

# LHCb Upgrade II

Klaas Padeken

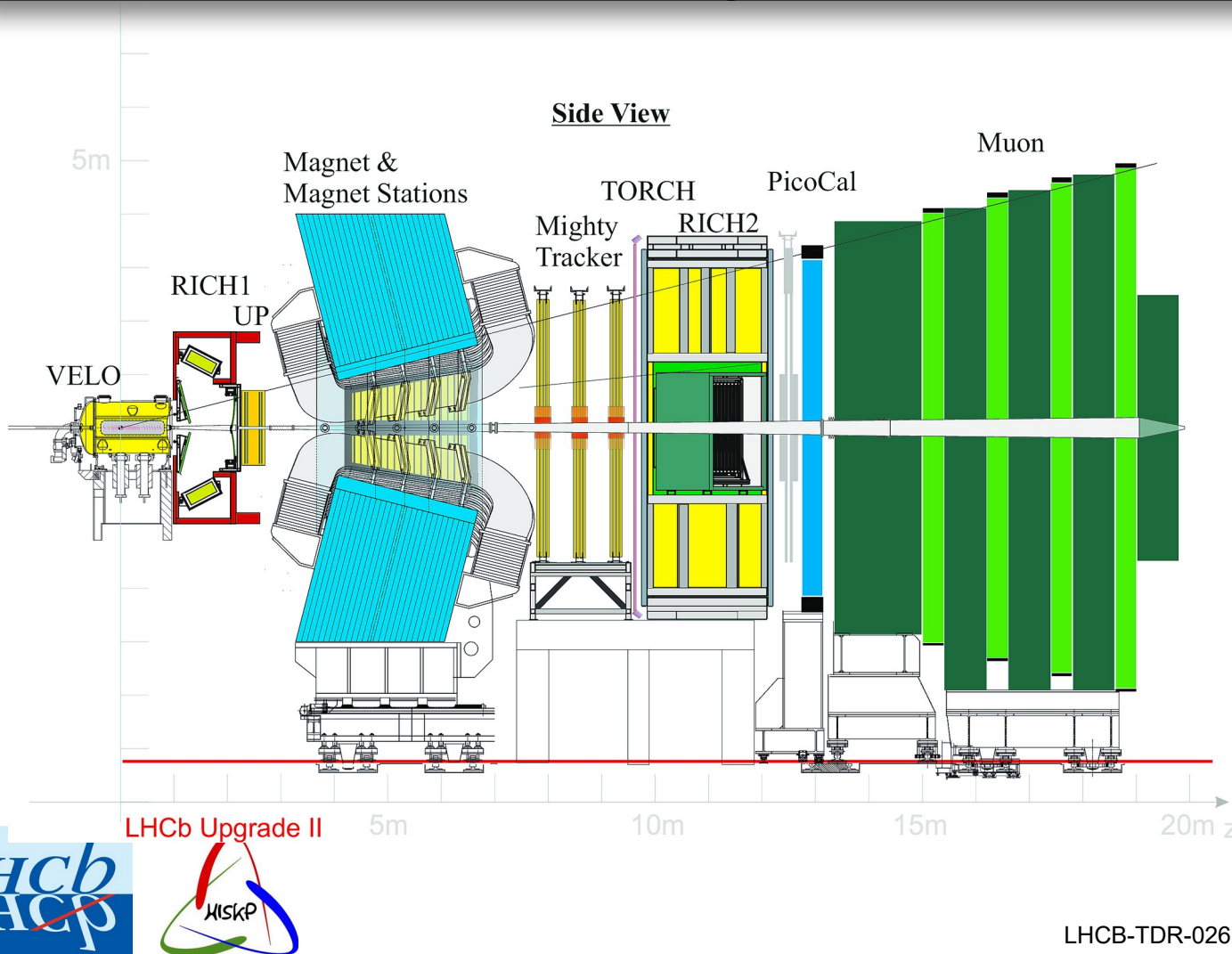


# General Introduction

LHCb Upgrade II

# The Upgrade II Detector (2034/2035)

Without a major upgrade to all detectors LHCb will not be able to run at these high luminosities.



## Velo

- 4D tracks with  $<20$  ps
- $1.2 \times 10^{12}$  tracks/cm<sup>2</sup> at  $r=1$ cm

## UT

- HVCMOS
- 9.0 Gbps

## Magnet Stations

- new

## MT/SciFi

- Higher occupancy and radiation

## RICH

- 50ps timing
- SiPM (higher resolution)

## TORCH

- new (25ps timing layer)

## ECAL, HCAL

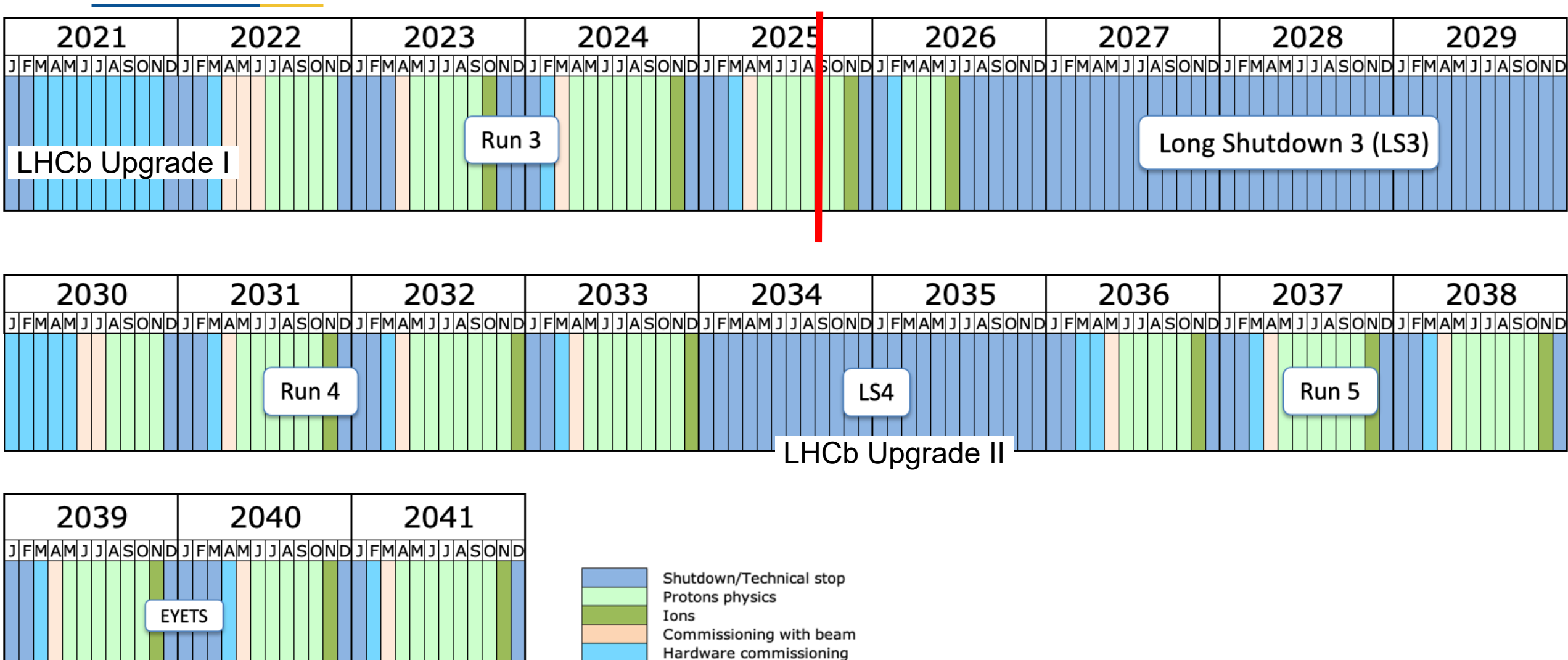
- SpaCal+Shashlik
- time + space resolution

## MUON Stations

- higher granularity
- maybe shielding

# Timeline

Now

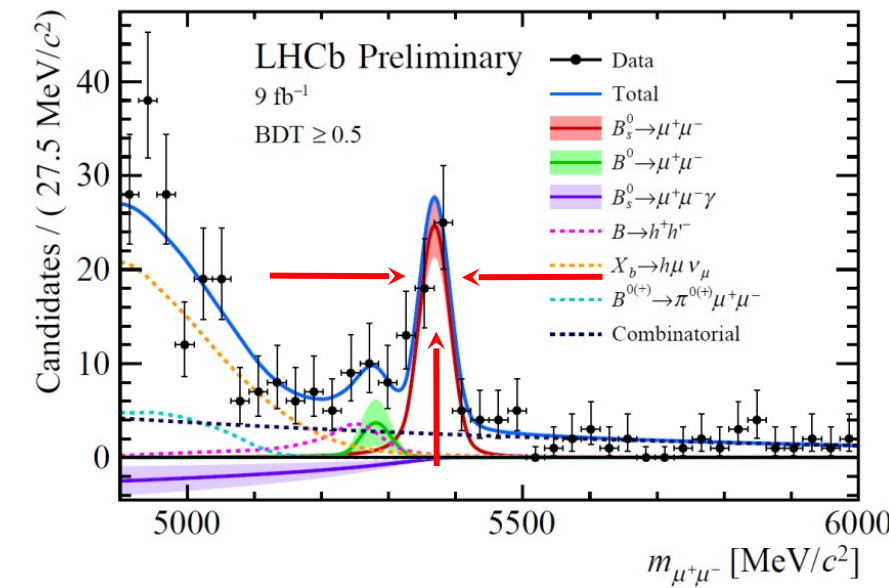
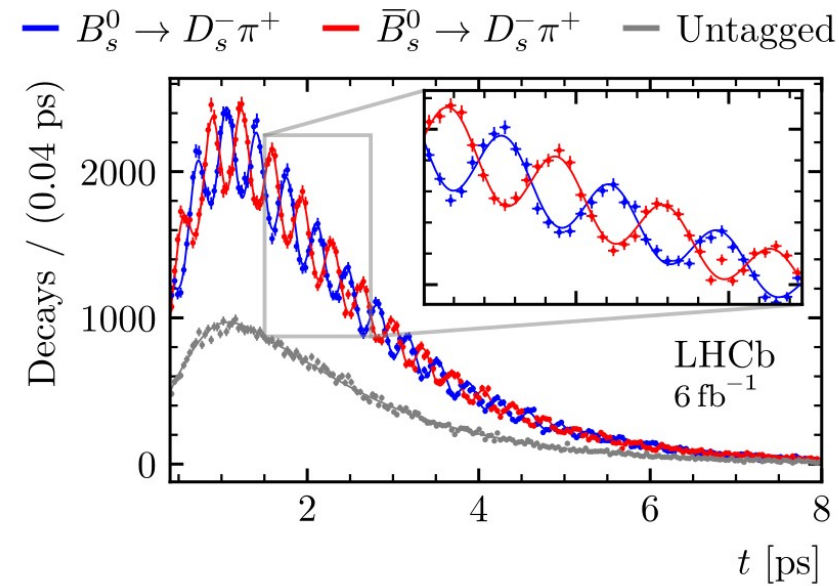
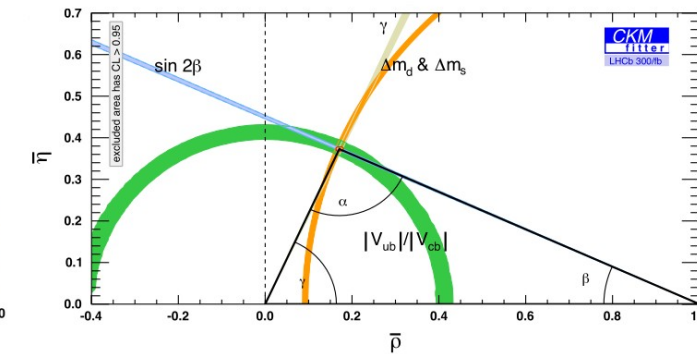
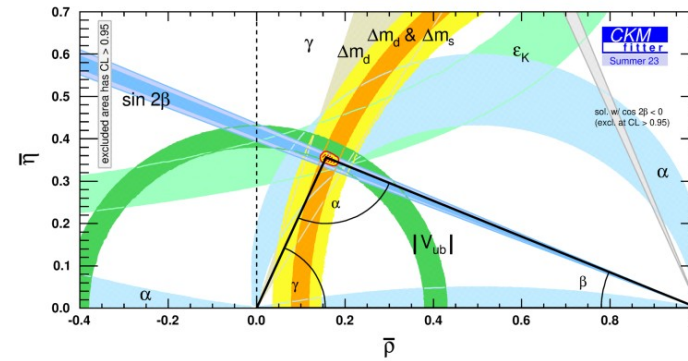




# Goal of the Upgrade

- More statistics
- Higher Precision

→ Better Physics Results



# The Upgrade II Conditions (2034)

Run 3-4

$$2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

$$50 \text{ fb}^{-1}$$

$$\langle \mu \rangle = 7$$

radiation hard

Run 5-6

$$1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

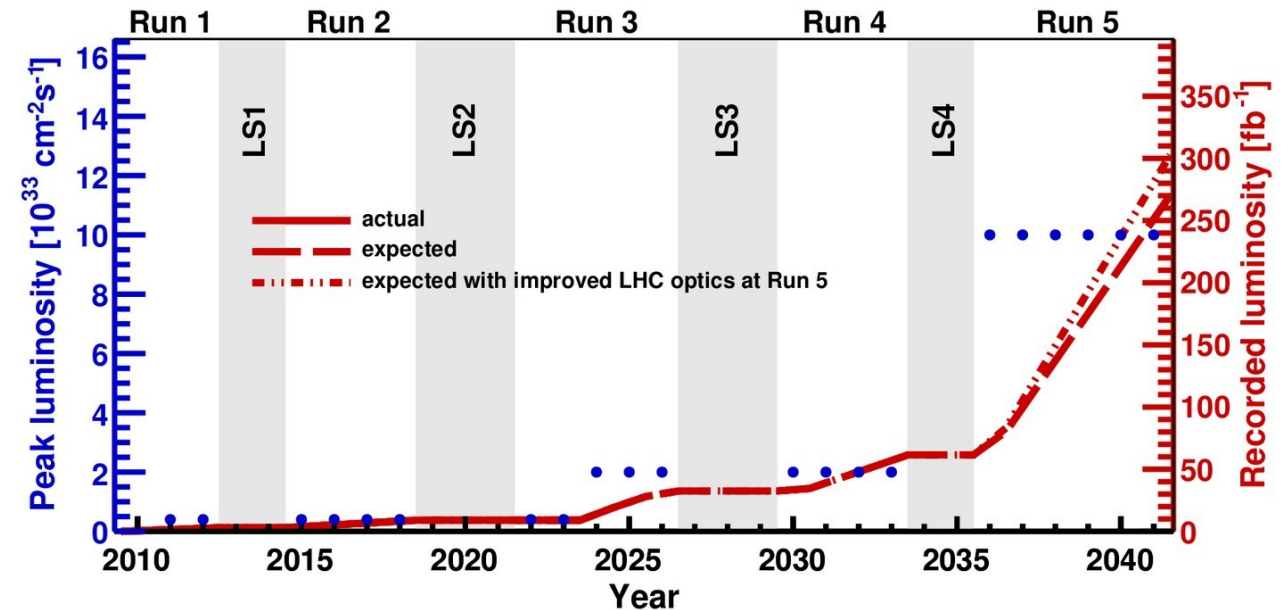
$$250 \text{ fb}^{-1}$$

$$\langle \mu \rangle = 50$$

Current detectors will not work in this radiation environment

Streamless Readout

$$\text{acceptance } \eta = 1.9 \text{ to } 5$$



LHCB-TDR-026



# The Upgrade II Conditions (2034)

Run 3-4

$$2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

$$50 \text{ fb}^{-1}$$

$$\langle \mu \rangle = 7$$

radiation hard

Run 5-6

$$1.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

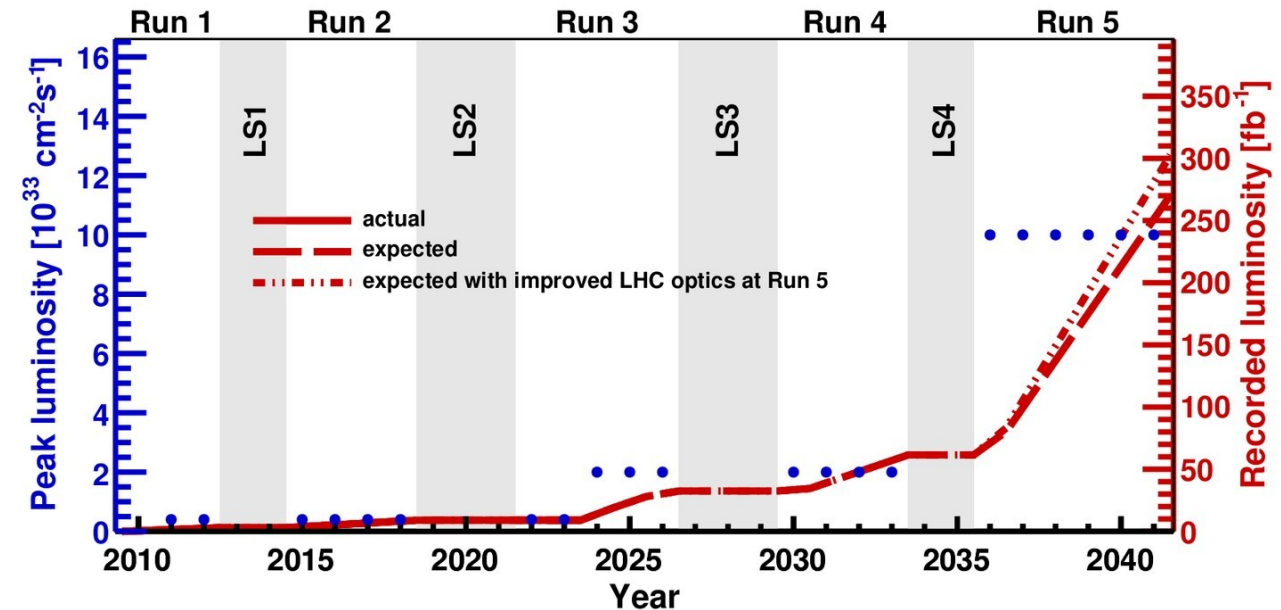
$$250 \text{ fb}^{-1}$$

$$\langle \mu \rangle = 50$$

Current detectors will not work in this radiation environment

Streamless Readout

acceptance  $\eta = 1.9$  to 5



LHCB-TDR-026

Untriggered readout  
@40MHz

# Streaming Readout

LHCb uses no Hardware Trigger

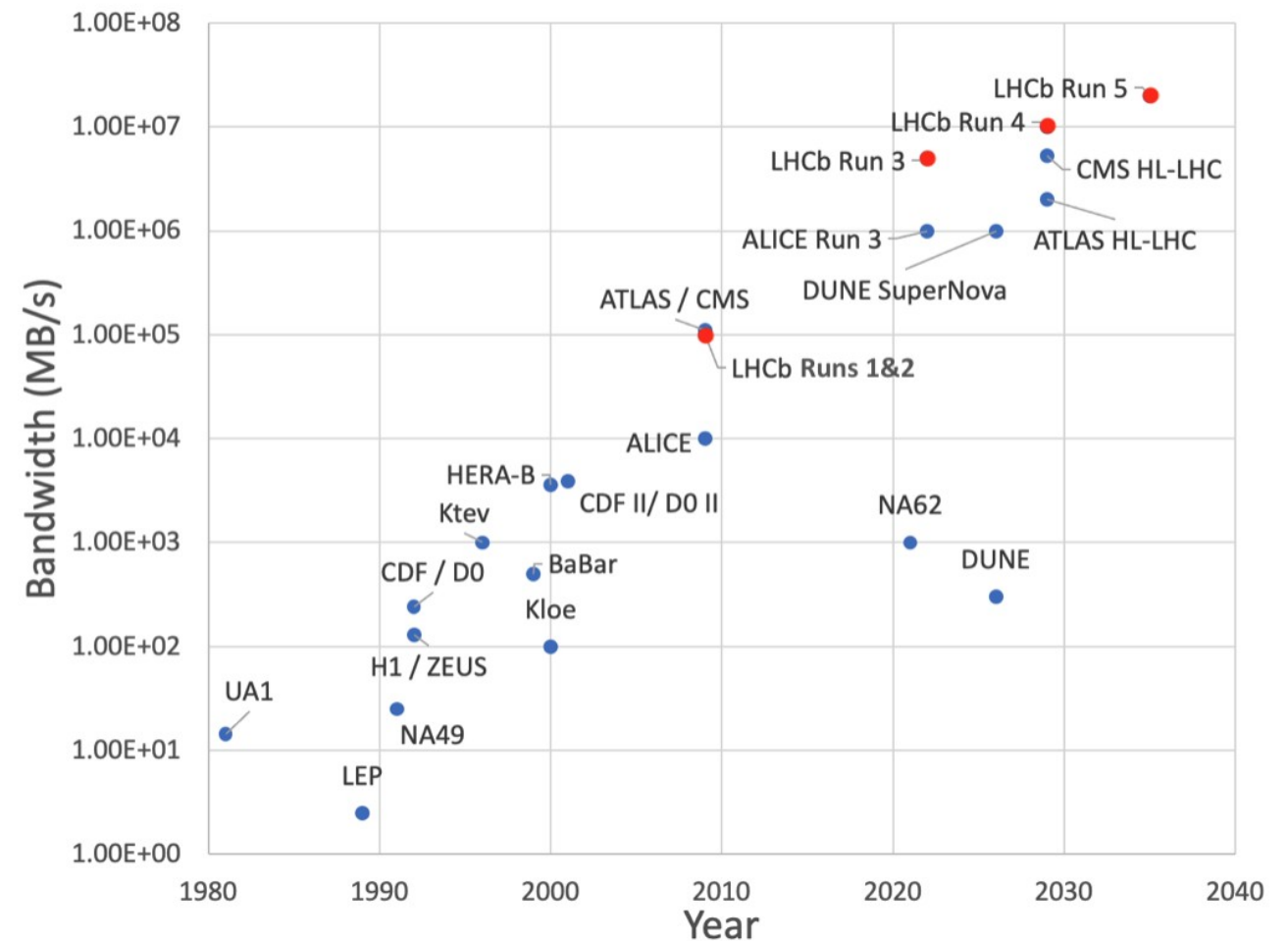
All data is processed and reconstructed

LHCb is the experiment with the worlds highest bandwidth output!

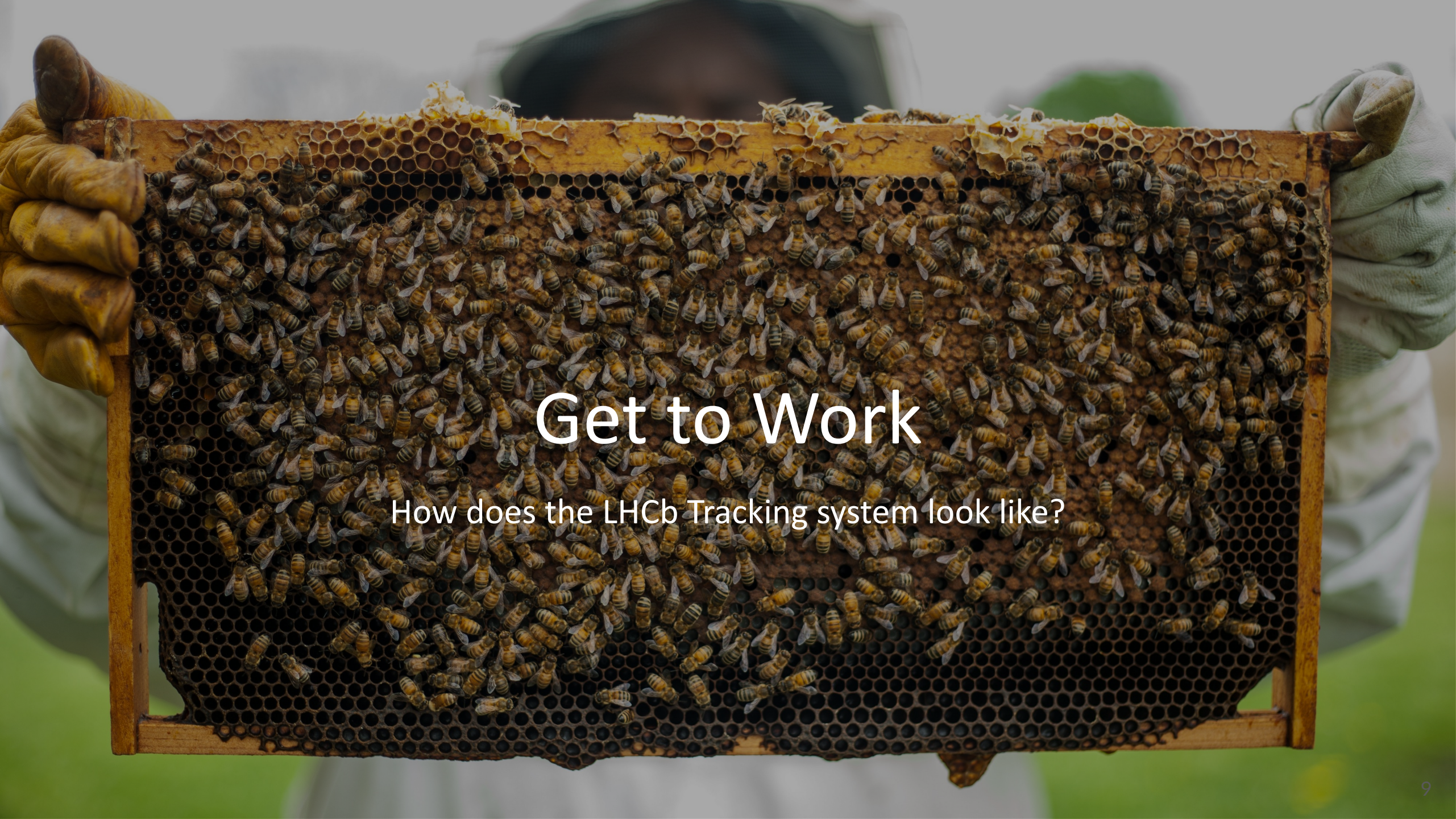
LHCb now is at the level of the coming ATLAS and CMS upgrades  $\sim O(\text{TB/s})$

