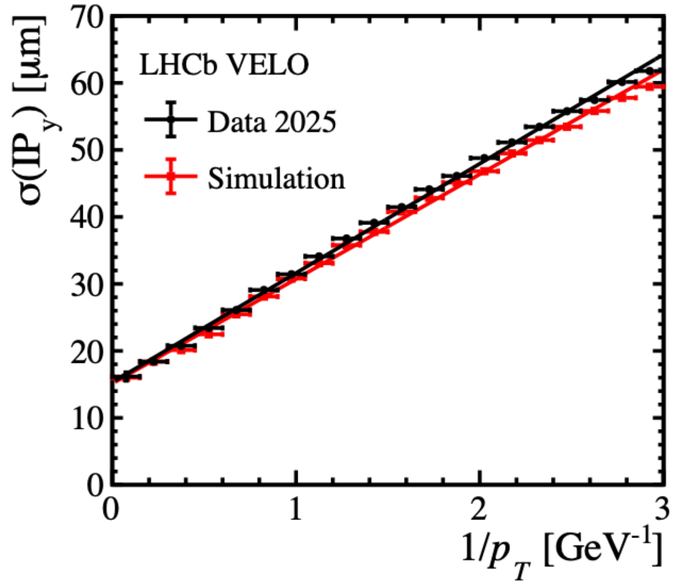
# VELO PERFORMANCE

**Intense radiation damage environment, we need hit efficiency > 99%**

**Impact parameter resolution as expected after the removal of shims!**



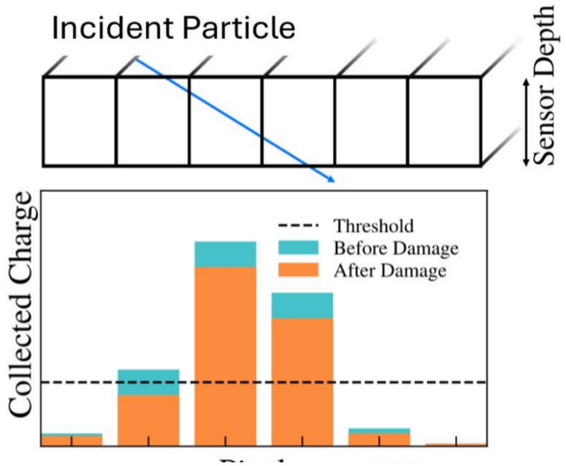





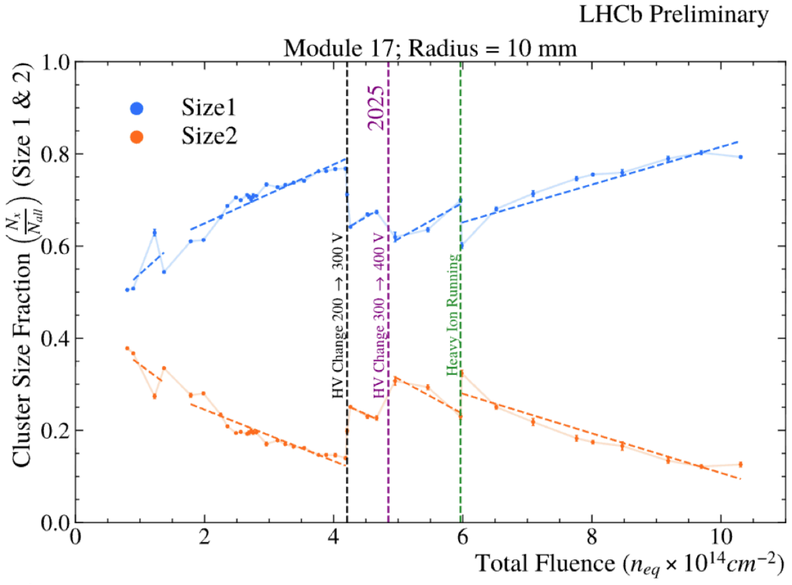
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# RADIATION DAMAGE

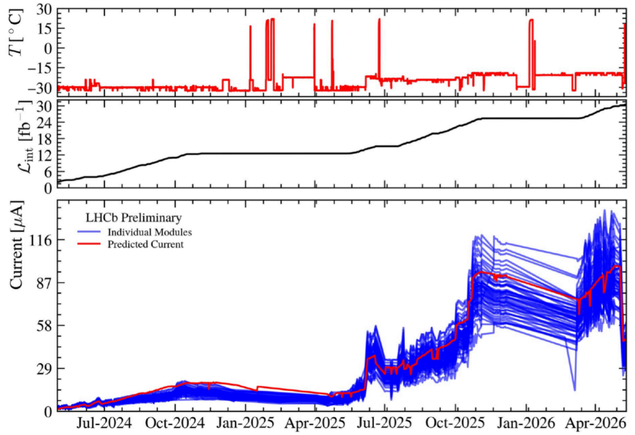


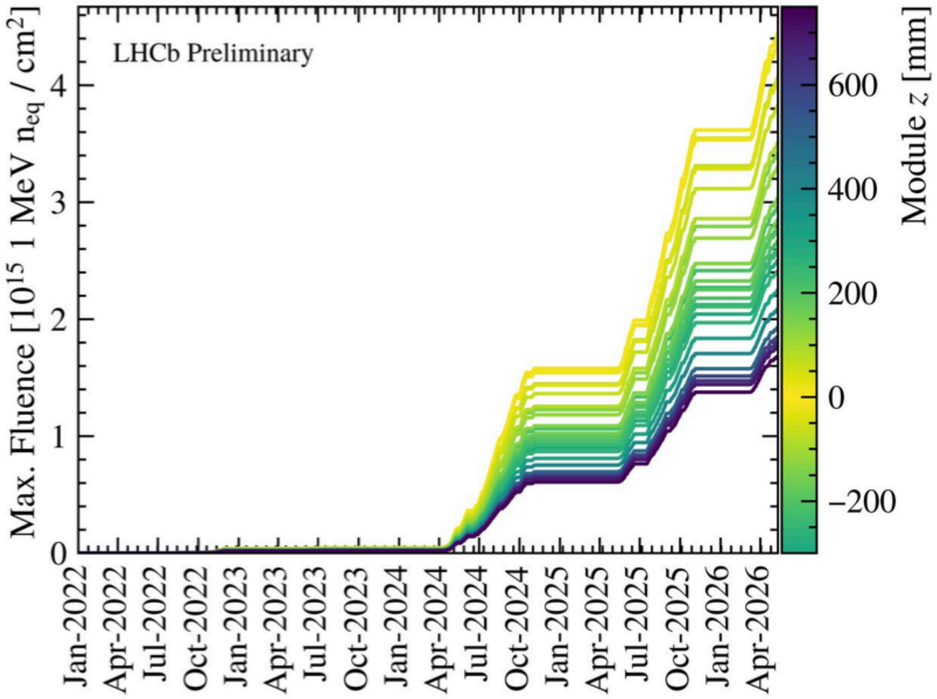

Fracion of larger clusters (>=2) decreases with fluence

HV increase recuperates performance




Fluence is tracked through leakage current measurements, taking into account annealing






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# HIGHLY IONISING BACKGROUNDS

During the2025 ion running a few ASICs got damaged;

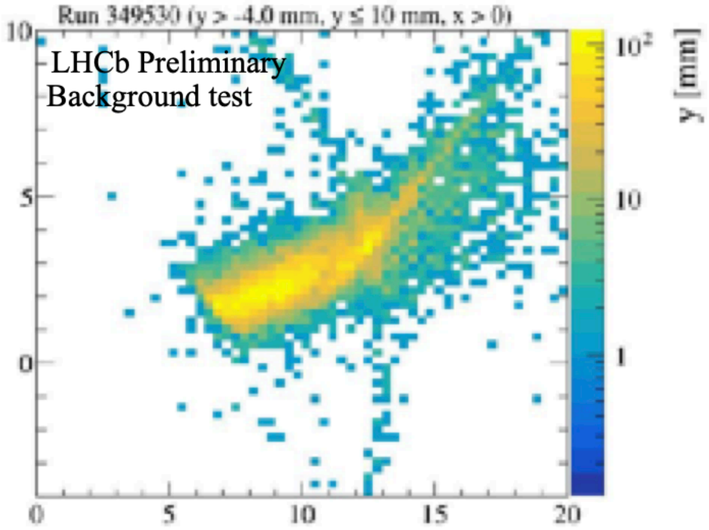
We observed correlation with both HV increases as well as highly ionising objects

Extensive studies identified two sources; beam-gas interactions and beam-beam backgrounds

Stand alone ion background test was performed in July with VELO modules and a vertical slice of the detector readout chain

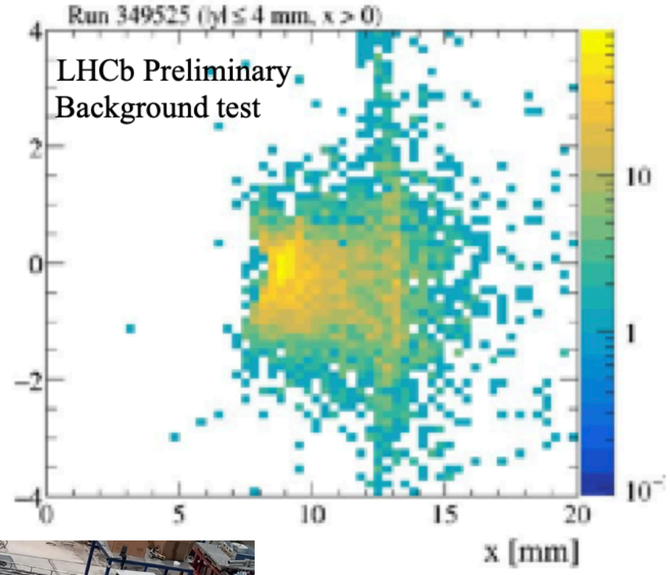
Vertical

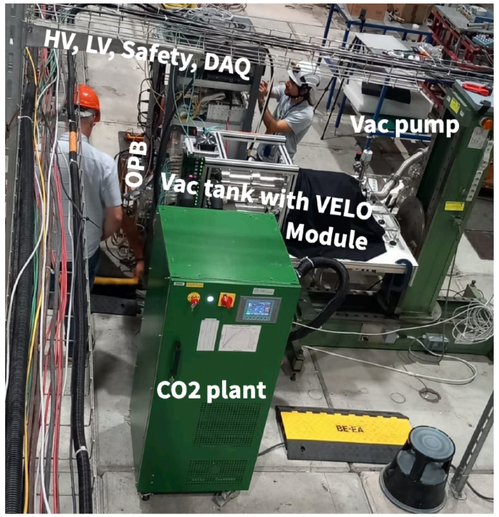
"Cow-lick" like background




Horizontal

"Remora" like background






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DO RIO DE JANEIRO

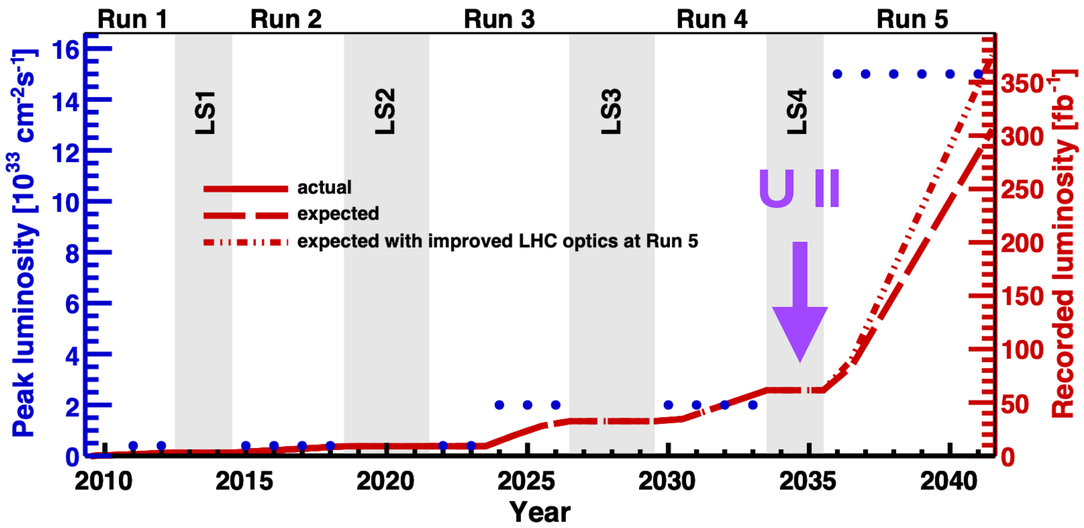
# UPGRADE II



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# LHCB UPGRADE II

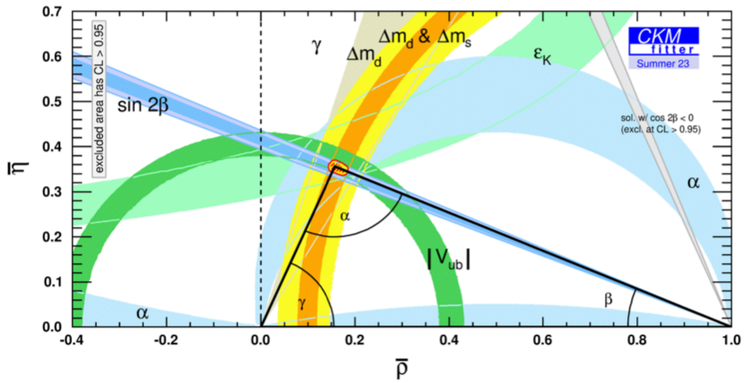
**We will build a second upgrade in LS4 to achieve ultimate precision on LHCb physics program.**



