# HV-MAPS for the Mighty-Tracker of the upgraded LHCb detector

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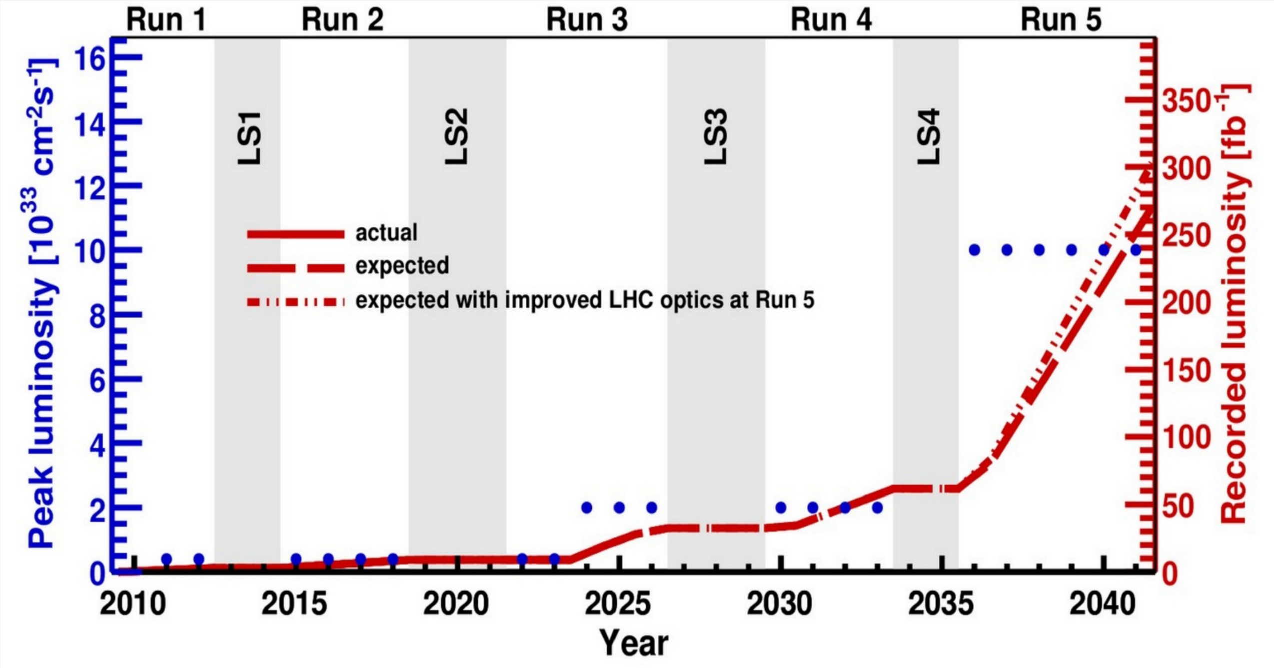
# LHCb – a forward spectrometer at the LHC

- Designed to explore large cross section for $b\bar{b}$, $c\bar{c}$ production in the forward region

- Integrated luminosity:
  today: 31.7 $fb^{-1}$
  end of Run 4: ~50 $fb^{-1}$
  end of Run 5: ~300$fb^{-1}$




- Very broad physics program:
  flavor physics, rare decay & CP-vioalation, EW physics, QCD, exoctic particles, fixed target, heavy ion physics

# The LHCb Upgrade II

**RICH 1&2:**
Increased granularity
Time measurement

**Magnet & magnet stations**

**Mighty-Tracker**
→ next slide

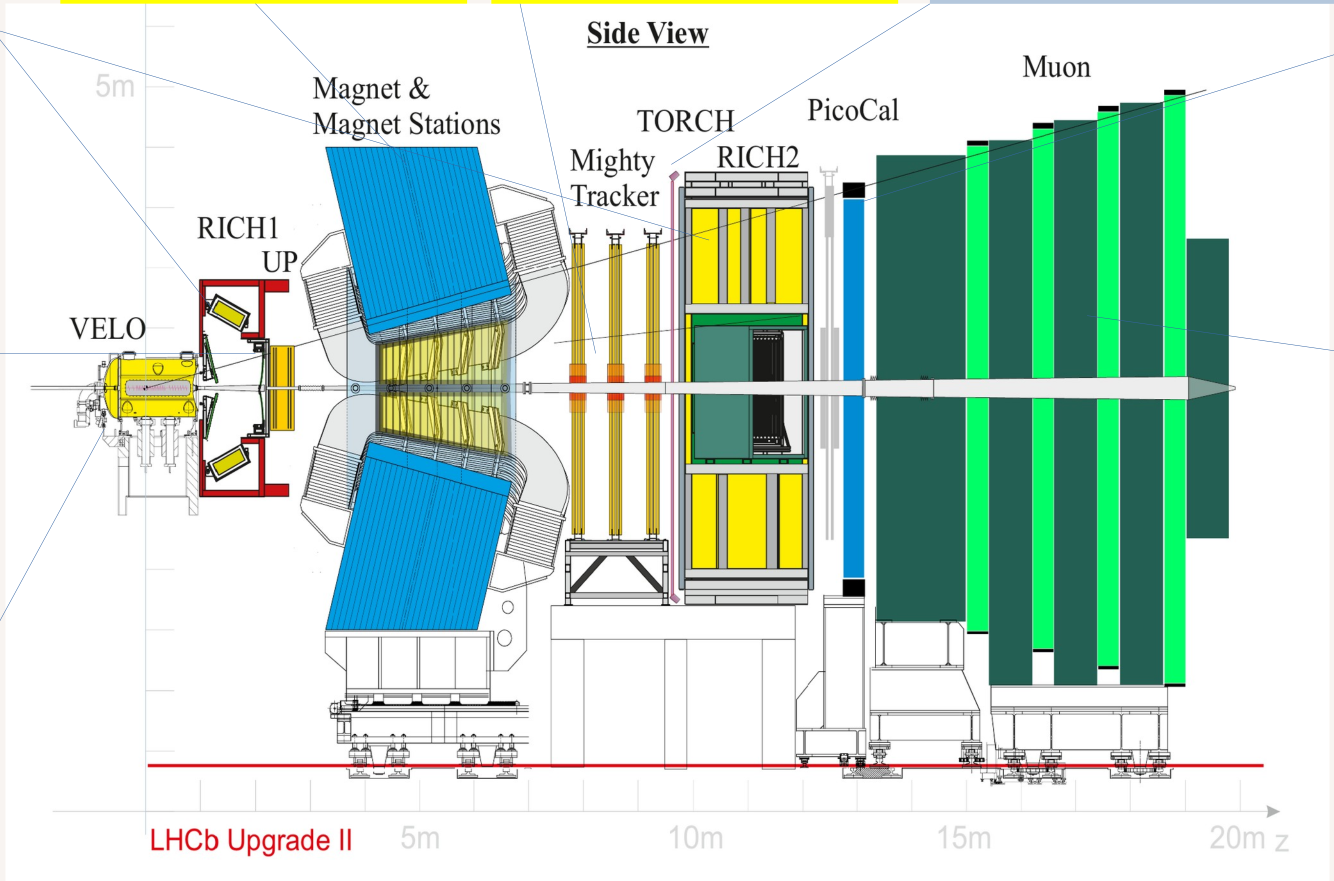
**Torch:**
TOF – Quarz tiles

**PicoCal:**
Timing & granularity
Inner: SpaCal
Outer: Shashlik

**UP:**
Pixels in DMAPS technology

**Muon System:**
Inner: µ-Rwell
Outer: MWPC

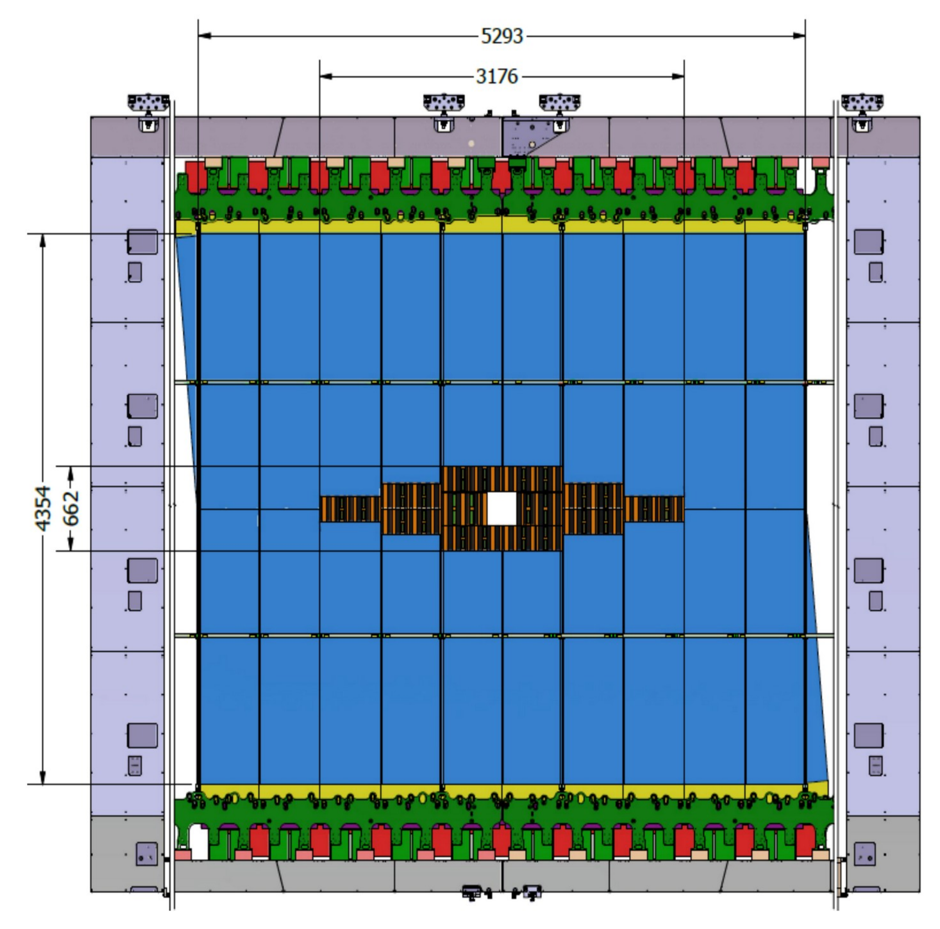
**Vertex locator: (VELO)**
Pixels
Timining 50ps
New RF foil




Tracking

PID

# The Mighty-Tracker




**Outer region (Mighty-SciFi):**

- 3 stations à 4 layers → ~300m$^2$ detector area
- scintillating fibres with SiPM readout
- 250µm fibres
- SiPM operated at liquid $N_2$ temperatures

**Inner region (Mighty-Pixel):**

- Silicon pixels in HV-MAPS technology
- 6 layers à 1.3m$^2$
- Options for Mighty-Pixel sensor:
  - MightyPix ← this talk
  - RadPix ← DRD3 development

# Challenges for the MightyPixel:

**Environment:**

- Particle rate: 13MHz/$cm^2$ *
- NIEL: 2.5 x $10^{14}$ $n_{eq}/cm^2$ *
- TID: 40 MRad *
- Bunch crossing spacing: 25 ns