We will have to 10TB/s in LS3 (new RICH and ECAL

For Upgrade II in LS4 we expect a Bandwidth requirement of 25TB/s





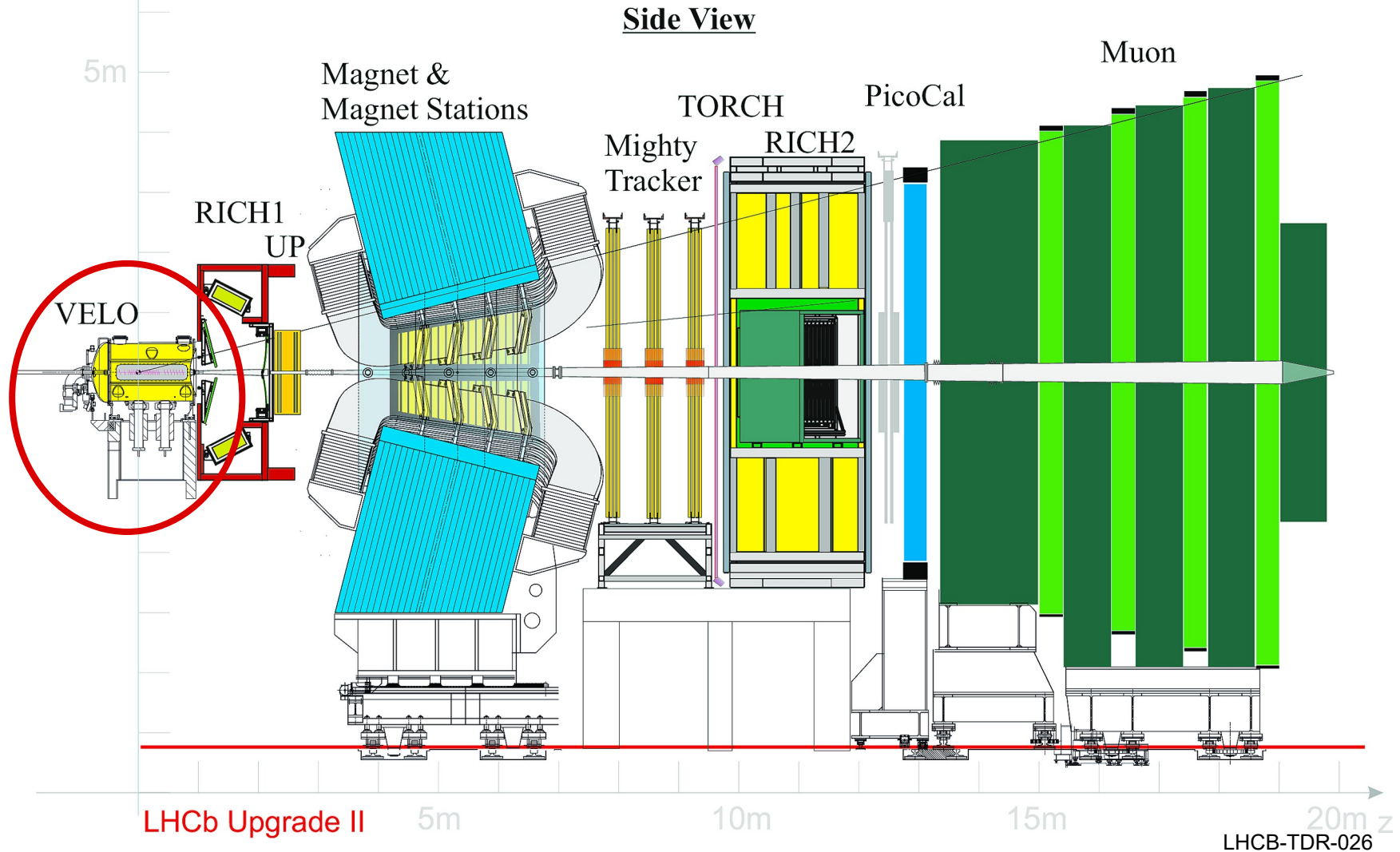


# Get to Work

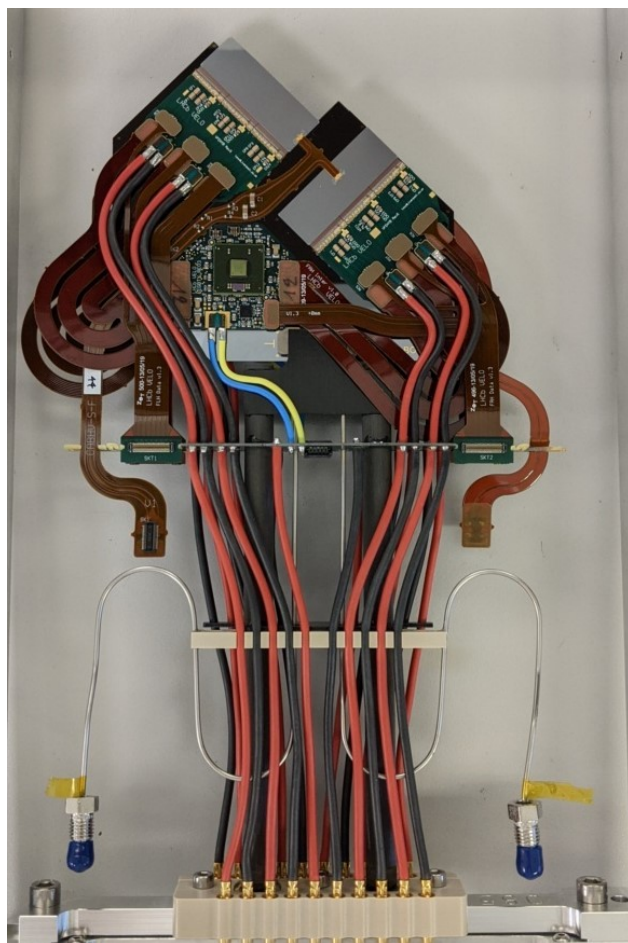
How does the LHCb Tracking system look like?



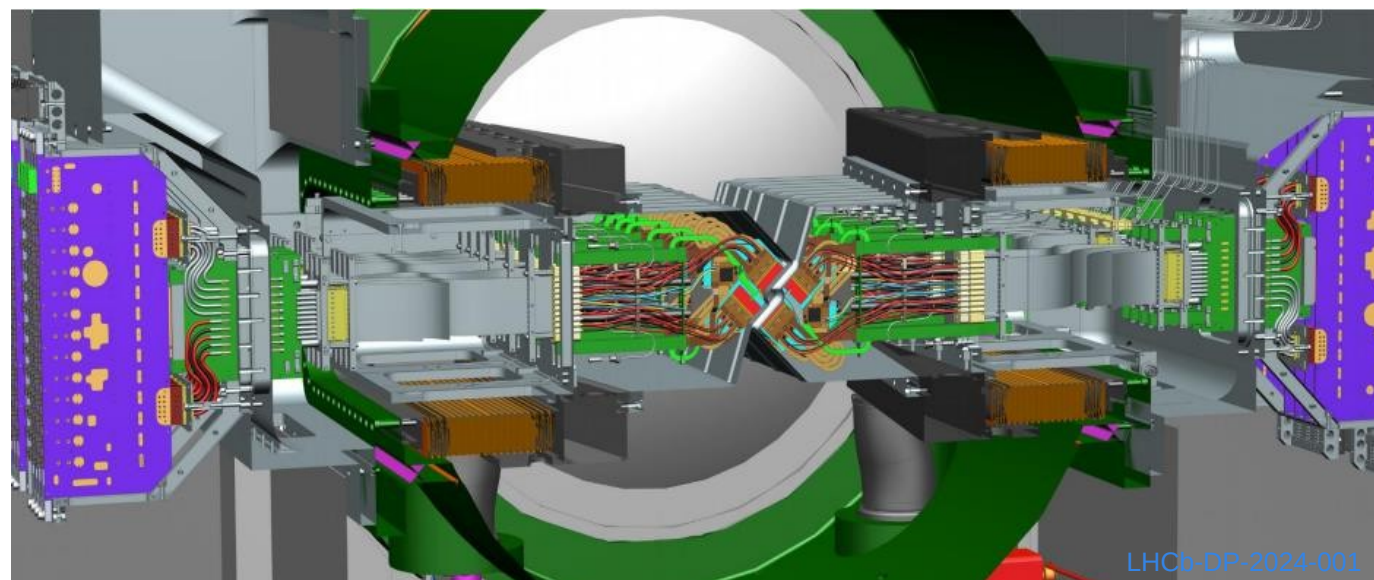
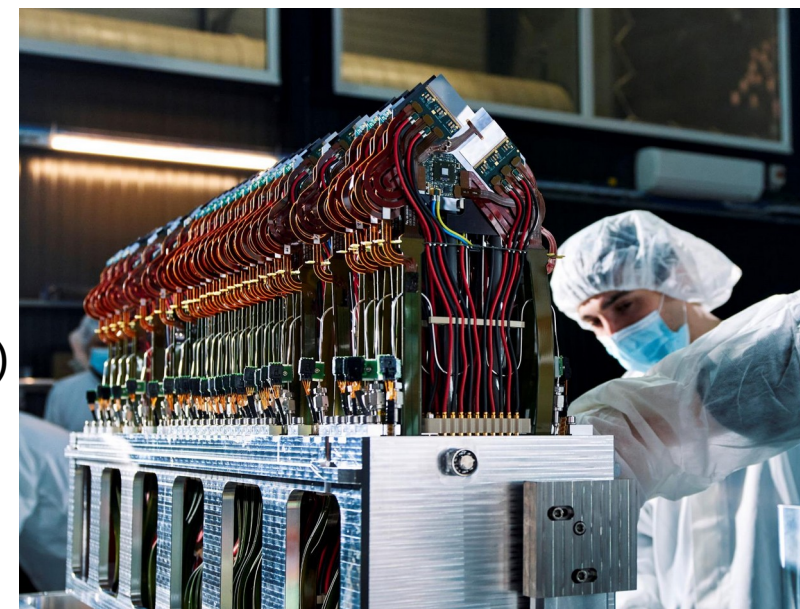
# Upgrade II Velo



# Current Velo

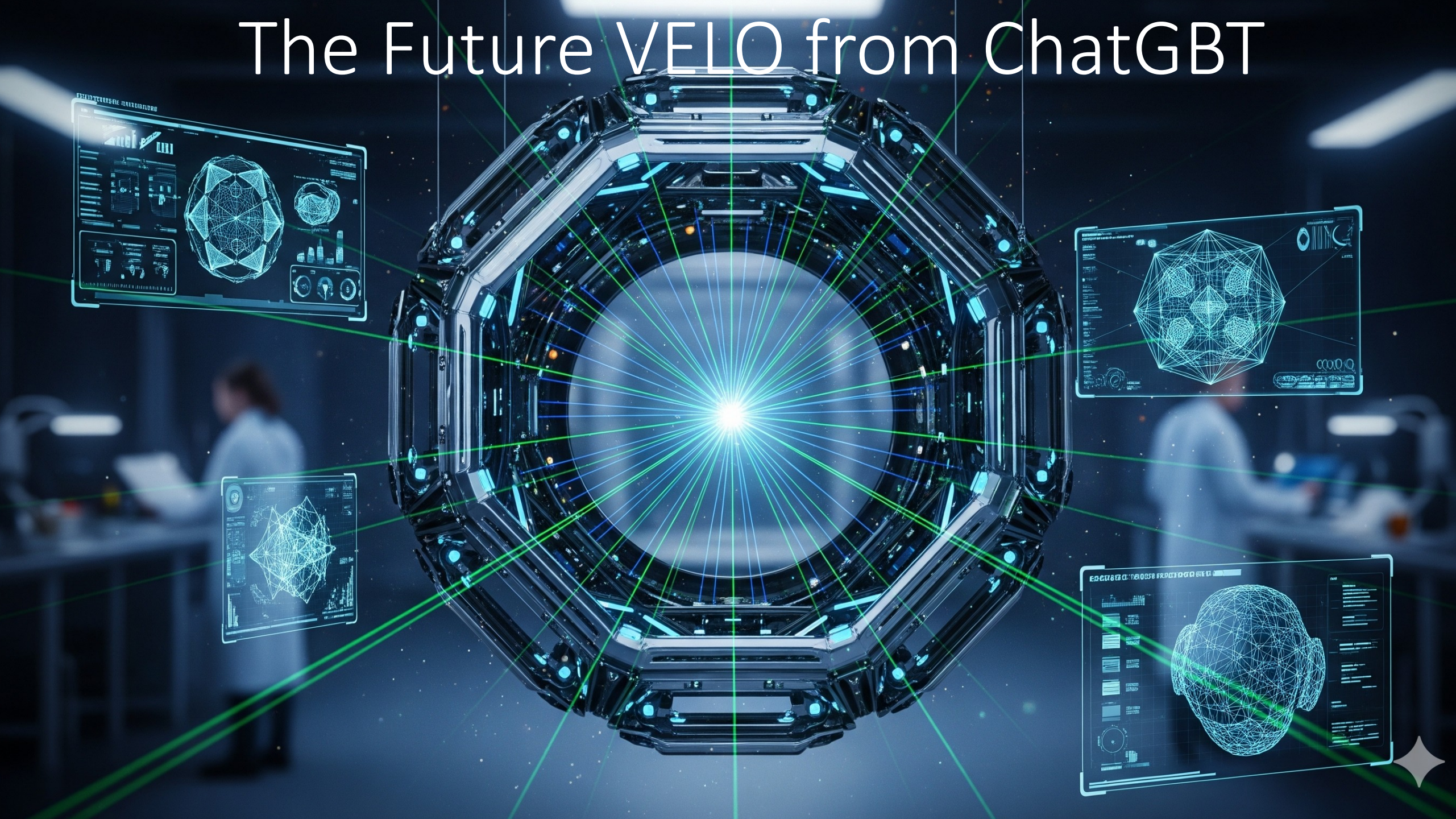


- L-shaped sensor arrangement
- Readout close to sensor
- As close to IP as possible (moves in)
- Primary and secondary vacuum ( $<10$  mbar)
- 52 modules ( $0.12$  m<sup>2</sup>)
- $55\mu\text{m}$  pixel pitch
- $250\mu\text{m}$  ( $180\mu\text{m}$ ) RF Foil
- Micro-Channel CO<sub>2</sub> cooling





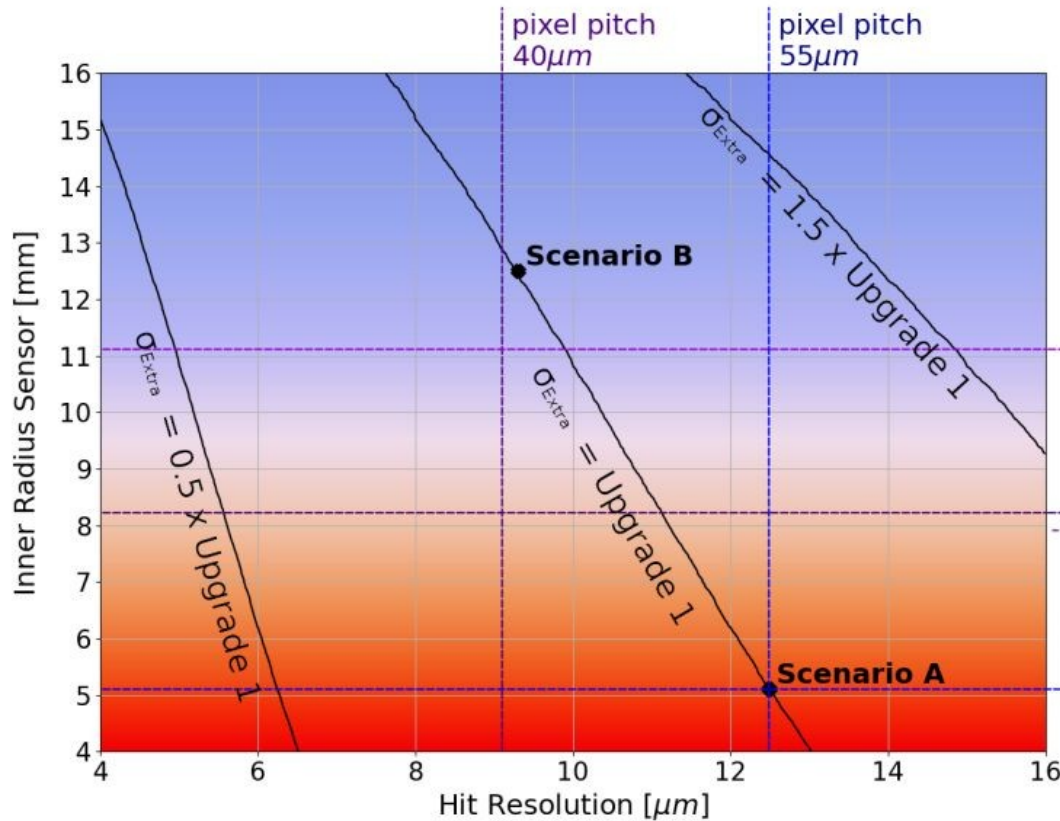
# The Future VELO from ChatGBT



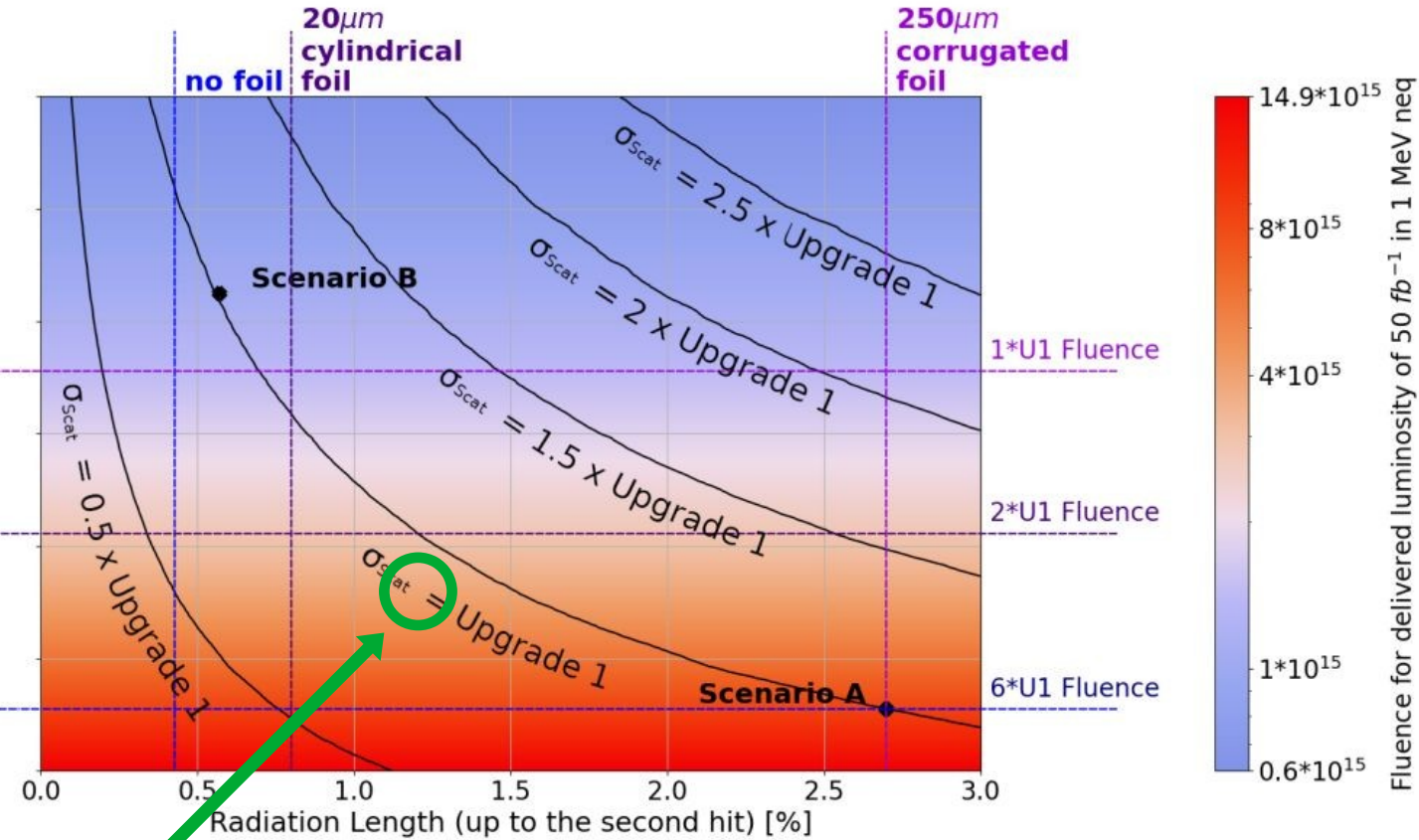


# VELO Optimization

## Extrapolation Term



## Scattering Term

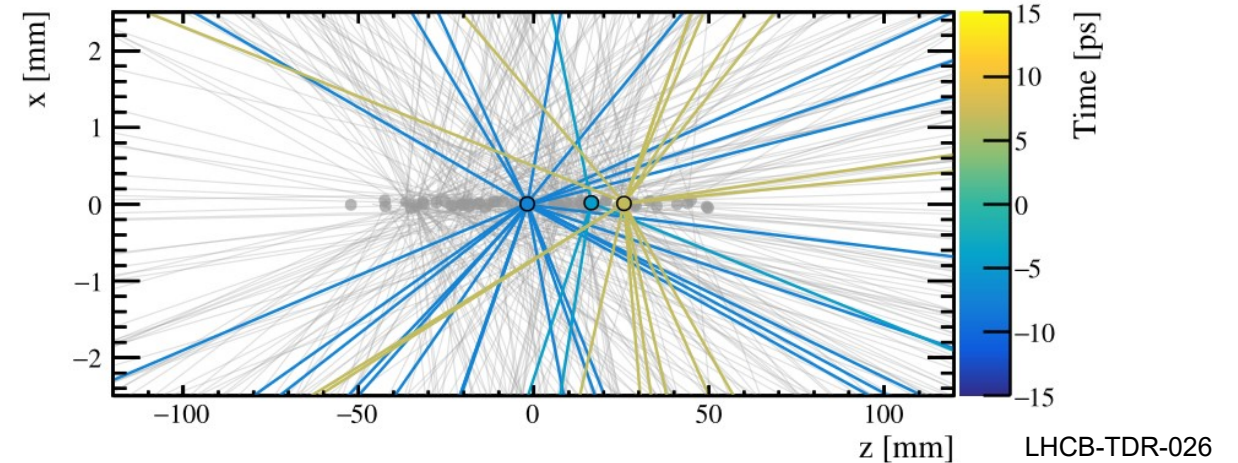
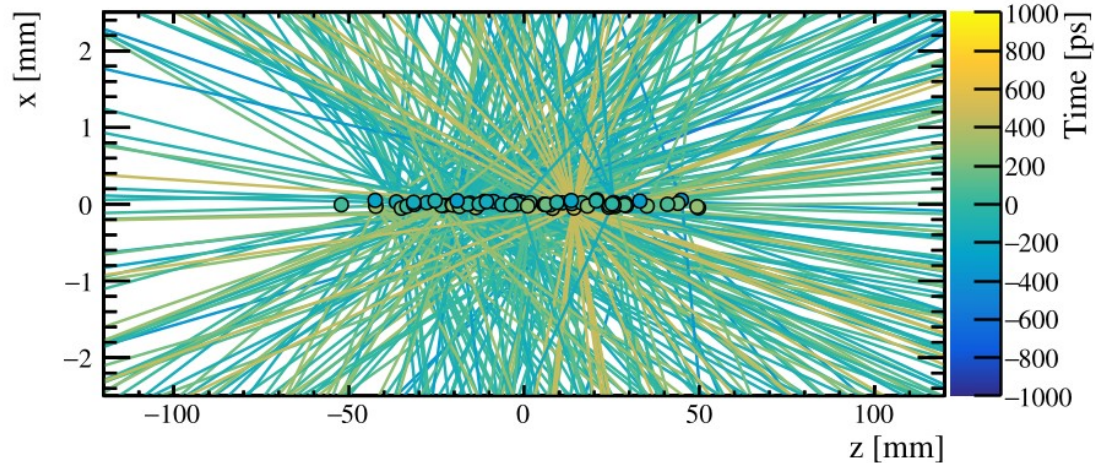


LHCb-PUB-2022-001

Current Preference Scenario X, SX:  $R_{\min} = 7.2 \text{ mm}$ , Fluence =  $3 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ , Cylindrical Foil

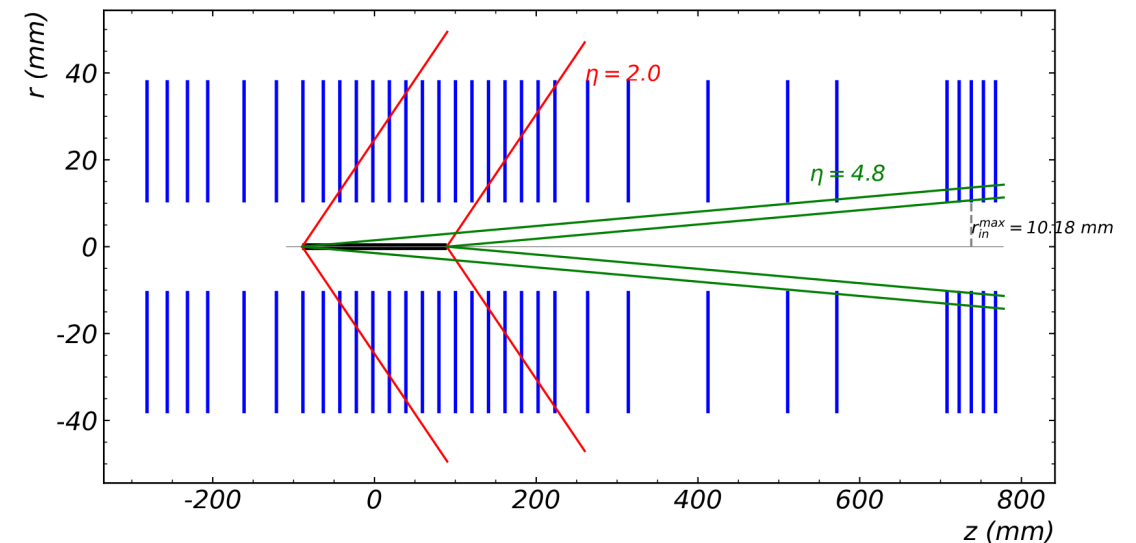


# Velo Upgrade

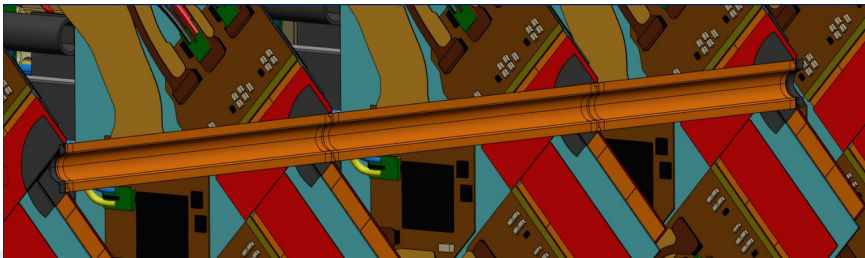
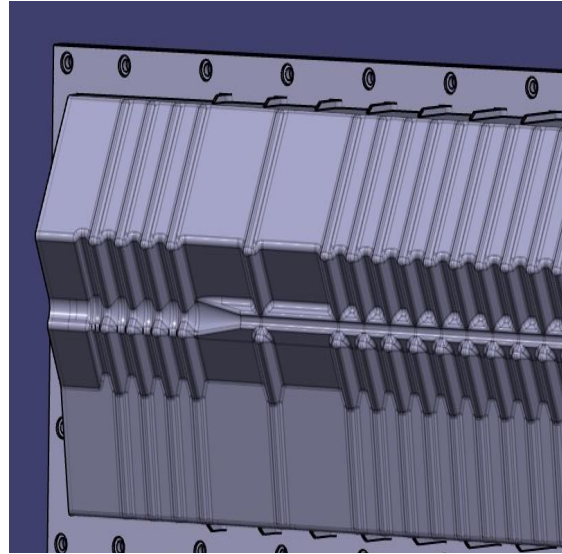
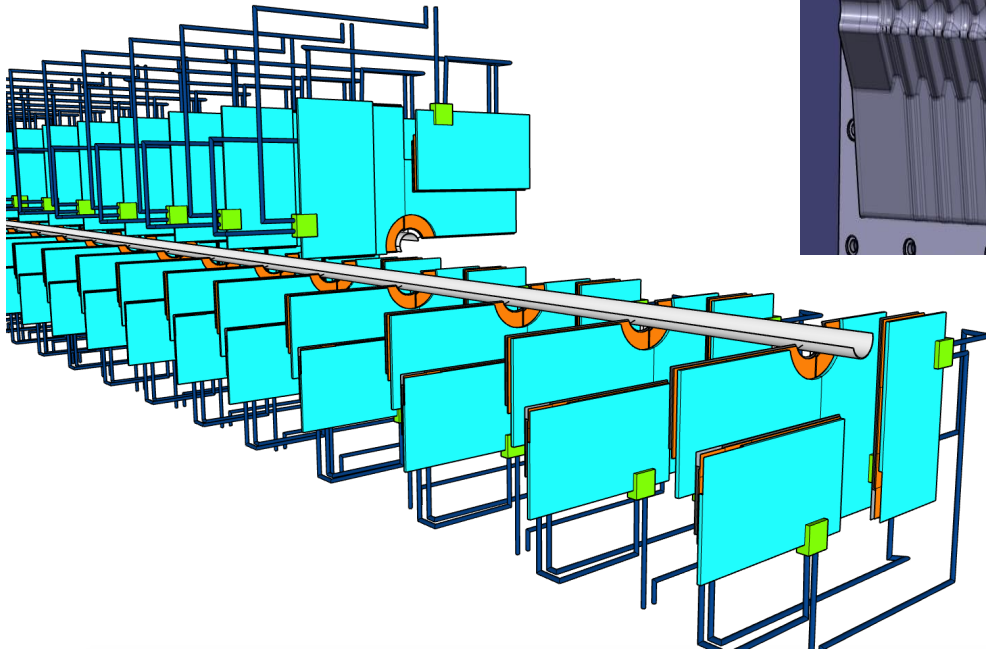