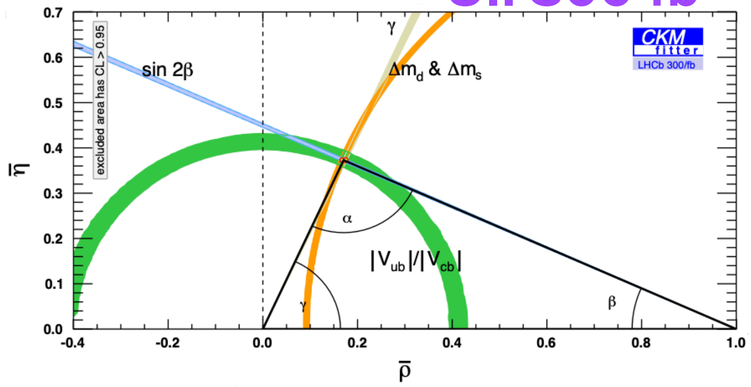

**Luminosity increase to $1 \times 10^{34} \mathrm{cm}^{-2} s^{-1}$, translating to approximately a μ of ~30**

**Maintain or improve physics reconstruction performance**

CKM 2023




UII 300 fb$^{-1}$

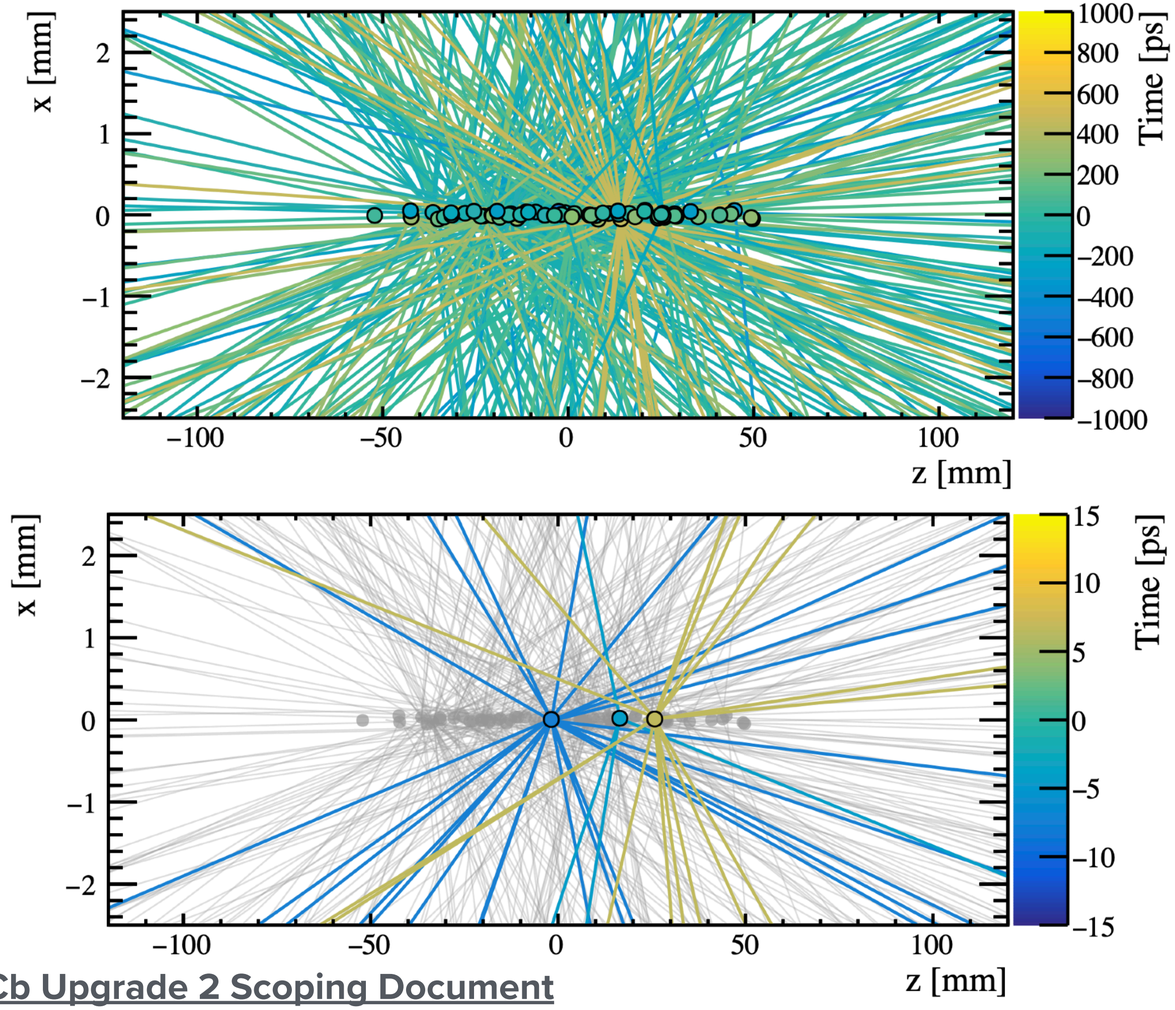



LHCb Upgrade 2 FTDR
LHCb Upgrade 2 Scoping Document


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# VERTEXING IN UPGRADE 2

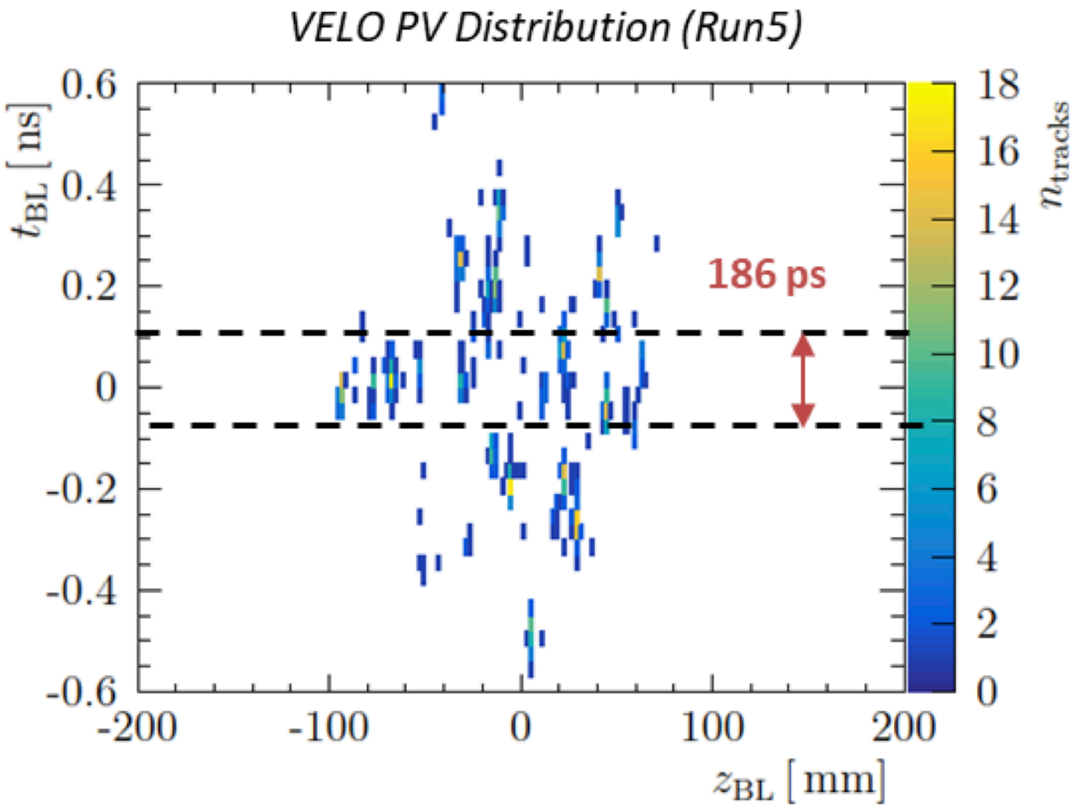
MC event $\mathscr{L} = 1.5 \times 10^{34} cm^{-2} s^{-1}$




