High-Voltage Monolithic Active Pixel Sensors for the Mu3e Experiment

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Emmy Noether-Programm

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DFG

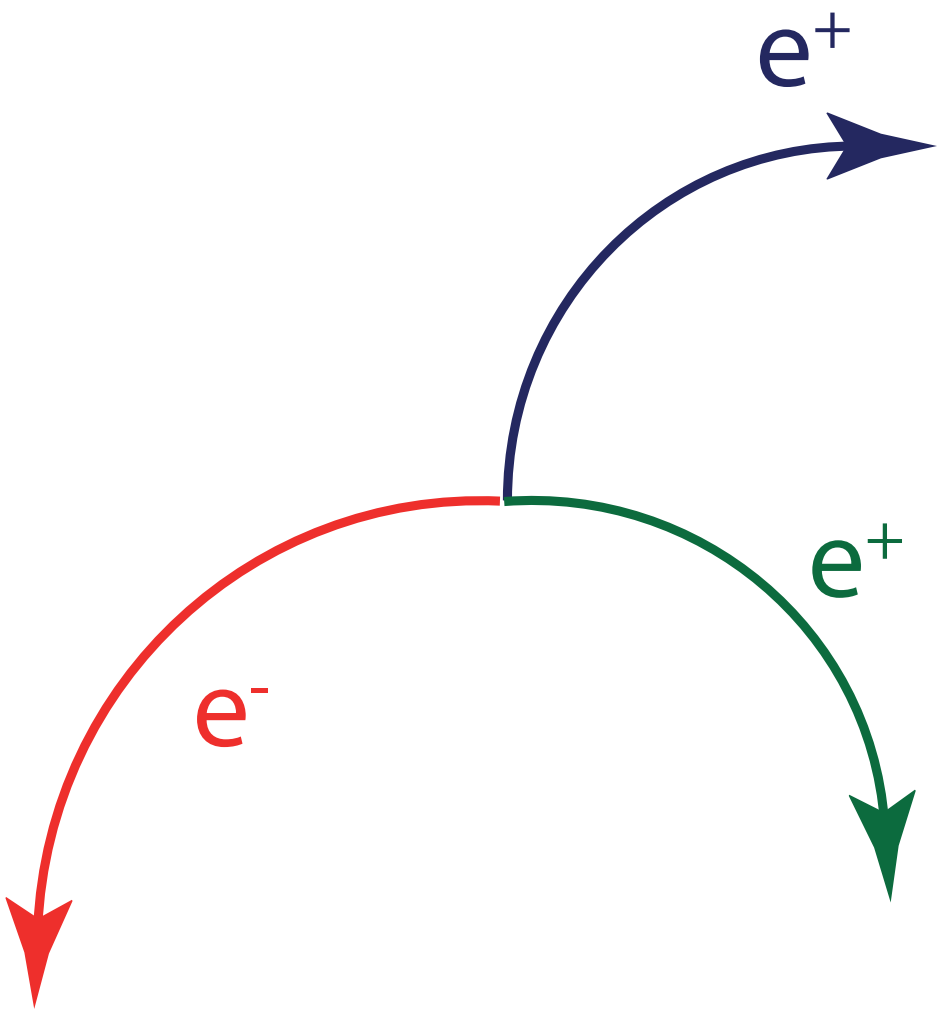
Overview

- The Mu3e Experiment
- High-Voltage Monolithic Active Pixel Sensors (HV-MAPS)
- The MuPix Sensors
- The Mu3e Data Acquisition

The Mu3e Experiment:

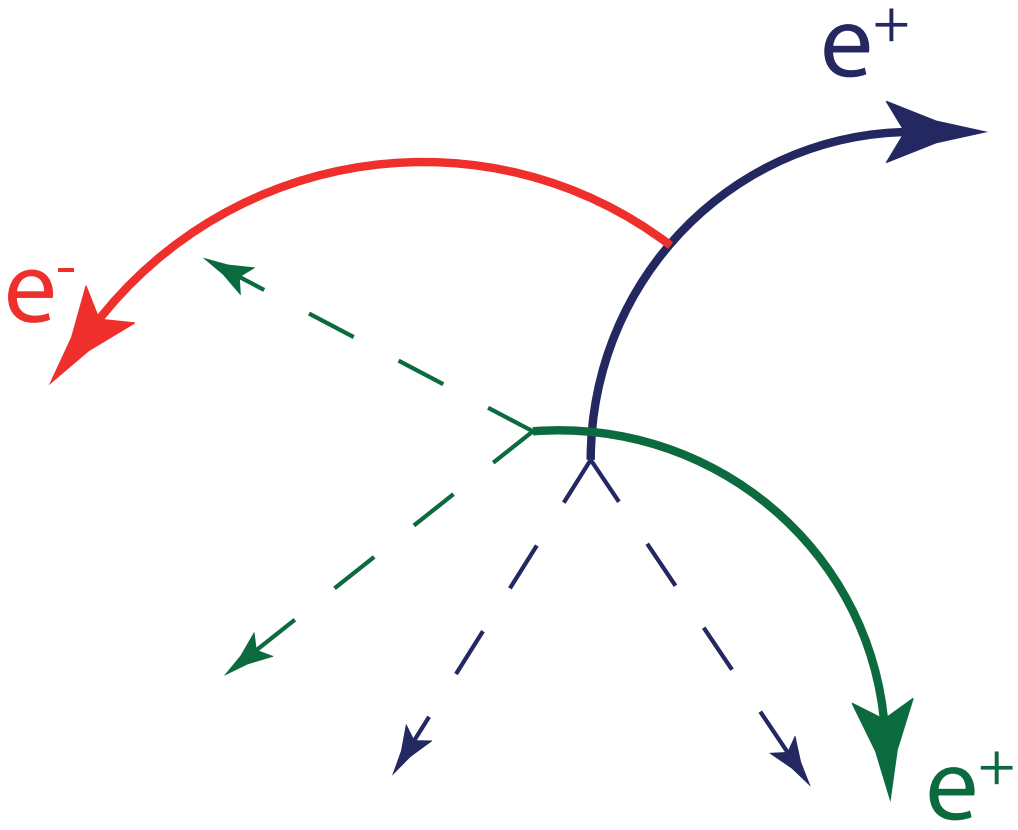
Searching for $\mu^+ \rightarrow e^+e^-e^+$
with a sensitivity of 10^{-16}
($2 \cdot 10^{-15}$ in phase I)

The signal



- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: ½ m_μ = 53 MeV/c

Accidental Background



- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

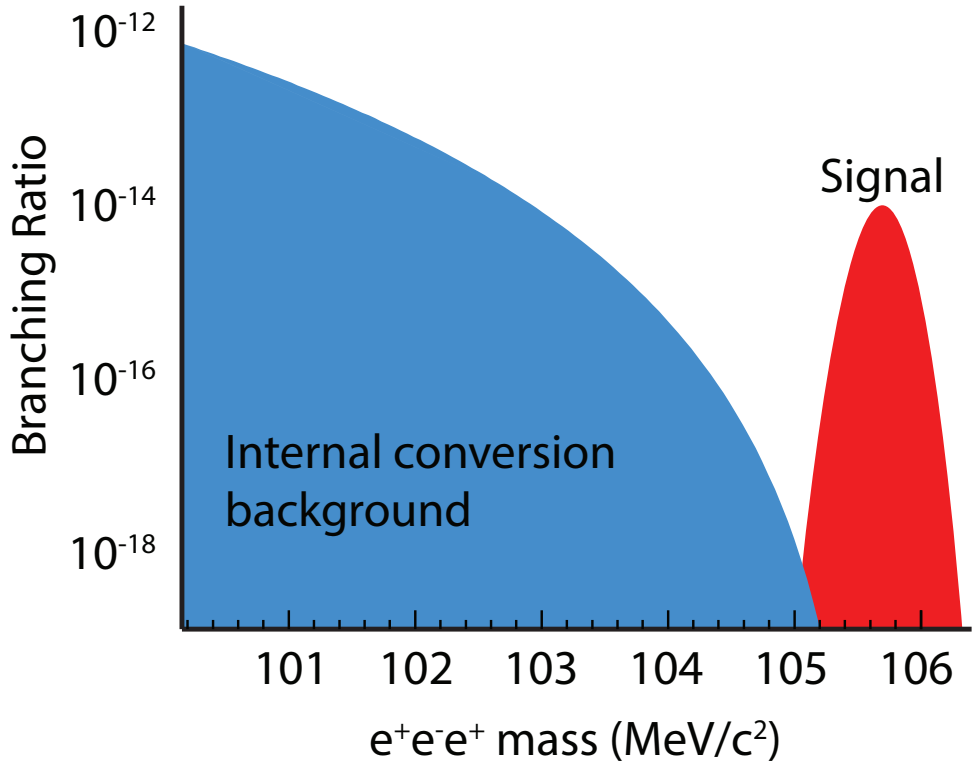
- Need very good timing, vertex and momentum resolution

Internal conversion background

- Allowed radiative decay with internal conversion:

$$\mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos



- Need excellent momentum resolution

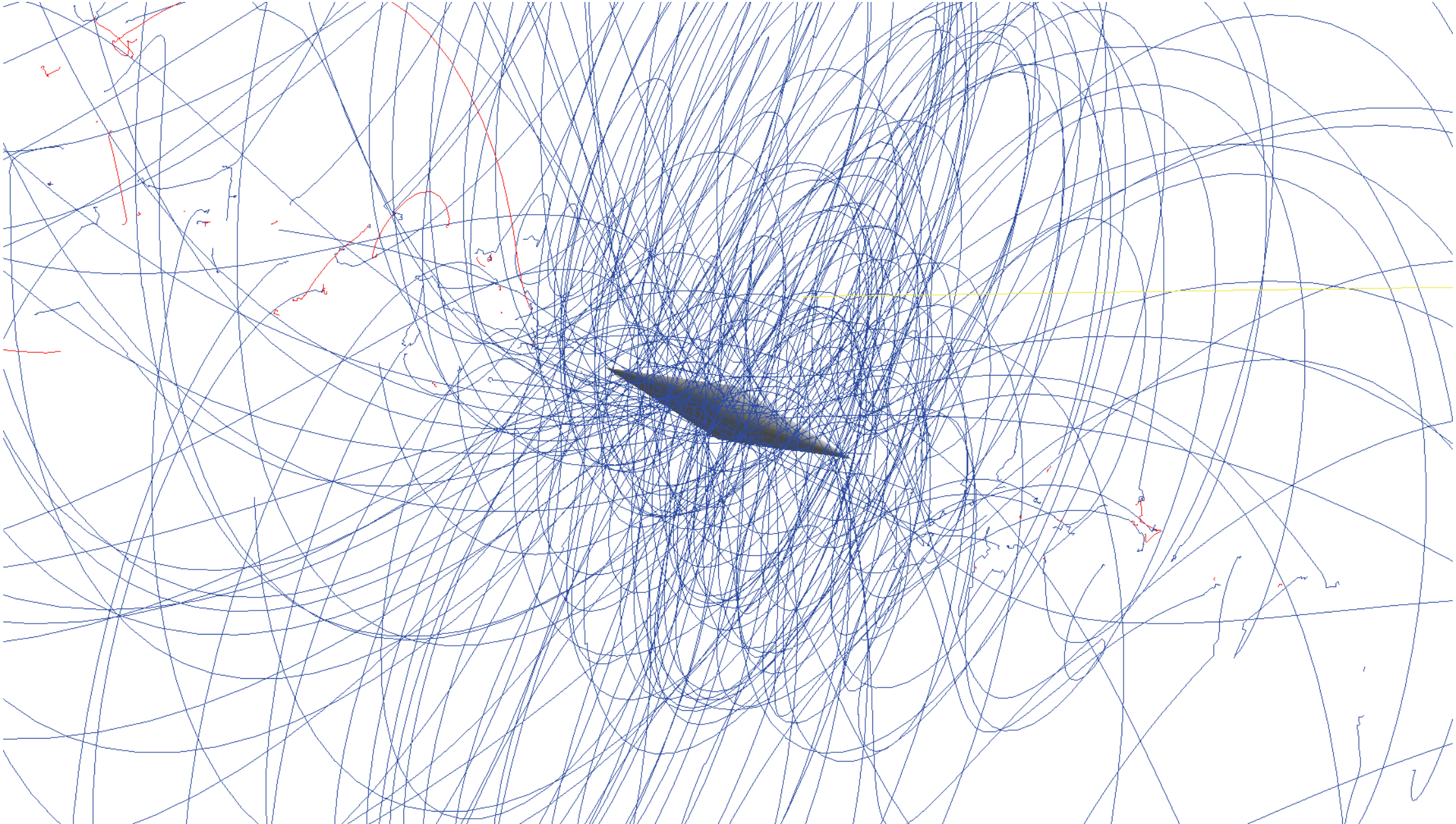
- New: NLO available from Matteo Fael and Signer et al. - now 10-20% easier

Building the
Mu3e Experiment

aiming for a branching ratio sensitivity of 10^{-16}

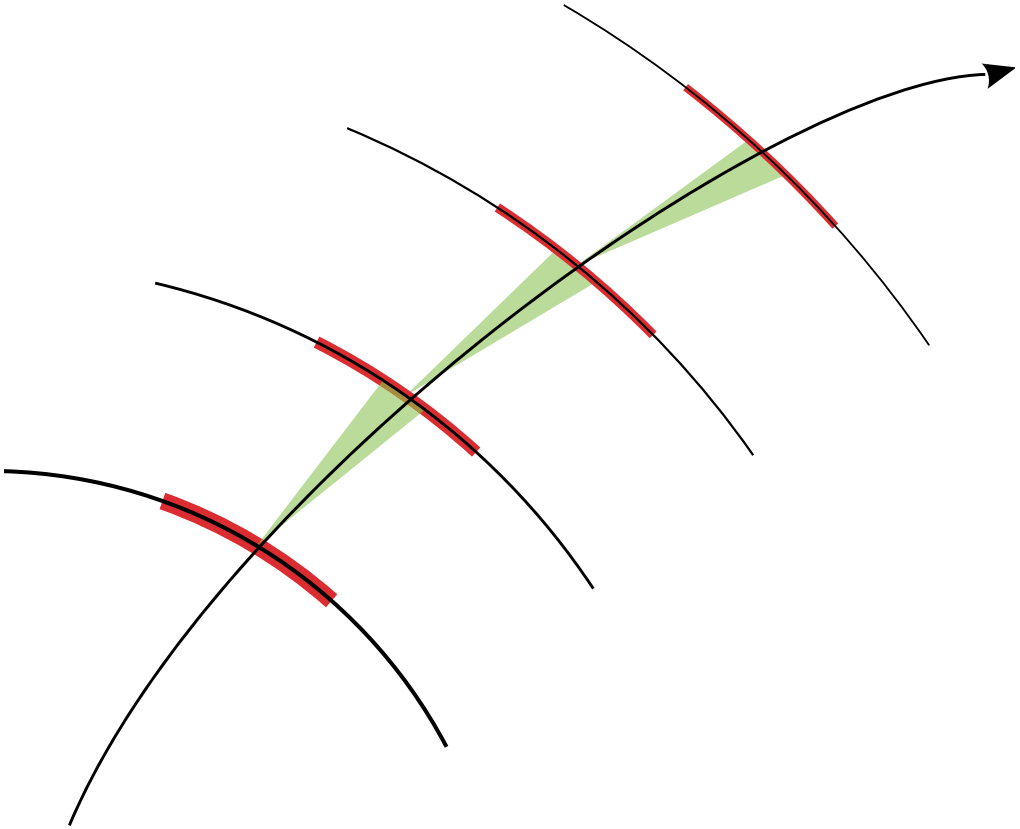
2 Billion Muon Decays/s

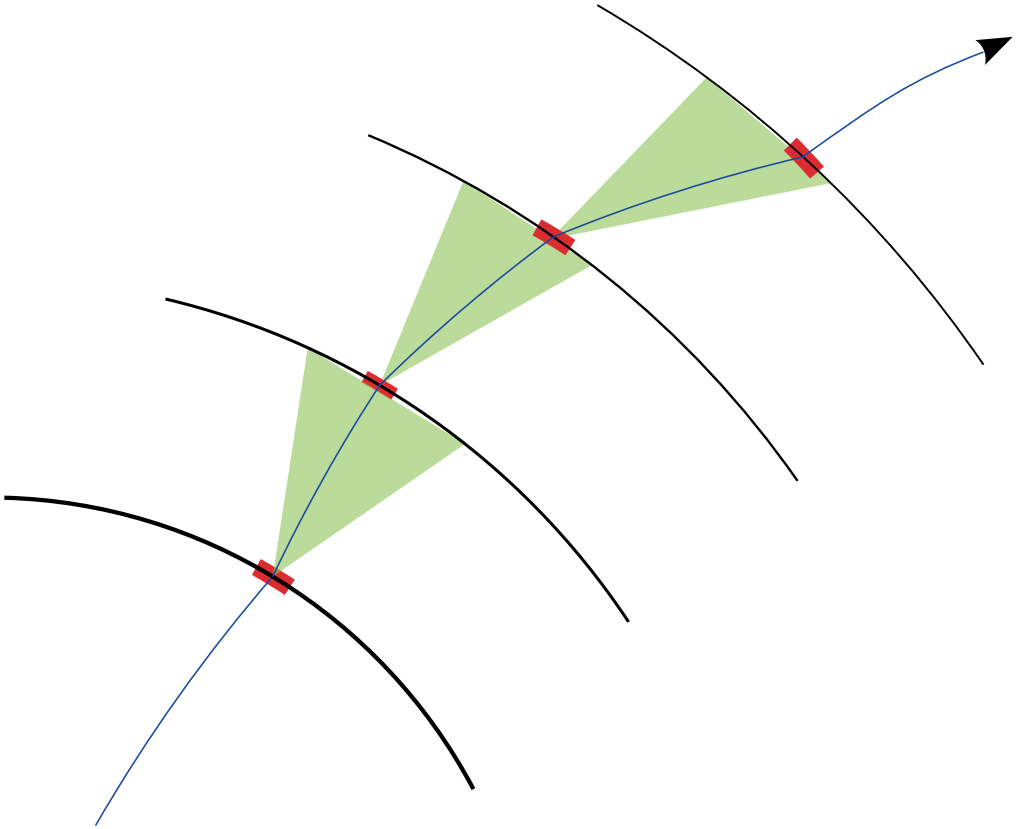
50 ns, 1 Tesla field



Momentum measurement

- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

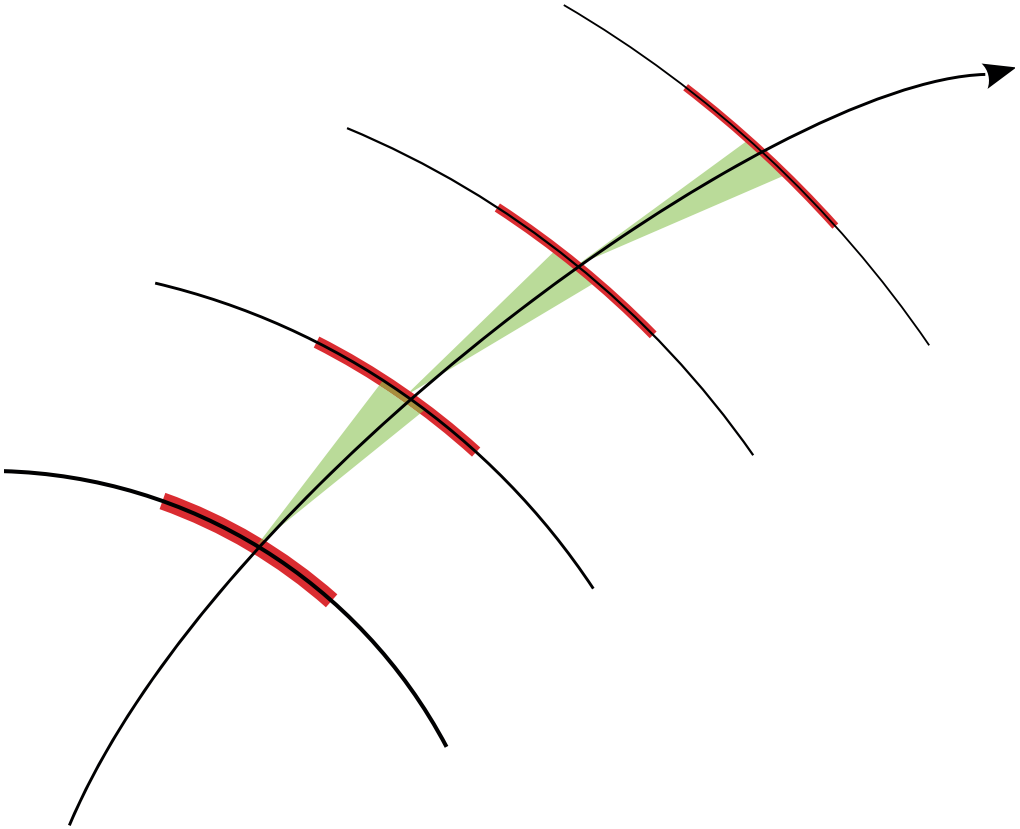


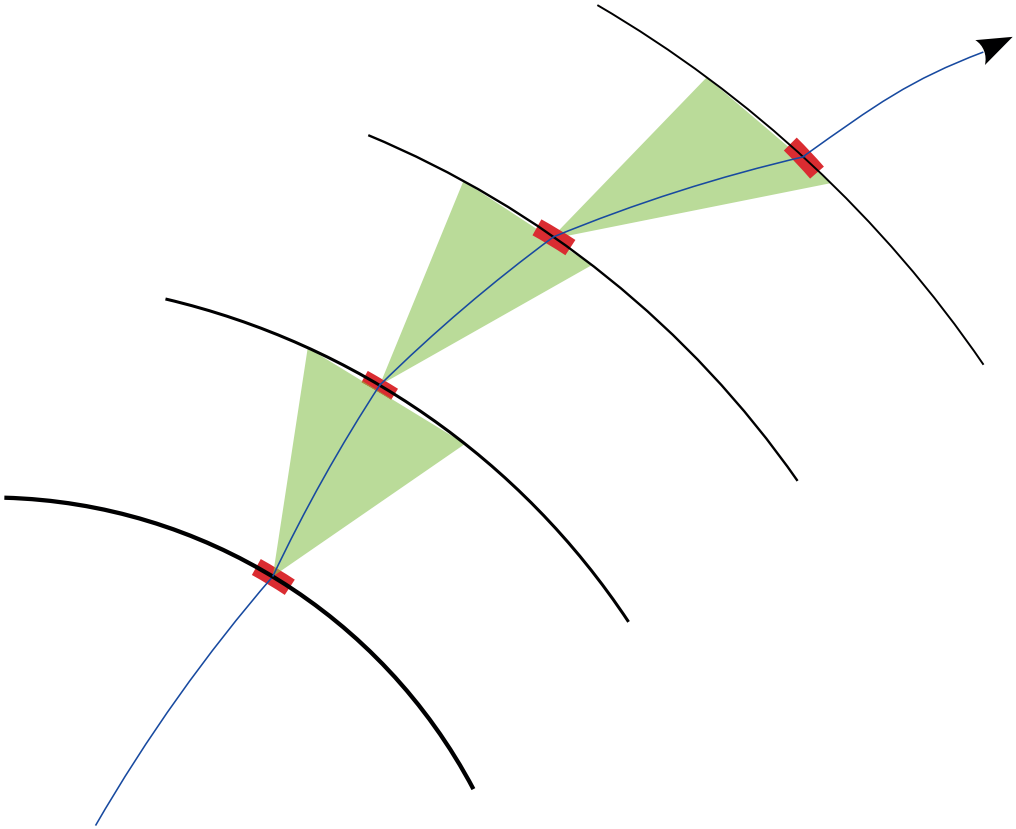


Momentum measurement

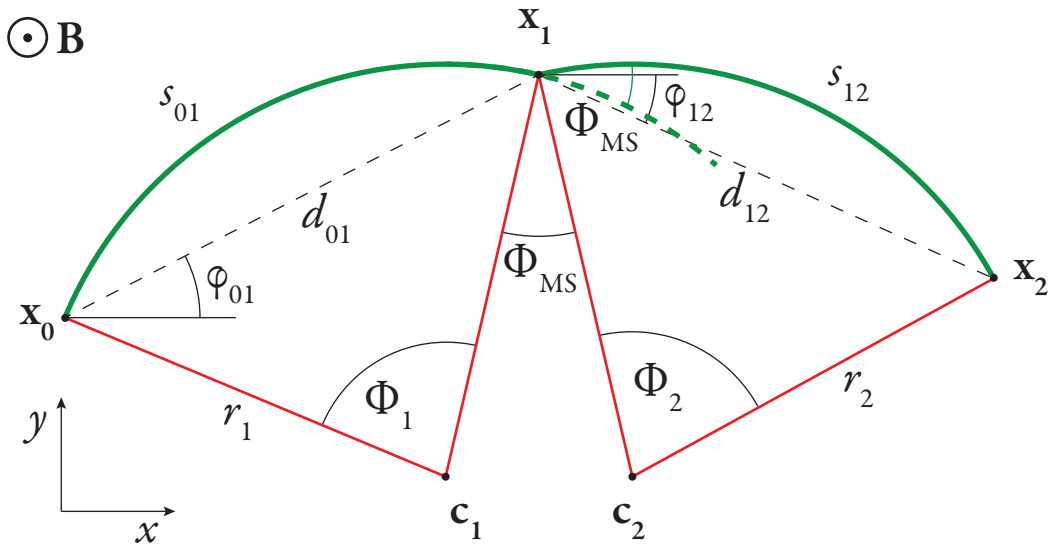
- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

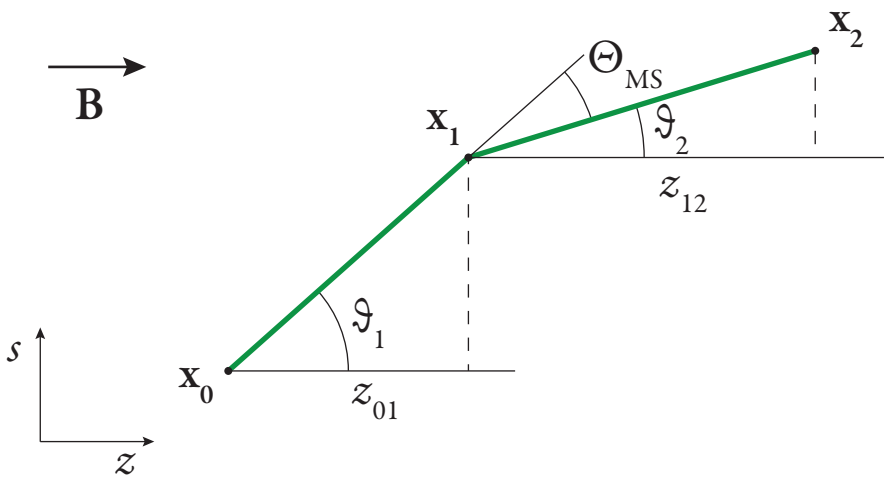
- At ~ 30 MeV/c momentum: Scattering completely dominates
- Large pixels: 80 μm
- Very little material: 0.1% X_0 per layer





