The LHCb VELO detector: operation, performance and future upgrades

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on behalf of the LHCb VELO group

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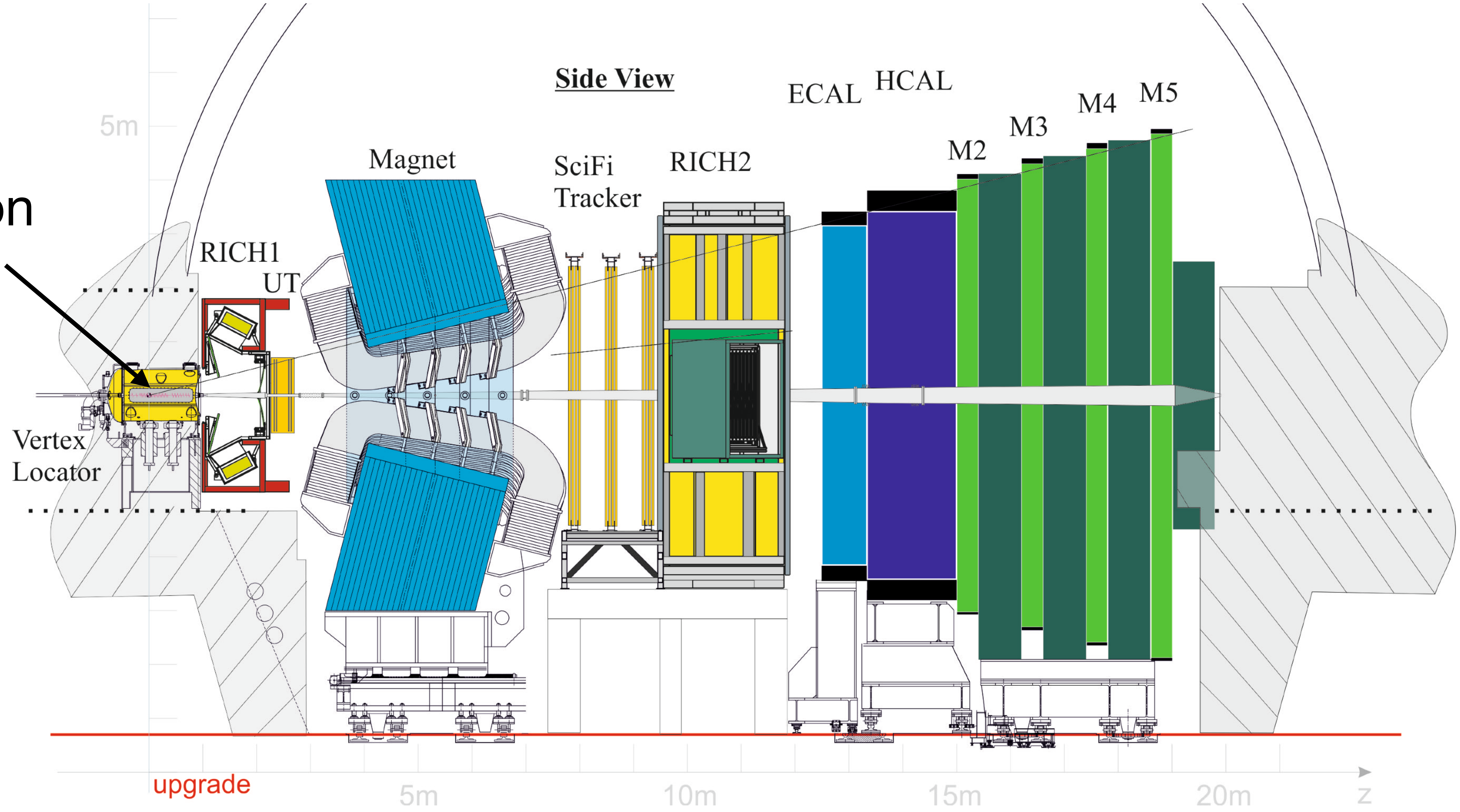
LHCb Experiment

Exploring the differences between matter and antimatter by studying physics of the heavy b and c quarks.

LHCb forward detector

Designed to study particles produced at small angles relative to the beam line.

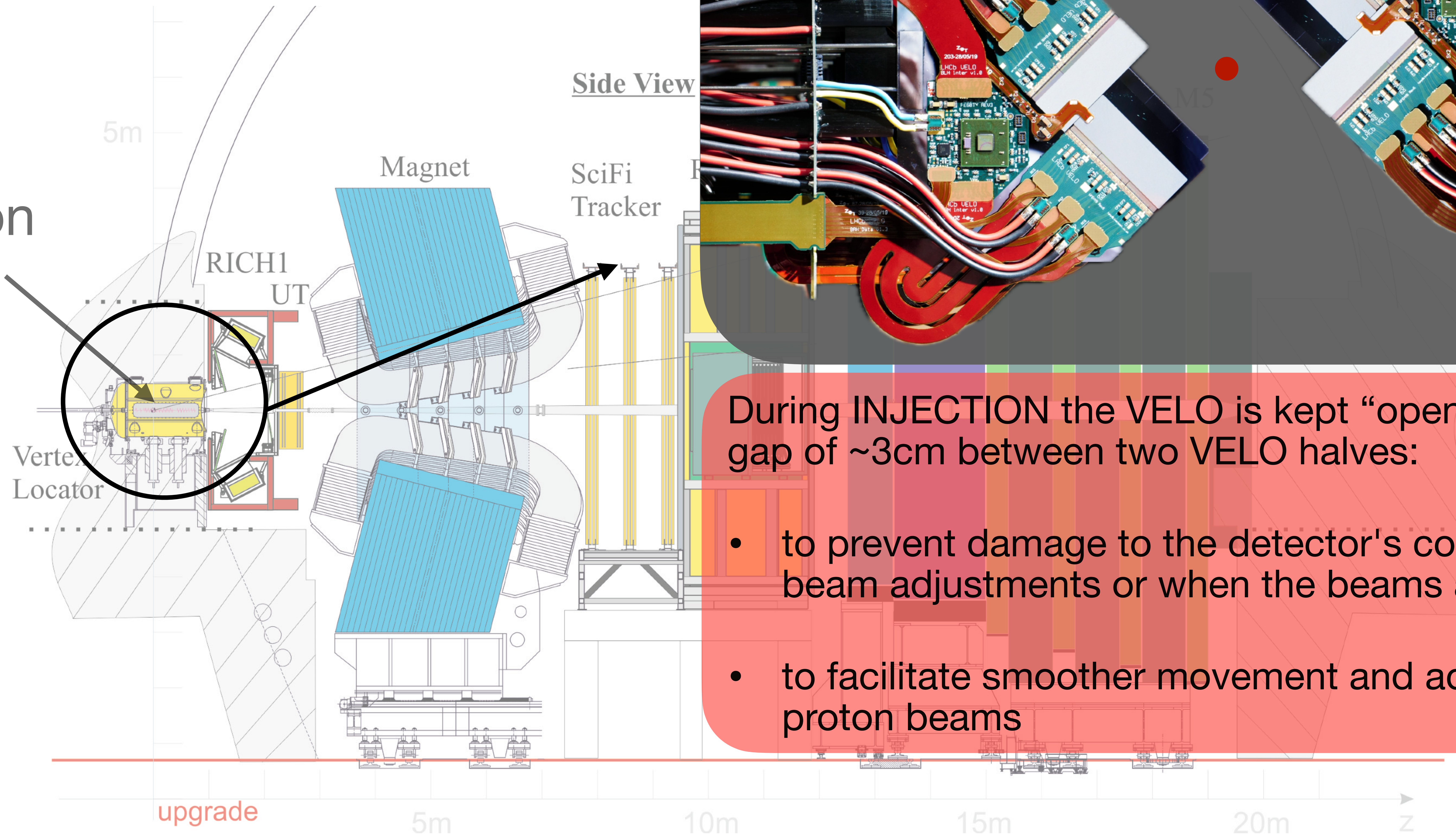
proton-proton interaction point

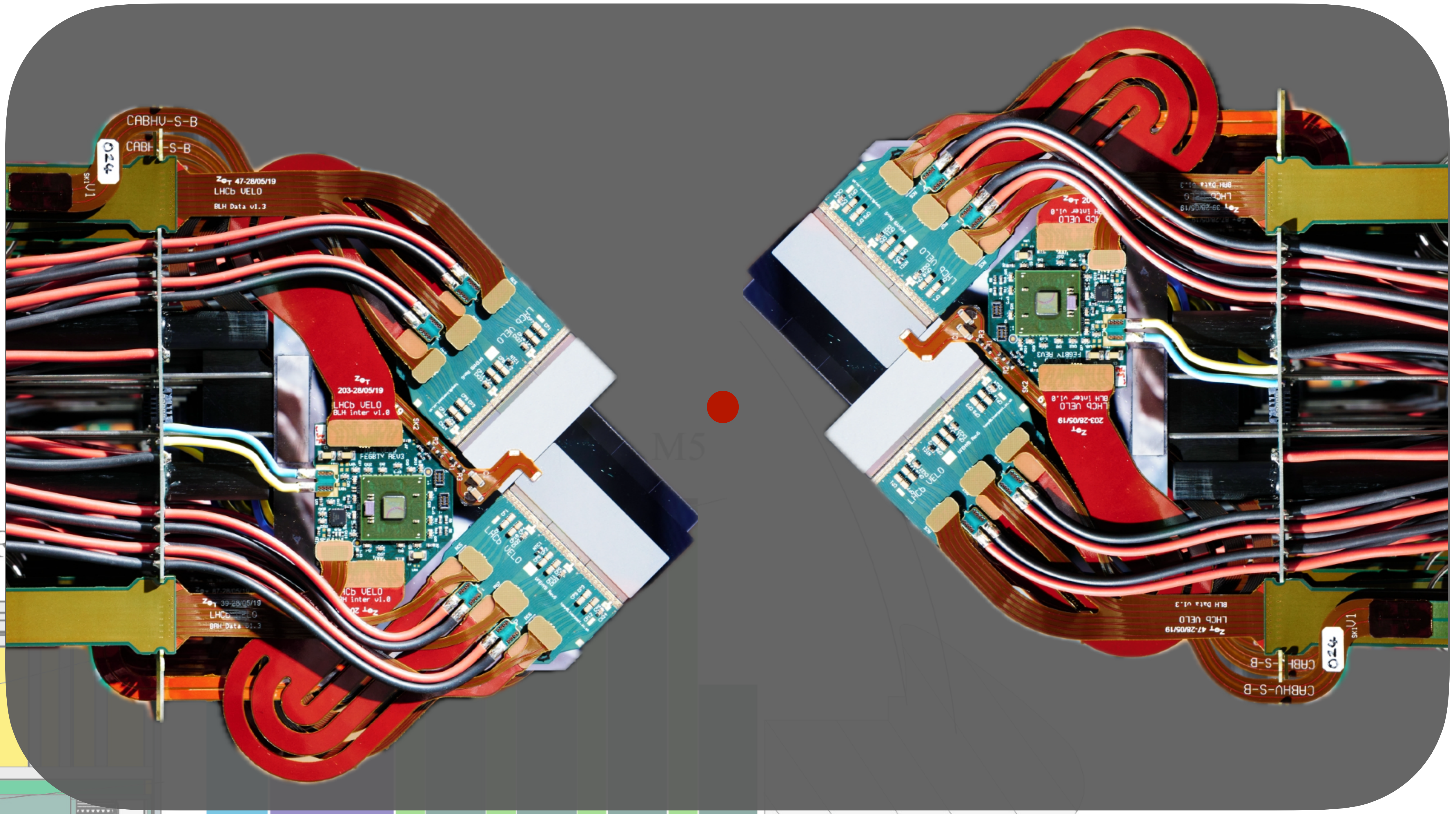


VErtex LOcator

A movable detector

proton-proton interaction point





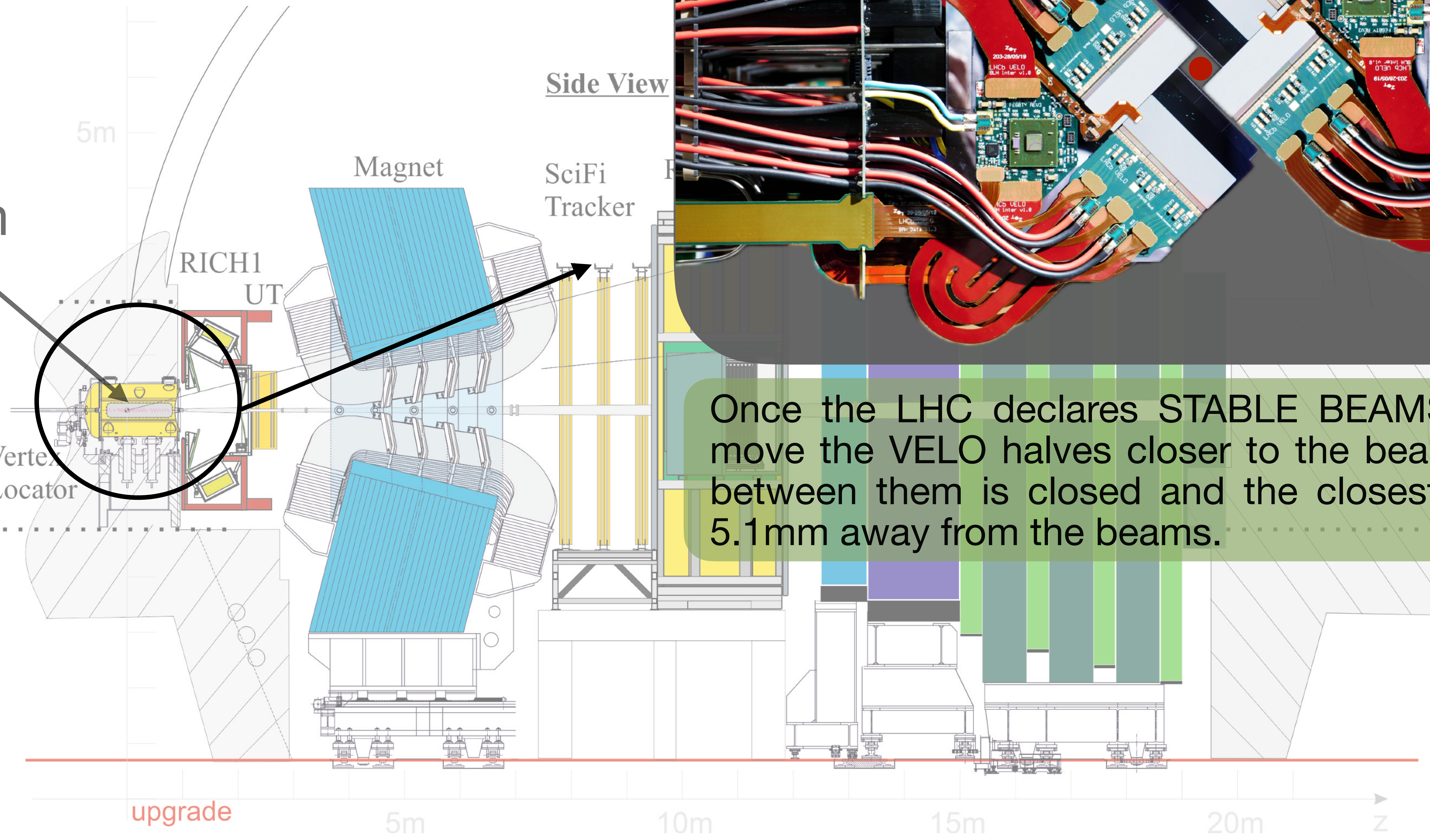
During INJECTION the VELO is kept “open”, i.e. there’s a gap of ~3cm between two VELO halves:

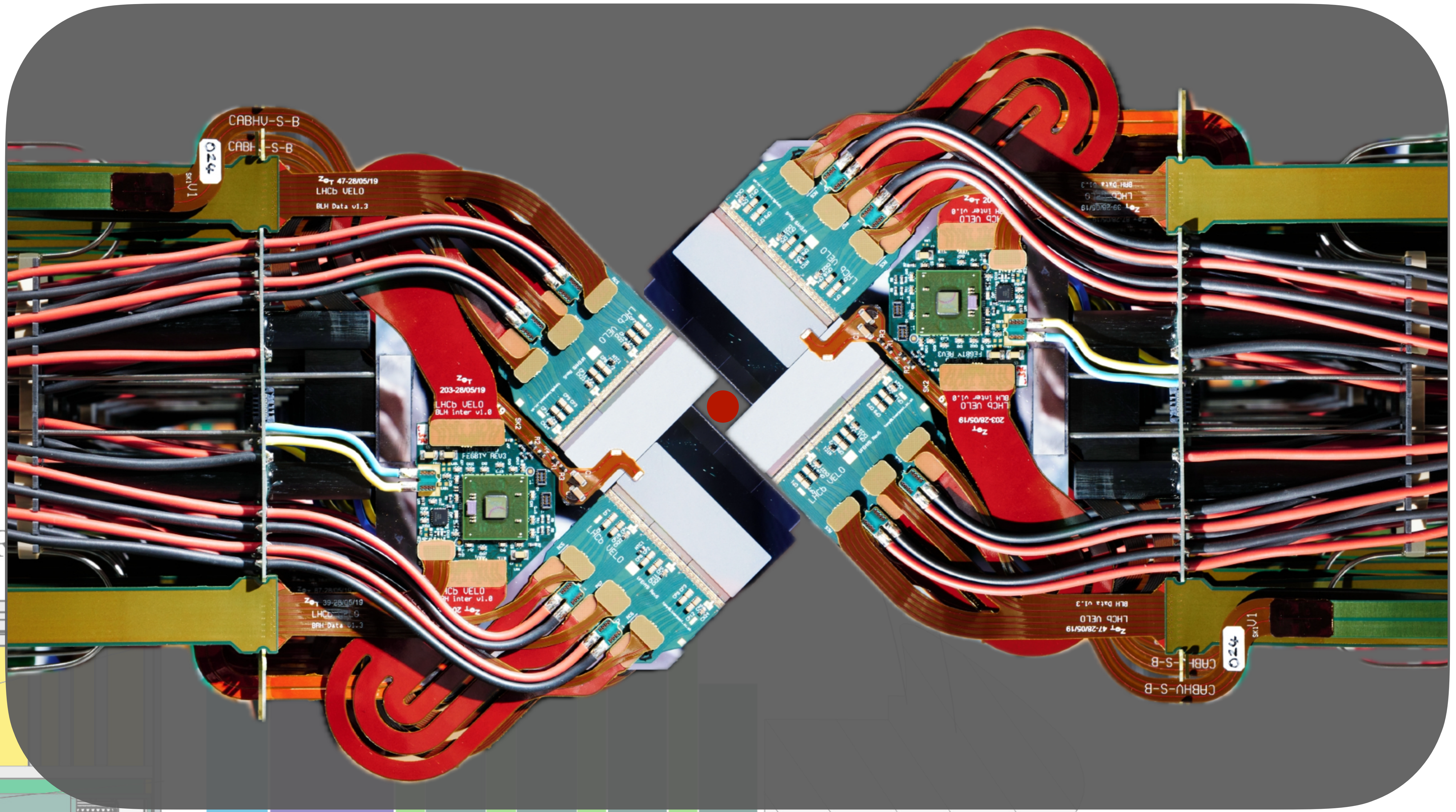
- to prevent damage to the detector's components during beam adjustments or when the beams are unstable
- to facilitate smoother movement and adjustments of the proton beams

VErtex LOcator

A movable detector

proton-proton interaction point

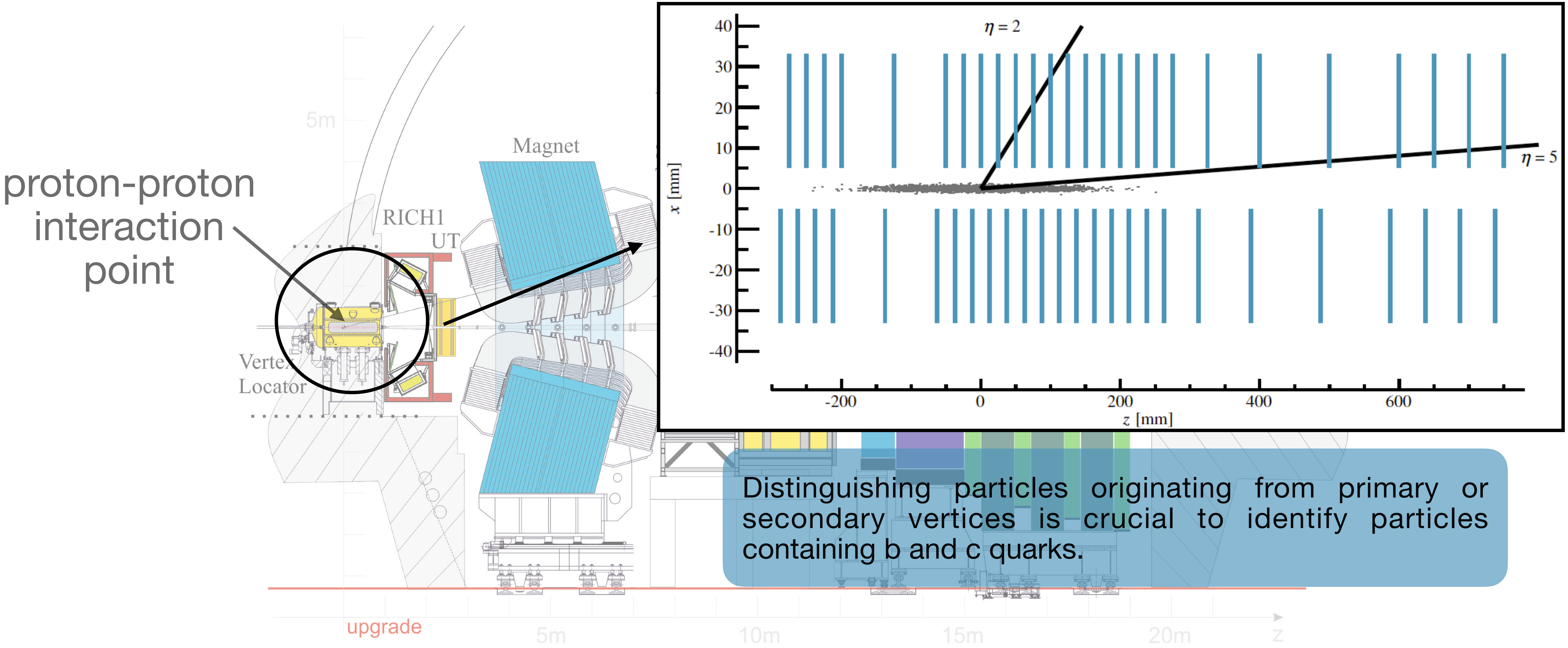




Once the LHC declares STABLE BEAMS we gradually move the VELO halves closer to the beam until the gap between them is closed and the closest active area is 5.1mm away from the beams.

VErtex LOcator

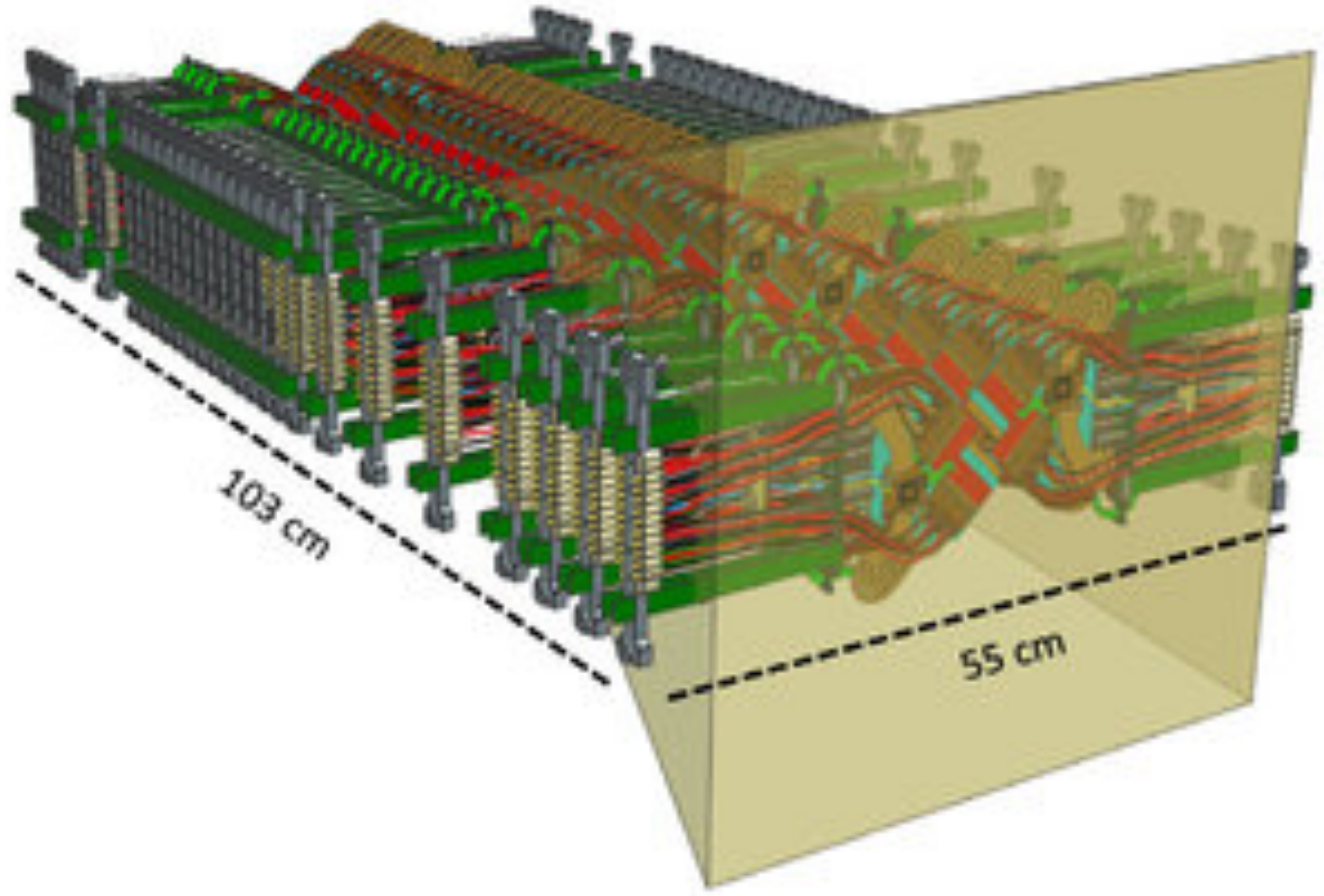
Particle tracking and vertex reconstruction

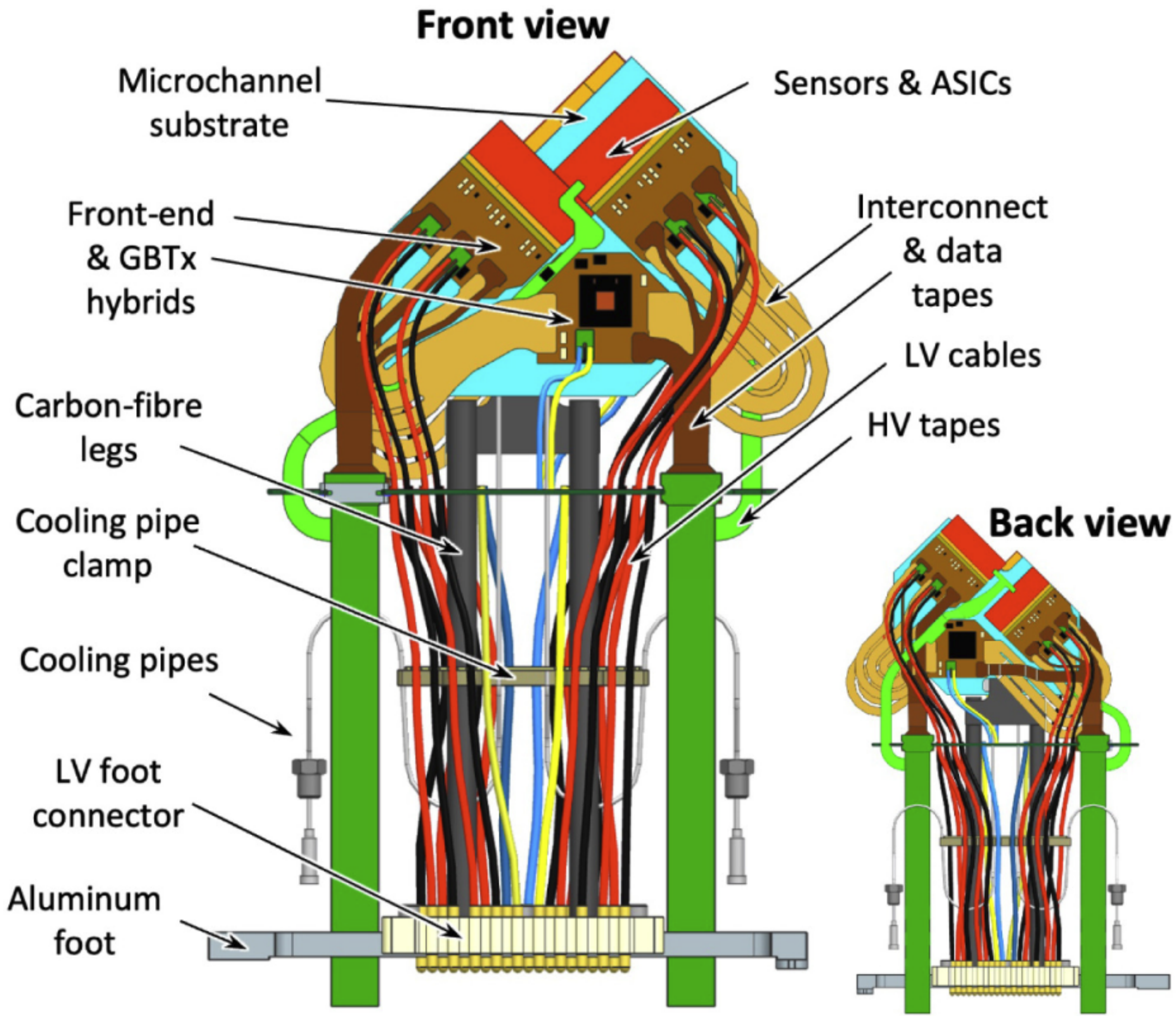


Distinguishing particles originating from primary or secondary vertices is crucial to identify particles containing b and c quarks.