LHCb Upgrade 2 Scoping Document

**It becomes unattainable to deliver correct PV - displaced vertex association at this luminosity**

**Luckily, z PV position and PV time are uncorrelated**

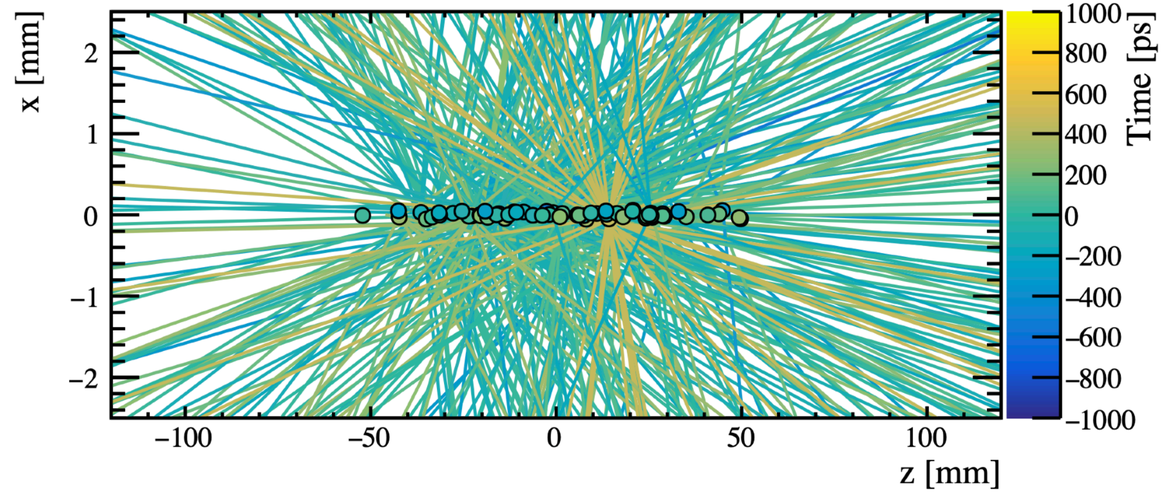


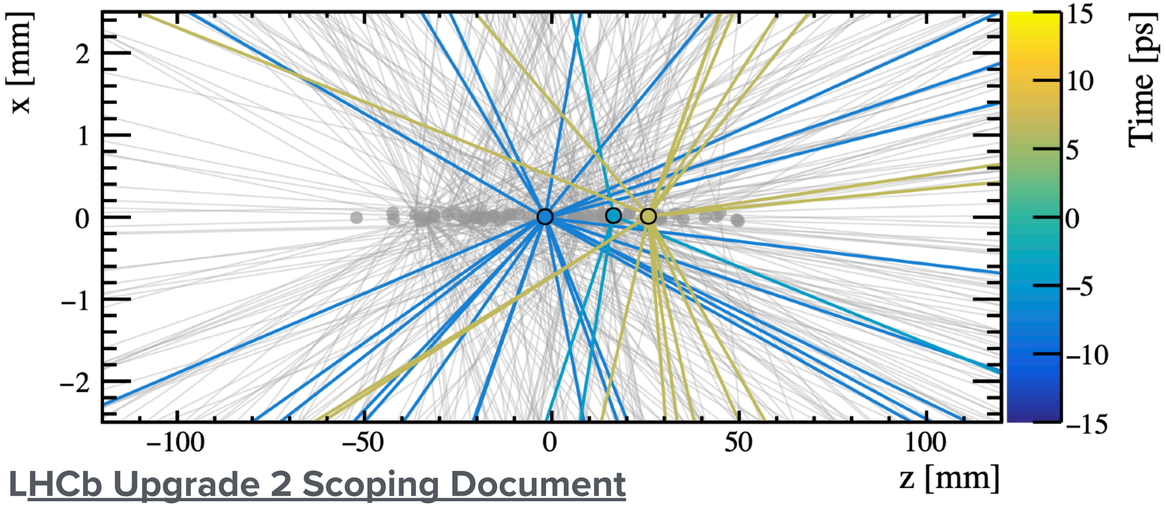



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# VERTEXING IN UPGRADE 2

MC event $\mathscr{L} = 1.5 \times 10^{34} cm^{-2} s^{-1}$



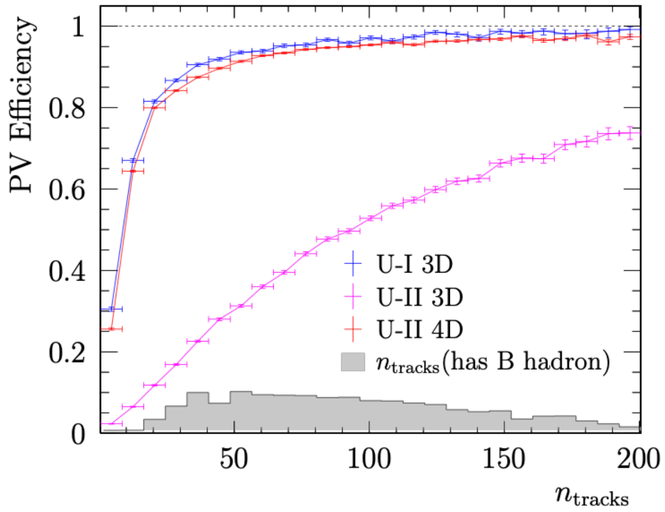



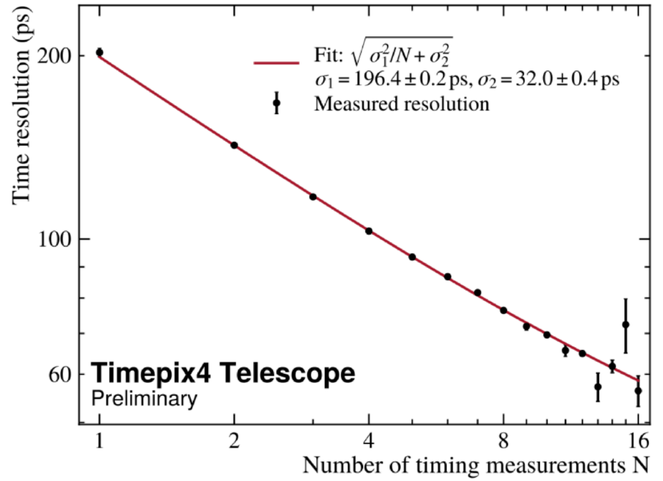

LHCb Upgrade 2 Scoping Document

**With a 30ps PV window, vertex association in UII is comparable to UI conditions.**

**We can improve it by constructing a $\sigma_t^{PV}$ from track times with $\sigma_t^{\text{track}}$ = 20 ps**

**In order to achieve this in the VELO acceptance and material budget we need time information in every hit. Timing layer is not enough!**






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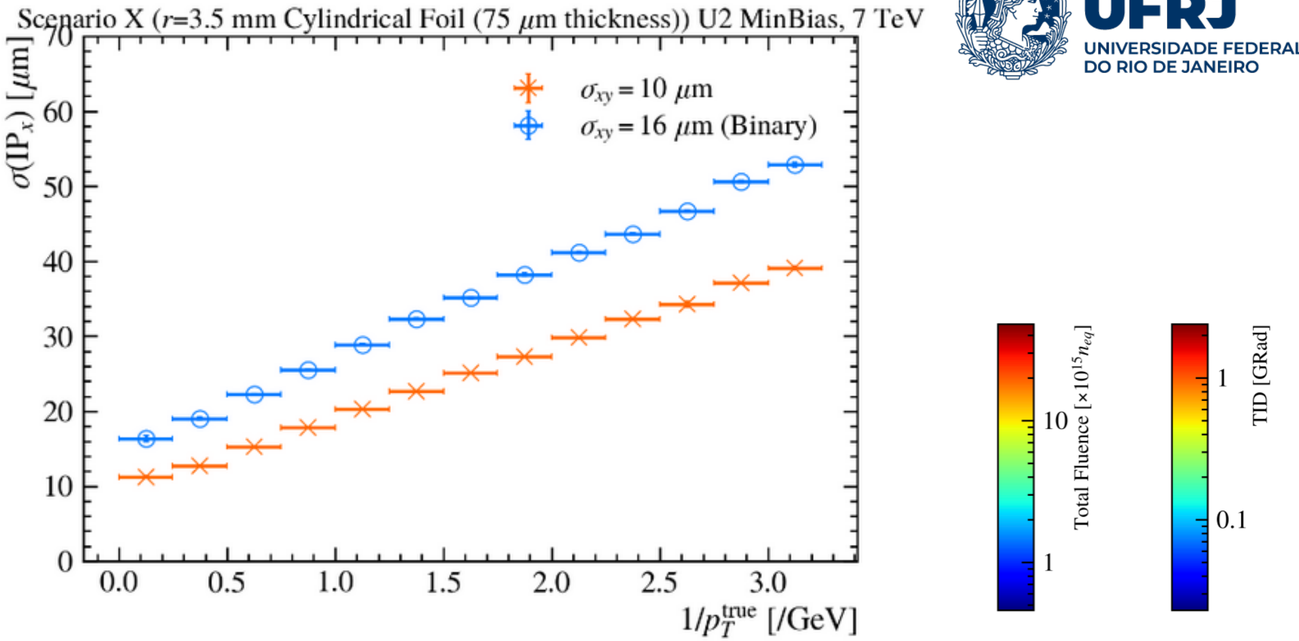
# THE VELO U2 DESIGN

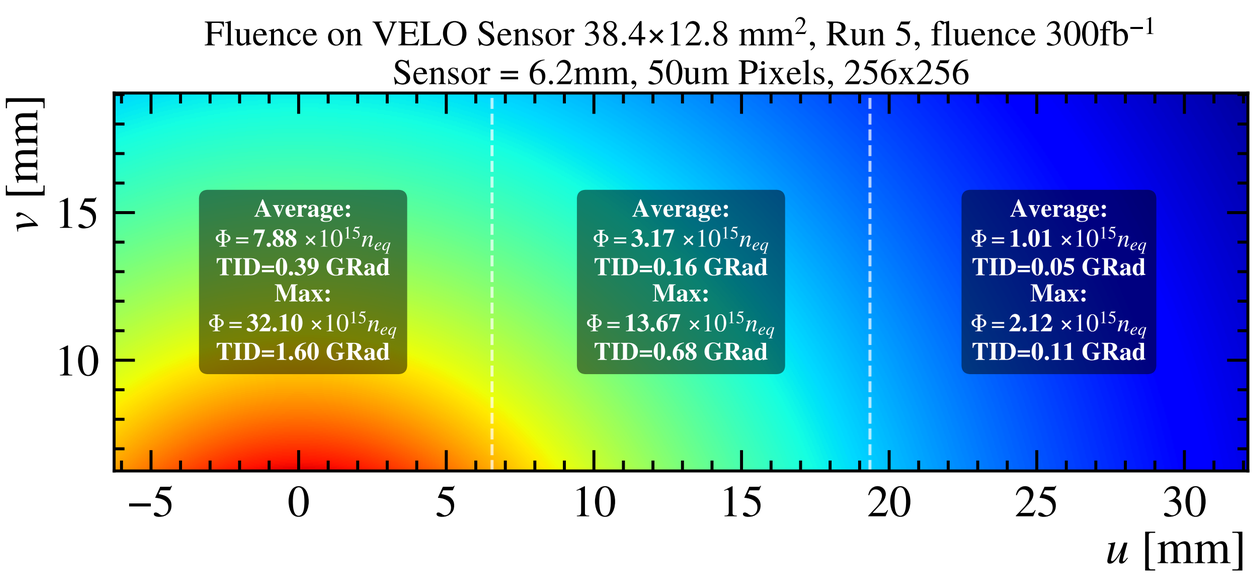
The detector should deliver similar or better spatial resolution (IP, PV) in comparison to Upgrade 1.

U2 environment requires modules to be further from the beam lines w.r.t. U1, which degrades IP resolution.

Compensation is done by achieving better hit resolution, lighter RF Box and less material in the acceptance.

