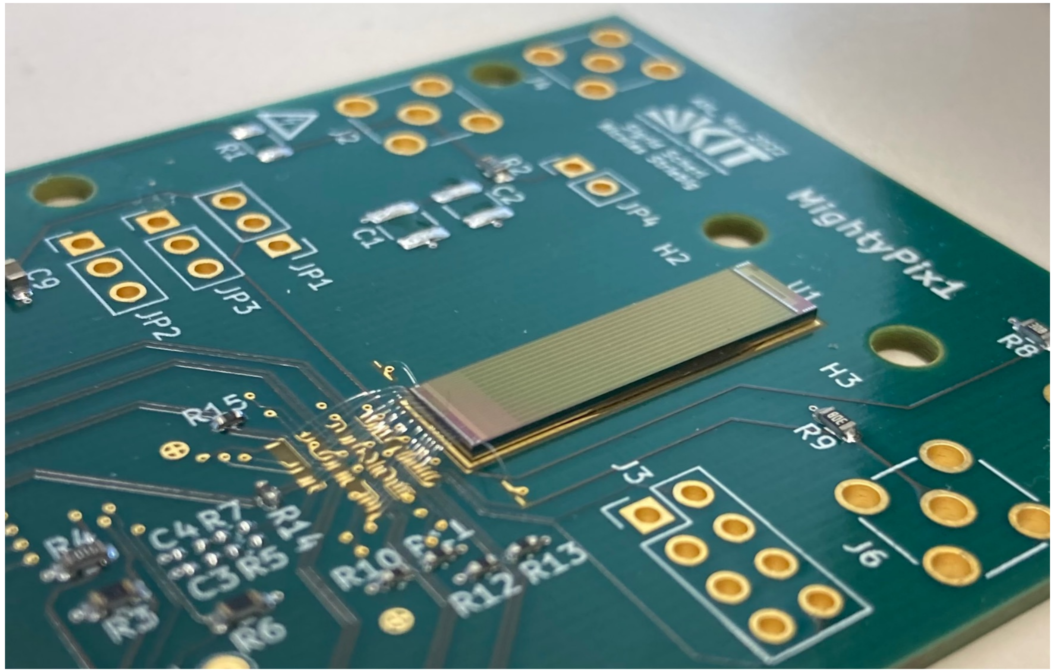
MightyPix at the LHCb Mighty Tracker

Verification of an HV-CMOS pixel chip's digital readout



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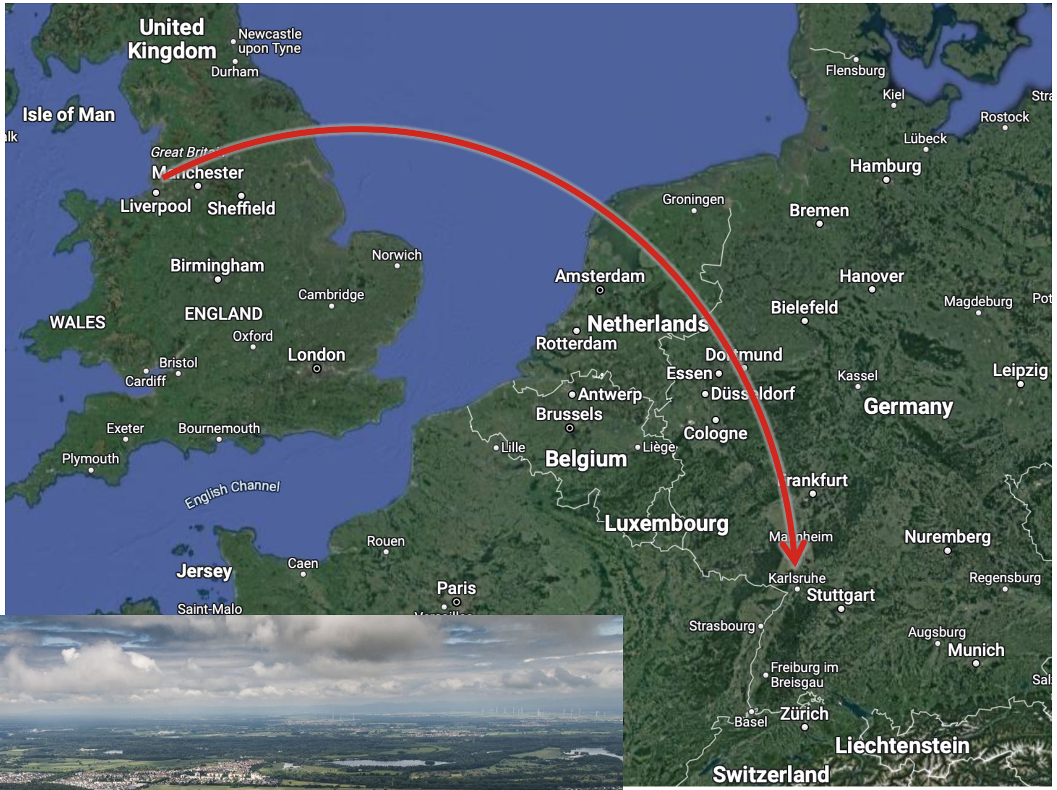
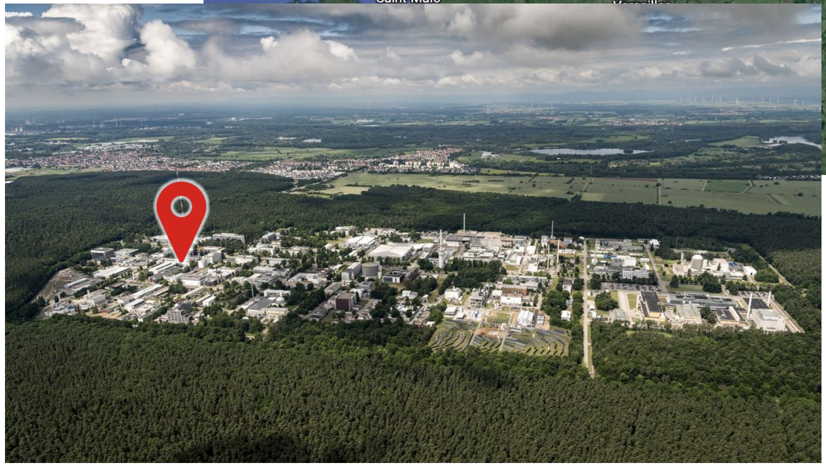
Supervisors: Dr Eva Vilella (UoL), Prof Dr Ivan Perić (KIT), Dr Karol Hennessy (UoL/CERN)

18 - 19 May 2023, Particle Physics Annual Meeting, University of Liverpool

Where am I?

- Part of the HV-CMOS group in Liverpool
- Last 1.5 years at KIT in Germany
- **Asics and Detector Lab**
  → develops new HV-CMOS sensors
- **MightyPix** for the Mighty Tracker at **LHCb**





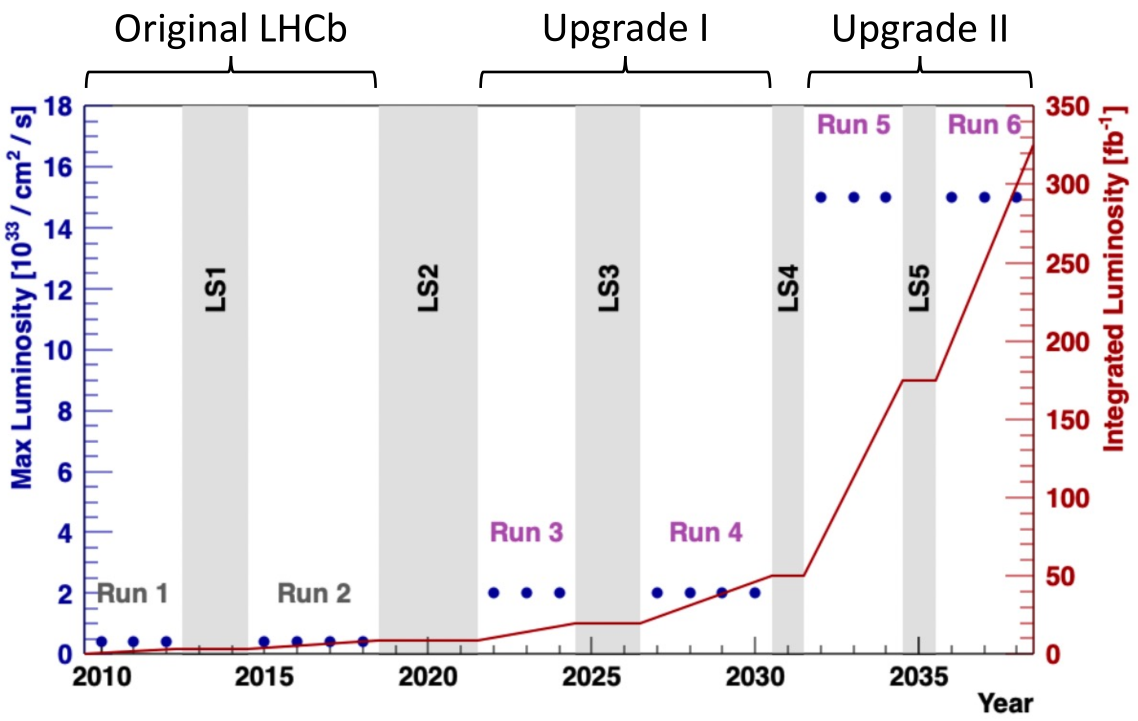
Karlsruhe Institute of Technology

What am I doing?

- Participate in test beams
- Dabble in chip design
- **Simulations of chip efficiency**

LHCb at the HL-LHC

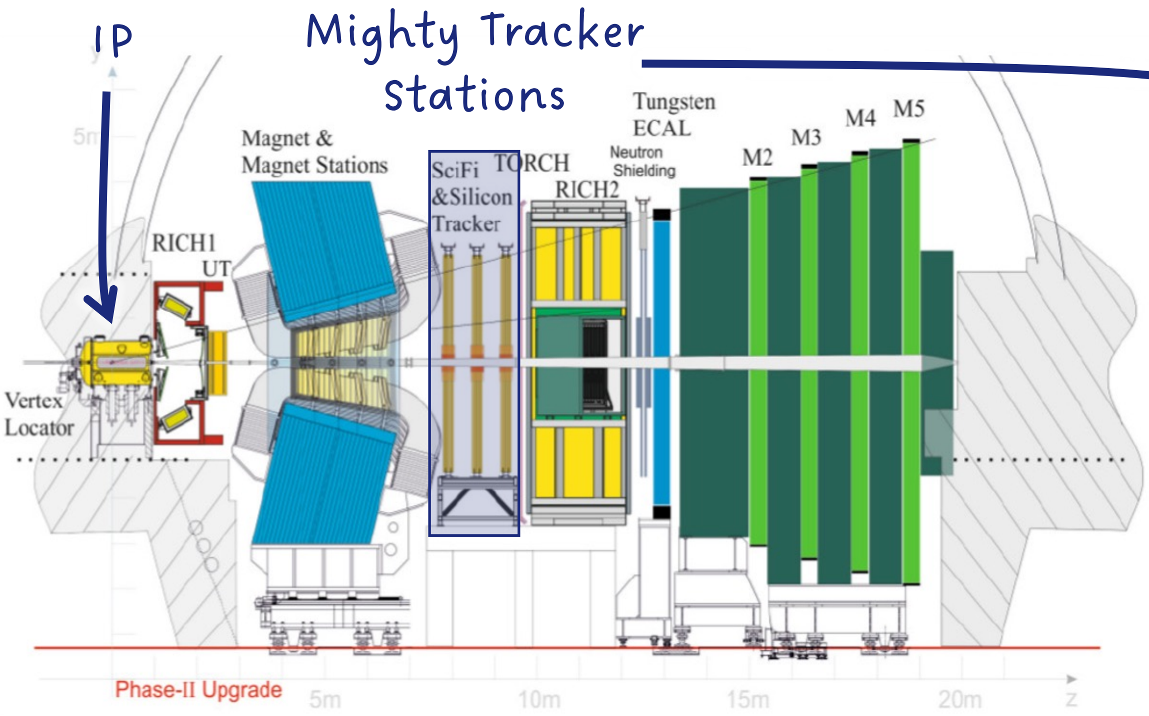
- Upgrade towards High-Luminosity LHC
- Reach almost 10 × higher luminosity and collect up to 6 × more data
- Increased readout speed of 40 MHz bunch-crossing rate
- New software-only trigger
- New detector upgrades



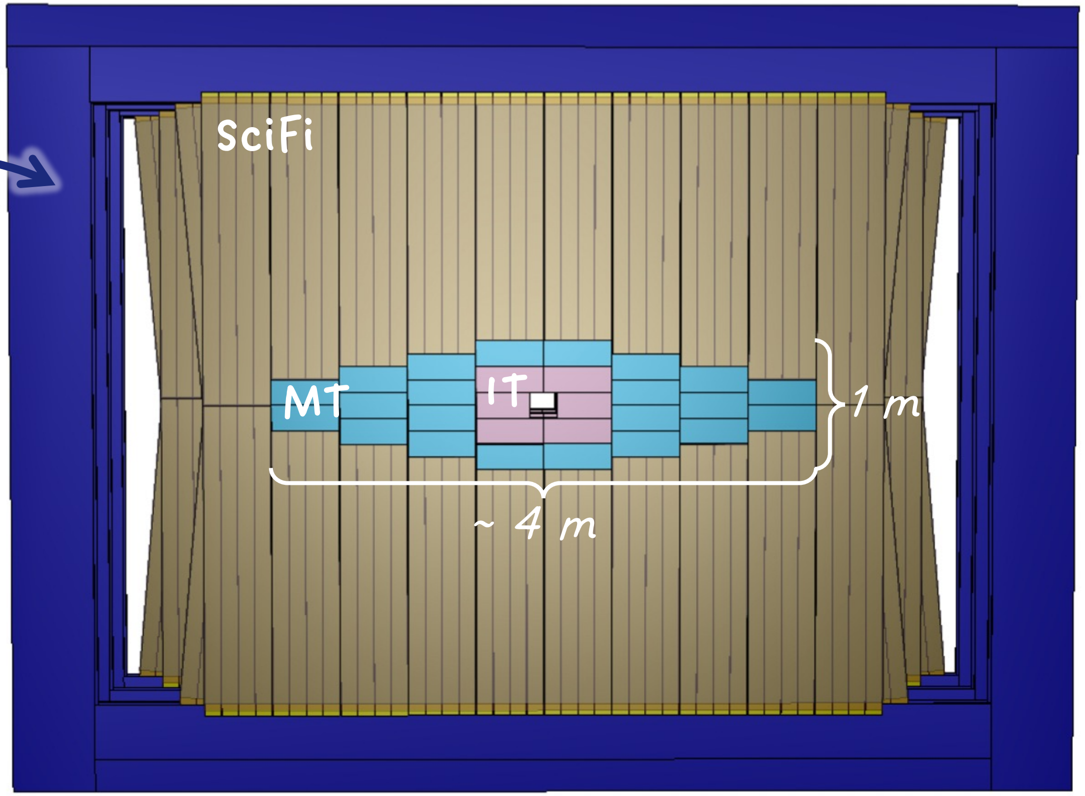
Luminosity profile for the LHCb detector. [1]

LHCb at the HL-LHC

Detector upgrades to handle increased rate → New hybrid tracker: ***Mighty Tracker***



Schematic side view of the Upgrade II LHCb detector. [1]