Multiple Scattering Track Fit



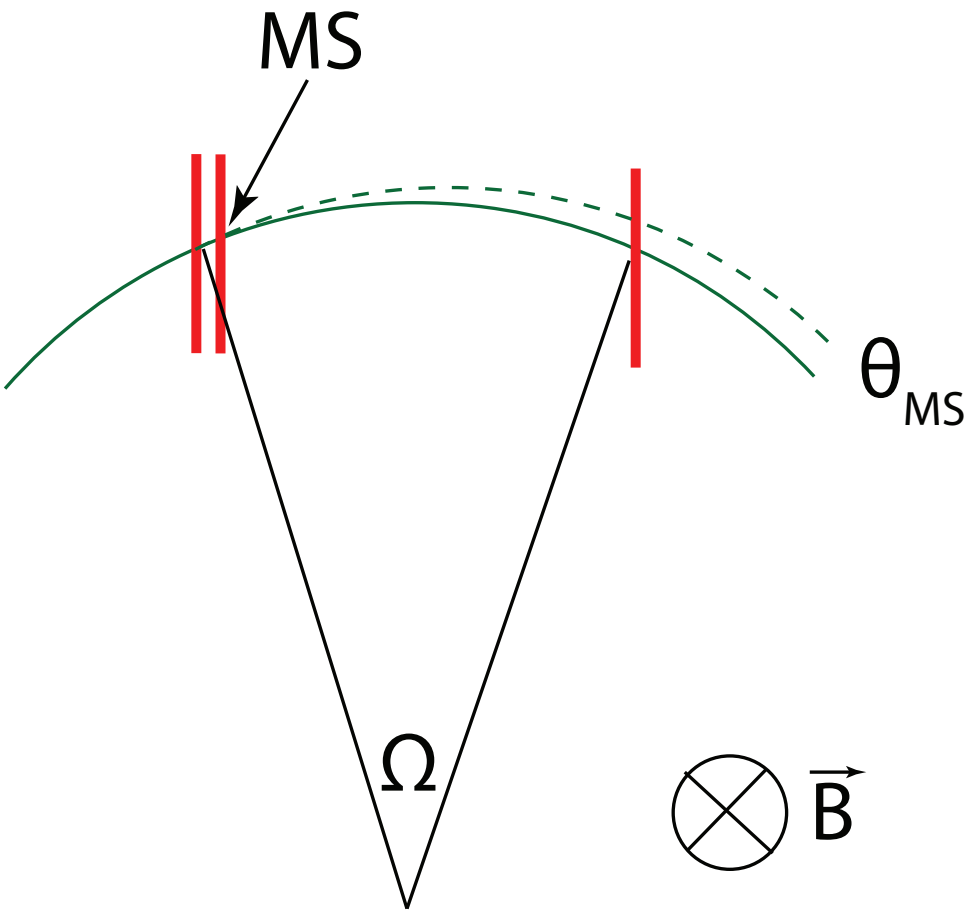


- Treat hit measurements as arbitrarily precise
- Consider scattering in each detector plane
- Two hits, two helices: Underconstrained problem

- Minimize scattering angles
- Use multiple scattering theory to define χ^2

Nucl. Instrum. Meth. A 844C, 135 (2017)

Momentum measurement

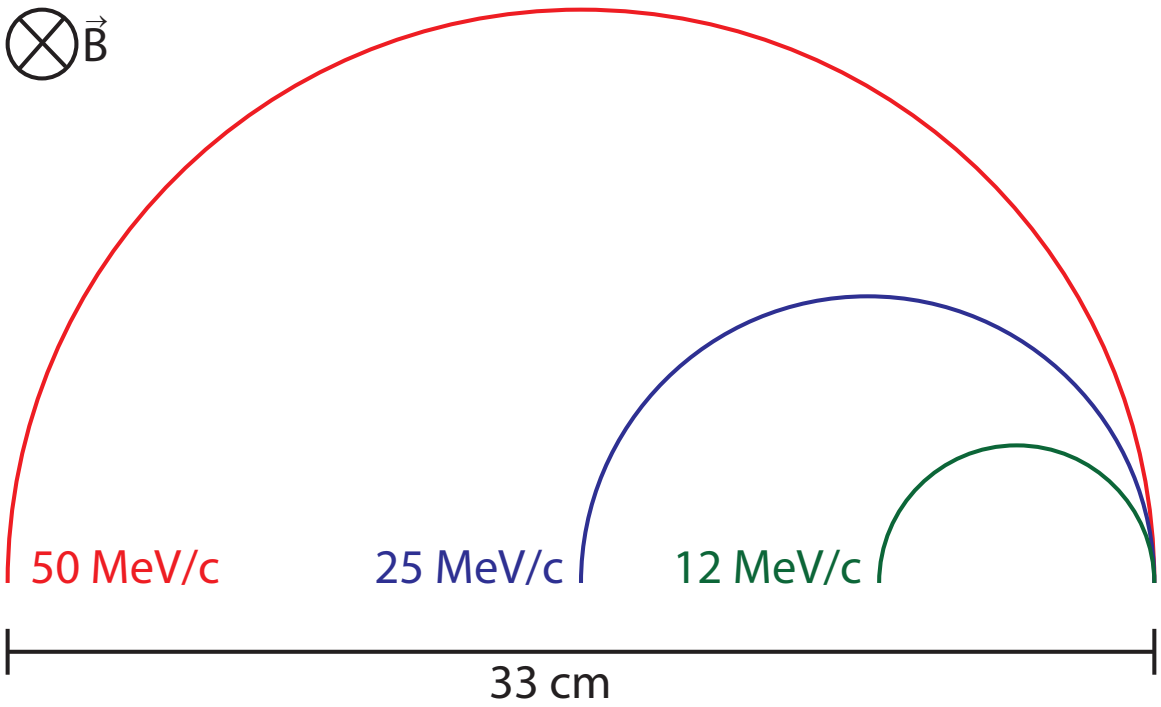


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

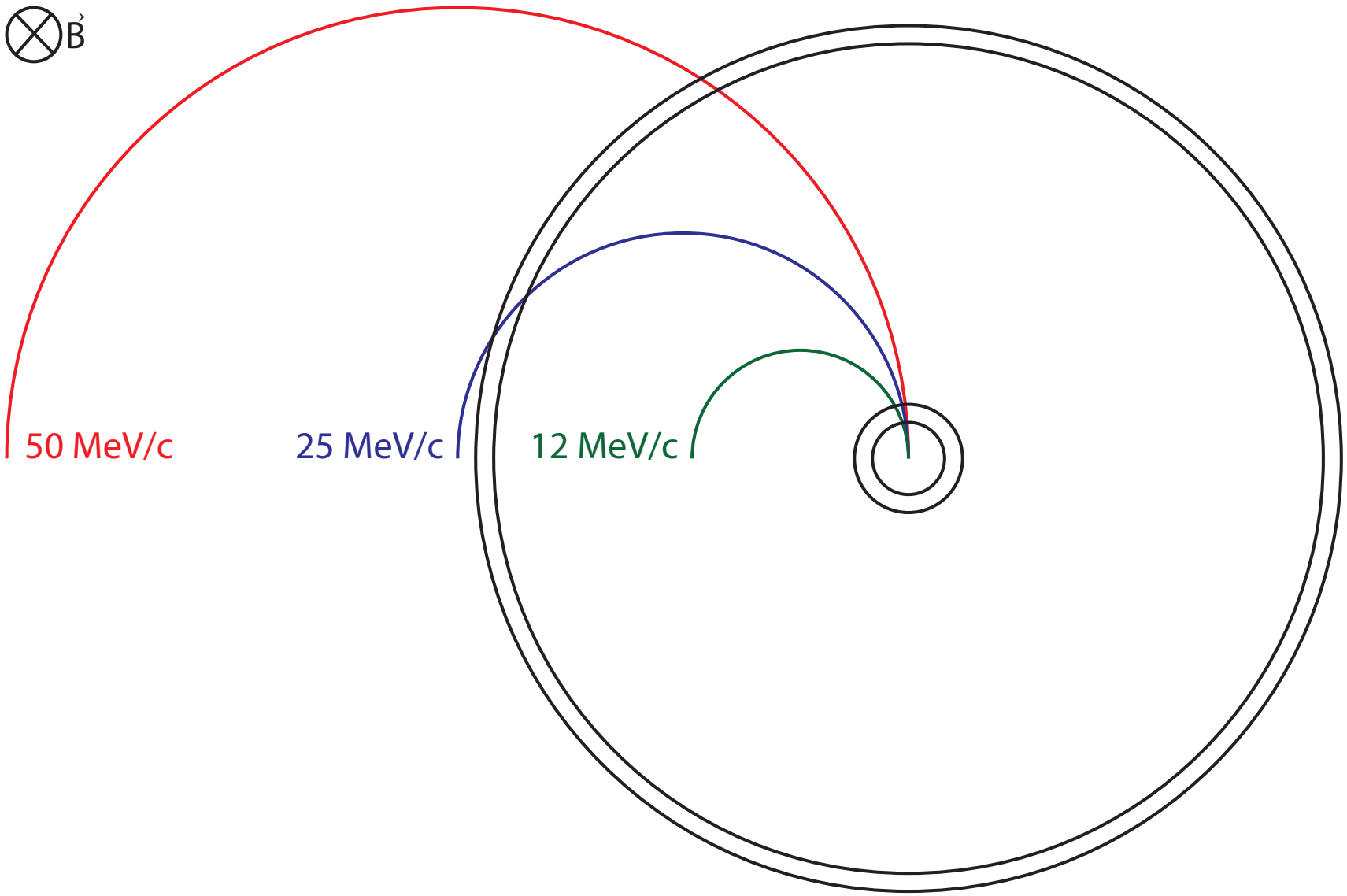
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

- Precision requires large lever arm (large bending angle Ω) and low multiple scattering θ_{MS}

Precision vs. Acceptance



Precision vs. Acceptance



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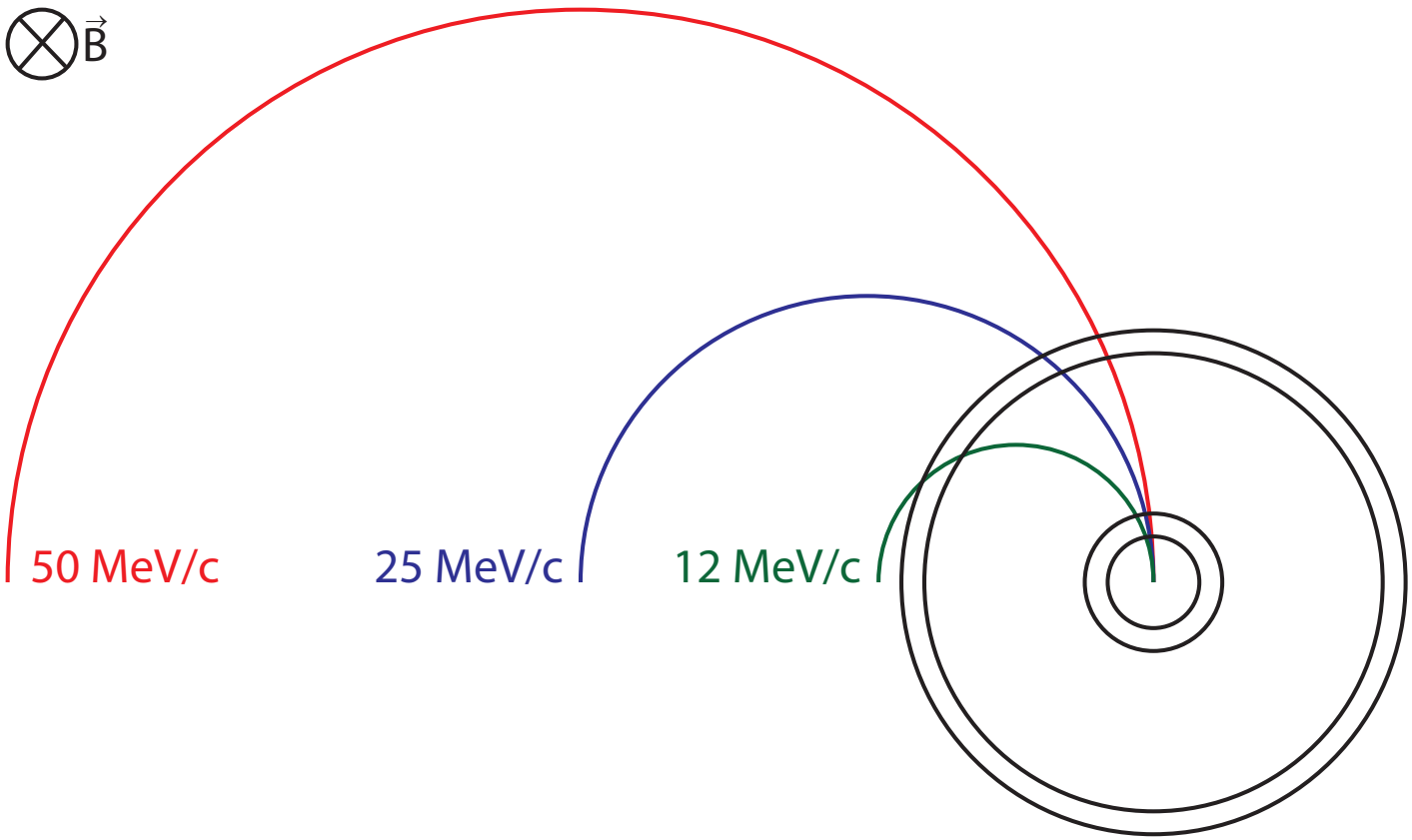

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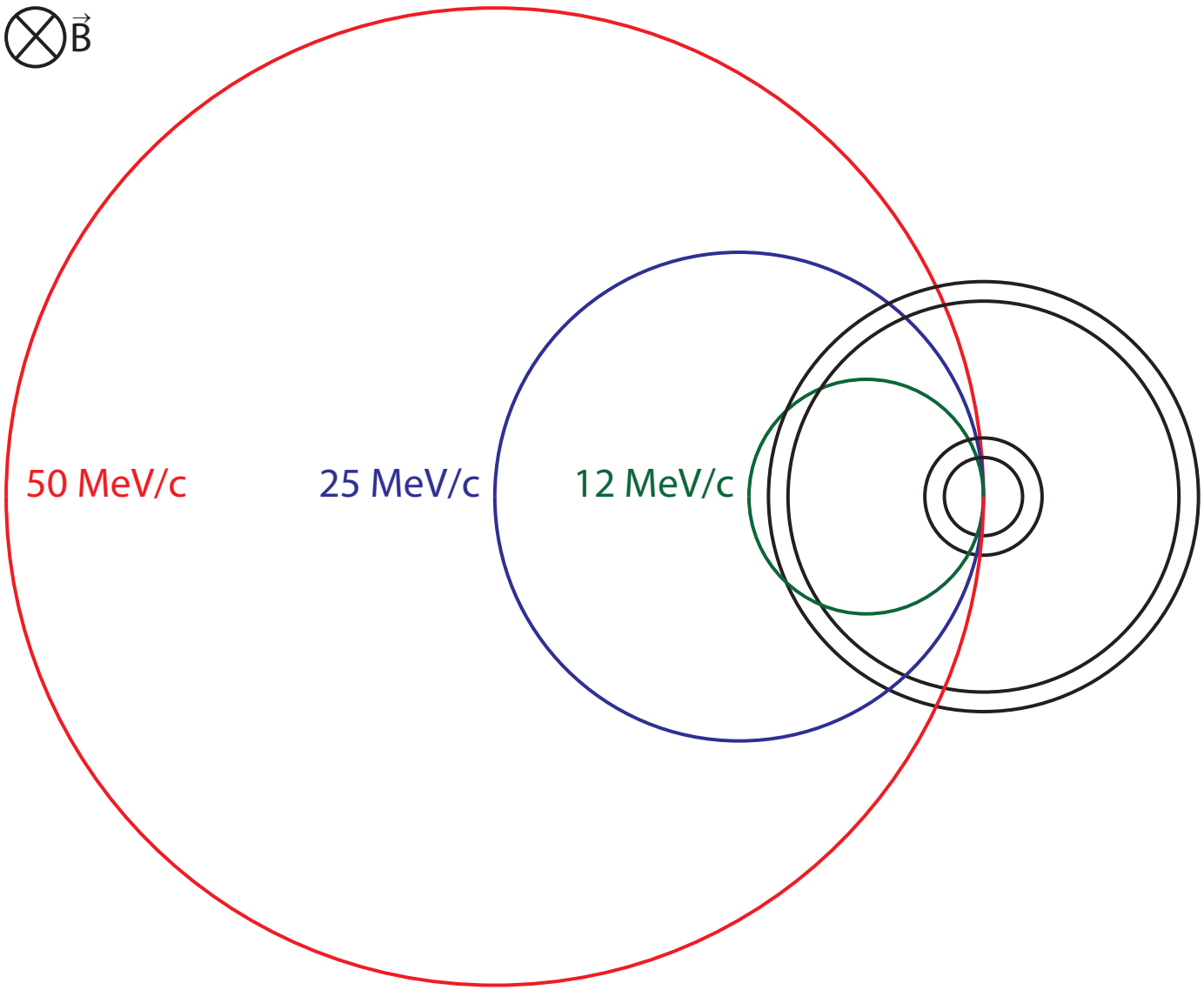

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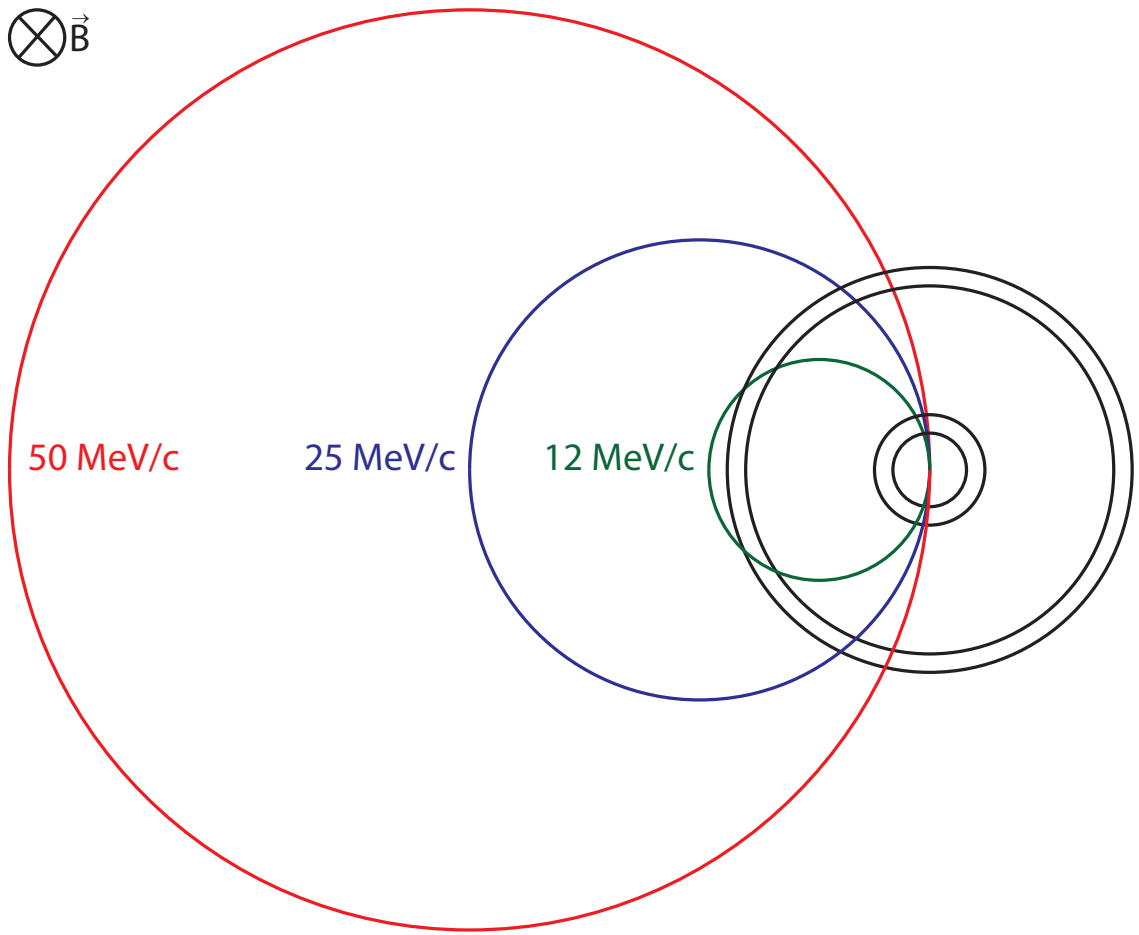
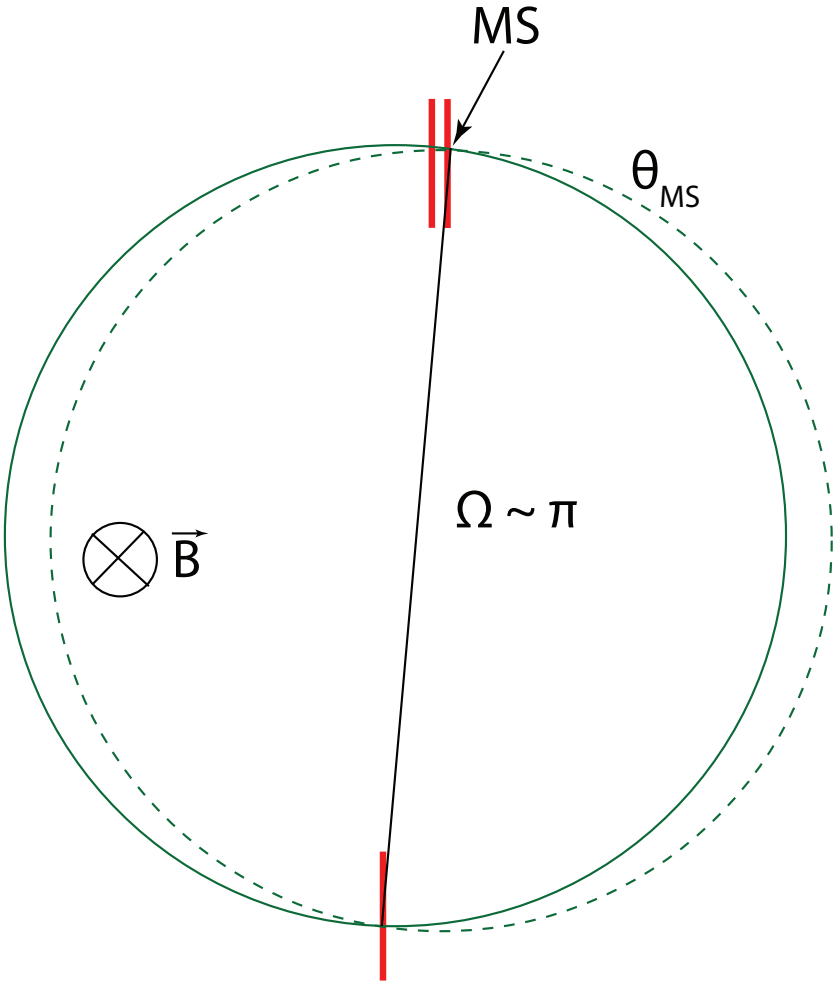
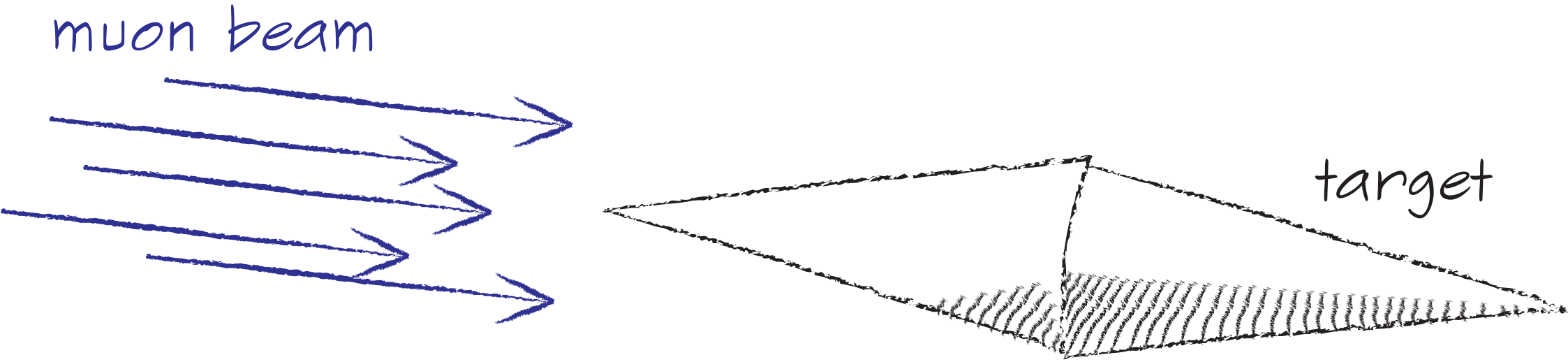
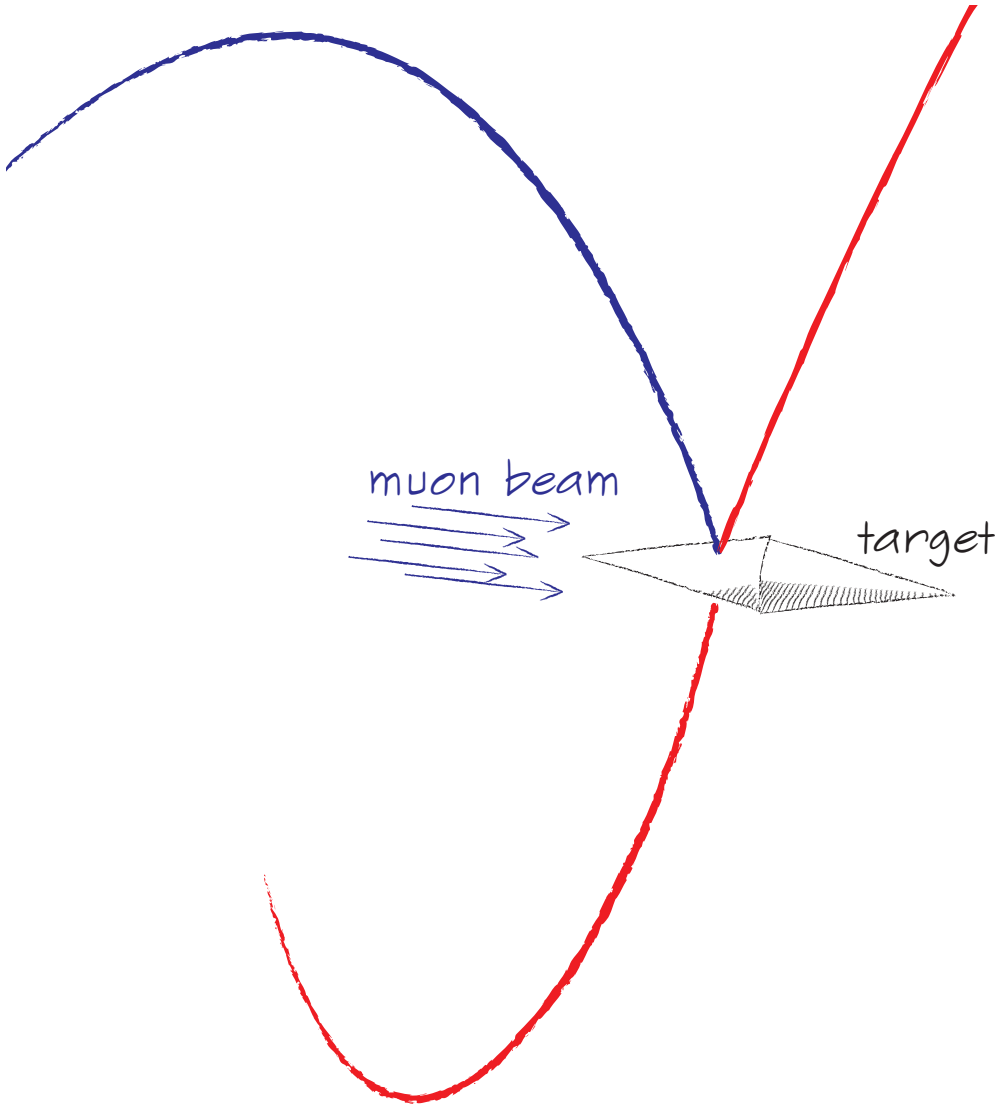