VELO

VELO = 52 modules





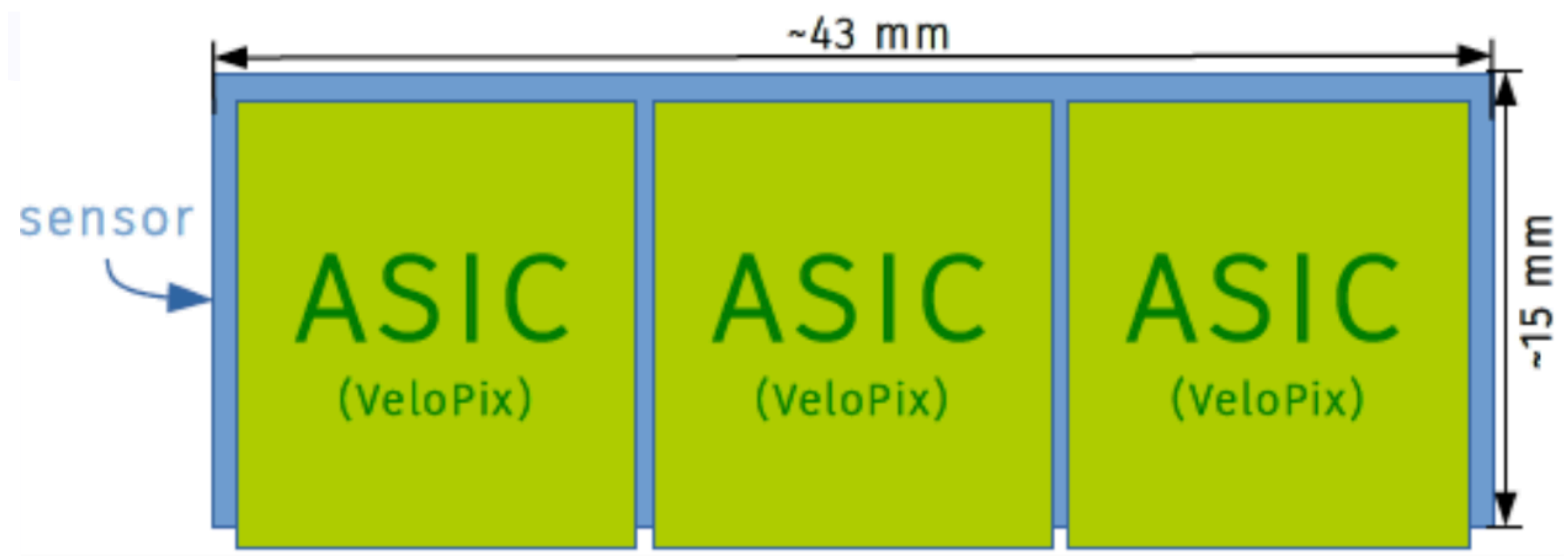
VELO

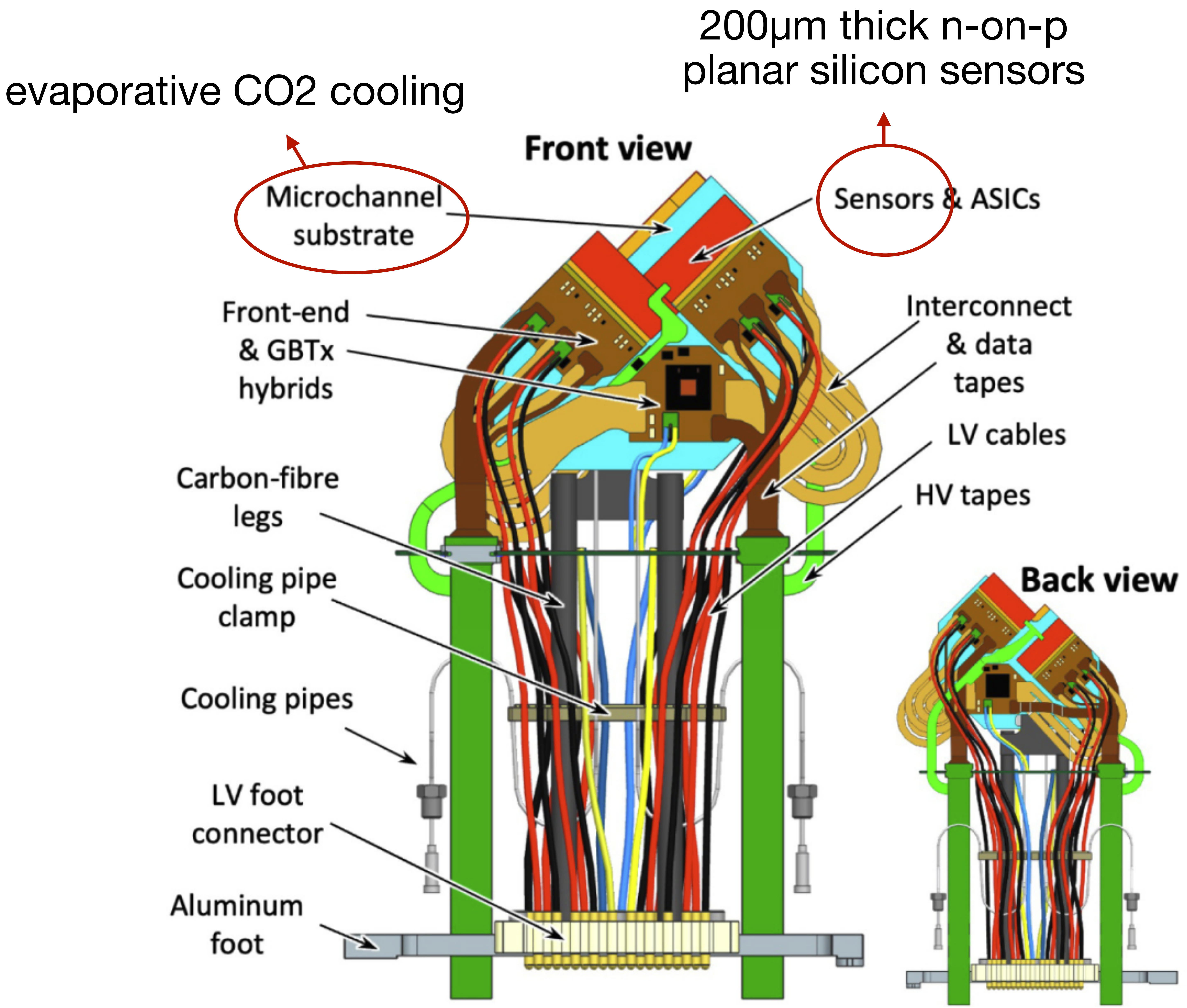
VELO = 52 modules

module = 12 VeloPix ASICs

ASIC = 256x256 pixels

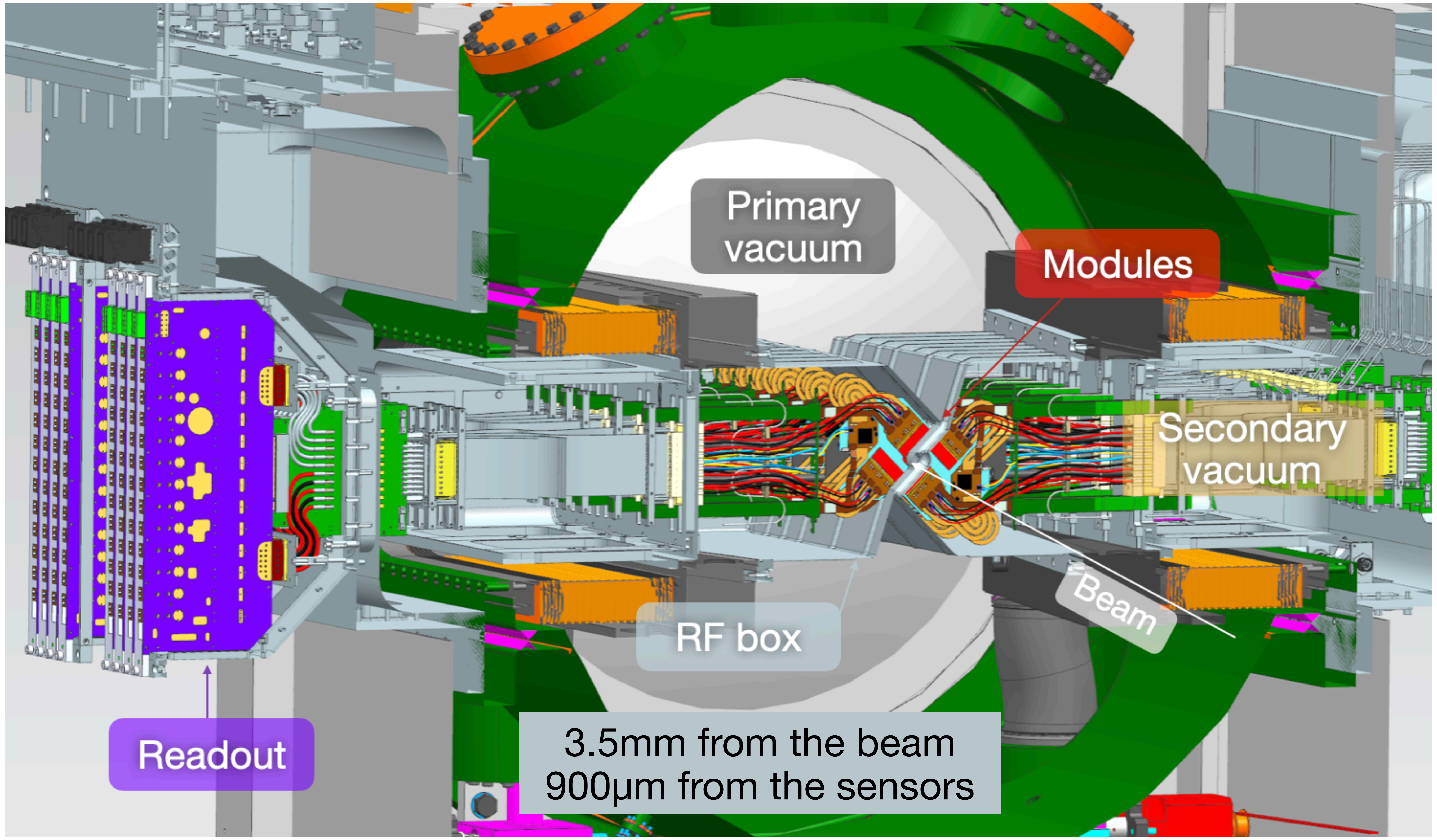
pixel = 55x55μm²

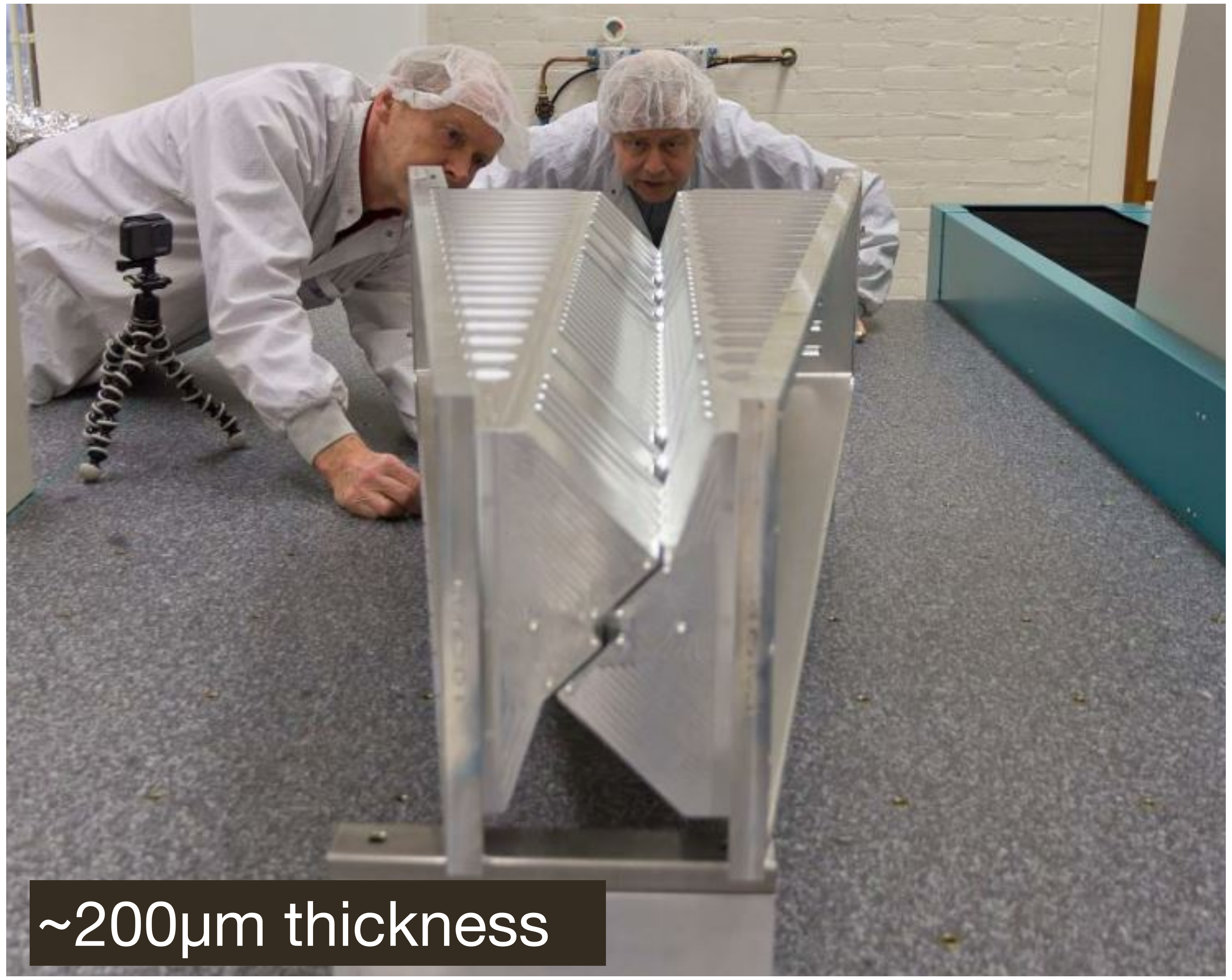




RF box

- It separates the VELO detector vacuum from the LHCb beam vacuum
- It suppresses heating from transient fields generated by the beam passage