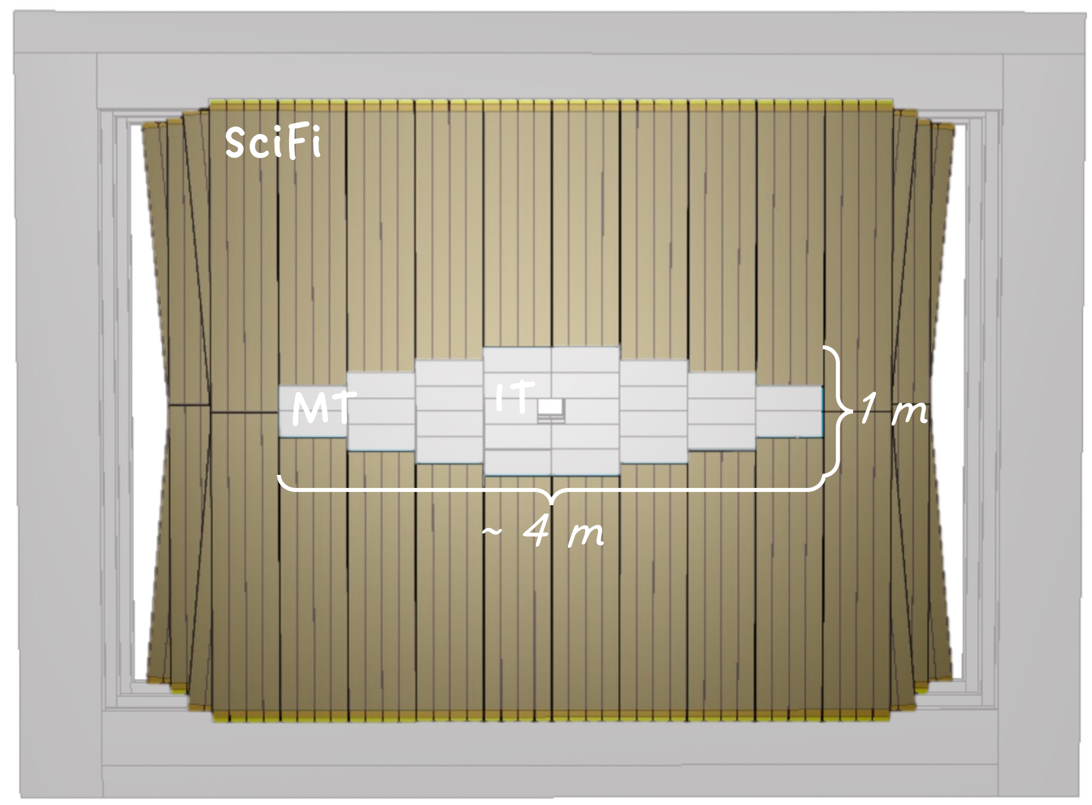


Schematic of one layer of the Mighty Tracker. [1]

The Mighty Tracker

New hybrid tracker composed of:

- ***SciFi Tracker***
  - Twelve layers of scintillating fibres with SiPM readout

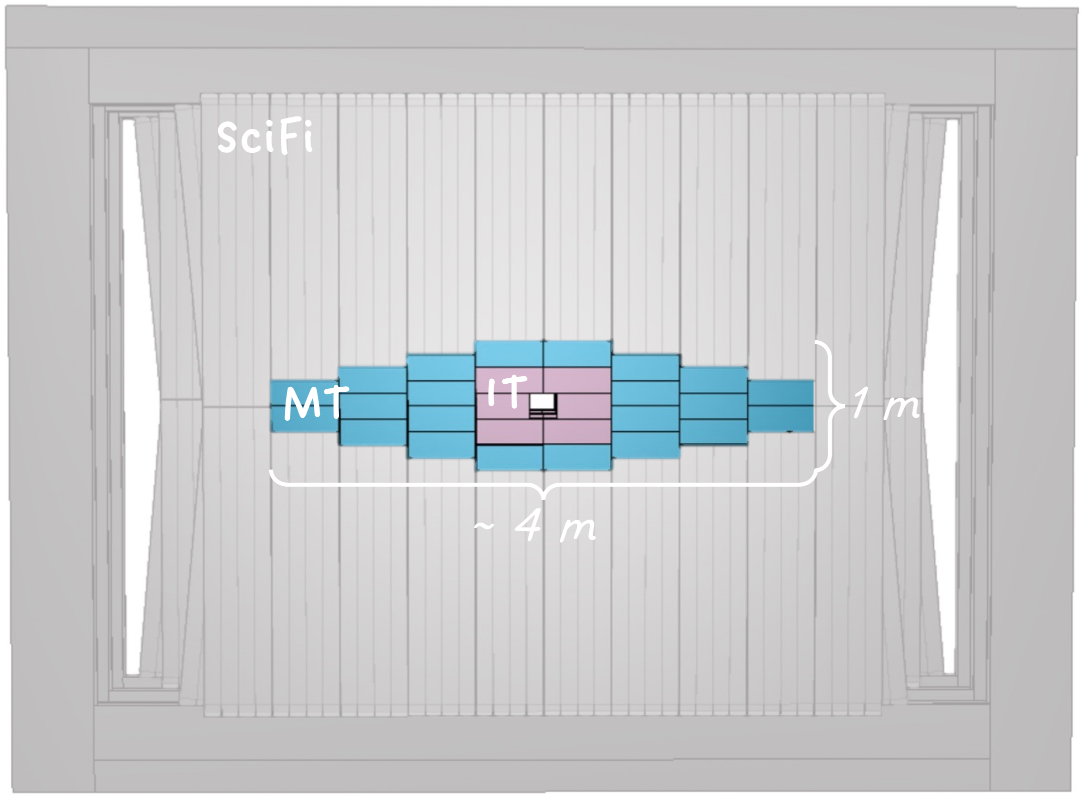


Schematic of one layer of the Mighty Tracker. [1]

The Mighty Tracker

New hybrid tracker composed of:

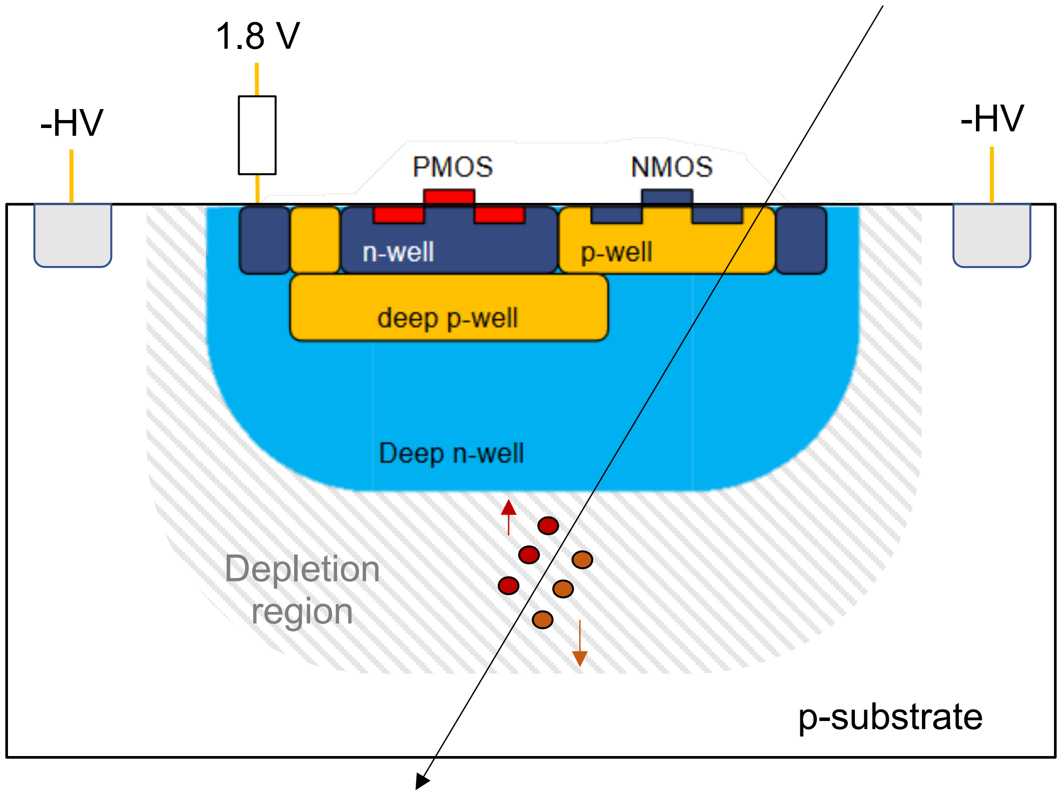
- ***SciFi Tracker***
  - Twelve layers of scintillating fibres with SiPM readout
- ***Inner and Middle Tracker*** (IT+MT)
  - Instrument six layers with silicon sensors → HV-CMOS pixel chip ***MightyPix***
  - Meet requirements of radiation hardness and granularity
  - In total over 46000 silicon sensors to cover area of 18 m^2 (minus beam-pipe hole)



Schematic of one layer of the Mighty Tracker. [1]

What's HV-CMOS Technology?

- HV-CMOS = High Voltage Complementary Metal-Oxide-Semiconductor
- Sensors also called HV-MAPS = HV Monolithic Active Pixel Sensors
- Working principle:
  - Sensing element and readout ASIC in one
  - n-well/p-substrate diode acts as sensor
  - Readout electronics isolated from high voltage by deep n-well
  - High reverse bias (> 200 V) creates thick depletion region between deep n-well and p-substrate
  - Photons and charged particles create electron/hole pairs, collected via drift



Working principle of HV-CMOS sensors.

MightyPix

- Based on knowledge from ATLASPix[1] and MuPix[2]
- Final requirements:
  - High granularity
  - Assign hits to correct bunch crossing
  - Low power consumption
  - Radiation hard
  - Cooled to around 0°C
- First prototype: ***MightyPix1***

Parameter	Required Value
Chip size	$\sim 2\ \mathrm{cm} \times 2\ \mathrm{cm}$
Pixel size	$\sim 50\ \mu\mathrm{m} \times 150\ \mu\mathrm{m}$
Time resolution	$< 3\ \mathrm{ns}$
Power consumption	$< 0.15\ \mathrm{W/cm^2}$
NIEL[3]	$6 \times 10^{14}\ 1\ \mathrm{MeV}\ \mathrm{n_{eq}/cm^2}$
Cooling	$< 0^{\circ}\mathrm{C}$

[1] HV-CMOS pixel chip proposed for ATLAS @ CERN
[2] HV-CMOS pixel chip produced for Mu3e @ PSI
[3] Non Ionising Energy Loss, includes safety factor of 2

MightyPix1

Version:

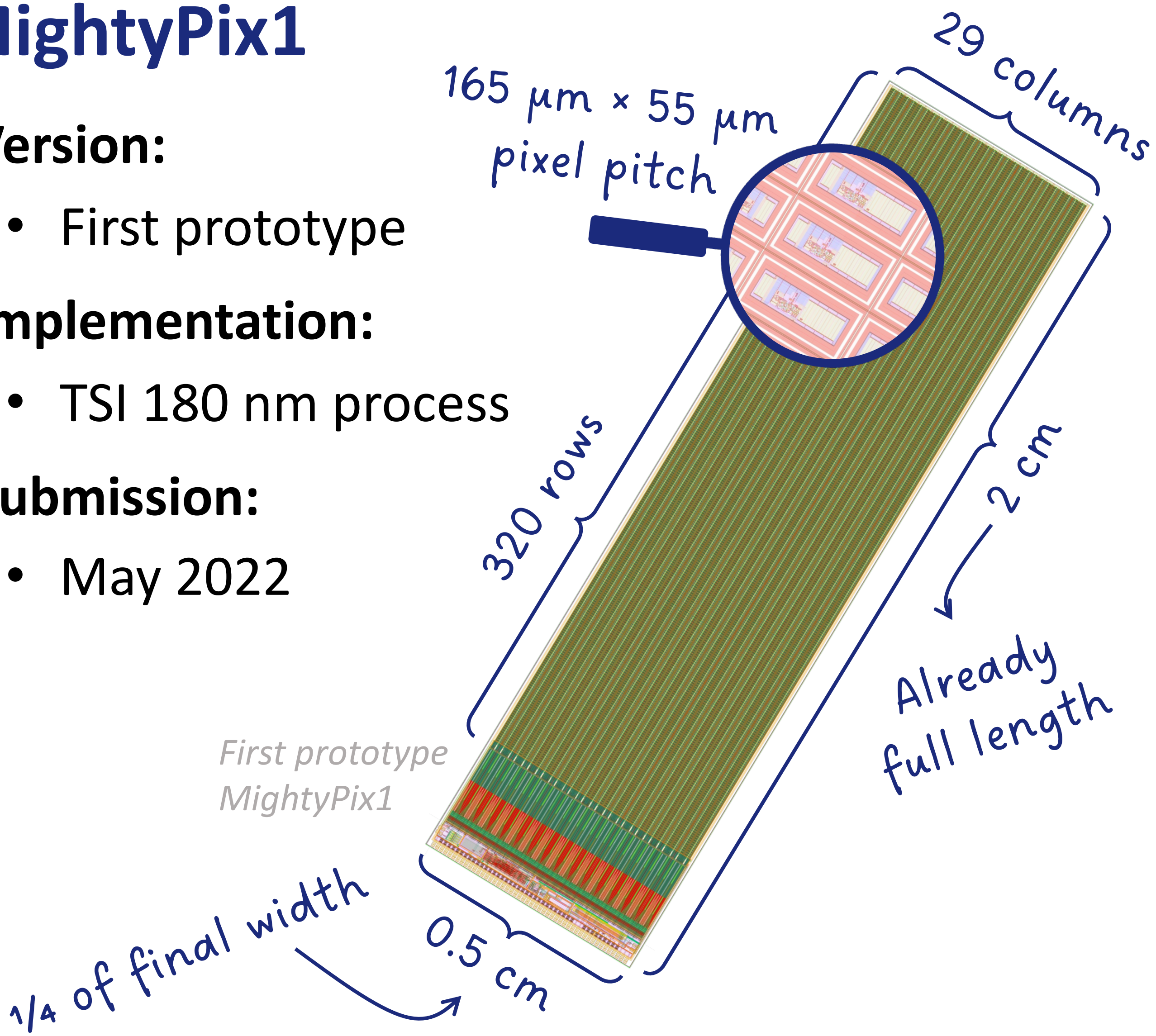
- First prototype

Implementation:

- TSI 180 nm process

Submission:

- May 2022



Data format:

- 2 × 32 bit words per hit

Data output rate:

- 1.28 Gbit/s going to lpGBT

Digital interfaces:

- TFC: Timing and Fast Control
- I^2C: Slow Control
- SR: Config. shift register interface

Clock generation:

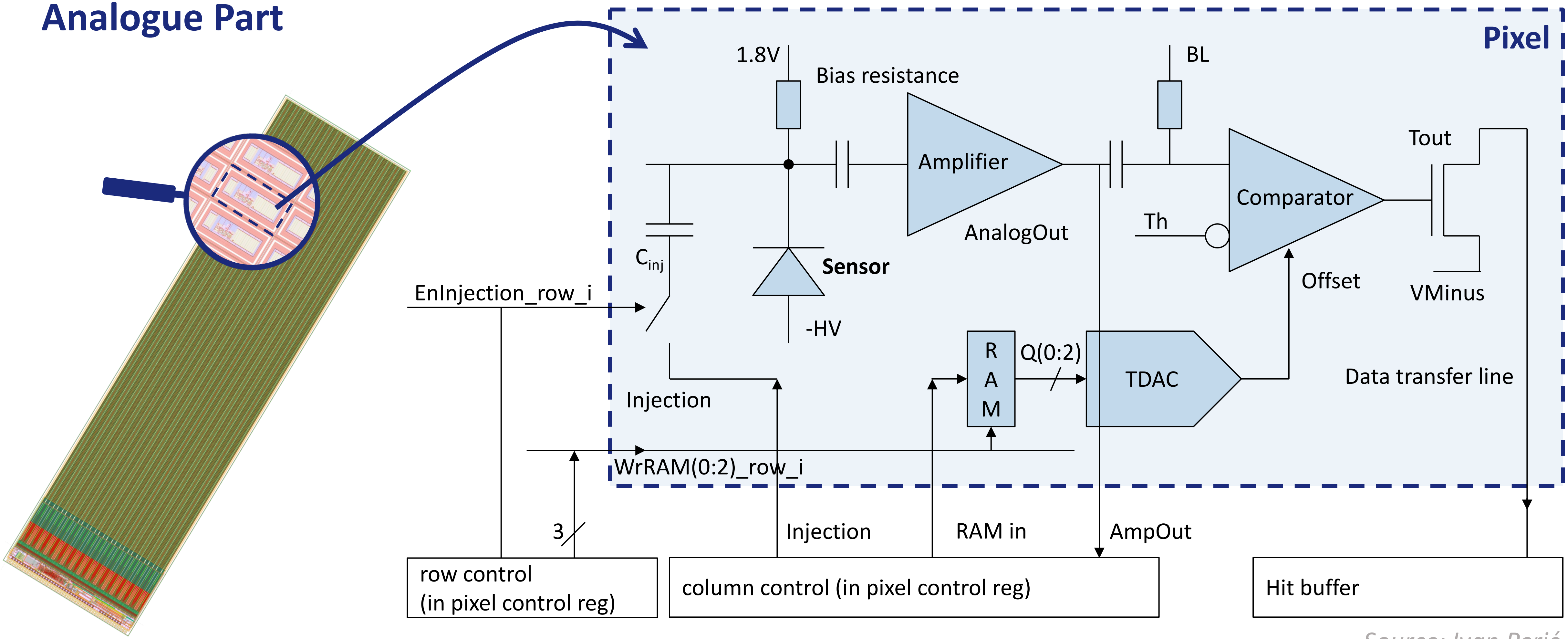
- External: 40 MHz and 640 MHz coming from lpGBT
- Internal: CML and CMOS PLL with 40 MHz reference clock