**Material budget:**

- Per layer: 1-2% X0

* numbers do not include safety factors

**Powering & power consumption:**

- Power consumption <150mW/$cm^2$
- Serial powering

**Slow control:**

- Large system : ~22k sensors
  O($10^9$) channels

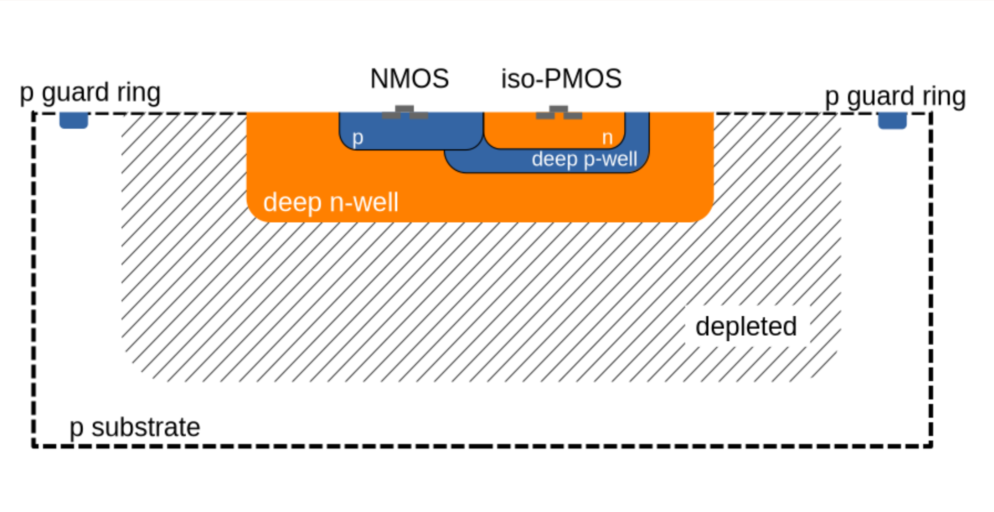
# SPECIFICATIONS IN A NUTSHELL

- The sensors have to guarantee an in-time efficiency* of >99% over the entire lifetime of the experiment at a power consumption < 150mW/cm².
- Spatial resolution is given by the binary resolution of pixels

(*i.e. an hit efficiency > 99% with correct bunch crossing identification, corresponding to ~3ns time resolution for a 25ns bunch crossing spacing)

# HV-MAPS technology

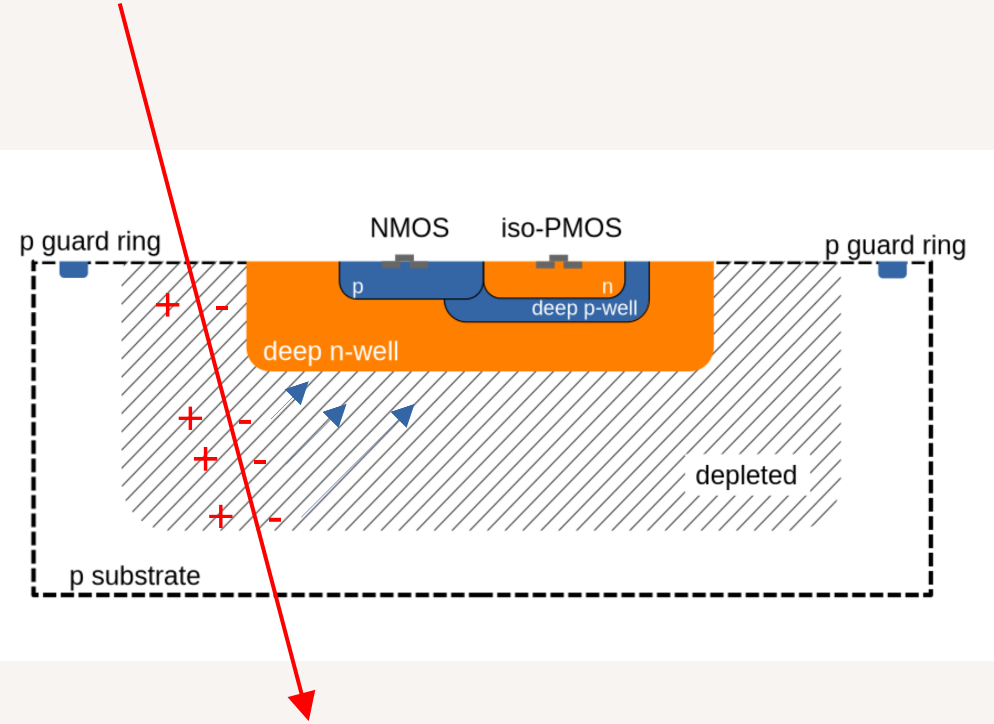
I. Peric, Nucl.Instrum.Meth. A582 (2007) 876-885




- produced in commercial HV-CMOS processes

- pn junction formed by reverse biased deep n-well and p substrate

# HV-MAPS technology

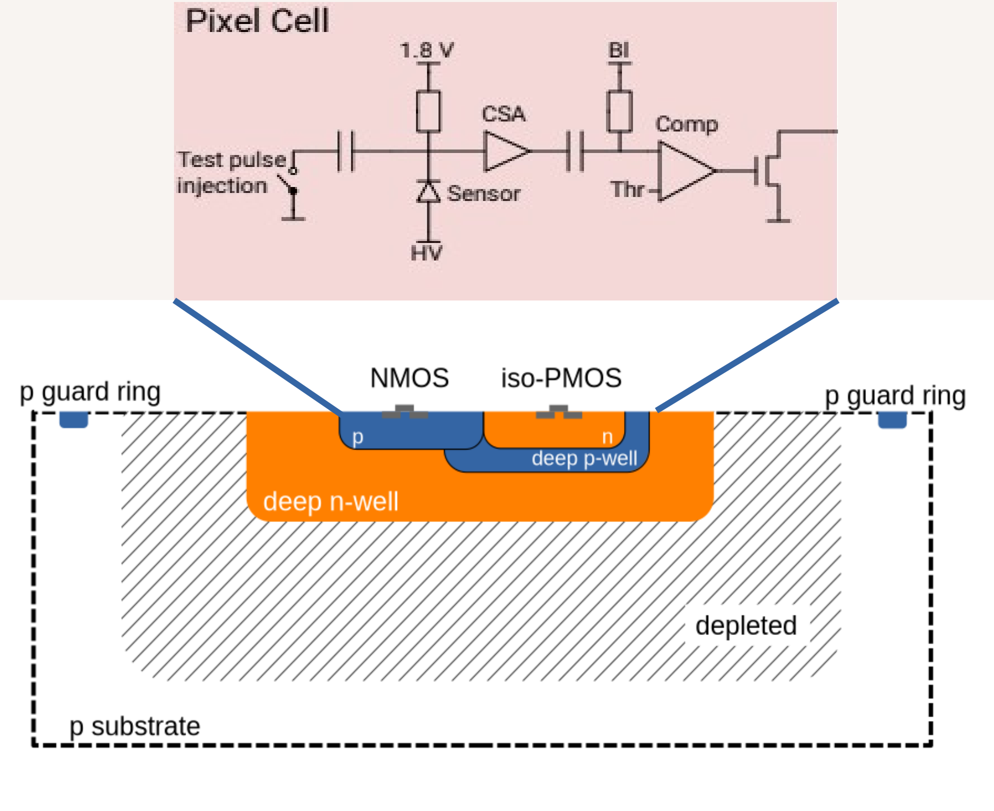



- produced in commercial HV-CMOS processes

- pn junction formed by reverse biased deep n-well and p substrate

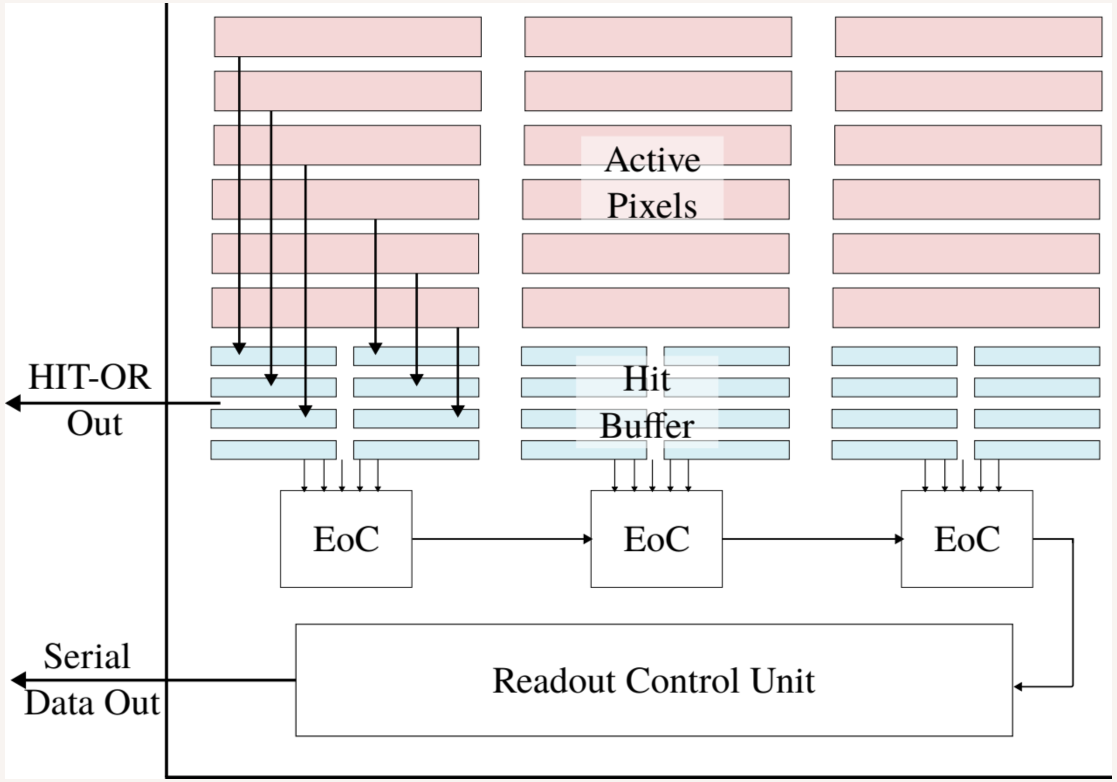
- fast charge collection via drift

# HV-MAPS technology




- produced in commercial HV-CMOS processes
- pn junction formed by reverse biased deep n-well and p substrate
- fast charge collection via drift
- **every pixel houses tuneable amplifier & comparator**

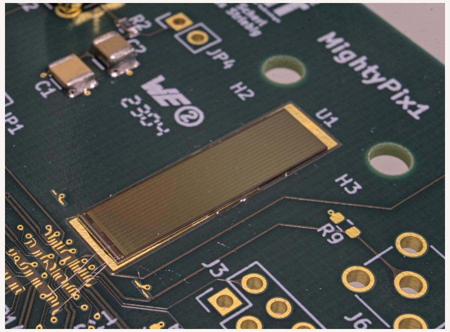
# HV-MAPS technology




- produced in commercial HV-CMOS processes
- pn junction formed by reverse biased deep n-well and p substrate
- fast charge collection via drift
- every pixel houses tuneable amplifier & comparator
- **hit information (ToA, ToT) stored in periphery**
- **hit driven readout controlled by FSM**