Keep 10 $\mu$ m impact parameter resolution:

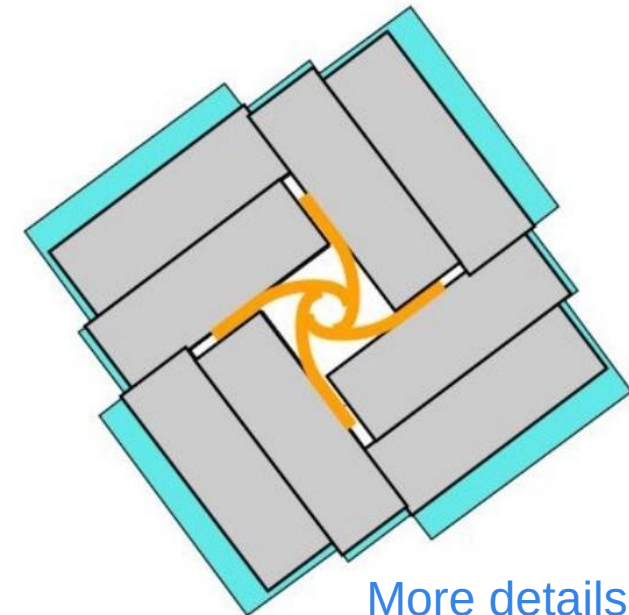
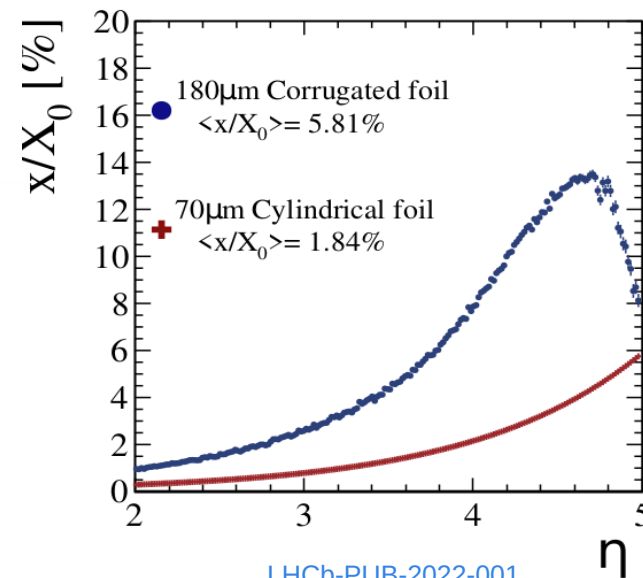
- 28 nm Hybrid ASIC
- 50 ps time timestamps per hit
- 50 $\mu$ m pixel pitch 3D sensor
- 94-250Gbit/s (B/A) output for the hottest ASIC
- NIEL:  $10^{16}$  1MeV  $n_{eq}/cm^2$
- TID: 400 MRad



# RF Foil



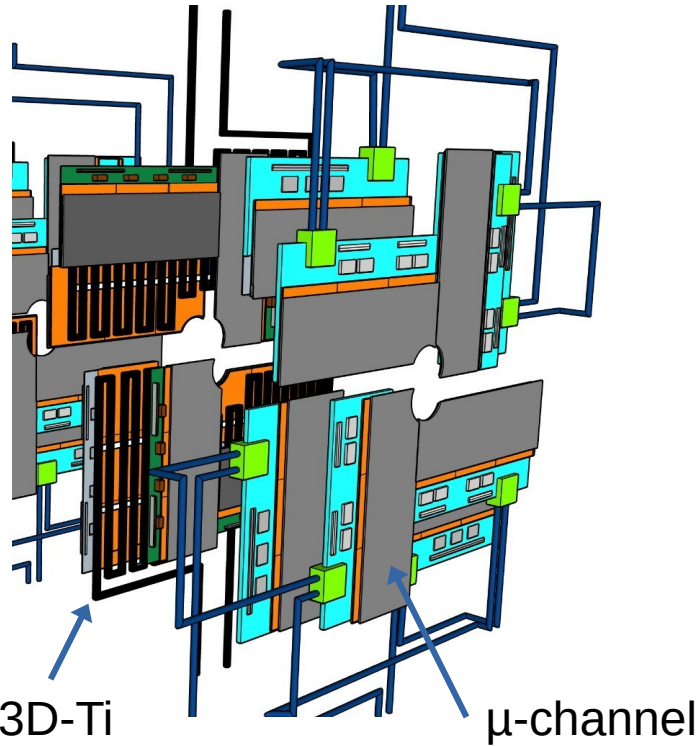
- Current RF foil corrugated design
- Probably will be pushed to a more cylindrical profile
- Pushes the material away from the beam where possible
- Foil 70 $\mu\text{m}$  (Al) electrically minimum (75 $\mu\text{m}$  baseline)
- Box or Iris closing is also studied



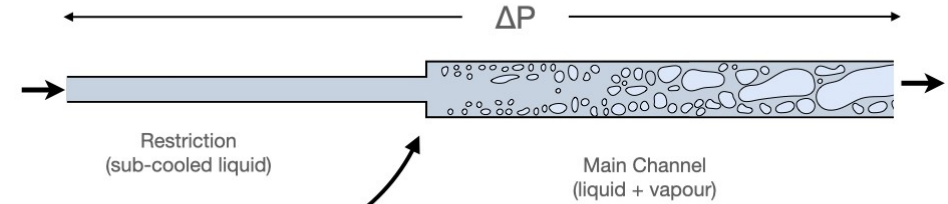
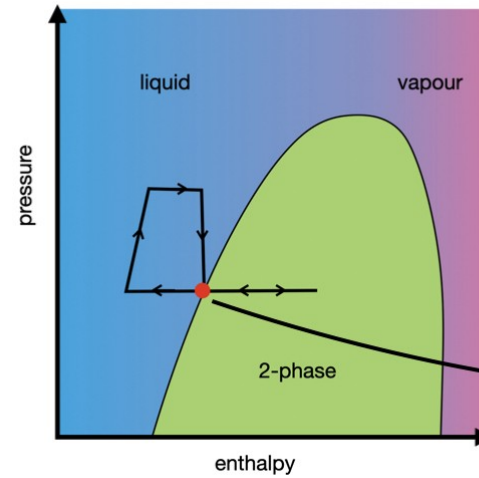


# Cooling

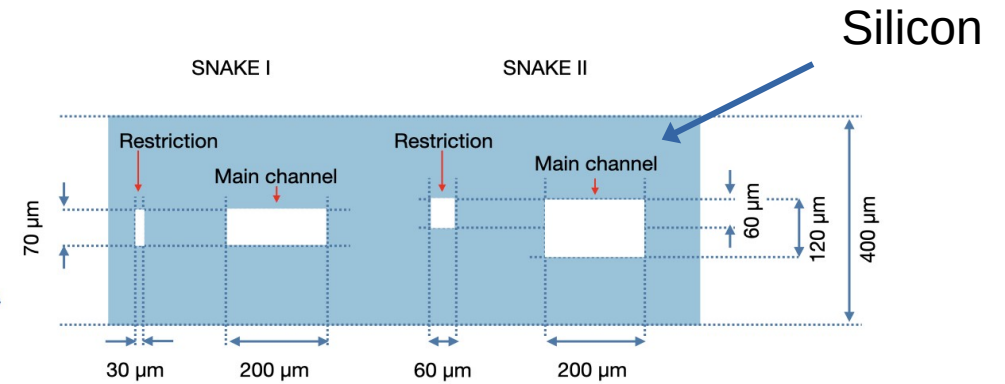
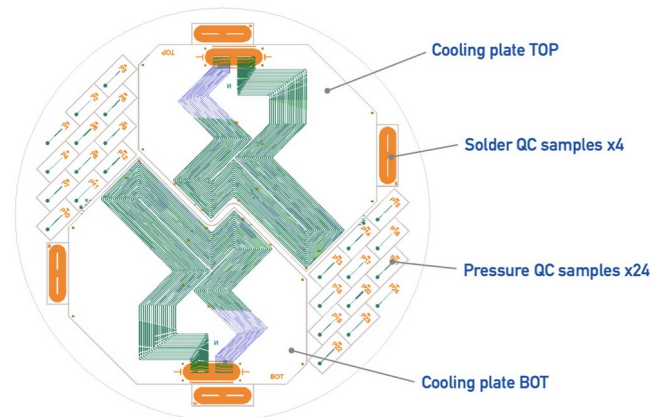
So far  $\mu$ -channel CO<sub>2</sub> cooling was used also 3D printed Ti was considered



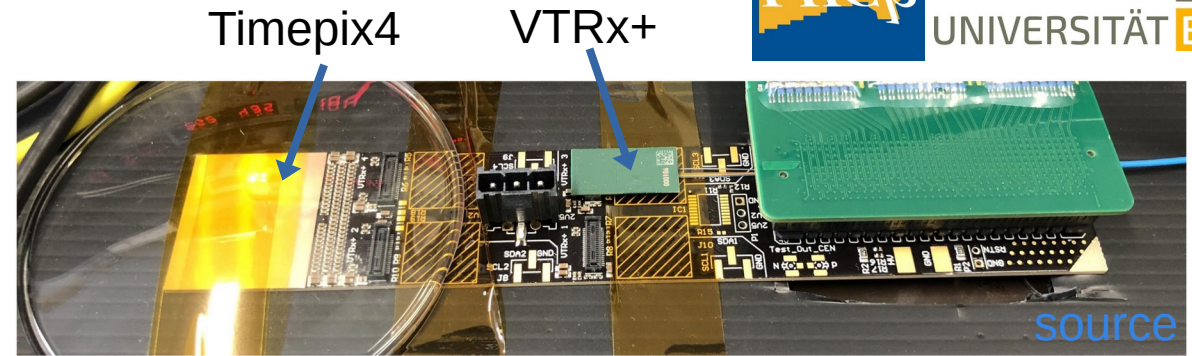
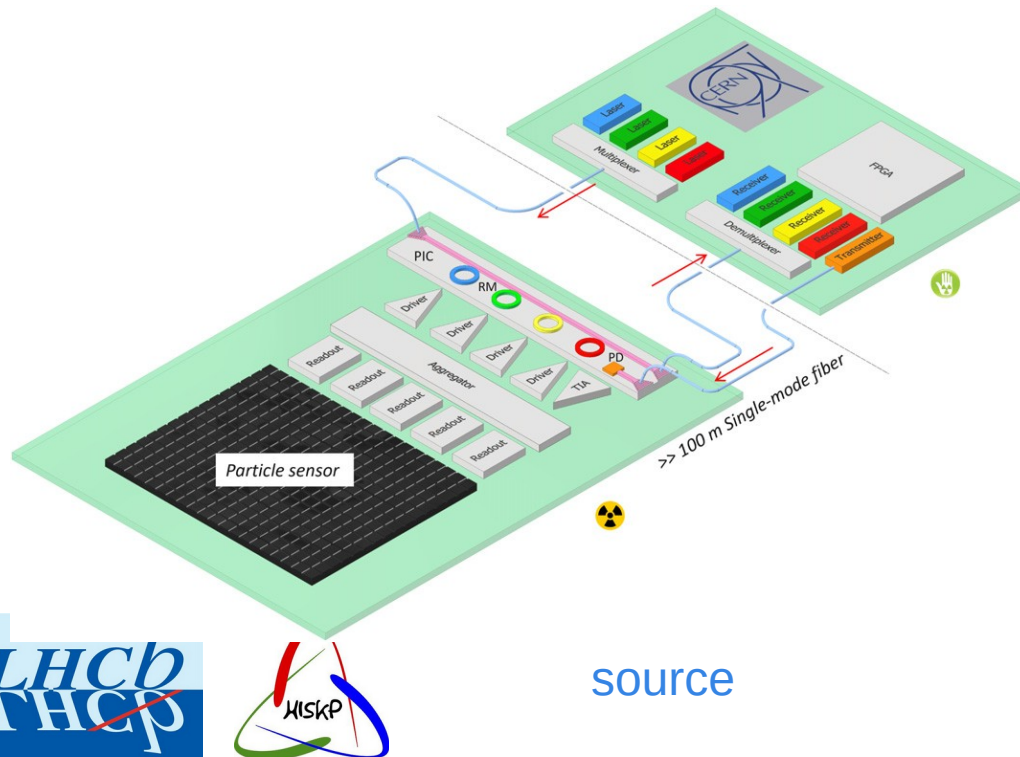
LHCb-PUB-2022-001



LHCb-PUB-2021-010



- Need to go to about 100-250Gb/s per ASIC
- Dircet to VTRx+
- Silicon photonics



VTRx+ is shown to be radiation hard (few 100MRad)  
10.24 Gb/s per VTRx+ (will not support 10 VTRx+ per module)

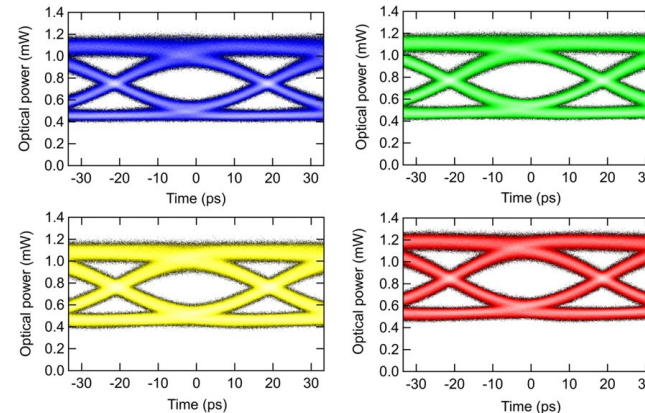
## Silicon Photonics:

## Integrate the optical output into the ASIC

## Use external laser source

## Change the light output by ring modulators

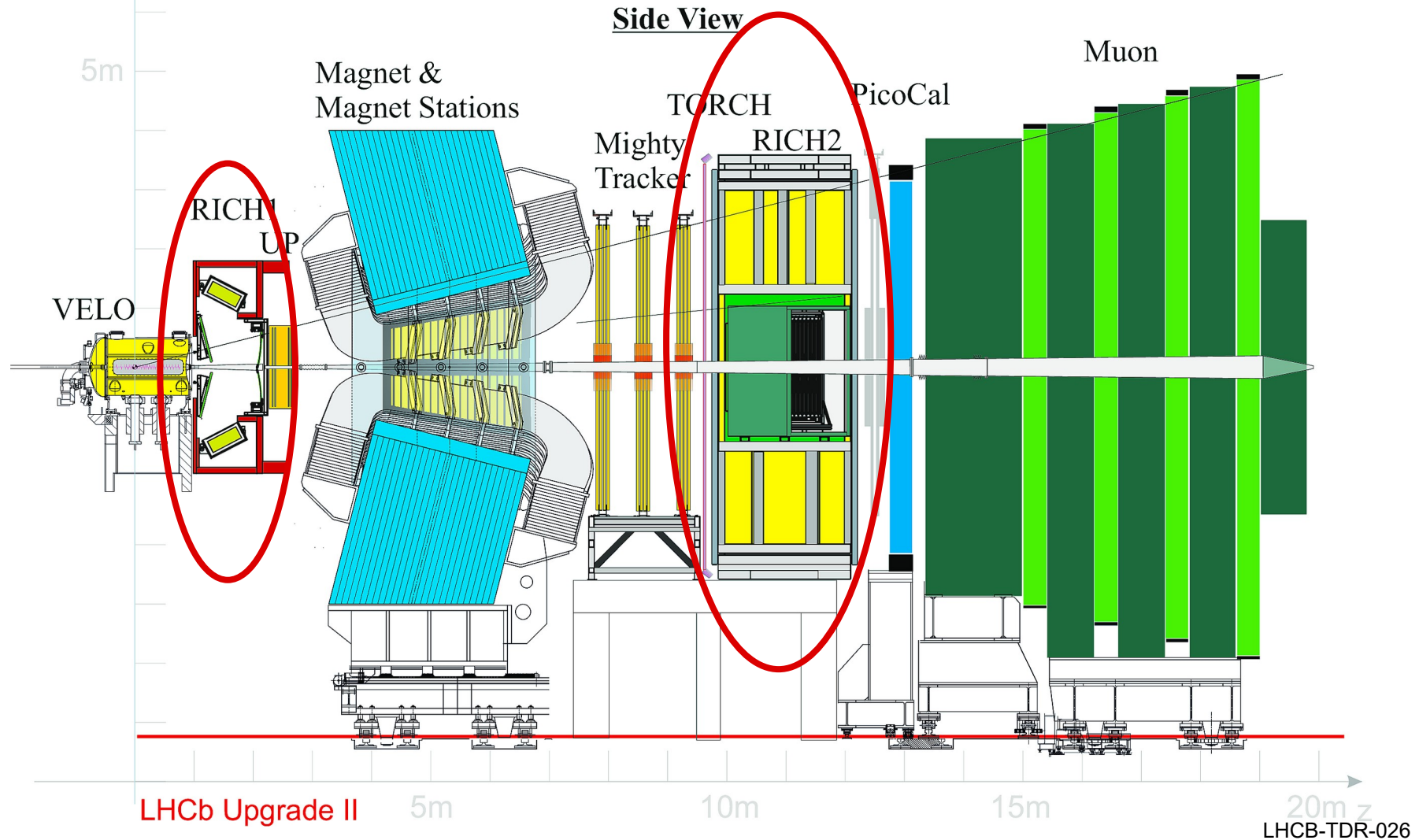
## Multiple wavelength can be modulated from the same fiber



Shown to work for  
25Gb/s per modulator



# Upgrade II PID



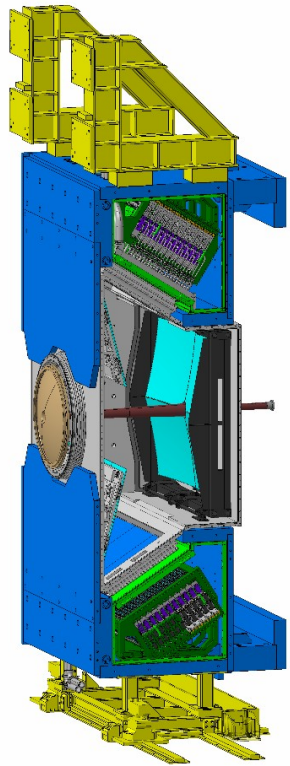




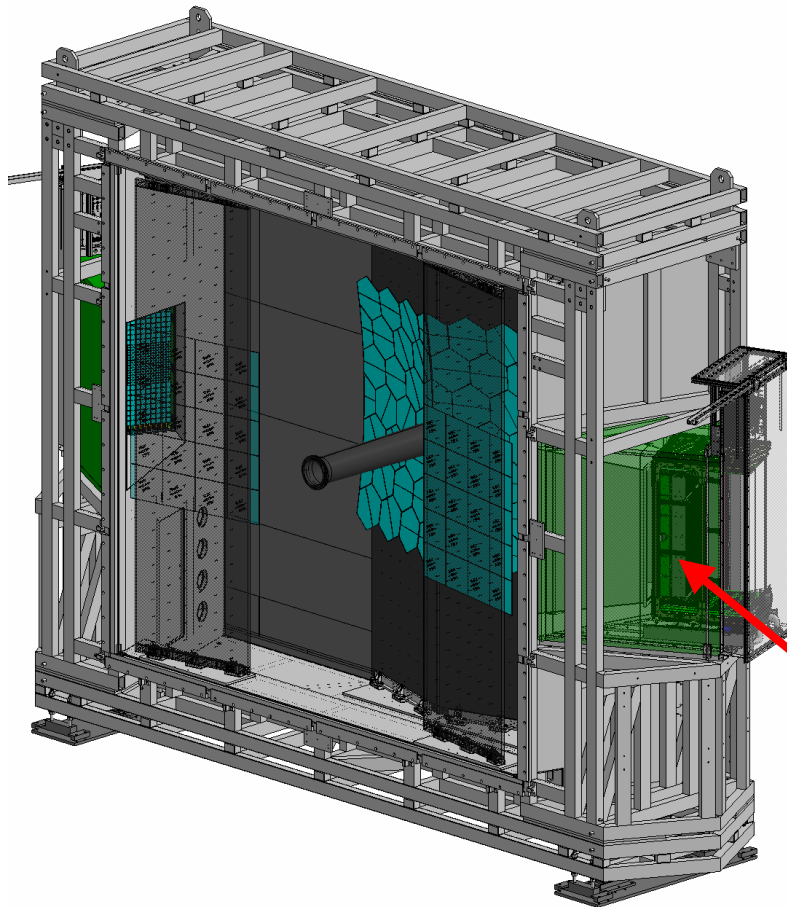
Not sure about this one ChatGBT?  
The RICH 1 and 2



# RICH Upgrade

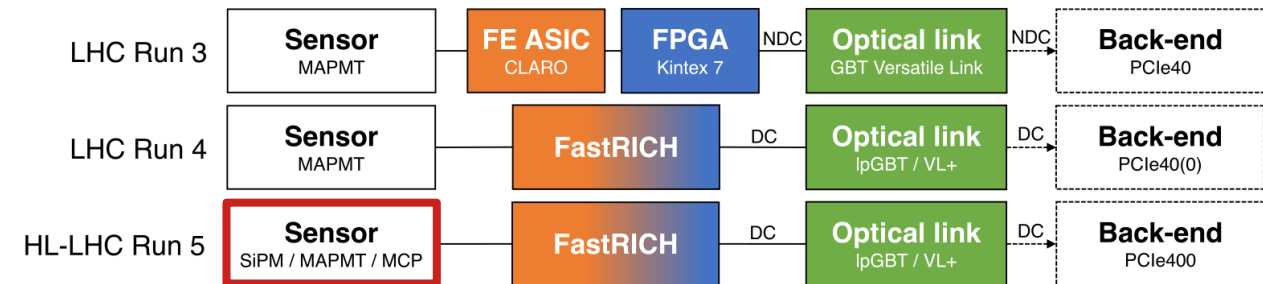


RICH 1  
3- 65 GeV PID



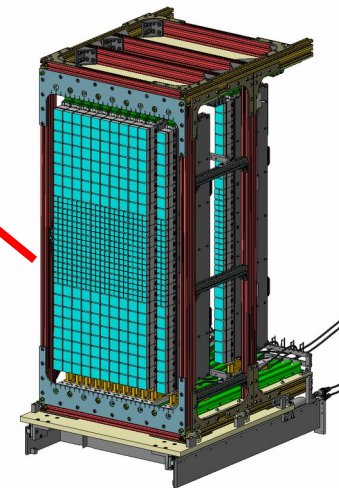
RICH 2  
15-10 GeV PID

## Main upgrade: Readout and Sensors



LHCB-TDR-026

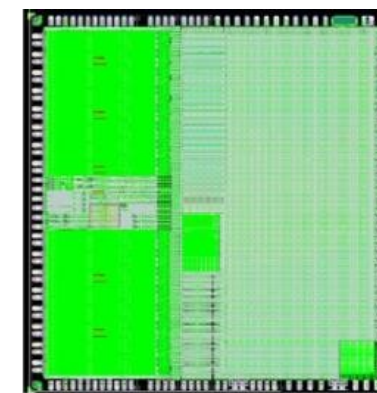
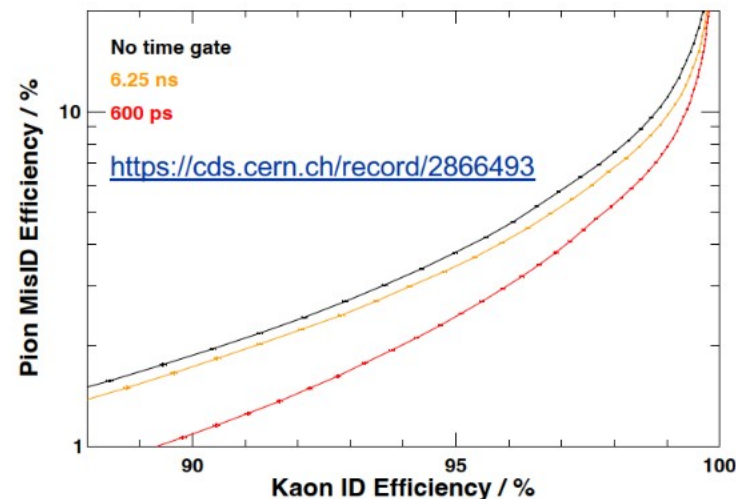
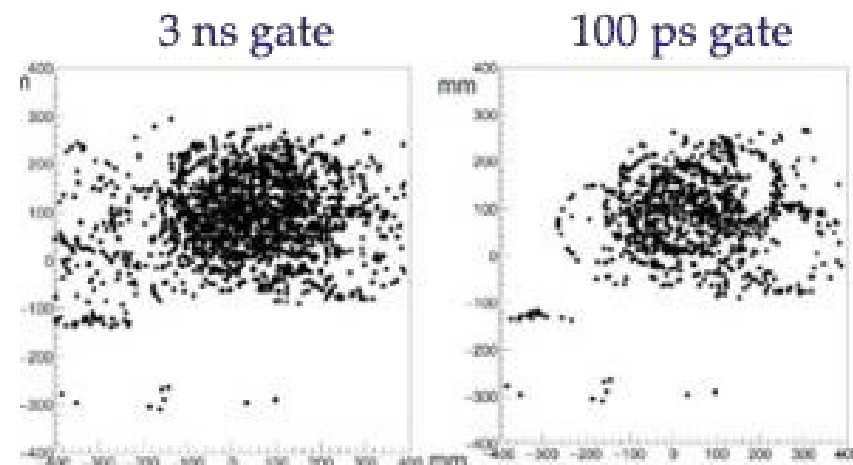
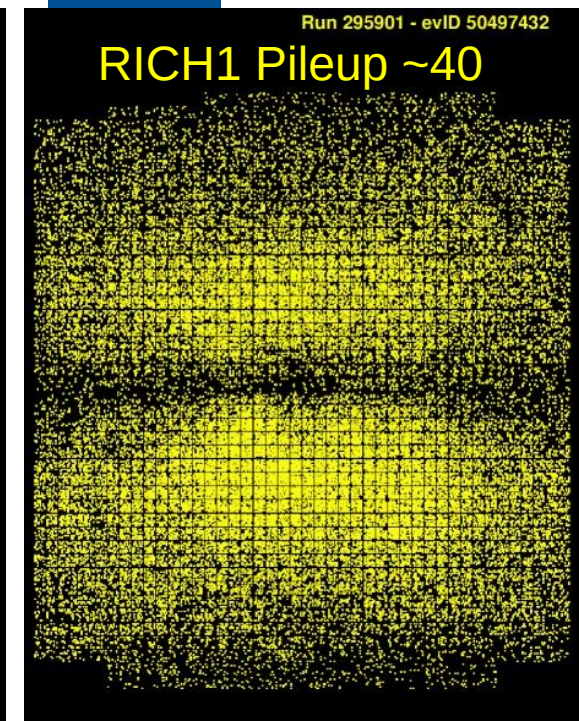
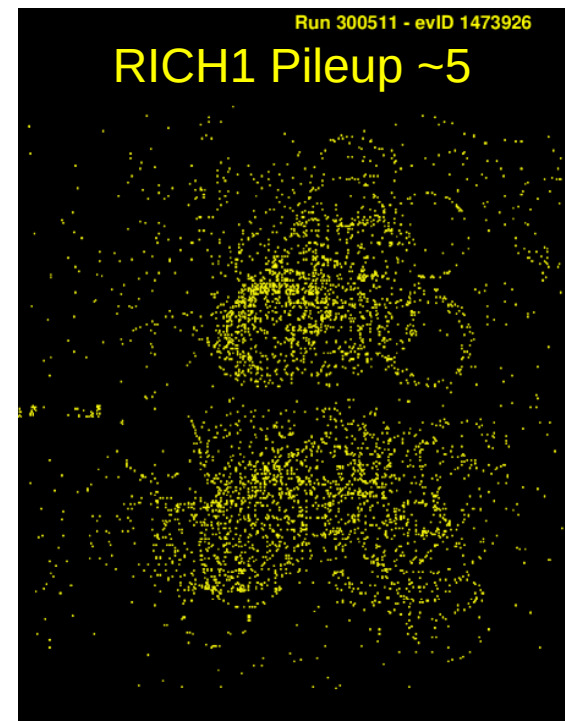
- 100 ps photon resolution (FastRICH electronics)
- PMT → SiPM or MCP-PMT (higher granularity)