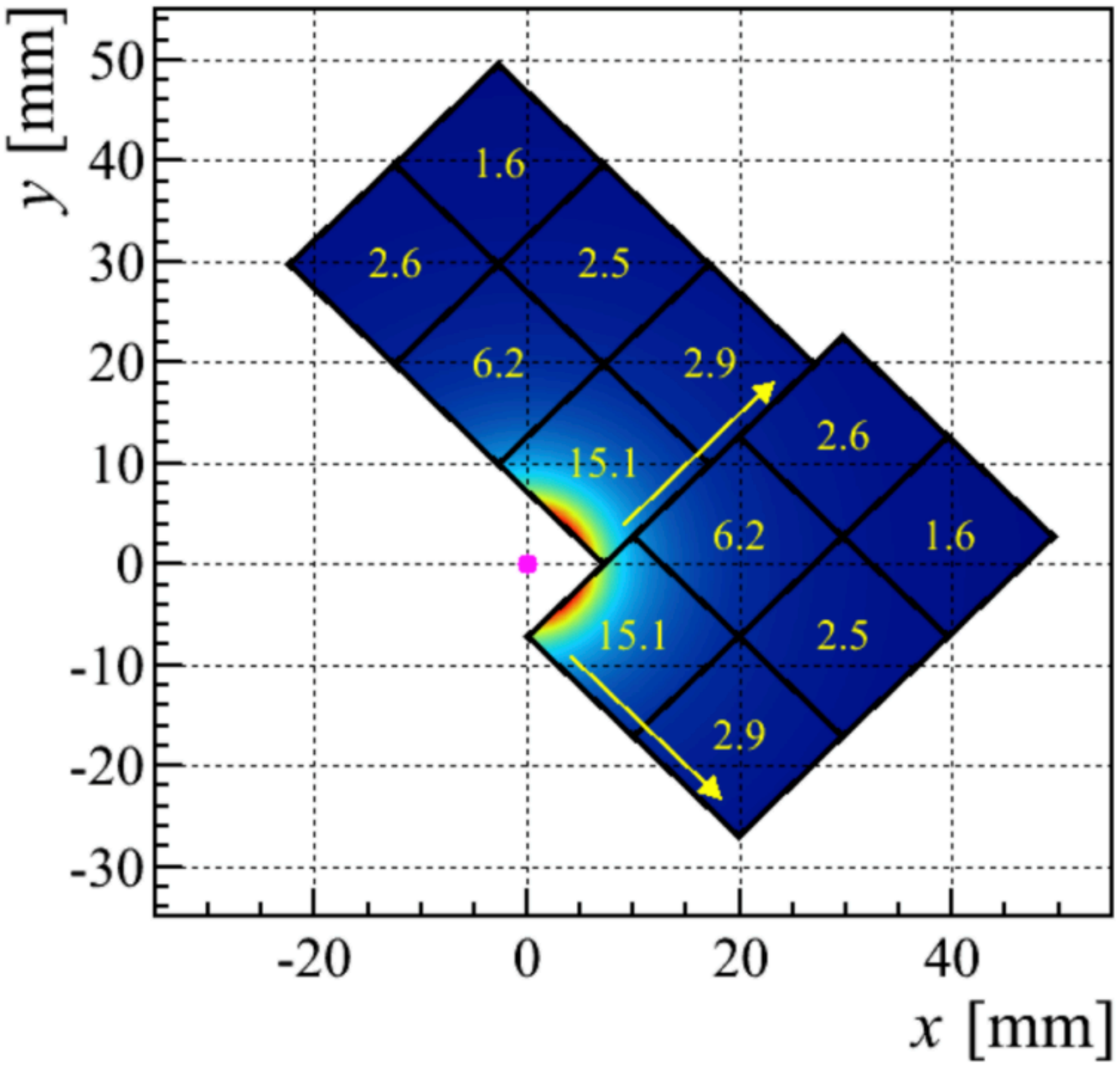




VELO Operational Environment

- First active element is 5.1mm from interaction region
- Non-uniform irradiation
- Expected total dose of 400MRad
- Hottest ASIC has a rate of 15.1 Gbit/s
- Leakage current of 7nA/pixel at end of life
- Hit efficiency > 99%
- Timing resolution: 25ns

Data rate per ASIC [Gbit/s]



VELO Commissioning
Equalisation

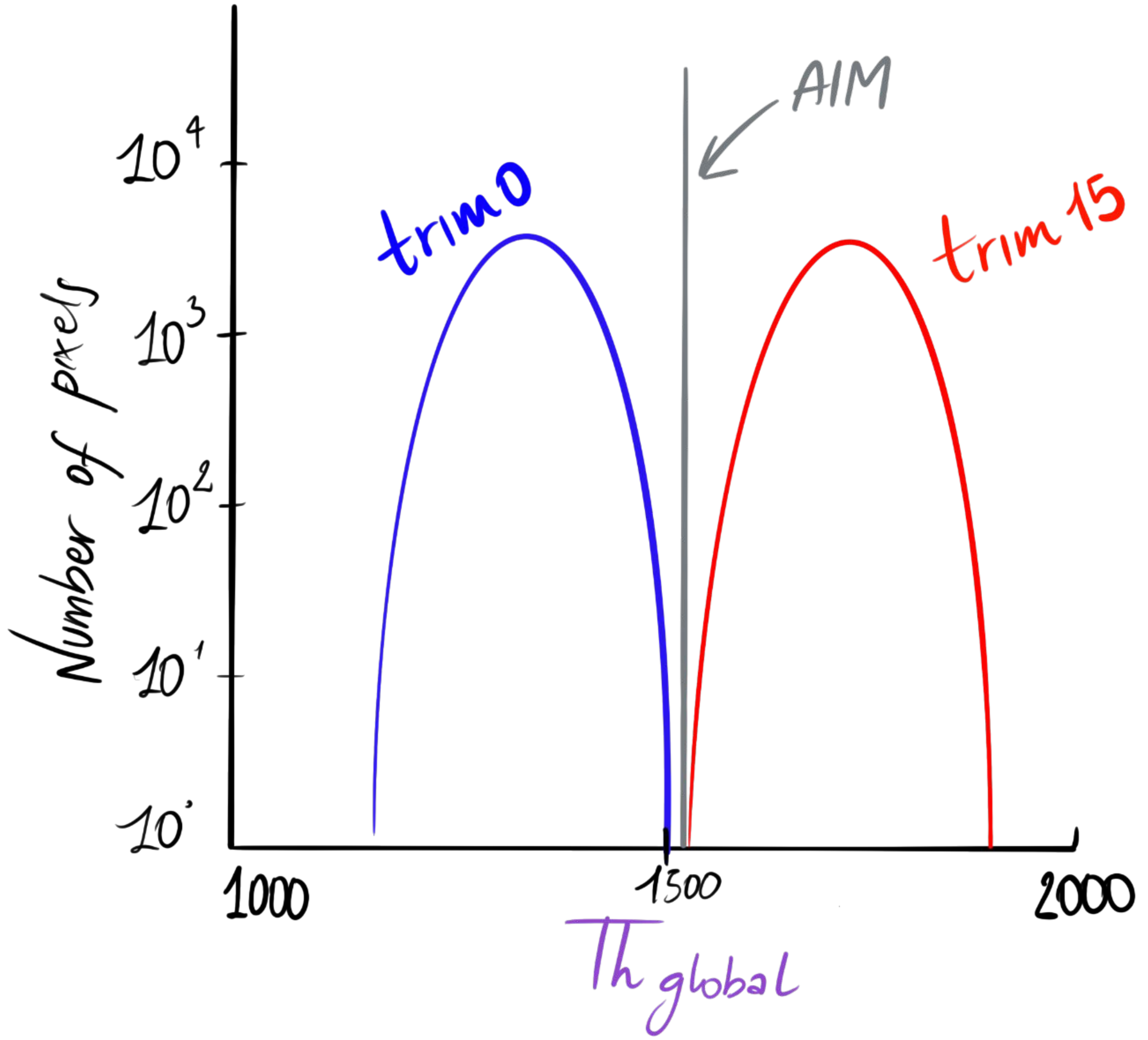
Goal: same pixel output for same given input

$$Th_{local} = Th_{global} + trim$$

Noise threshold set for each ASIC (↑ Th_{global})

4-bit fine-tuning offset parameter for each pixel (↑ $trim$)

Noise distribution

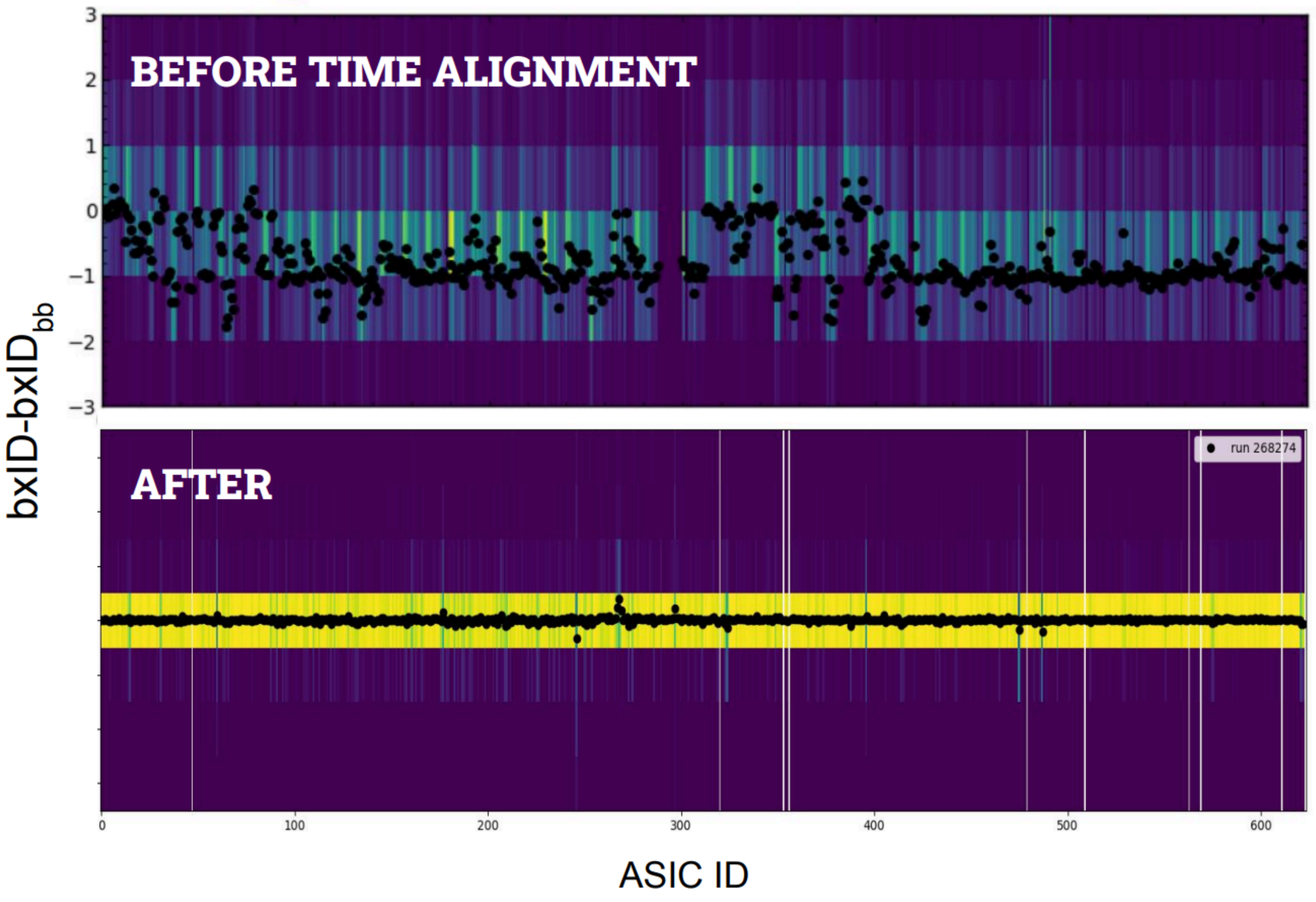


- Conduct scans at minimum and maximum trim values for each pixel.
- Set target threshold at midpoint between the two distributions
- Compute trim values for each pixel, aiming for a distribution peaking at the target threshold.
- Conduct noise run to ensure no noisy pixels are detected, confirming successful equalisation.

VELO Commissioning
Time alignment

Goal: ASICs responding at the same time

- **Coarse Alignment**: aligns VELO responses to the LHC clock using isolated bunches, adjusting delays in increments of one bxID.
- **Fine Alignment**: ensures consistent response to both low and high amplitude signals within the same bxID, adjusting electronic phases to correct for signal delay variations shorter than one bxID.

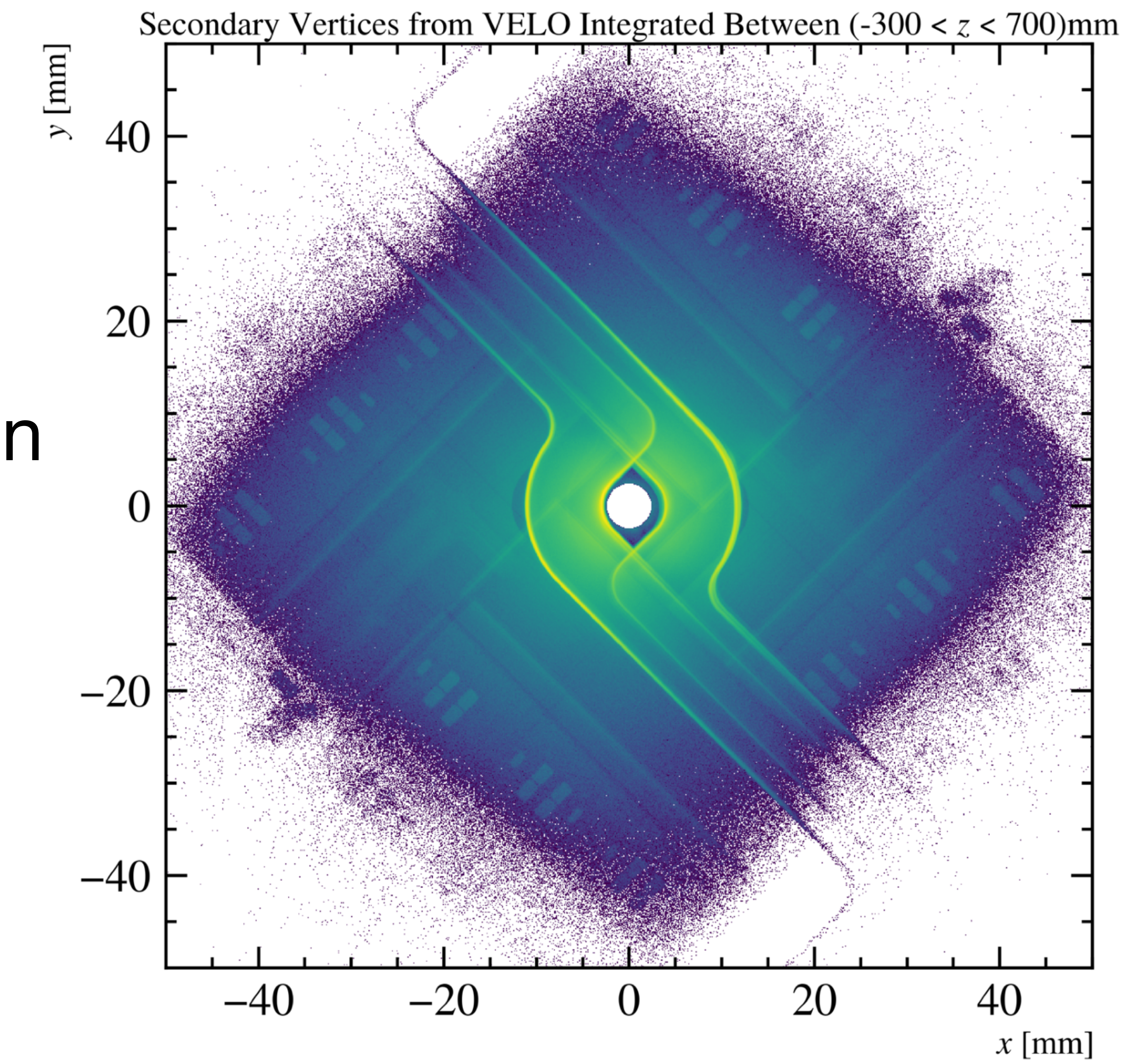


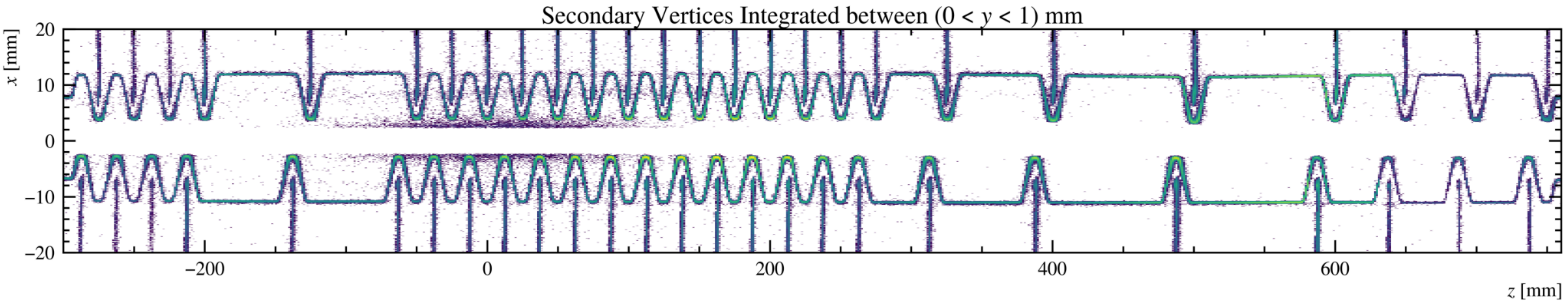
VELO Commissioning
Tomography

Equalisation + time alignment ⇒ vertex reconstruction

Using vertices with a least 3 tracks it's possible to:

- reconstruct particle interaction with material (modules and RF box)





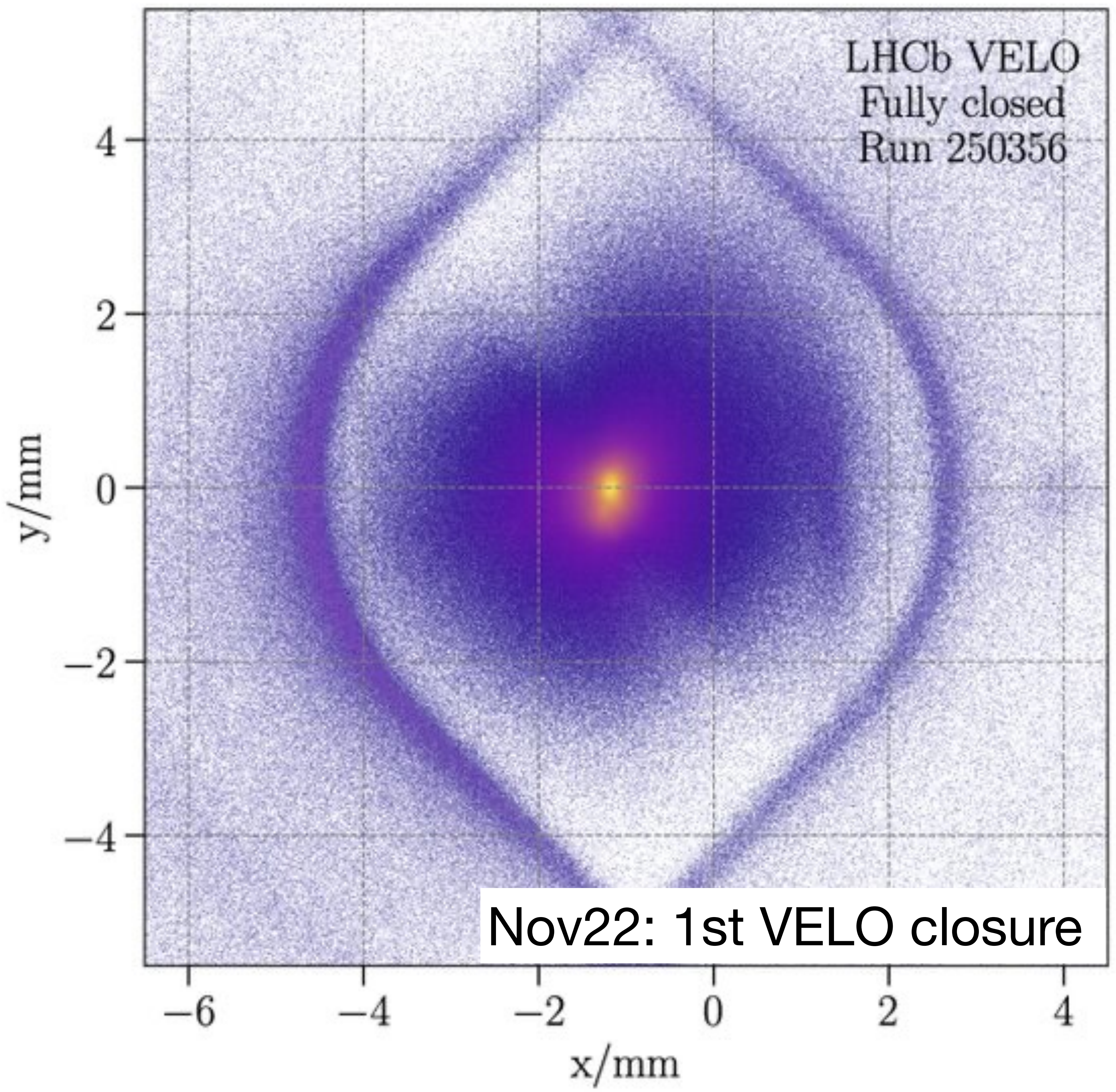
VELO Commissioning
Tomography

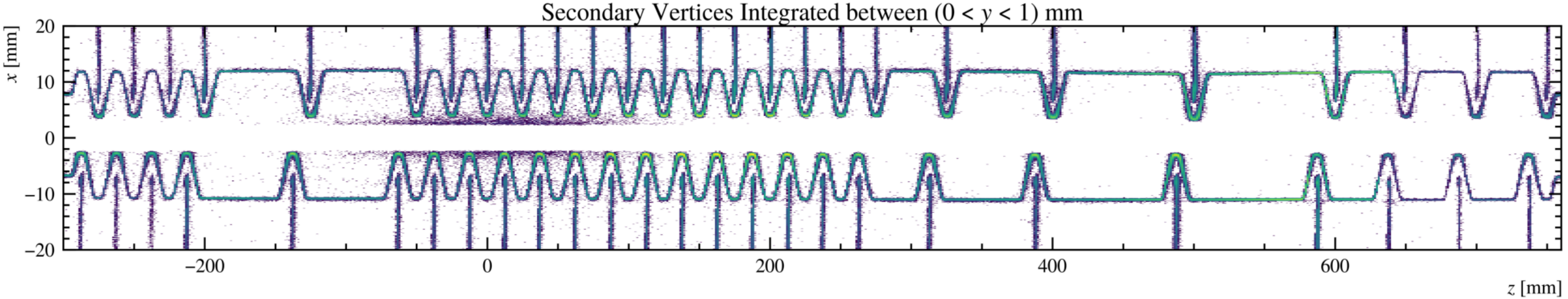
Equalisation + time alignment ⇒ vertex reconstruction

Using vertices with a least 3 tracks it's possible to:

- reconstruct particle interaction with material (modules and RF box)

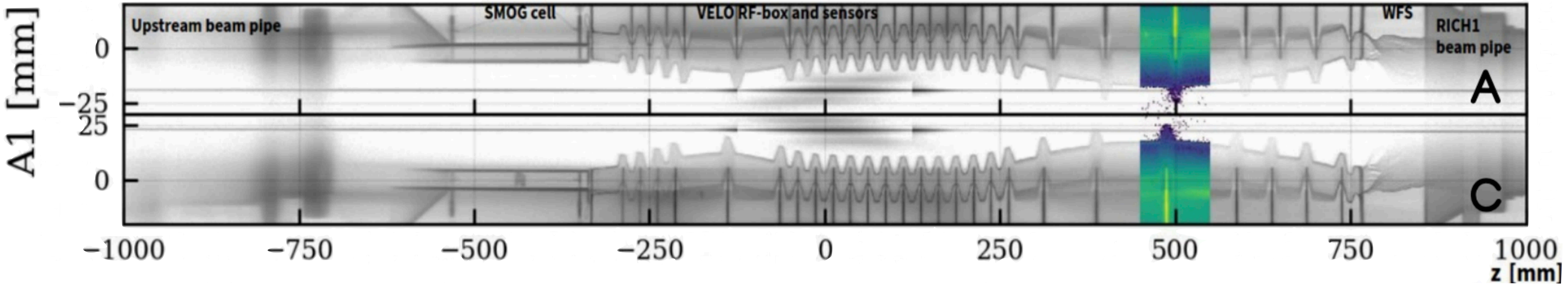
- closing/centering the VELO halves around the beam





RF box incident
January 2023

- Loss of control in LHC vacuum protection system: a pressure differential exceeded safe limit (200mbar vs 10mbar)
- Permanent deformation of the RF foil
- VELO modules and cooling not damaged and operational
- VELO kept partially open (24.5mm per side) during 2023 data taking