# The MightyPix Family

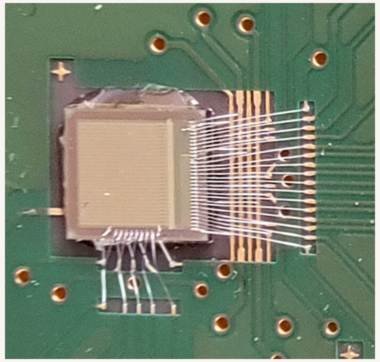
## MightyPix1




TSI 180nm
Area: 5 mm x 20 mm
Pixel size:
50 µm x 165 µm

submitted 06/2022

## LF-MightyPix



LFoundry LF15
Area: 3.5 mm x 4 mm
Pixel size:
100 µm x 100 µm

submitted 05/2024

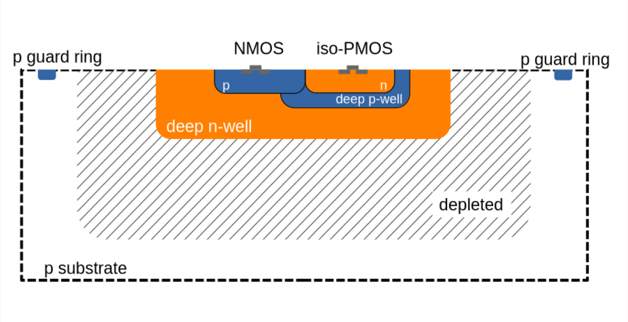
## MightyPix2

AMS ah18
Area: 21mm x 19mm
Pixel size:
84 µm x 84µm

submitted 10/2025

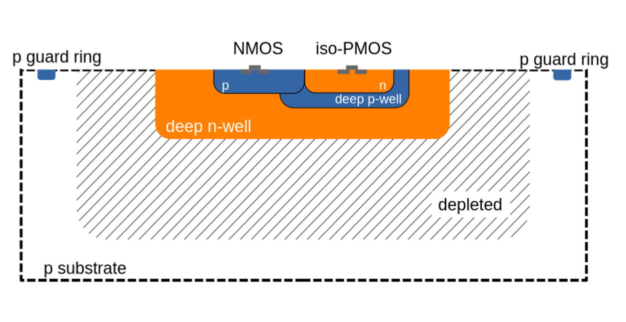
# The MightyPix Family

## MightyPix1




TSI 180nm
Amplifier-type: CMOS
Comparator: CMOS

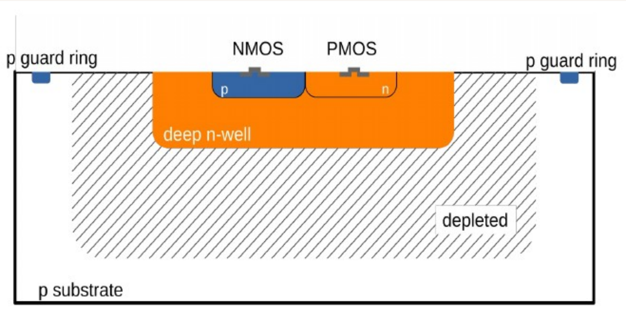
## LF-MightyPix




Similar to MightyPix1, but different chip guard ring design.

LFoundry LF15
Amplifier-type: NMOS
Comparator: CMOS

## MightyPix2




AMS ah18
Amplifier: CMOS
Comparator: NMOS

# MightyPix: Specific features for LHCb

TFC (fast commands@320Mbit/s)

ECS (configuration@10Mbit/s)

1280 / 640 / 320 Mb data link

Mulitplexer 4:2, 4:1

Serial powering

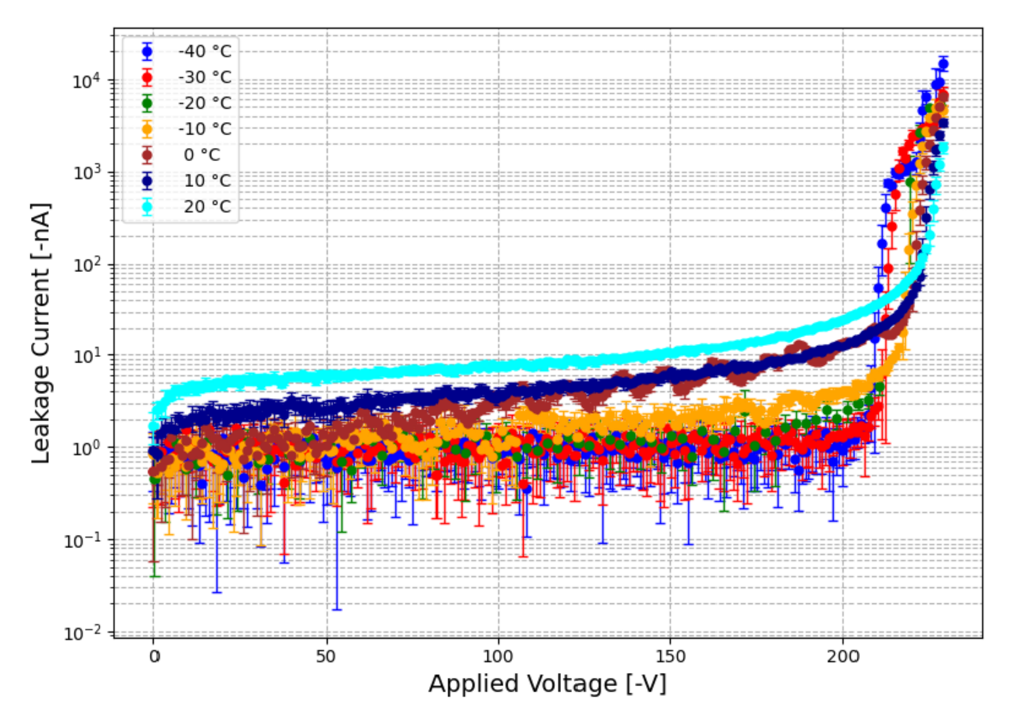
→ shunt LDO’s on chip

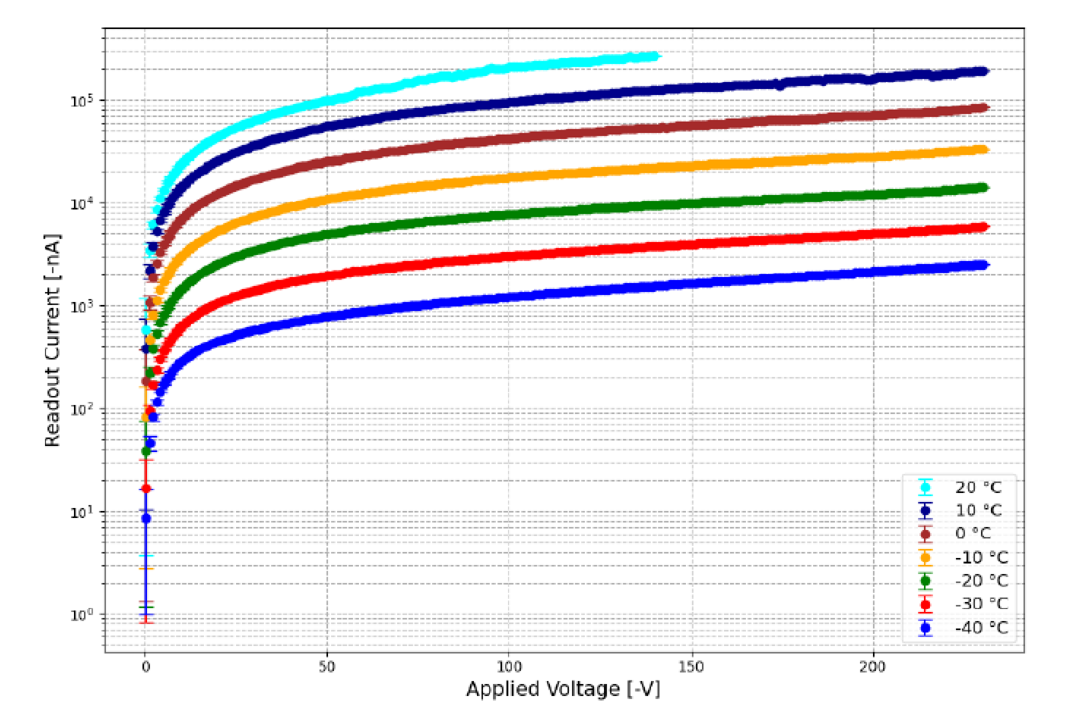
→ DC balancing for all communication links (data, TFC, & ECS )

Hadronic environment → SEE

→ triple redundant configuration & power on, glitch filter, hamming-2 encoded state variables to protect FSM implemented on MightyPix2