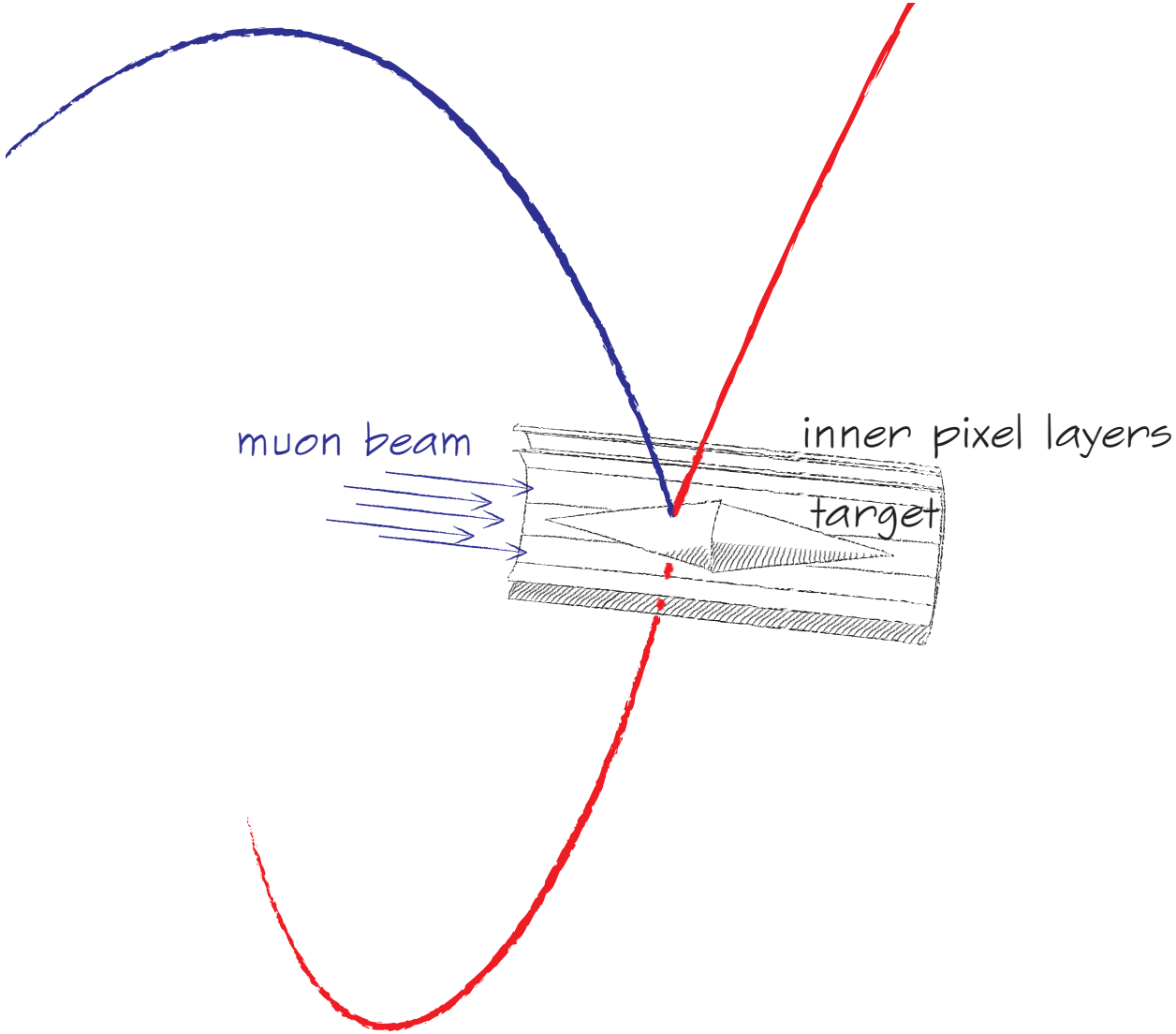
Detector Design



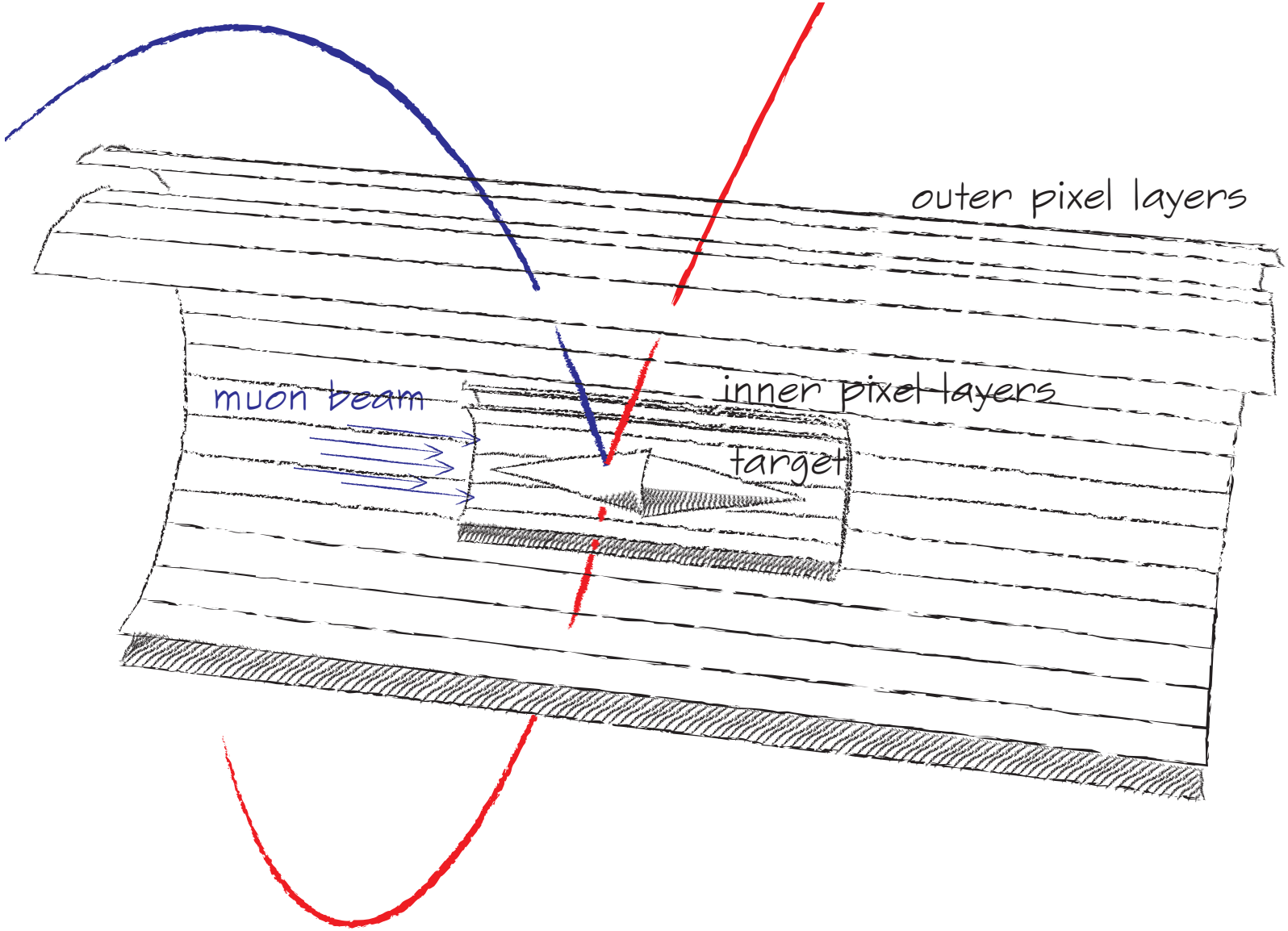
Detector Design



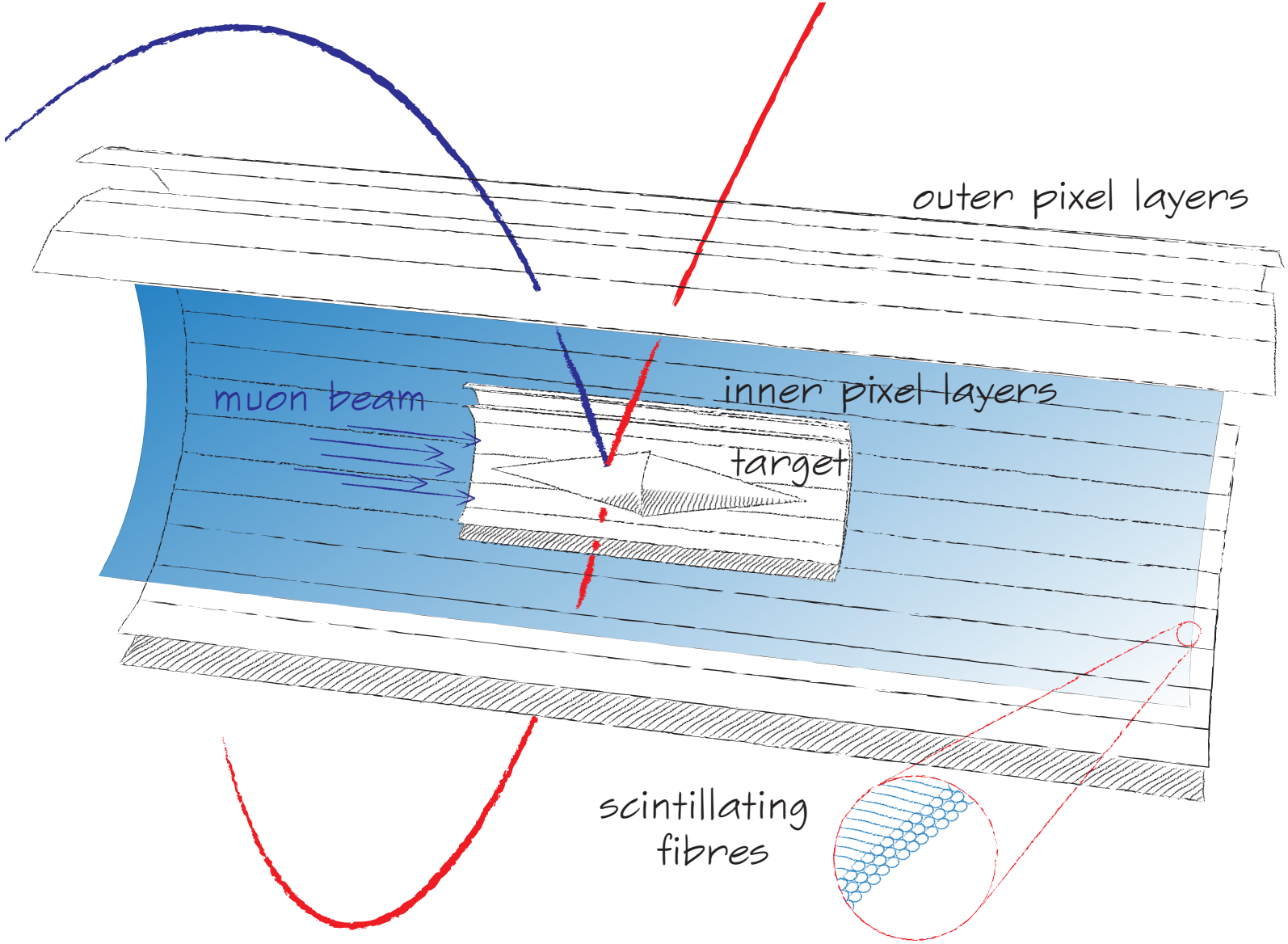
Detector Design



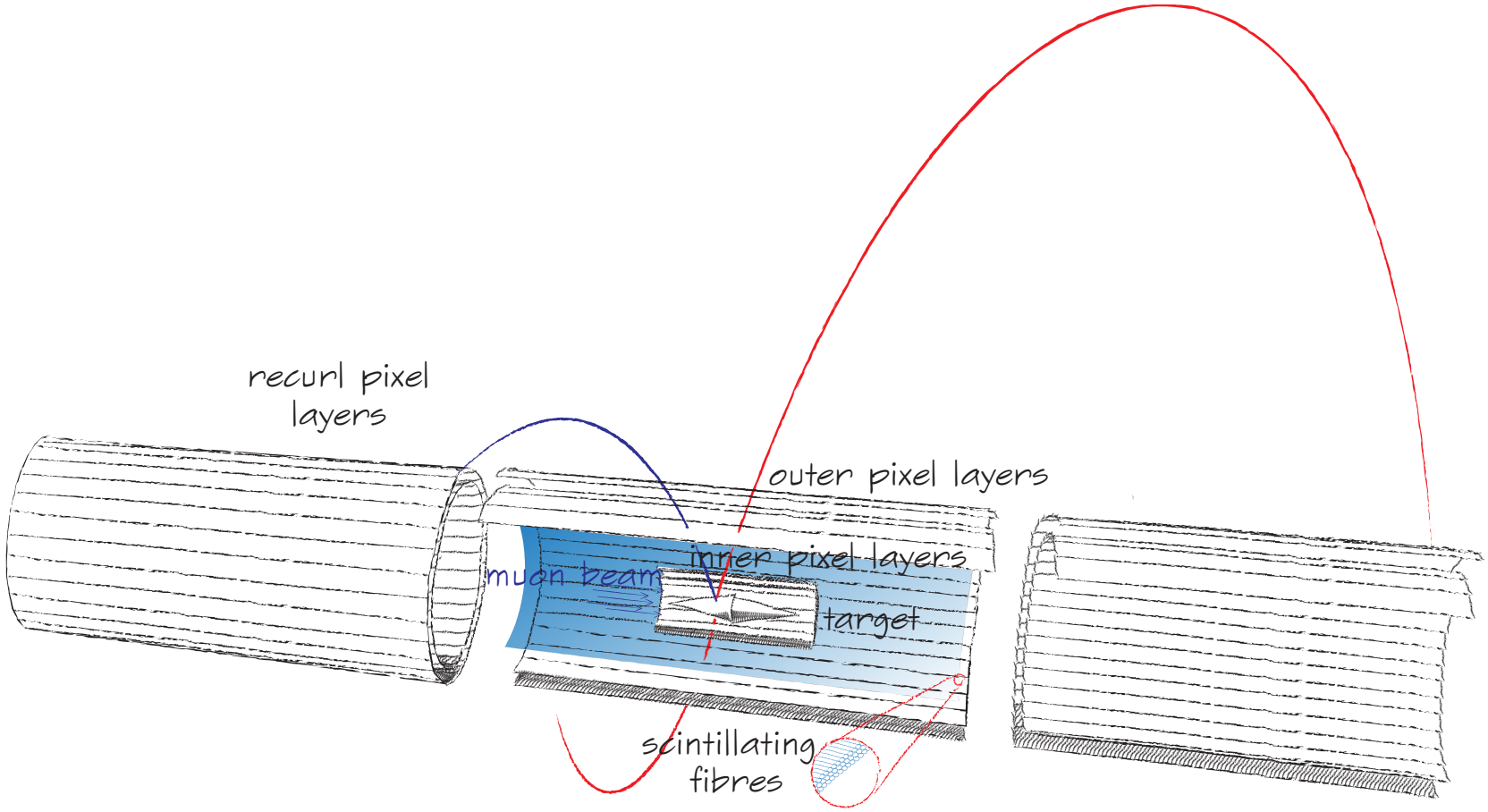
Detector Design



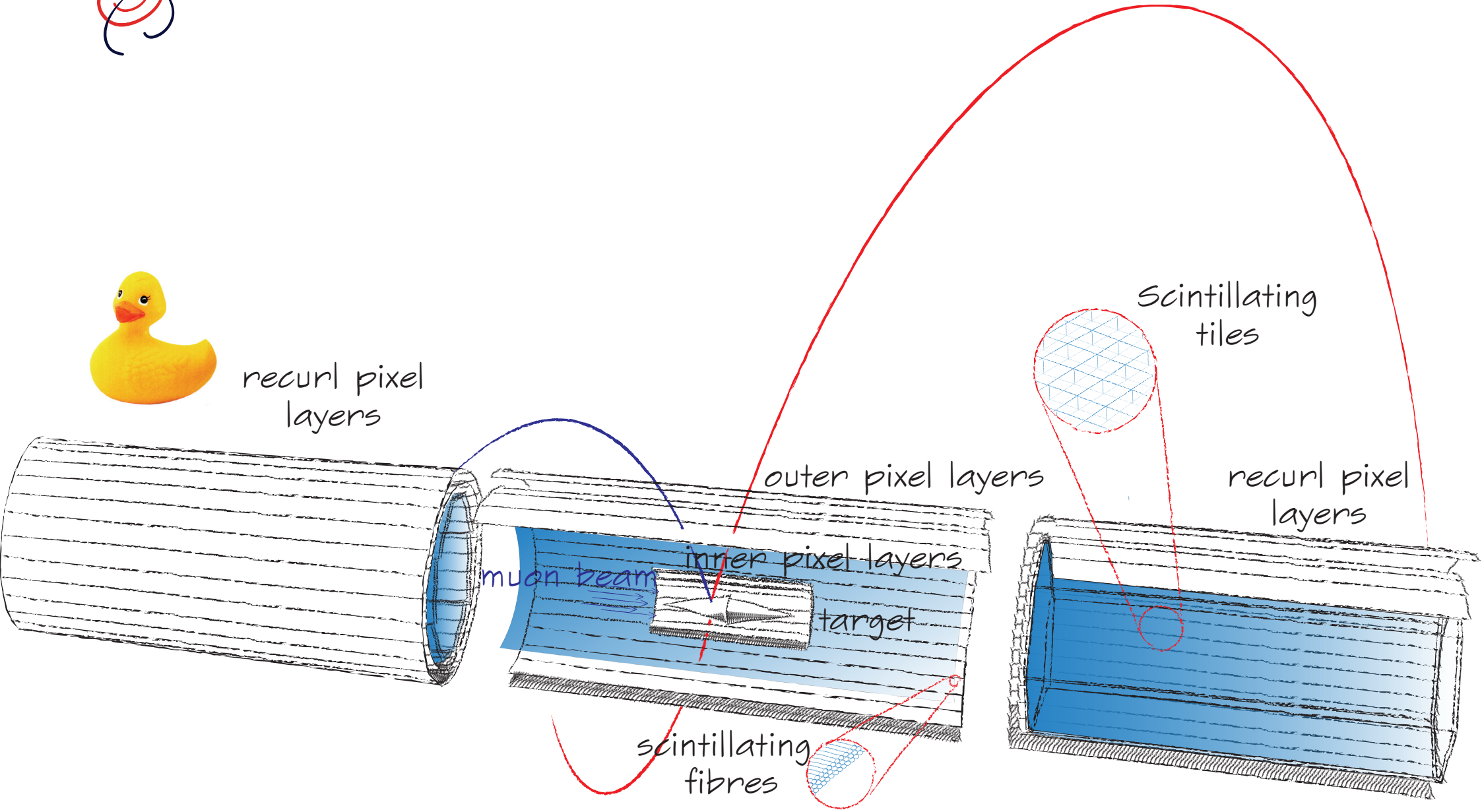
Detector Design



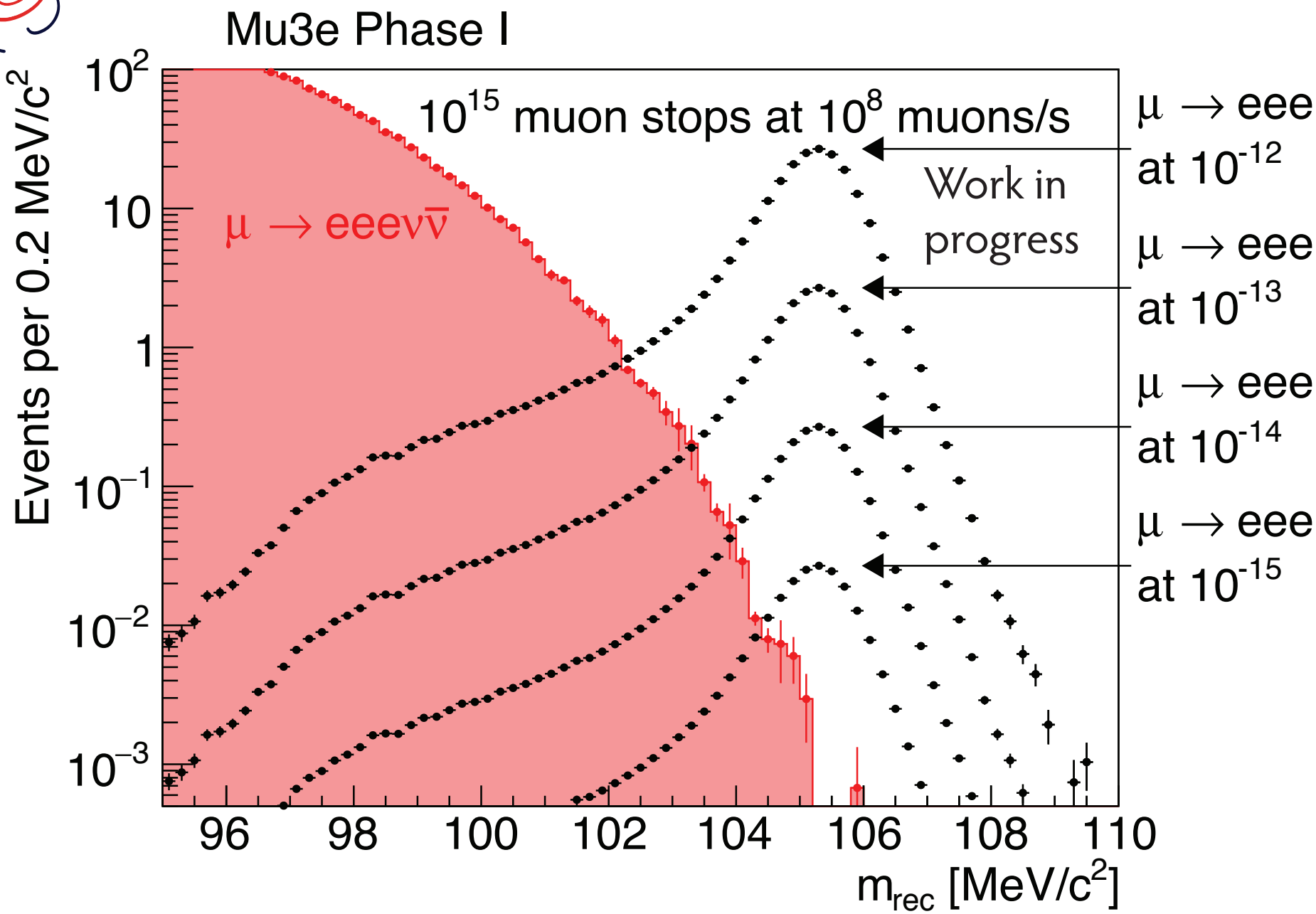
Detector Design



Detector Design



Performance Simulations: Mass reconstruction

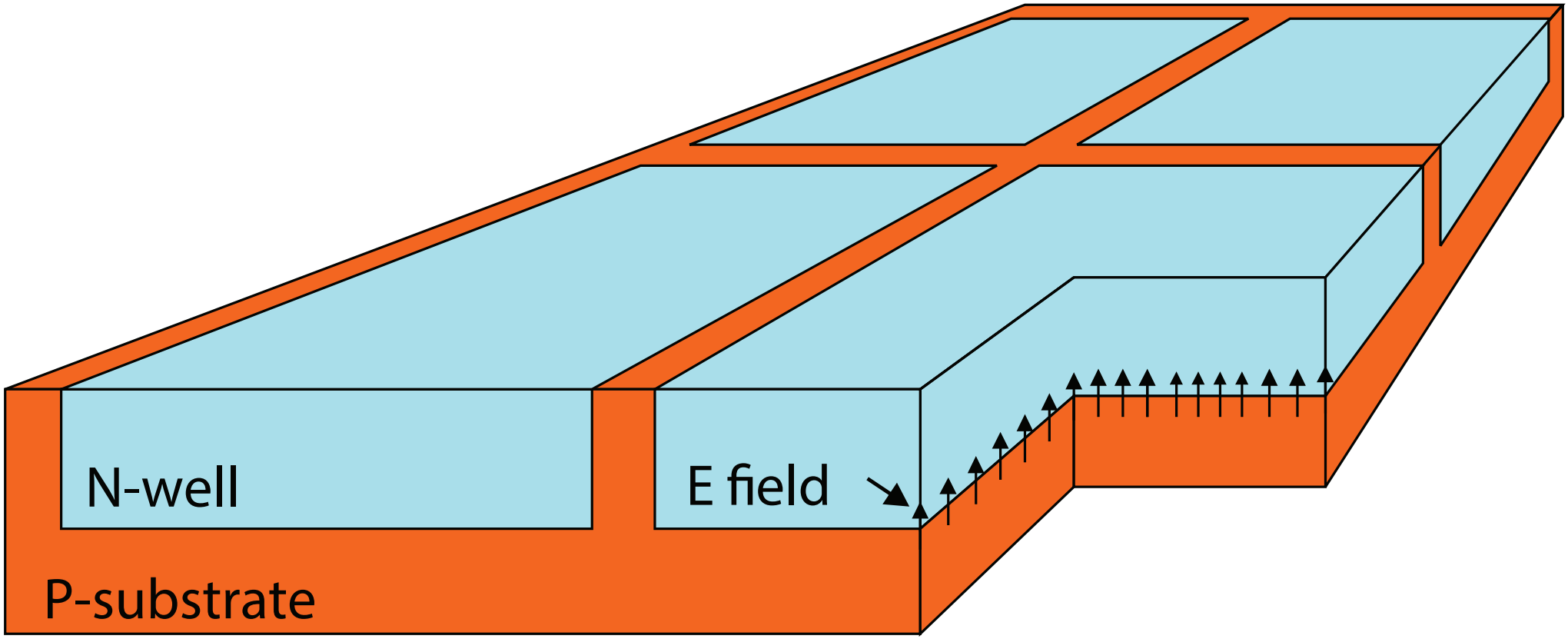


High-Voltage
Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

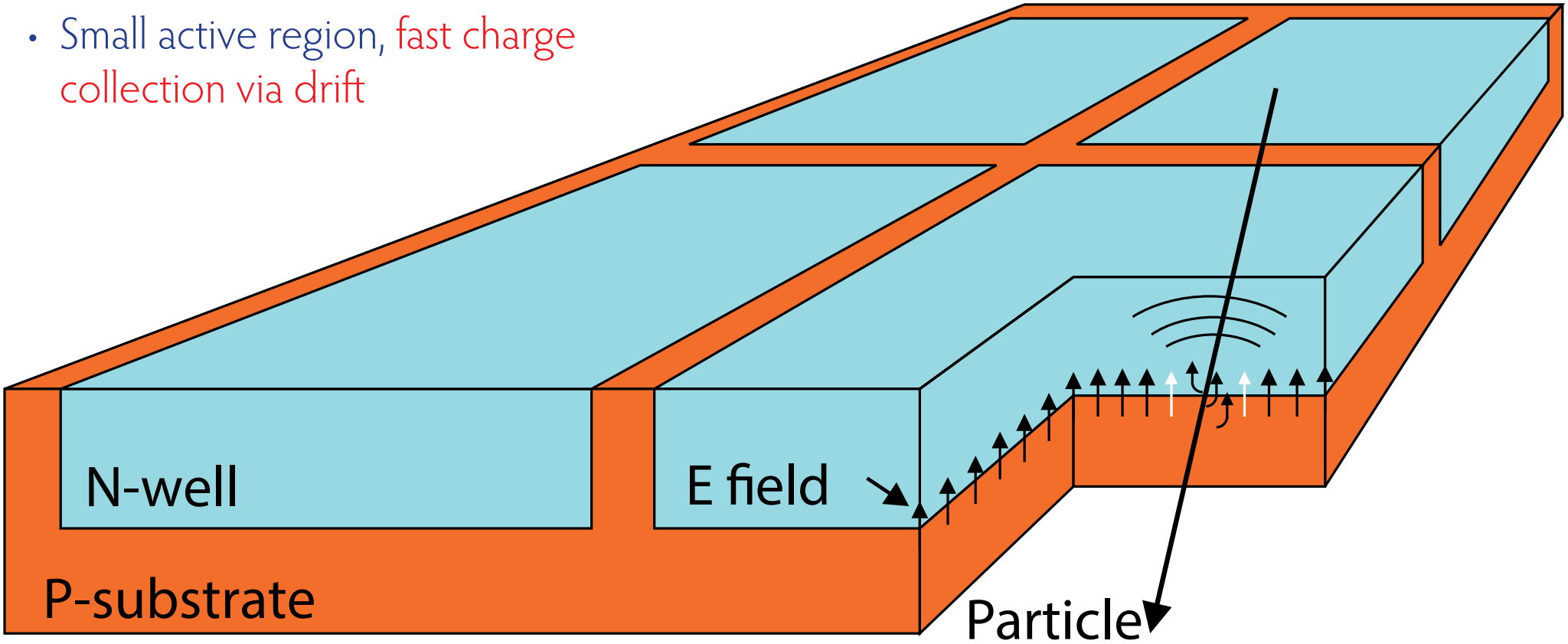
- Use a high voltage commercial process (automotive industry)



Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift



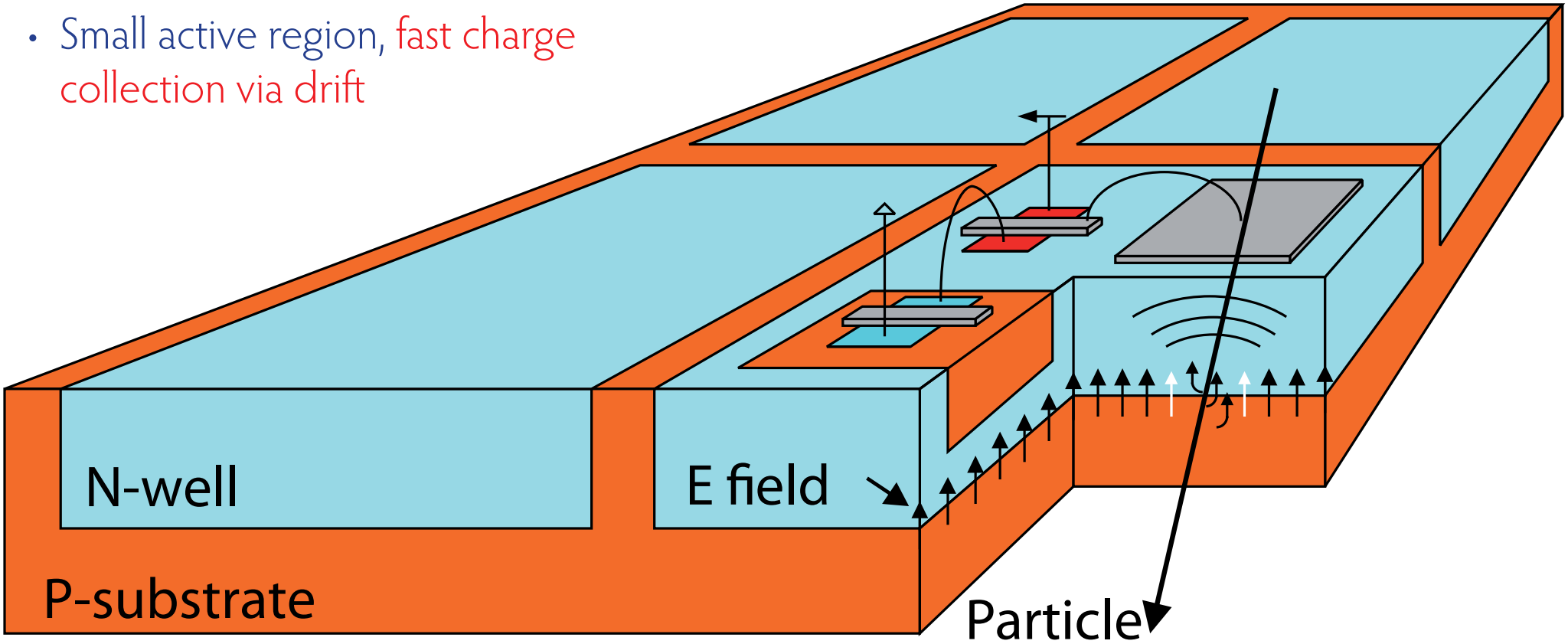
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift

- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm

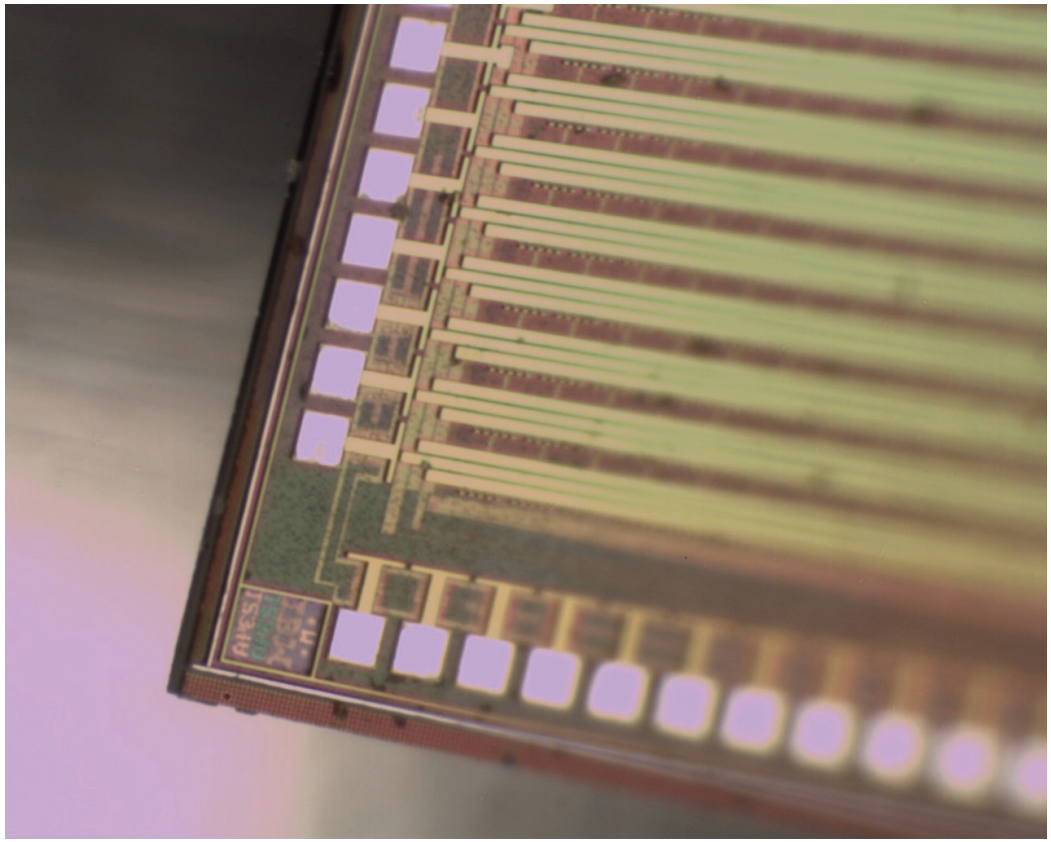
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



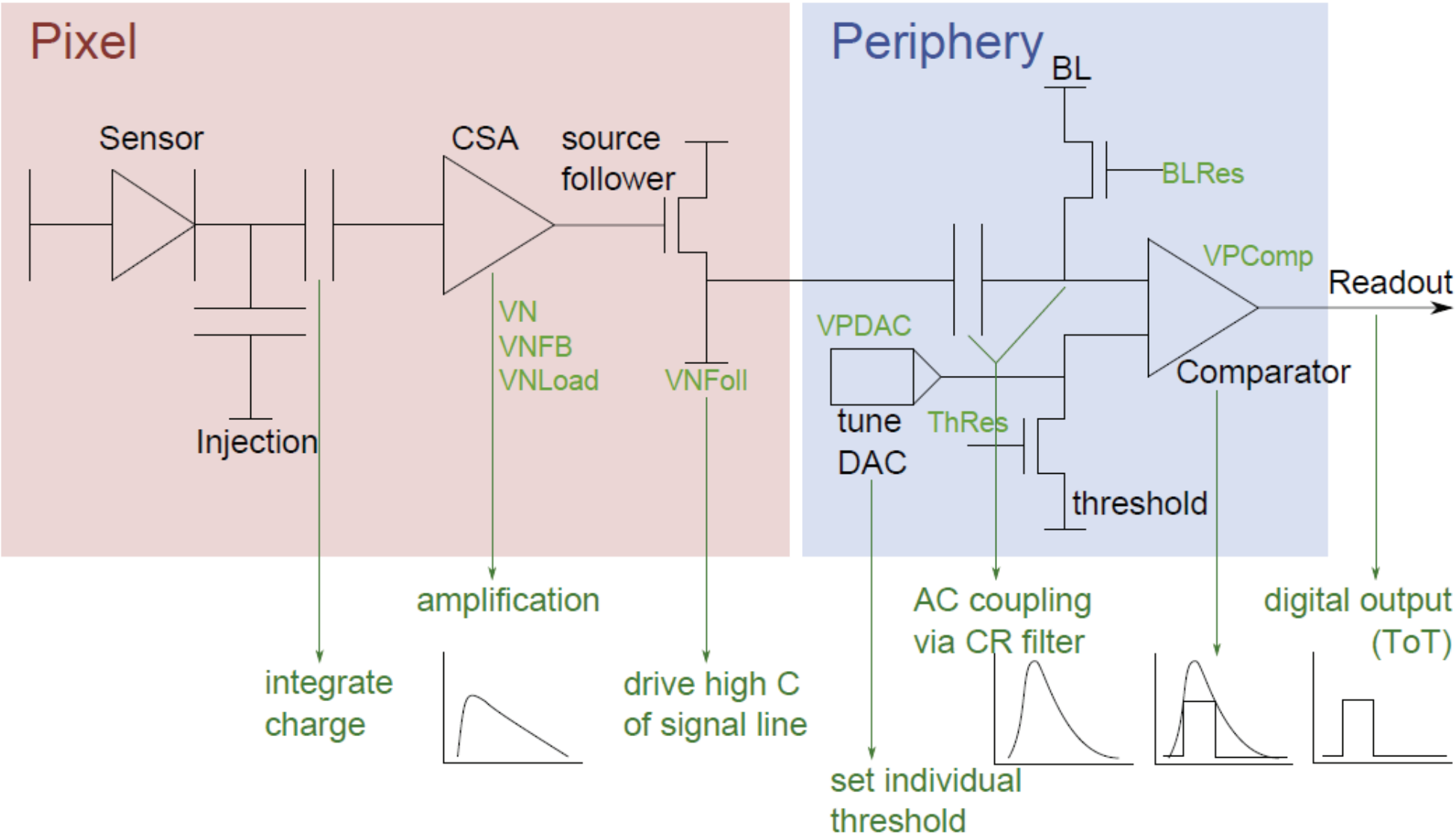
The MuPix Prototypes

Developed a series of HV-MAPS prototypes

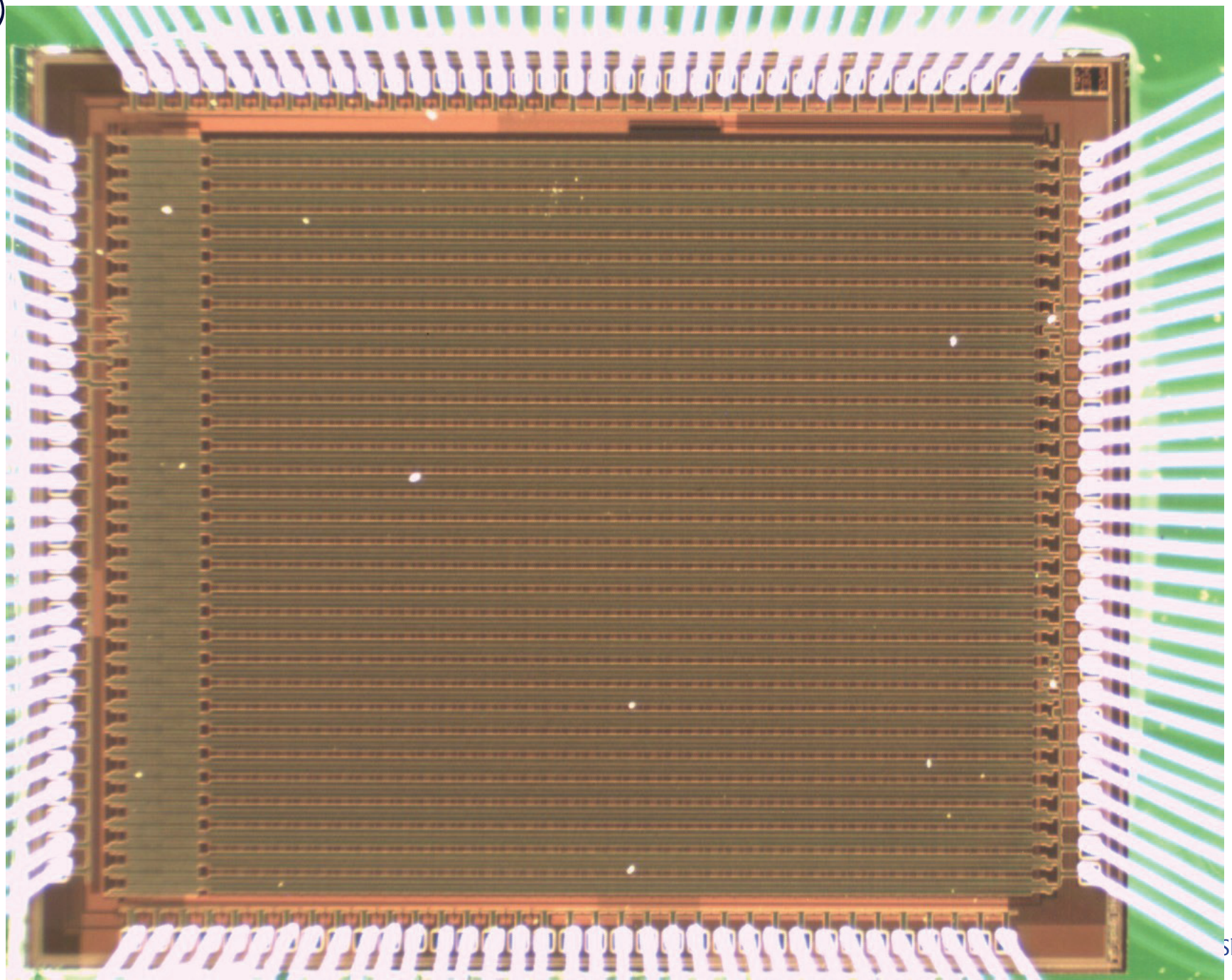
- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, is a full system-on-a-chip
- Well characterized, working very nicely
- Next step is going big: 2 x 1 cm^2 MuPix8 under test



MUPIX electronics (MuPix7)

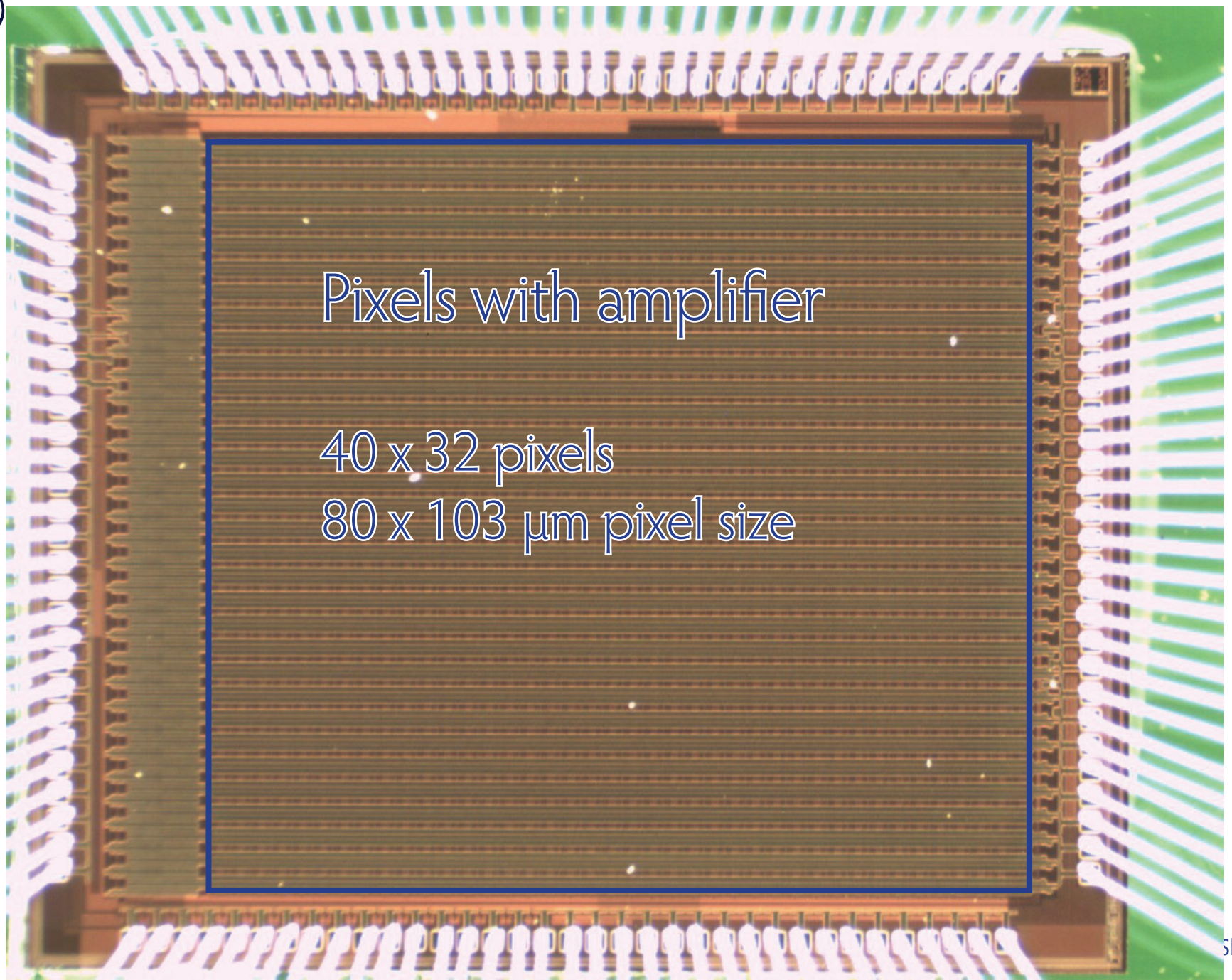


MuPix7



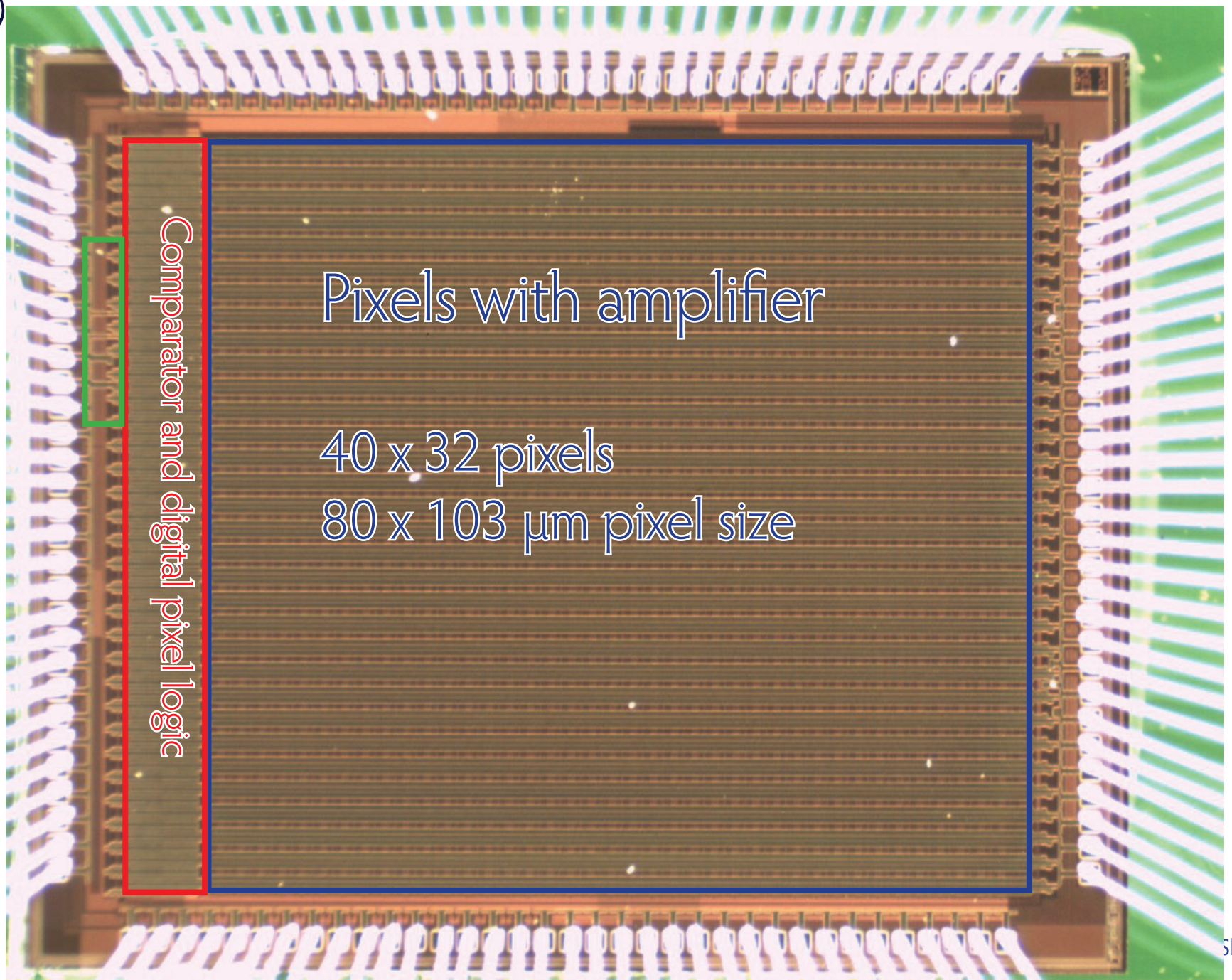
3 mm

MuPix7



3 mm

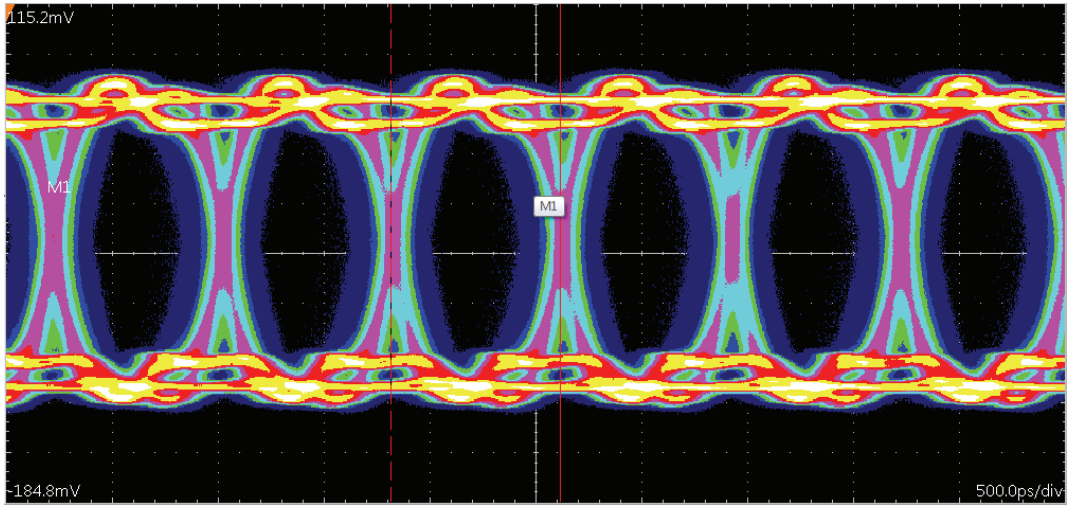
MuPix7

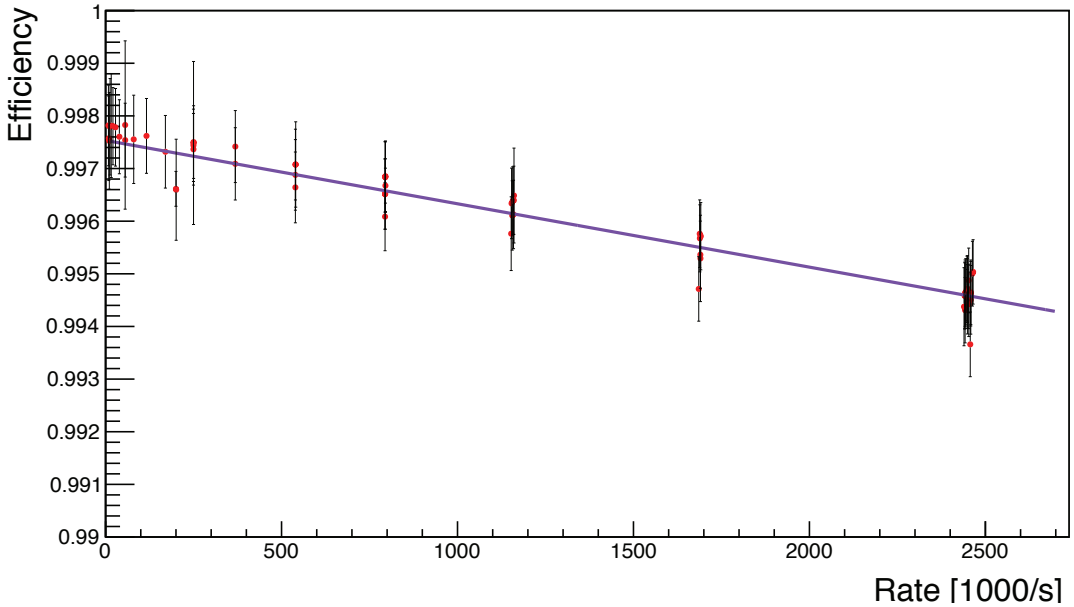

Comparator and digital pixel logic
Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size

3 mm

Fully digital output

- Hits are streamed out on a 1.25 Gbit/s LVDS link
- Up to 30 MHz hits
- Tested up to 2.5 MHz - no loss of efficiency beyond single pixel dead-time (~ 1 μs)