Bias voltages:

- Integrated 10 bit voltage DACs

MightyPix1: Readout of a Hit

Analogue Part

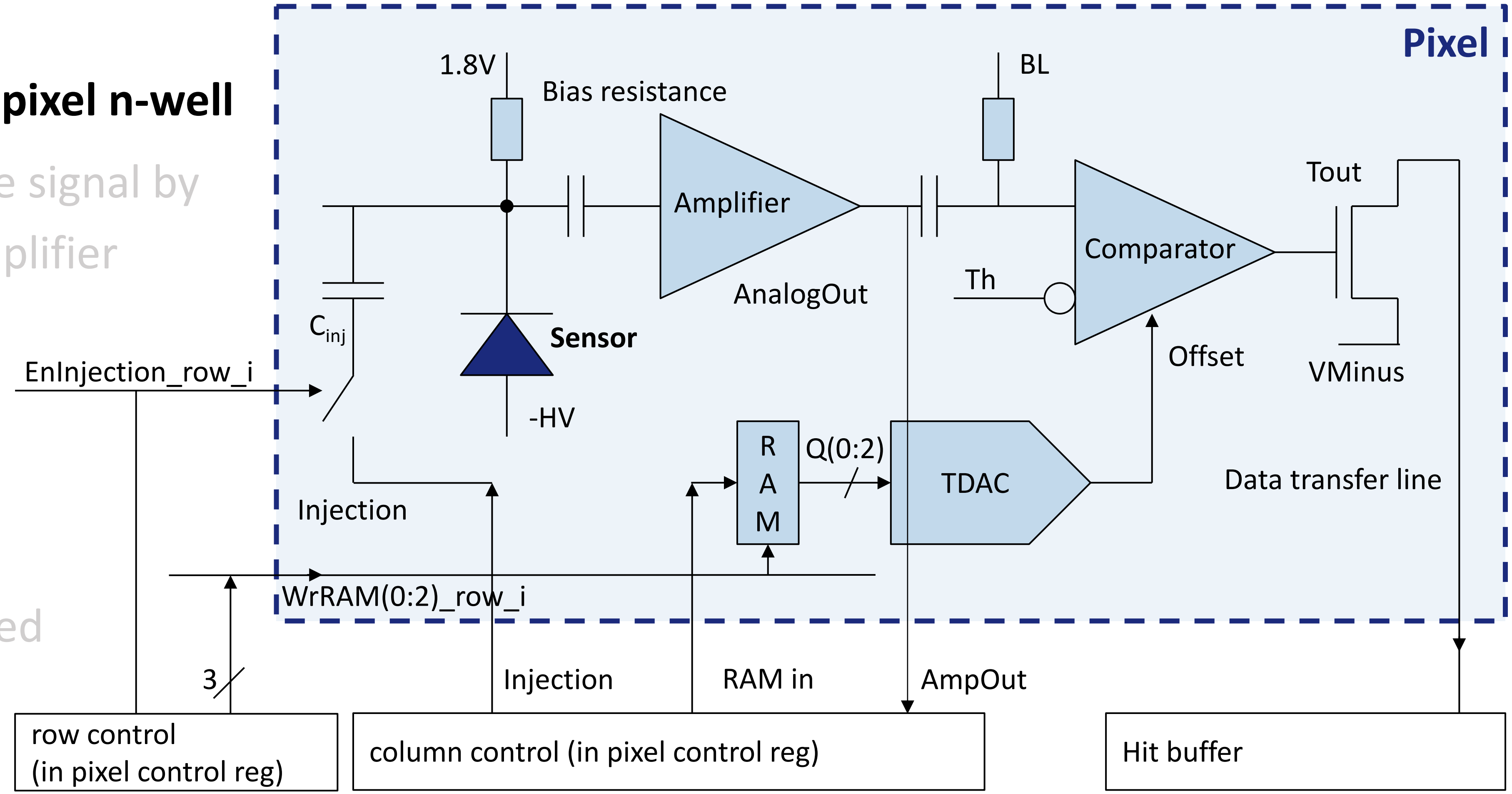


Source: Ivan Perić

MightyPix1: Readout of a Hit

Analogue Part

1. Charge collected by **pixel n-well**
2. Converted to voltage signal by Charge Sensitive Amplifier
3. Analog voltage pulse converted to digital signal by comparator
4. Hit information stored in hit buffer



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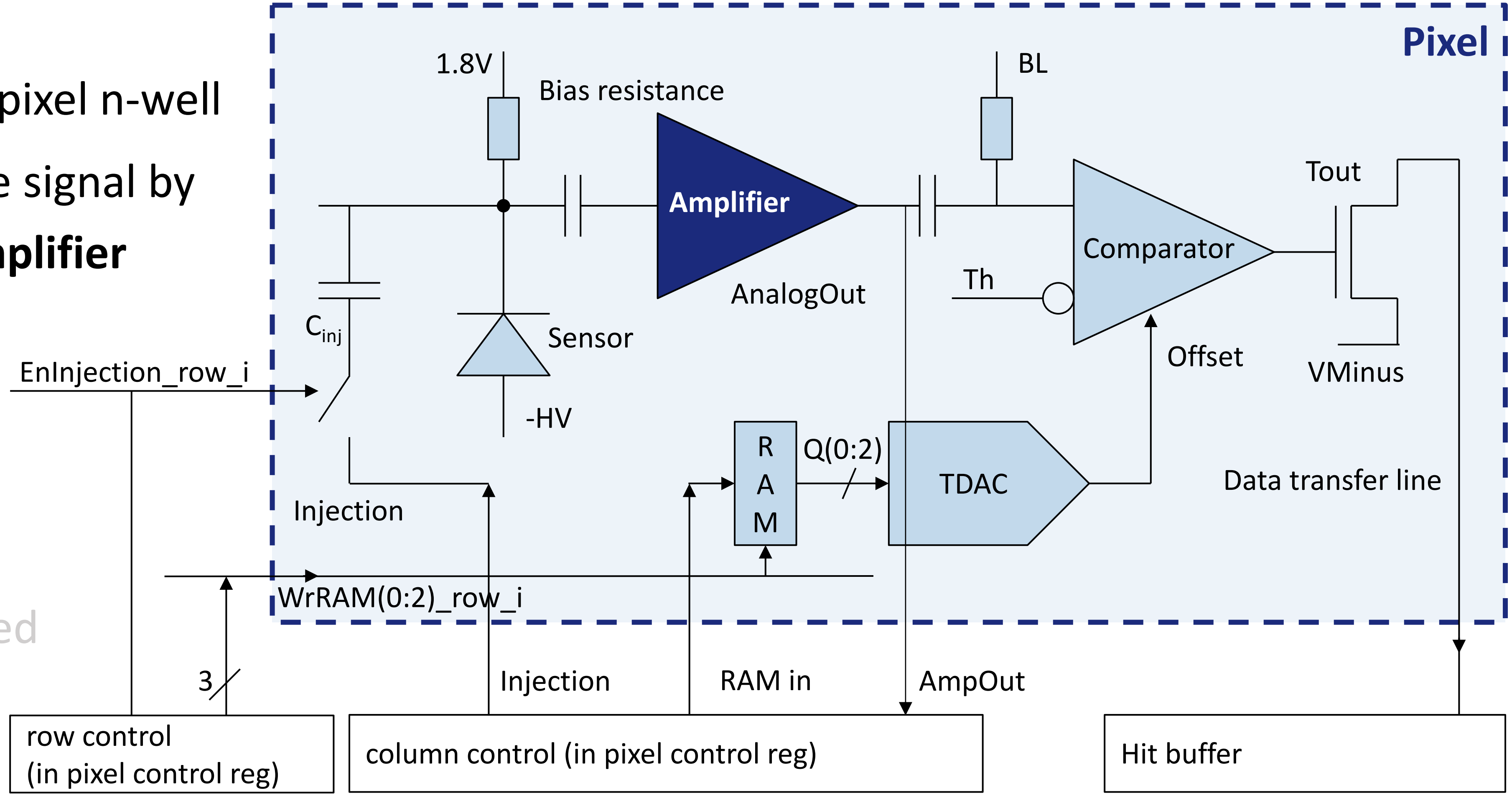

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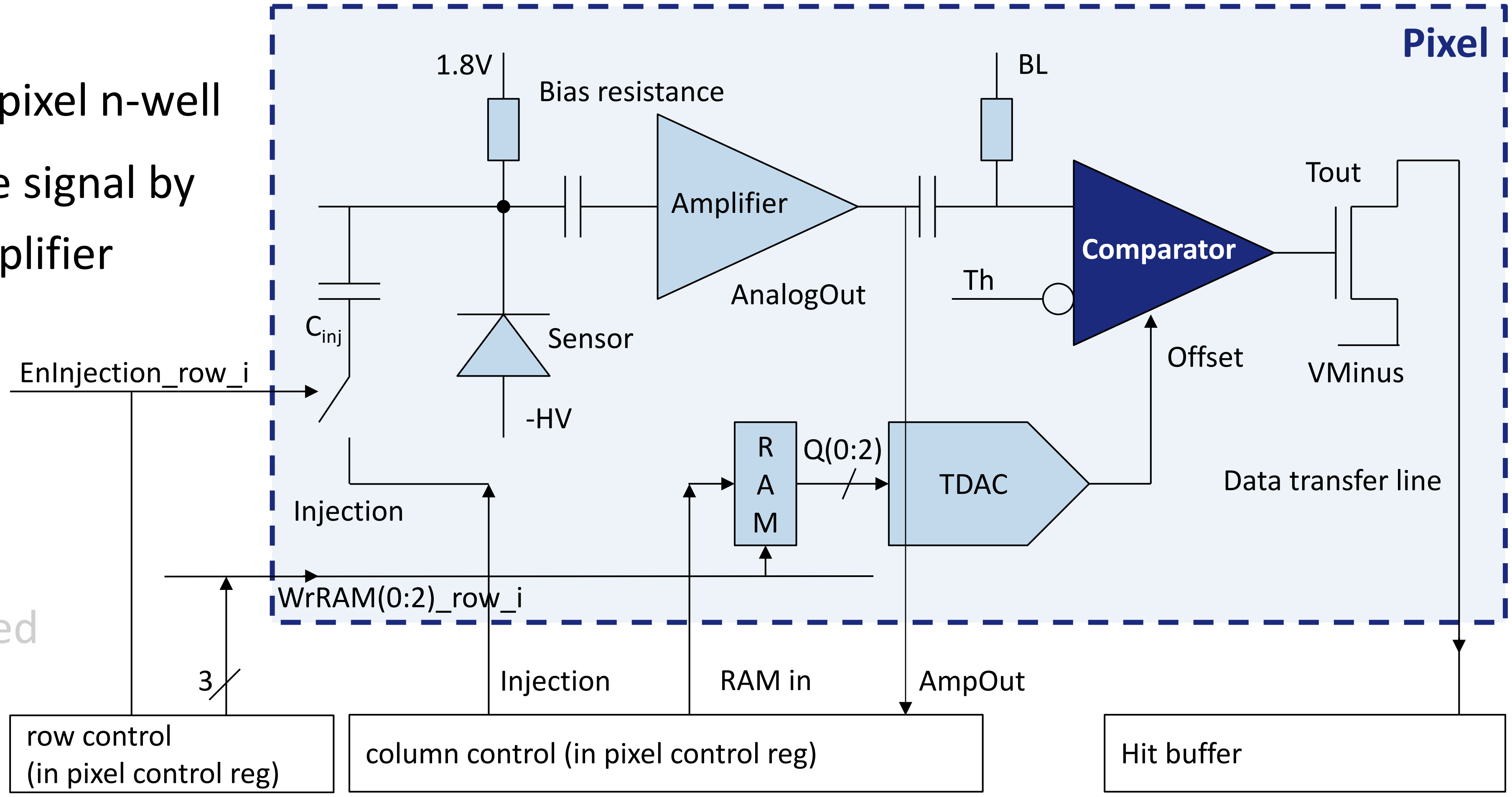

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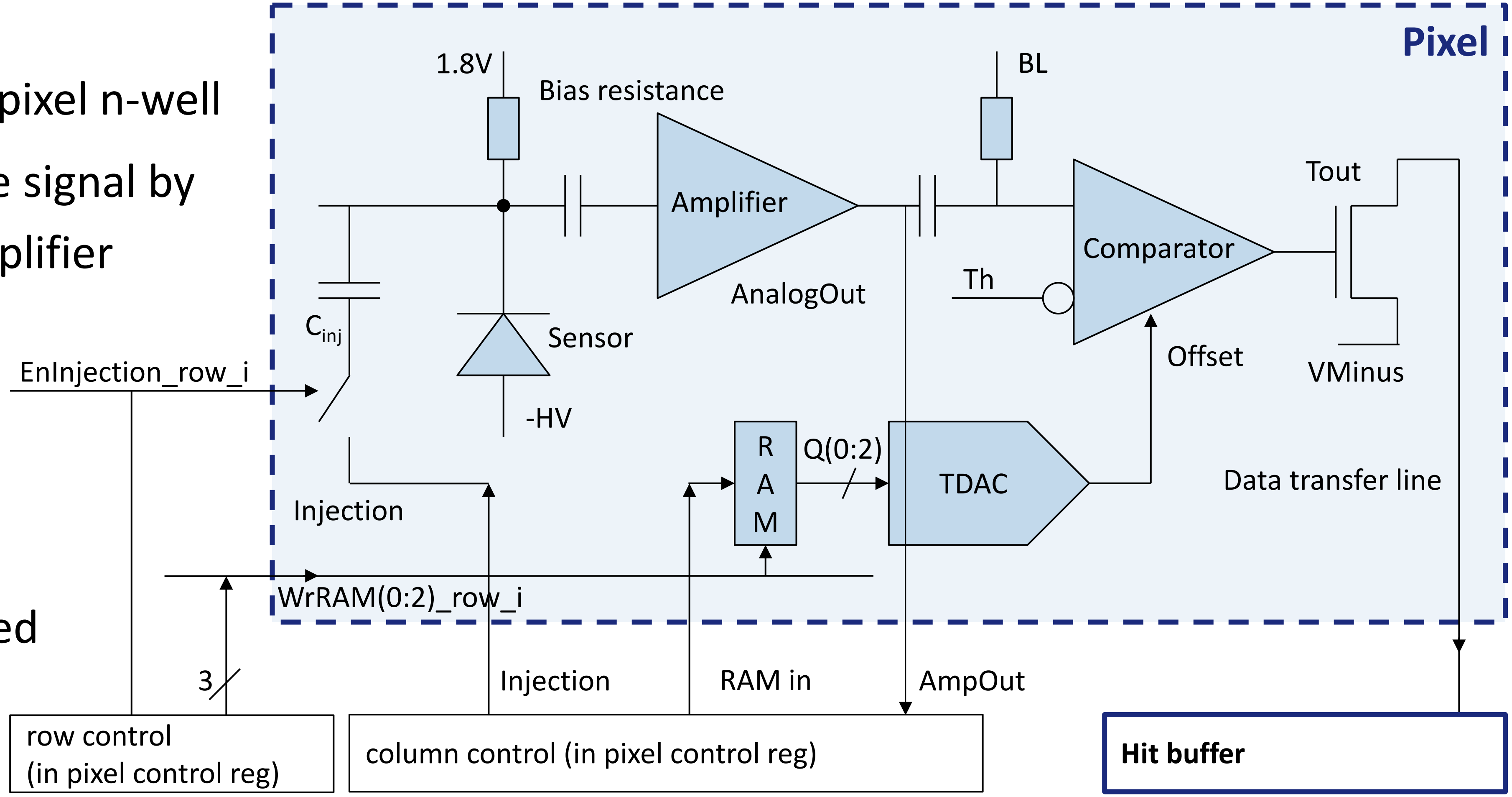
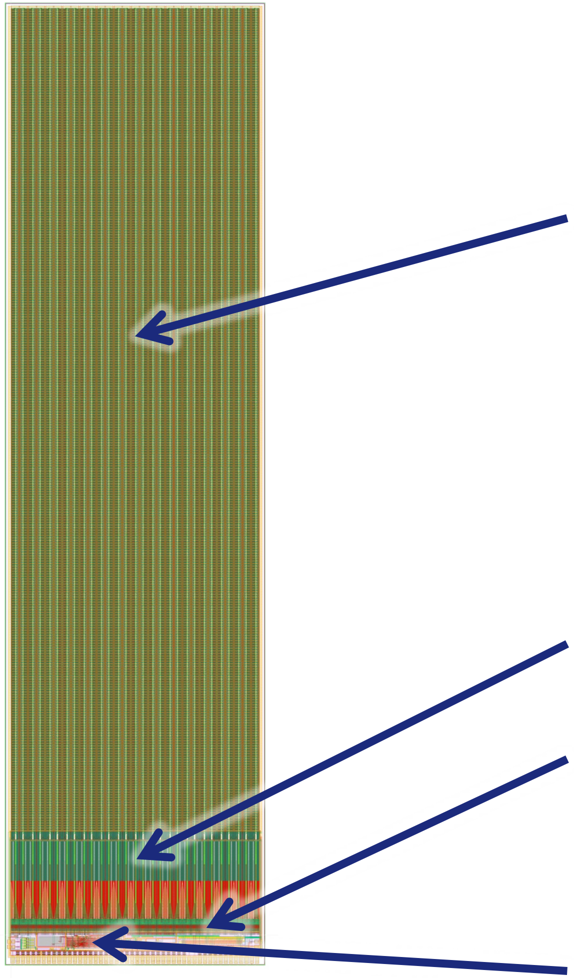