# MightyPix1: IV curves

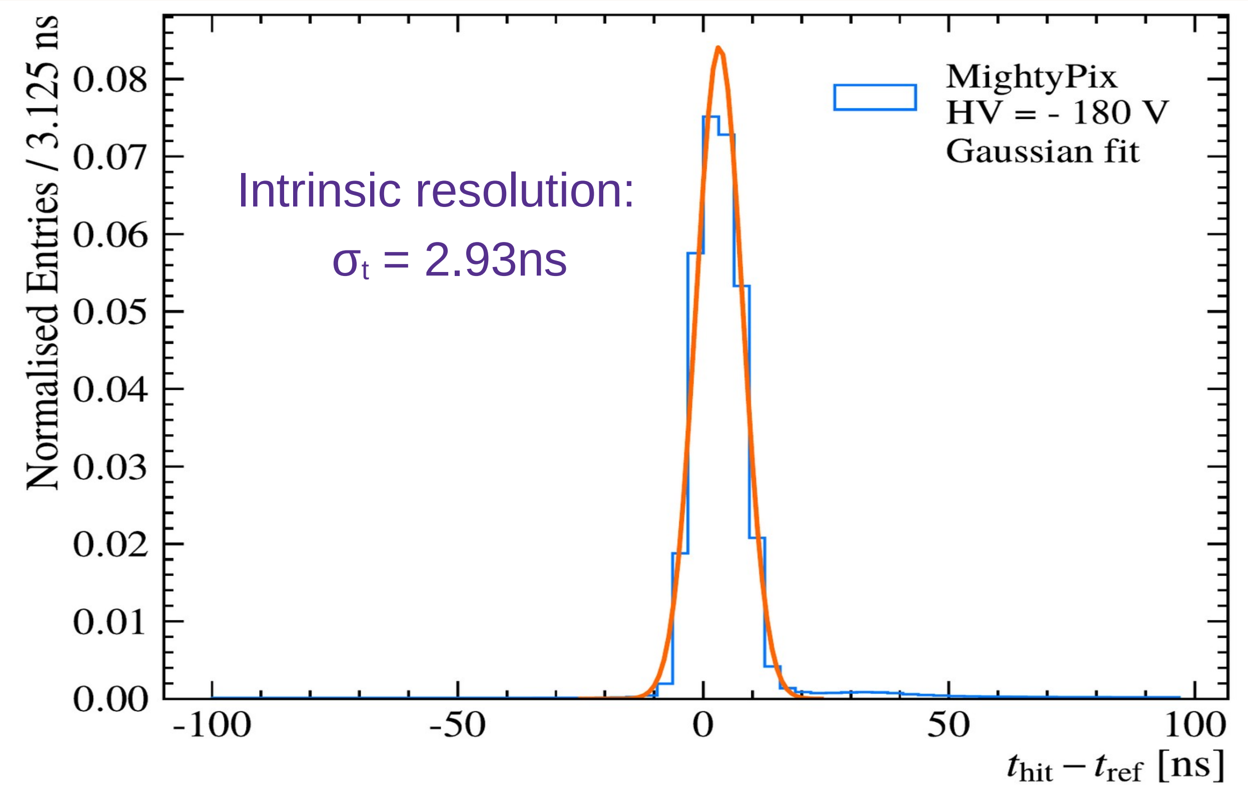



**before irradiation**

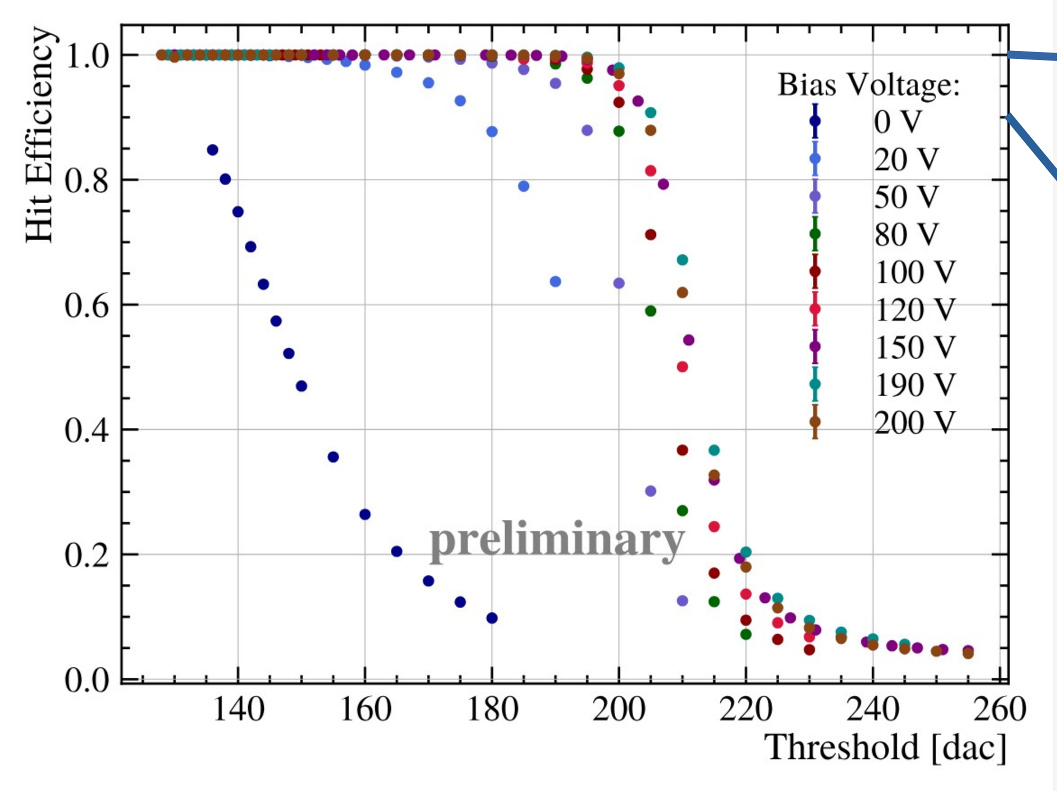
**after $1x10^{15}n_{eq}/cm^2$**

# MightyPix1: Time resolution

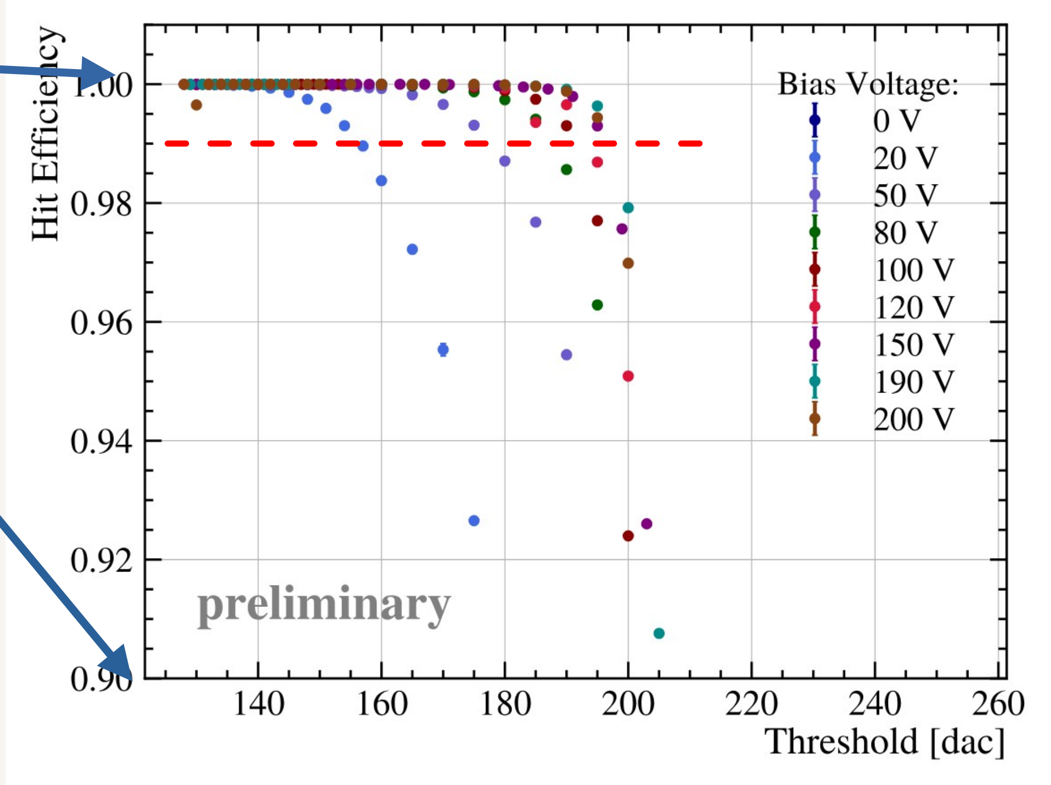



Only operational after FIB repair, but with very good performance demonstrated in lab with $^{90}Sr$.