Current status

2020

RF box installed

2021

2022

VELO assembled

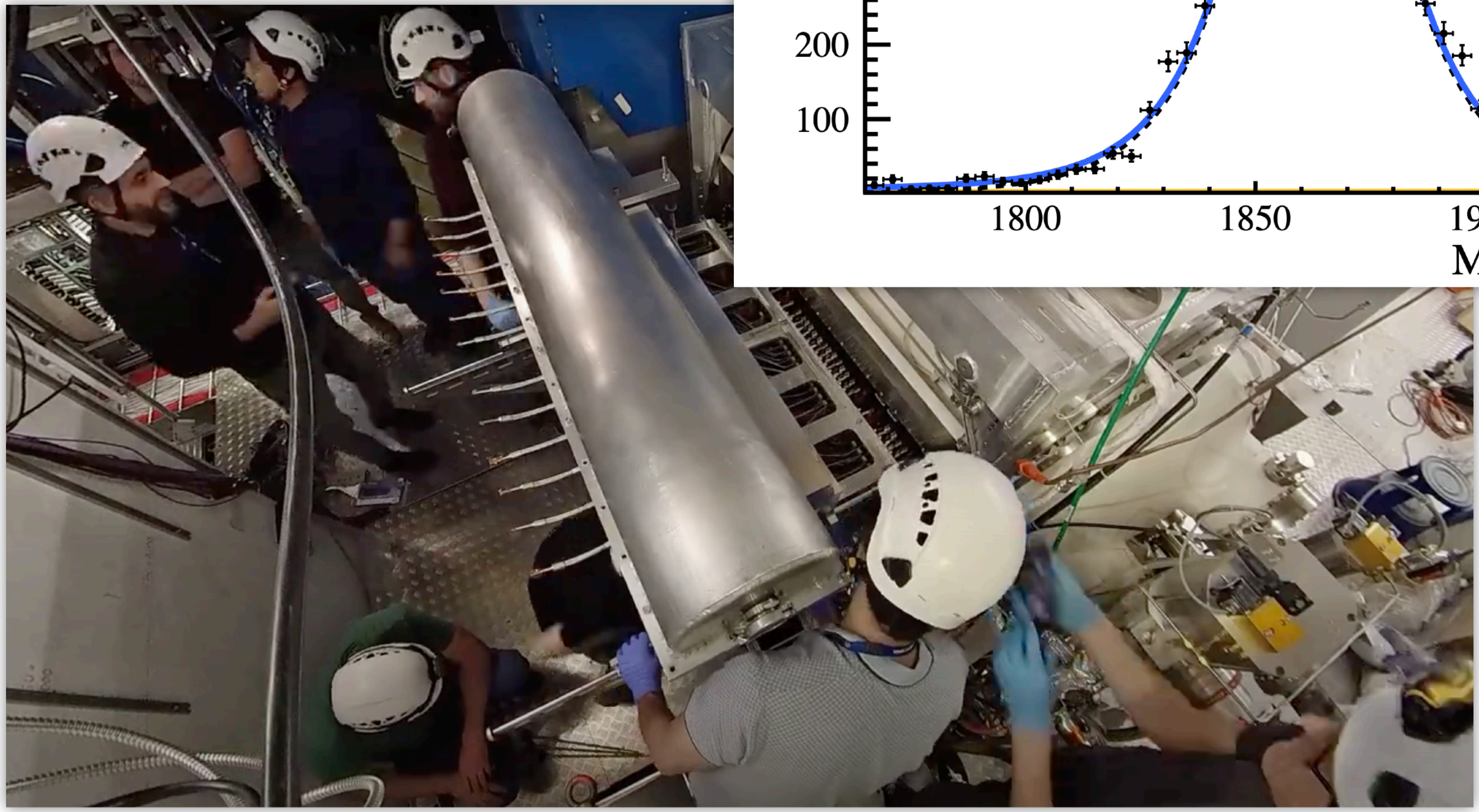
1st VELO closure

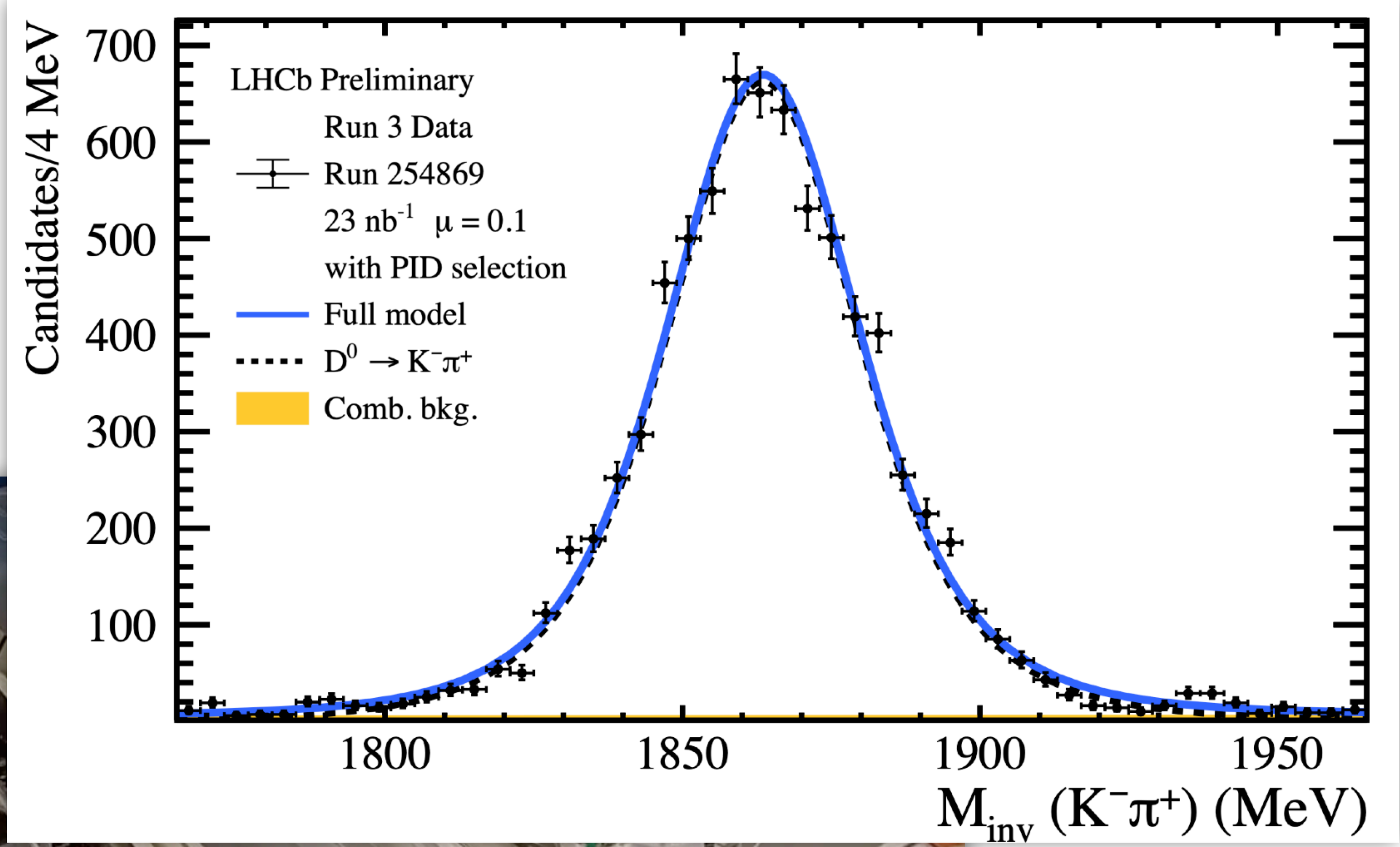
2023

RF box incident

2024

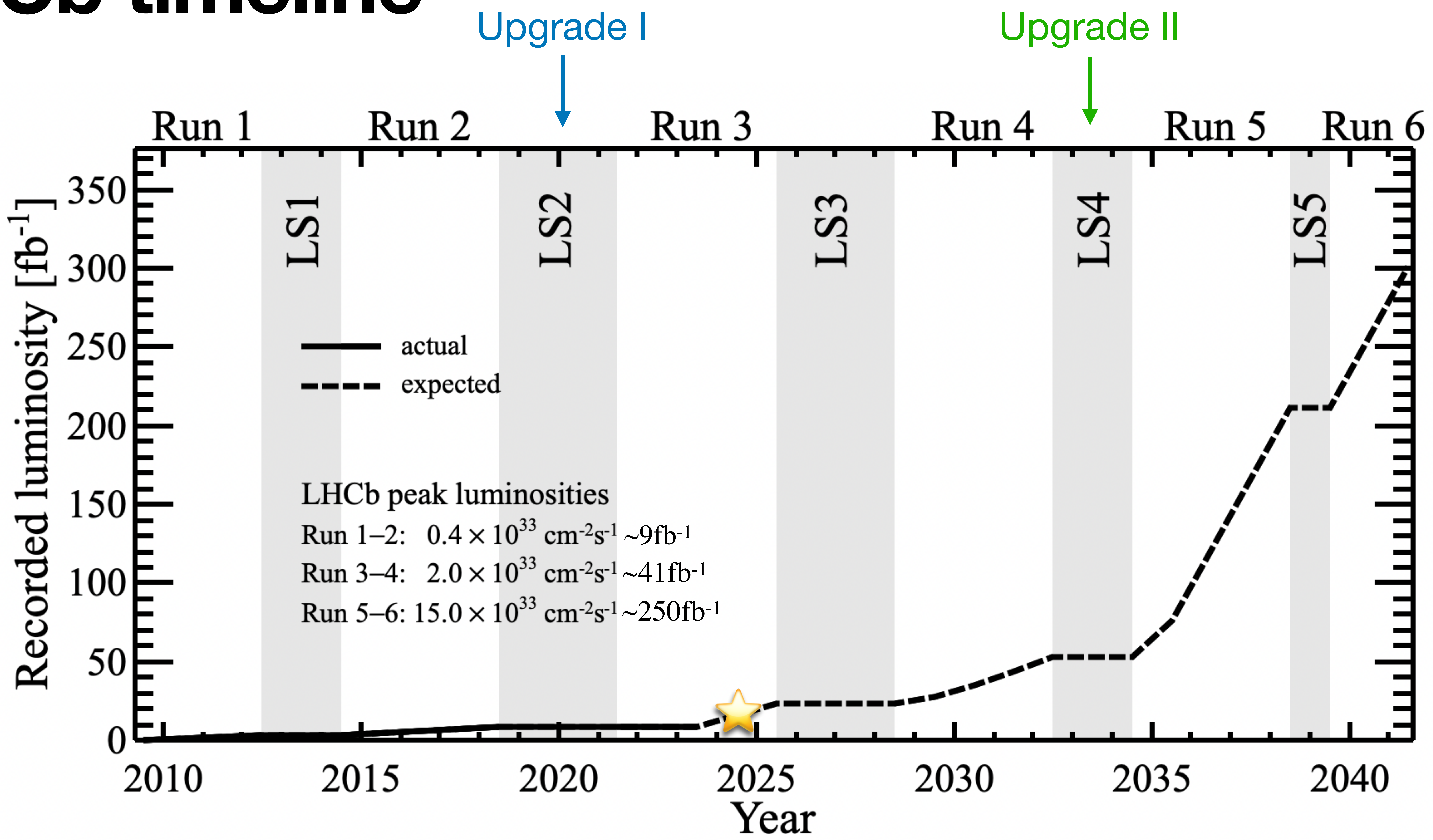
RF box replaced





LHCb VELO Position: IN Gap: 0.0 mm

LHCb timeline



Need for VELO Upgrade II

High-Luminosity LHC challenges

- More particles: the increase in luminosity is particularly challenging for the VELO, which has the highest track density.

- More radiation damage: necessity of robust detector components to maintain long-term operational stability.

Current VELO limitations

- Existing modules not optimised for higher data rates

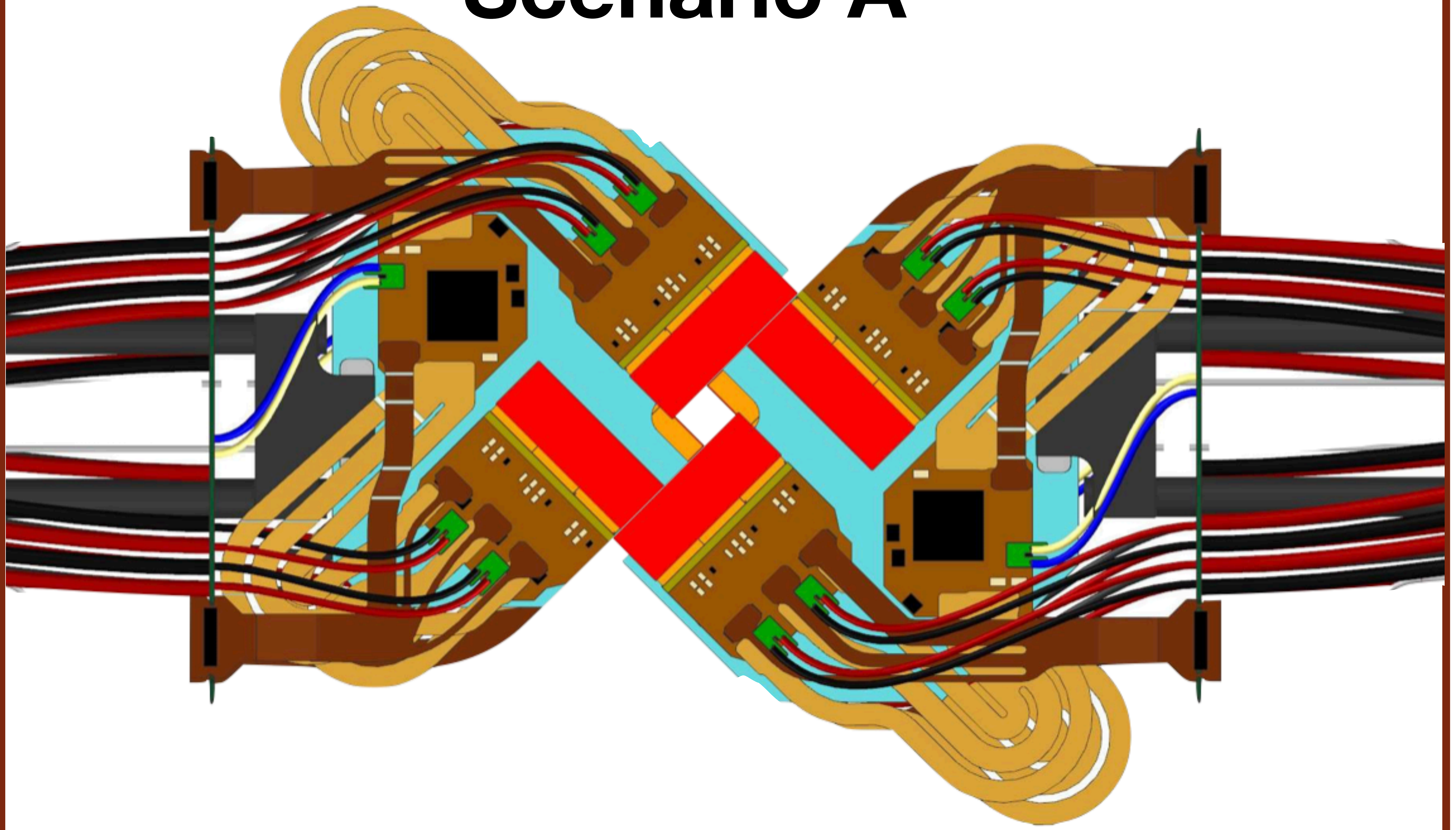
- Need of ultra-fast timing for improved resolution

Upgrade goals

- Maintain and enhance performance with 7 times more pile-up wrt Run3

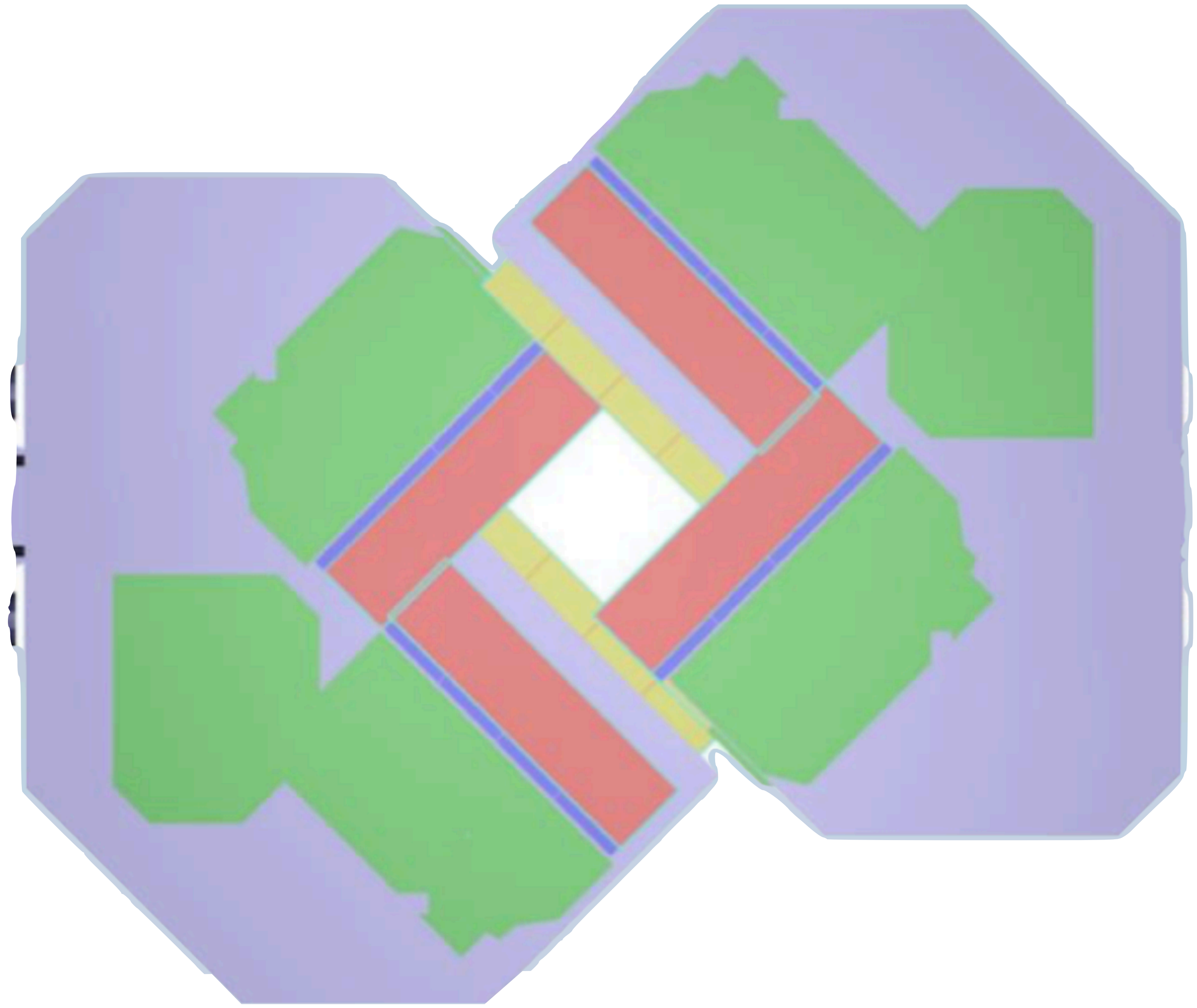
Possible VELO layouts

Scenario A



- Same geometrical layout as Upgrade I
- Intense radiation: may require yearly replacement
- High data rates

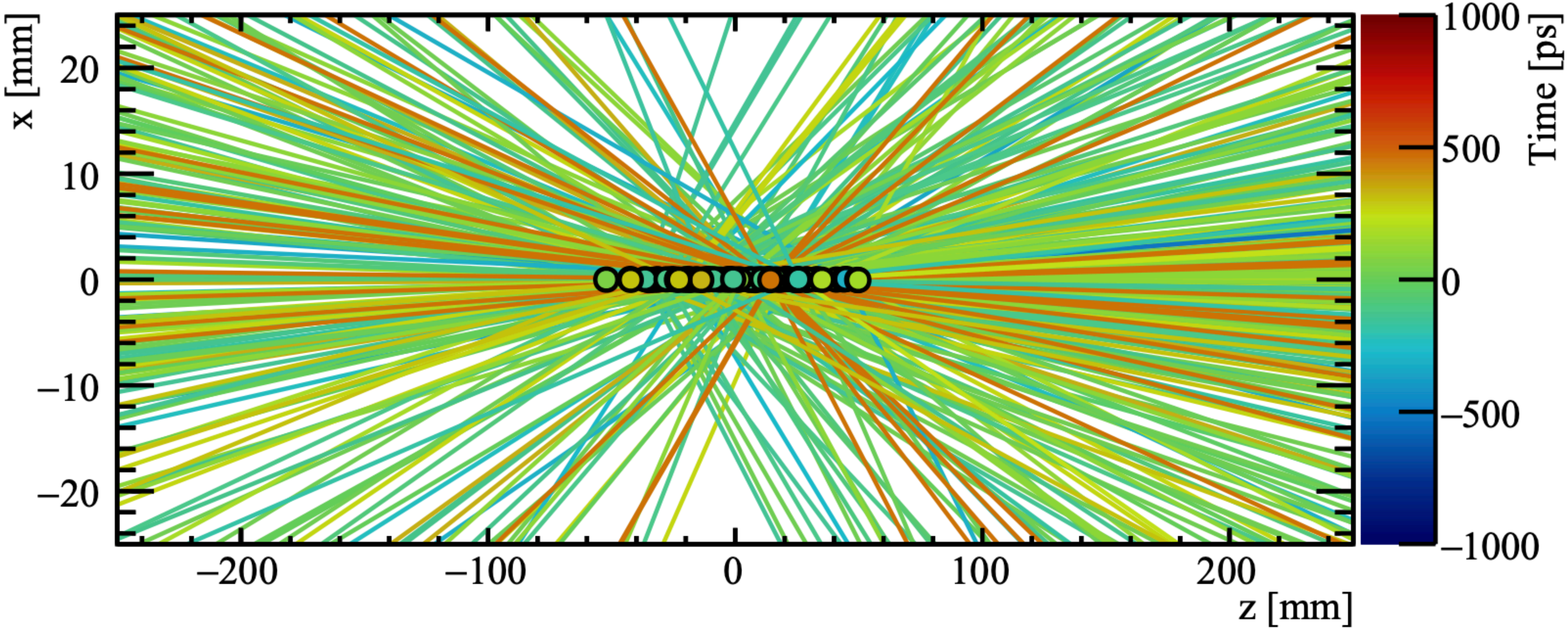
Scenario B



- Increased distance from beams (from 5.1mm to 12.5mm)
- Smaller pixel pitch (from 55μm to 42μm)
- Technologies similar to Upgrade I