Planned Rich2 readout

# Challenges for PID

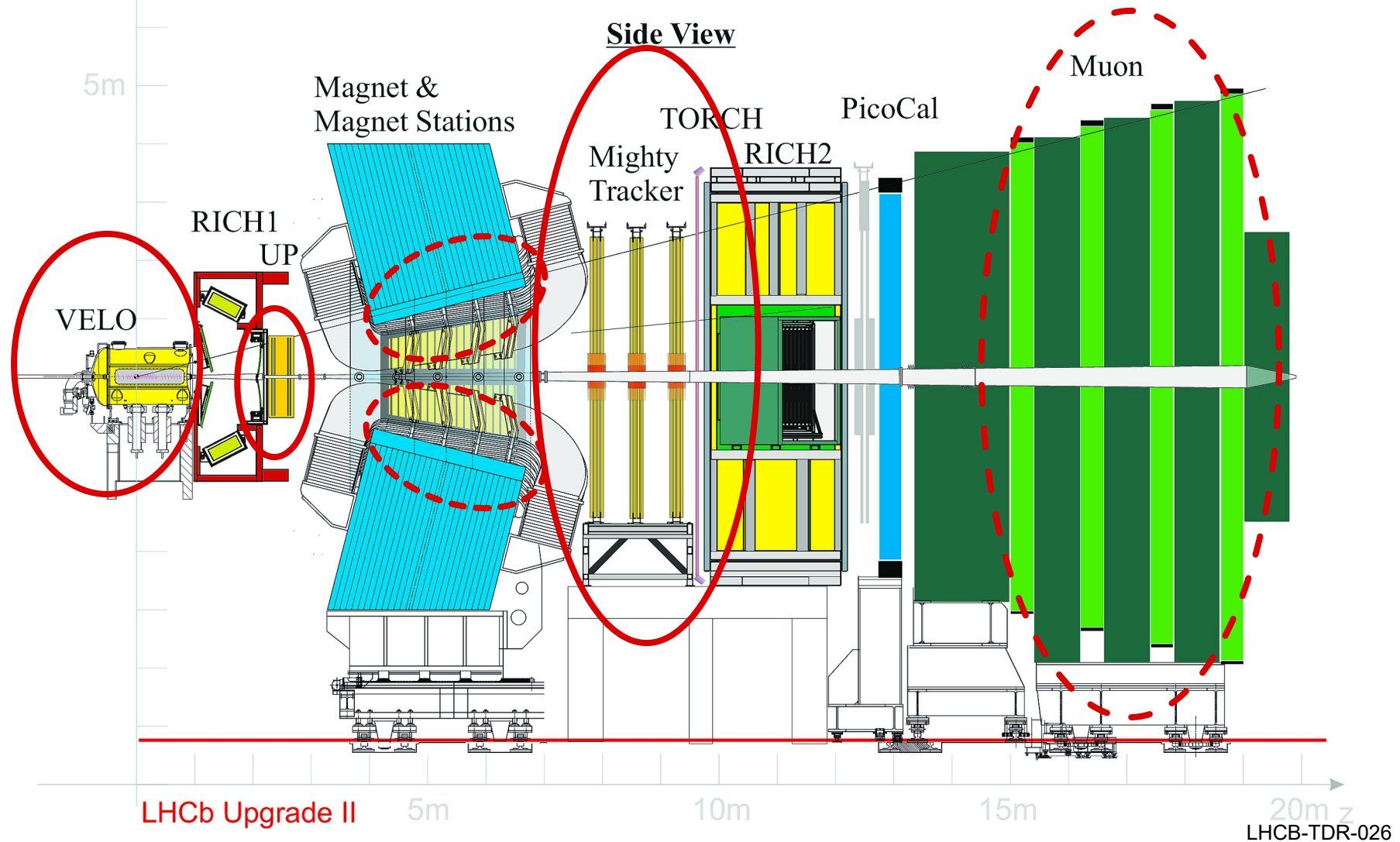
- Need to reduce the number of photons to reconstruct Cherenkov rings
- FastRICH ASIC can deliver 25ps timestamps
- Other mirror configurations under investigation
- SiPM or MCP under investigation
  - Cryogenic cooling for SiPMs planned
  - MCP aging issues under development



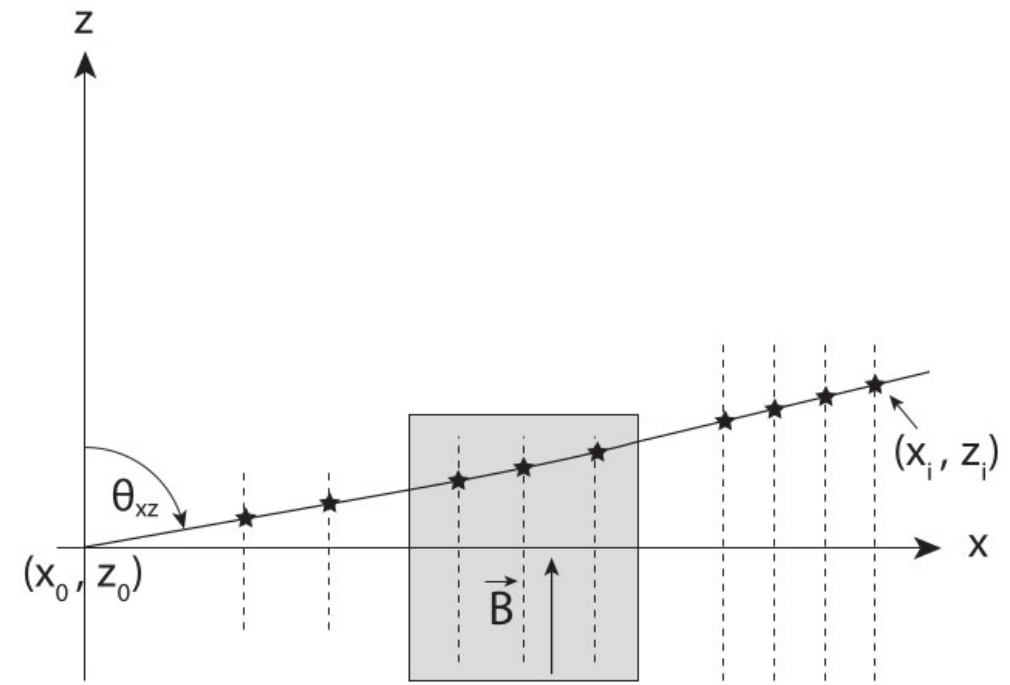
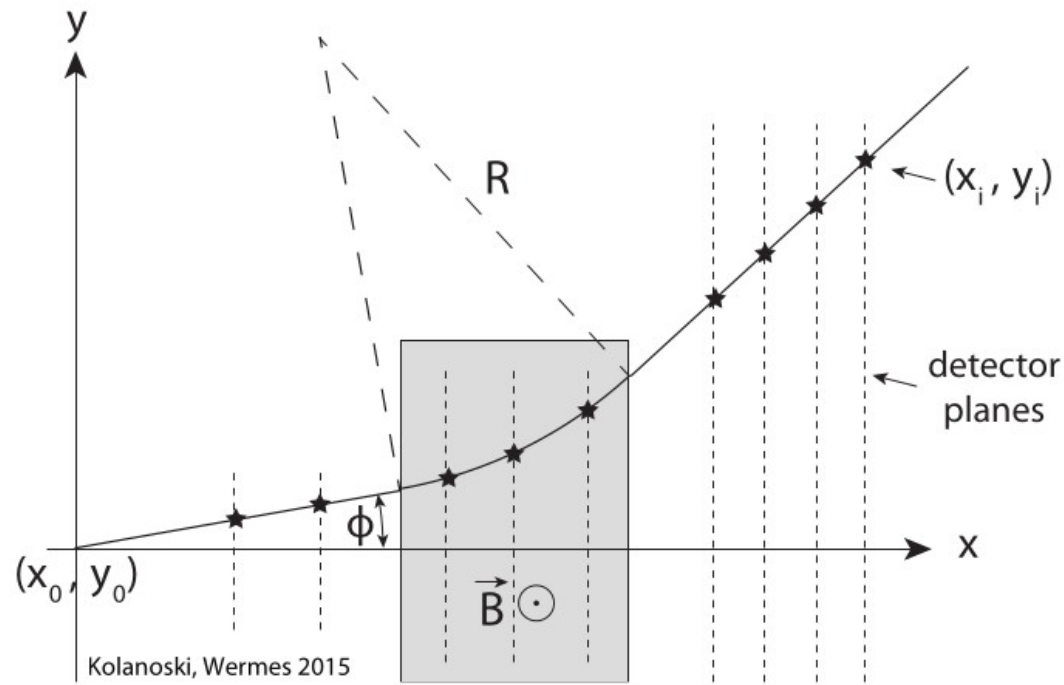
16-channel ASIC (65 nm technology)  
Fast RICH ASIC in the lab since June



# Upgrade II Tracking



# Tracking in LHCb



LHCb is the text book forward arm spectrometer

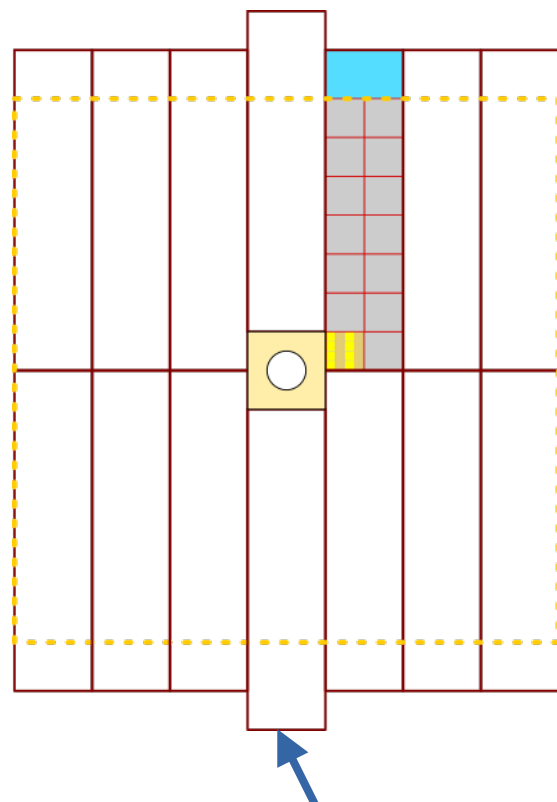


Upstream Pixel





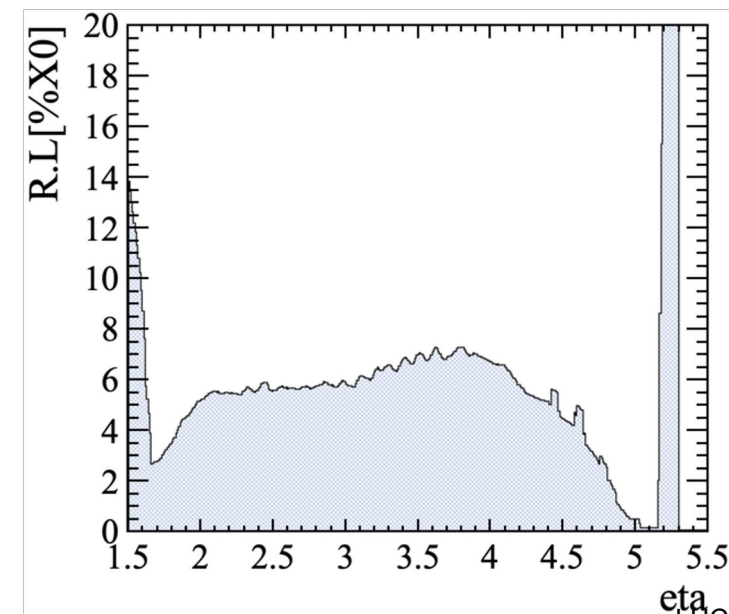
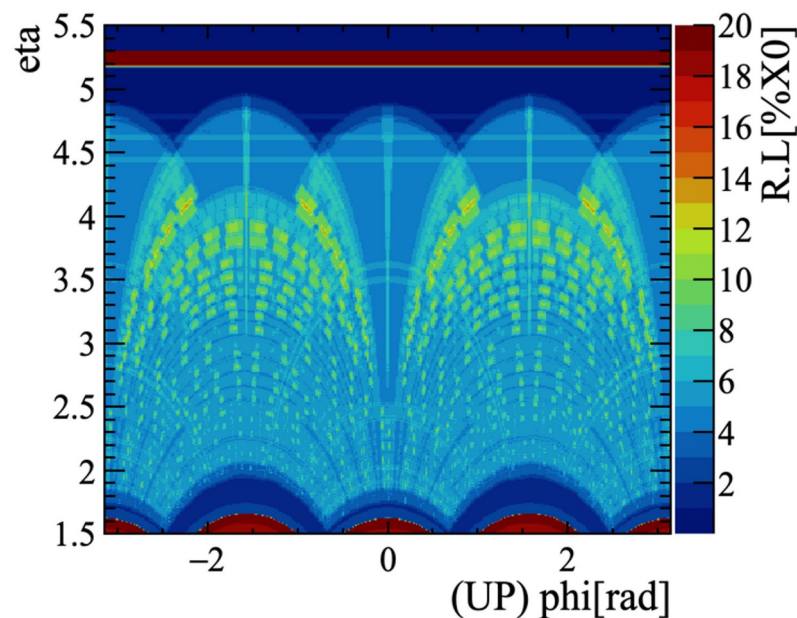
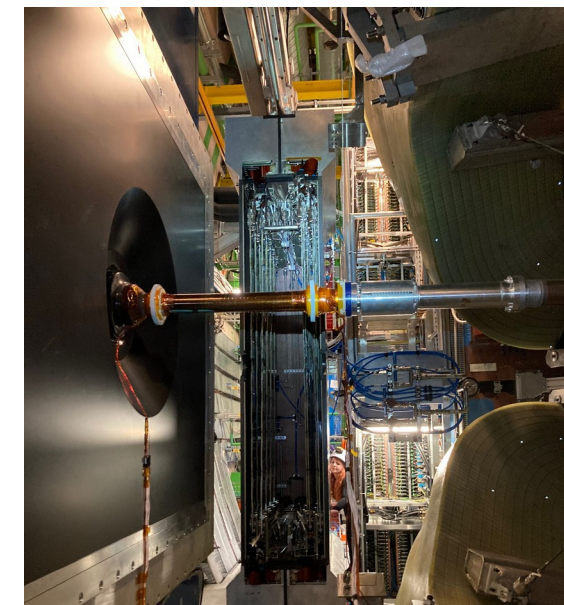
# Upstream Pixel



See why this design later

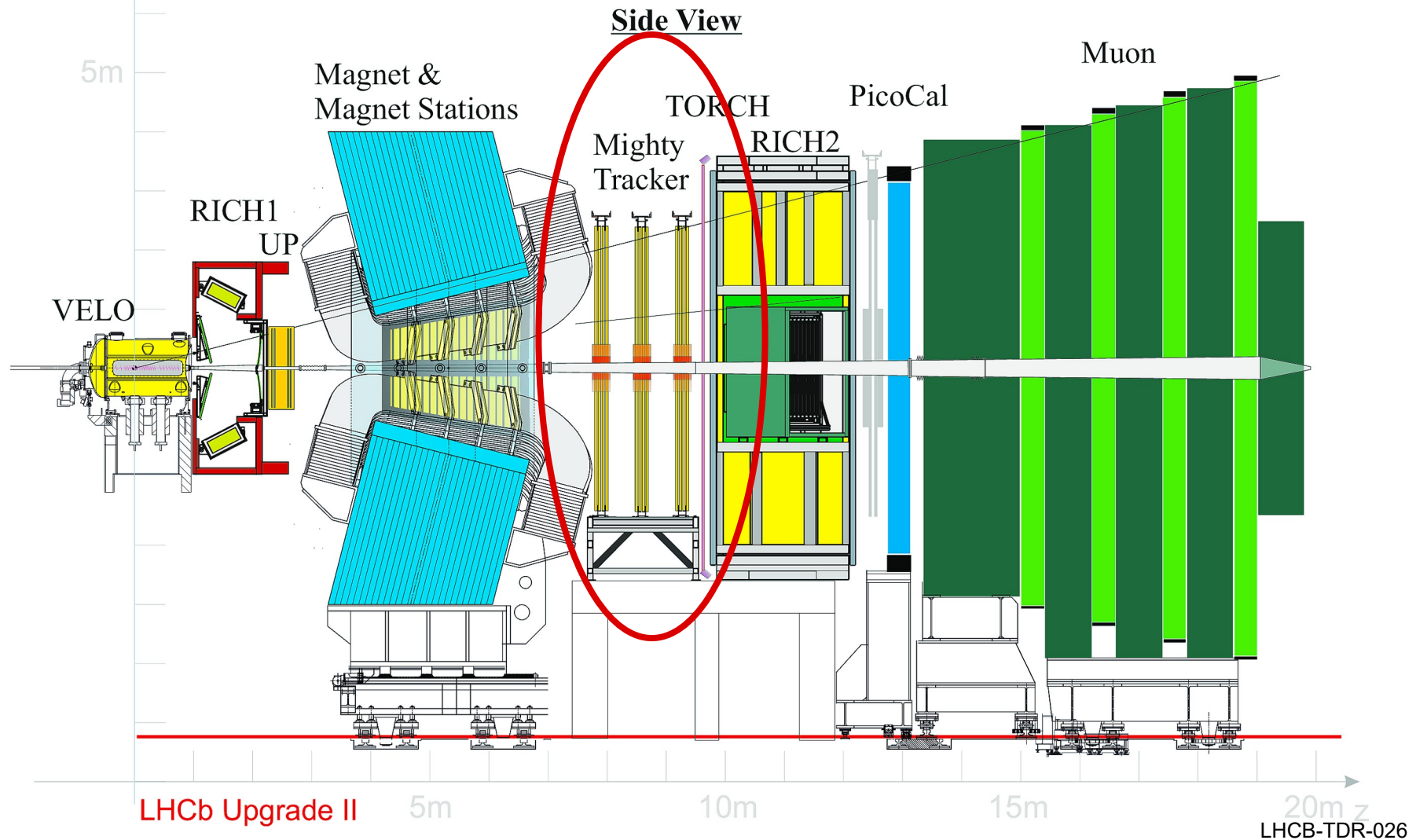
- 4 Layers
- Monolithic Sensors
- 9 m<sup>2</sup> active area
- 74 (34) MHz/cm<sup>2</sup> at 4cm (6cm) from beampipe
- NIEL:  $3 \cdot 10^{15}$  1MeV  $n_{eq}/\text{cm}^2$
- TID: 240 MRad

Planned to use the same sensor as Mighty-Pixel and probably similar module design





# Upgrade II Mighty-Tracker





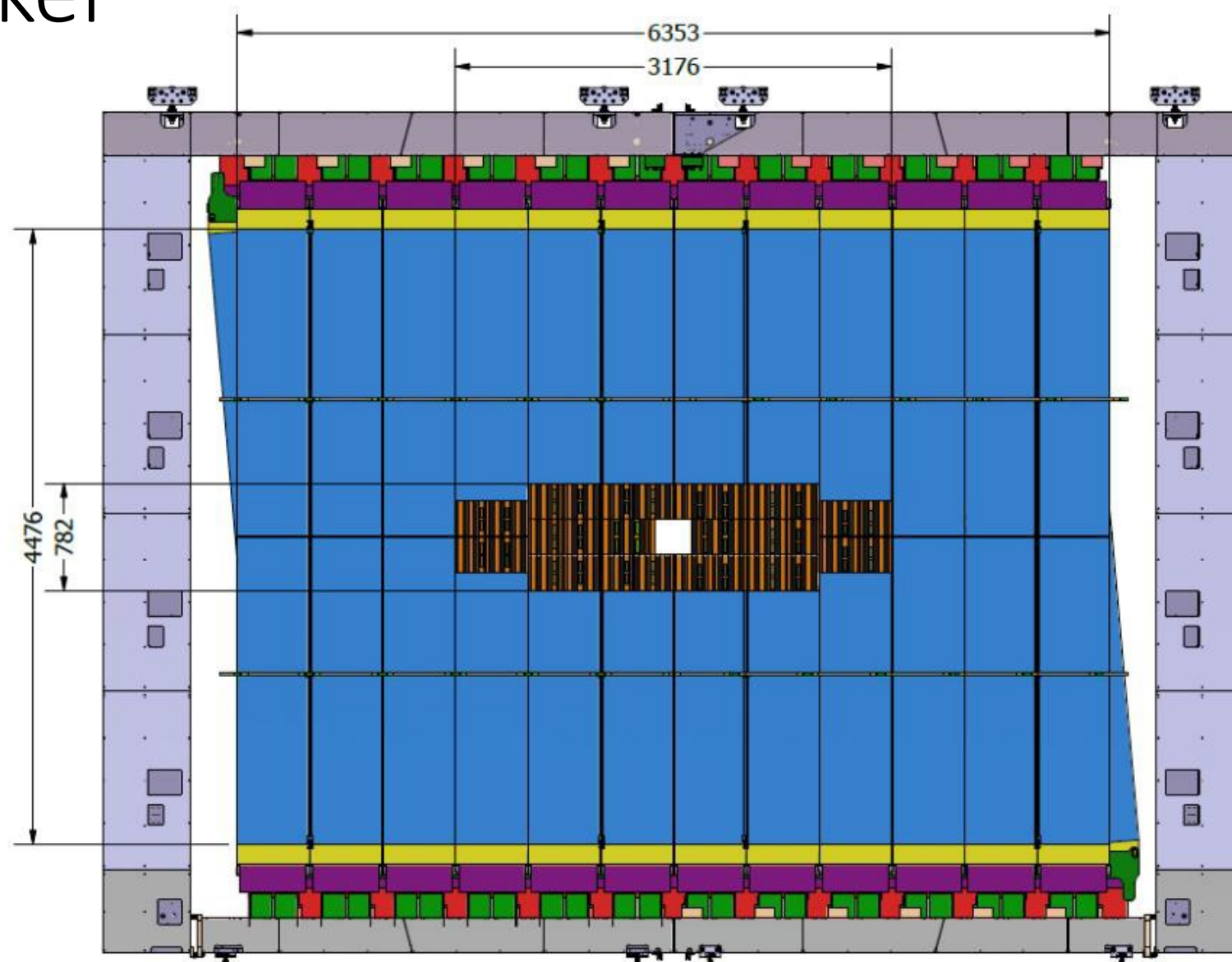


**MIGHTY  
TRACKER**



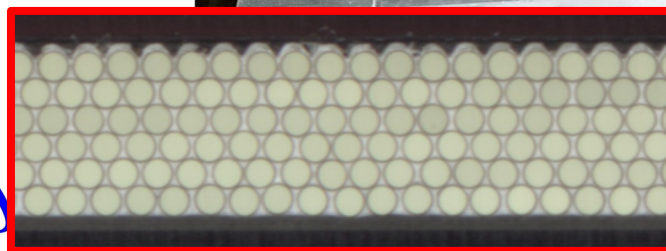
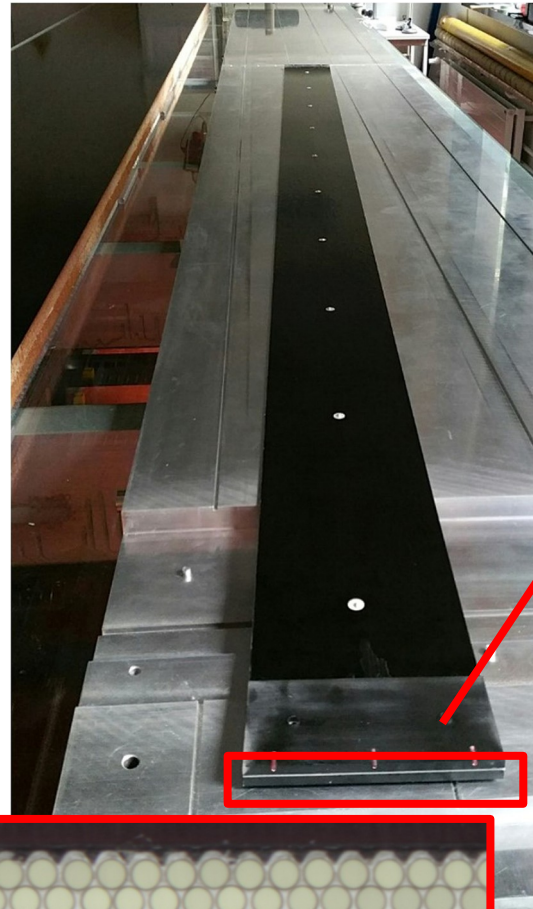
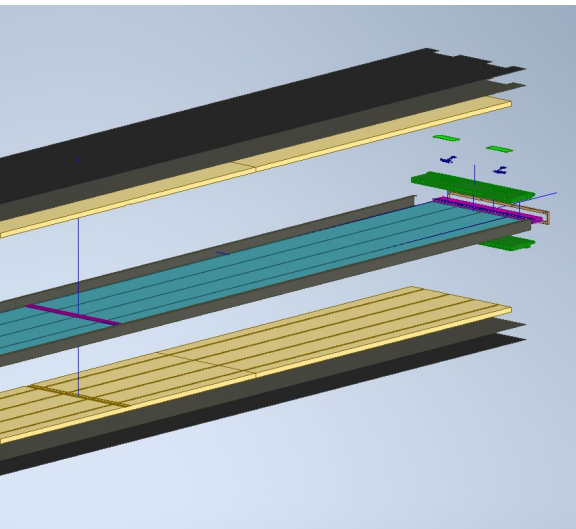
# The Mighty Tracker

- Mighty SciFi tracker for the outside 12 layers in 3 stations (170m<sup>2</sup> effective)
- Mighty Pixel for the high occupancy regions in 6 layers (9 m<sup>2</sup>)