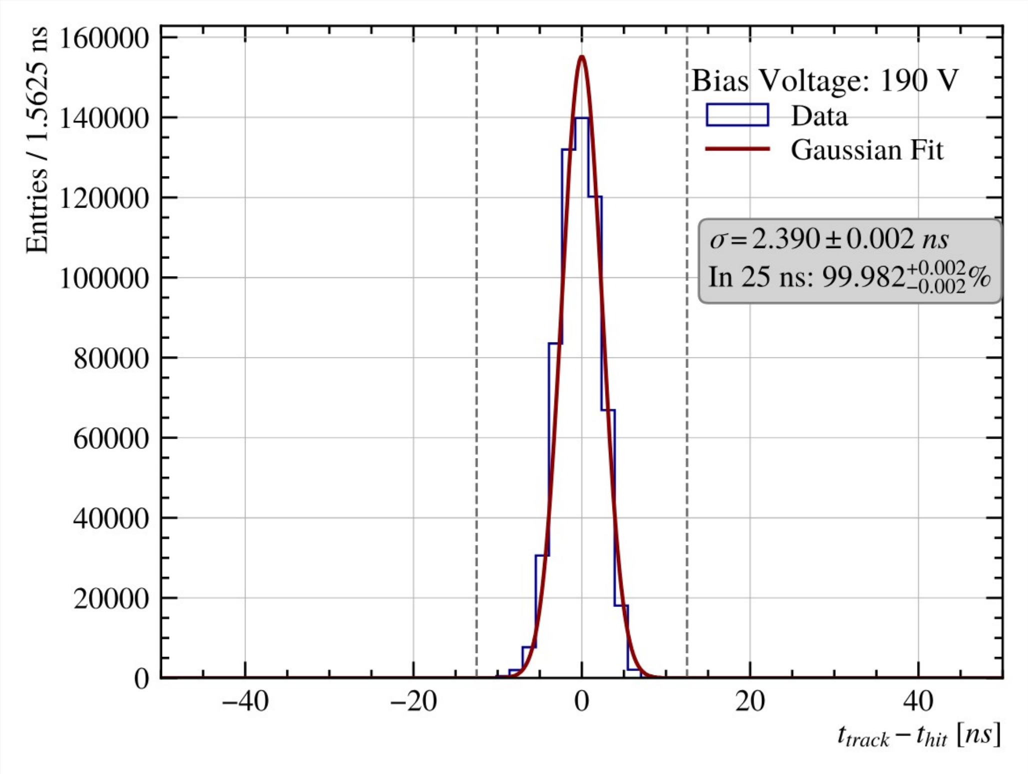
# LF-MightyPix: Efficiency

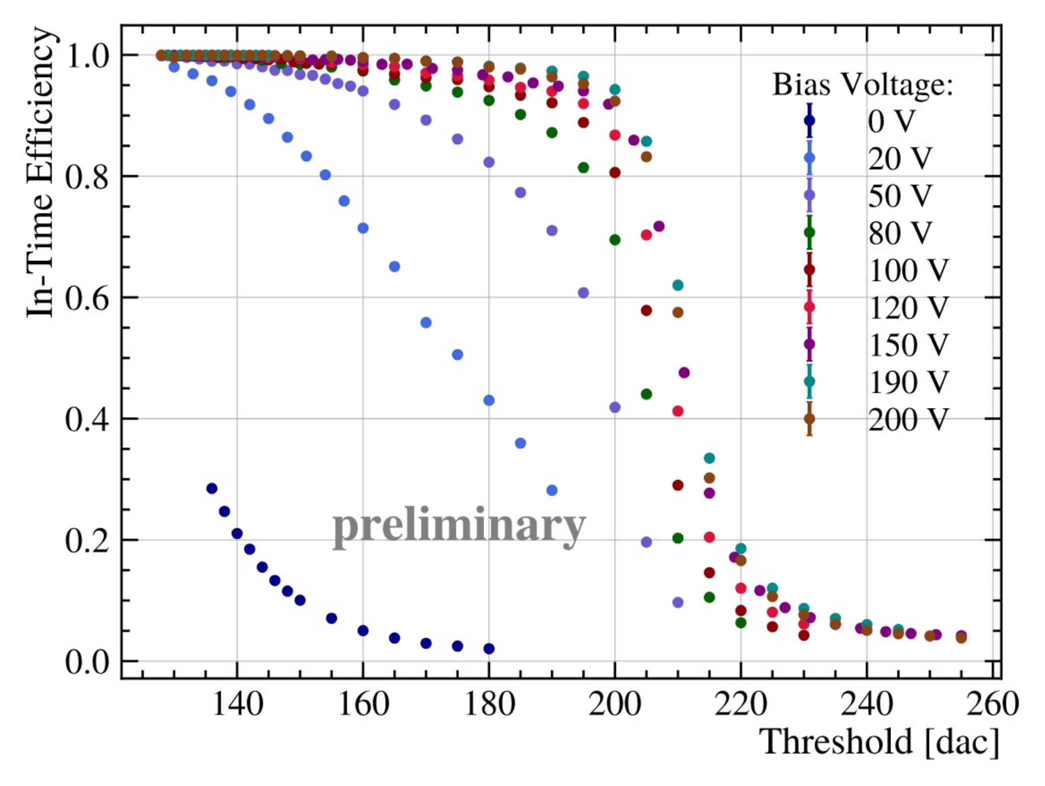



zoom-in



# LF-MightyPix: In-time efficiency



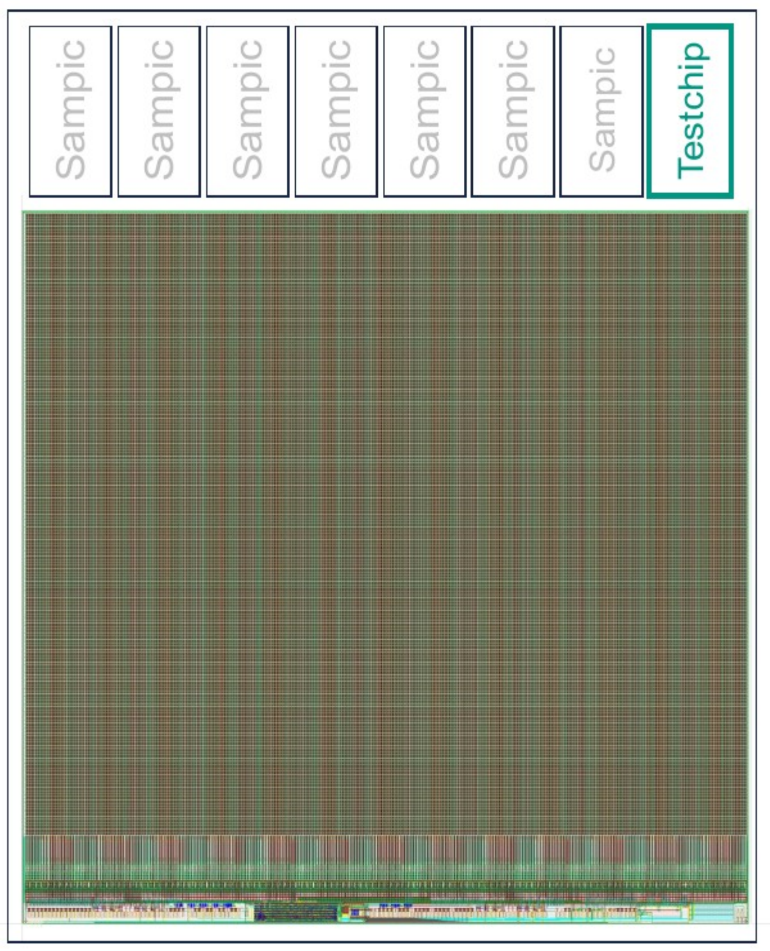




**In_Time Efficiency = In-Time Fraction * Efficiency**

# MightyPix2: Overview

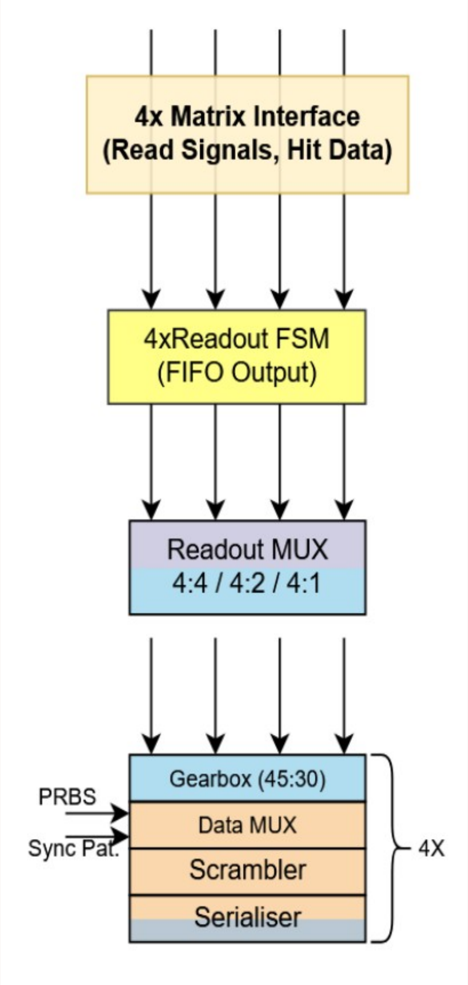
- AMS ah18 engineering run
- Features:
  - 244 x 194 pixel (full size: 244 x 240)
  - pixel size 84 µm x 84 µm
  - 21 x 19 mm²
  - **fully compatibility to LHCb** (TFC, ECS, readout architecture, serial powering...)

- Dedicated chip with test-structures
  -> allow systematic studies on TID damage, SEU & serial powering




https://mightypix2.docs.cern.ch/

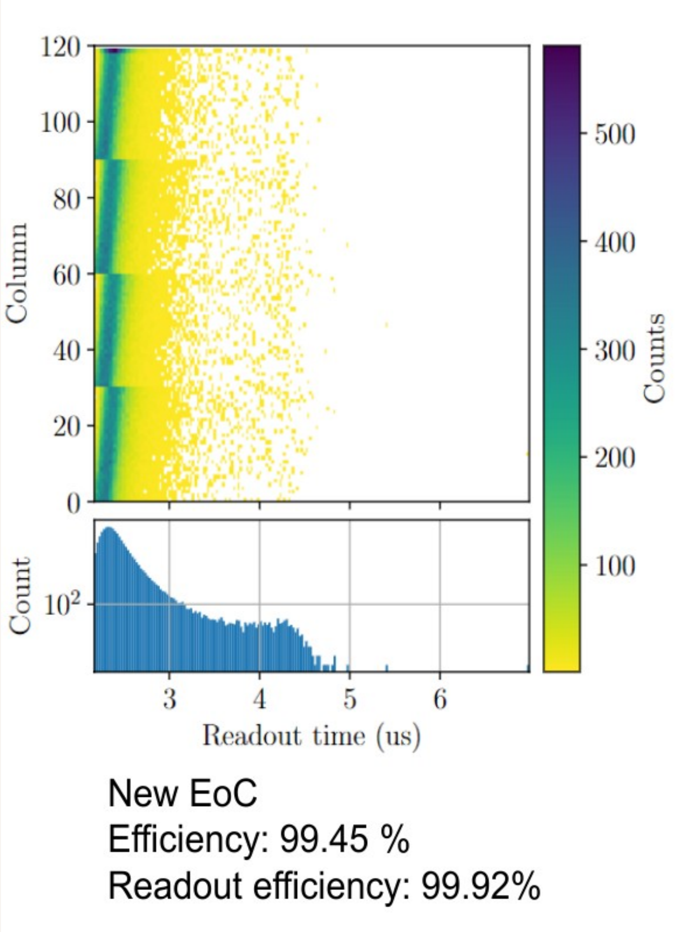
# MightyPix2: readout & rate simulation




**Rate simulation:**
Dedicated software tool* to verify hit rate capability.

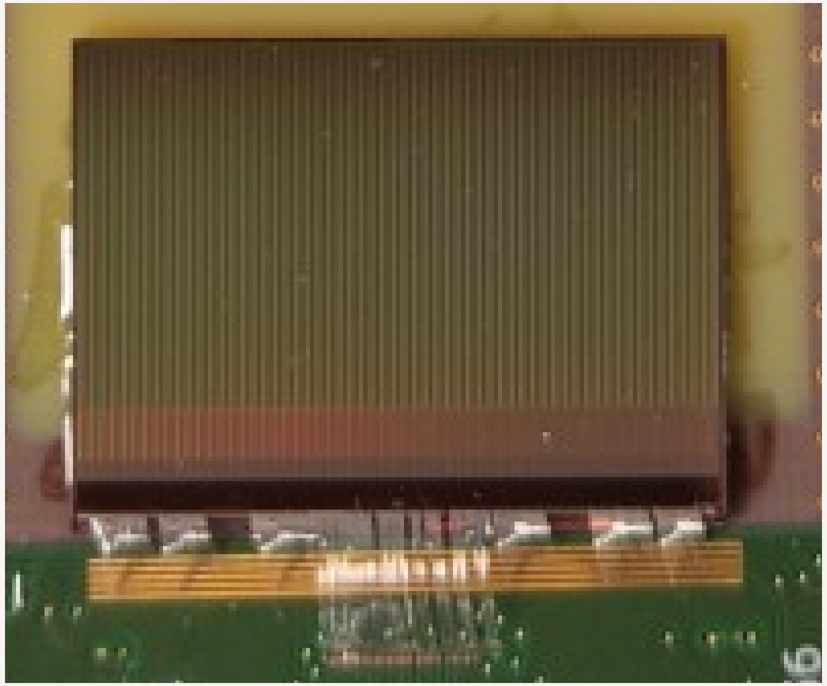
**Set-up:**
- full pixel matrix
- actual MP2 readout design
- p-p run conditions
- Hit rate of 35MHz²

**Result:**
- Very high readout efficiency from improved EOC
- Speed limited by links




* MightyPix at the LHCb Mighty Tracker — verification of an HV-CMOS pixel chip's digital readout
S. Scherl (Liverpool U. and KIT, Karlsruhe, IPE) et.al. DOI: 10.1088/1748-0221/19/04/C04045

# Radiation hardness of HV-MAPS: TelePix2 as a primer for MightyPix



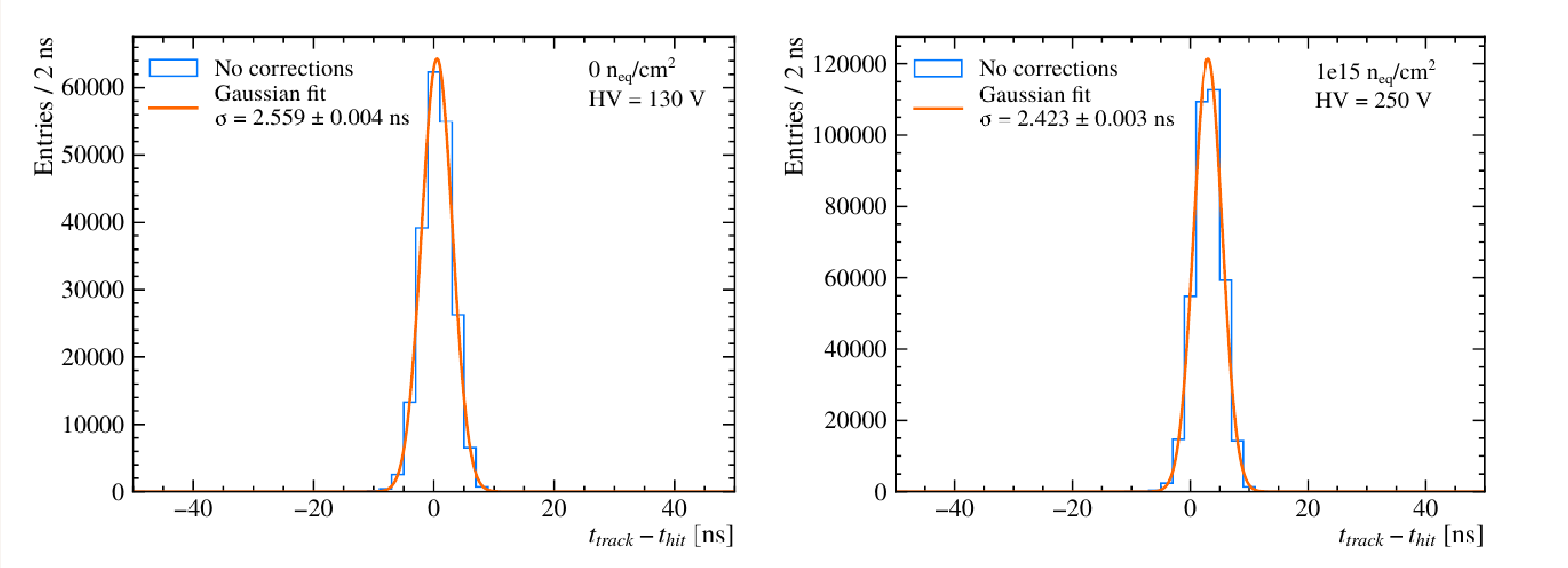
- developed as time reference for DESY test beam telescope *

- foundry, substrate and design of pixel array same as MightyPix1, except pixel size:
  165 µm x 25 µm  for TelePix2
  165 µm x 50µm for MightyPix1

- several irradiaton campaigns:
  NIEL: up to $1x10^{15}$ $n_{eq}/cm^2$
  TID: high dose/high rate up to 40 MRad
  low dose/low rate up to 1-2 MRad