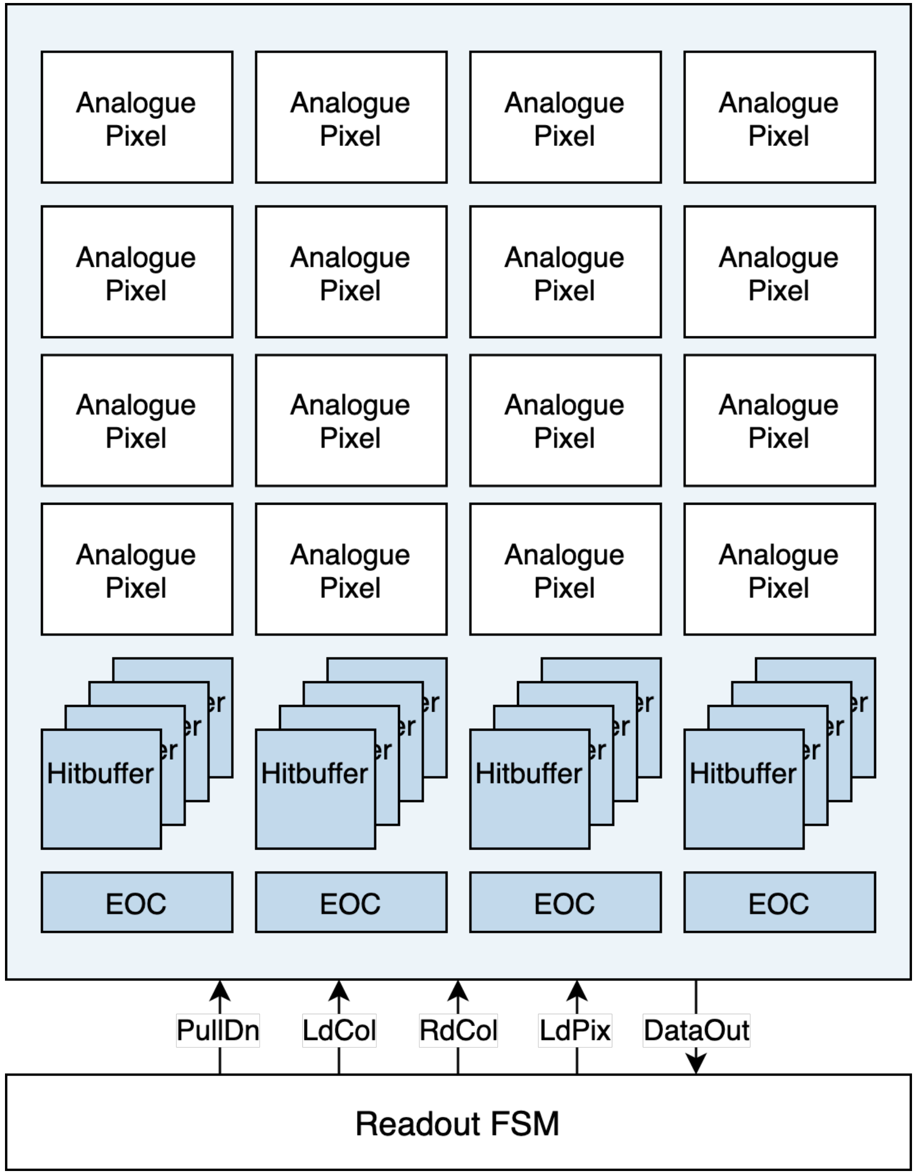
Source: Ivan Perić

MightyPix1: Readout of a Hit

Digital Part

→ Readout driven by Readout Control Unit (RCU) Finite State Machine (FSM)



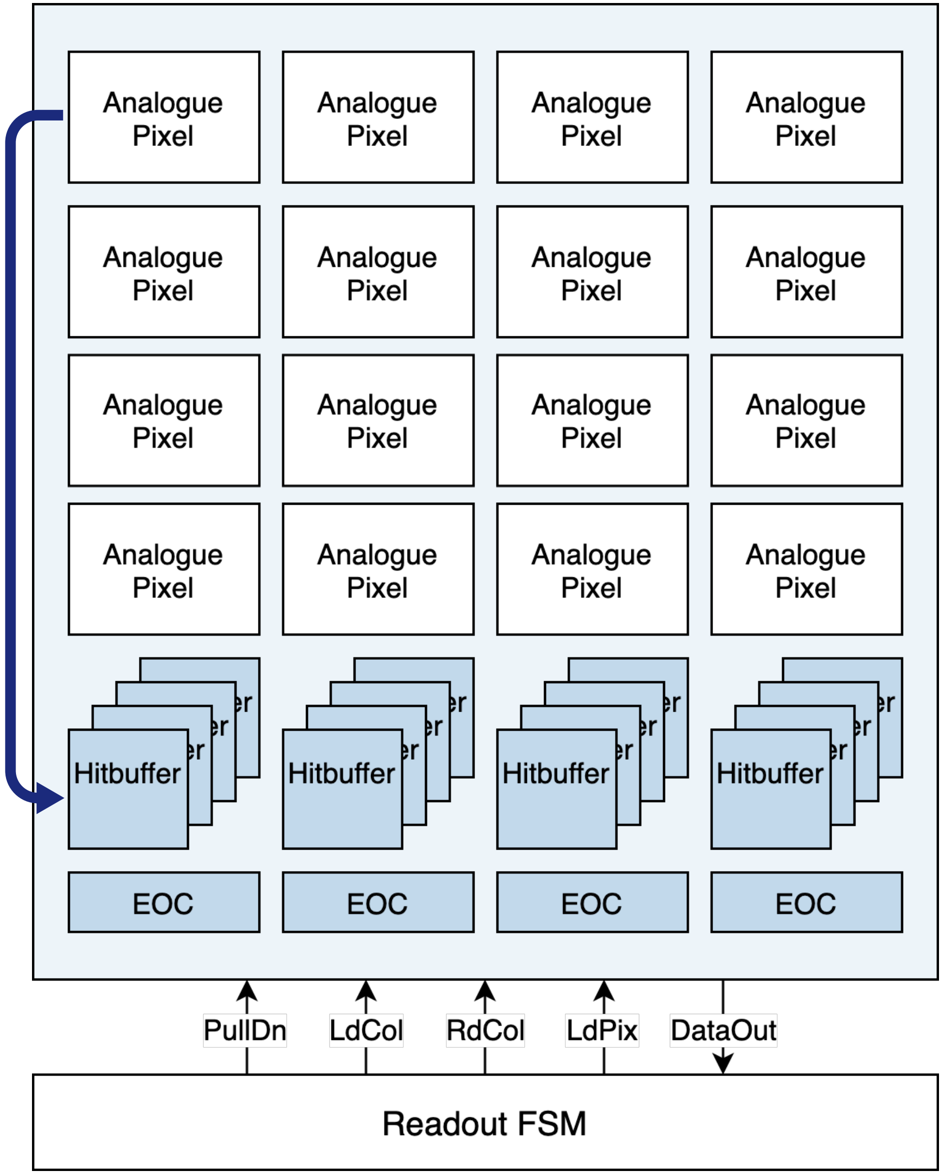


Source: Nicolas Striebig

MightyPix1: Readout of a Hit

Digital Part

4. Hit information stored in hit buffer
5. Data loaded from highest active hit buffer to End of Column (EoC) buffer, go on to next one
6. Read data from EoC
7. For every hit 2 × 32 bit data words
8. Parallel scrambler analogue to VELOPix
9. Data sent into serializer tree and sent out



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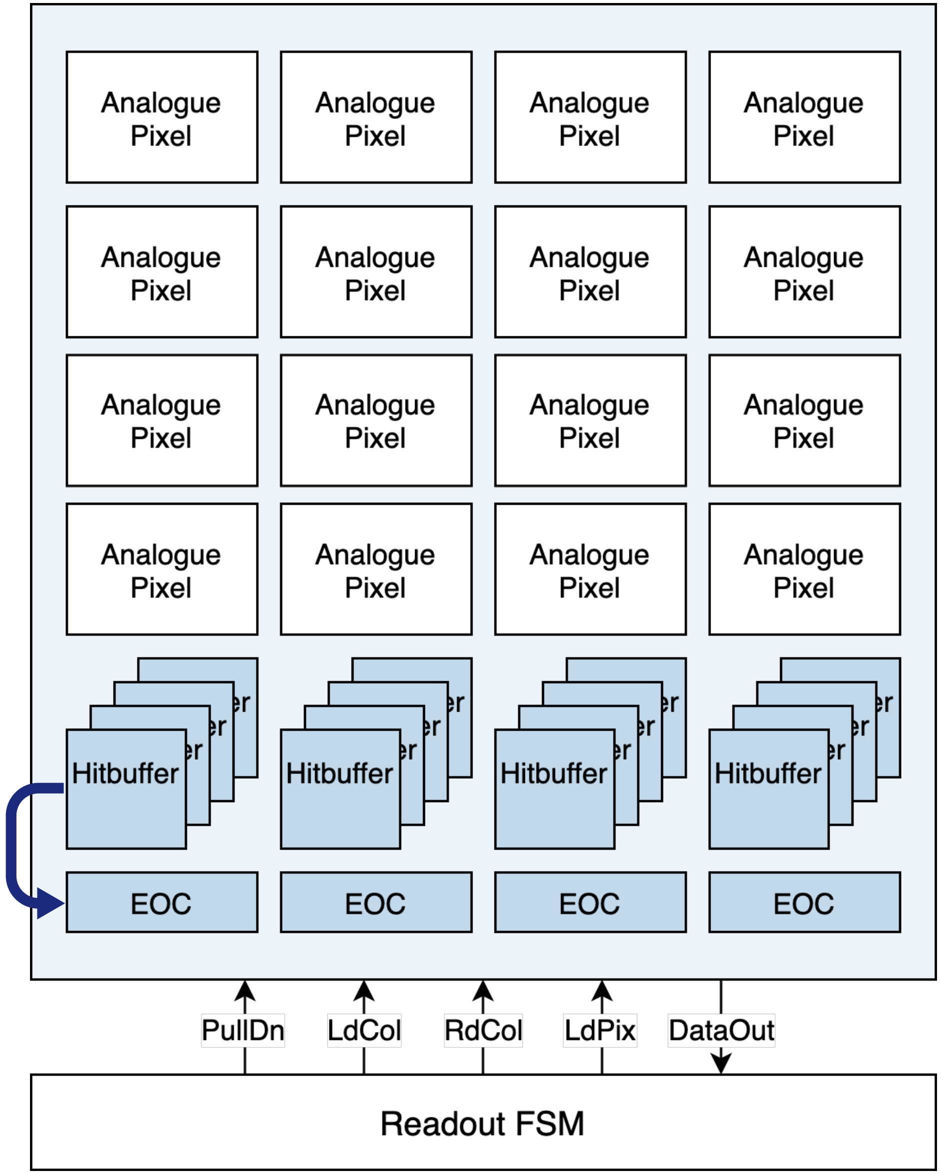

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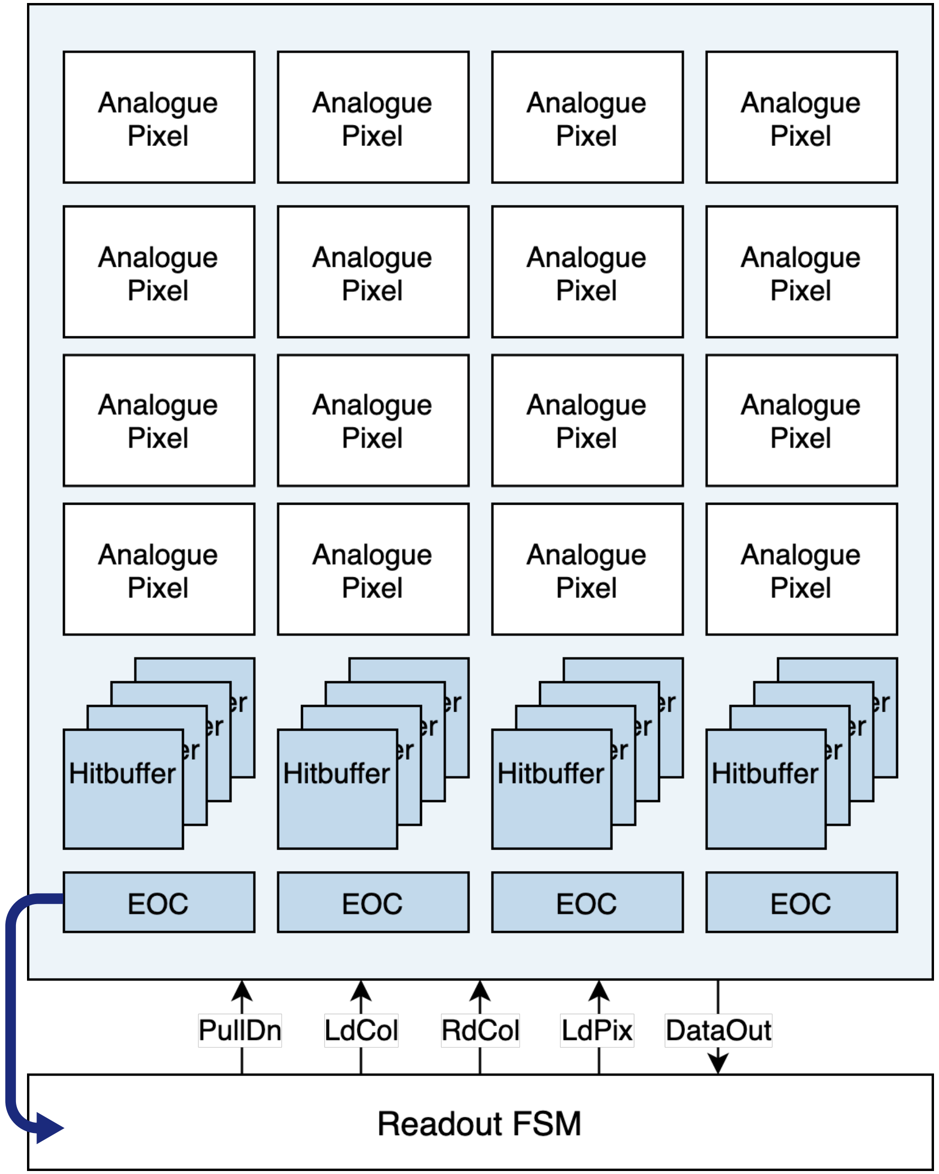