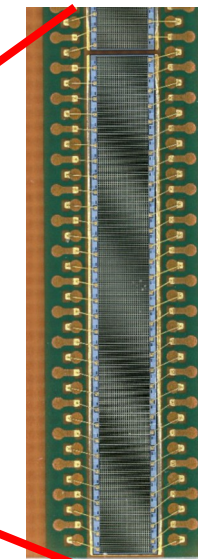
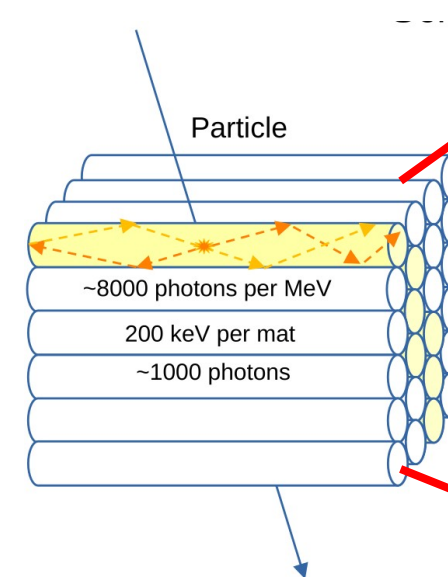


# SciFi Working Principle (Current SciFi)

Module:  
Long fibers  
Minimal support material



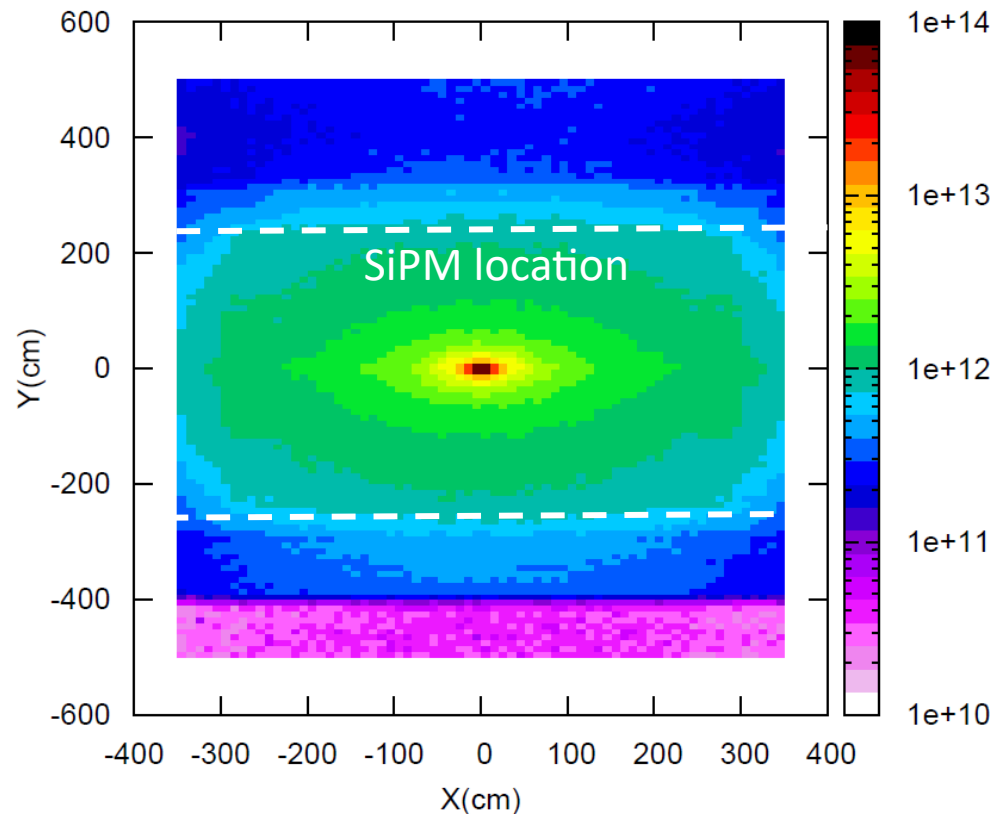
- Very successful application to instrument a large area
- Low material budget ( $X/X_0 \leq 1\%$  per detector layer)
- XUVX layout ( $\pm 5^\circ$  for U and V)
- Main complexity to produce homogeneous fiber mats
- $70 \mu\text{m}$  resolution





# SiPM Challenges

1MeV neutron Eq. fluence/cm<sup>2</sup> for 50fb-1 (100mb)

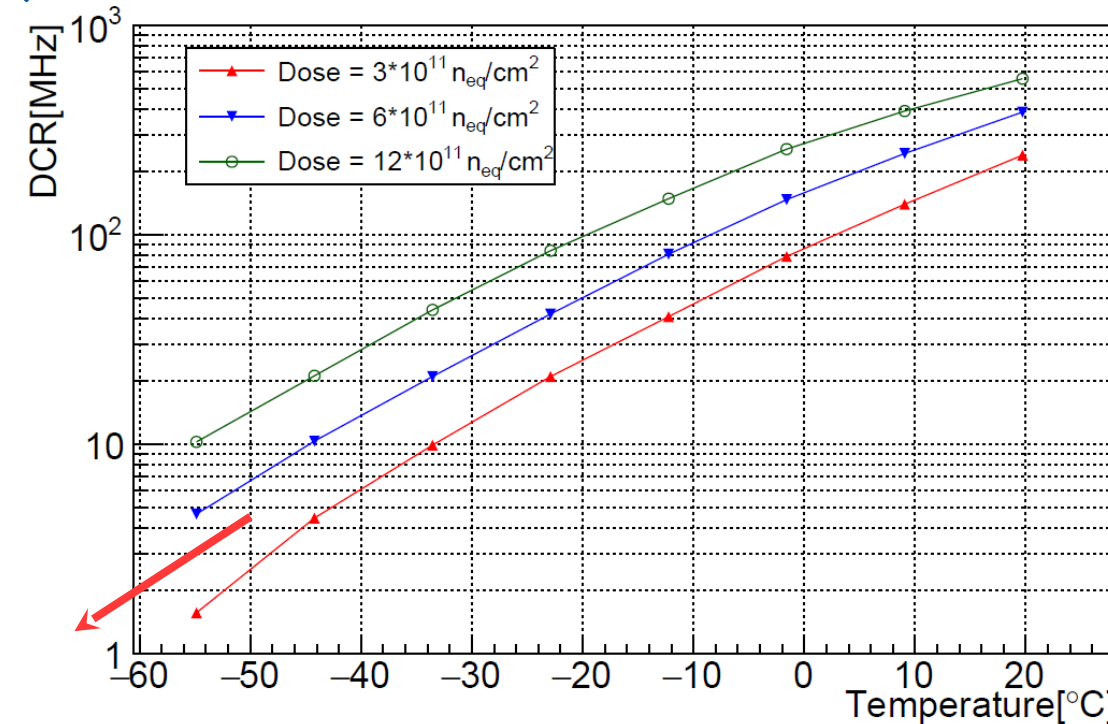


Unirradiated SiPM:

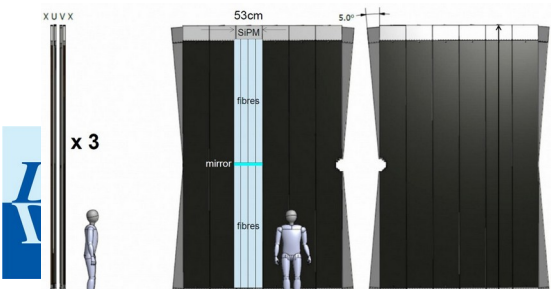
Dark Count Rate (DCR)  $\sim 0.04\text{MHz}$

Expect  $6 \cdot 10^{11} n_{eq}/\text{cm}^2$

$\rightarrow$  DCR  $\sim 550\text{ MHz}$  at  $20^\circ\text{C}$

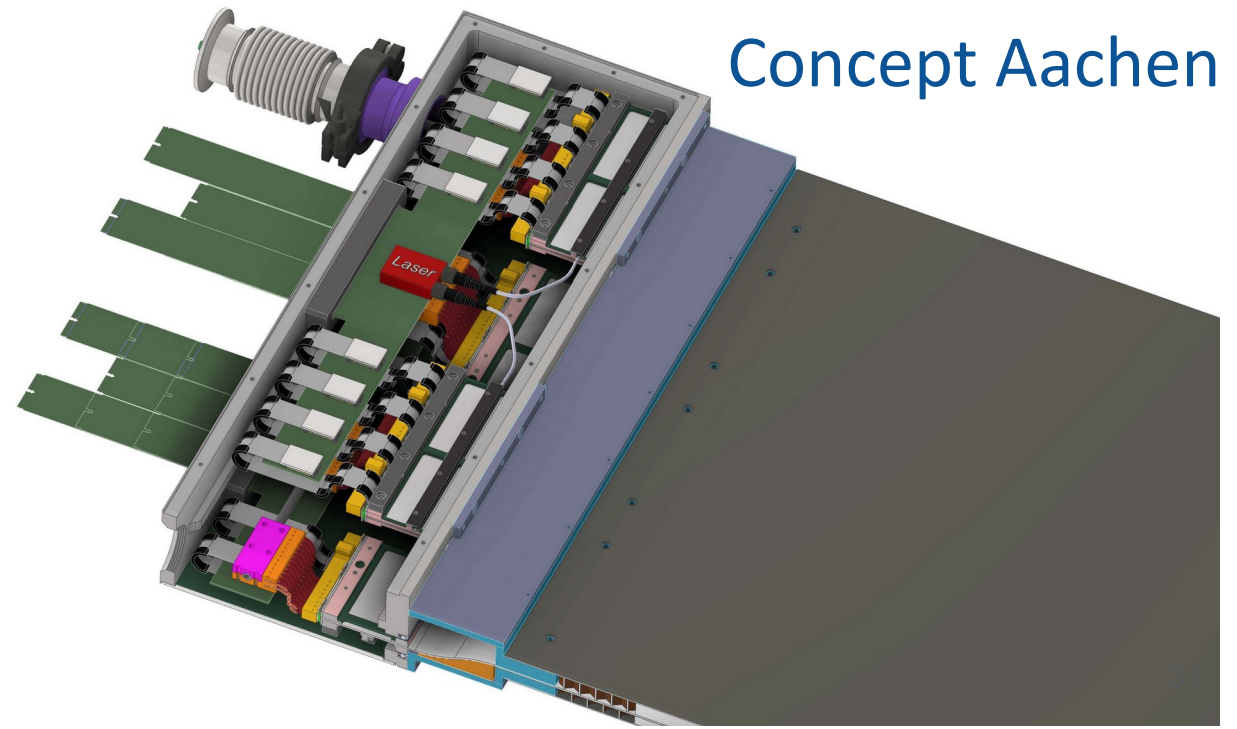
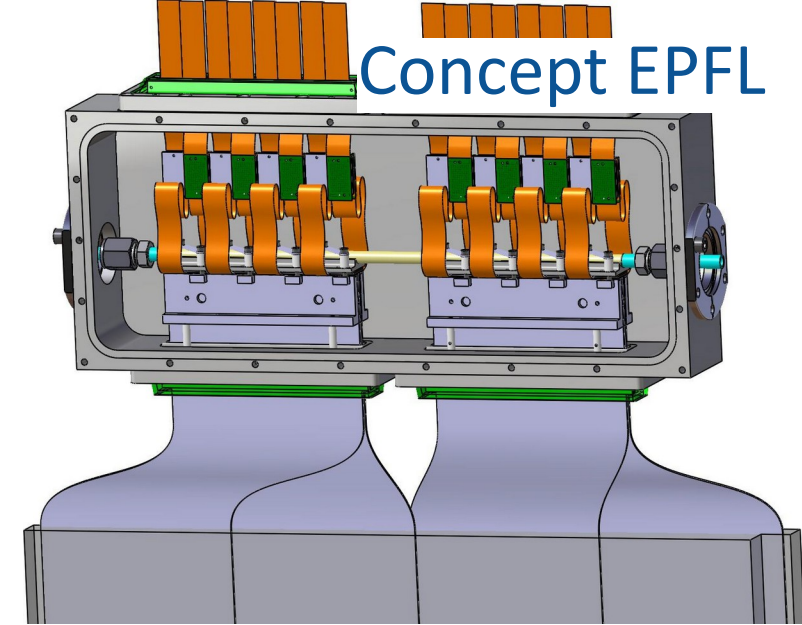
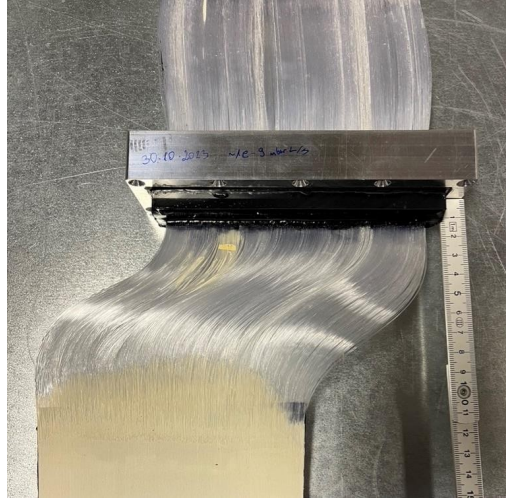


You expect  $\sim \frac{1}{2}$  DCR per 7K  $\rightarrow$  Cryogenic temperatures



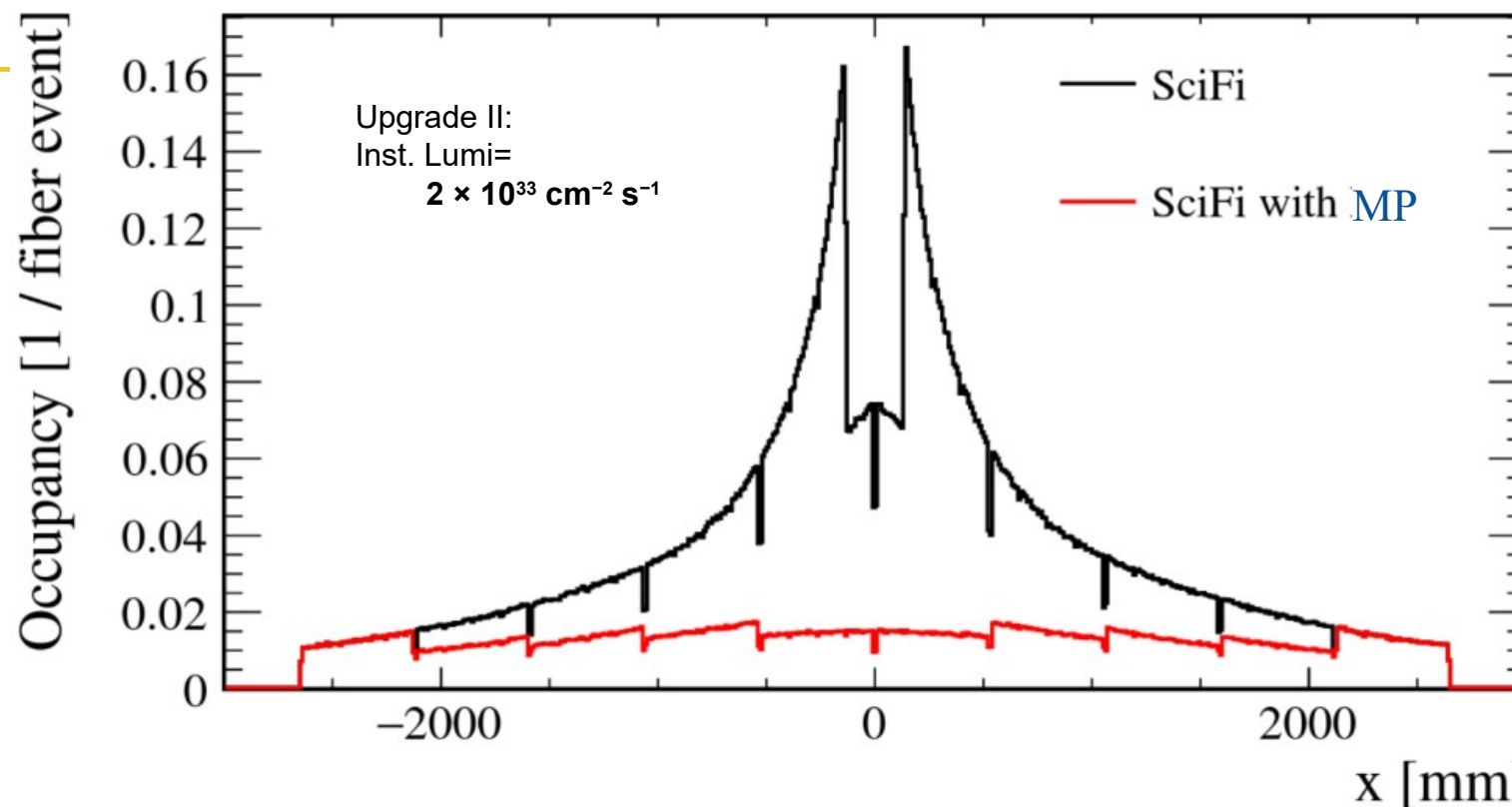
# Cryogenic SciFi

- Goal is a “noise free” detector
- Challenges: cryogenic cooling for a larger tracking detector
- Fiber bending at the end
- Thermal insulation of the coldbox
- Use liquid N<sub>2</sub>
- About 3 kW cooling power needed
- First test show great promise





# Why do we need the Mighty-Pixel

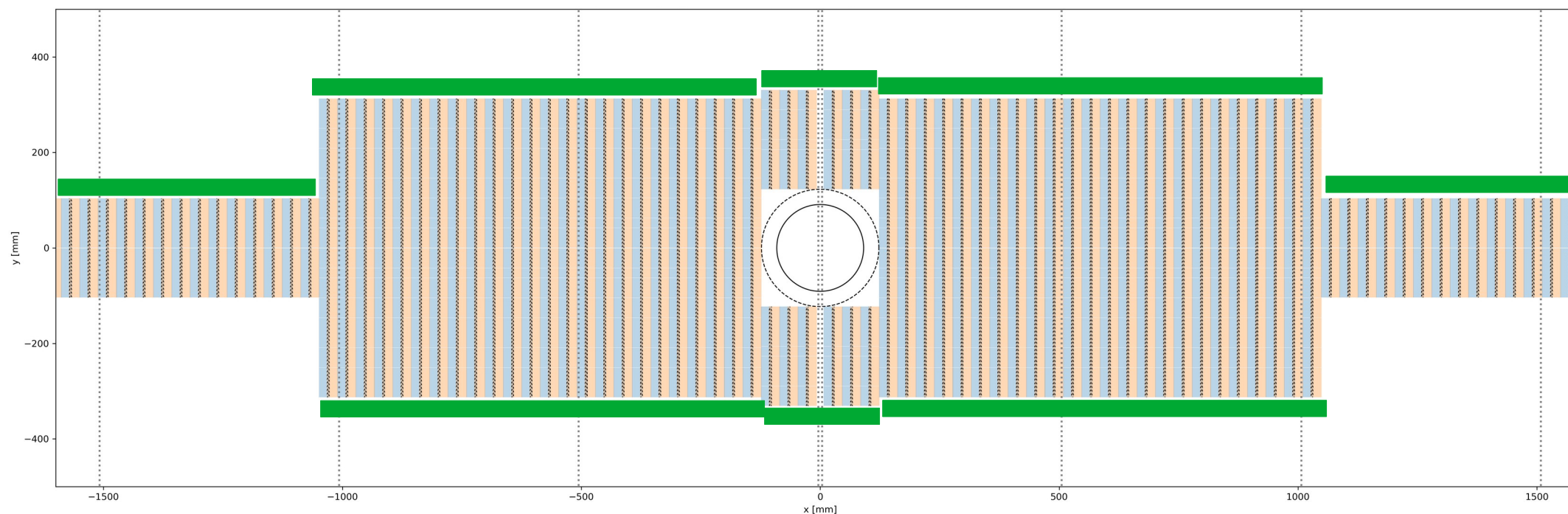


LHCB-TDR-023

The number of hits/fiber/event is too high to allow efficient tracking  
Need to have a higher granularity in the central region.

# Mechanical Layout

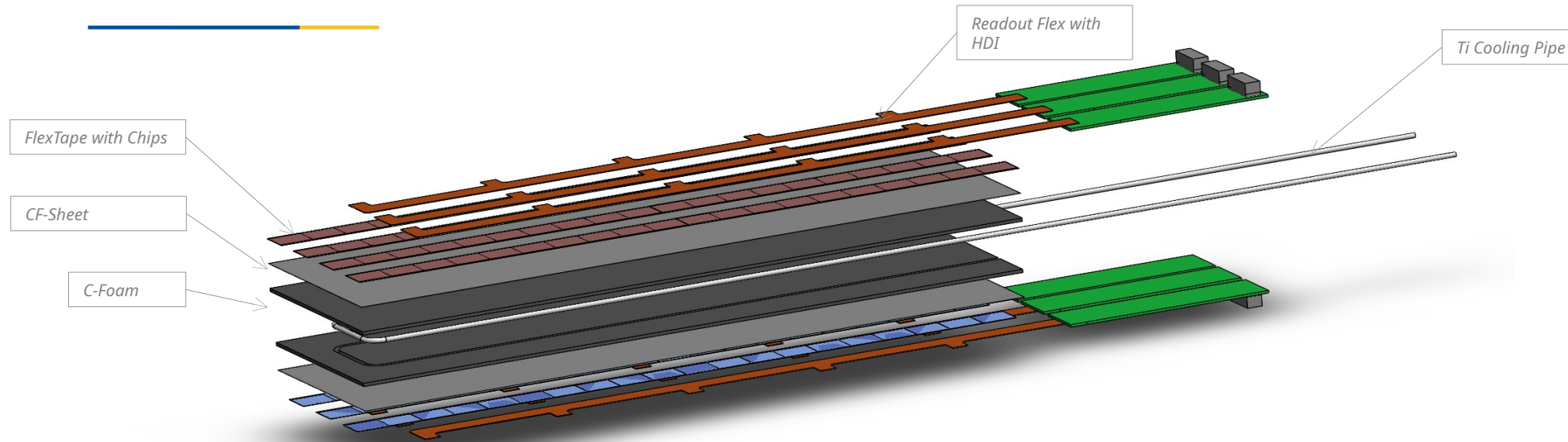
One Layer  $1.49\text{m}^2$   
 $9\text{m}^2$  in total  
 2 Layers per station  
 6 Layers in total



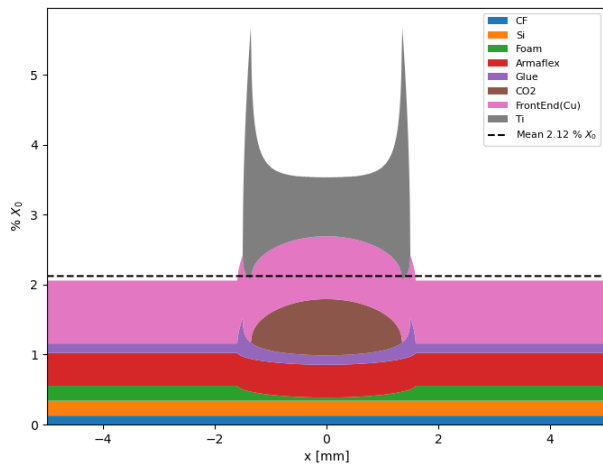
- Module width given by the beamhole (26cm)
- Shape follows the highest acceptable occupancy in the fiber region
- Readout is moved out as far as possible from the hottest region



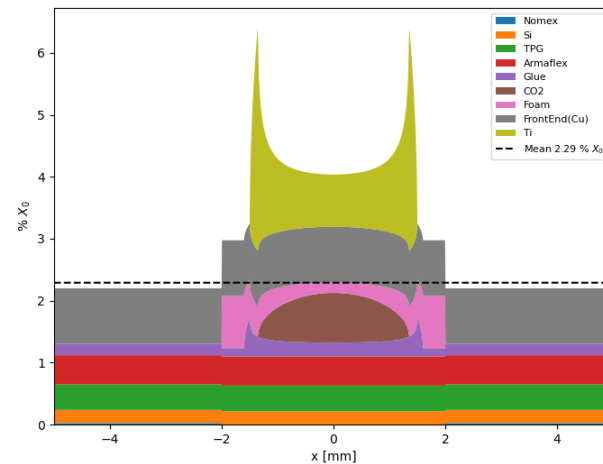
# Module Stack



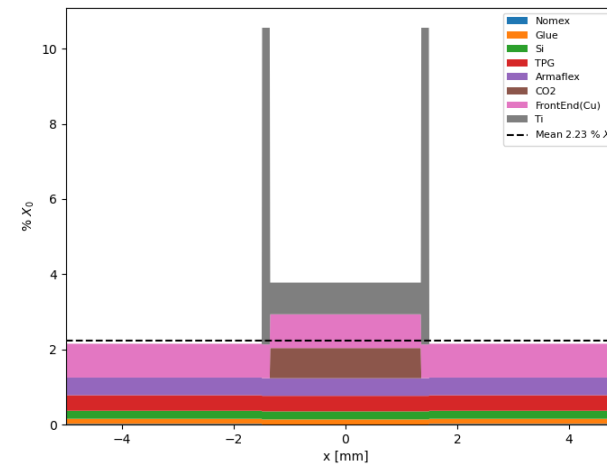
Baseline Ti Tube  
w. Foam



Nomex Ti Tube  
No Foam



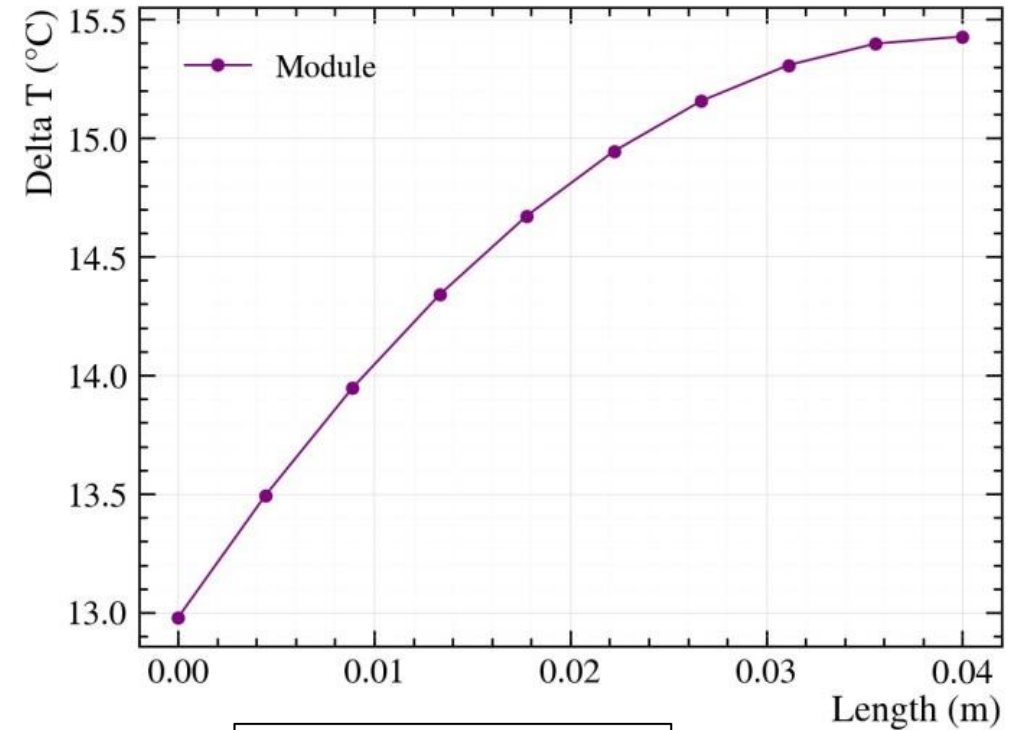
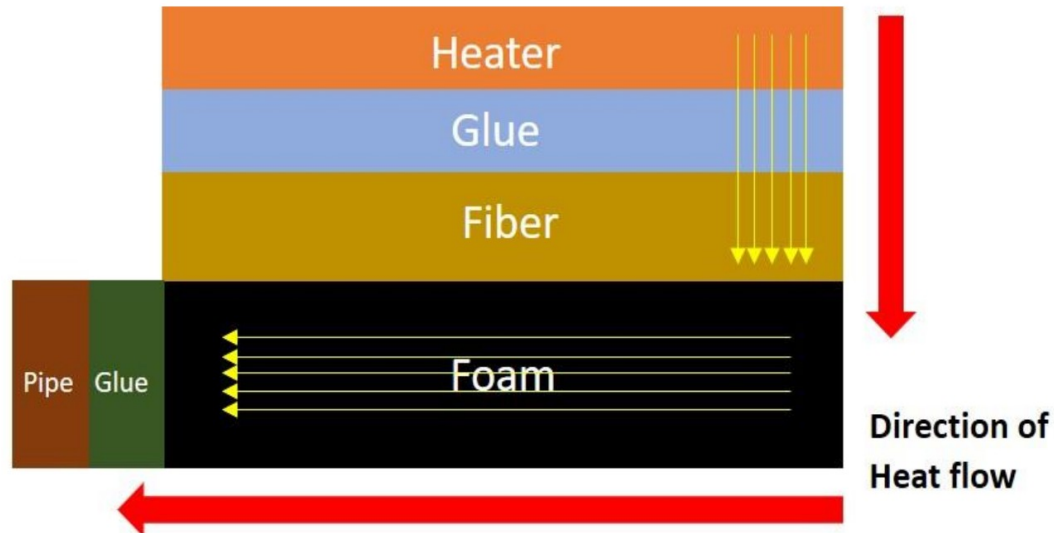
Square Ti Tube  
No Foam