* arXiv:2503.08177

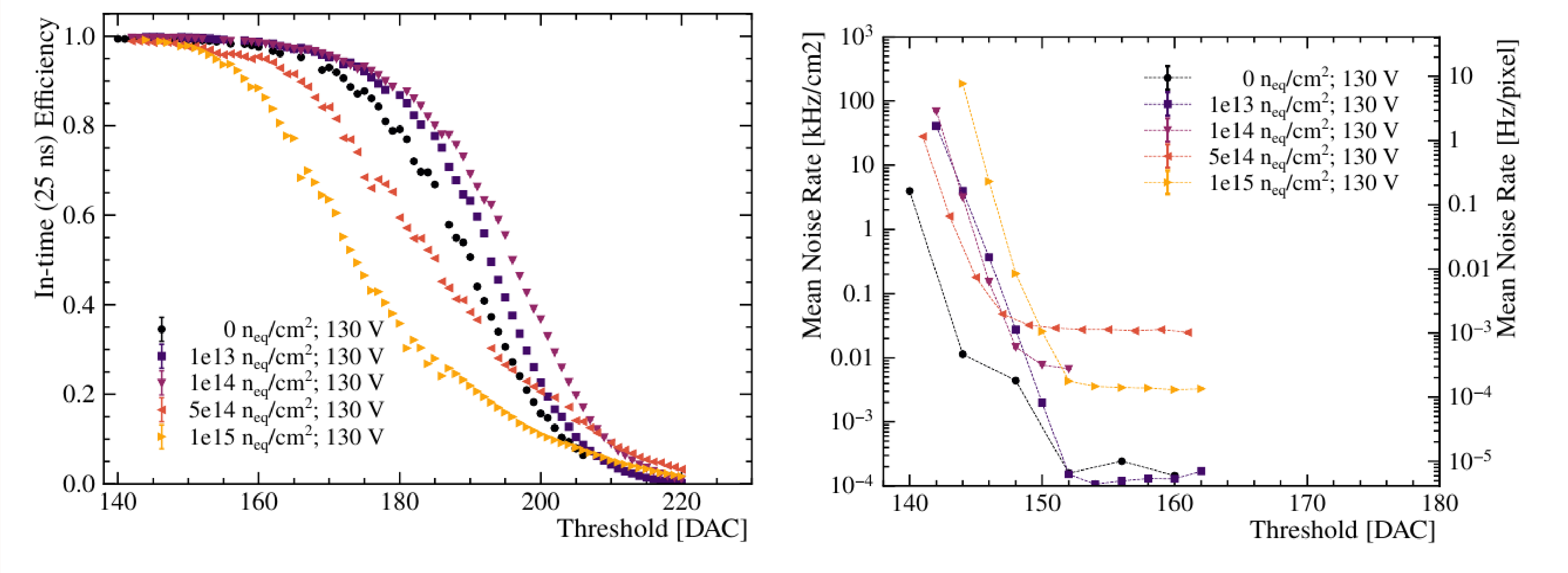
# Time resolution after neutron irradiation