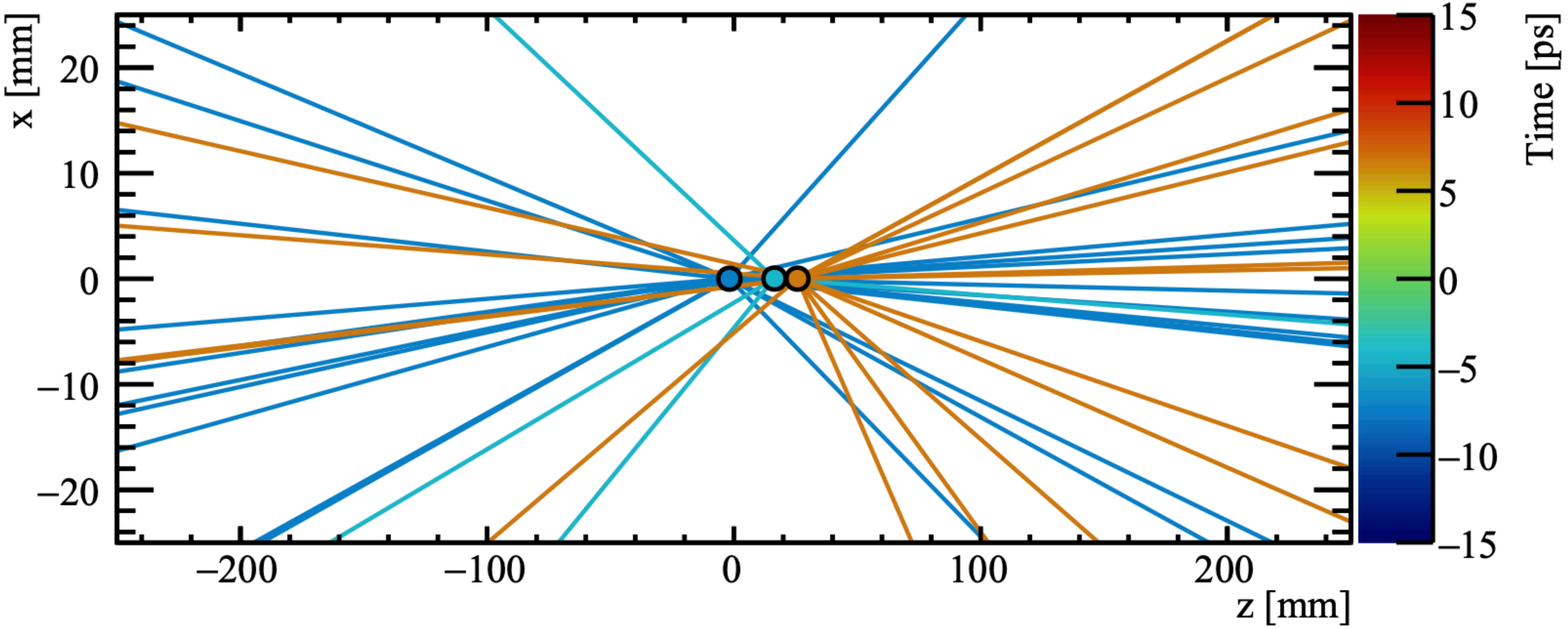
Impact of temporal information

Typical pp collision: ~42 interactions per bunch crossing

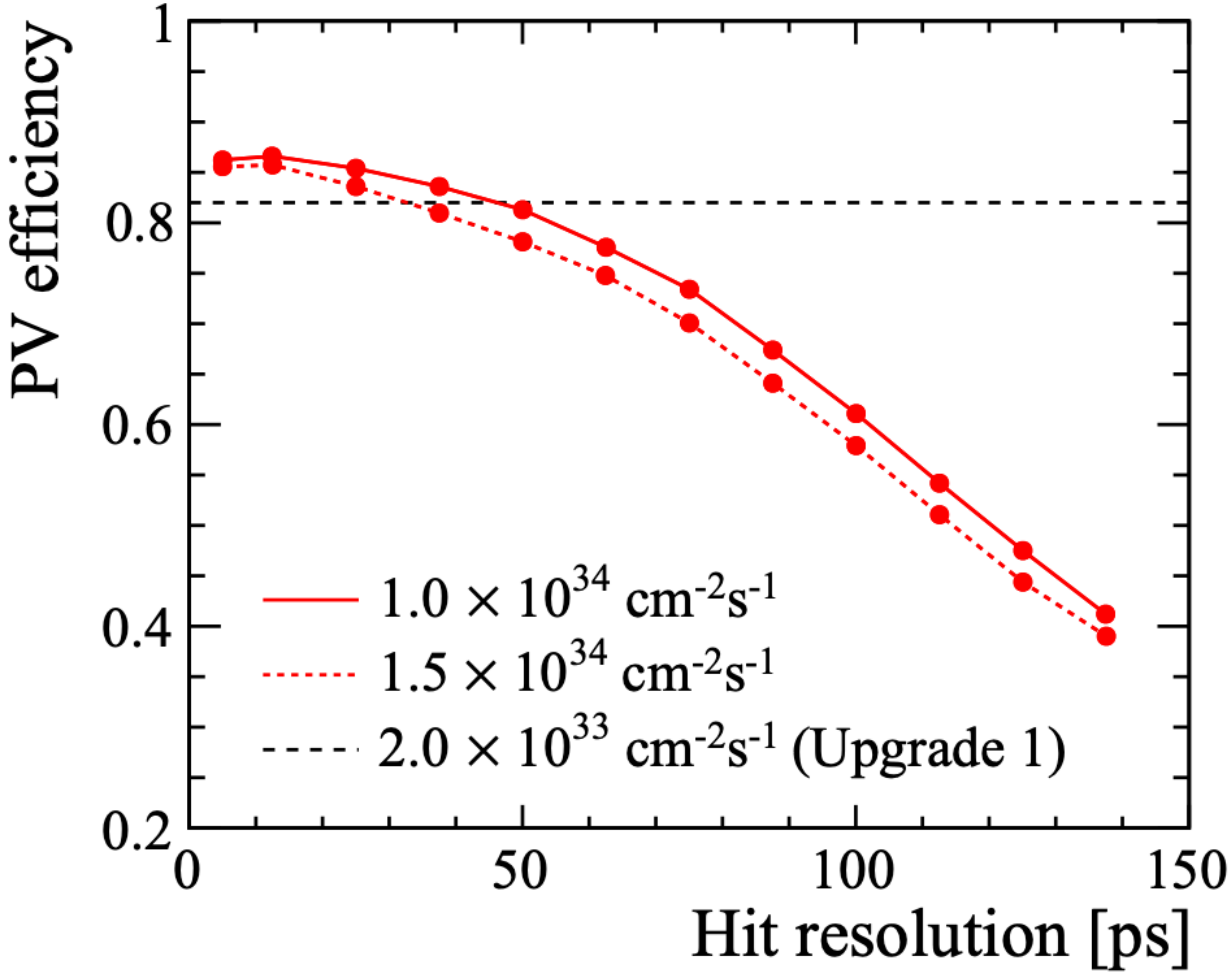


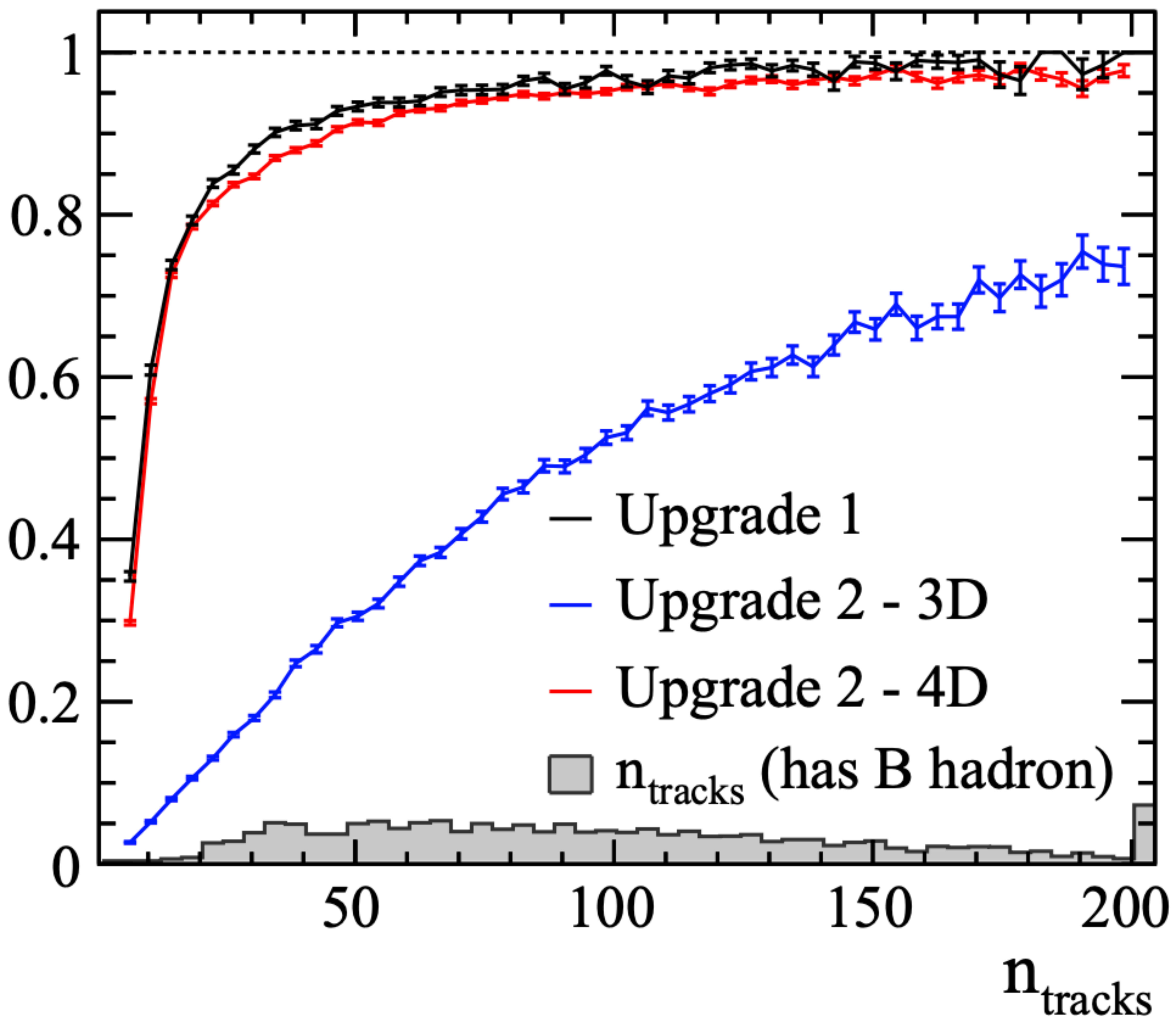
Impact of temporal information

Timing information reduces the effective pile-up.



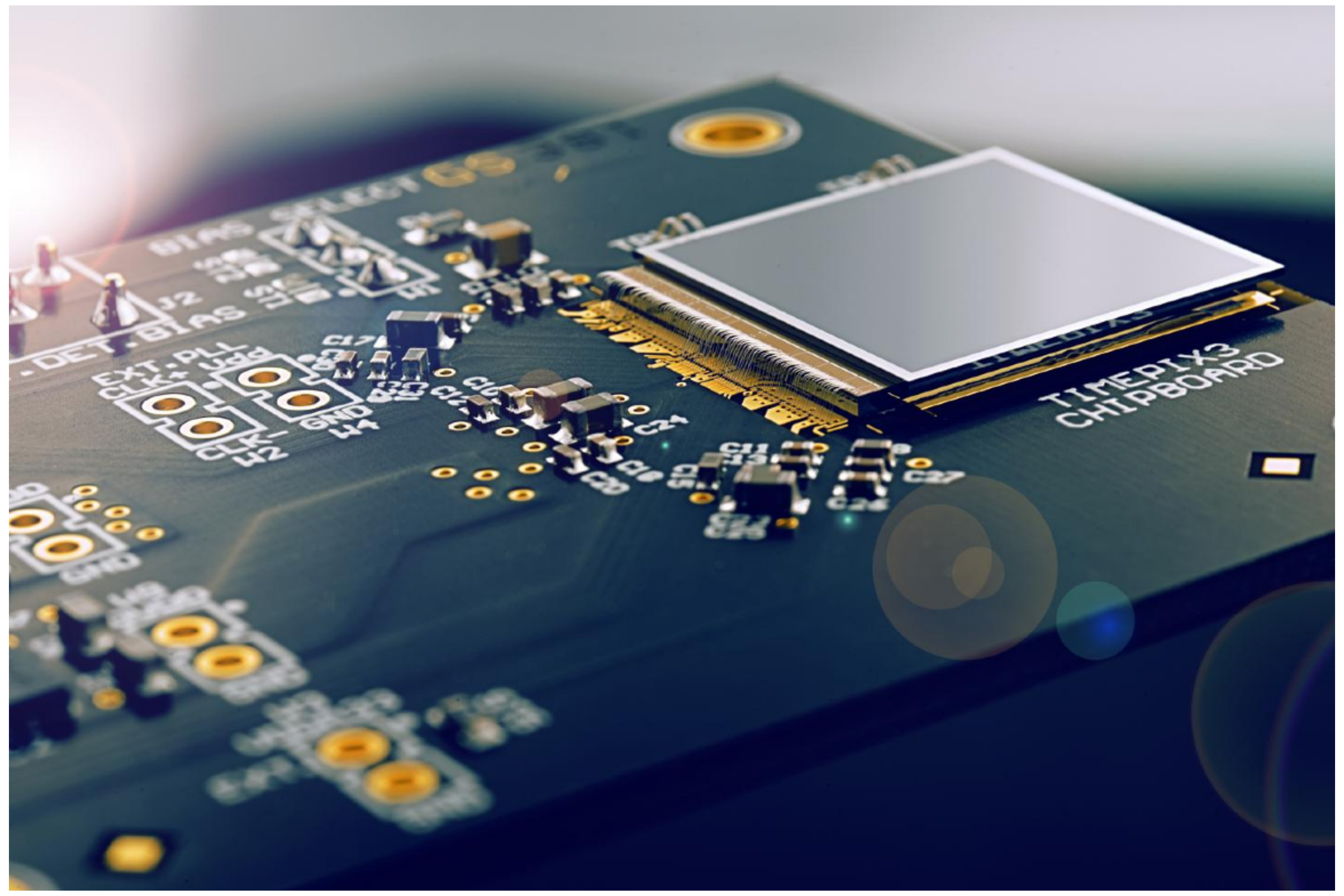
Impact of temporal information (Scenario A)