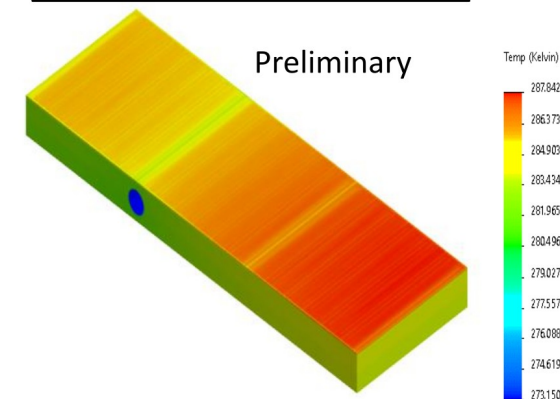
# Cooling

- Baseline two phase CO<sub>2</sub>
- The natural detector layout favours a colder beamhole area
- For -10°C at chip → -25°C coolant
- Sensor power dictates the number of cooling lines

*Heat load = 0.3W/cm<sup>2</sup>*



T Pipe = 0°C  
T Hottest = 14.6°C  
ΔT = 14.6 °C





# MightyPix 1

There is a problem with the configuration of the MP1

→ could be roughly fixed by FIB surgery

The time binning is rough

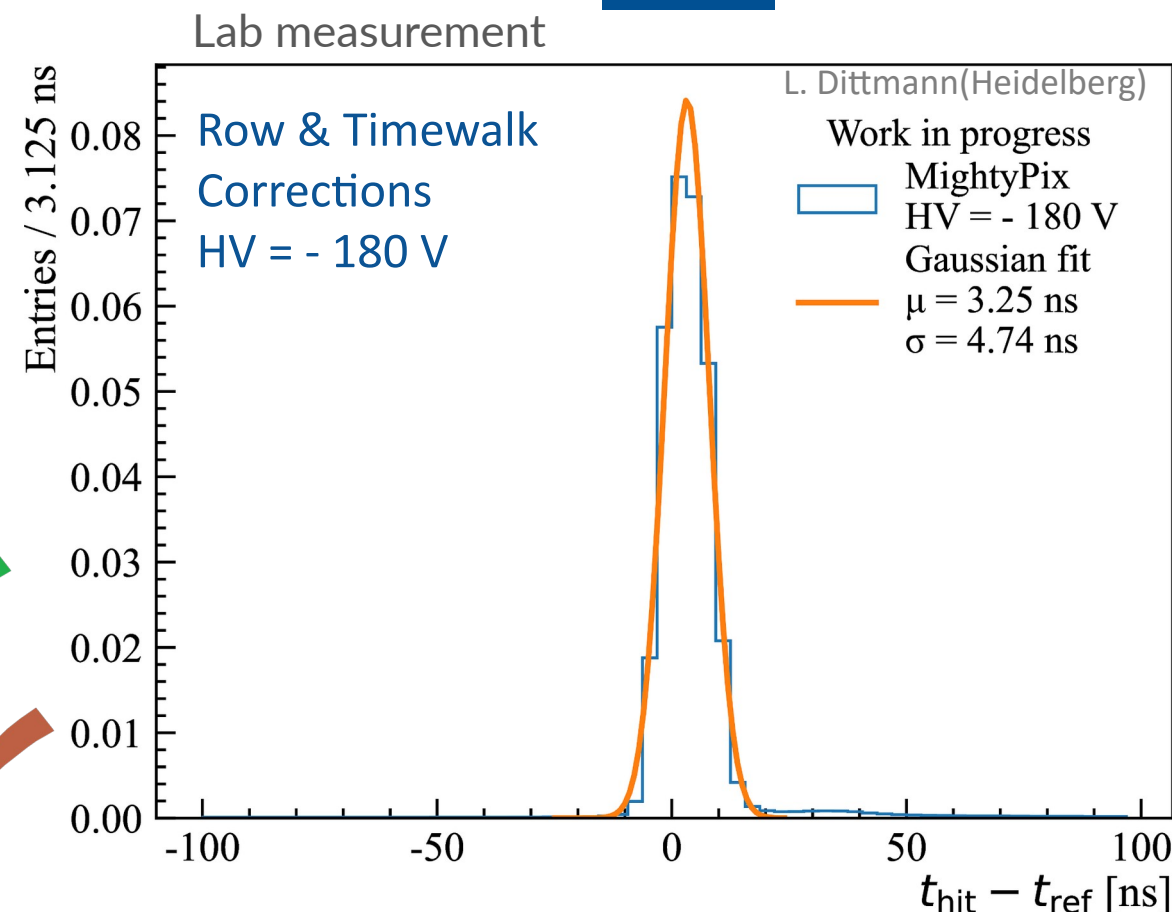
4.74 ns measured → ~ 2.9 ns intrinsic uncertainty

Power consumption 190-250 mW/cm<sup>2</sup> (scaled to full chip)

-----

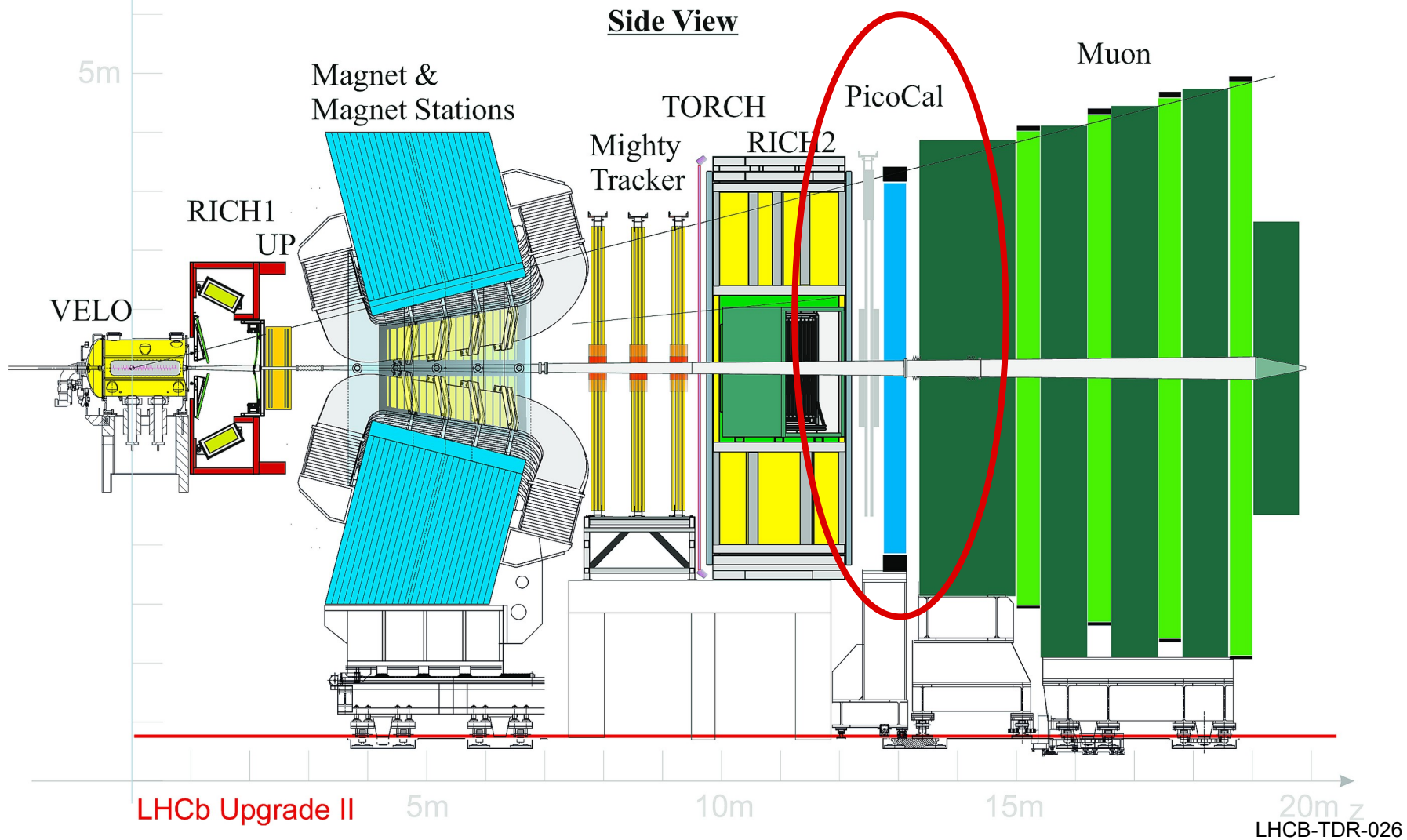
Due to chip repair we can not use this chip in the testbeam

→ Same analog pixel design in TelePix 2 (½ the pixel size)



Many Thanks to our colleagues from DESY, KIT and Heidelberg we are validating this with the TelePix 2

# Upgrade II PicoCal



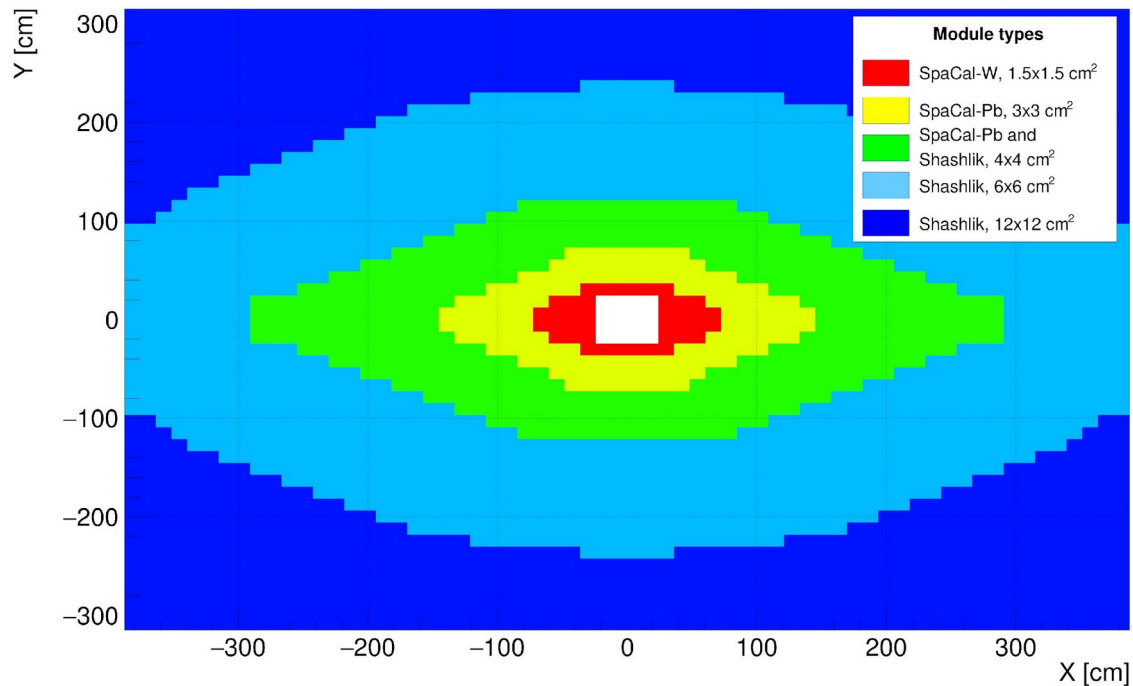


# Interesting... The PicoCal

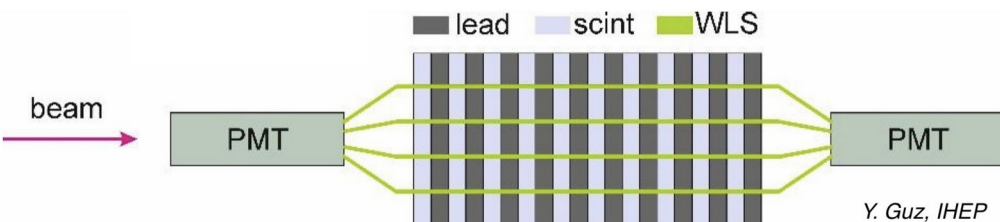


# PicoCal

PicoCal 2024 - baseline



## Shashlik



Readout follows the occupancy  
Adopt technologies to cover full area

## SpaCal technology for inner region

$1.5 \times 1.5 \text{ cm}^2$  cell - W absorber + crystal fibres

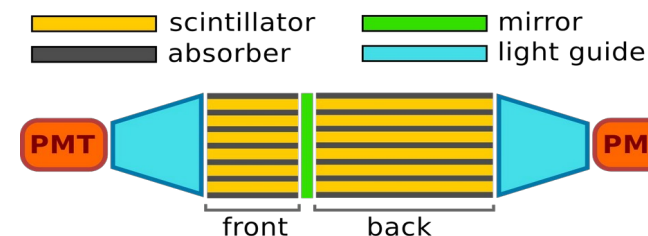
- Development of radiation-hard crystal fibres
  - Polystyrene fibres for Run 4, then replaced by crystals
- $3 \times 3$ ,  $4 \times 4 \text{ cm}^2$  cell - Pb absorber + plastic fibres:
- Need radiation-tolerant plastic fibres

## Shashlik technology for outer region

$4 \times 4$ ,  $6 \times 6$ ,  $12 \times 12 \text{ cm}^2$  cell

- Timing improved with faster WLS fibres and double-sided readout

## SpaCal





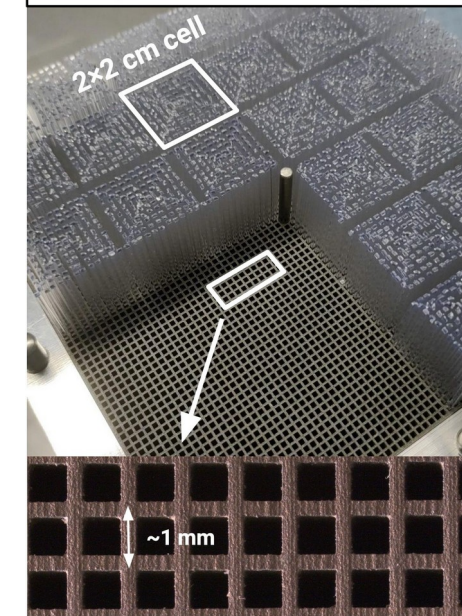
# PicoCal Status of R&D

- Tungsten Absorber: successful prototype 3D printed
- Lead absorber: Low pressure casting
- Encouraging energy resolution:
  - Sampling term: 11.2%
  - Constant term: 1.2%
- Time resolution < 20ps above 20GeV

## Fiber:

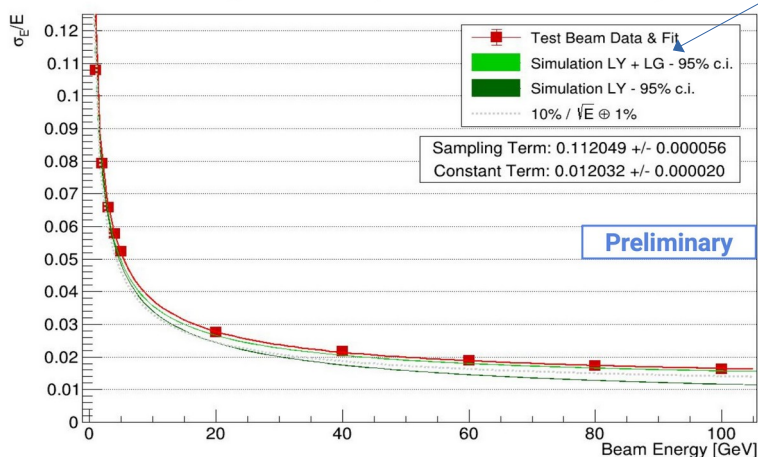
- Found organic scintillators that are promising
- Crystal scintillators under investigation

Module-size tungsten absorber with plastic scintillating fibers



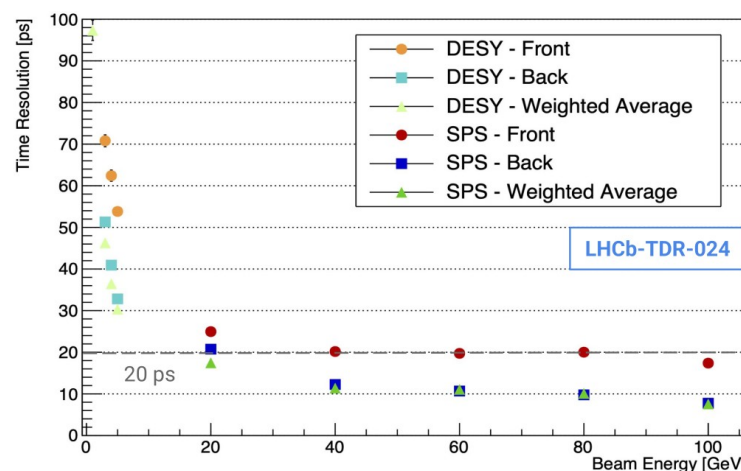
## SpaCal-Pb single module

Energy resolution (DESY II & SPS North Area)



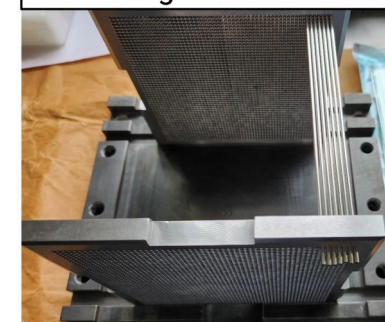
## SpaCal-Pb double-sided

Time resolution (DESY II & SPS North Area)

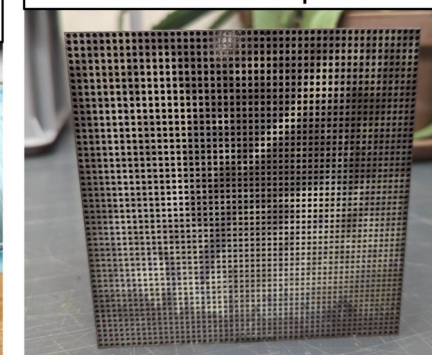


## Further Information

Stainless steel capillary tubes aligned with masks

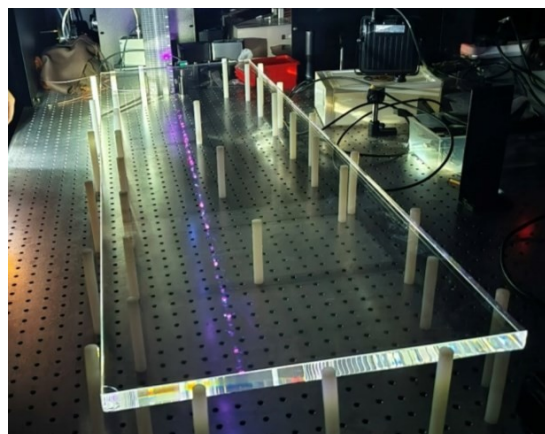
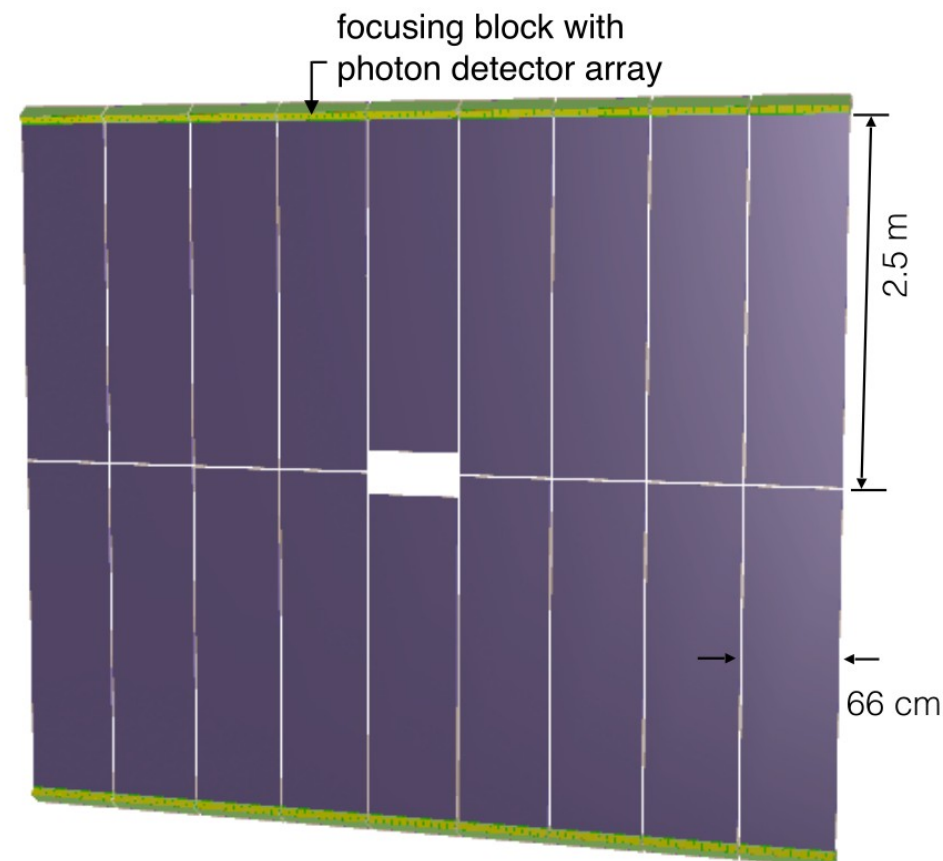
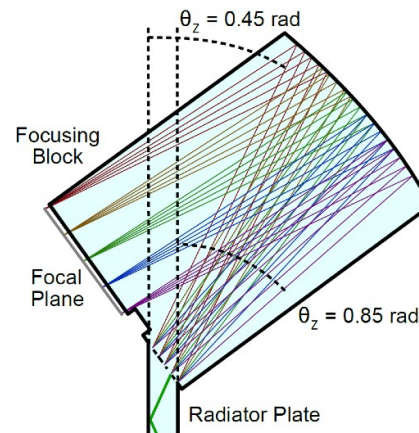


Lead absorber piece



# TORCH

- Provide time information for the RICH2
- Cherenkov light passed transported via total reflection
- 25ps time binning
- Use FastRich Readout
- Can use Microchannel-plate-PMTs may use SiPMs (to use the same technology as RICH)
- Challenges:
  - Space in cavern
  - Flatness of fused silica
  - Occupancy

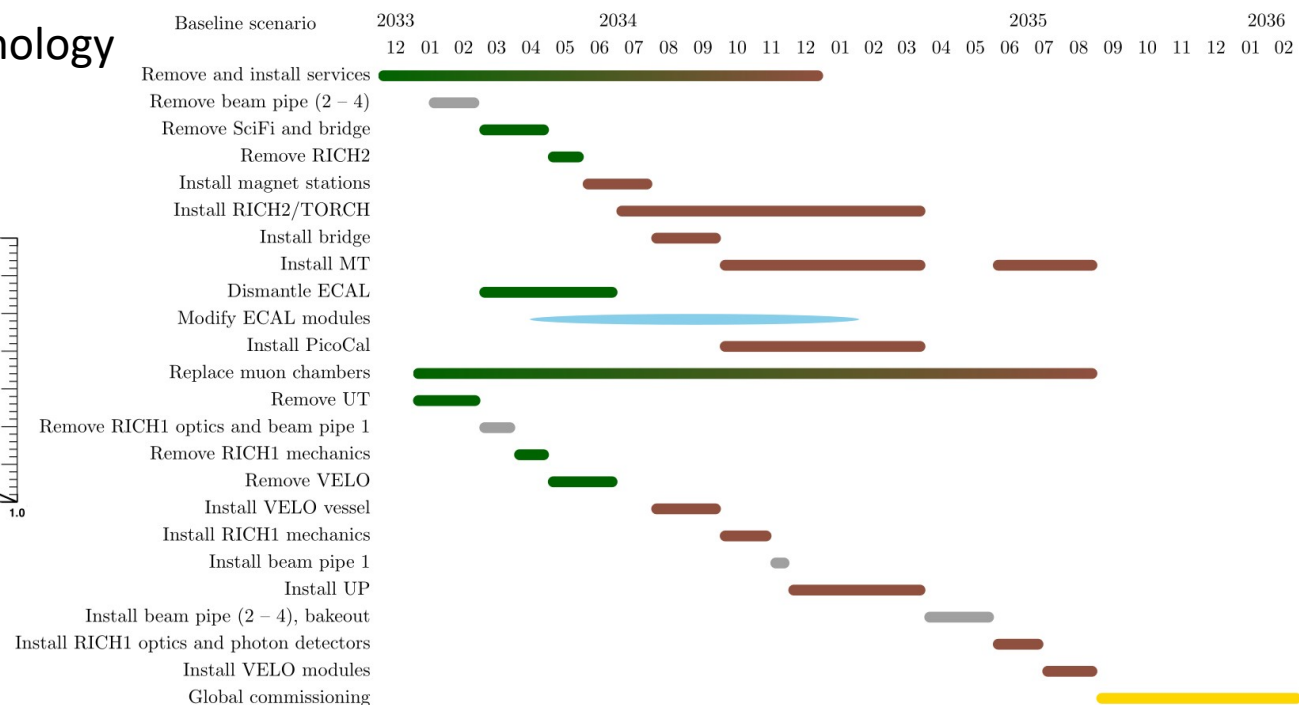
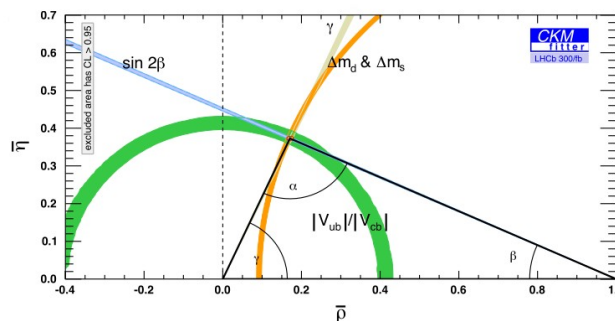
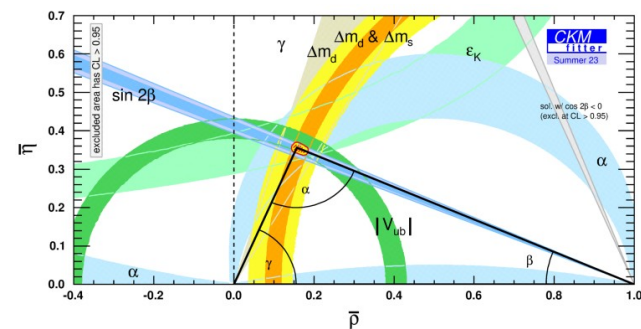
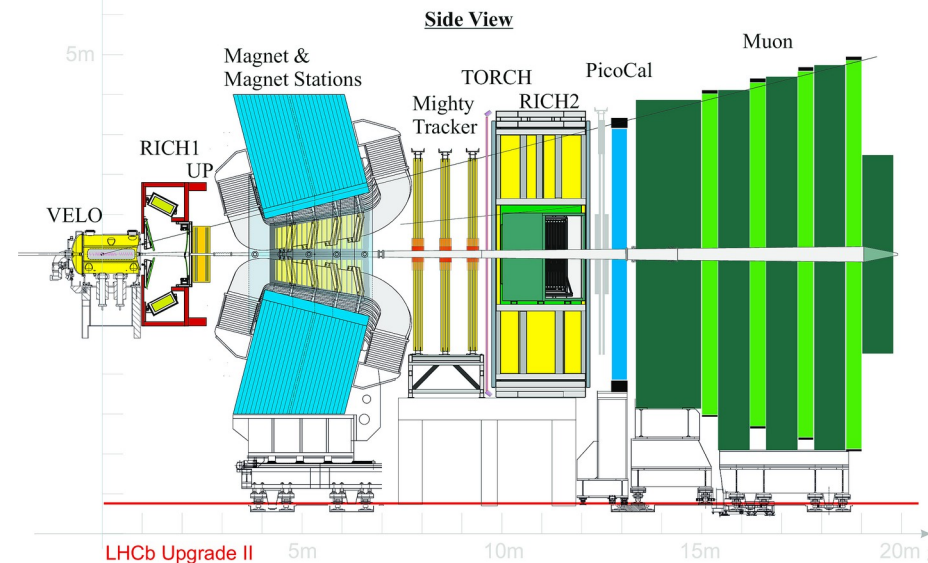