Timing is mandatory



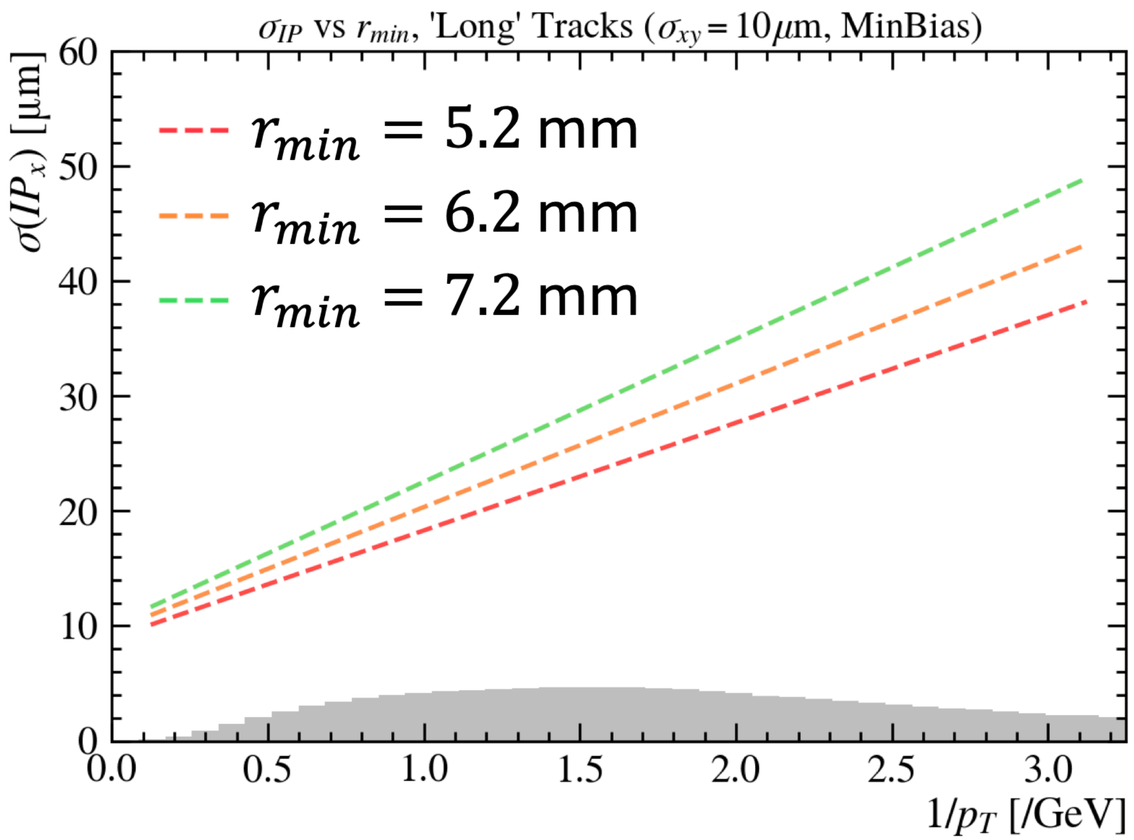



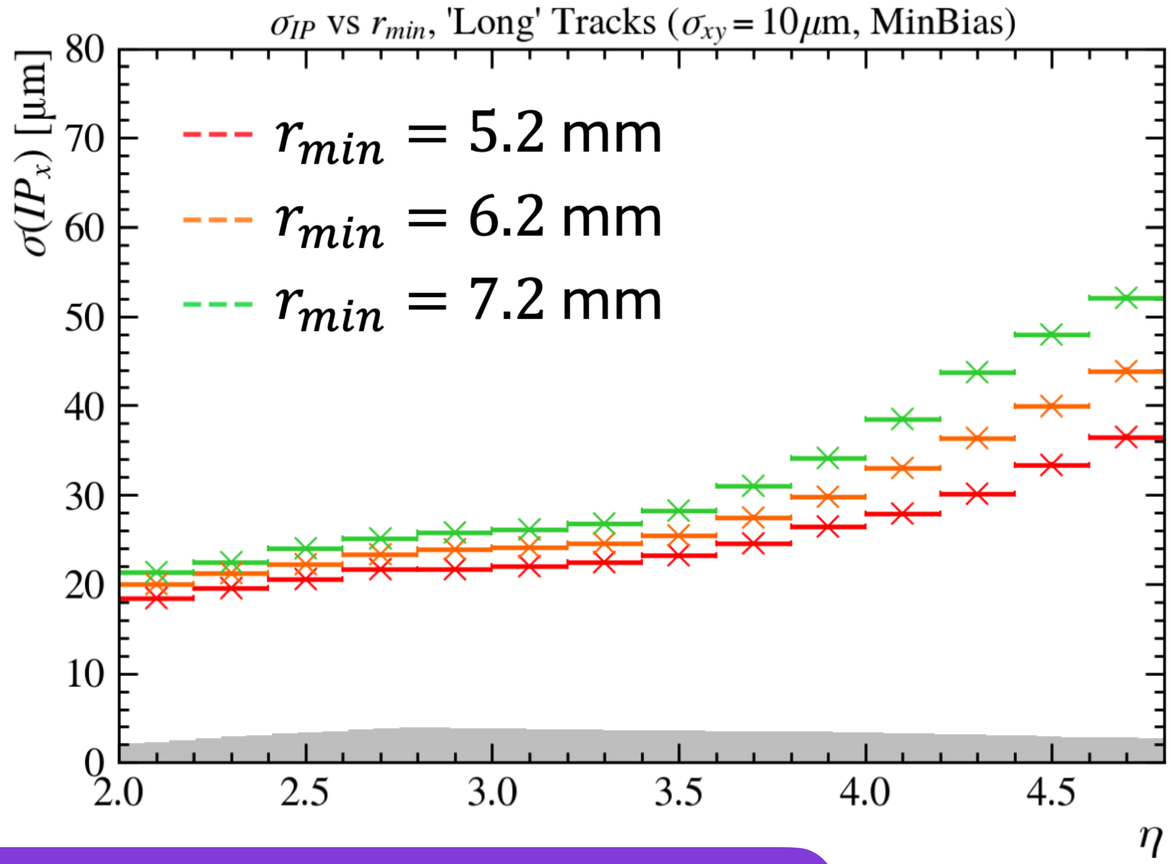



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# SIMULATION

## Impact of Rmin on resolution

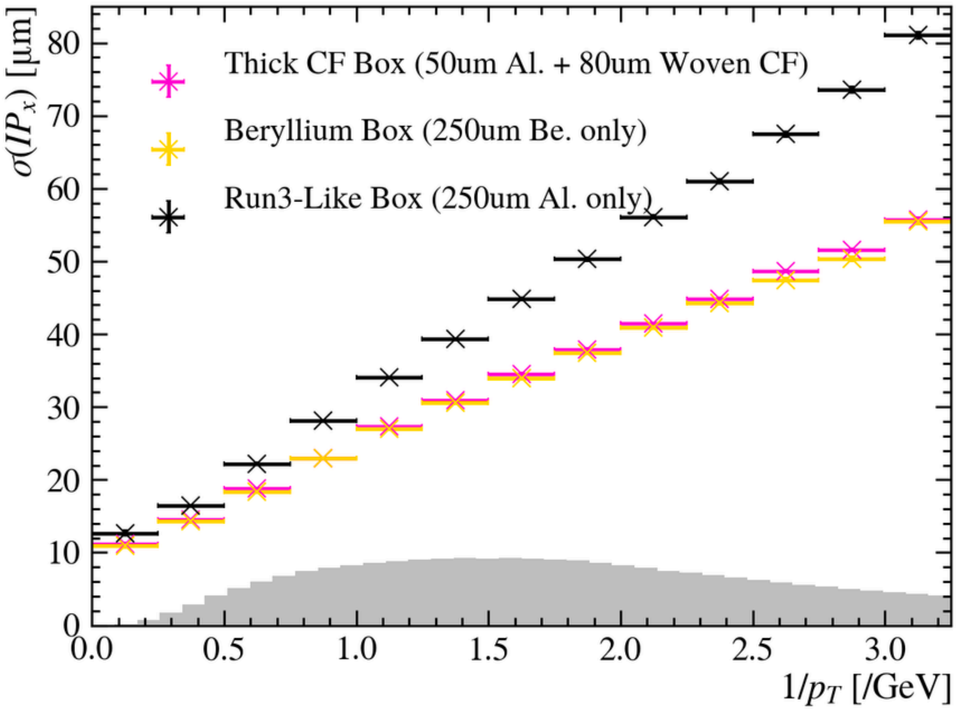


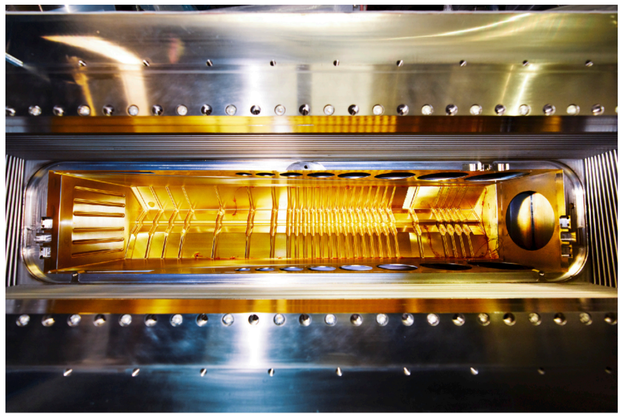




**ASIC can do 6.2 mm considering Rate and Radiation**


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# SIMULATION RF BOX





RF Box protects the detector from beam-induced RF fields.

Reducing the amount of material in the box reduces scattering before 1st point of measurement; big impact in performance.

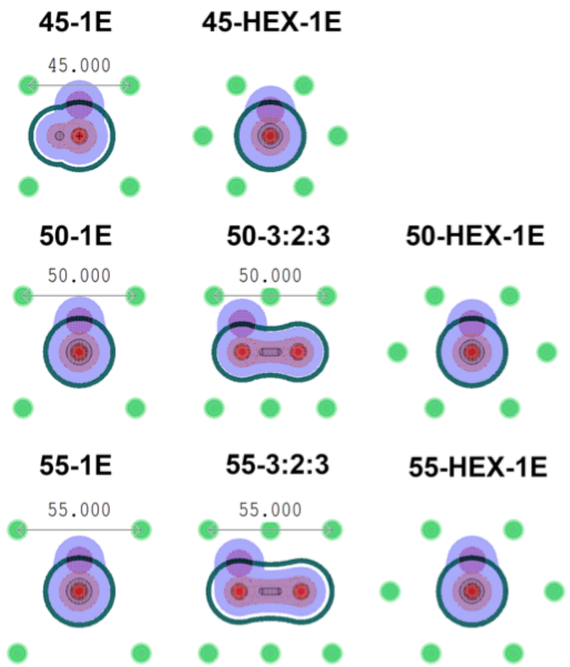
Two solutions in development:
- 80um Carbon fibre box coated with 50 um aluminium
- Beryllium shield

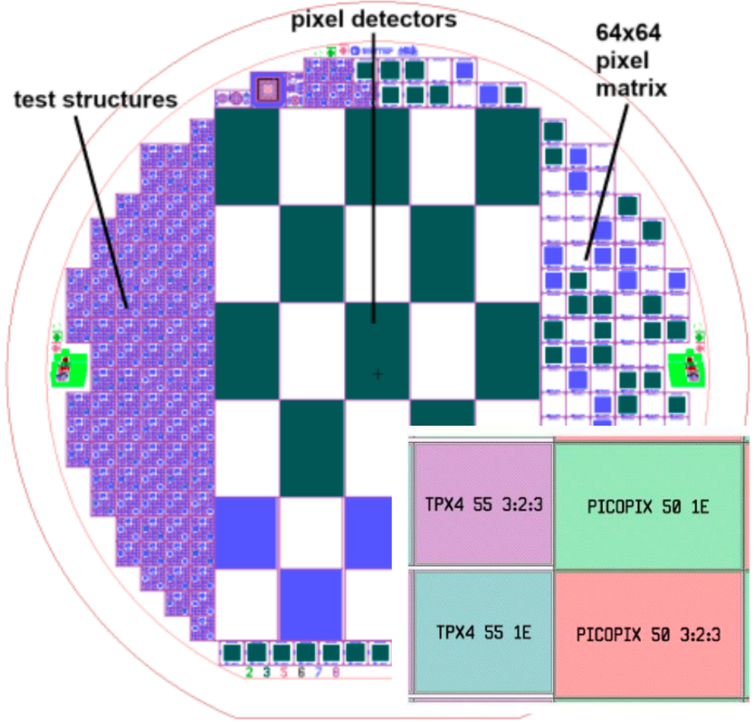


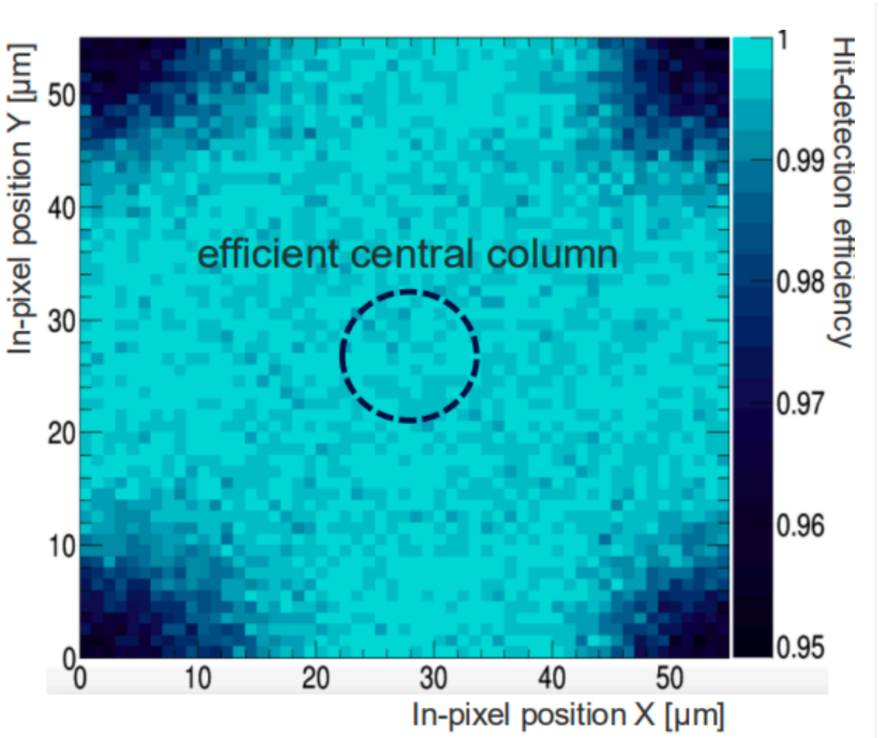
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# SENSORS

**3D sensors are the solution that matches the performance ($\sigma_{x,y}$, $\sigma_t$) and radiation hardness up to $10^{16}\,1\,\mathrm{MeV n_{eq}\,cm^{-2}}$**




**Cocktail of prototypes being produced with choices between 150 and 230 um thickness, different aspect ratio and different column arrangement.**

**Perfomance of sensors driven by column geometry and Q/ Capacitance coupling.**

VELO U2 @ VERTEX



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# ASICS

**2 Different solutions being designed to achieve the challenging requirements.**

Both ASICs designed for 28 nm technology
Tolerant to 1 GRad
Readout data at 100 Gbps