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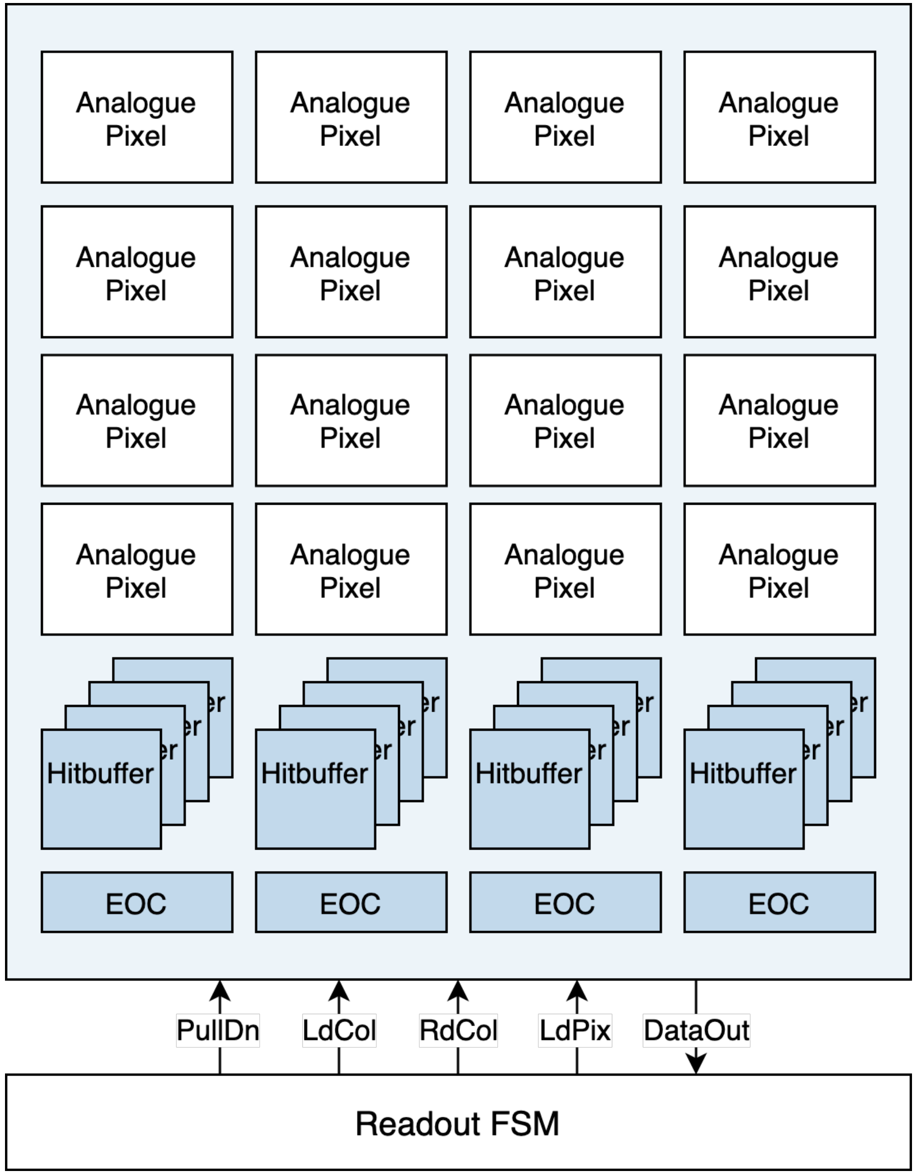

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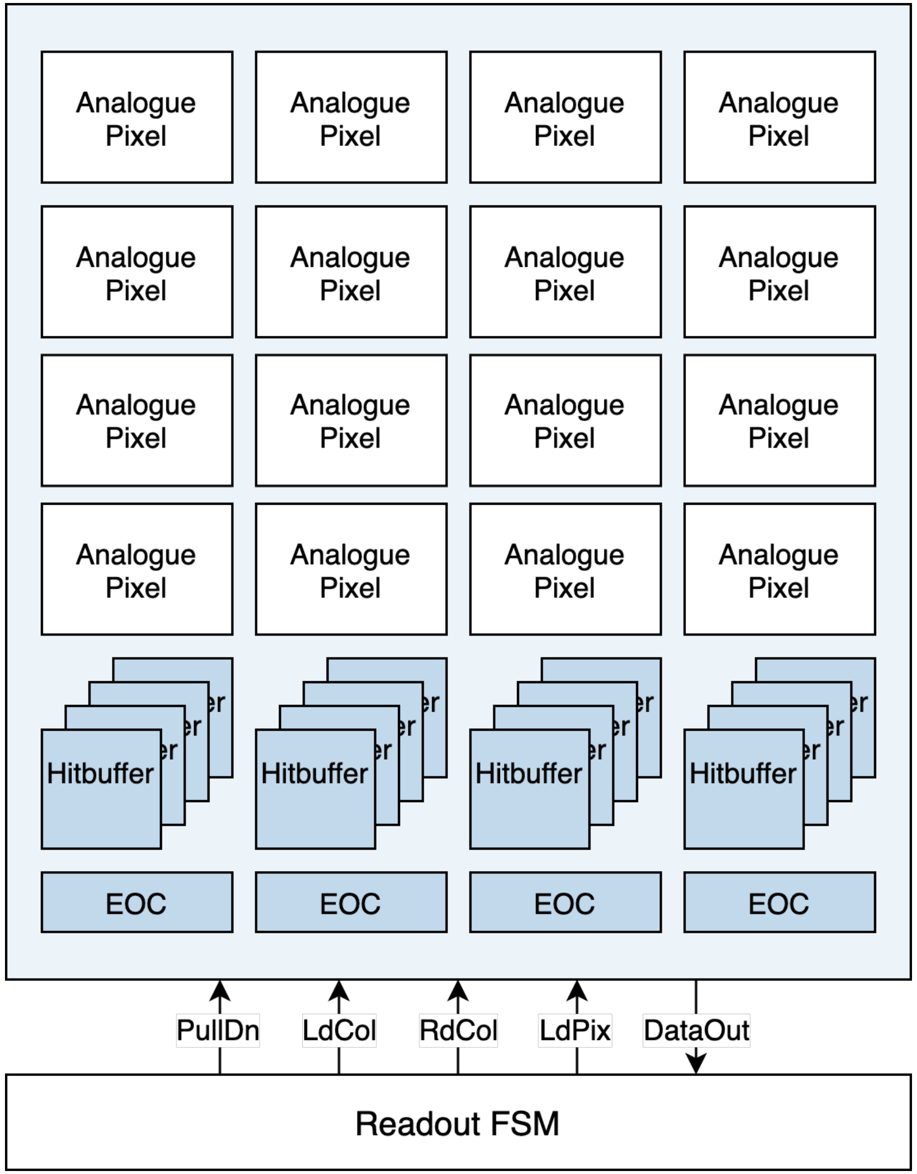

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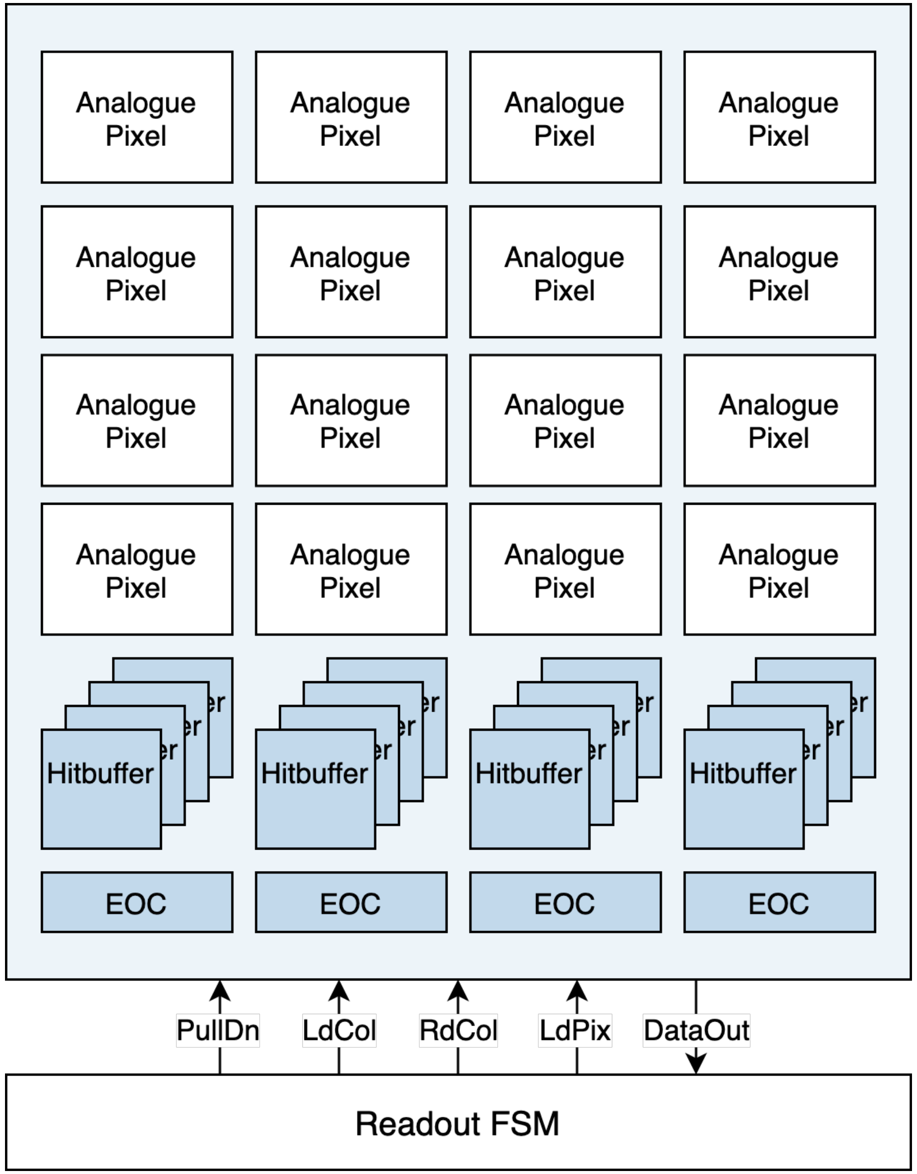
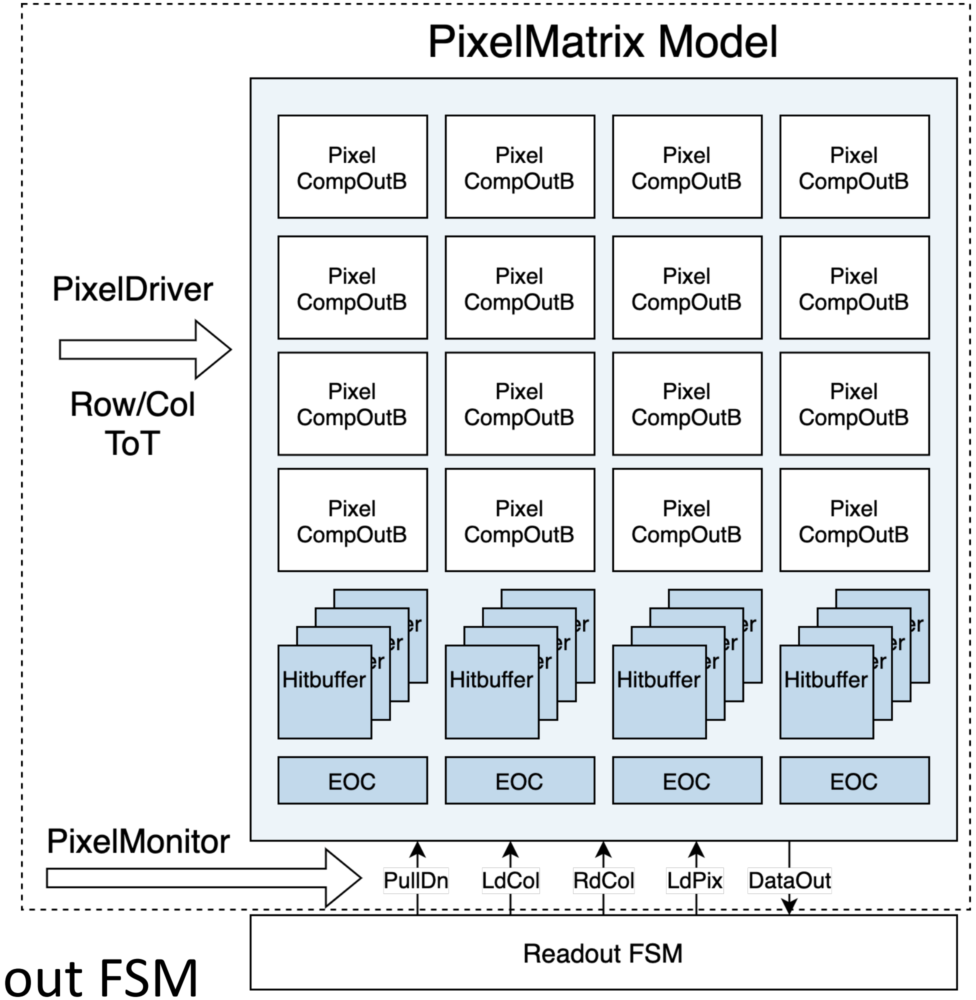


Source: Nicolas Striebig

MightyPix1: Efficiency Simulations

Can MightyPix handle the hit rate at LHCb?

- Expected rate at Mighty Tracker:
  - Max. ~ 17 MHz/cm^2
  - Additionally 5% of two-pixel clusters
- Simulate efficiency with model of MightyPix1
  → Efficiency = ratio of detected to total events
- Parametrizable model of pixel matrix
  - Send simulation data to model
  - Comparison of input data with data seen by Readout FSM
  - Check if model correctly detects all hits that are sent in

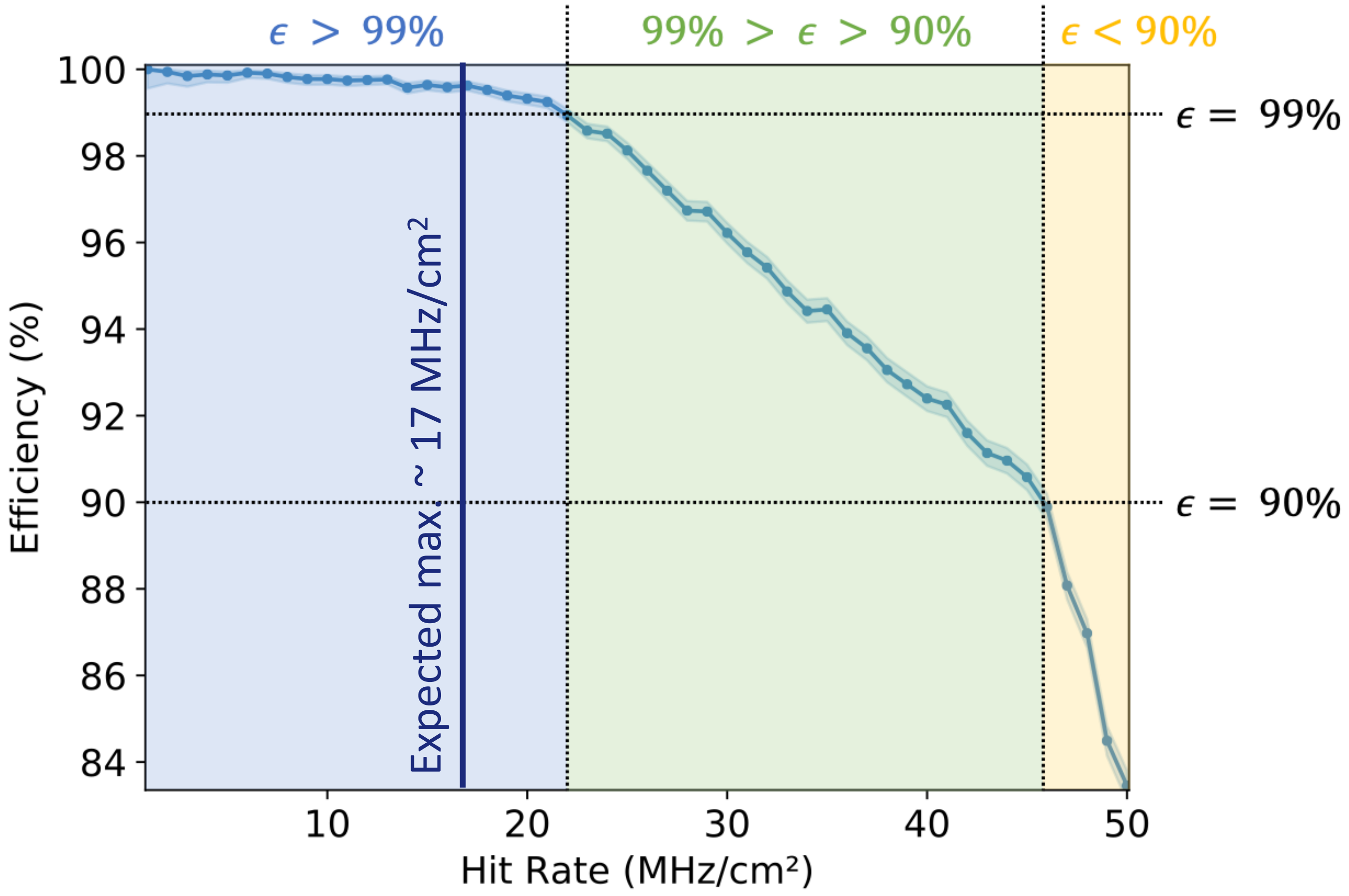


Source: Nicolas Striebig

MightyPix1: Efficiency Simulations

- Randomly generated Poisson distributed hits
  (Used until I get fancy simulation data, that other groups are currently working hard to produce)
- Each data point corresponds to 4×10^5 events

MightyPix1 shows over 99% efficiency for maximum hit rates expected at the Mighty Tracker!