Surface measurement of large fused silica plate



# Summary

- Exciting times ahead of us
- 9 years to go
- Start production in 4 years
- Just 1 year to install a fully new detector
- Upgrade II will push the frontier of detector technology



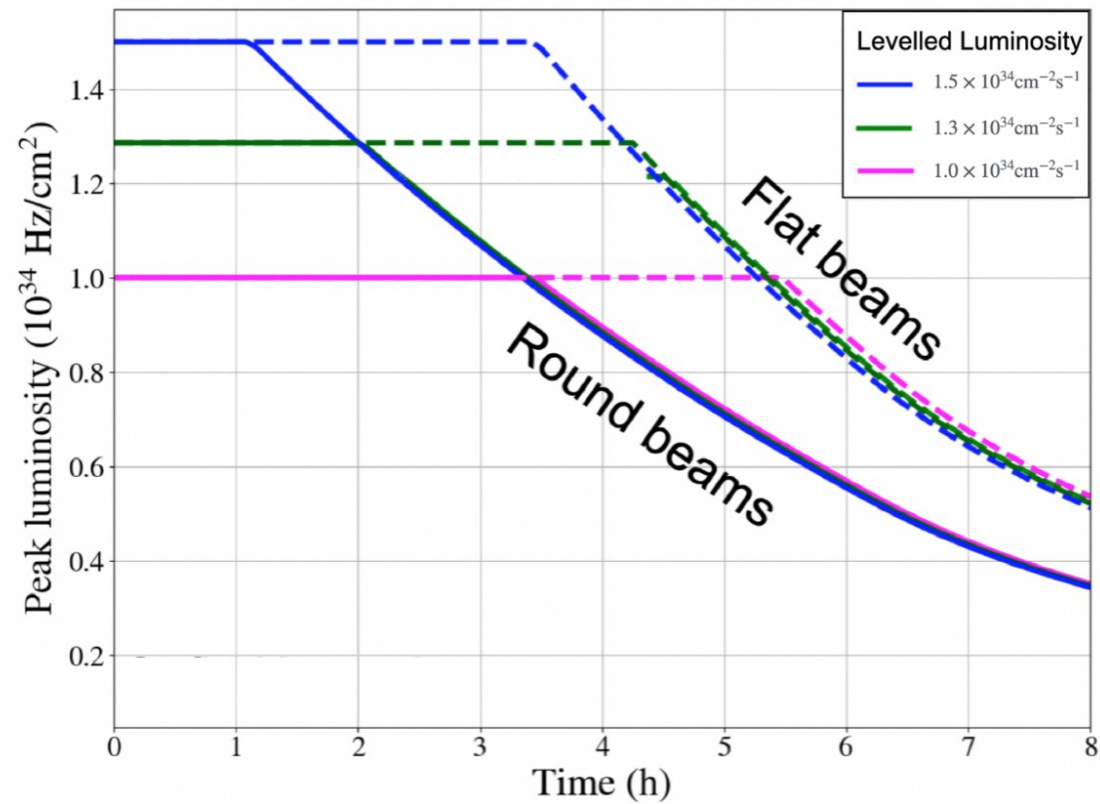




# Backup



# Luminosity



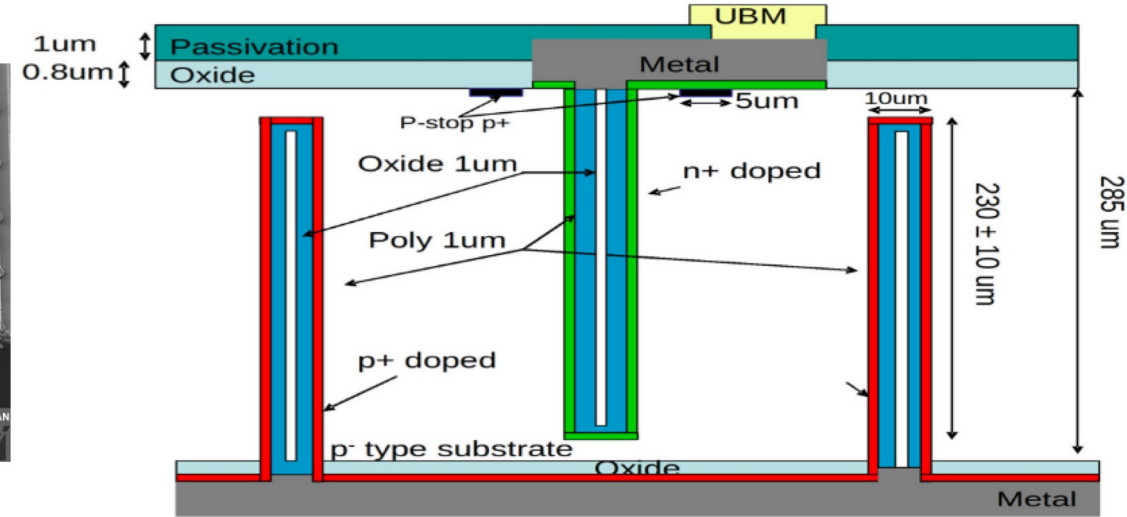
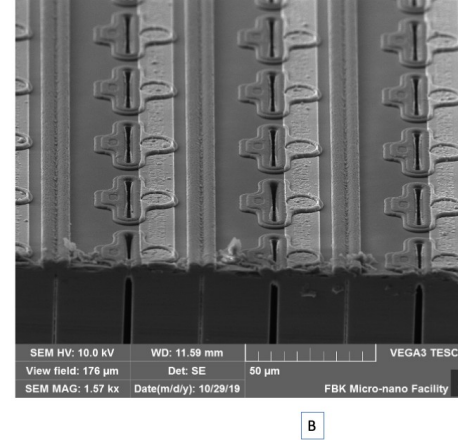
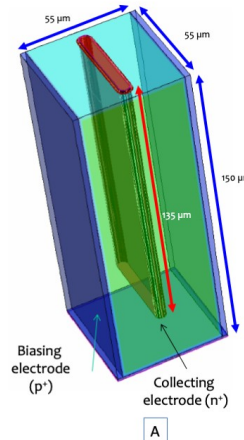
LHCb-TDR-026

|                                                                                   | Round optics |       | Flat optics |       |
|-----------------------------------------------------------------------------------|--------------|-------|-------------|-------|
| Levelled $\mathcal{L}_{\text{peak}}$ ( $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ) | 1.0          | 1.5   | 1.0         | 1.5   |
| $\beta_x^*/\beta_y^*$ (m)                                                         | 1.5/1.5      |       | 0.5/1.5     |       |
| $N_{\text{bunch}}$ total/colliding in LHCb                                        | 2760/2574    |       | 2760/2574   |       |
| Levelled pile-up                                                                  | 28           | 42    | 28          | 42    |
| Delivered $\mathcal{L}_{\text{int}}$ per year ( $\text{fb}^{-1}$ )                | 42.16        | 49.34 | 48.73       | 63.36 |
| Levelling time $t_{\text{lev}}$ (h)                                               | 3.42         | 1.08  | 5.42        | 3.42  |
| Optimal fill length $t_{\text{opt}}$ (h)                                          | 7.67         | 7.58  | 7.58        | 7.42  |
| $t_{\text{lev}}/t_{\text{opt}}$                                                   | 0.45         | 0.14  | 0.72        | 0.46  |
| RMS luminous region ( $z$ ) at $t = 0$ (mm)                                       | 43.30        | 43.31 | 38.41       | 38.45 |
| Peak pile-up density at $t = 0$ ( $\text{mm}^{-1}$ )                              | 0.29         | 0.40  | 0.41        | 0.54  |

# Velo Sensor

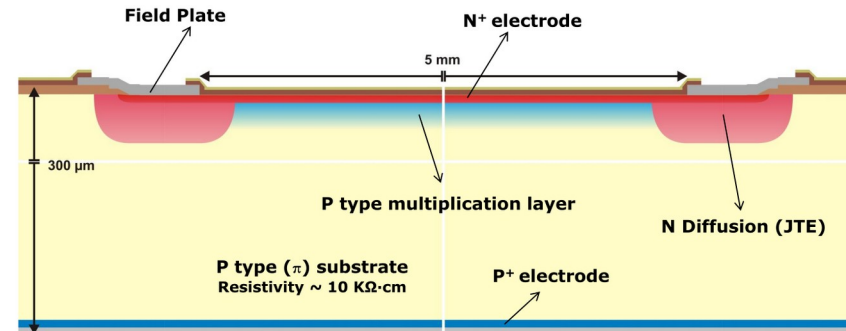
3D sensor (trench or column):

- Radiation tolerance up to  $10^{16}$  MeV  $n_{eq}$
- Difficult to produce
- 10ps resolution per pixel possible



## LGAD

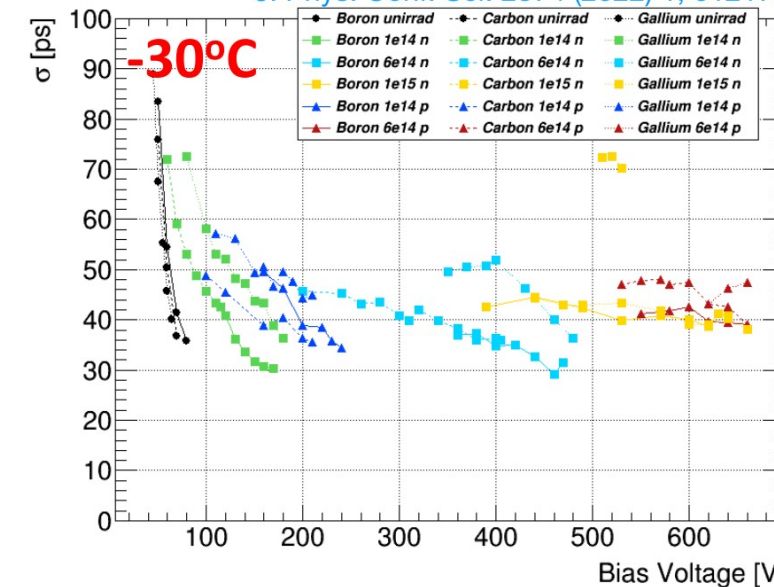
- Time resolution ~40ps
- Radiation tolerance\* ~3-4  $10^{15}$  MeV  $n_{eq}$



\*radiation tolerance is under study and probably can be improved

source

J. Phys. Conf. Ser. 2374 (2022) 1, 012175



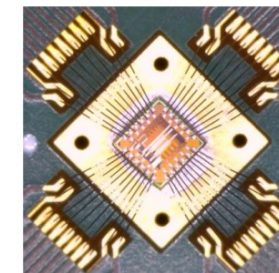


# Velo ASIC

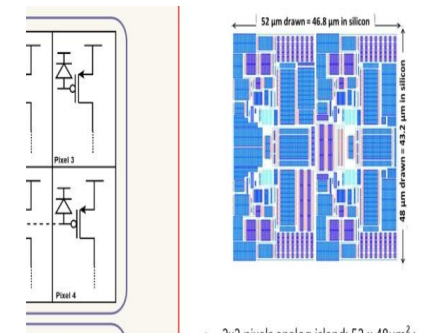
| Feature                 | IGNITE (3D Integration)                                                    | LA-PicoPix (Per-Pixel Compensation)                                  |
|-------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------|
| <b>Power Management</b> | Split Analog & Digital ASICs for uniform power distribution                | On-pixel power compensation to correct local fluctuations            |
| <b>Pixel Size</b>       | Smaller pixels ( $\sim 45 \mu\text{m}$ ) due to separate processing layers | Larger pixels ( $\sim 50 \mu\text{m}$ ) but single ASIC architecture |
| <b>Post-Processing</b>  | Requires 3D integration + TSV (Through-Silicon Vias)                       | No TSV needed $\rightarrow$ Simpler data processing                  |
| <b>Scalability</b>      | Potential for higher density integration                                   | Easier manufacturing & integration                                   |

Two developments ongoing:

- IGNITE (TimeSPOT development)
- PicoPix (Timepix4 development)



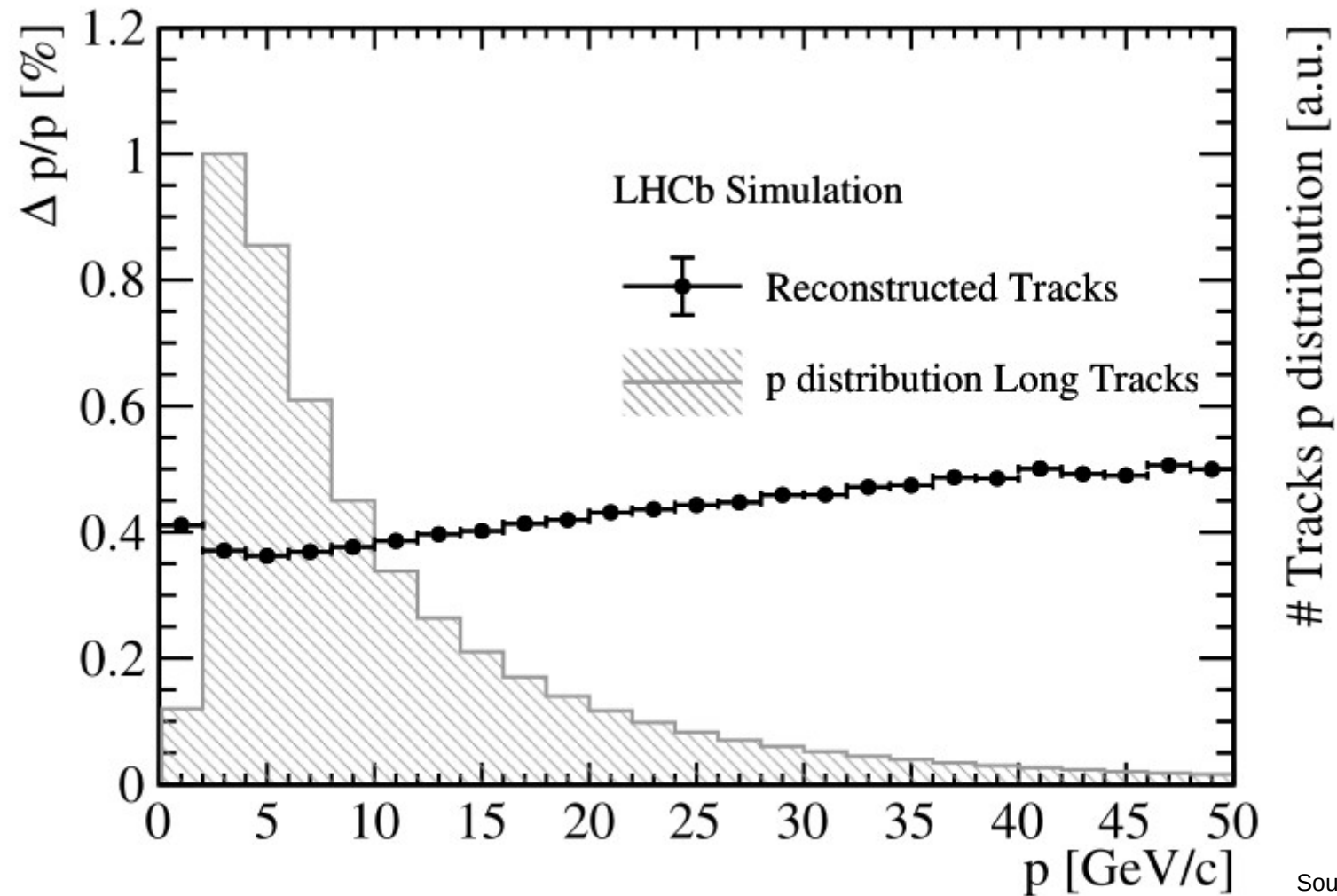
**Ignite0** test ASIC  
(2023)



**PicoPix** analog  
pixel cell

[More Details](#)

# Tracking in LHCb



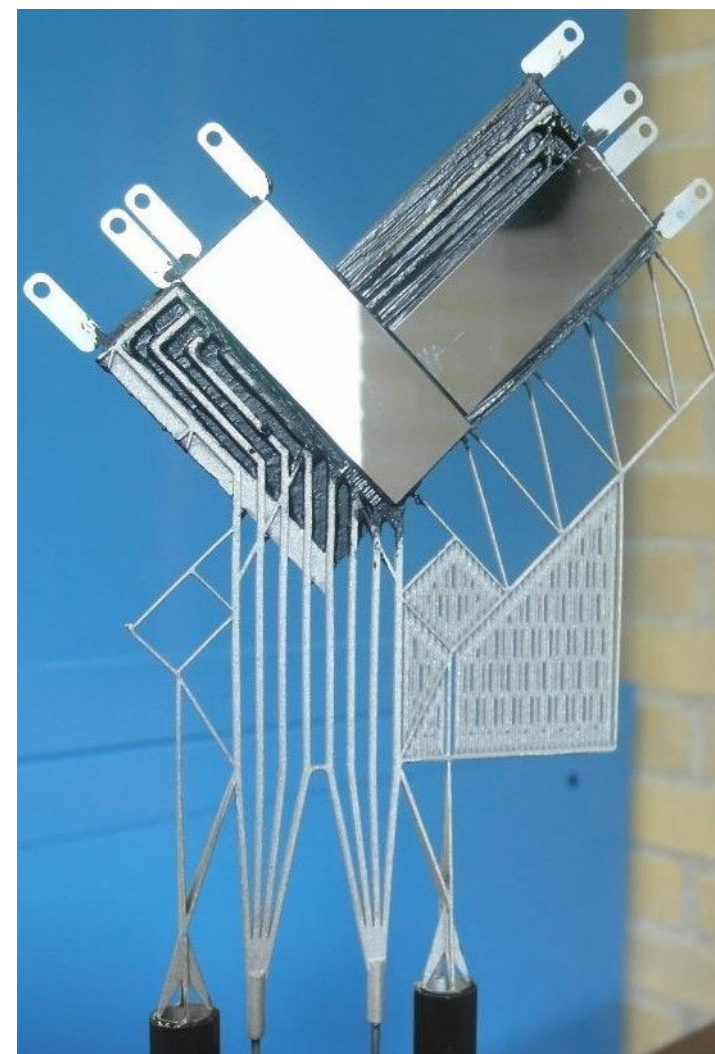
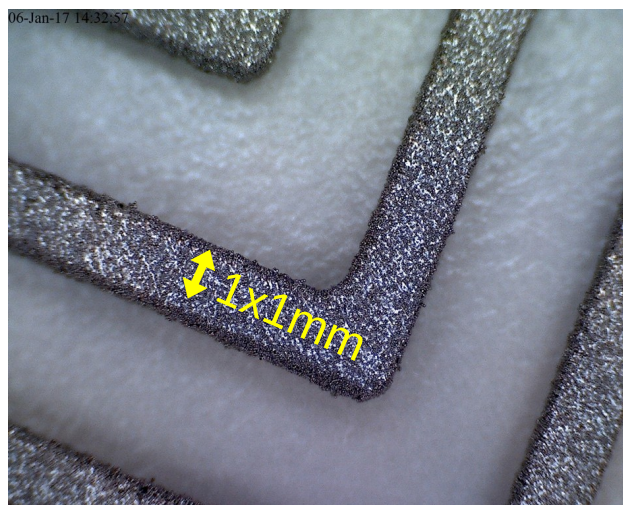
Source  
P. A. Günther (2023)



# 3D Titanium

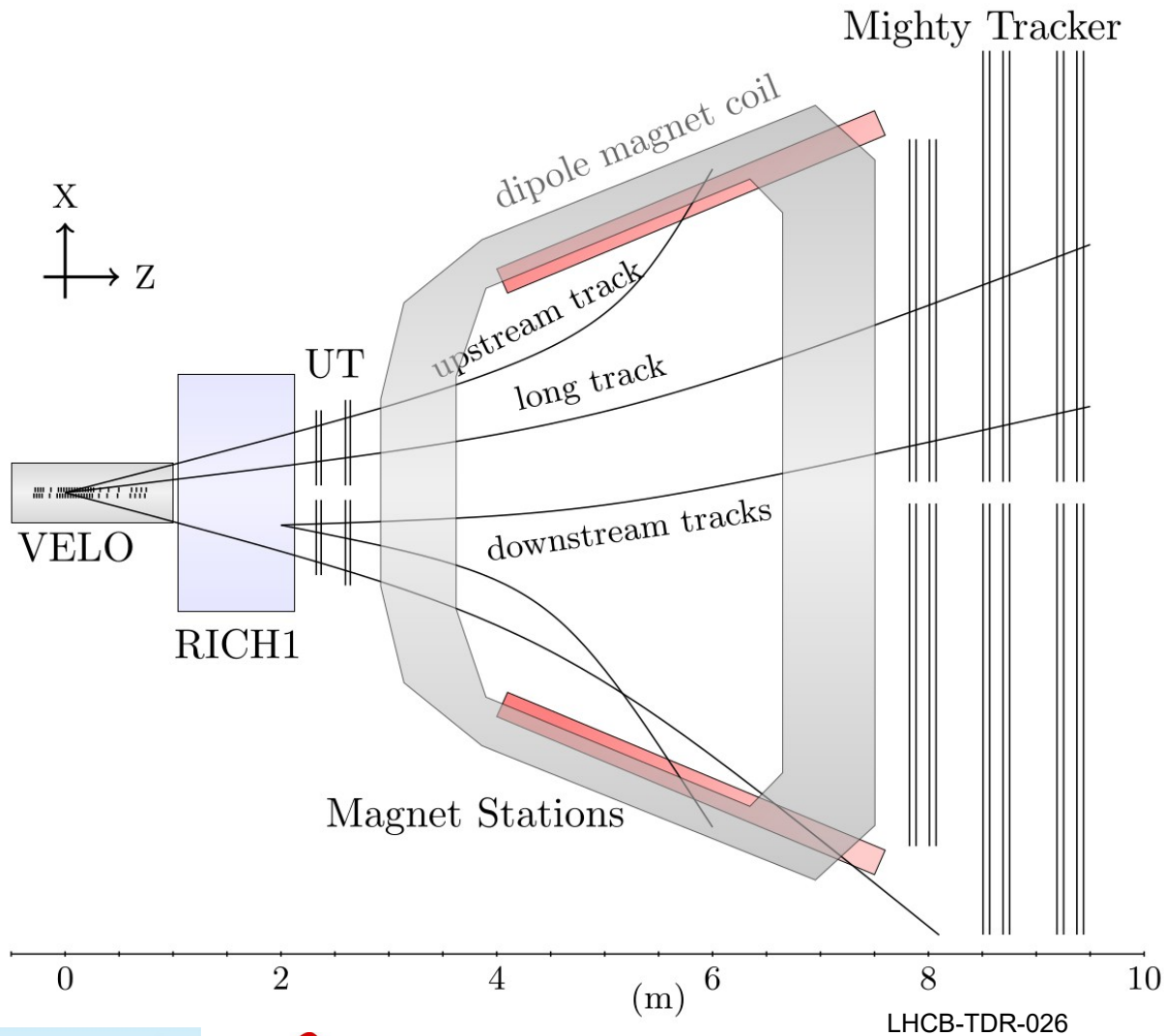
LHCb-TALK-2022-310

- Fully developed for current Velo
- More flexible for various pressure drops
- More  $X_0$



Klaas Padeken

# LHCb Tracking Requirements



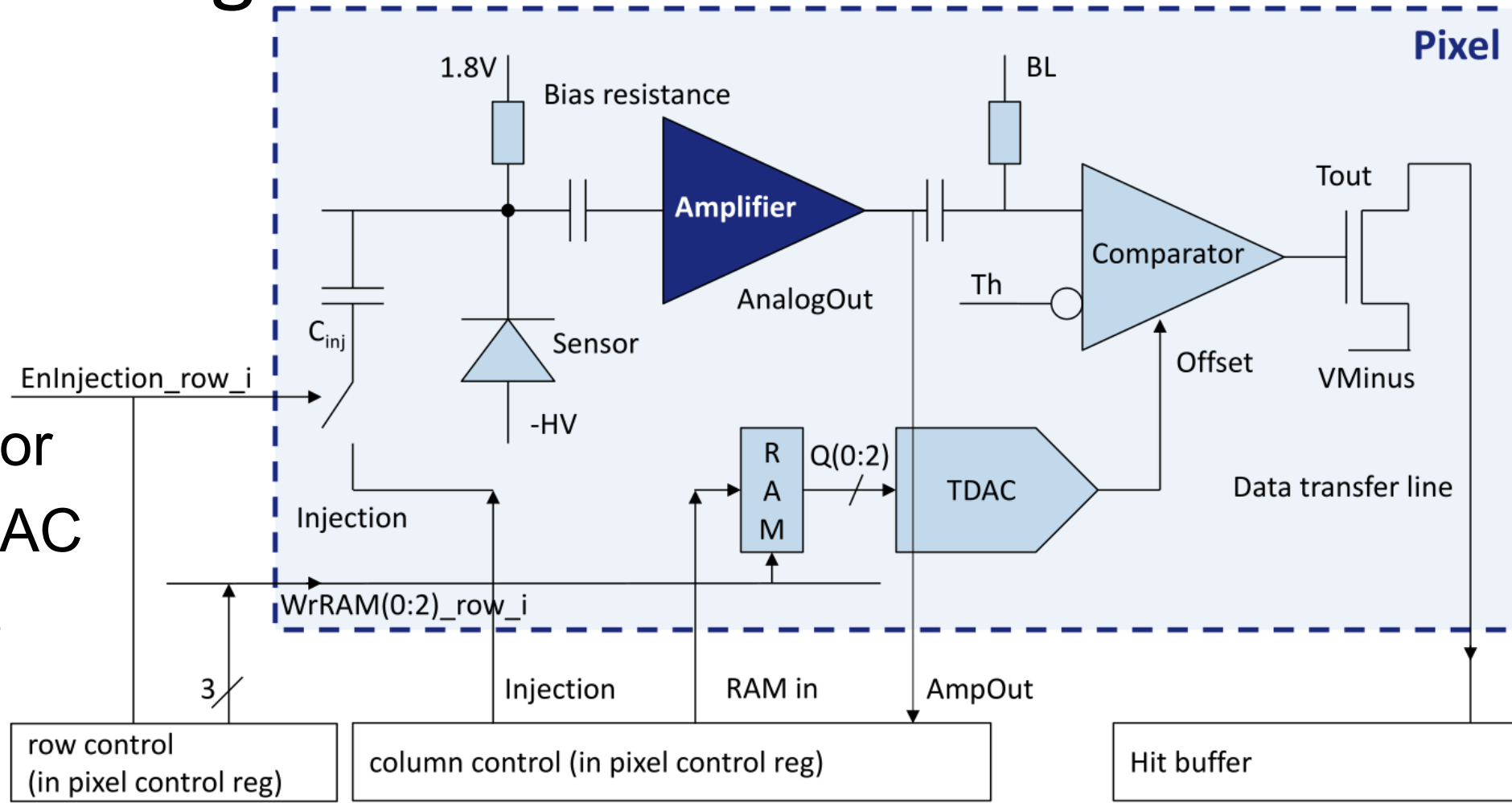
- reconstruction of hadron decays
  - many final state particles
  - high pointing precision
- the highest efficiency possible
  - ➔ many layers
- long lever arm
  - ➔ limited by the cavern
- **high resolution**
- **low material budget**