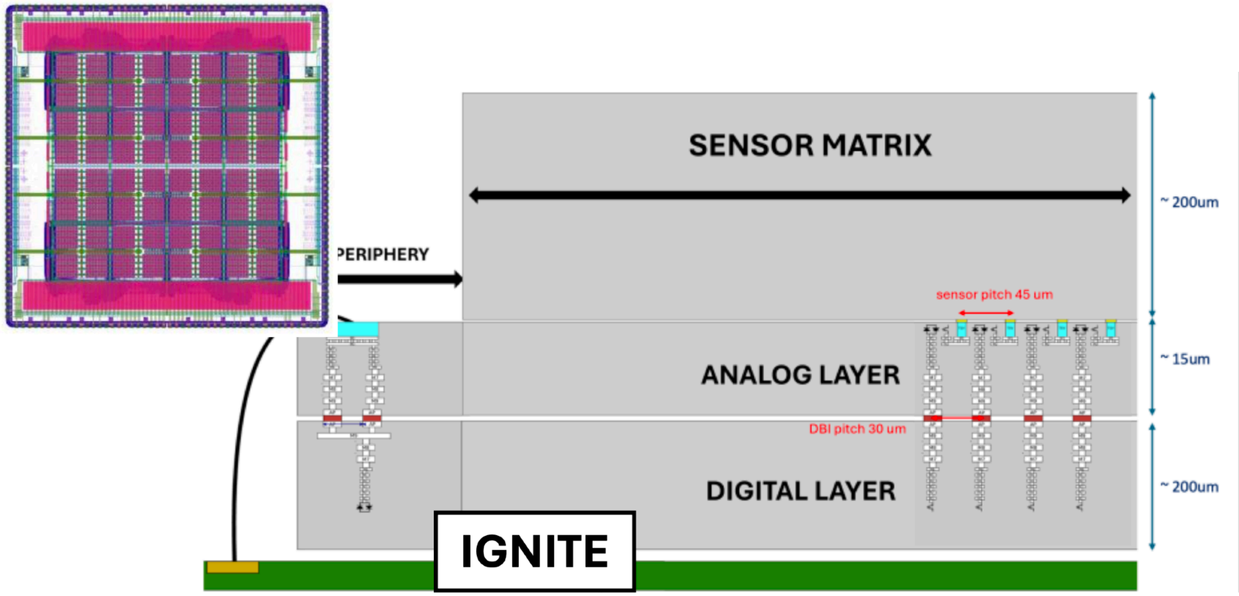
**IGNITE (INFN) uses a vertical integration design, with two chips (analog, digital) bonded together.**

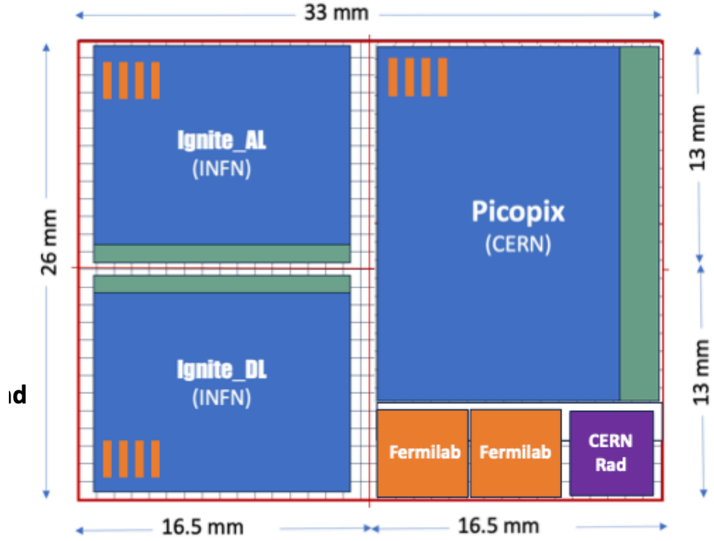
**LA-Picopix (Nikhef/CERN), ASIC derived from the Medipix family, embedded clustering incorporates SPRINT 4x25 Gbps links**

**Ignite ER 320x256 pixels, 45 µm pitch.**

**Picopix: 384x256 pixels, 50 µm pitch.**

**Wafer submission: EoY, hybrid testing in 2027**



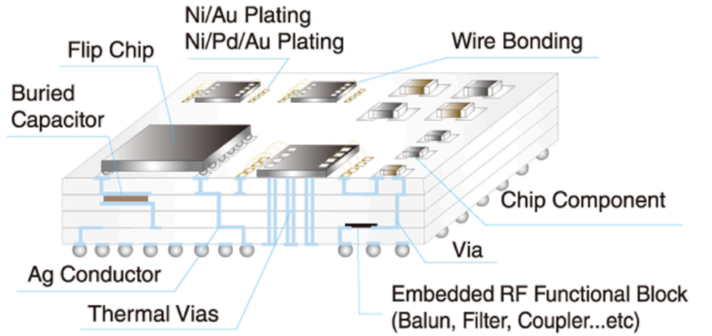



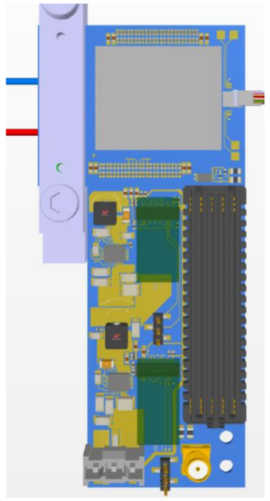


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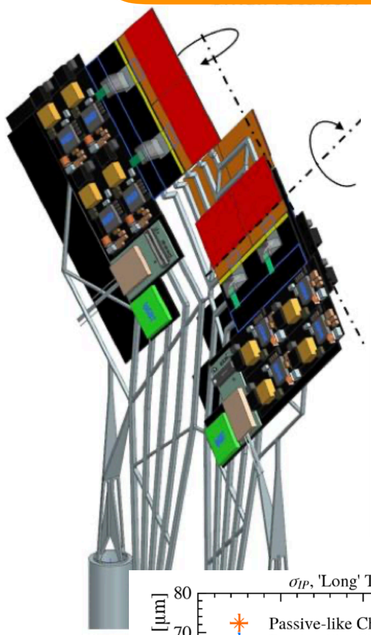
# MODULE SUBSTRATES