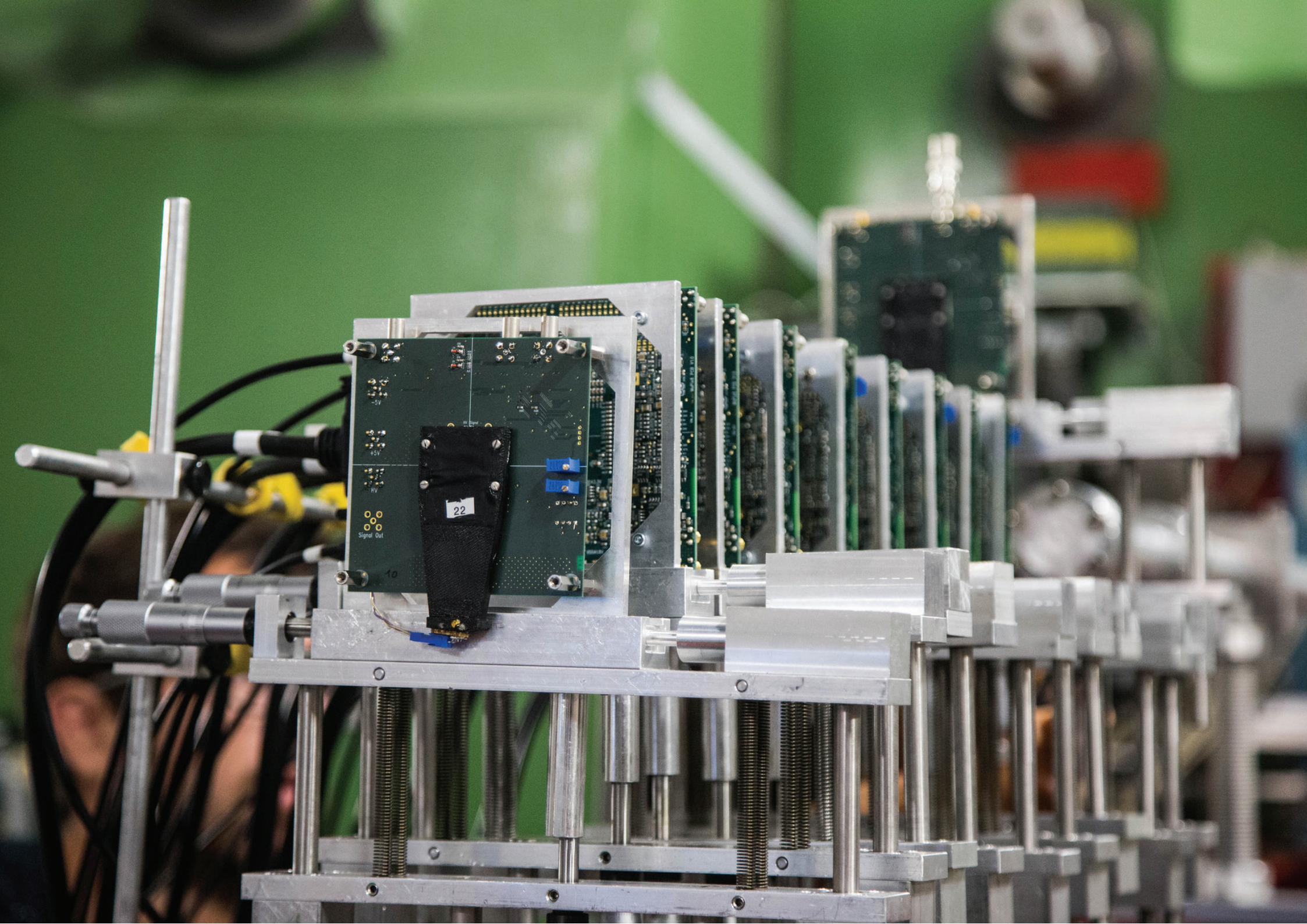


Beam tests

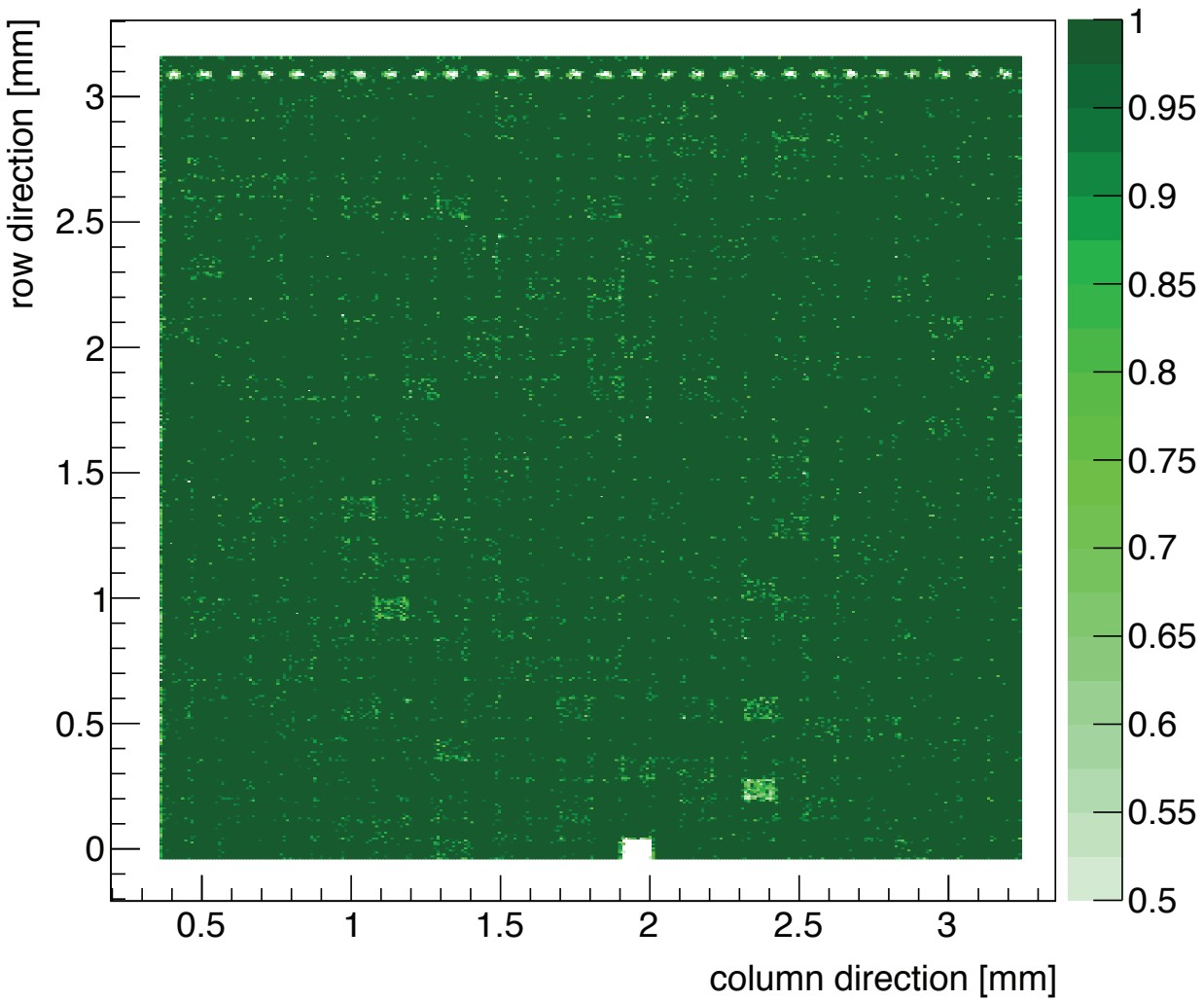
Tests done at

- CERN 250 GeV pions
- DESY 5 GeV electrons
- PSI 250 MeV pions
- Mainz 855 MeV electrons

- Thanks for all the beam time and support!


-5V
+5V
HV
Signal Out
22

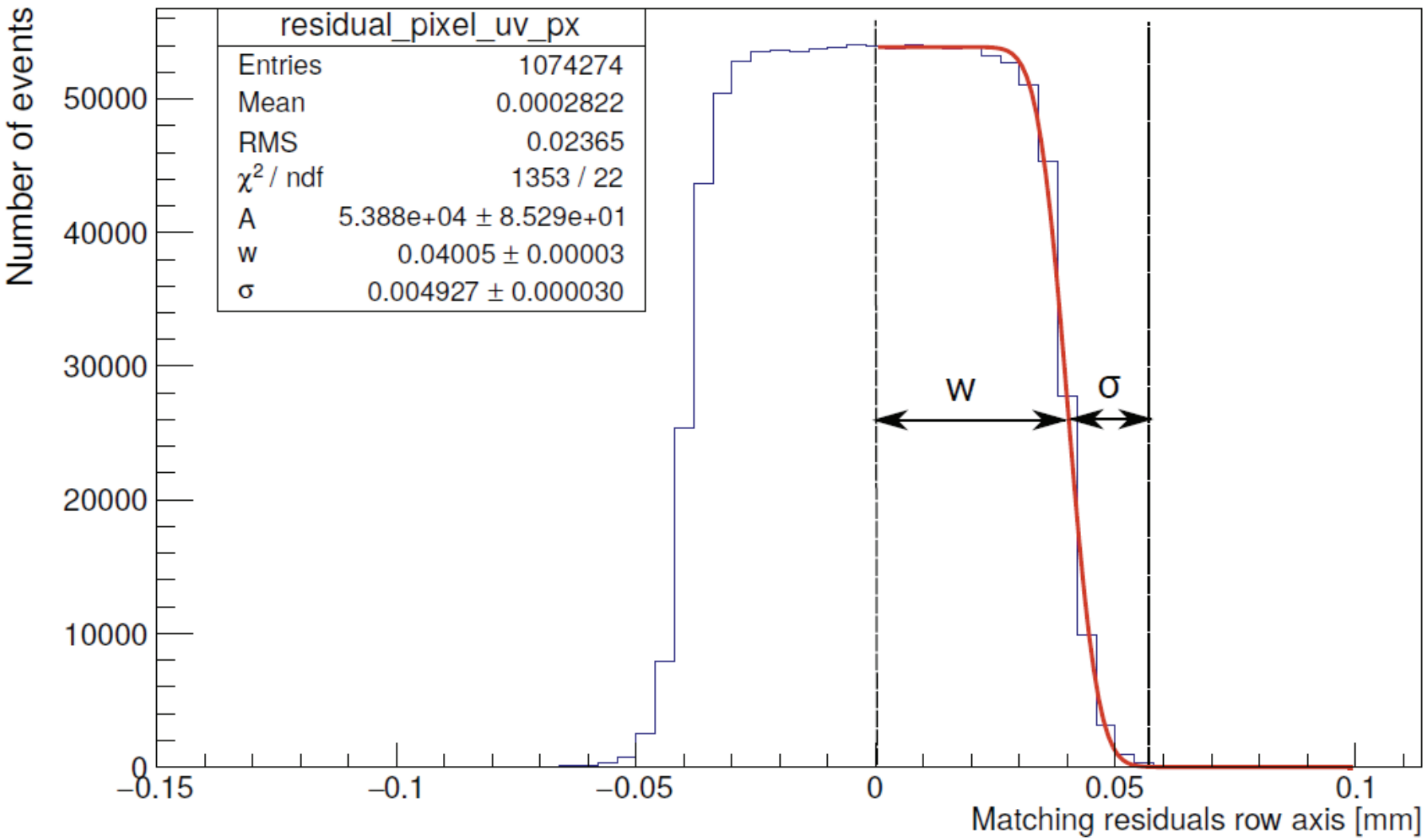
MuPix7 Performance: Efficiency



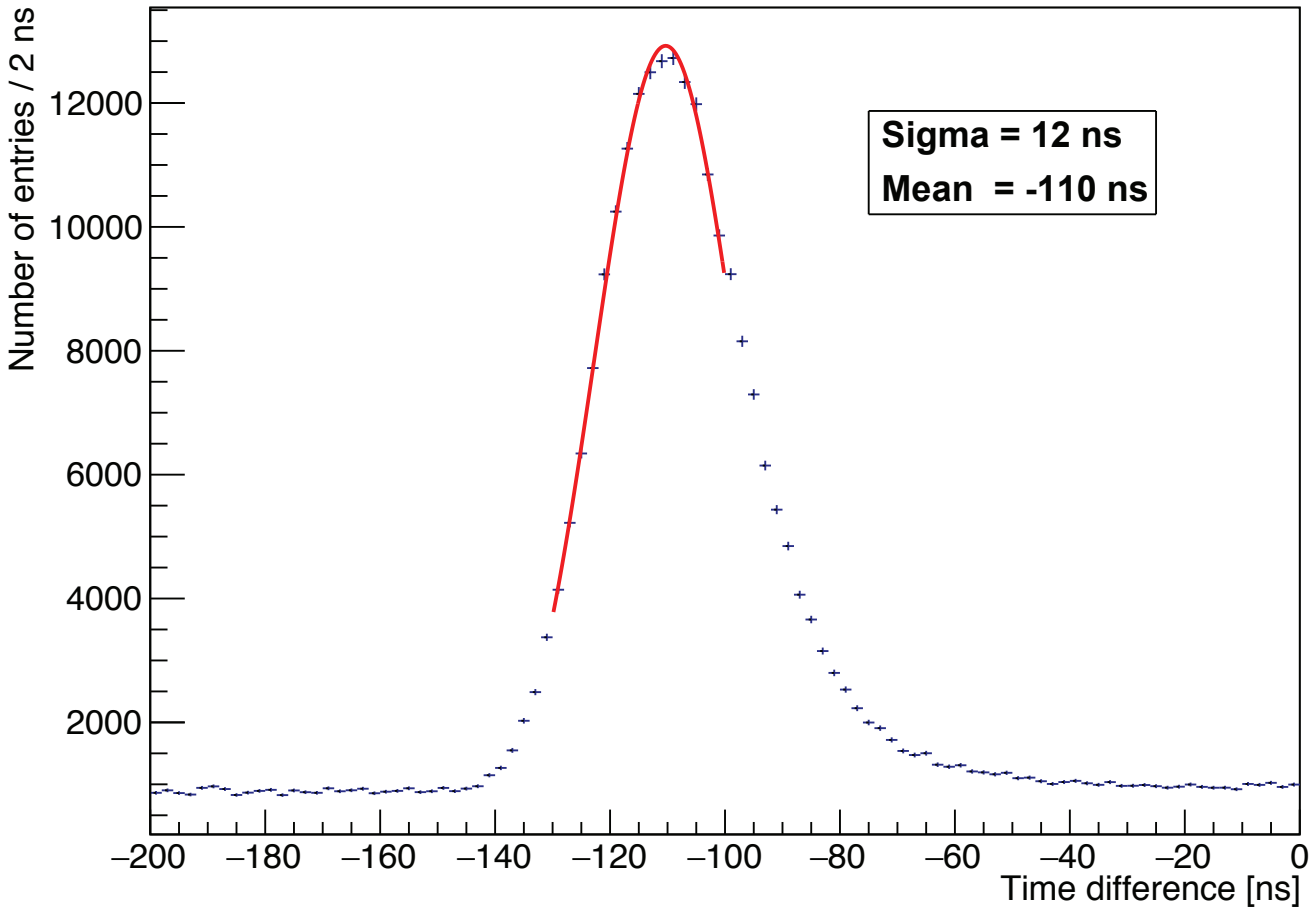
- Beam test at DESY with 4 GeV electrons
- 50 µm sensor, 90° incidence
- Using high-resolution EUDET-Telescope as reference
- All features well understood

MuPix7 Performance: Spatial Resolution

Digital readout: Resolution given by pixel size
(plus reference telescope resolution)



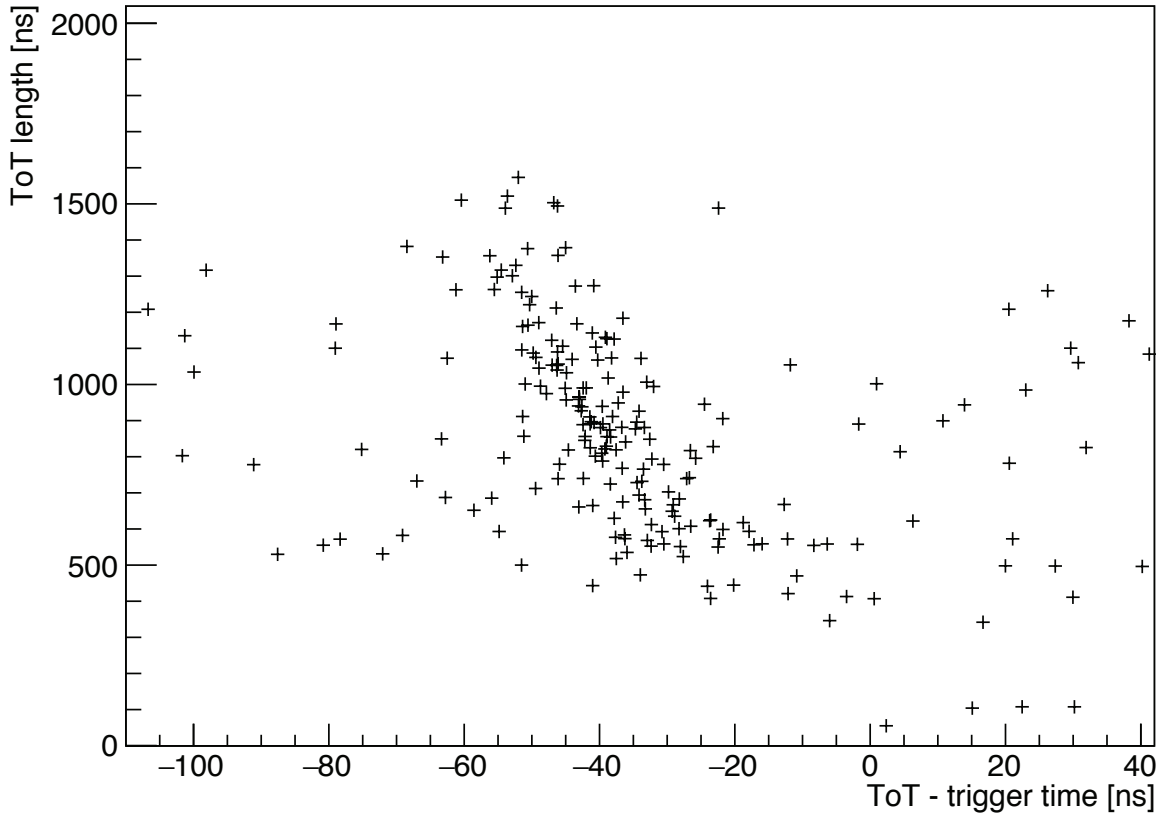
MuPix7 Performance: Time Resolution



- Using 16 ns timestamps
- Relative to scintillator reference
- Sizeable tail: time-walk

MuPix7 Performance: Time resolution

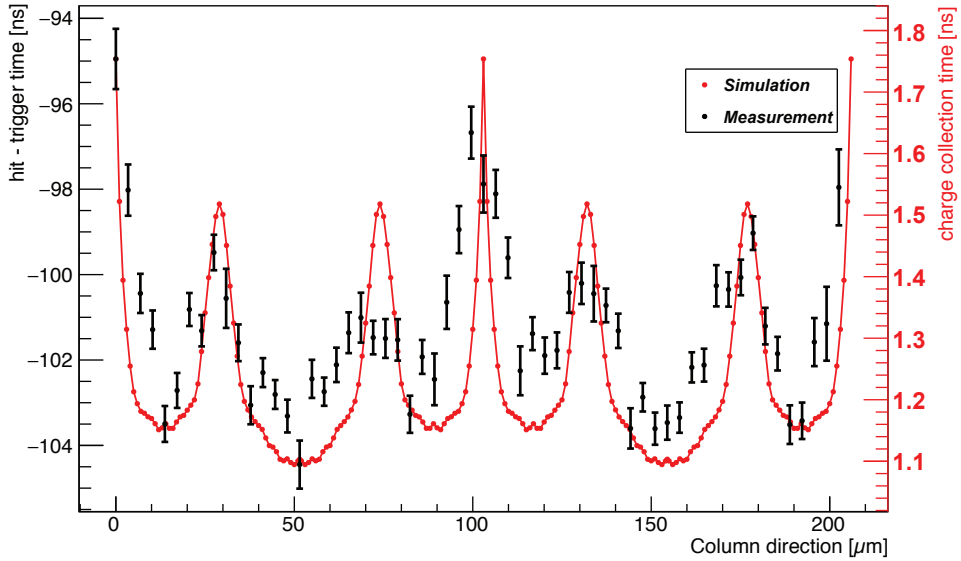
- Single pixel with time-over-threshold signal (~ signal size)
- MuPix8 has signal size for all pixels and finer timestamps
- Can do time-walk correction

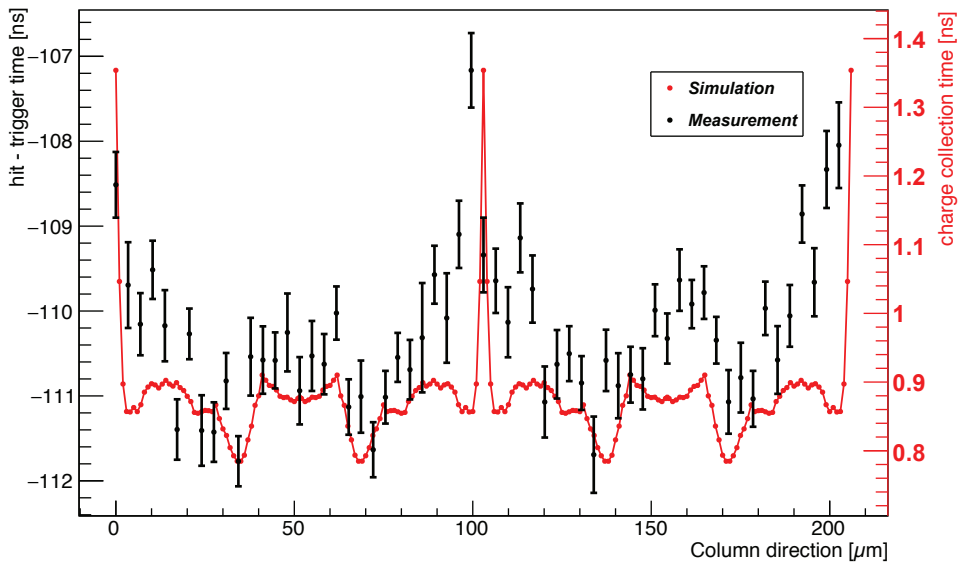


MuPix7 Simulation and Data

- Measurements of time delay
  (At fixed threshold: proxy for signal size)
  with sub-pixel resolution

- Simulation using TCAD: All features can be reproduced

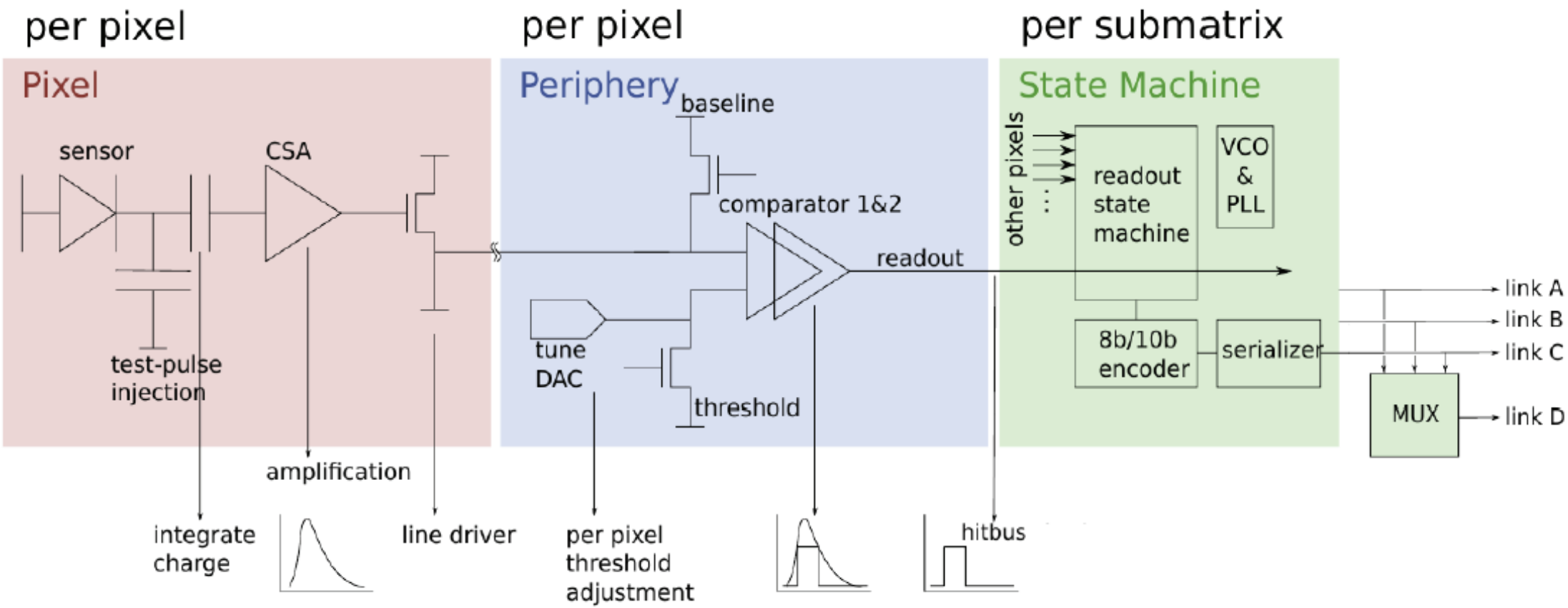




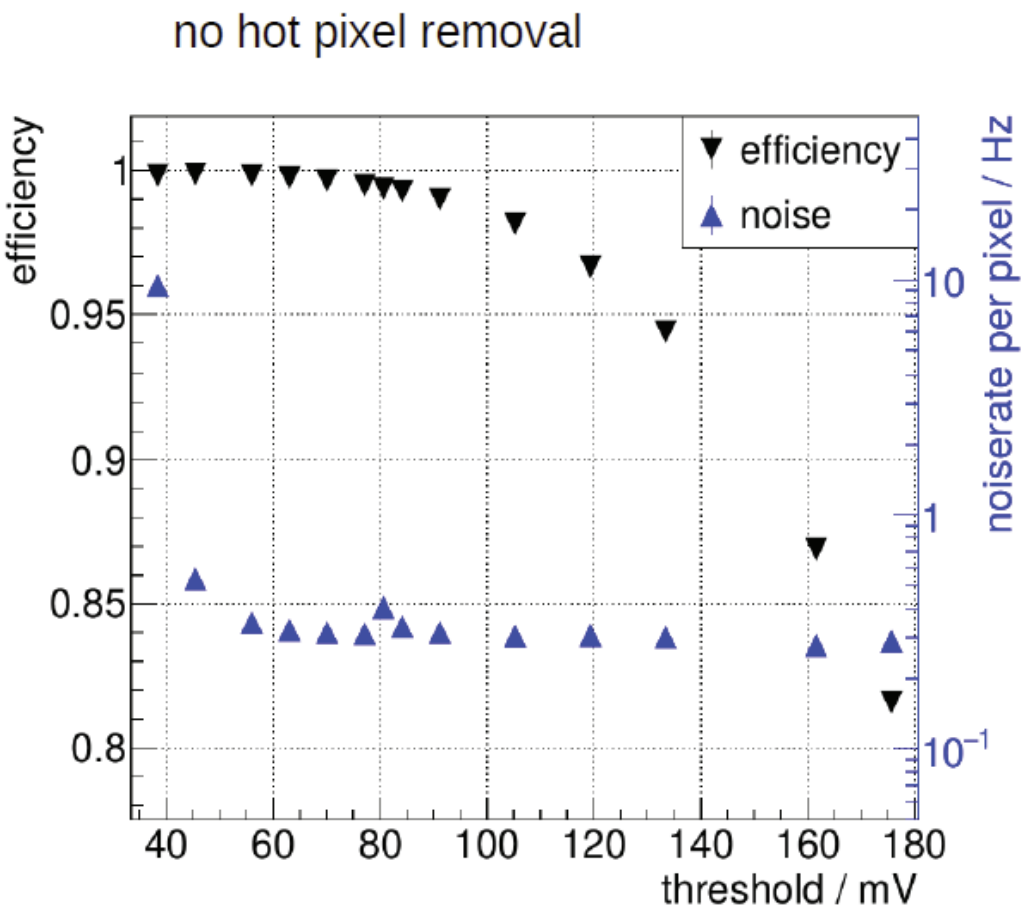
MuPix8

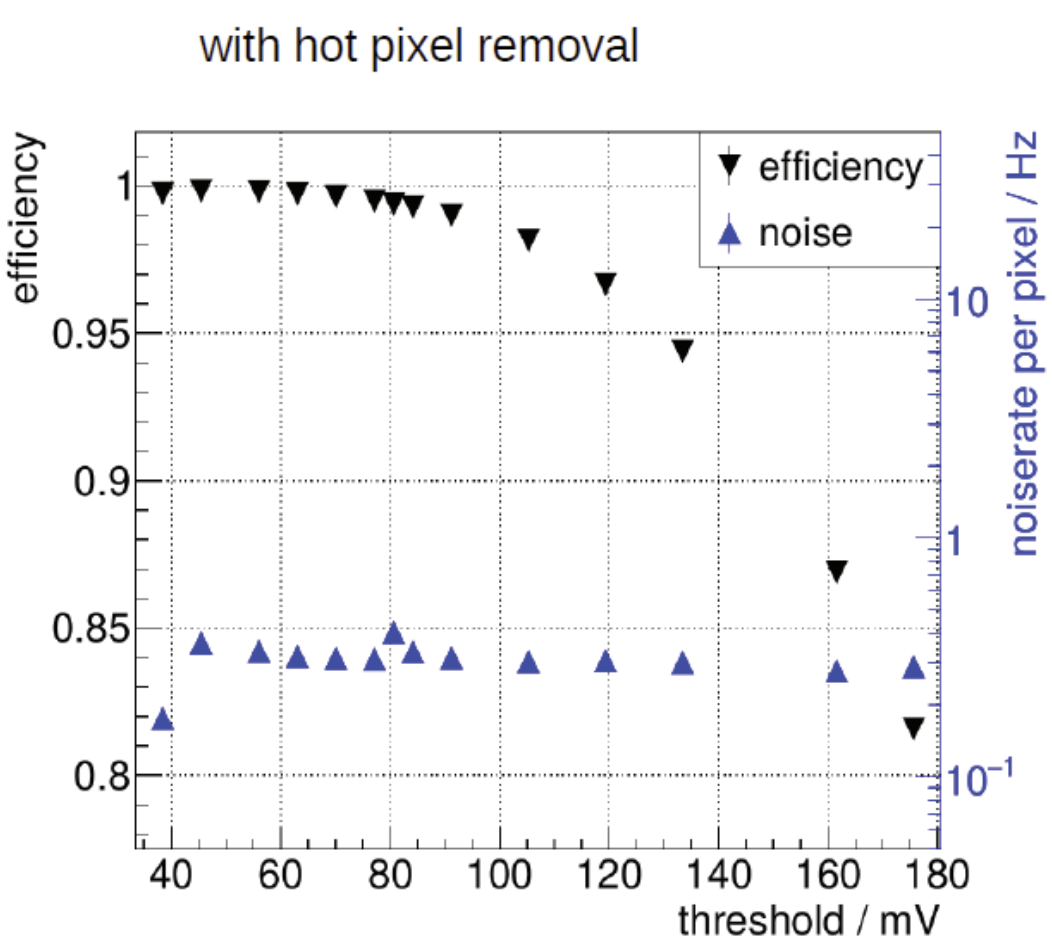
- MuPix8, the first large sensor (2 cm x 1 cm) now available
- Currently under test
- Three sub-matrices with different signal transmission to periphery
- Results from matrix A with the Mupix7-like source follower