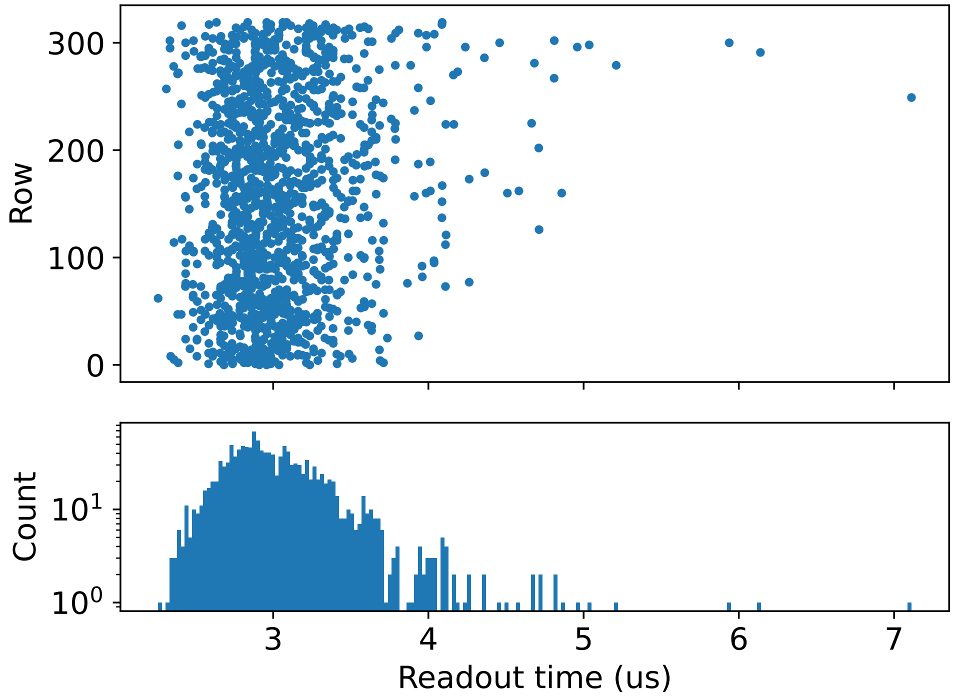
Why does the efficiency drop off?

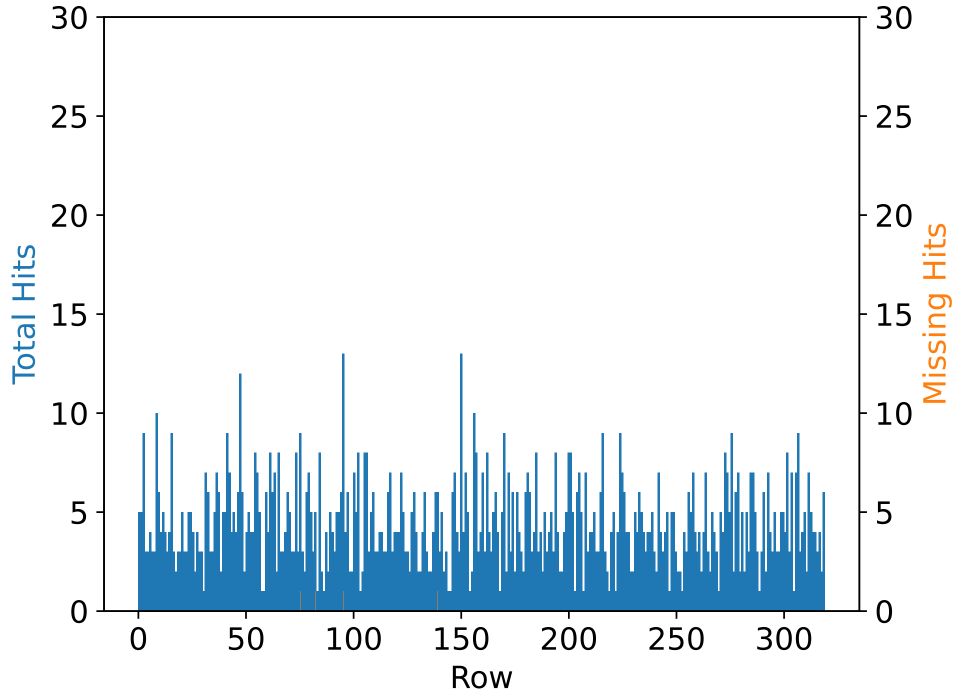
- Low efficiency means hits are not detected correctly
- A hit is missed if it occurs in a pixel who’s hit buffer is still occupied
- Lower rows are given priority in readout

  → Chance to miss a hit increases with row number

Why does the efficiency drop off?

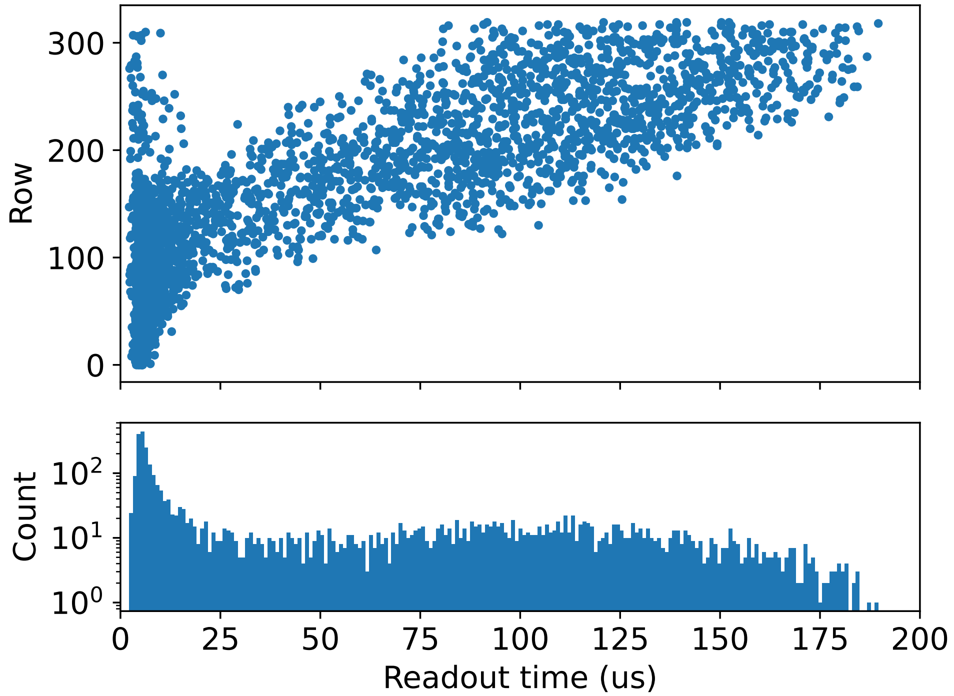
- At 17 MHz/cm^2 99.95% of hits get detected correctly

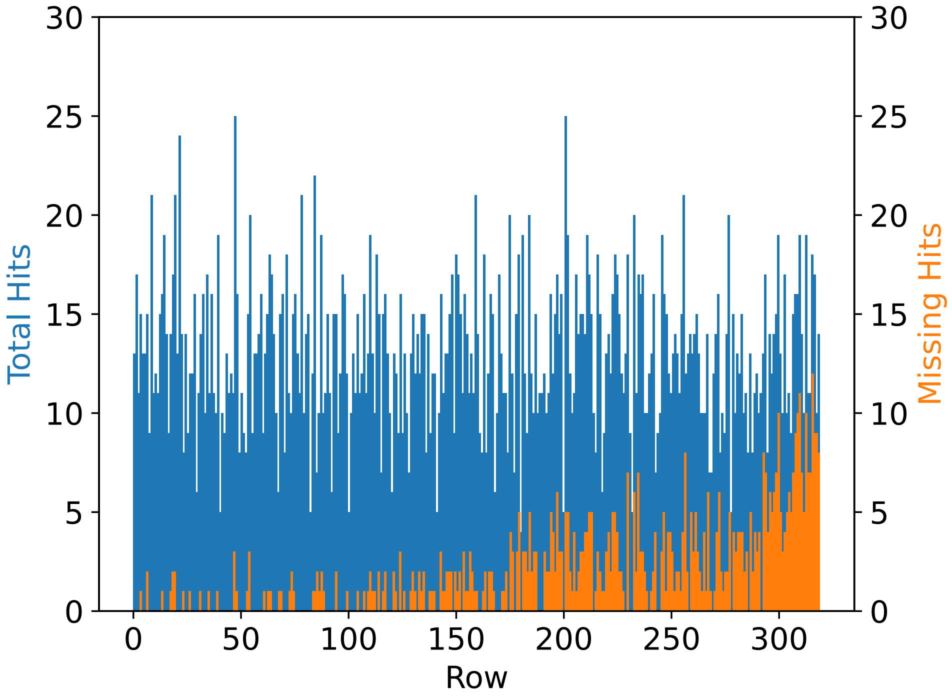




Why does the efficiency drop off?

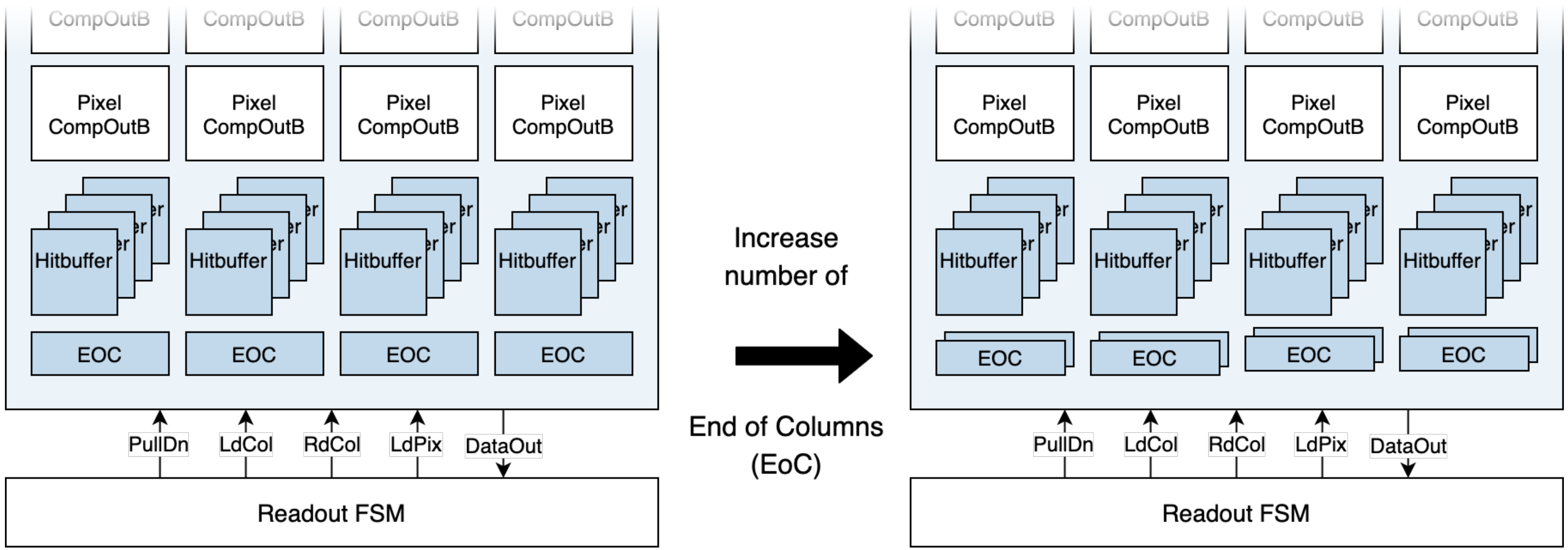
- At 17 MHz/cm^2 99.95% of hits get detected correctly
- But at 50 MHz/cm^2 the efficiency is only at 85% and a clear dependency on row number can be seen





Increasing the MightyPix Efficiency

- Increase speed of hit buffer readout
- Can do this by: Increasing number of End of Columns



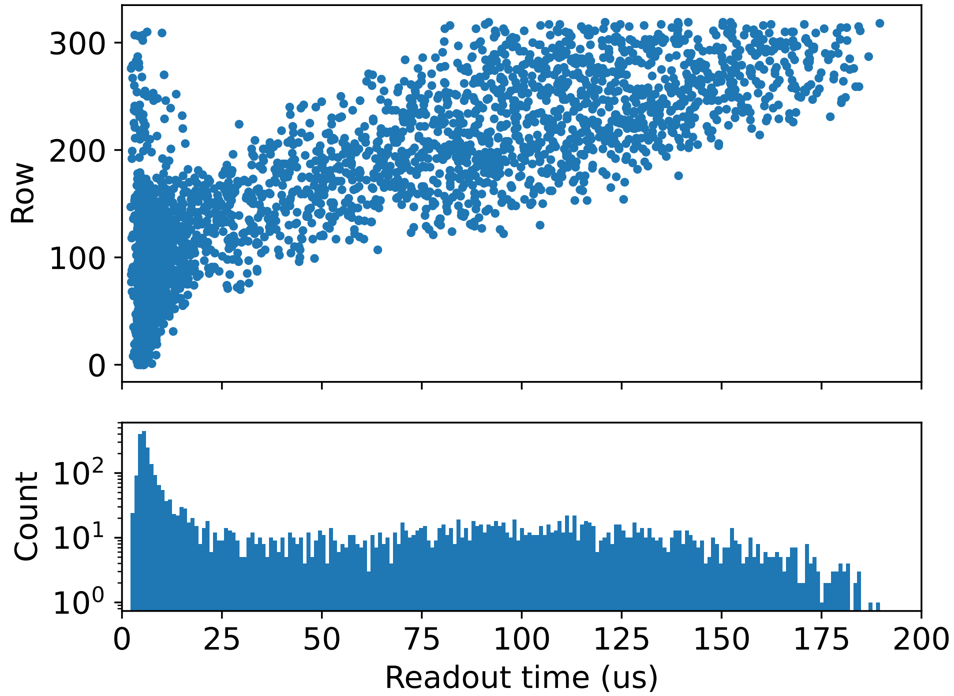
Increasing the MightyPix Efficiency

Plots for 50 MHz/cm² (>3 x expected max. rate)

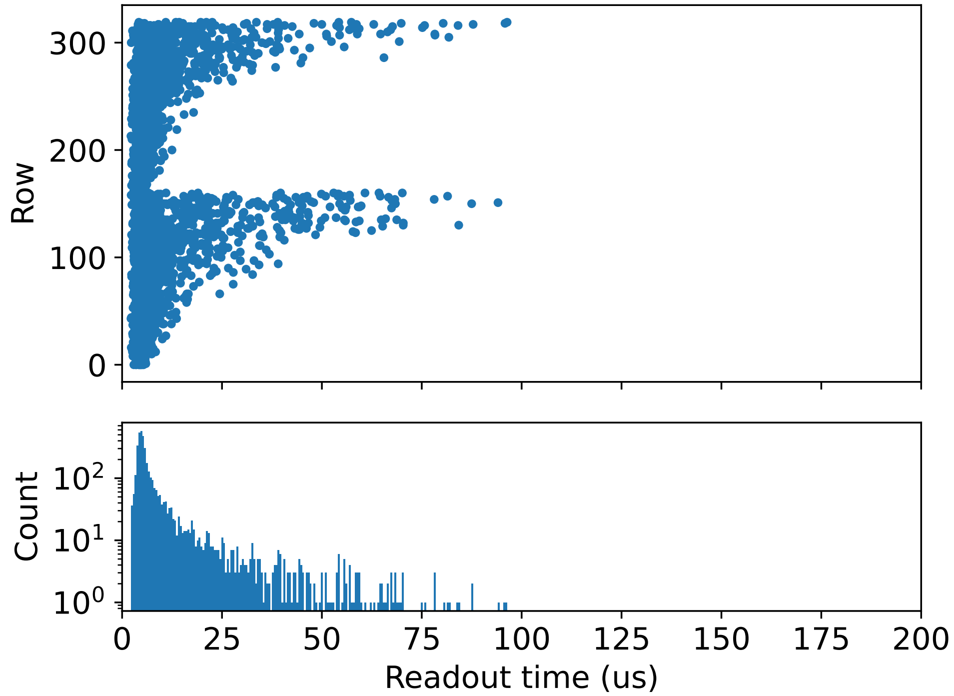
- Example: Double number of EoCs

→ Before: **1 EoC** for 320 hit buffers

→ Now: **2 EoC** for 320 hit buffers



Increase number of End of Columns (EoC)