**LTCC is a solution capable of integrating electronics and cooling within the module substrate**

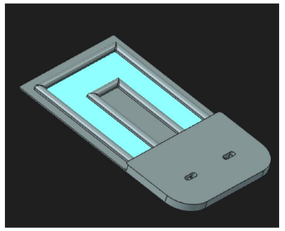


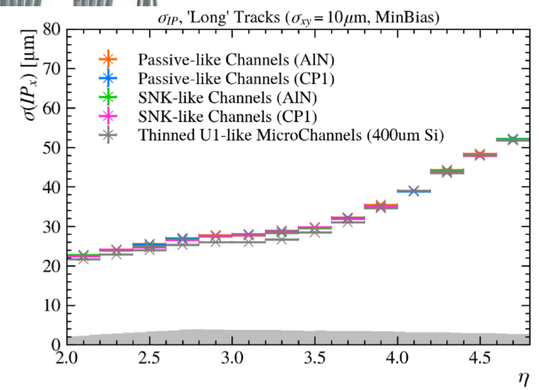



**3D printed substrates**

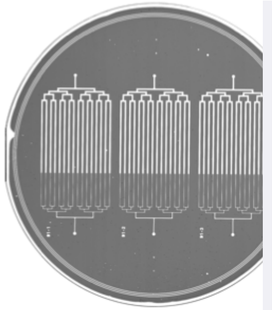




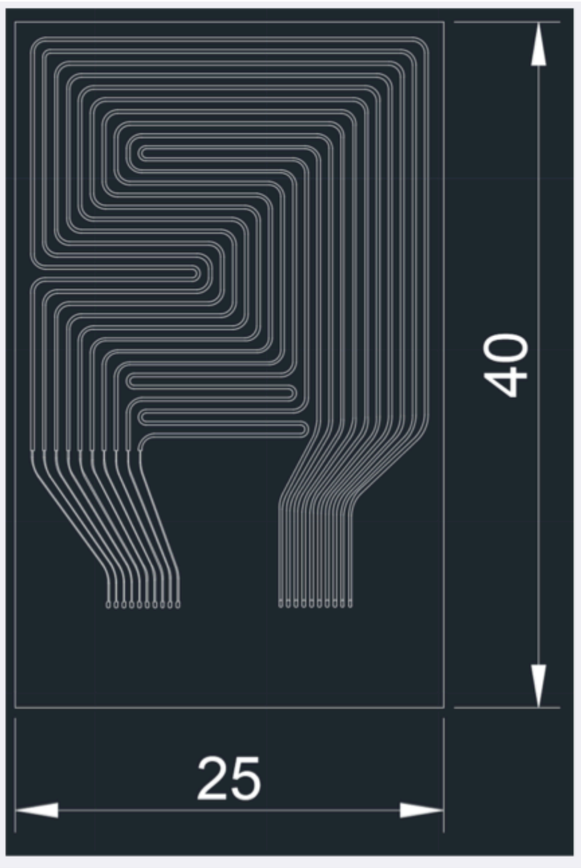





**Silicon Microchannels**



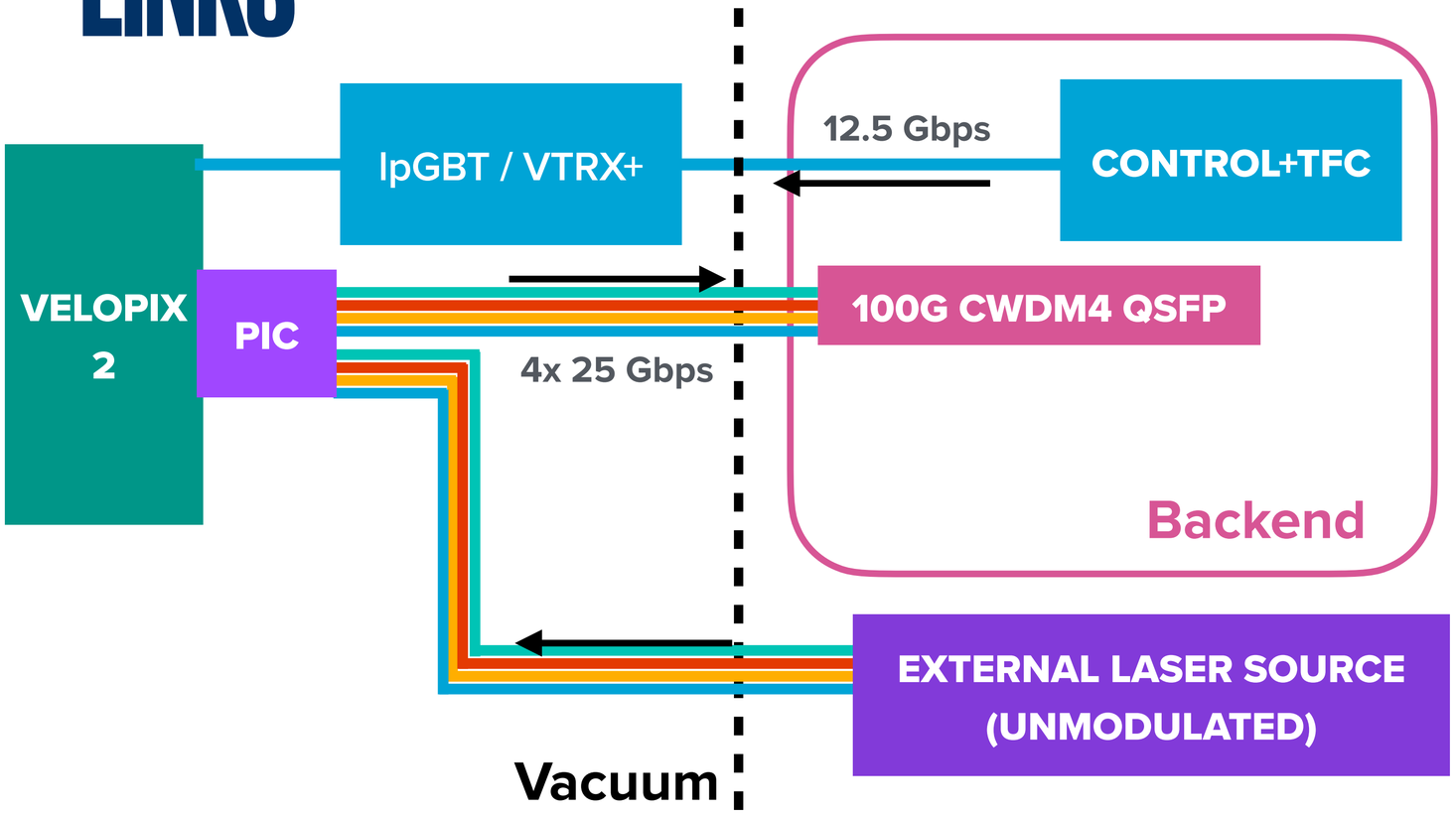






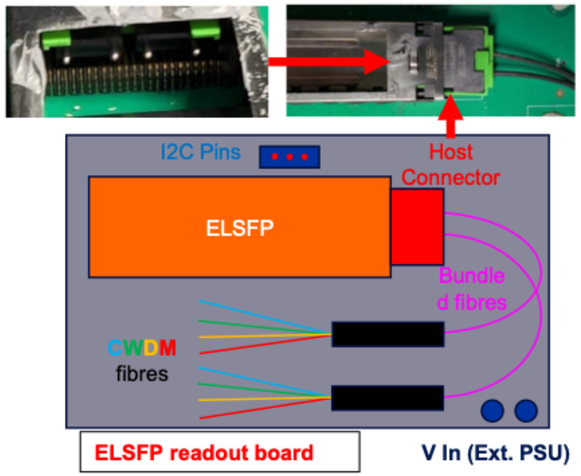

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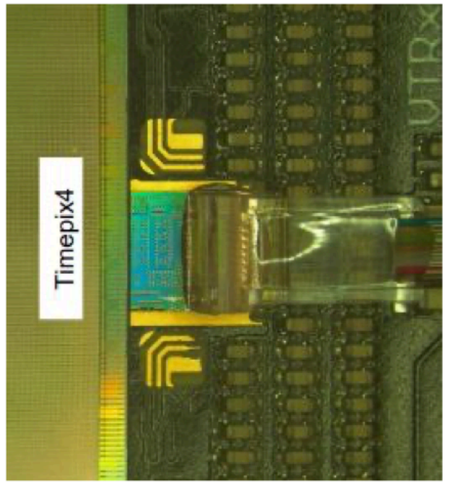
# LINKS




Photonic IC (PIC) has 25 Gb/s up to 4 links

VTRX+ runs at 12.5 Gb/s per link.




VTRX+ will be the solution for the control link, but data links to be decided.

PIC solution is a great candidate; it offers huge bandwidth with very low material and power consumption

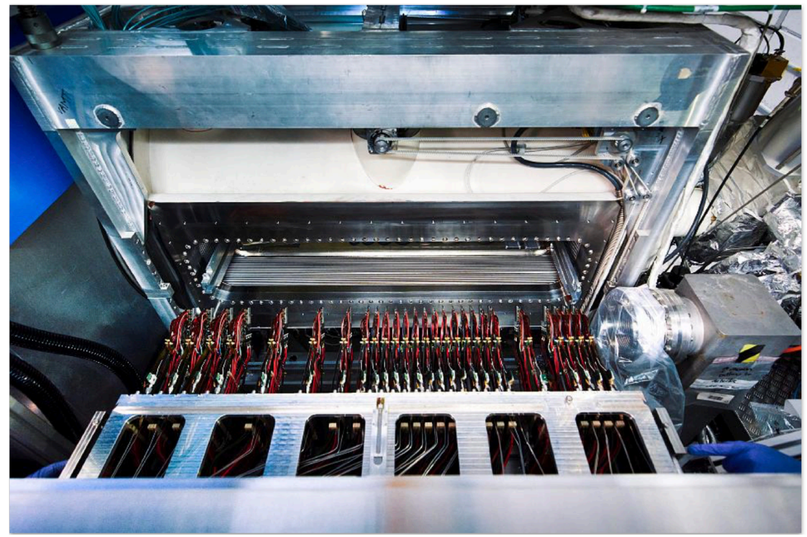
# CONCLUSION

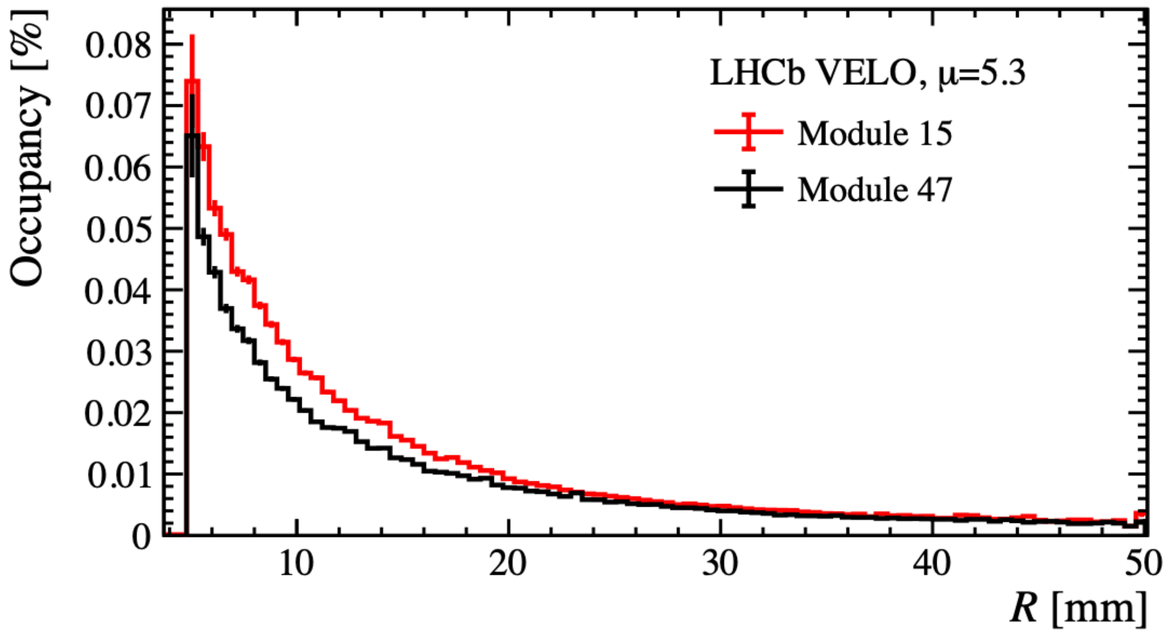
VELO Upgrade I has successfully been installed, commissioned and operated in Run3

Detector design with difficult environment, secondary vacuum, movable, very high radiation fluences that close to the beam

Upgrade II will add timing information to every single hit in order to cope with new luminosity

Next year is huge for VELO Upgrade II; Sensor prototypes, ASIC submission and TDR all in 2027.







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# THANK YOU!



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# BACKUP

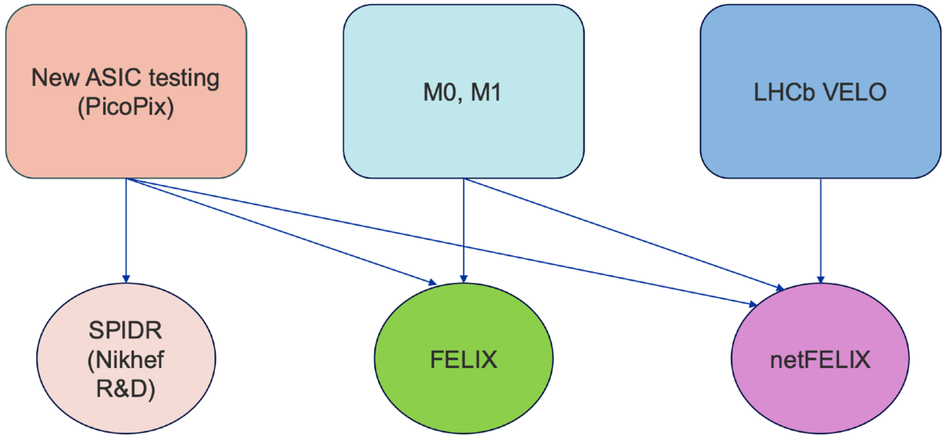


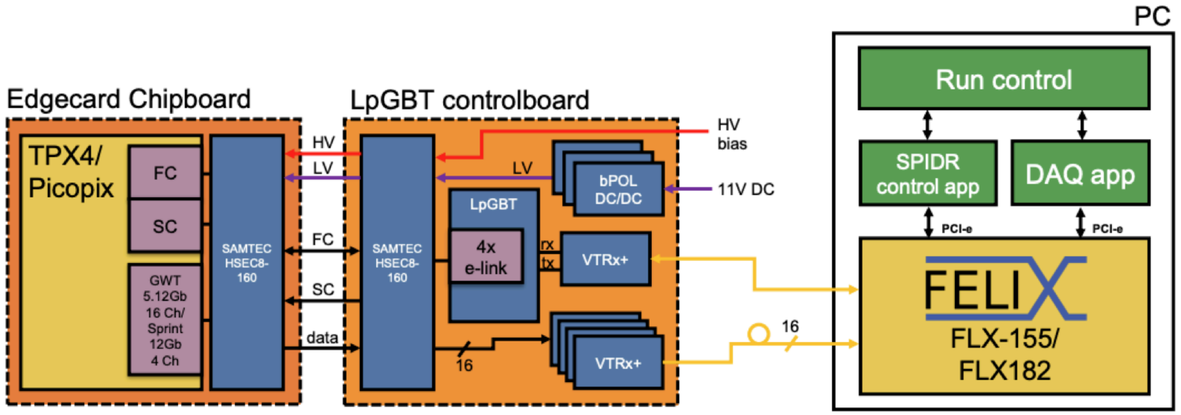
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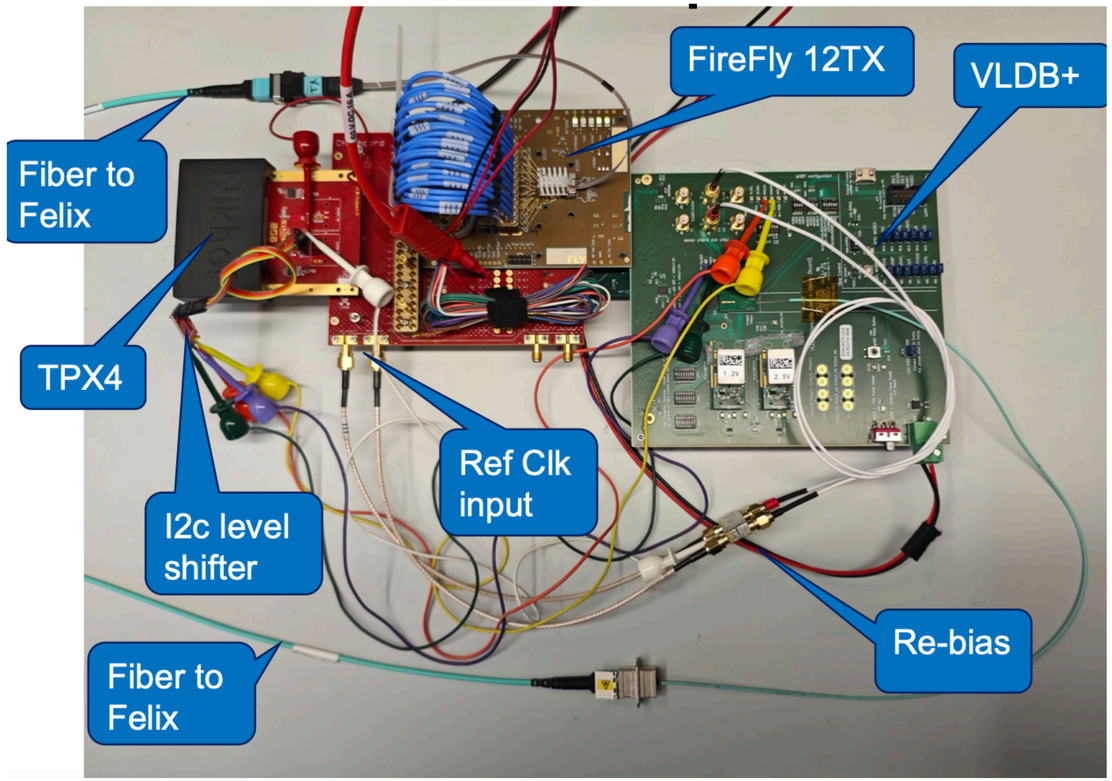
# BACKEND DEVELOPMENT