**before irradiation** **after $1x10^{15}n_{eq}/cm^2$**

# In-time efficiency & noise after neutron irradiation

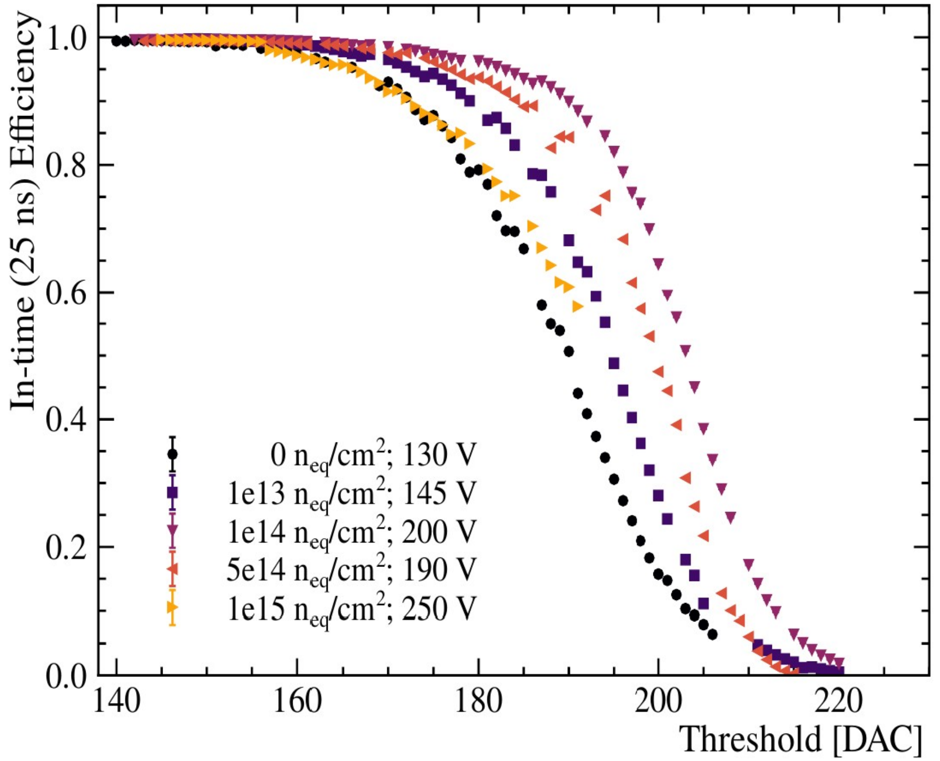
Constant voltage for all fluences



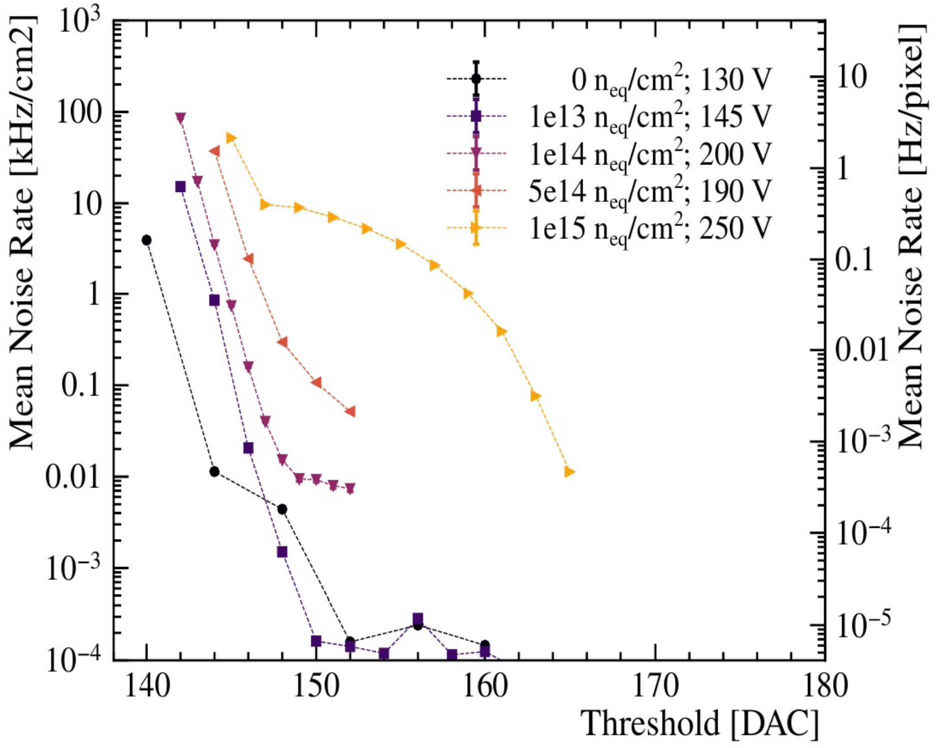

**In-time efficiency** **Noise rate**

# In-time efficiency & noise after neutron irradiation

Max. operation voltage for all fluences

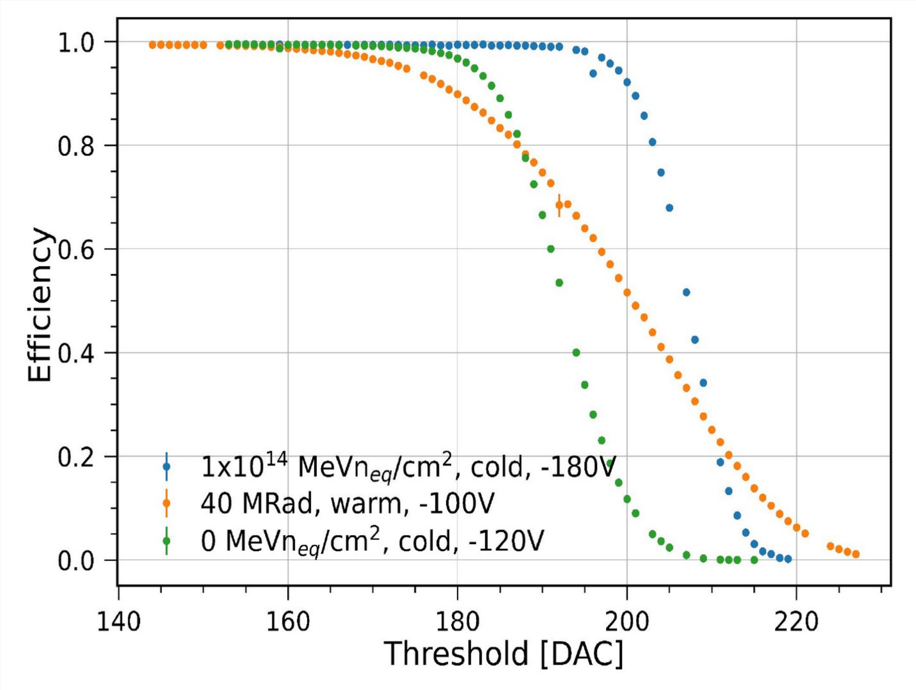


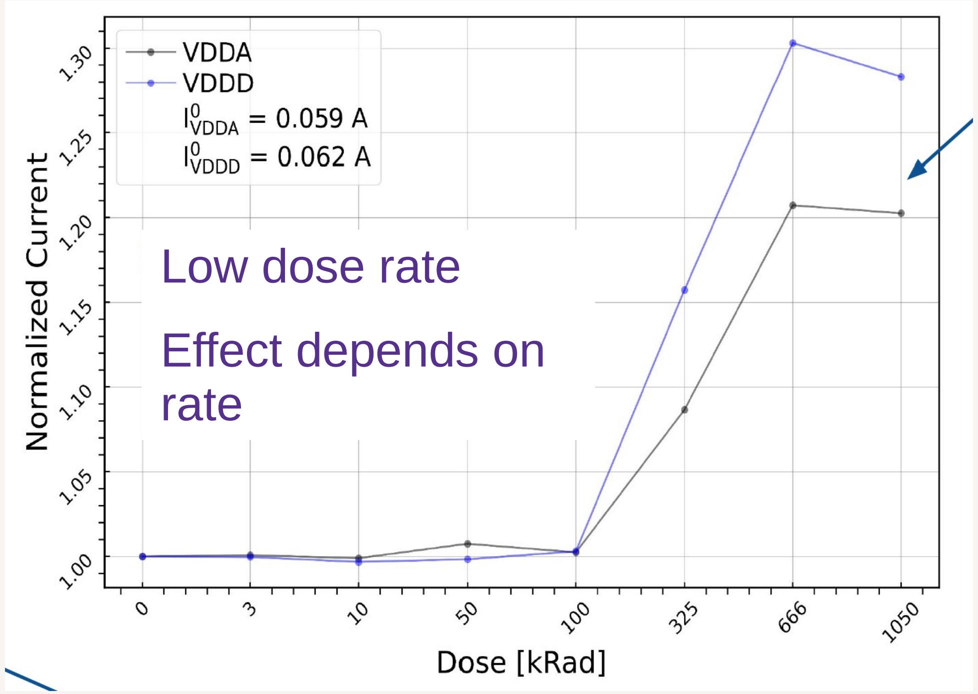

**In-time efficiency**




**Noise rate**

# Efficiency & power consumption after TID irradiation



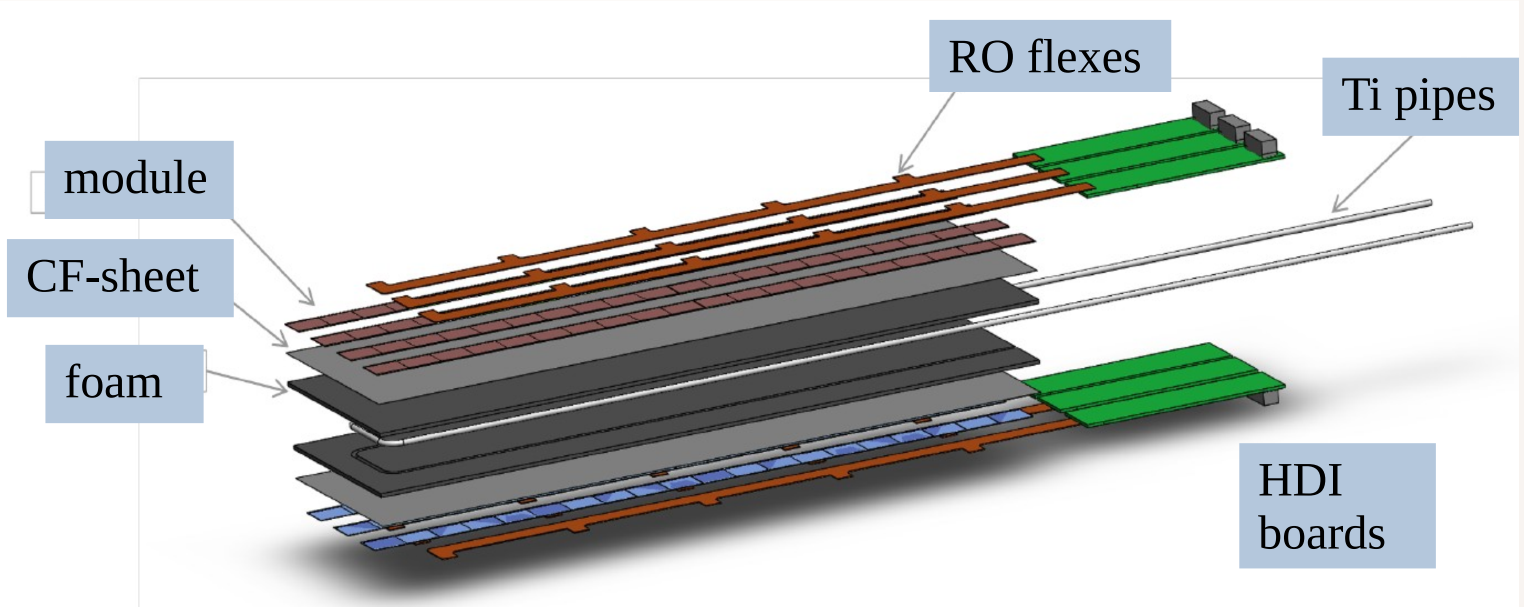




**Acceptable performance after irradiation with protons and X-rays, but spurious increase of low voltage currents. Dose rate dependent effect, under investigation.**

# FULL STAVE

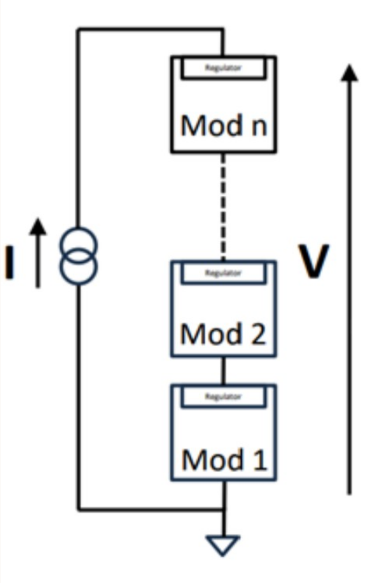
**Assembly:**

- 6 columns, each housing
  6 modules a 5 sensors
  i.e. 180 sensors per stave
- Core:
  CF sandwich panel with heat conducting foam and Titanium cooling pipe
- Readout flex:
  Length depends on position of  HDI



# POWERING SCHEME

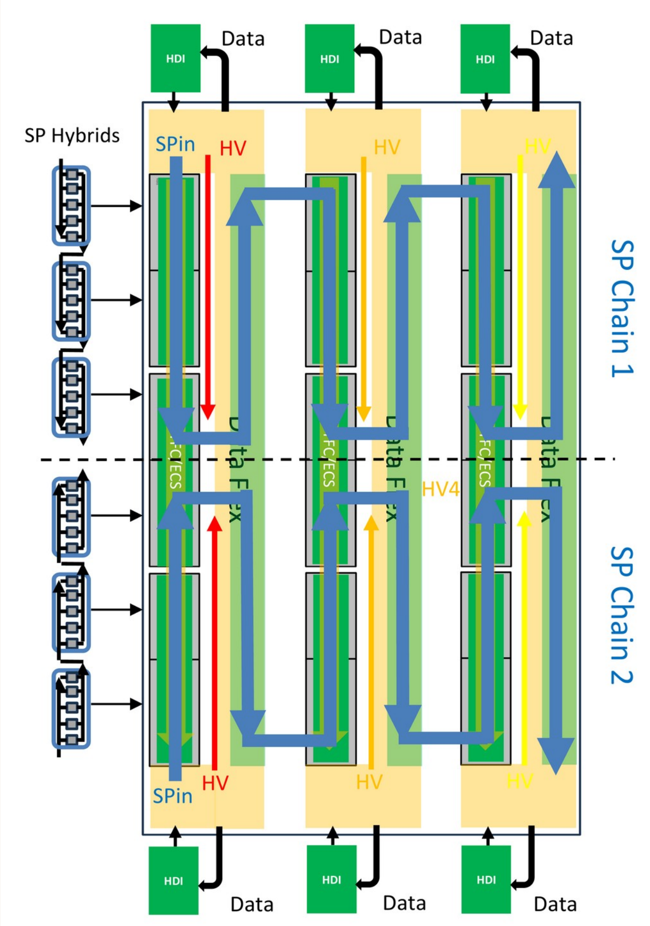
**Serial powering:**




- To minimize material budget serial powering of MightyPix sensors is foreseen

- A module contains 5 sensors which are powered in parallel

- Two serial power chains per full stave containing 30 modules / 180 sensors



# SUMMARY & CONCLUSION

- LHCb aims for an Upgrade for LHC  Run 5 to cope an increase in luminosity by a factor of 5

- Inner region of current downstream tracker (scintillating fibre tracker) has to be replaced by a pixel detector

- The HV-MAPS based MightyPix sensor is currently developed for the Mighty-Tracker with MightyPix2 being the first sensor fully compatible for the application in LHCb

- Radiation hardness of the technology has been demonstrated

- We aim for a TDR in autumn 2026

# Backup

# SPECIFICATIONS

## MightyTracker-Pix

EDMS no. 3207186

| Parameter | MP Specification |
|---|---|
| Pixel size (bending plane) | $\leqq 100\ \mu m$ |
| Pixel size (non bending plane) | $\leqq 200\ \mu m$ |
| Substrate thickness | $<200\ \mu m$ |
| Pixel orientation | x |
| Max. Particle Rate | $17\ MHz/cm^2$ |
| Max. Hit Rate | $34 MHz\ cm^{-2}$ |
| Max. length of data word | 32 |
| Overall efficiency | >96% |
| In-time efficiency | >99% within 25 ns |
| Noise rate (End of life) | $\leq 400 kHz/cm^2$ |
| Transmission rate | 4 links of 1.28Gbit/s each |
| NIEL | $3 \times 10^{14} n_{eq}/cm^2$ |
| TID | 40 MRad |
| Power Consumption | $\leq 150\ mW/cm^2$ |

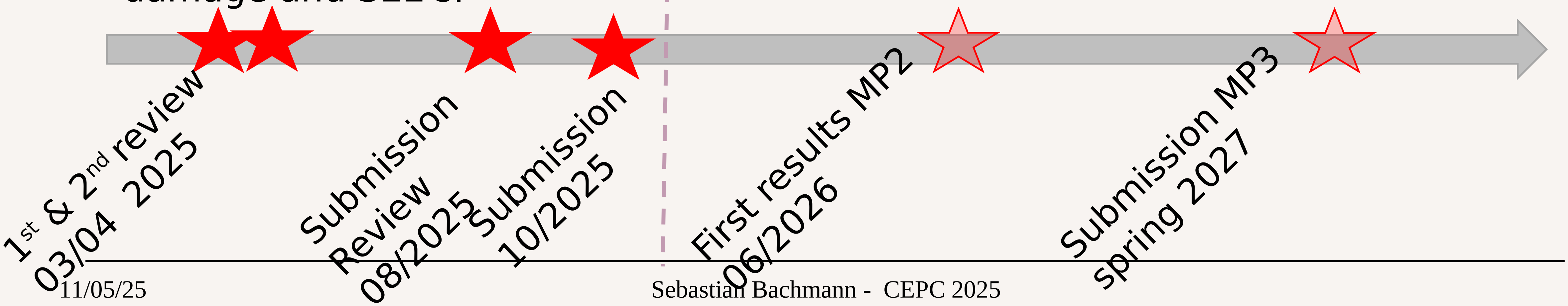
## Upstream Pixel

Yiming's slide from LHCC ASIC review

| Parameters | UP Specification | Remarks |
|---|---|---|
| *Sensor size* | ~ 2×2 cm² | Common with MT |
| *Pixel size, square*<br>*Pixel size, rectangular* | ≤ 85×85 μm²<br>≤ 50×200 μm² | |
| *Substrate thickness* | < 200 μm | |
| *Pixel orientation* | x | bending plane |
| *Max. Particle Rate* | 50 MHz/cm² | from Geant 4 + Pythia, @ 4 cm radius<br>previously 74 MHz/cm² @ $\mathcal{L} = 1.5 \times 10^{34}\ cm^{-2}s^{-1}$ |
| *Max. Hit Rate* | 100 Mhit/cm² | at 4 cm radius, 100 % margin |
| *Max. length of data word* | 32 | |
| *Overall efficiency* | > 96 % | Including dead area |
| *In-time efficiency* | > 99 % with in 25 ns | |
| *Noise rate (End of life)* | ≤ 400 kHz/cm² | @ max. 1% masked channels |
| *Transmission rate* | N × 1.28 Gbit/s | N ≤ 7 for matching with 1 LpGBT |
| *NIEL* | $4 \times 10^{15} N_{eq}/cm^2$ | from Fluka, safety margin 4 |
| *TID* | 250 Mrad | from Fluka, safety margin 4 |
| *Power Consumption* | ≤ 200mW/cm² | no margin,<br>budget ~ 10 μA/pixel (85×85 μm² pixel) |

# MP2 status and timeline:

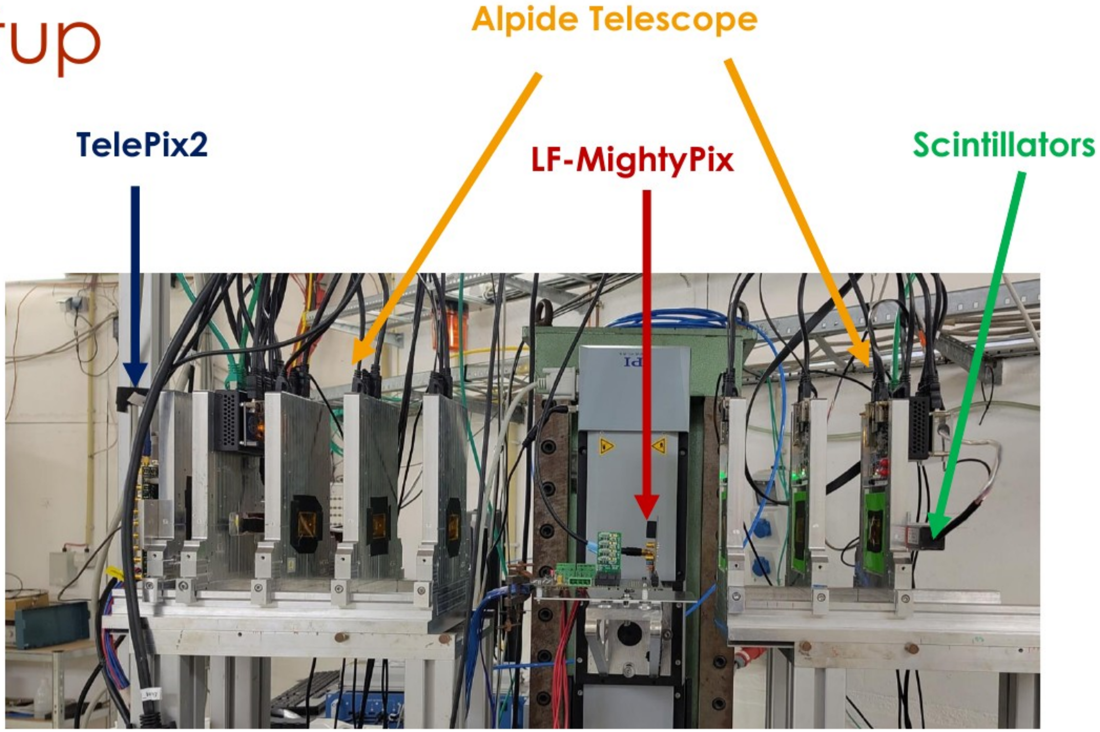
- MightyPix2 is designed for full compliance to the LHCb specifications.
- MightyPix2 has undergone a thorough review process with fruitful discussions. Recommendations have been implemented since then, especially on protection against single event effects (SEE).
- Critical issues to be demonstrated with MightyPix2 are tolerance wrt TID damage and SEE's.