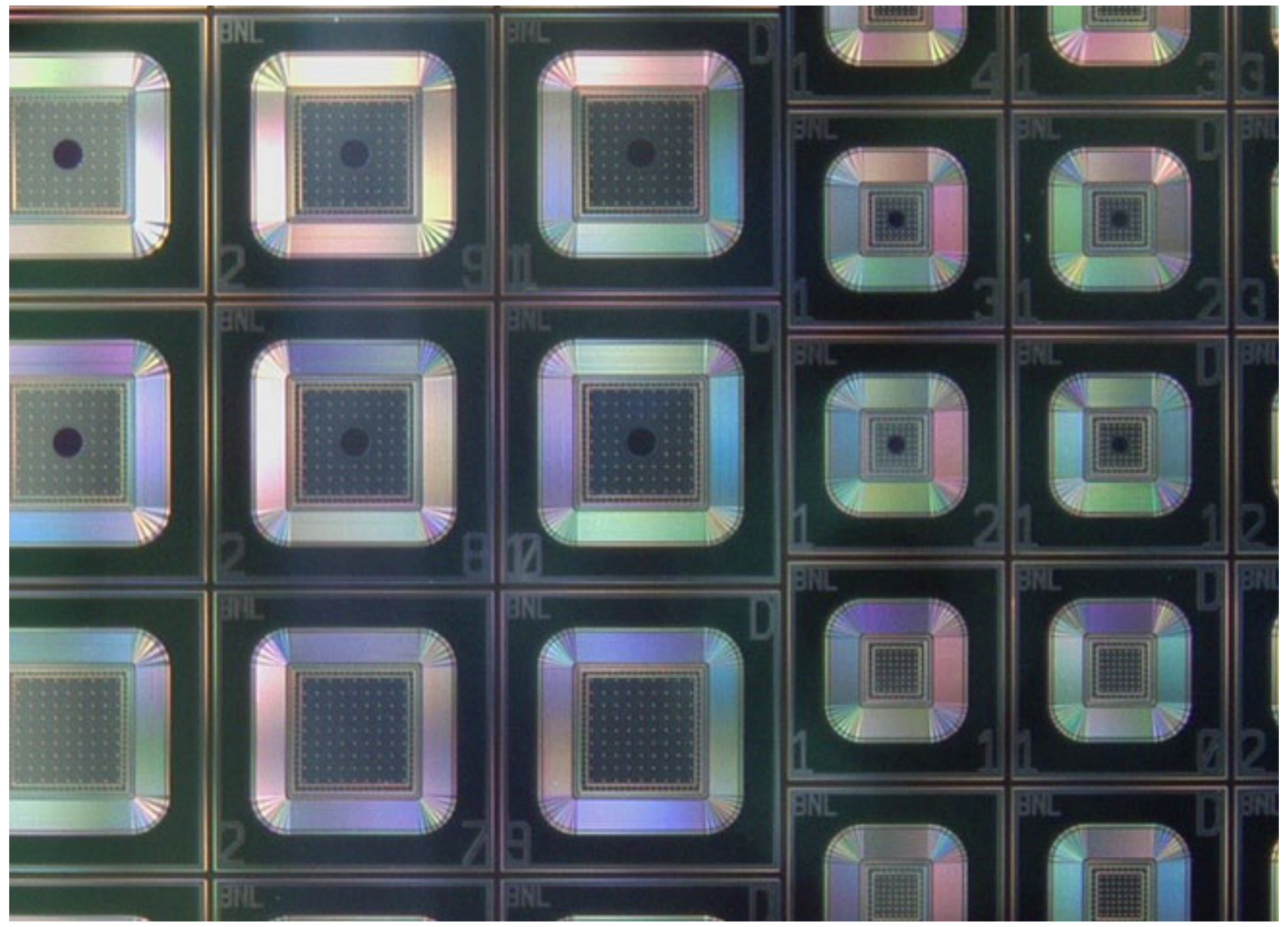


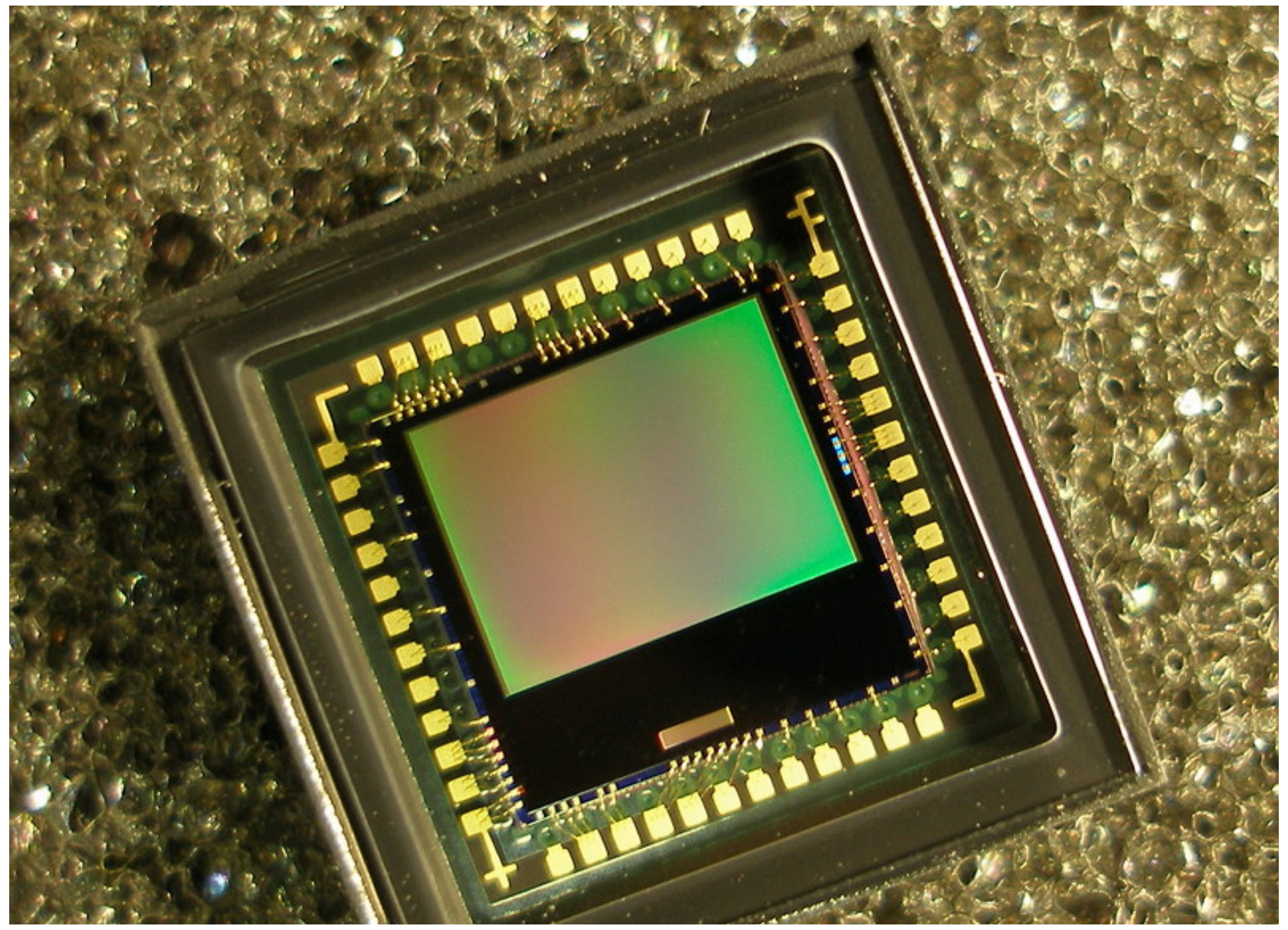


Candidate technologies for VELO Upgrade II

Each candidate offers unique advantages but also challenges





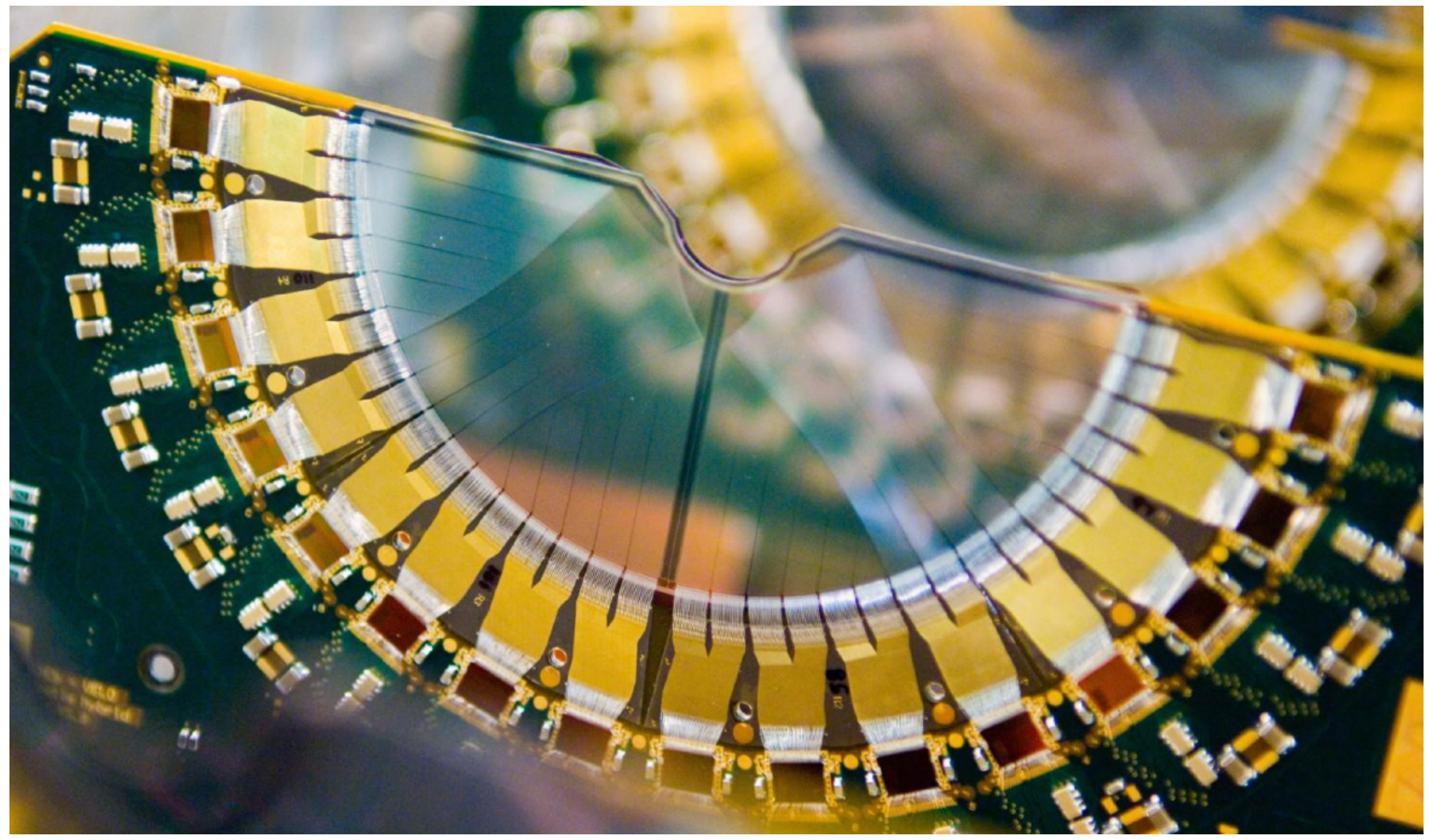


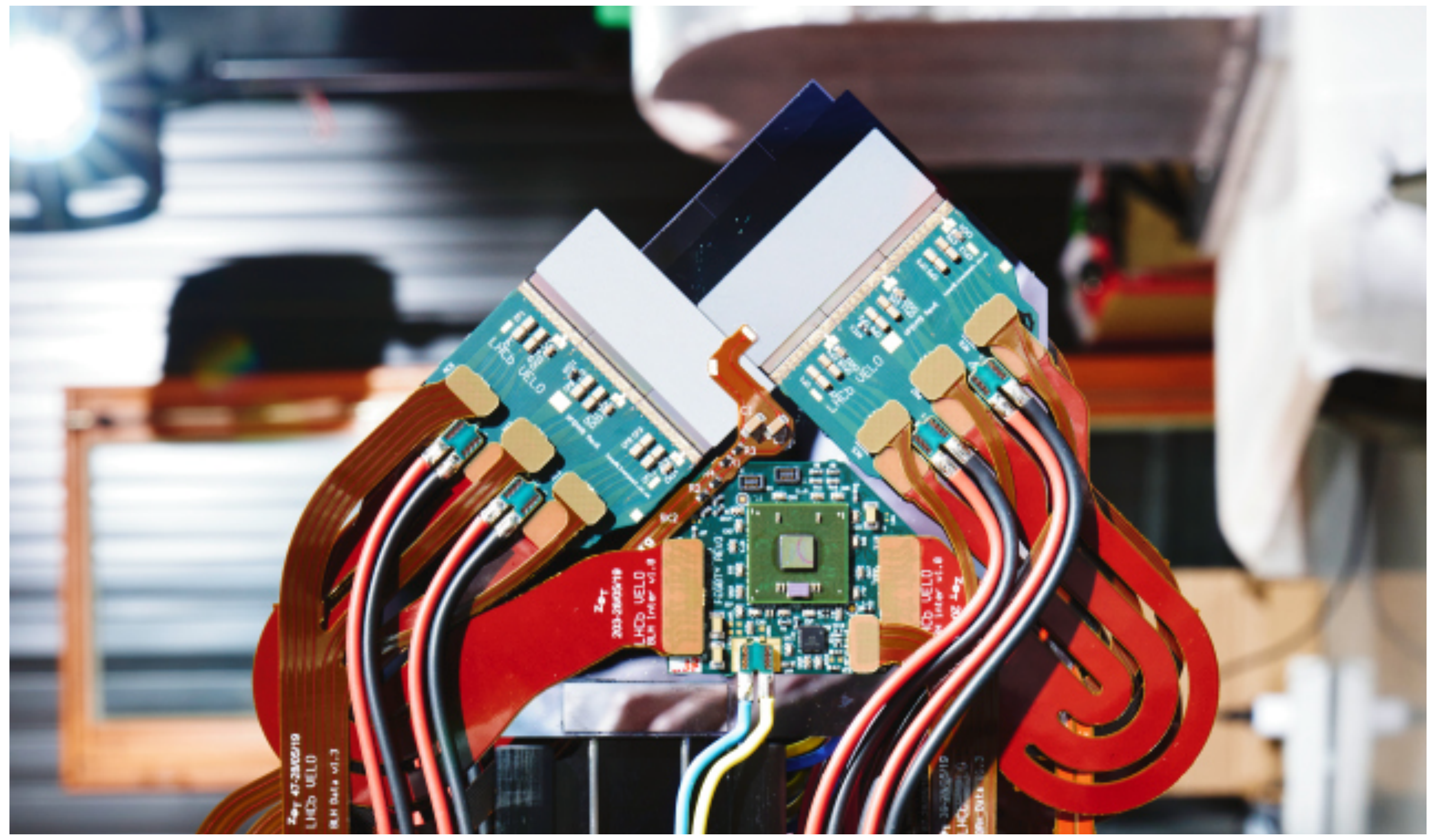
Continued R&D to optimise each technology for VELO Upgrade II.

Optimal technology: a balance of performance, cost, and fabrication complexity.

Conclusions

- VELO is crucial for LHCb, providing precise tracking and vertex reconstruction.
- Demonstrated exceptional performance in the first two years.
- Upgrade-II aims to handle higher collision rates and increased data flow.
- Integration of precise timing information will enhance track discrimination and vertex resolution.
- Studies for Upgrade-II are underway, with the detector planned to be installed in 2033.





Thanks for your attention!

Any questions?

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