**Continuous development of readout/ controls as the prototypes approach a final module**

**FELIX-based (NetFELIX) solution for detector backend to be adopted by LHCb**




VELO U2 Workshop Backend

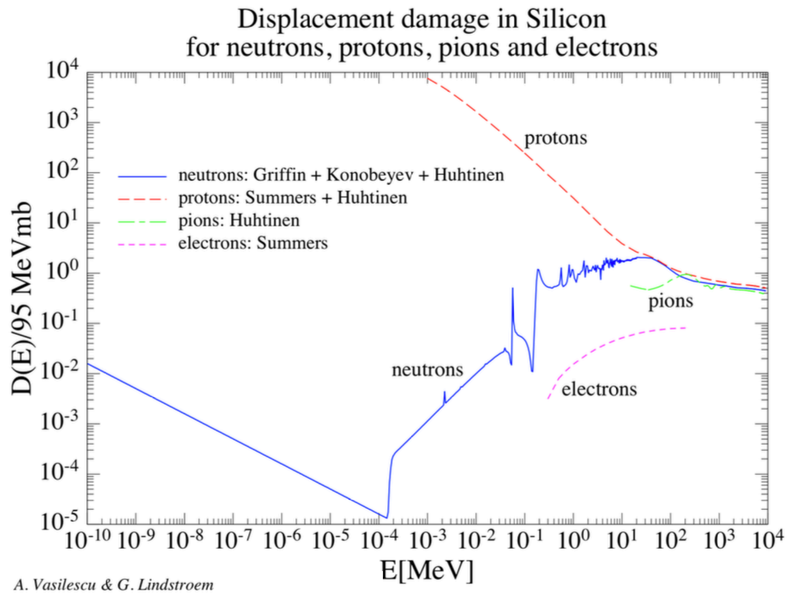


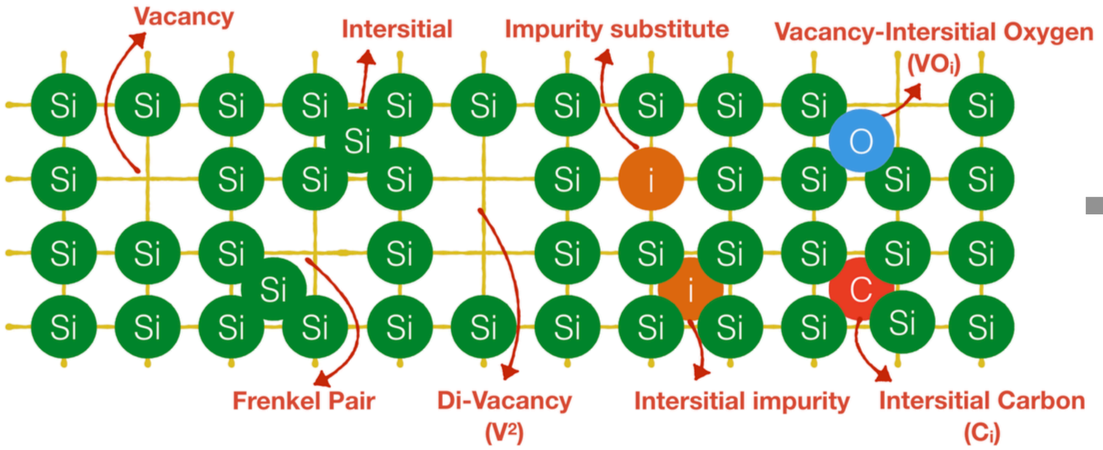
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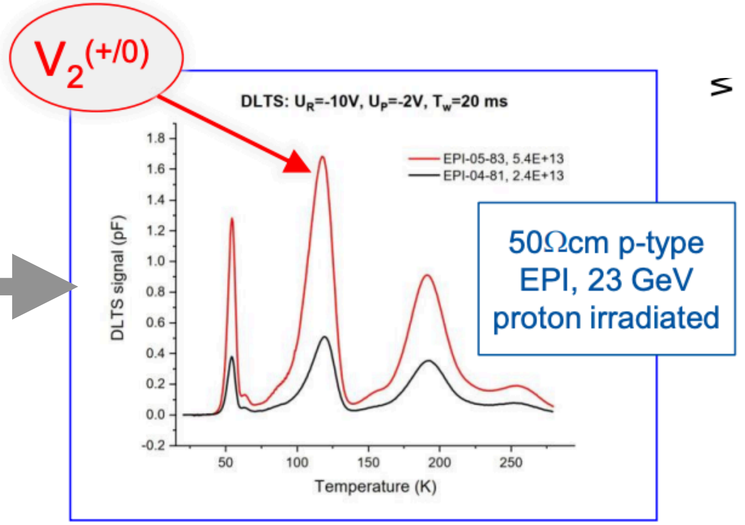
# RADIATION DAMAGE IN ONE SLIDE

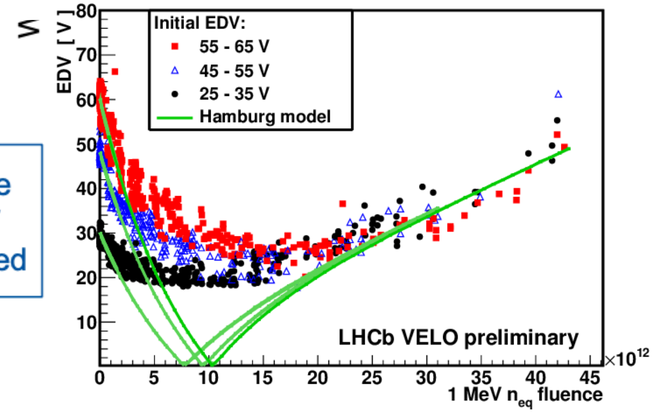
**Number of displacements proportional to the flux of 1 MeV neutrons**

**Displacements cause charge trapping due to energy levels created inside the energy gap**



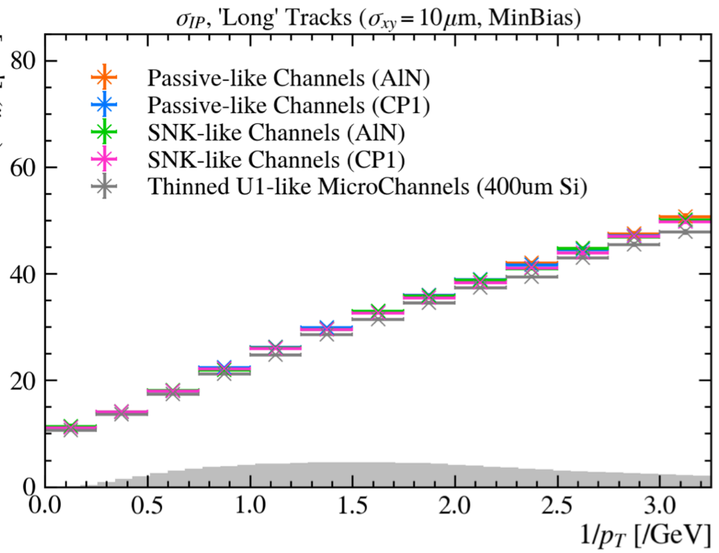


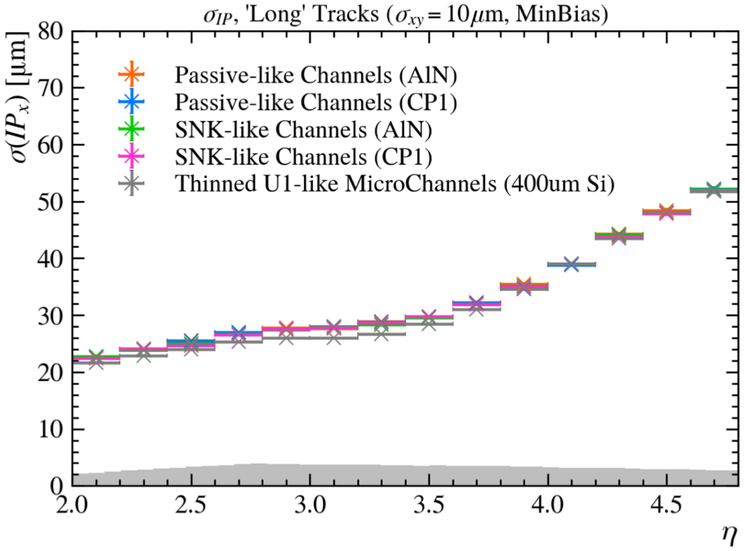

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Logic behind “average x/X0 <~ 0.5%” maintaining performance is valid

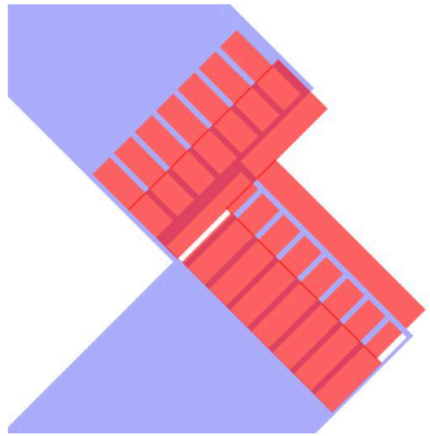
Logic behind “average x/X0 <~ 0.5%” maintaining performance is valid