MuPix8 Architecture

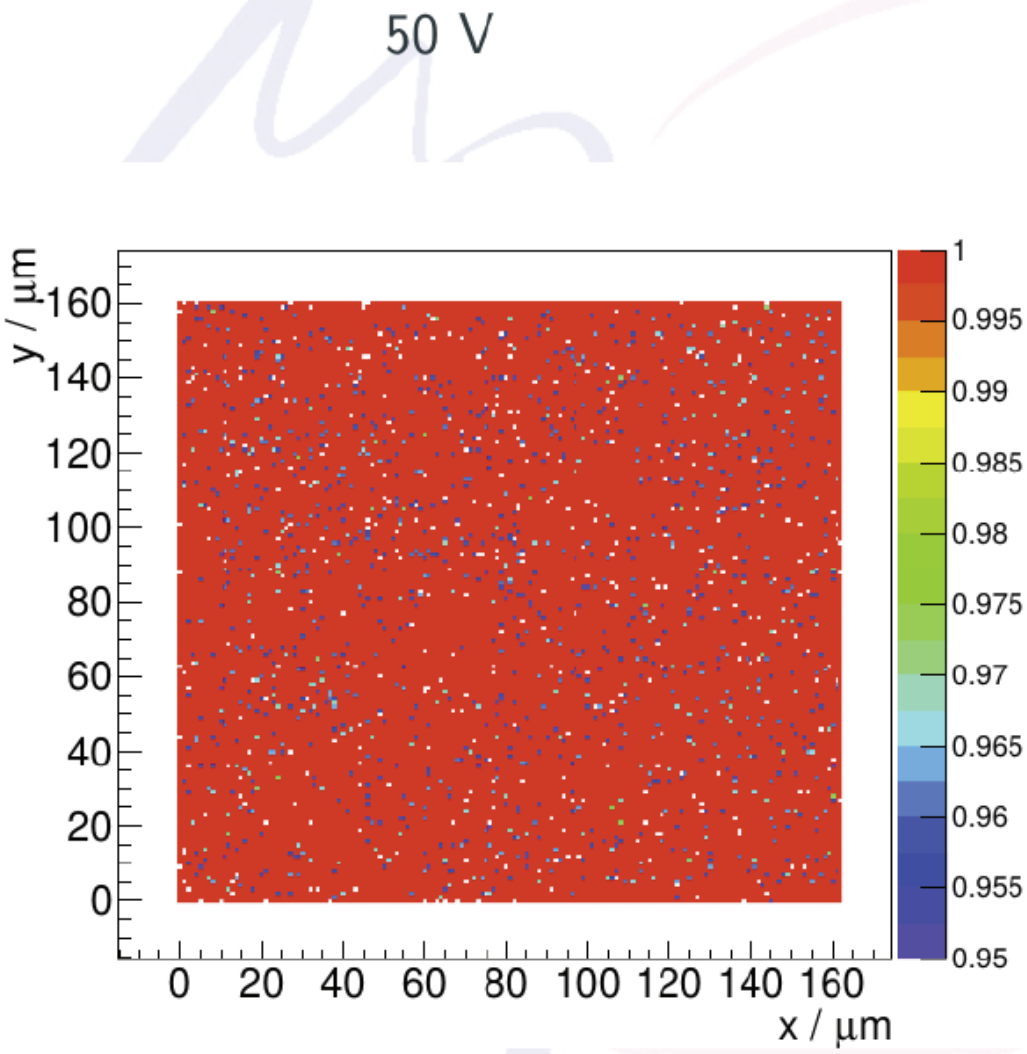


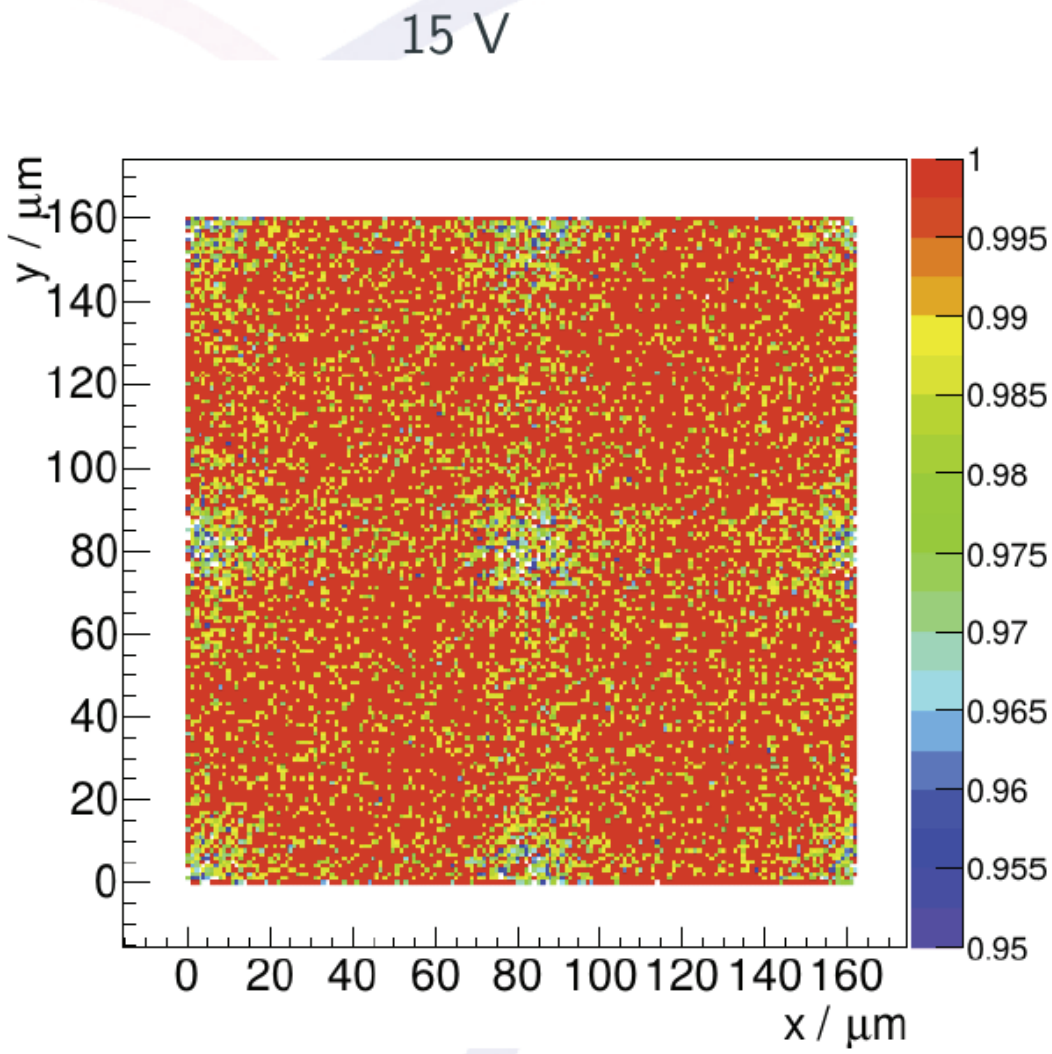
MuPix8 Performance





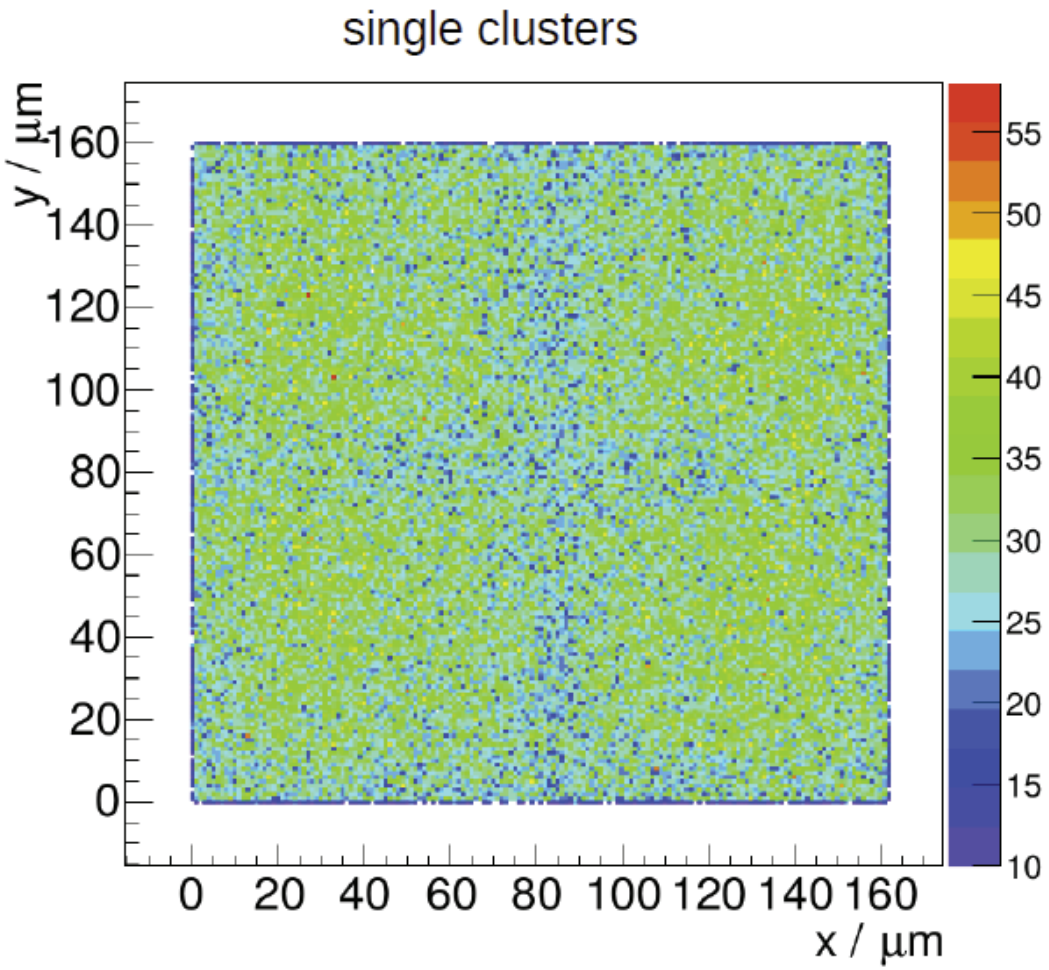
MuPix8 Performance

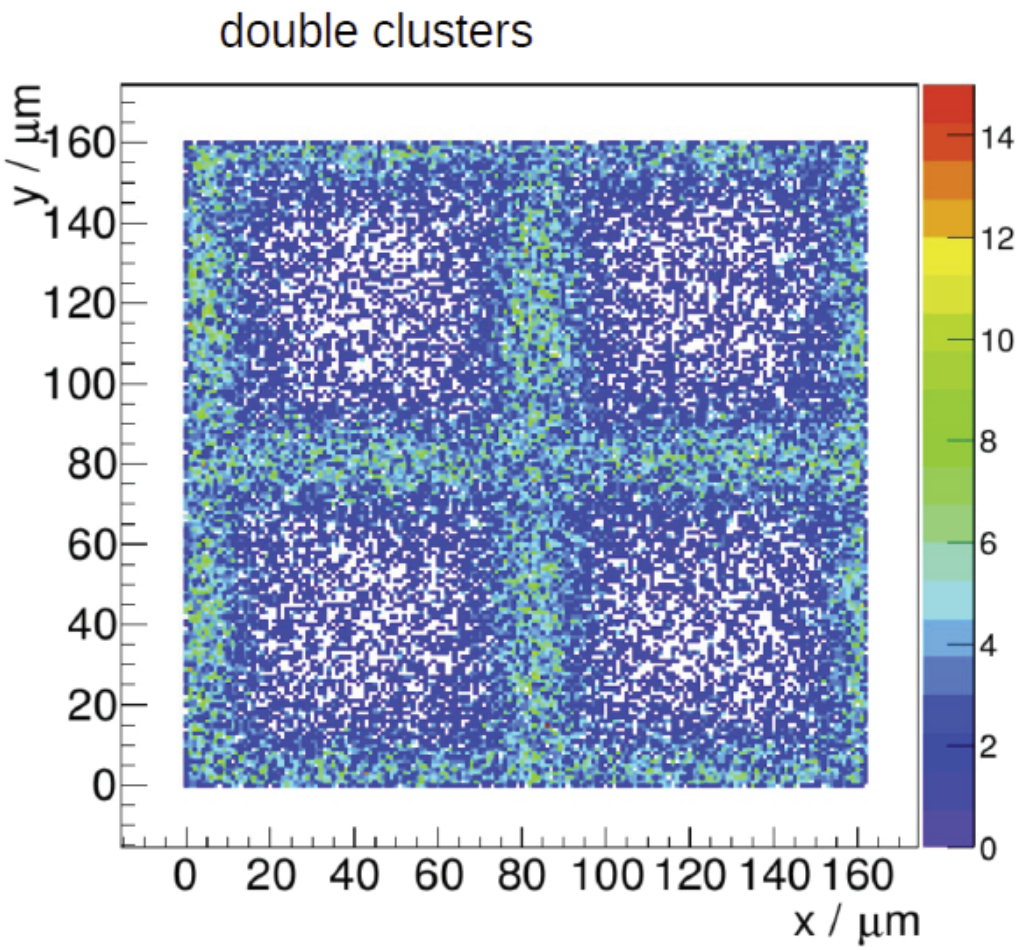




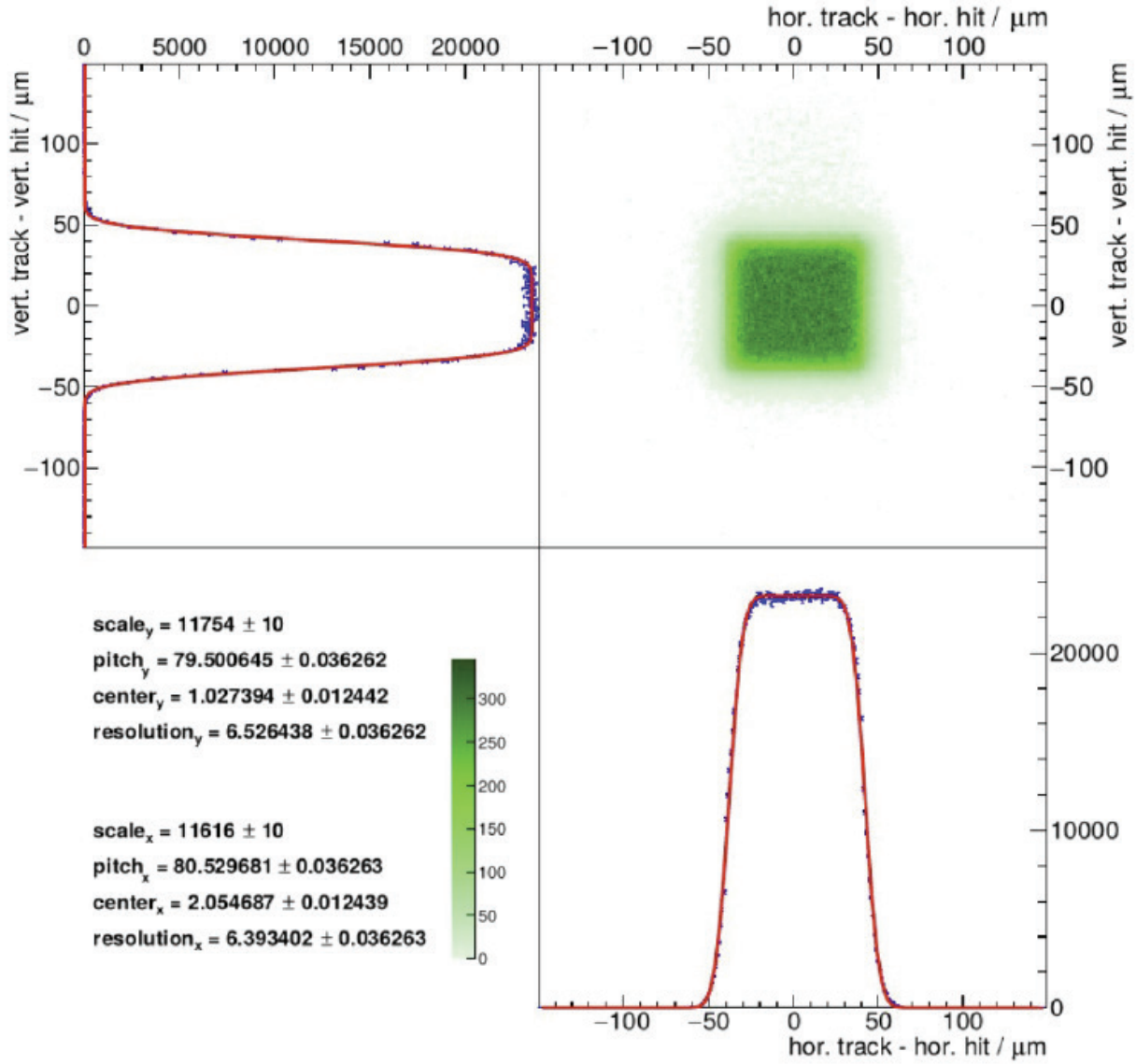
MuPix8 Performance

- Charge sharing only at pixel edges



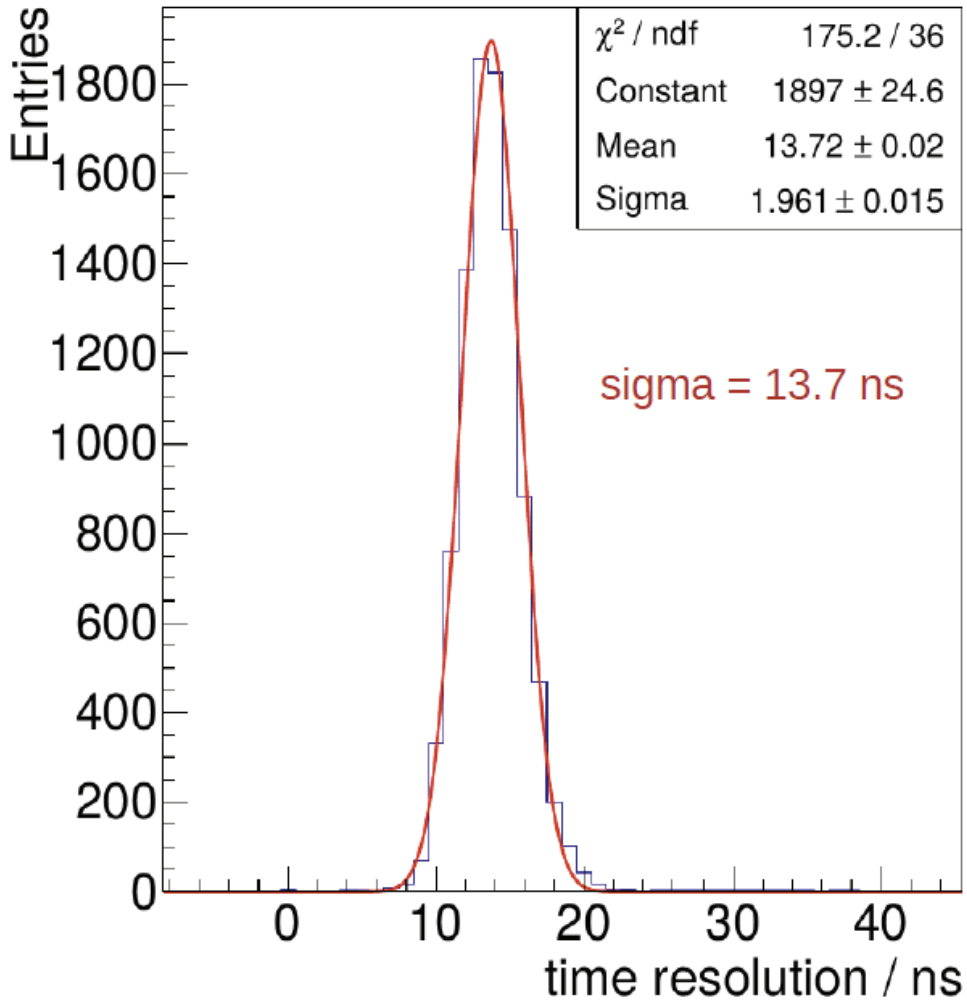


MuPix8 Performance



- Resolution given by pixel size (80 x 81 µm)

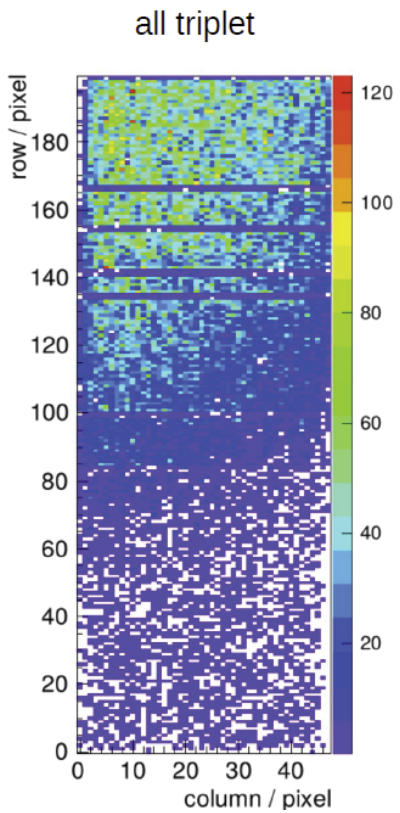
MuPix8 Performance

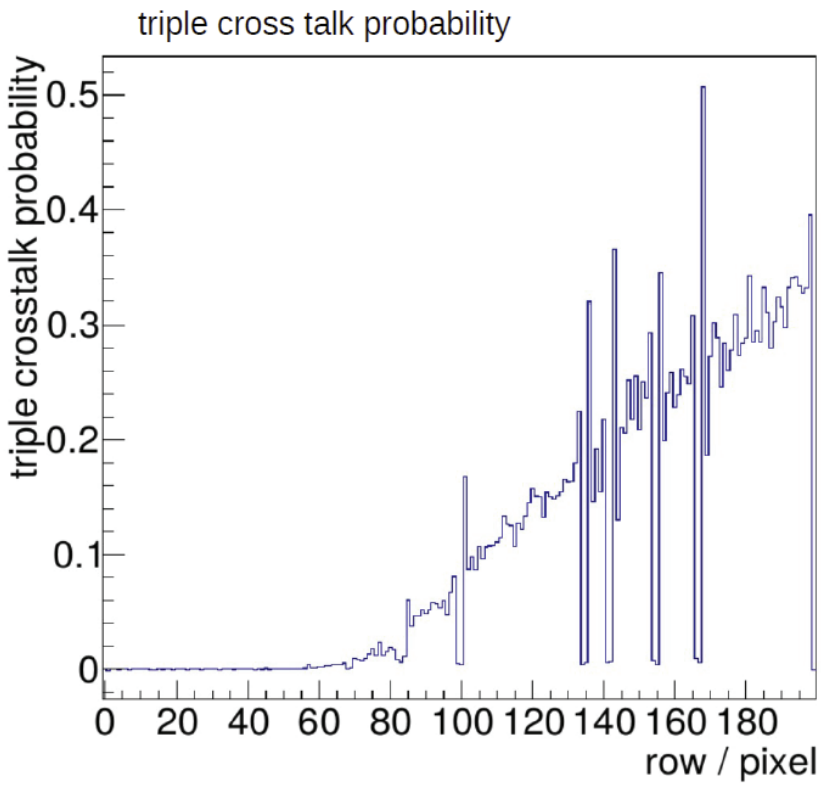


- 8 ns timestamps
- Some delays over the chip, large pixel-to-pixel variations: Need correction
- Further improvements possible, for matrix subset, 6 ns were obtained

MuPix8 issues

- Powering: Some voltage drop over chip, results obtained at 1.9 V or 2 V vs. 1.8 V nominal operation voltage
- Cross-talk: Long lines to the periphery have capacitive coupling





How to get to ~0.1 X_0 per layer

50 µm silicon is not self-supporting

- Need "no-mass" mechanics
- Also: "no-mass" connection to the outside world

See Joost's talk

Chips are active: ~ 300 mW/cm^2

- Need "no-mass" cooling
- Gaseous helium at very high flow speeds
- Prototype tests so far successful, full mock-up under construction

- Note: The PANDA luminosity detector will operate MuPix in vacuum: Cooling via diamond wafers

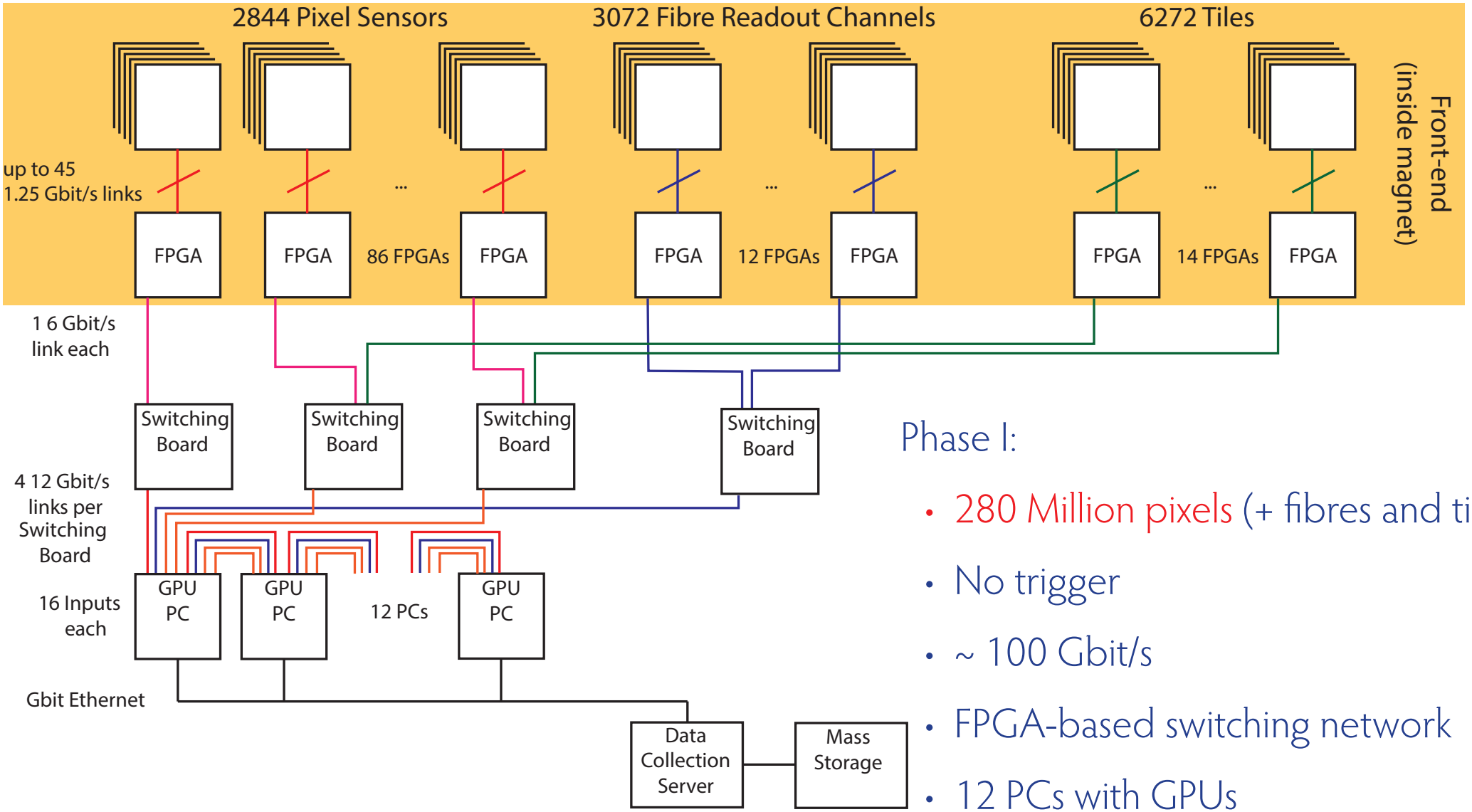
Data Acquisition

MuPix output

- 1.25 Gbit/s 8b10b encoded LVDS links
- Either three submatrices with a link each
  or
  one link multiplexing the sub-matrices
- Roughly 30 MHits/s per link maximum
- Hits are 32 bit: column, row, time, charge