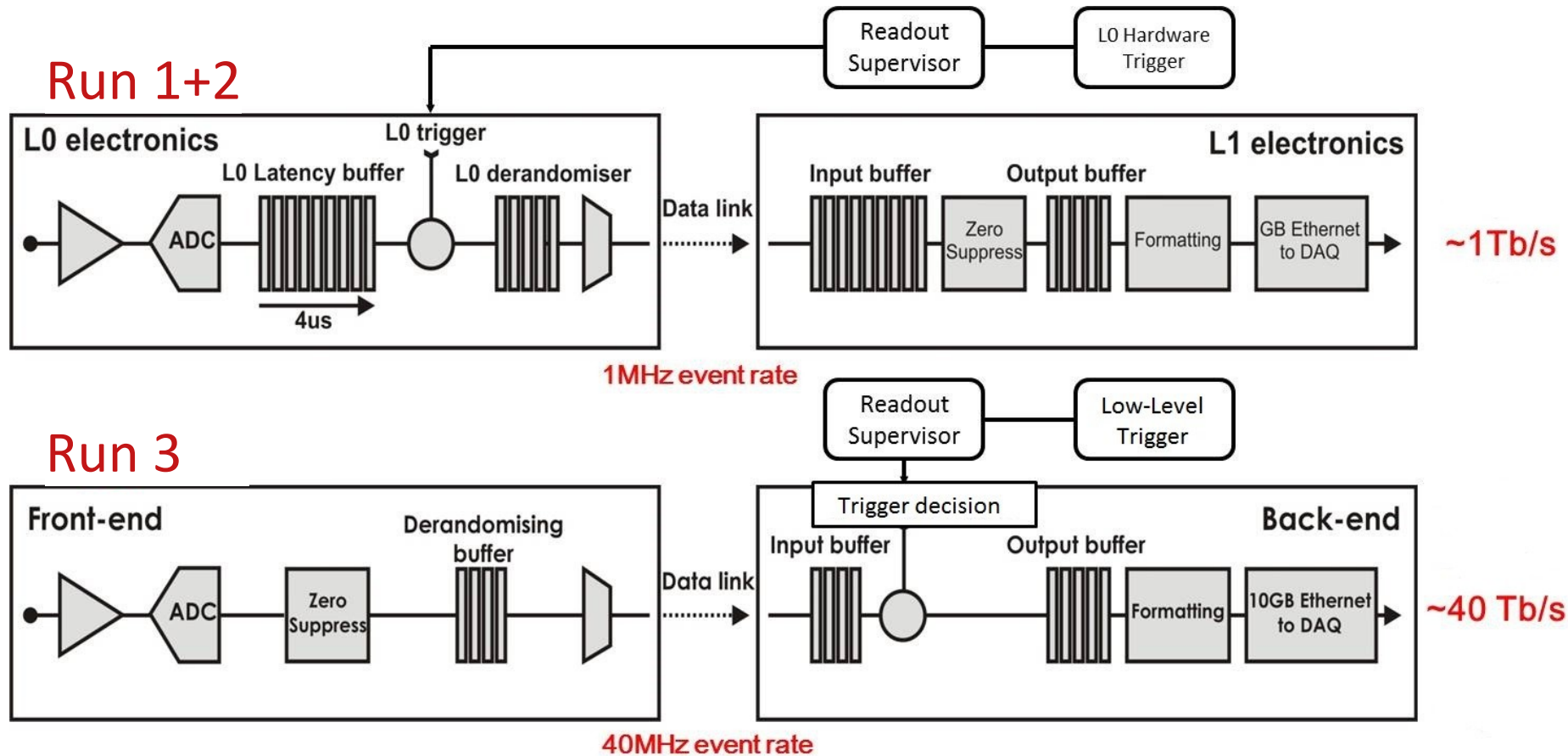
# Mighty Pixel Analogue Part

In Pixel:

- Sensor diode
- CSA amplifier
- CMOS Comparator
- Threshold tune DAC
- RAM for tune bits



# LHCb Upgrade I → “Triggerless” readout

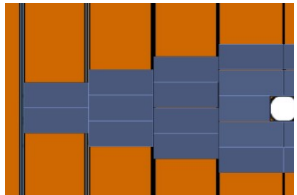


With a later High level Trigger more relevant data can be recorded!



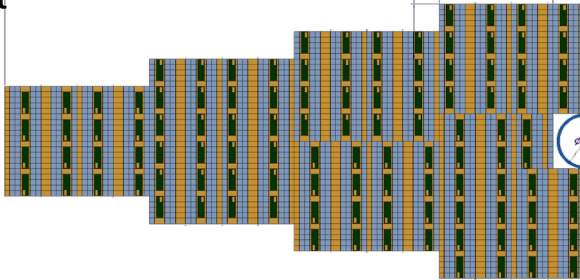
# A Short History of the Mighty

18m<sup>2</sup>  
Some Silicon area



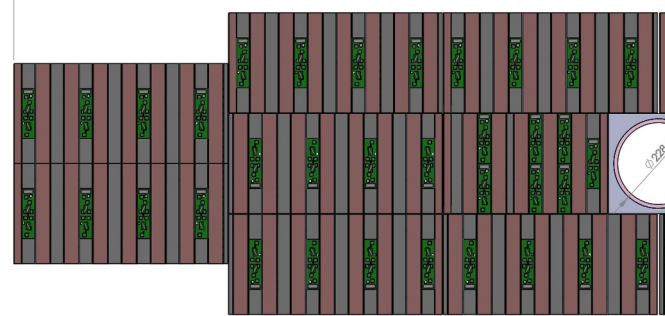
Fully integrate  
silicon into the  
fiber planes

18m<sup>2</sup>  
FTDR  
detailed ideas for readout

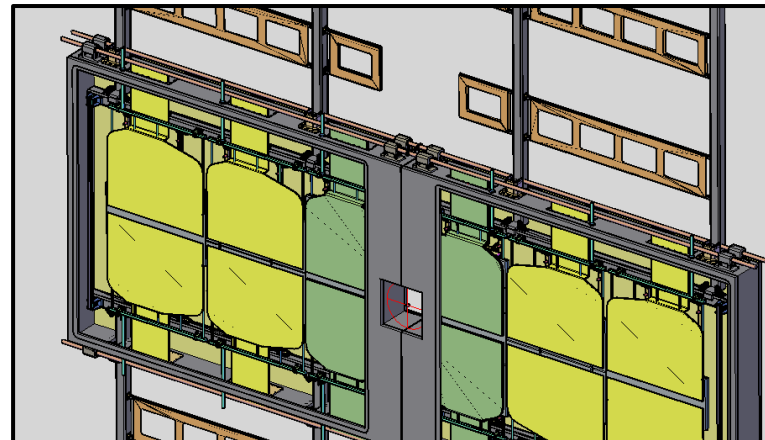


Separate silicon  
and fibers  
Ohh and we  
have to be cold

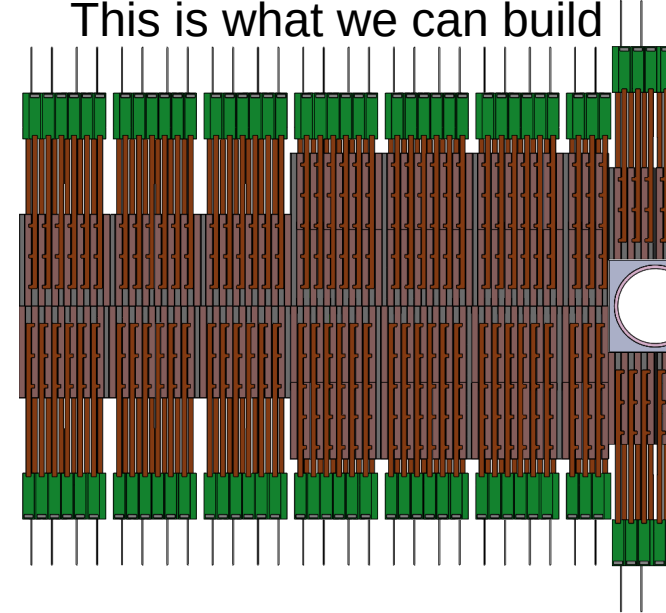
13m<sup>2</sup>/8m<sup>2</sup>  
Scoping document  
This is what we can afford



Support structures  
are designed and  
clear budget

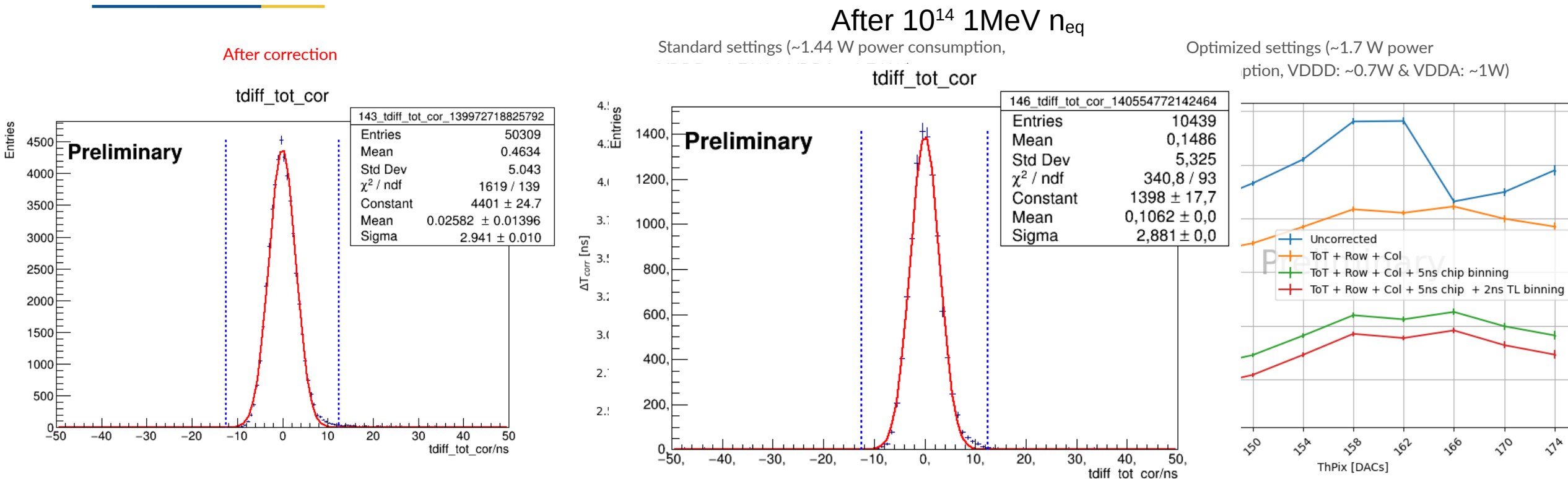


9m<sup>2</sup>  
Current design  
This is what we can build



Cooling solutions  
and auxiliary  
electronics are  
realistic

# Time Resolution- Results



- Time resolution highly threshold dependent  
→ No plateau
- Compatible with testbeam → ~3 ns w/o binning correction

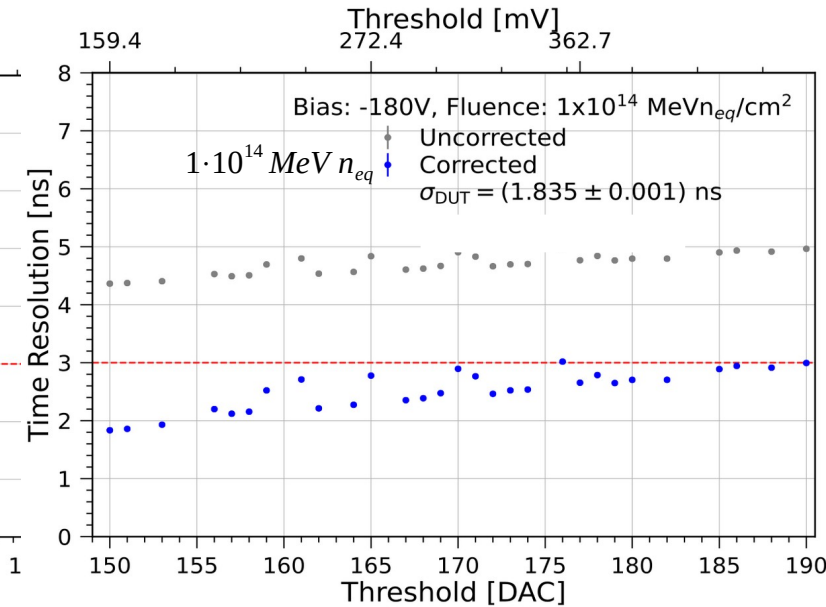
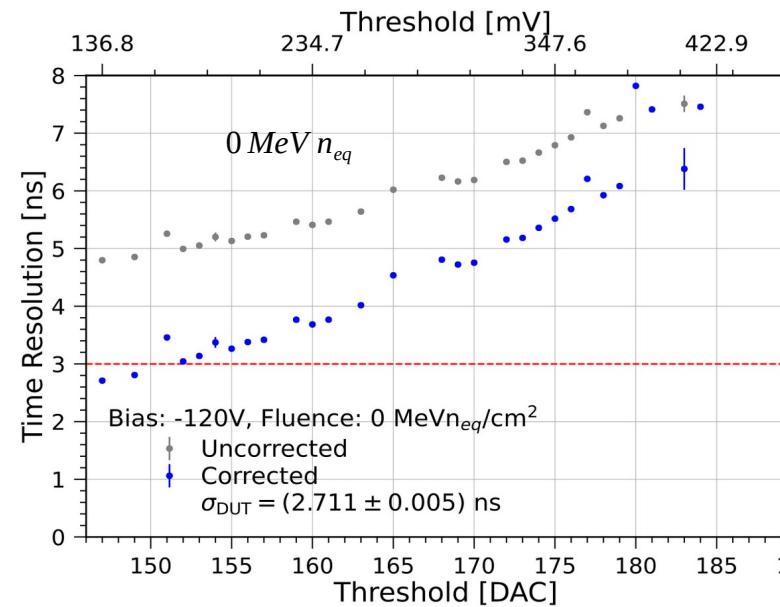
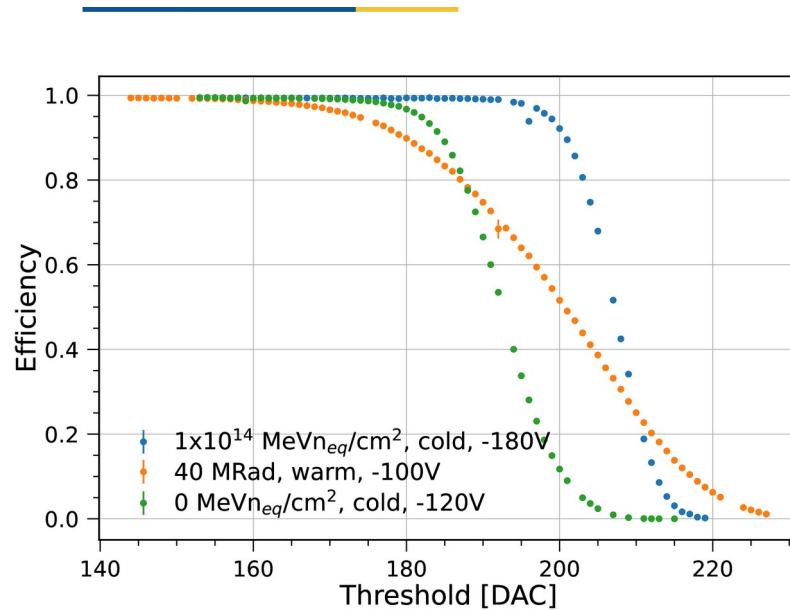
Fit fails if time walk is too large

N. Sommerfeld and H. Schmitz



# TelePix2

- Sensor designed for DESY testbeam as telescope sensor
- Same analog Pixel (with half the size) as the MightyPix1

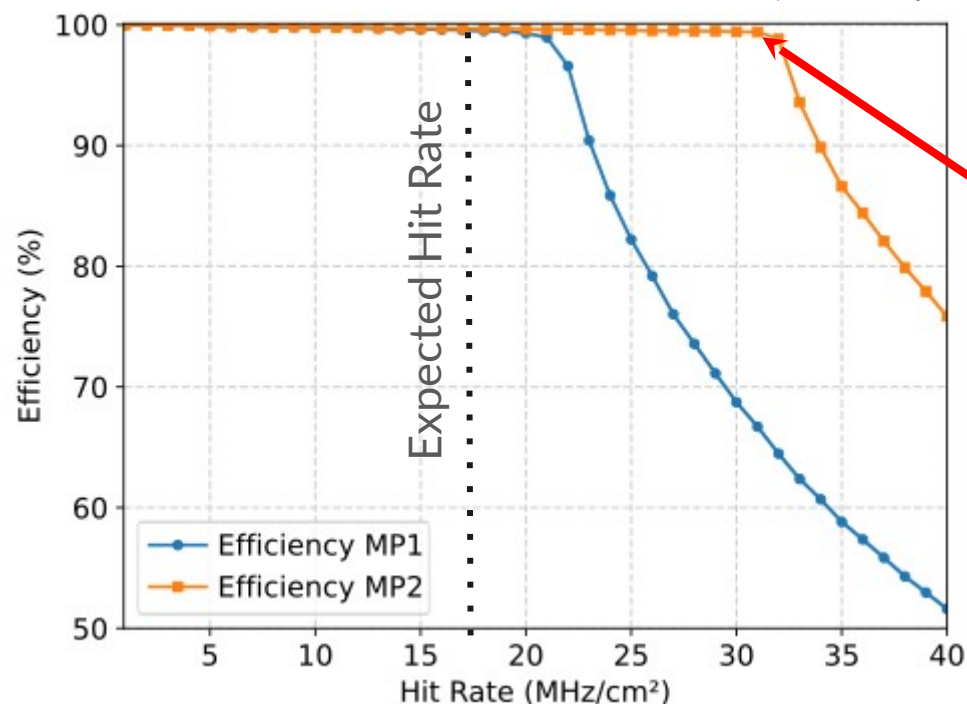


H. Schmitz and N. Sommerfeld

- Testbeam could show that sensor is radiation tolerant
- TID softens the slope
- Second TelePix sensor as time reference
- Higher irradiation allows for higher breakdown

# Hit Rate Simulation MightyPixel

S. Scherl (KIT/Liverpool)

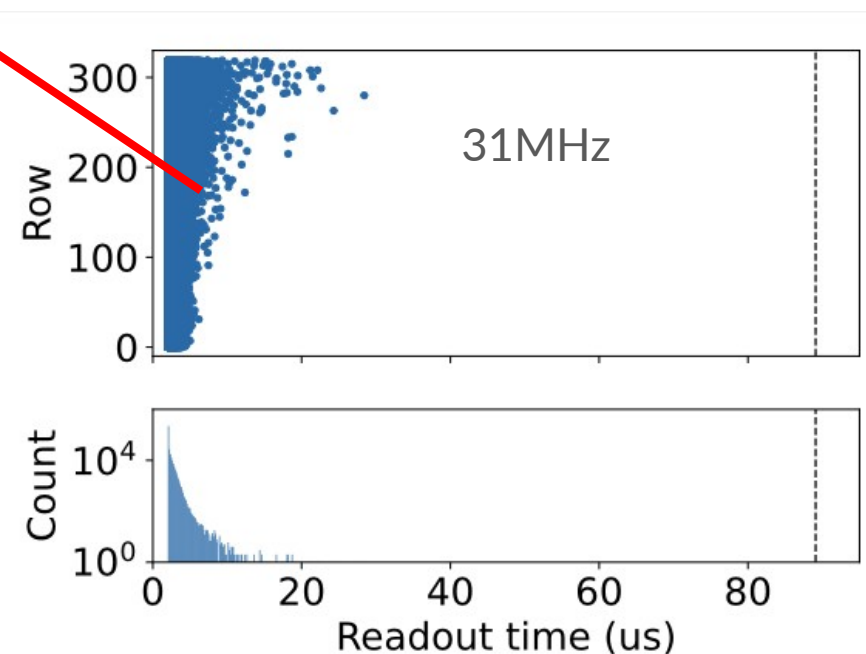


Expect a Hit rate up to **17 MHz/cm<sup>2</sup>**

MightyPix 1 should work up to **20 MHz/cm<sup>2</sup>**

MightyPix 2 will work up to **32 MHz/cm<sup>2</sup>**

Probably further reduction possible with less data

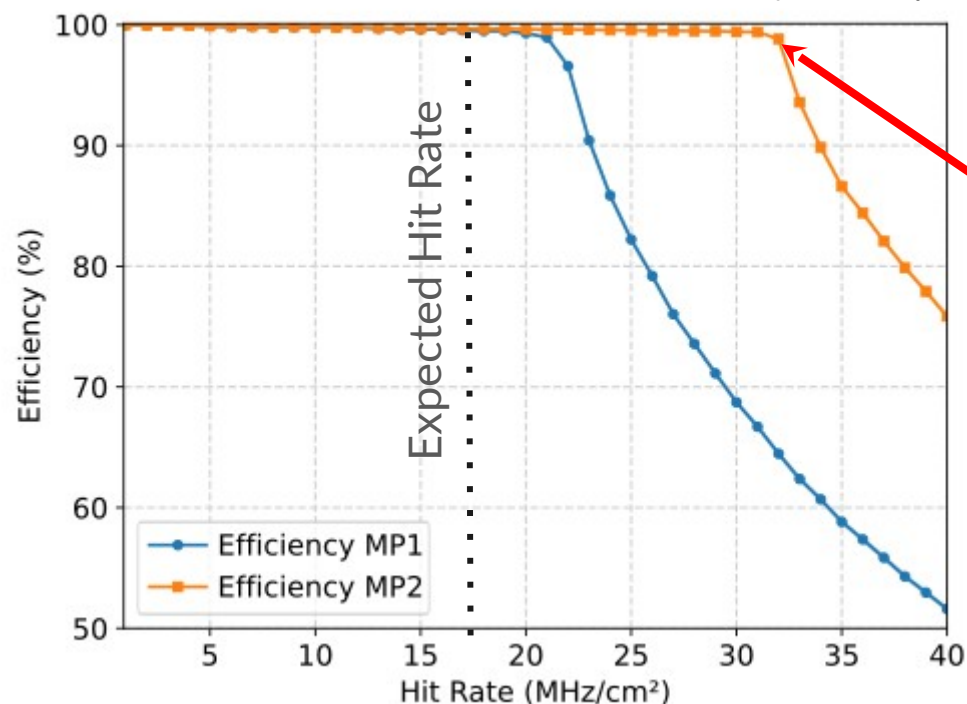


S. Scherl (KIT/Liverpool)



# Hit Rate Simulation MightyPixel

S. Scherl (KIT/Liverpool)

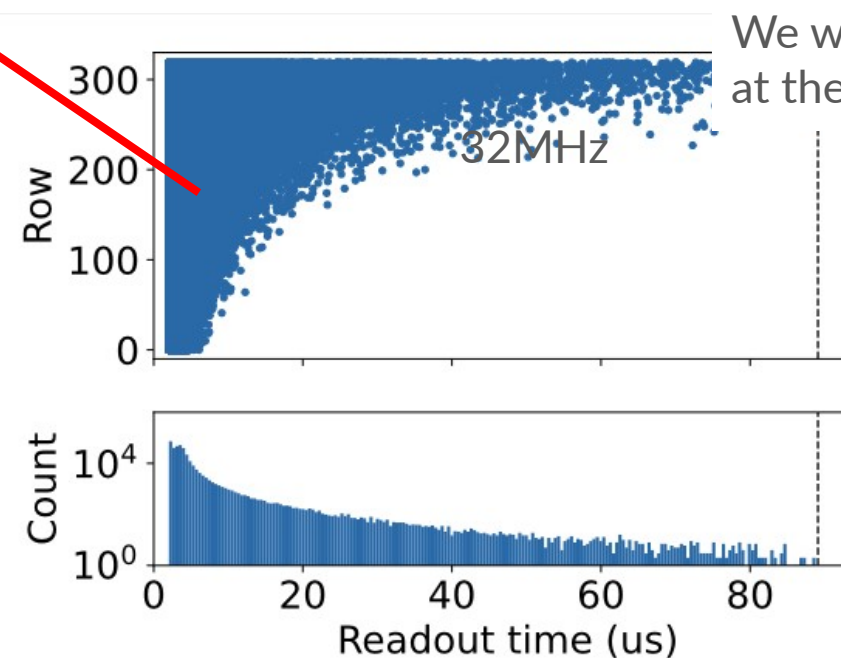


Expect a Hit rate up to **17 MHz/cm<sup>2</sup>**

MightyPix 1 should work up to **20 MHz/cm<sup>2</sup>**

MightyPix 2 will work up to **32 Mhz/cm<sup>2</sup>**

Probably further reduction possible with less data

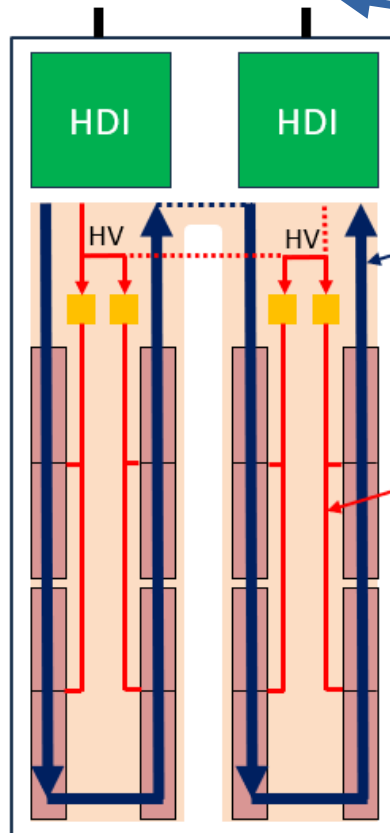
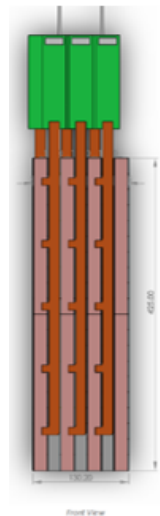


We will have a sharp drop at the maximum hit rate

S. Scherl (KIT/Liverpool)

# Power

## Serial Powering



Integrated MT module

Here we don't want to have the thick cables!

Serial Powering, 2 options:

1. Across 2 columns, 8 drops
2. Across 4 columns, 16 drops

Sensor Bias (HV), HV switch per column

1. Single HV feed to module
2. Dual feed for redundancy