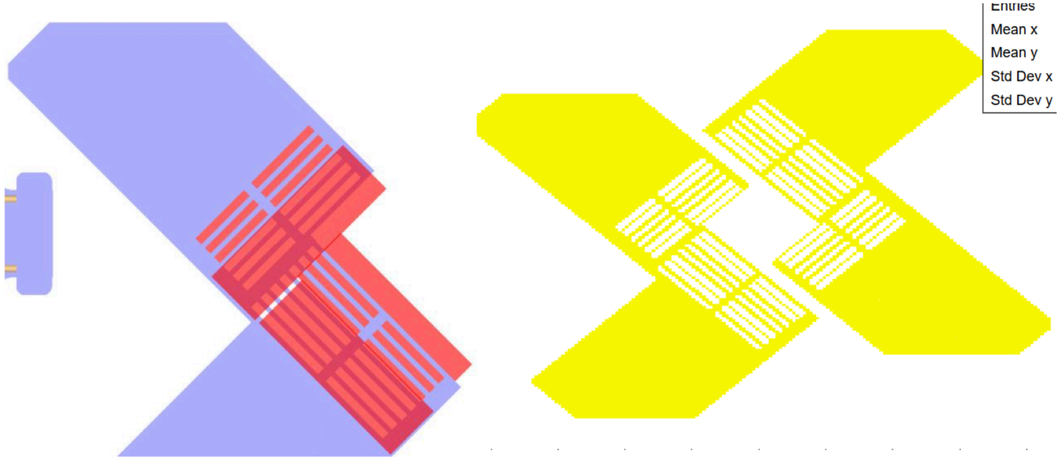
# SIMULATION/ SUBSTRATE

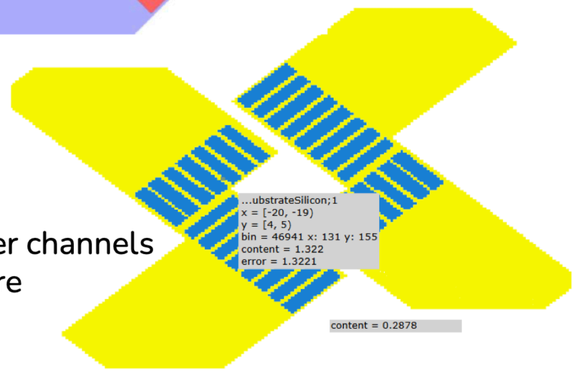



**What if the material in the VELO is concentrated in pipes rather than a U1-like substrate ?**






x/X0 = 1.3% over channels
0.28% elsewhere

Dan’s Talk

7

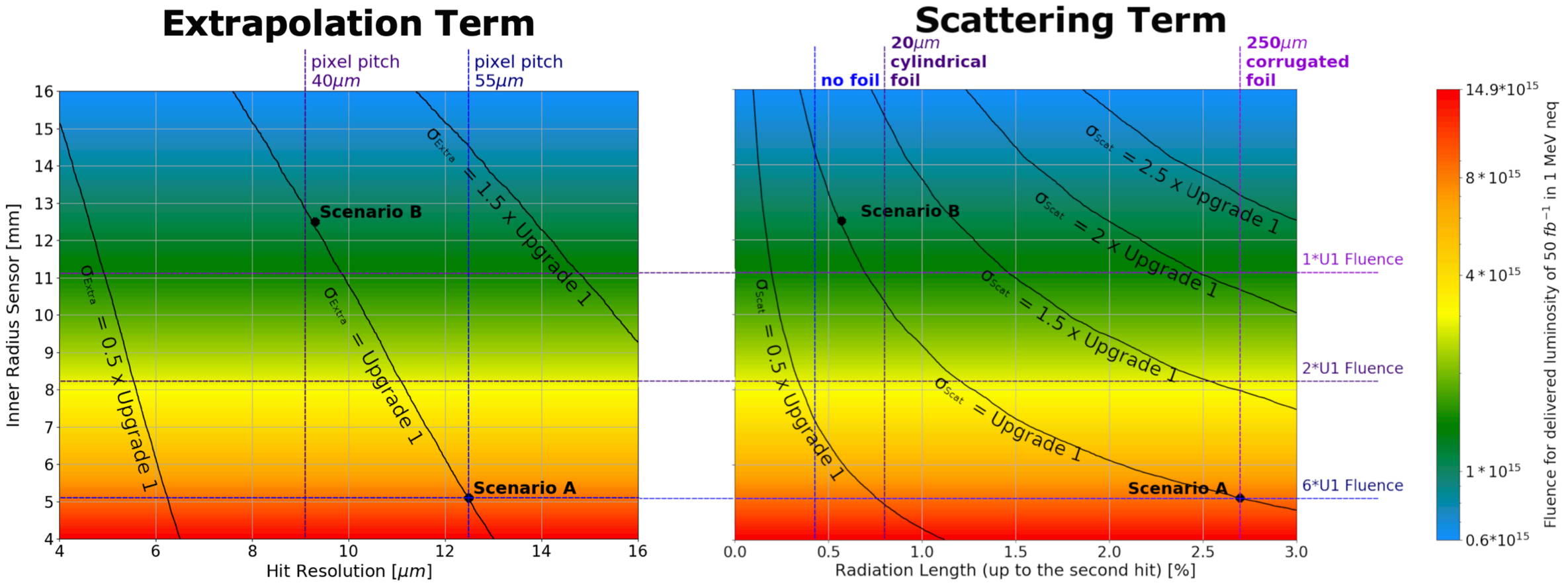


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# SCENARIO A/B/X

**Scenario A: Keep inner radius a la U1 (5.1 mm)**

**Scenario B: Relax inner radius to 12.5 mm, keeping particle rate the same as U1**




Scoping Document

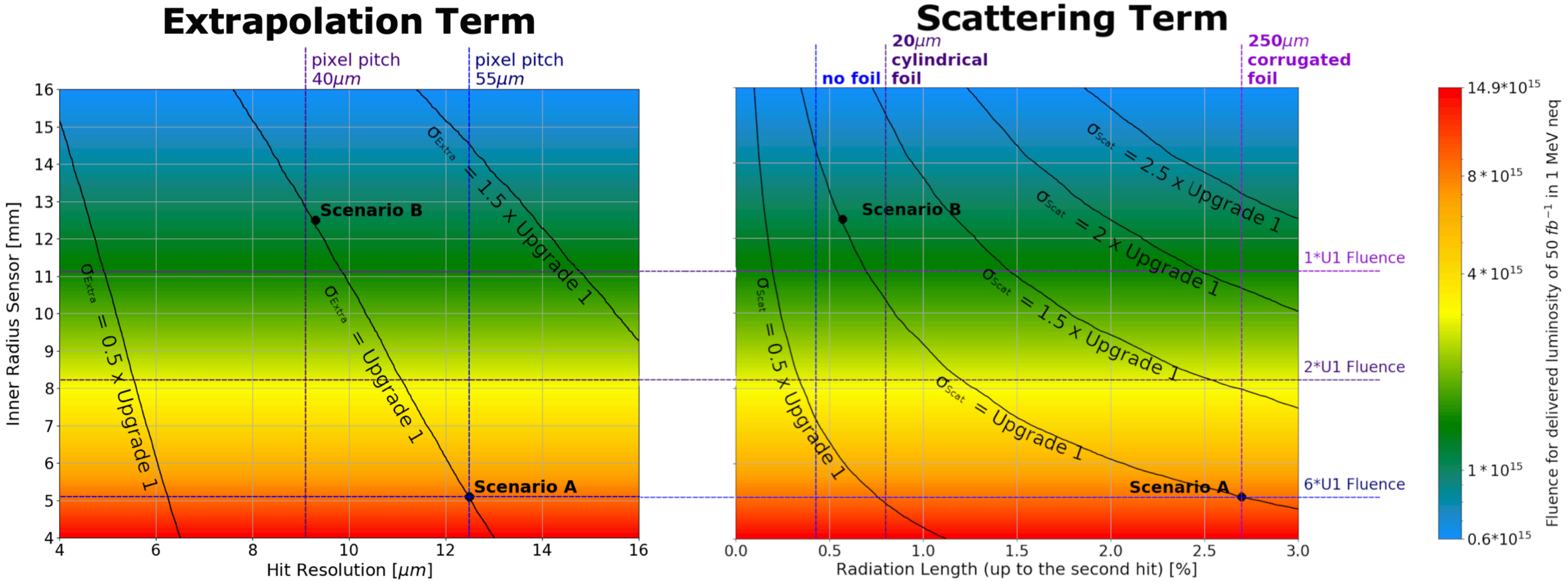


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# SCENARIO A/B/X

**Scenario A: ~7.5 times higher hit rate,**
**$8 \times 10^{15}$ 1 MeV $n_{eq}cm^{-2}$ per year**

**Scenario B: $1 \times 10^{16}$ 1 MeV $n_{eq}cm^{-2}$ total fluence**
**Requires 40 µm pitch + extra thin foil, sensor and ASIC**




**The answer is somewhere in the middle**

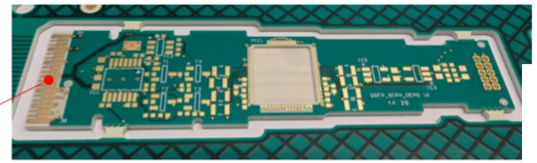
Scoping Document



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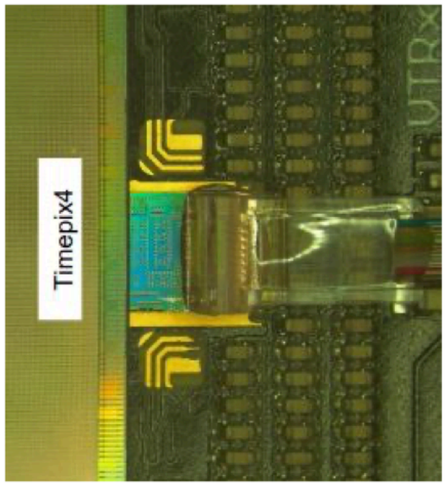
# LINKS

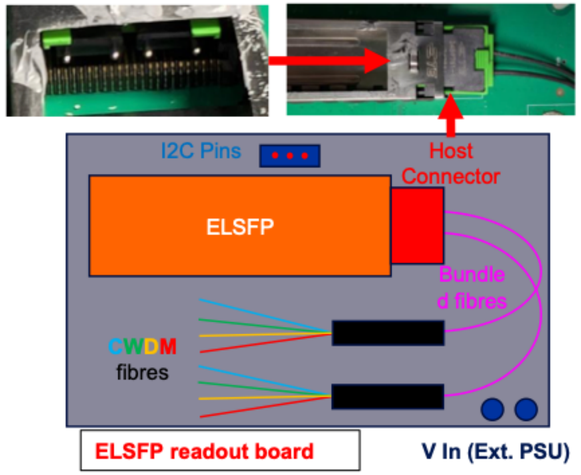
Fabricated PCB



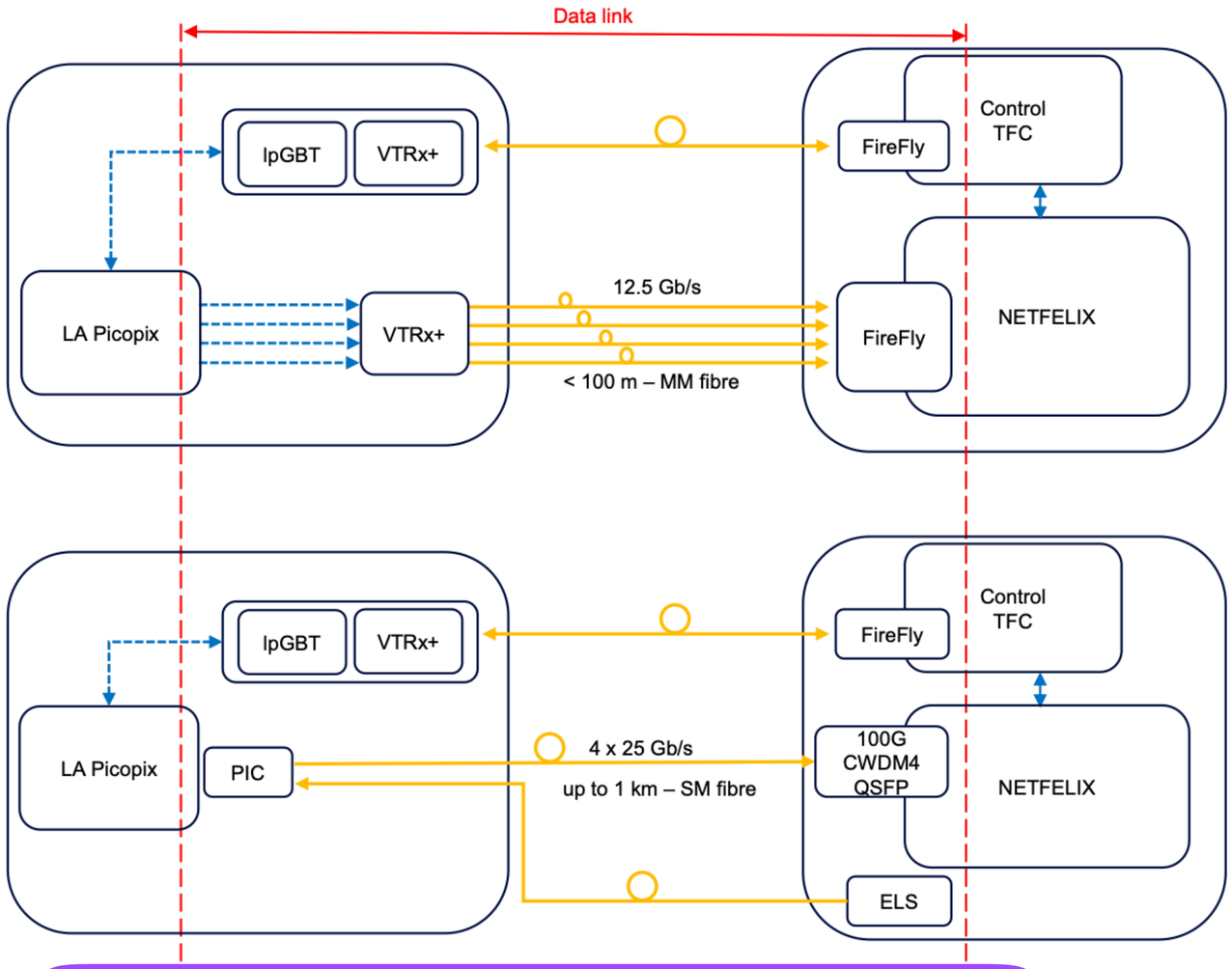
**Photonic IC (PIC) has 25 Gb/s up to 4 links**

**VTRX+ runs at 12.5 Gb/s per link.**




**Tests on VTRX+ performance under low temperature and vacuum ongoing, no issues observed.**




**VTRX+ will be the solution for the control link, but data links to be decided.**



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