- Hits are not strictly time sorted - see backup for the workings of the MuPix readout state machine

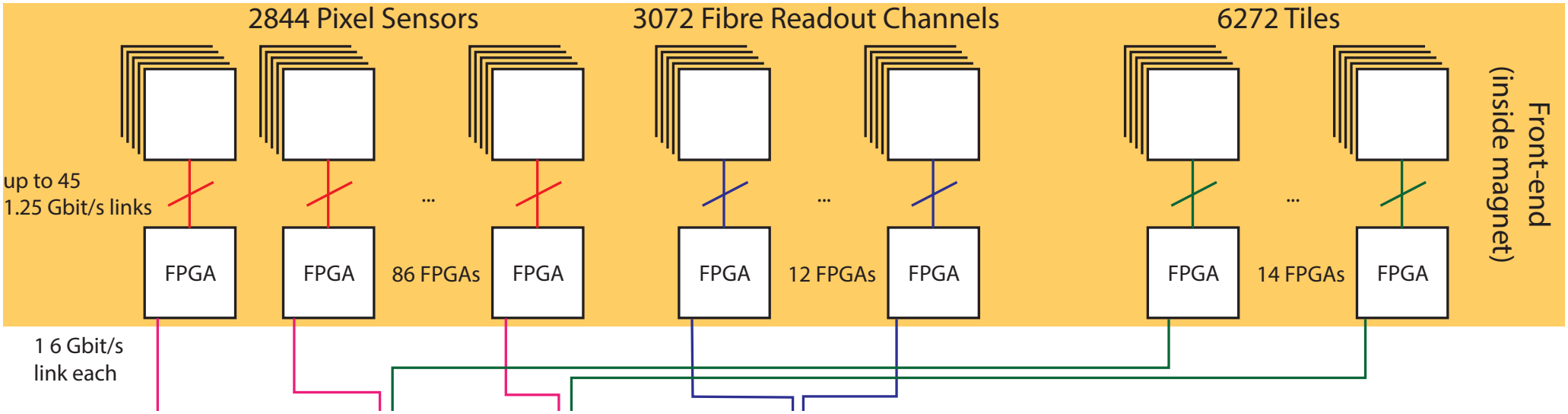
Data Acquisition



Phase I:

- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 100 Gbit/s
- FPGA-based switching network
- 12 PCs with GPUs

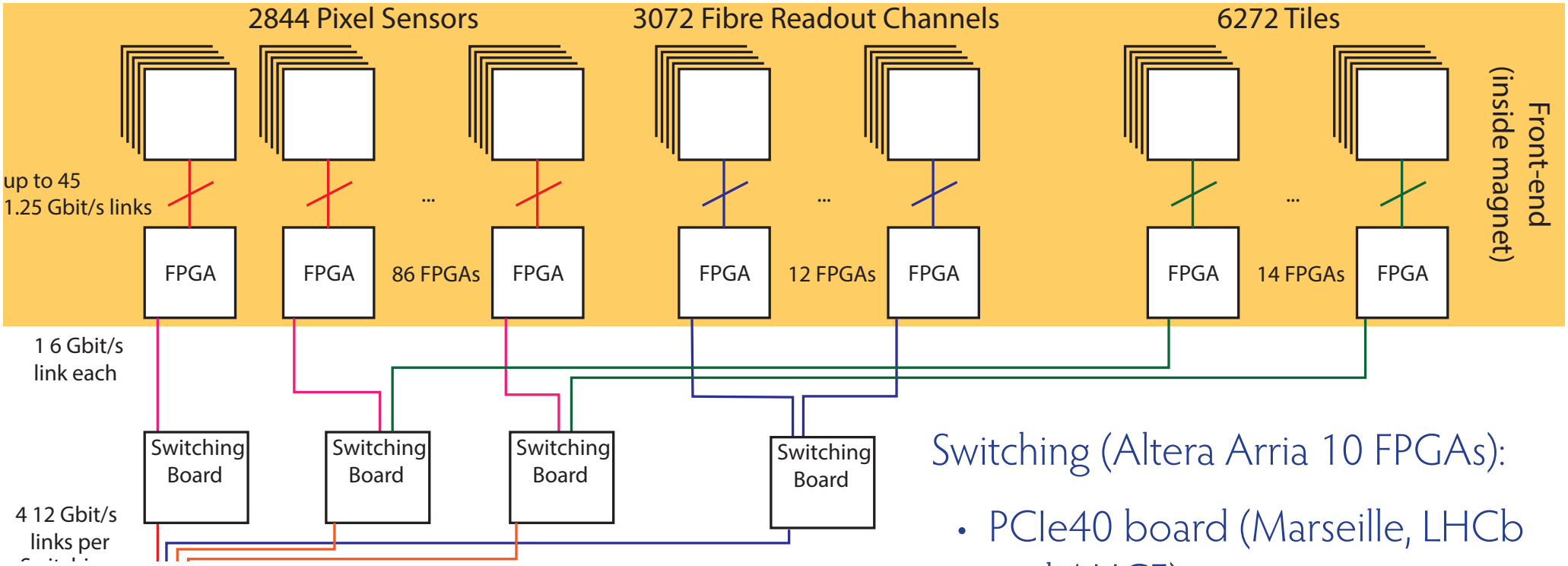
Data Acquisition



Front end (Altera Arria V FPGAs):

- Receive and decode data
- Correct for time-walk
- Time sorting (most resources)
- Slow control and configuration
- Send data out via 6 Gbit/s optical link

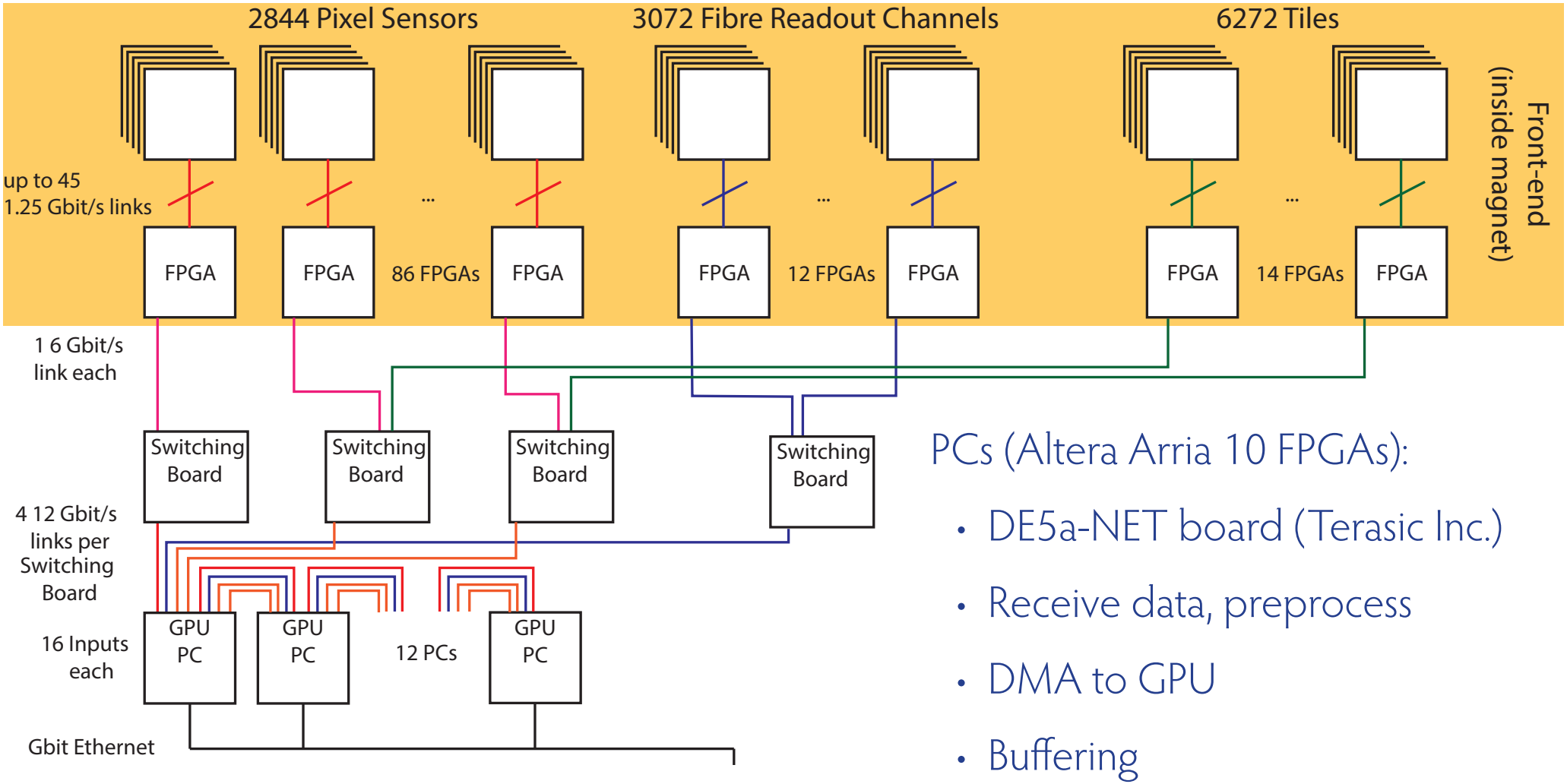
Data Acquisition



Switching (Altera Arria 10 FPGAs):

- PCIe40 board (Marseille, LHCb and ALICE)
- Merge datastreams
- Inject pixel configuration data
- Perform monitoring tasks

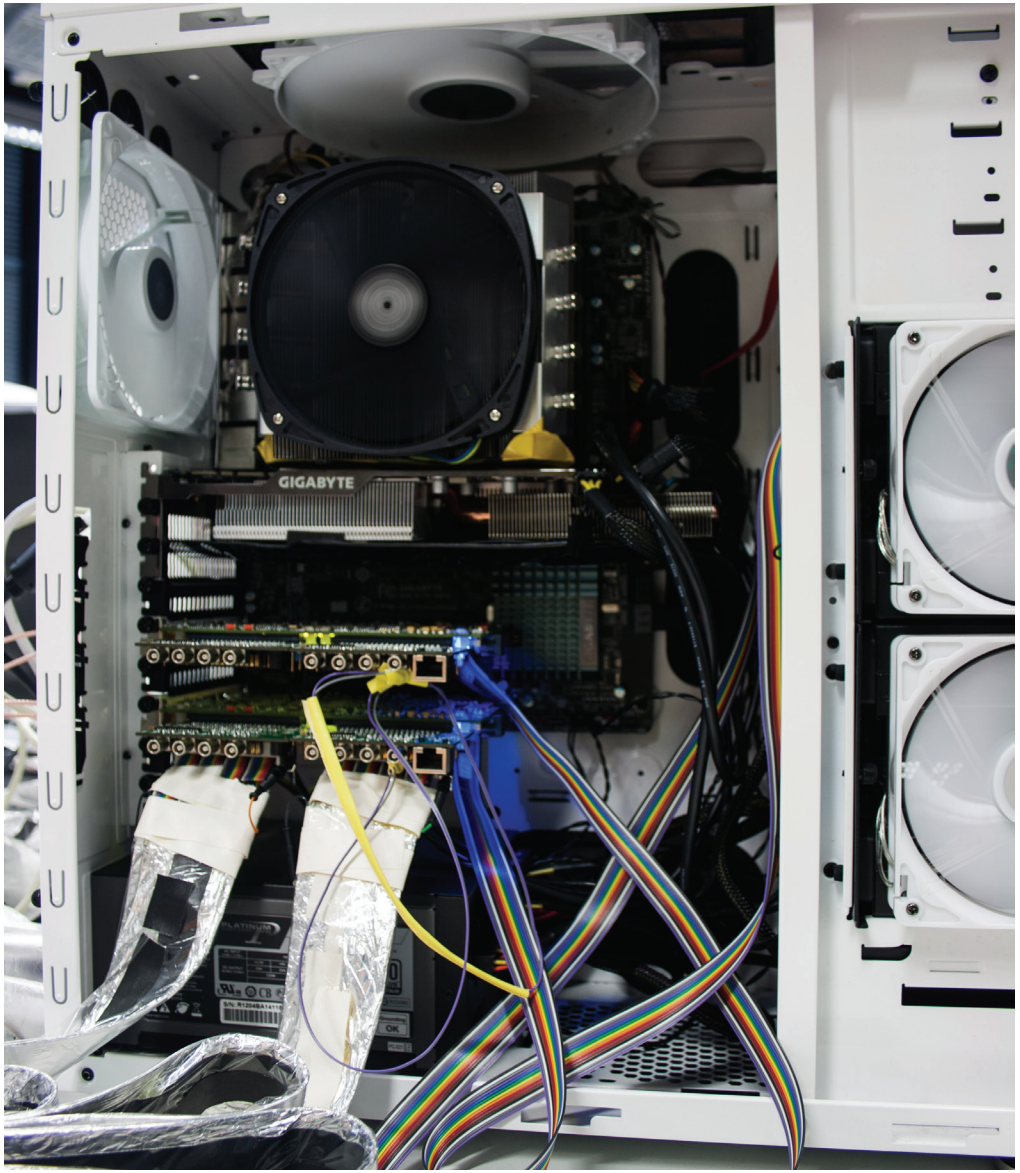
Data Acquisition



PCs (Altera Arria 10 FPGAs):

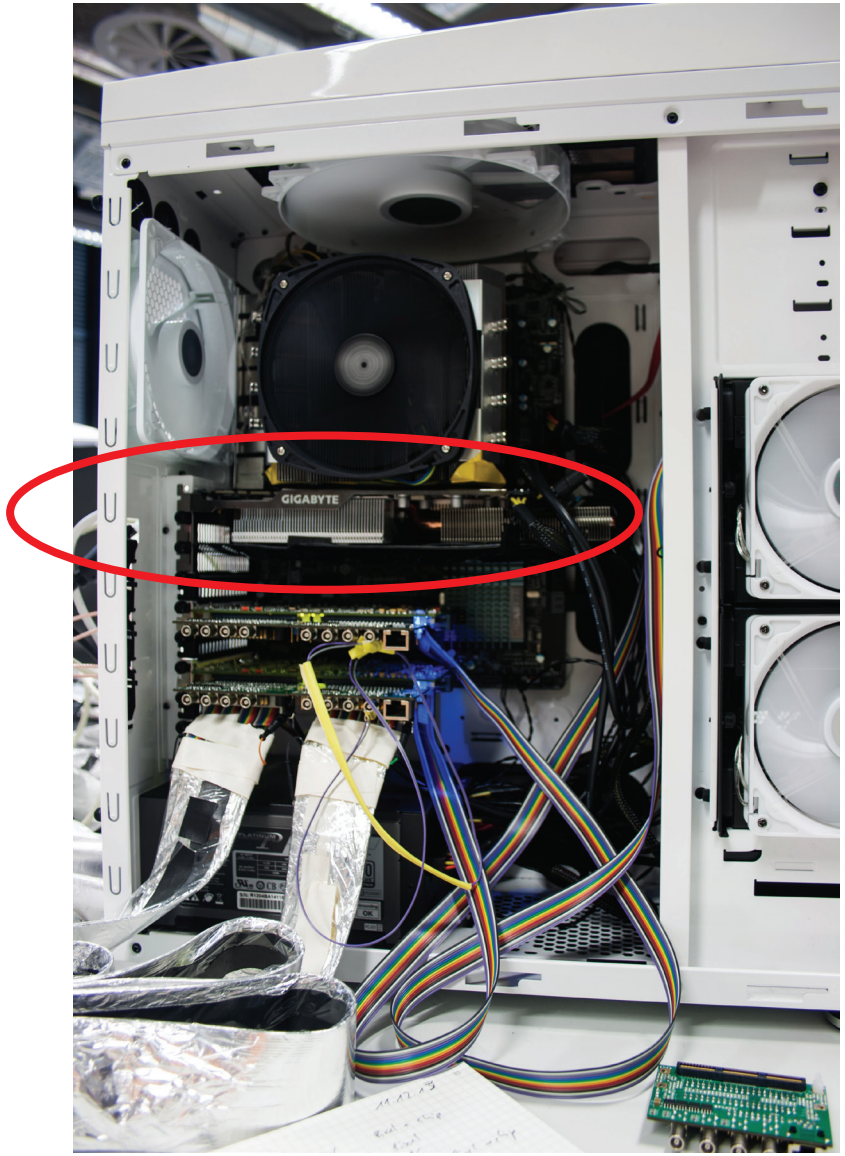
- DE5a-NET board (Terasic Inc.)
- Receive data, preprocess
- DMA to GPU
- Buffering

Online reconstruction



- 280 Million pixels (+ fibres and tiles)
- No trigger
- ~ 1 Tbit/s
- Need to find and fit billions of tracks/s

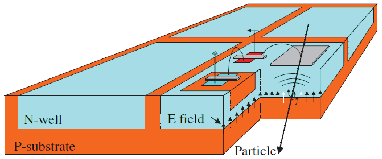
Online filter farm



- PCs with Graphics Processing Units (GPUs)
- Online track and event reconstruction
- 10^9 3D track fits/s achieved
- Data reduction by factor ~1000
- Data to tape < 100 Mbyte/s

Conclusion

- Mu3e aims for μ → eee at the 10^{-16} level
- First large scale use of HV-MAPS



- Working full prototypes MuPix7 and MuPix8
- Reconstruct 100 million tracks/s in 100 Gbit/s on ~12 GPUs

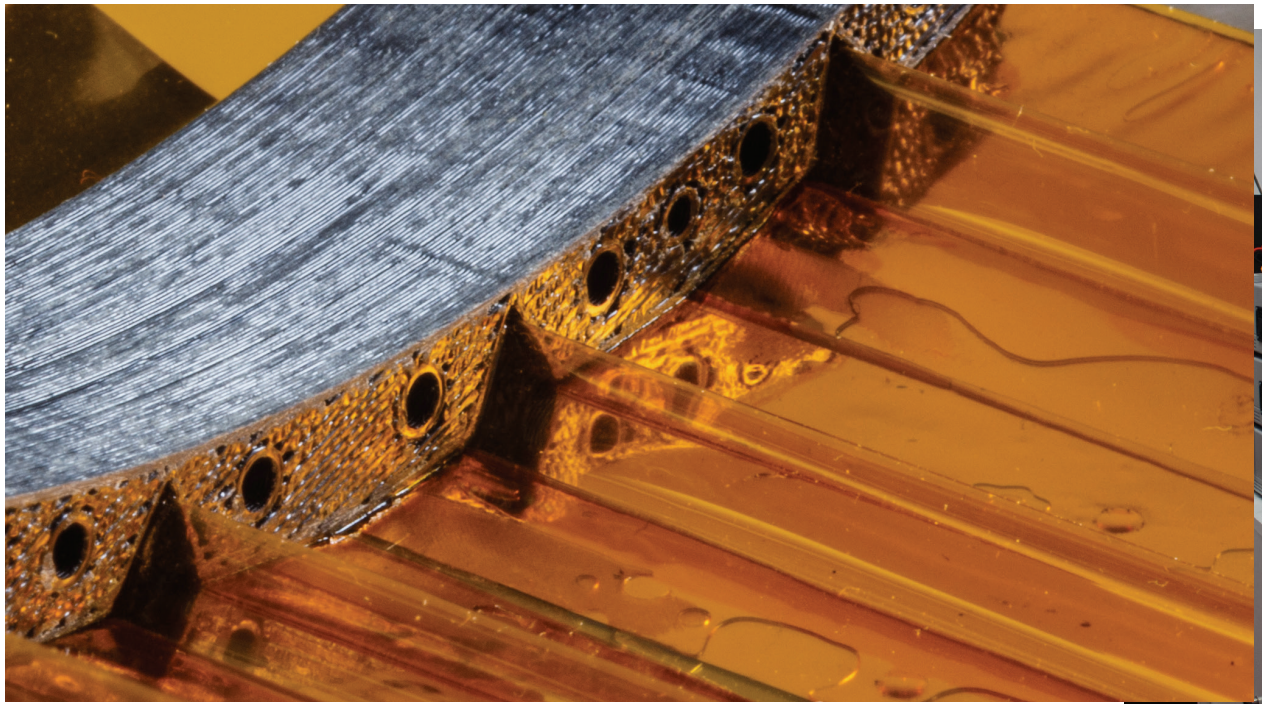
- Start data taking in 2020
- 2 billion muons/s not before 2024

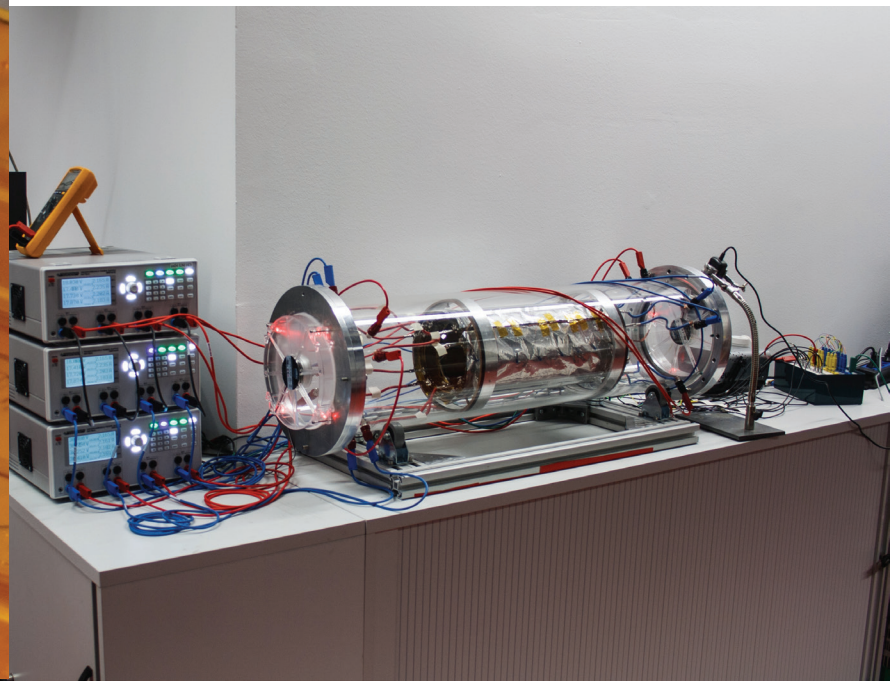
Backup Material

Cooling

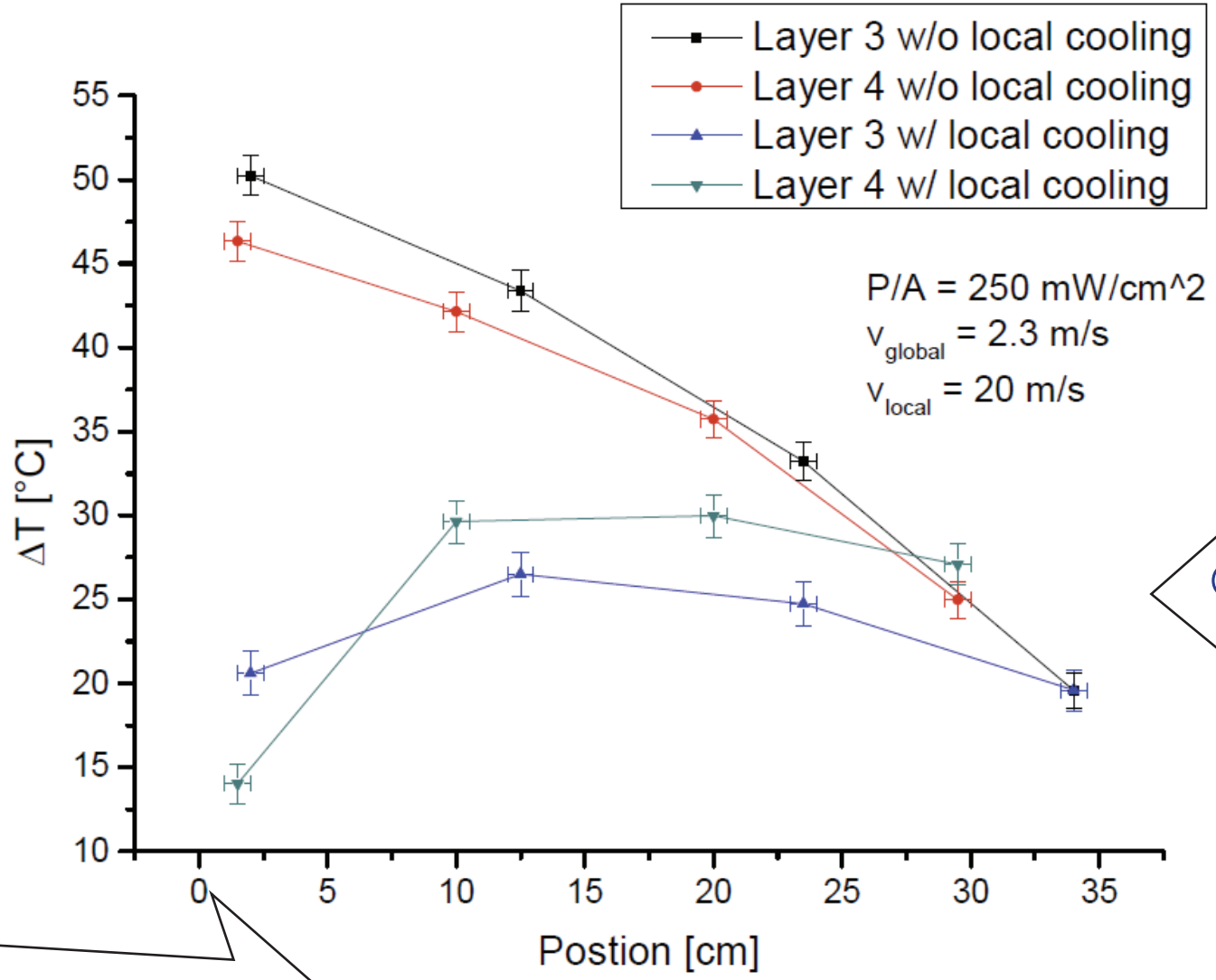
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 250 mW/cm^2 - total ~3 kW
- Simulations: Need ~ several m/s flow

- Full scale heatable prototype built
- 36 cm active length
- Vibrations studied using Michelson-Interferometer
- Can keep temperature below 70°C