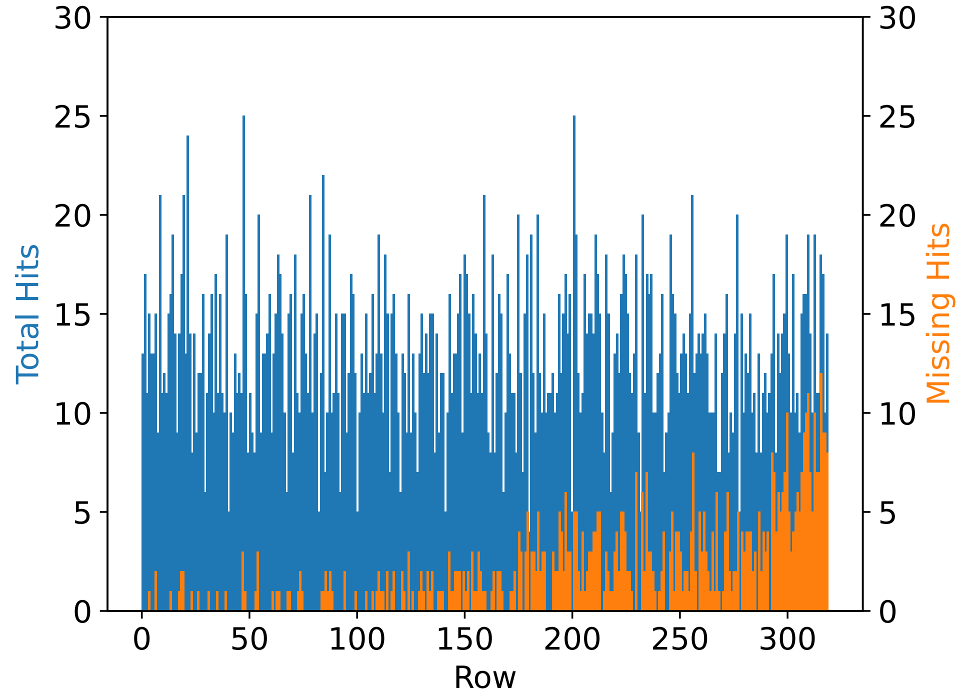
→ We got rid of the longest readout times

Increasing the MightyPix Efficiency

Plots for 50 MHz/cm² (>3 x expected max. rate)

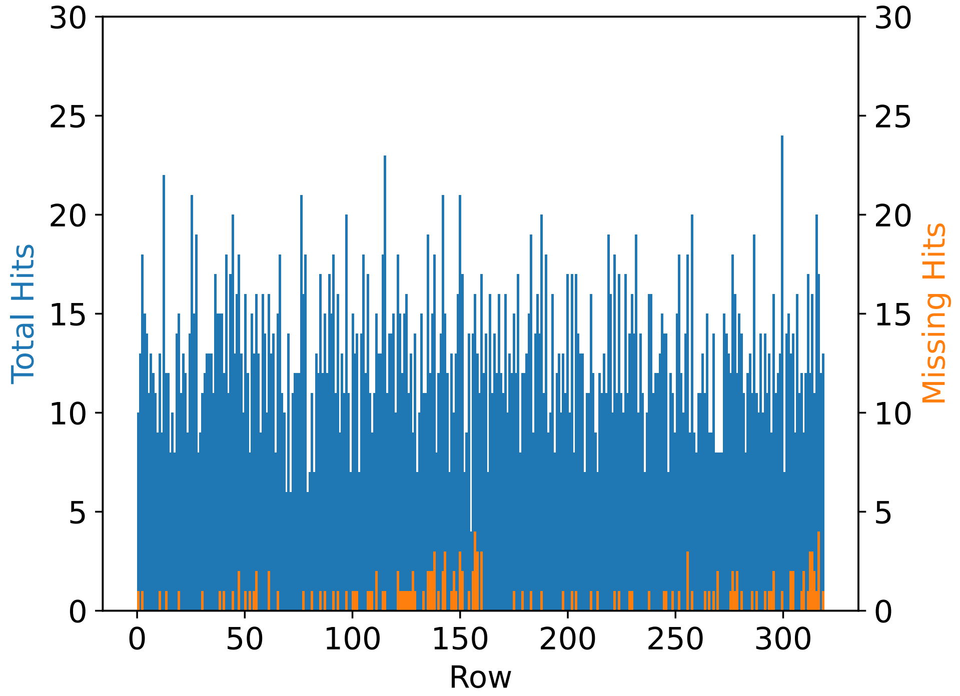
- Example: Double number of EoCs

→ Before: **1 EoC** for 320 hit buffers



Increase number of
→
End of Columns (EoC)

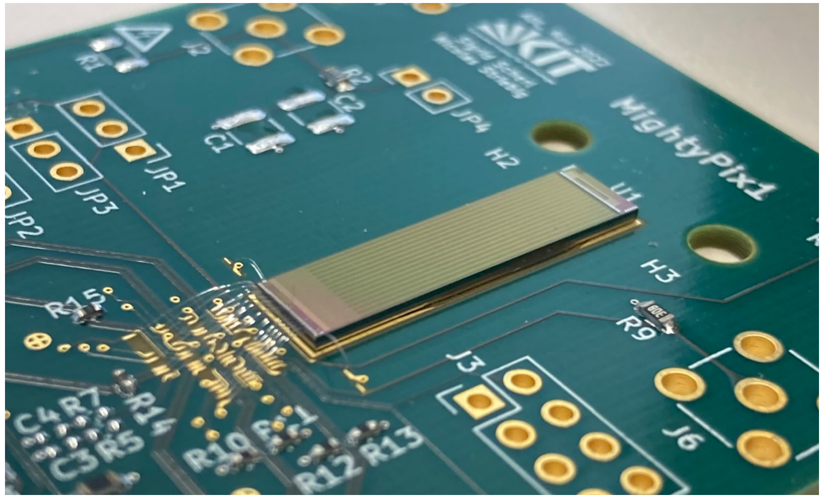
→ Now: **2 EoC** for 320 hit buffers



→ And therefore have far less missing hits

Summary and Next Steps

- Proposed new tracker for LHCb called ***Mighty Tracker***
  - To be instrumented with up to 18 m^2 of silicon sensors
  - Currently developing HV-CMOS pixel chip ***MightyPix***
- First prototype ***MightyPix1***
- Efficiency simulations for MightyPix1
  - Can handle highest expected hit rates
  - Design ideas to go even higher
  - Can input new simulation data when available
- Design of second prototype ***MightyPix2***



References

[1] LHCb Collaboration. *Framework TDR for the LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era*. CERN-LHCC-2021-012 ; LHCB-TDR-023. *https://cds.cern.ch/record/2776420*

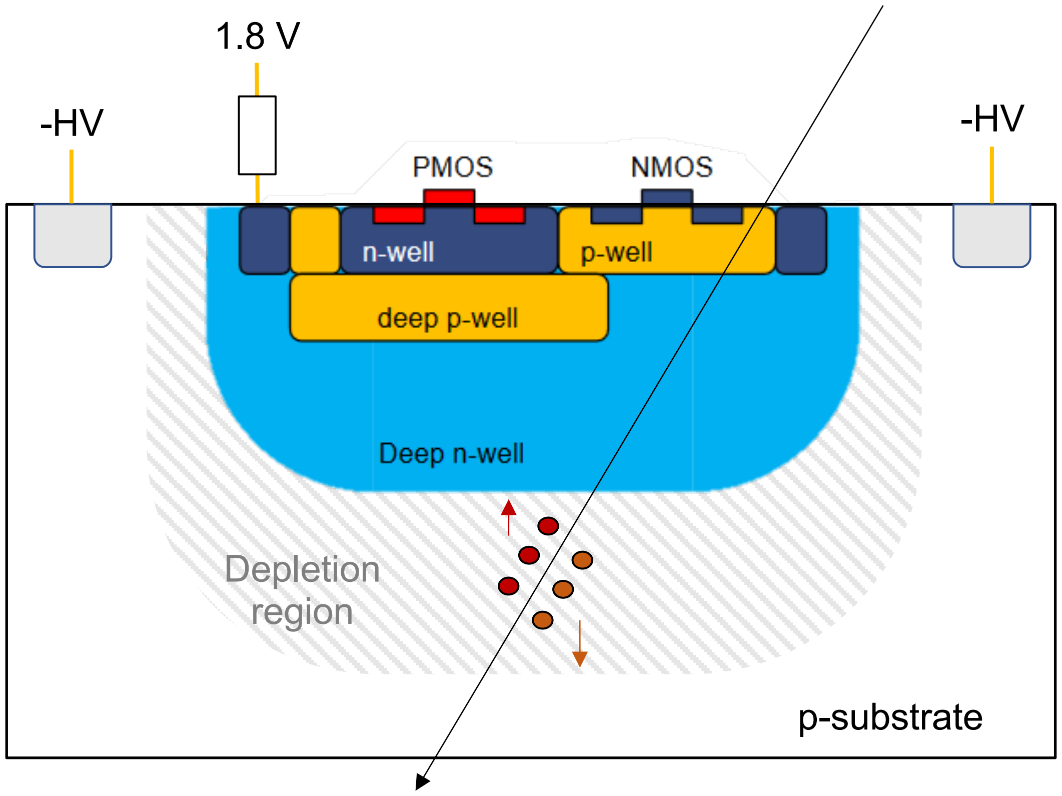
[2] T. Hume, V. Bellee, O. Steinkamp. *Occupancy studies for the LHCb Run4 Mighty Tracker*. LHCb-PUB-2022-003, CERN-LHCb-PUB-2022-003, 2022. *https://cds.cern.ch/record/2800986*

[3] *https://commons.wikimedia.org/wiki/File:Normal_Distribution_Sigma.svg*

Backup

Advantages of HV-CMOS Technology

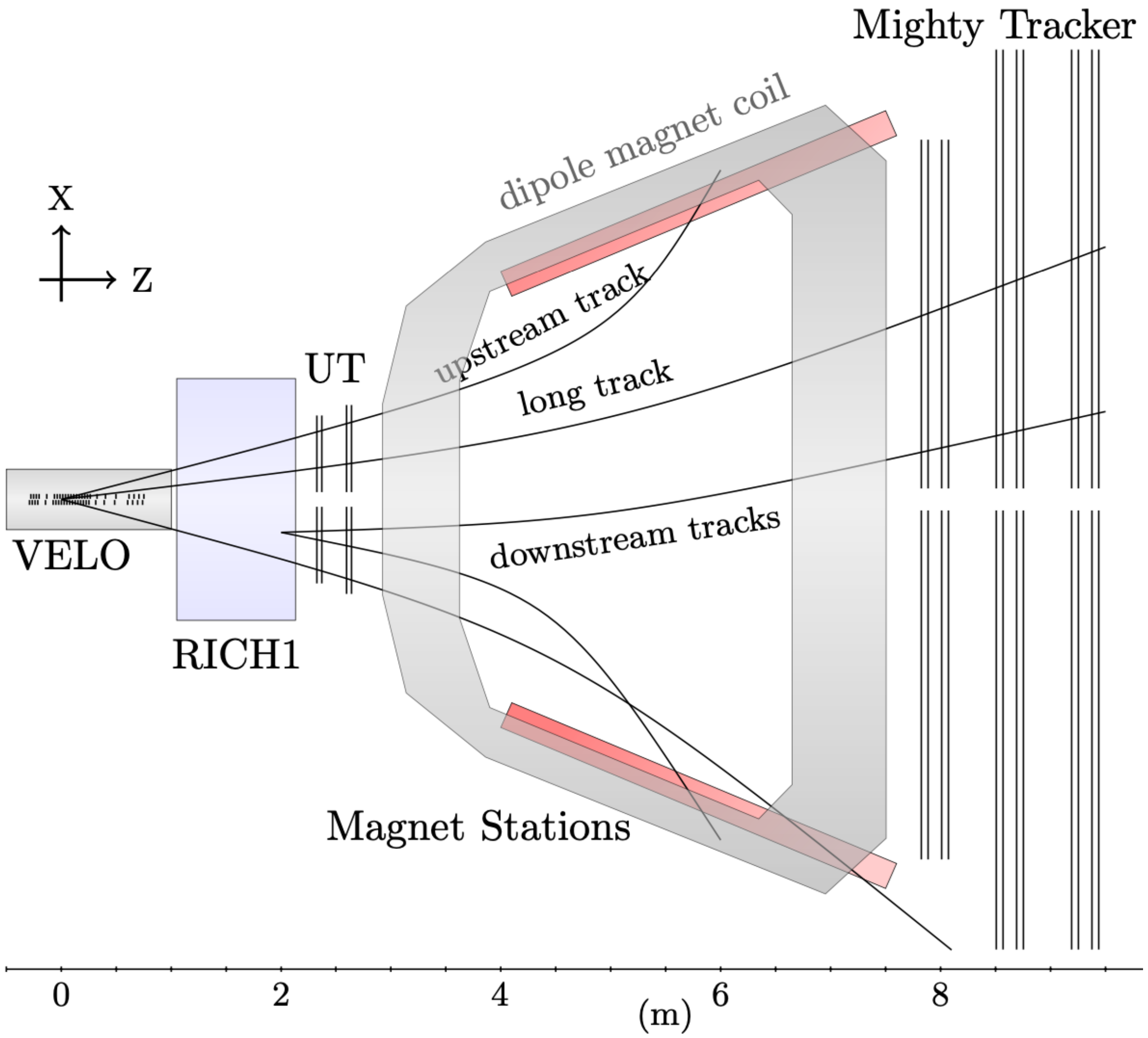
- HV-CMOS = High Voltage Complementary Metal-Oxide-Semiconductor
- Sensors also called HV-MAPS = HV Monolithic Active Pixel Sensors
- Advantages:
  - Very thin ~ 700 µm down to 50 µm
  - Radiation hard
  - Fast charge collection via drift
  - Cheaper than hybrid
  - Fabricated in standard CMOS process



Working principle of HV-CMOS sensors.