# DESY Testbeam (13/10 – 2/11/2025)

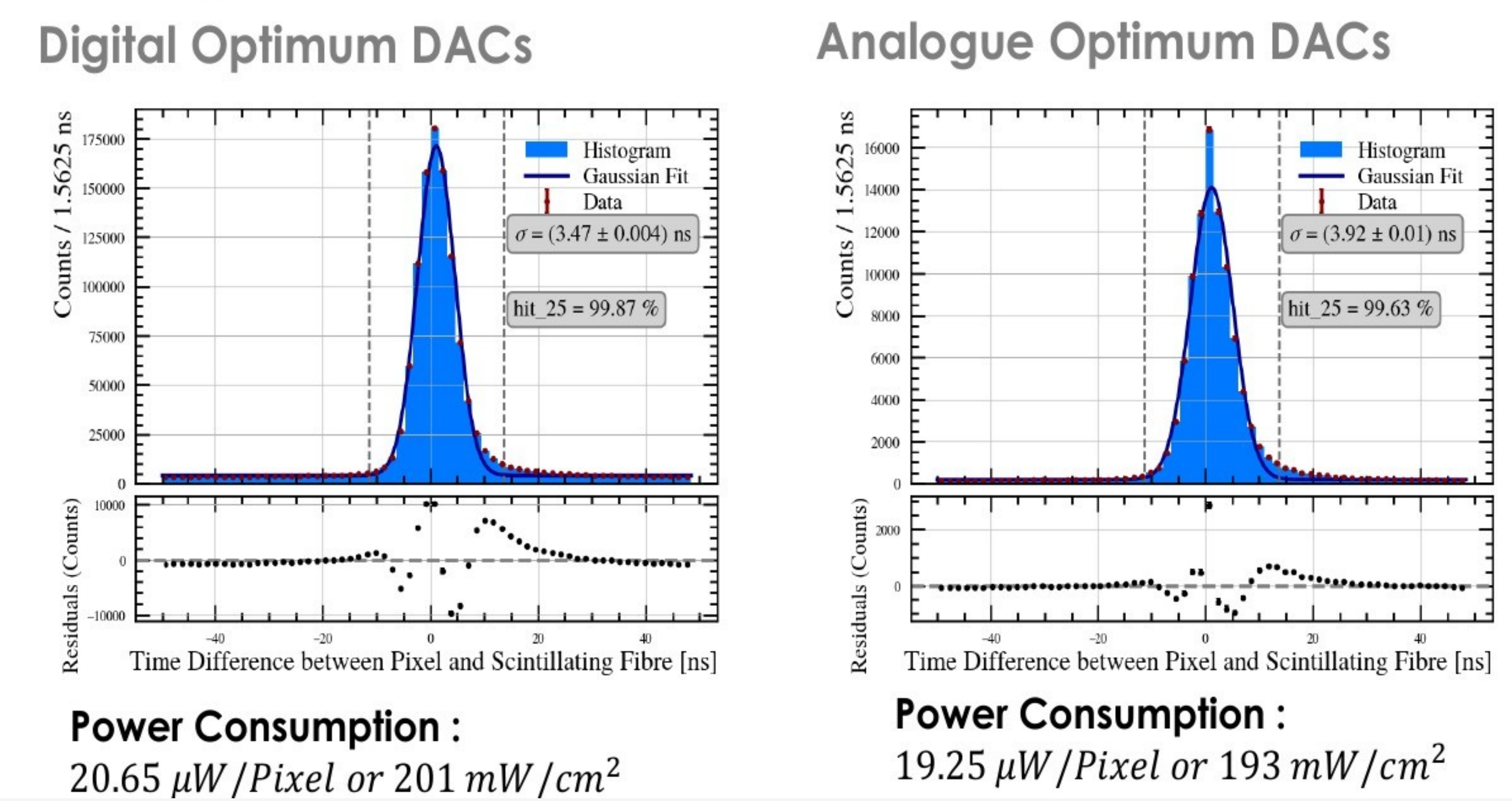
## Test Beam Setup

- DESY Testbeam Area 22
  - 4 GeV electrons
  - Alpide Telescope
  - TelePix2 Time Reference
- Running parasitically to Mu3e/P2
- LF-MightyPix readout using Gecco
- Data Analysis in Corryvreckan




22.10.2025 Celina Welschoff 3

# LF-MightyPix: Lab measurements (Sr-90)




**Excellent time resolution at reasonable low power consumption.**

*Definition of hit_25:*

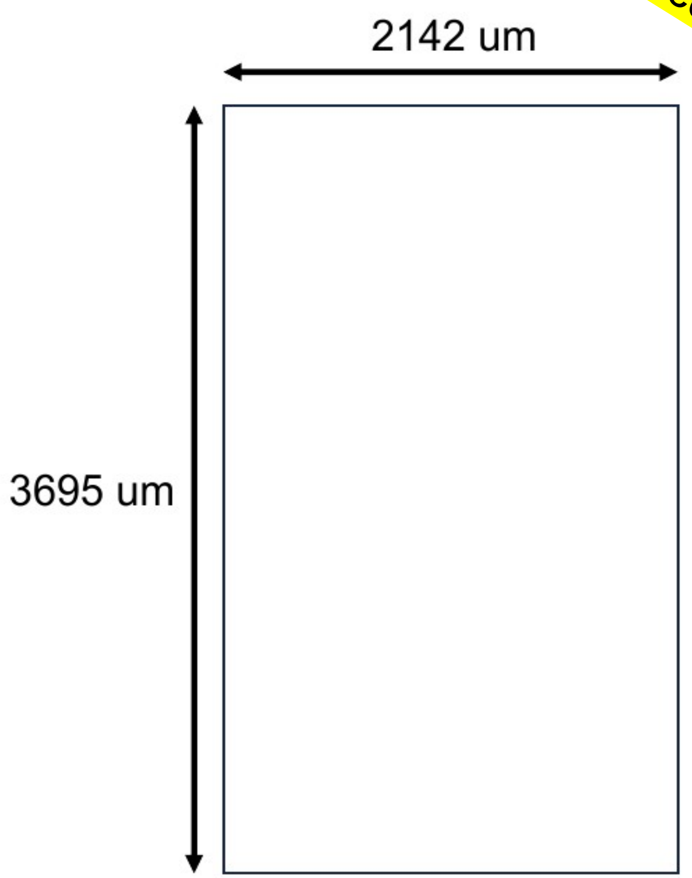
$$\text{In-Time-Fraction} = \frac{Number\ of\ hits\ in\ 25\ ns}{Total\ number\ of\ hits}$$

Conservative estimate
Of power consumption

# Dedicated Chip for Teststructures



- TID measurements
  - NMOS/PMOS
    - Rectangular long/short W/L
    - ELT
  - DRAM: Evaluate data retention time
  - SRAM: Evaluate static noise margin
- SEU/SET cross section measurements
  - DRAM
  - SRAM
  - TMR Configuration Registers
- Serial Powering
  - 2 SLDOs for serial/parallel configuration

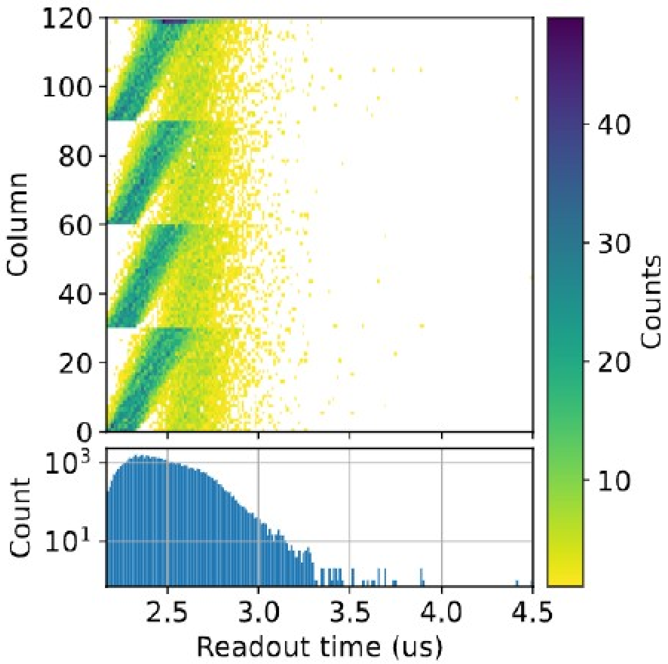


# SEU/SET Improvements

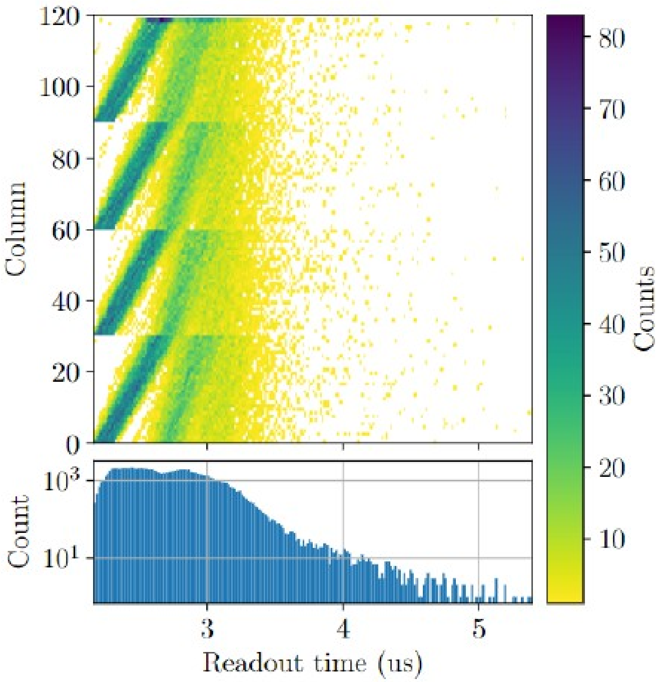
- **Glitch Filter**
  - SET glitch filter for async reset input
  - Reset syncronizers TMR protected
- **Hamming 2-encoded state variables**
  - 1 additional FF to detected single bit errors
  - Reduced risk of incorrectly jumping into invalid state
  - Allows monitoring -> Error output connected to Counter
- **TMR**
  - **TFC**
    - Slow clock domain part TMR protected
    - Deserializer part unprotected, but all single bit errors can be detected due to 6b8b encoding -> SEE can cause bitslip -> Receiver unlock
    - Clock tree is not triplicated, SET could cause bitslip -> Receiver unlock
  - **Registers**
    - Registerfile partially and chip configuration completely TMR protected

# Rate Simulation – Heavy Ion

- Heavy Ion run conditions
- 50 ns bunches
- 0.25 % interaction propability
- Much higher peak hitrate




Avg. 20 hits/interaction/cm²
Efficiency: 99.98 %
Readout efficiency: 99.98%




Avg. 40 hits/interaction/cm²
Efficiency: 99.97 %
Readout efficiency: 99.98%