Purpose of the Mighty Tracker

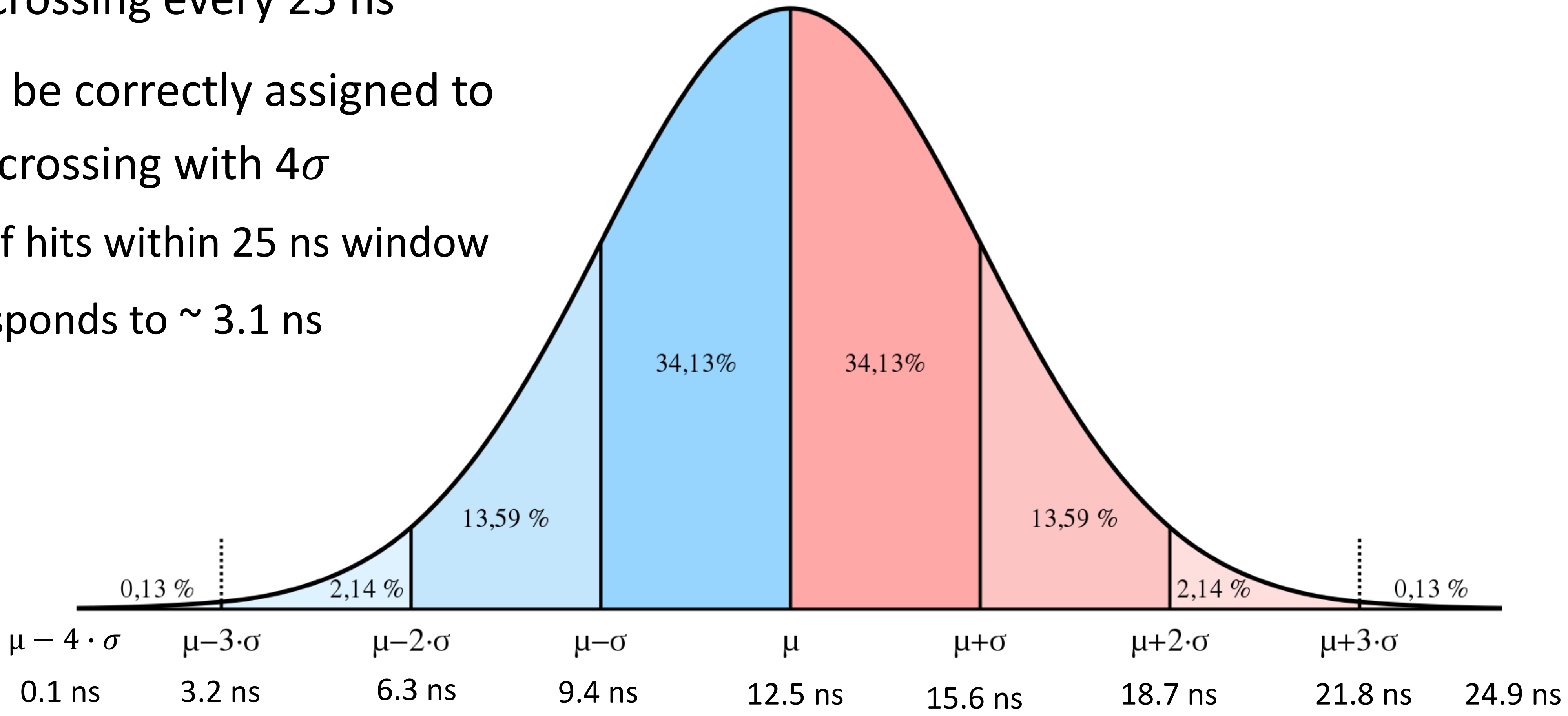
- High precision momentum measurement with VELO
- Measurement of track direction of charged particles for PID systems
- Need high granularity because of high track density
  → HV-CMOS sensors: 50 µm in bending plane, 150 µm in non-bending plane



Track types in LHCb, as seen from above. [1]

Why do we need a time resolution of < 3 ns?

- One bunch crossing every 25 ns
- Hits need to be correctly assigned to right bunch crossing with 4σ
  - 99.99% of hits within 25 ns window
  - 1σ corresponds to ~ 3.1 ns



Normal distribution. [3]

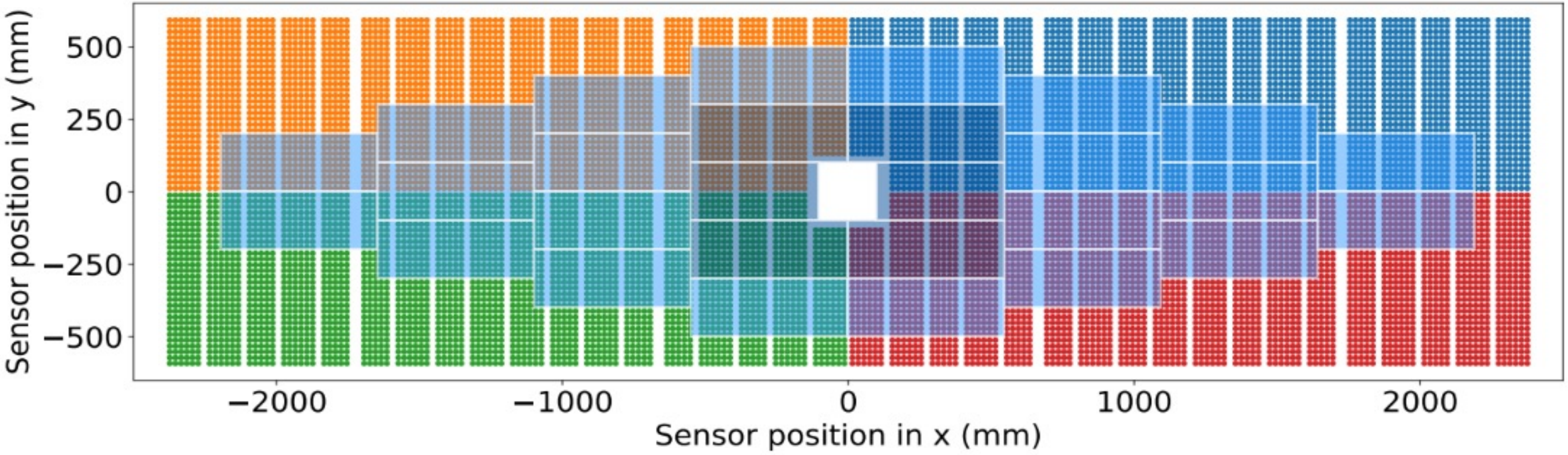
TFC Signals

- LHCb sends Timing and Fast Control (TFC) signals to all FE modules

- **BXReset:** Reset internal BX counter to synchronise chips to same BX
- **Snapshot:** Capture number of received TFC commands *(partially implemented)*
- **FEReset:** Reset all modules except TFC receiver, BX counter, chip configuration registers
- **Cal:** Could be used to control an on-chip injection circuit *(not yet implemented)*
- **Sync:** Chip outputs sync pattern, configurable via configuration register

Mighty Tracker Simulation Data

- Data simulated for *Occupancy studies for the LHCb Run4 Mighty Tracker* [2]
- More than 70 000 sensors over four quadrants and six tracker layers
- 500 events in total → limited statistics

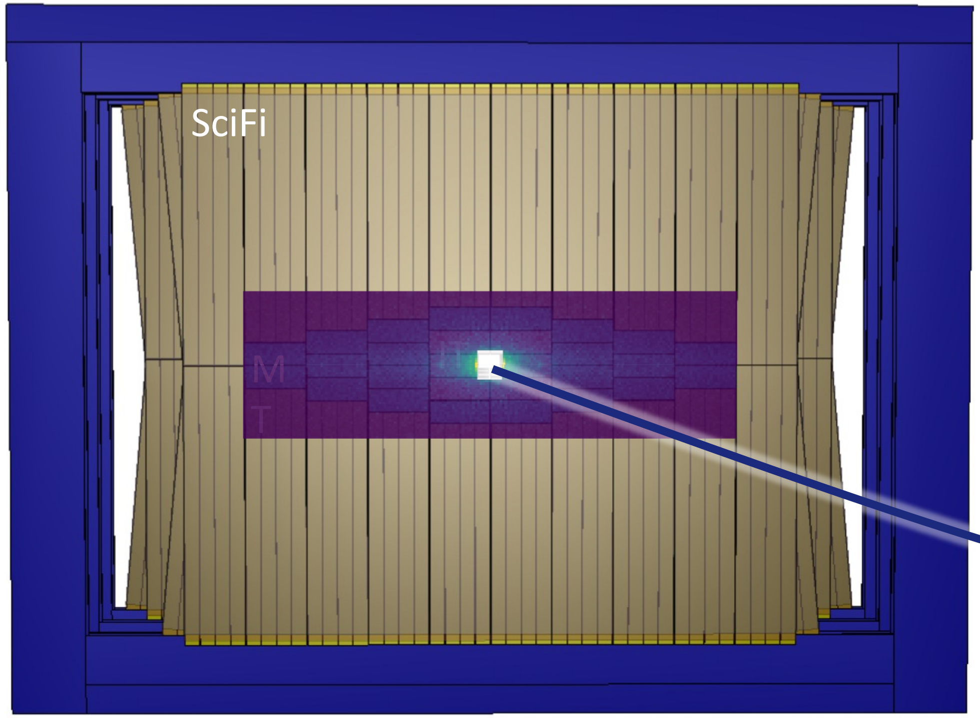


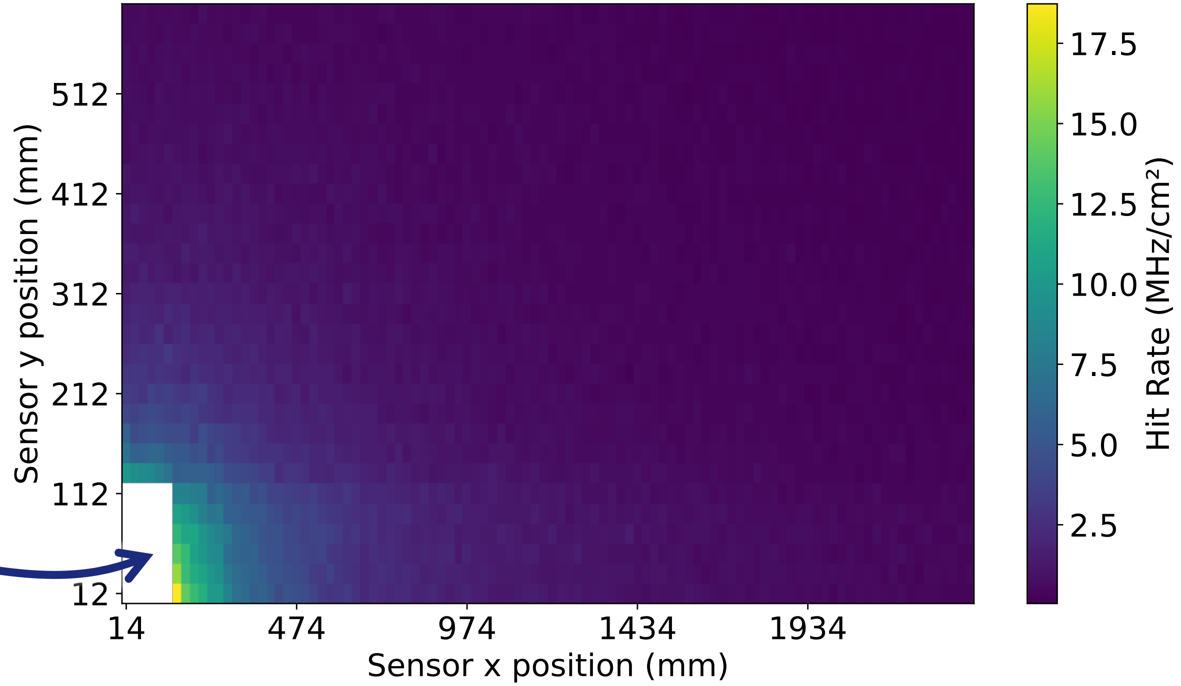
MightyPix1: Efficiency Simulations

Work in progress, not final results!

What's the efficiency of MightyPix over the whole Tracker area?

First estimate of hit rate across tracker from simulations by Hume, Bellee, Steinkamp [2]



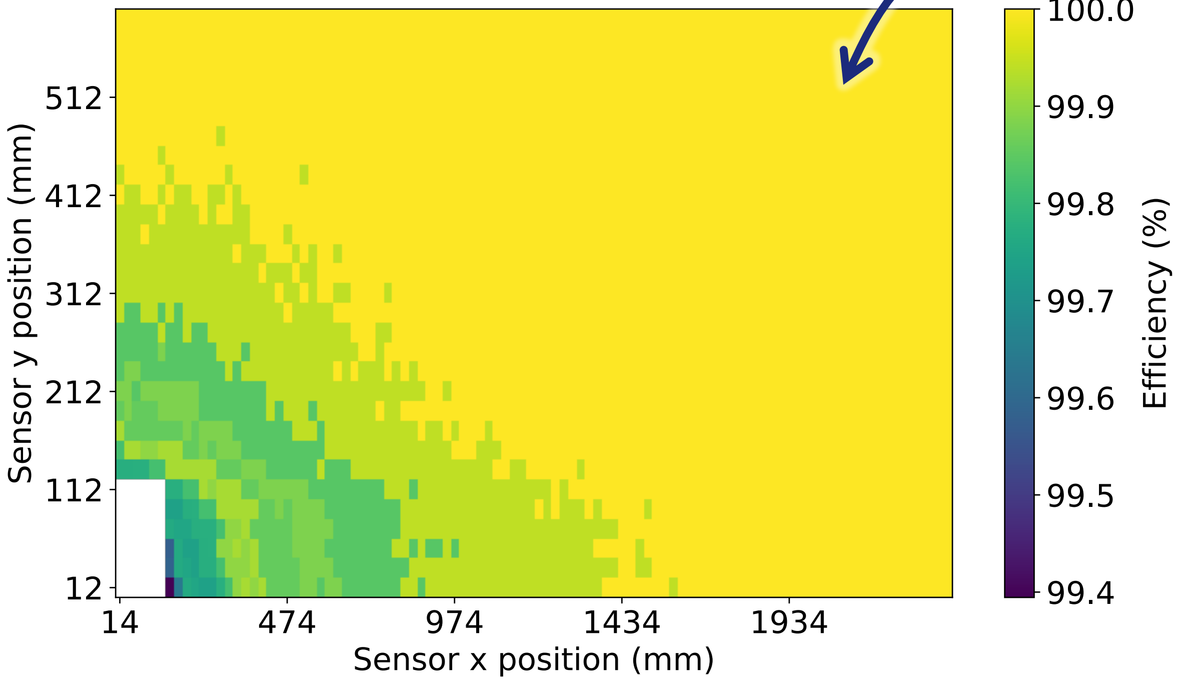


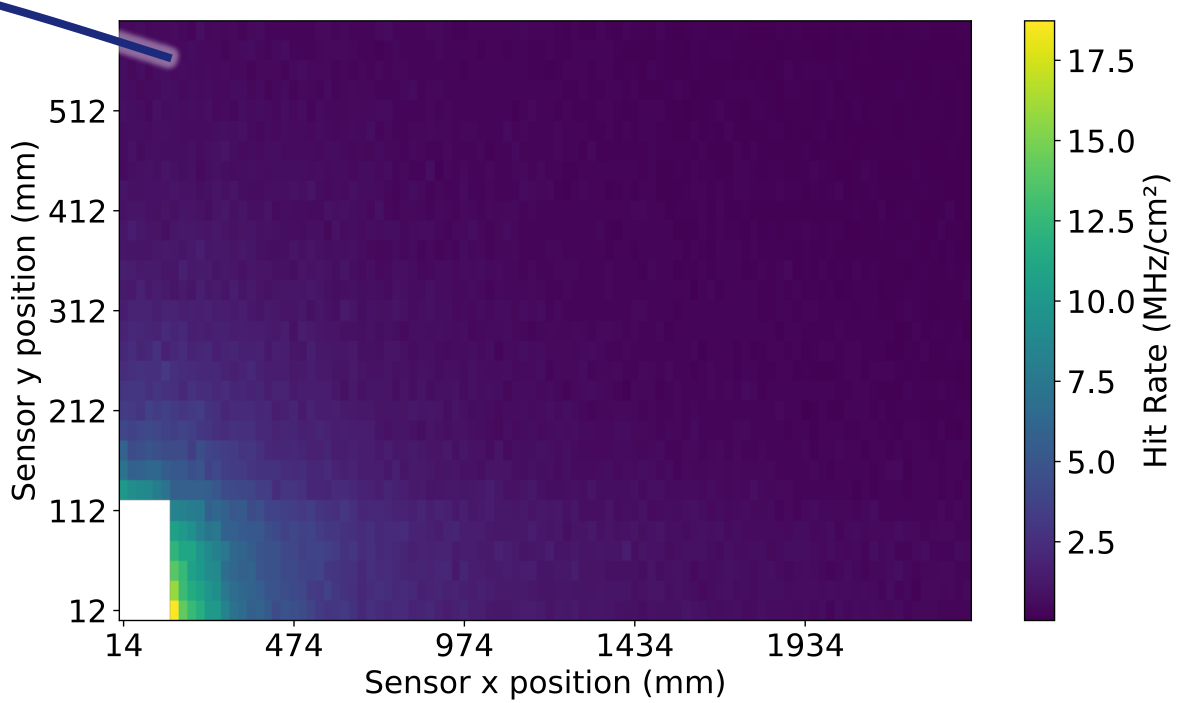
MightyPix1: Efficiency Simulations

Work in progress, not final results!

Combine simulated efficiencies and hit rate map

→ Efficiency of MightyPix1 over whole Mighty Tracker area





Efficiency Simulations with Mighty Tracker Simulation Data

- Data from *Occupancy studies for the LHCb Run4 Mighty Tracker* [2]
- Only for hottest MightyPix1 sensor
- 500 events in total → limited statistics
- Expect 5% of clusters where two pixels are hit

Clusters	No	Yes
Total Hits	1183	1240
Missing Hits	9	10
Efficiency	99.24%	99.19%

ToT	2 µs	5 µs
Total Hits	1183	1183
Missing Hits	9	14
Efficiency	99.24%	98.82%