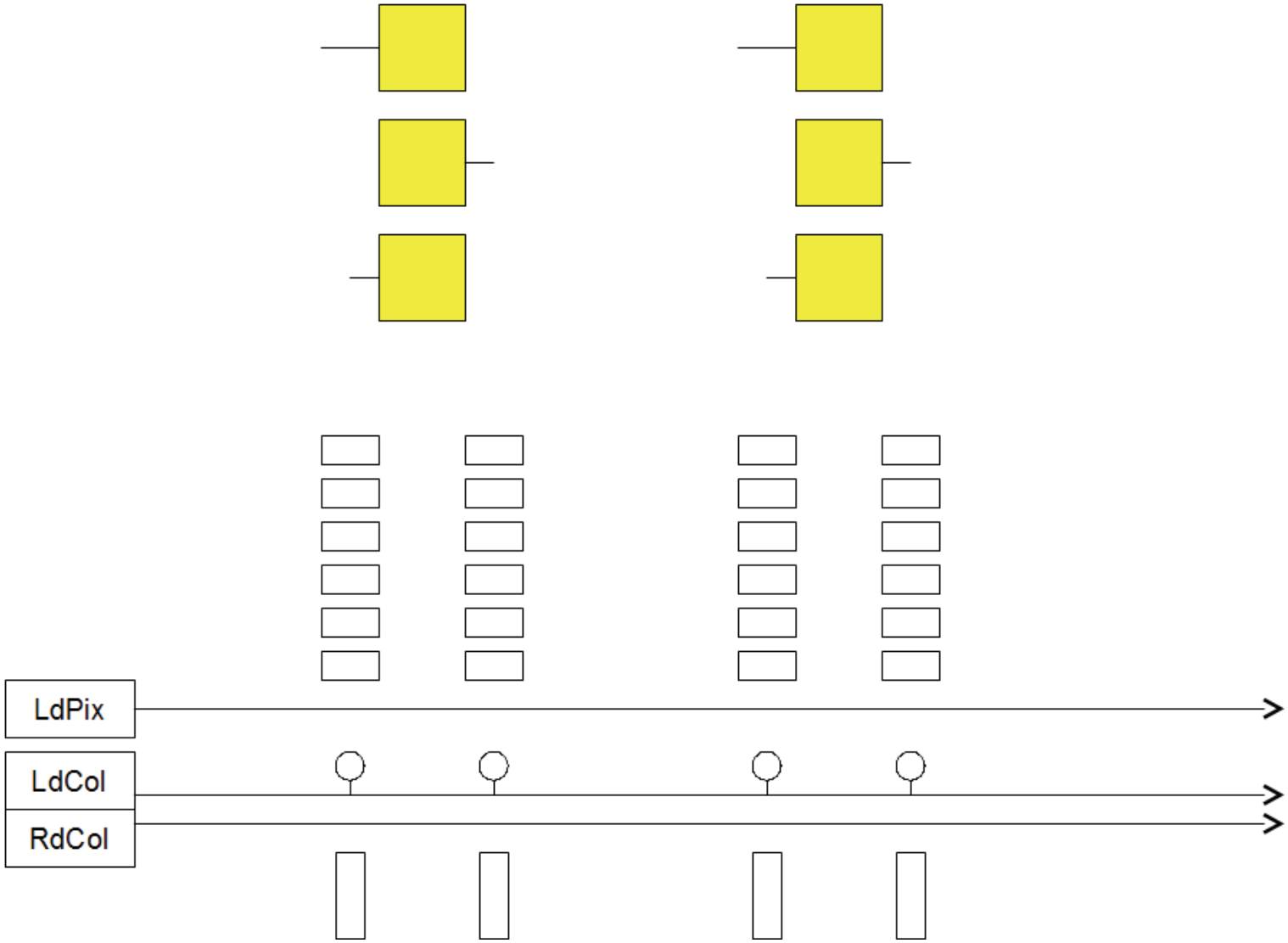
Cooling tests



Global helium stream

Local helium stream

Readout



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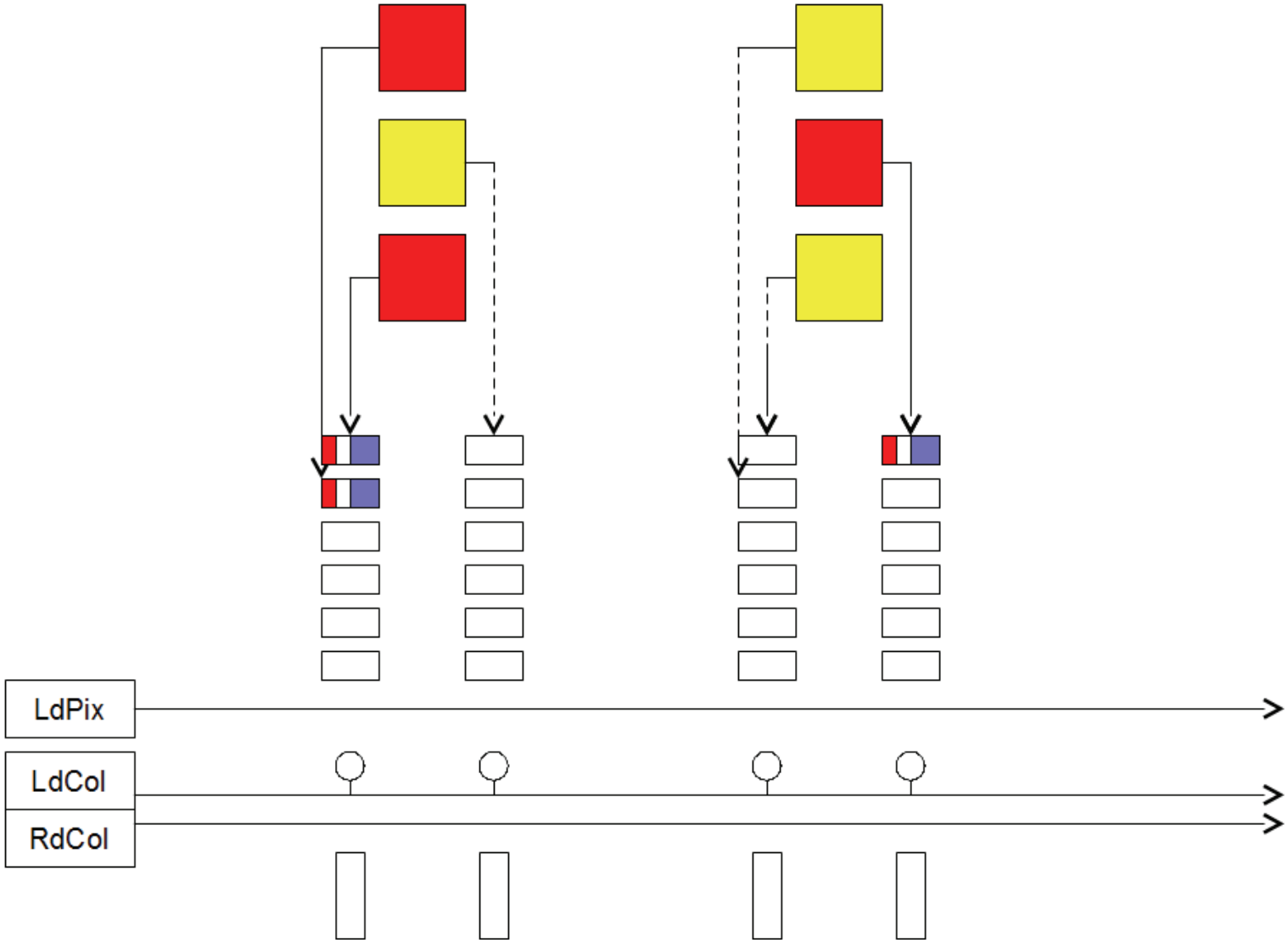

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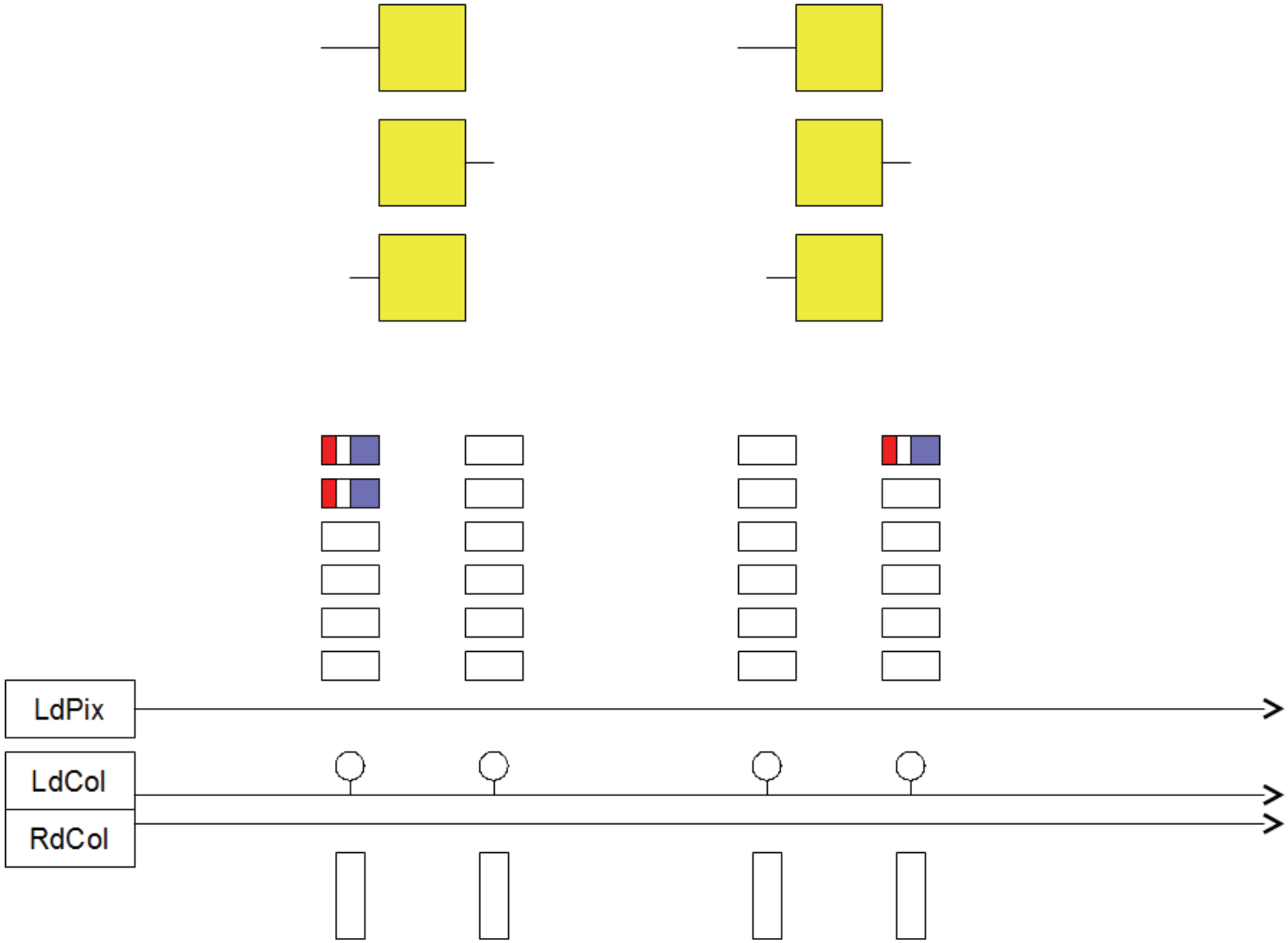

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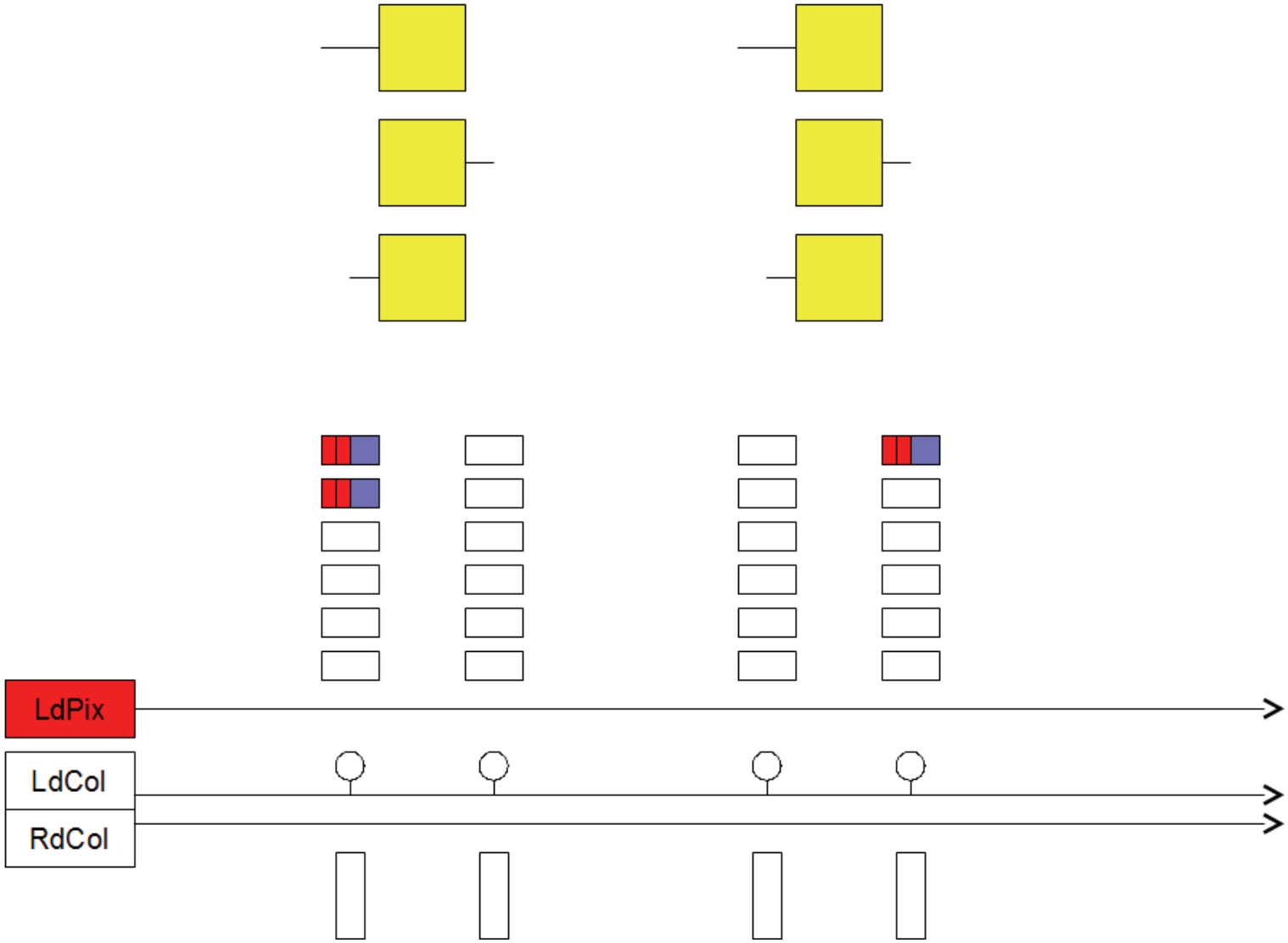

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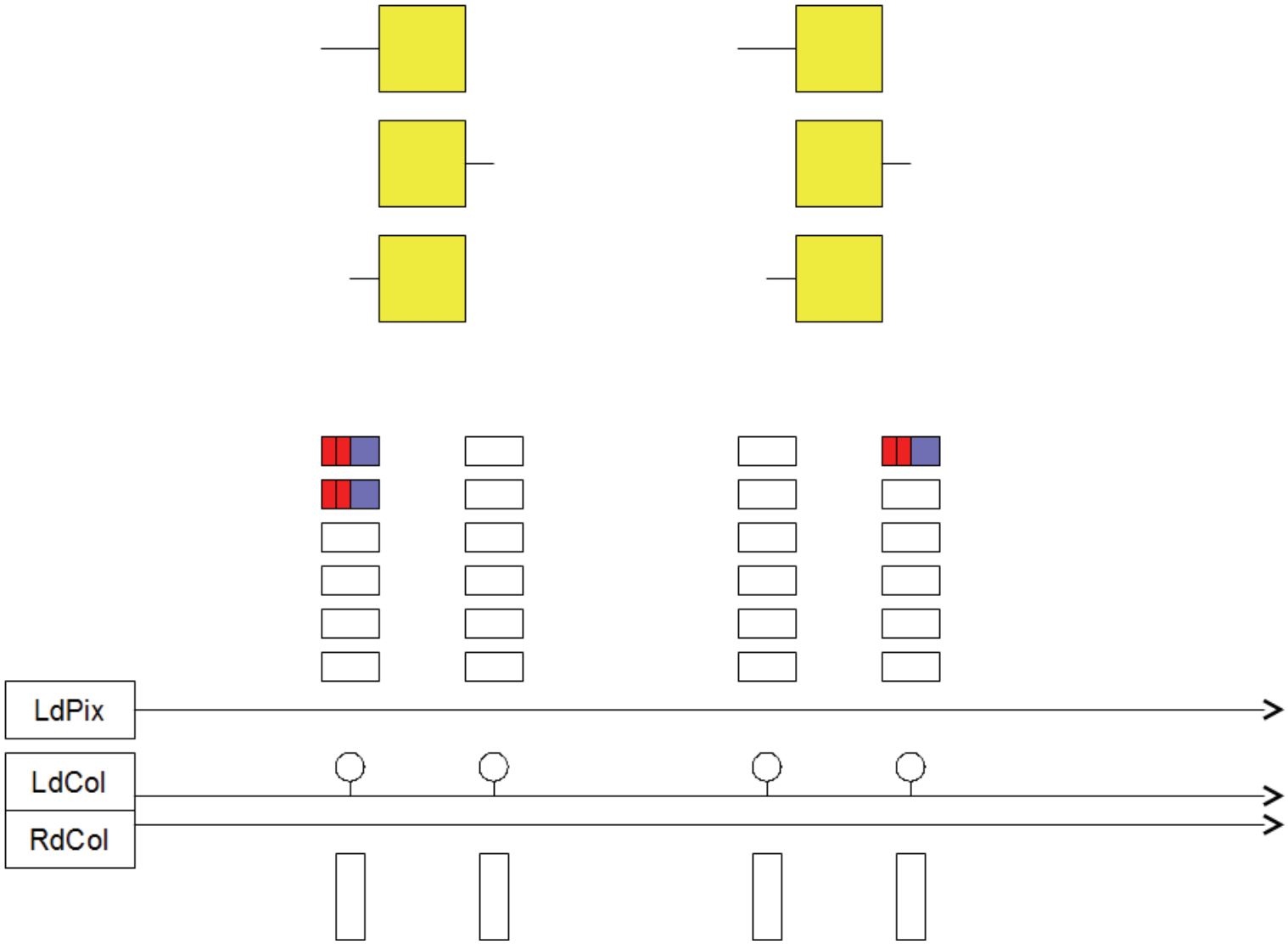

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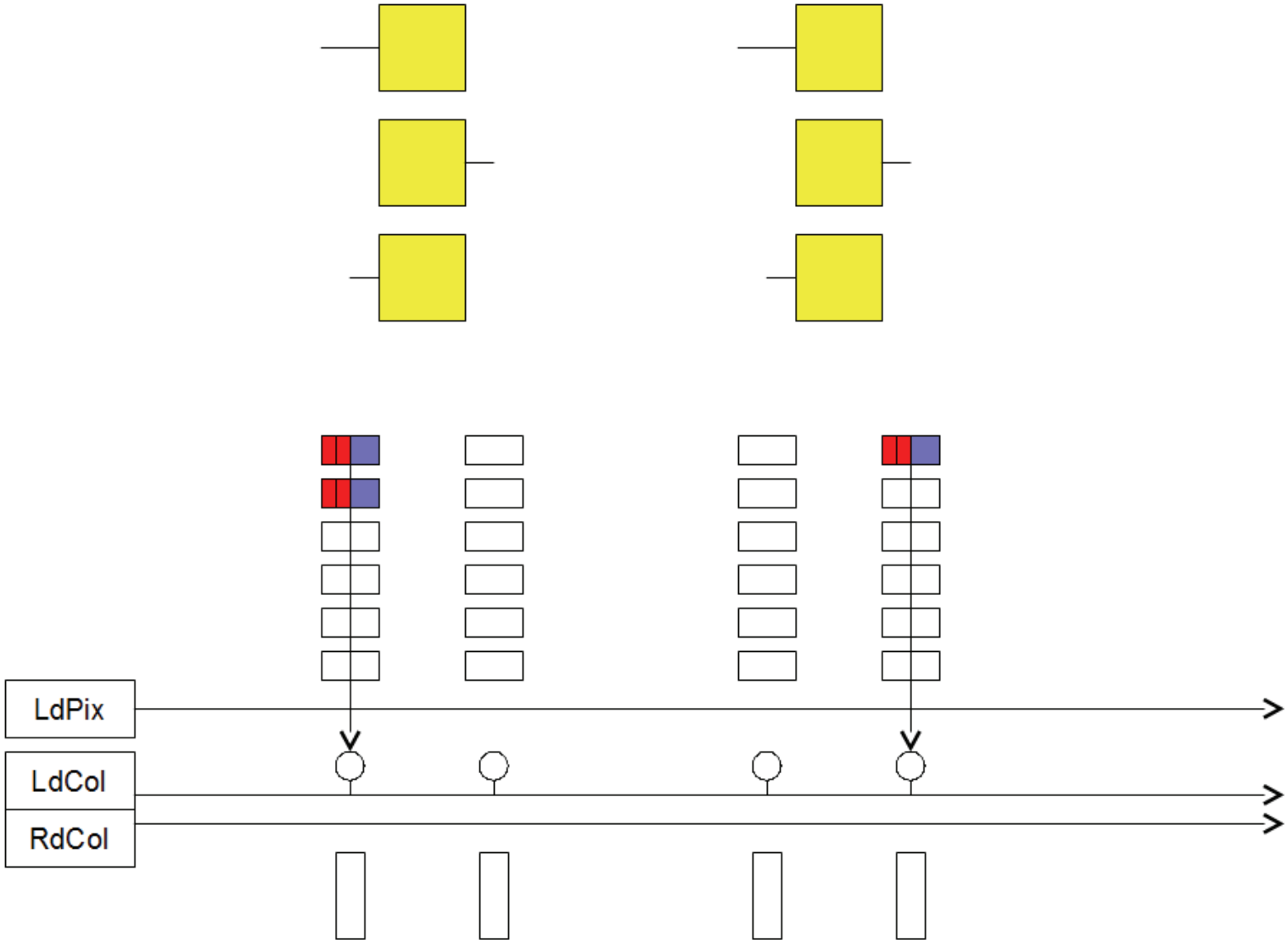

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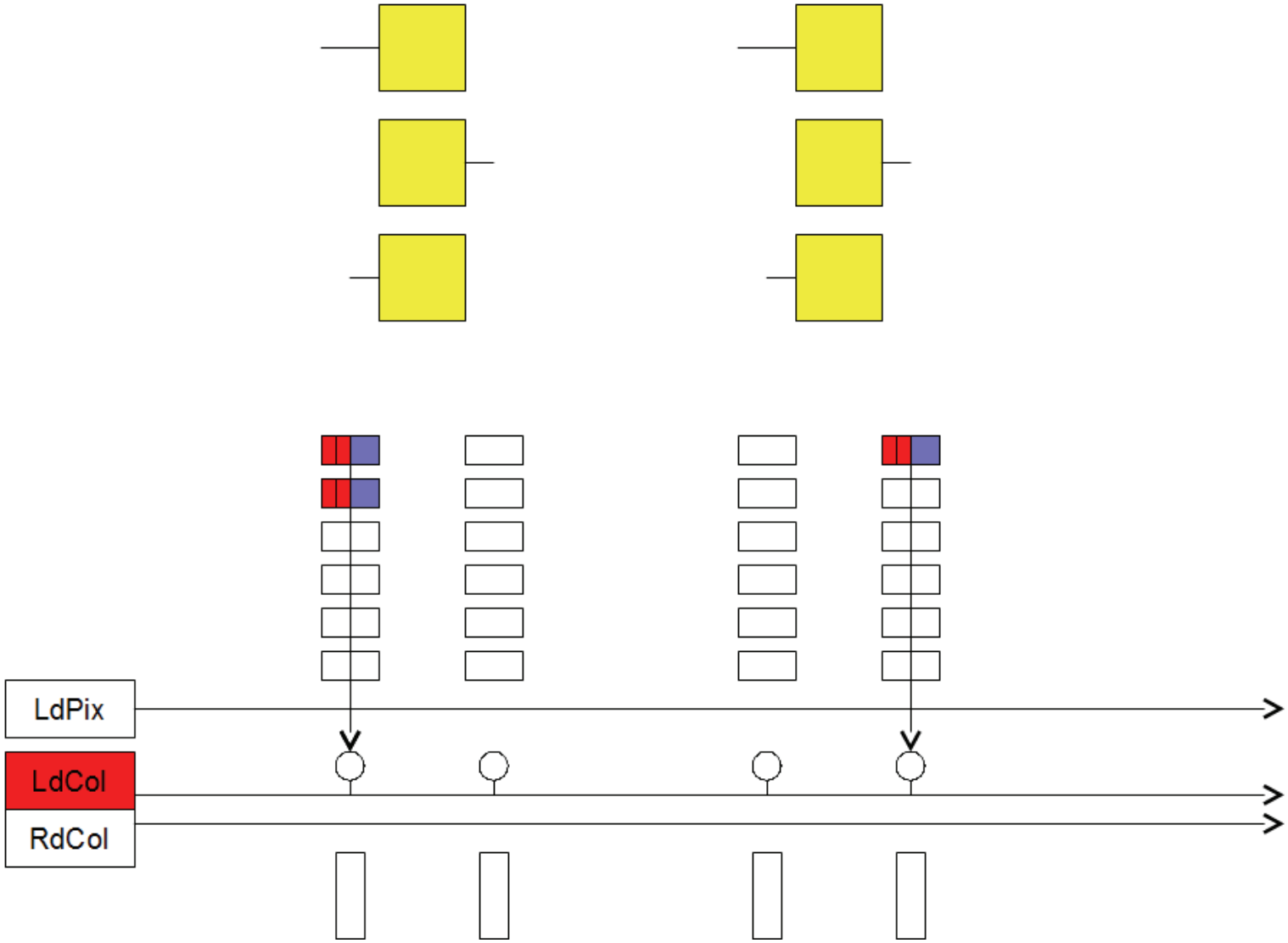

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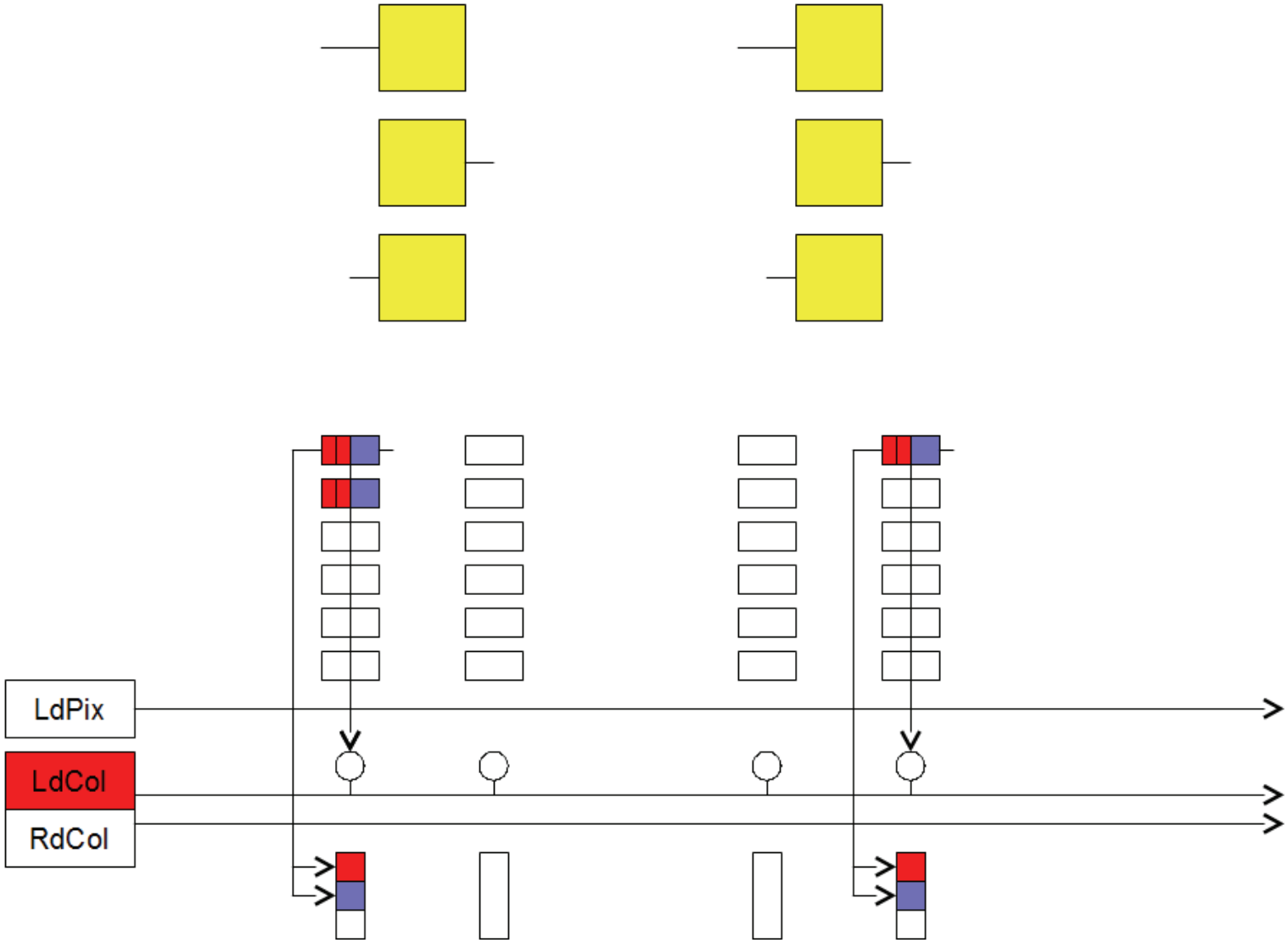

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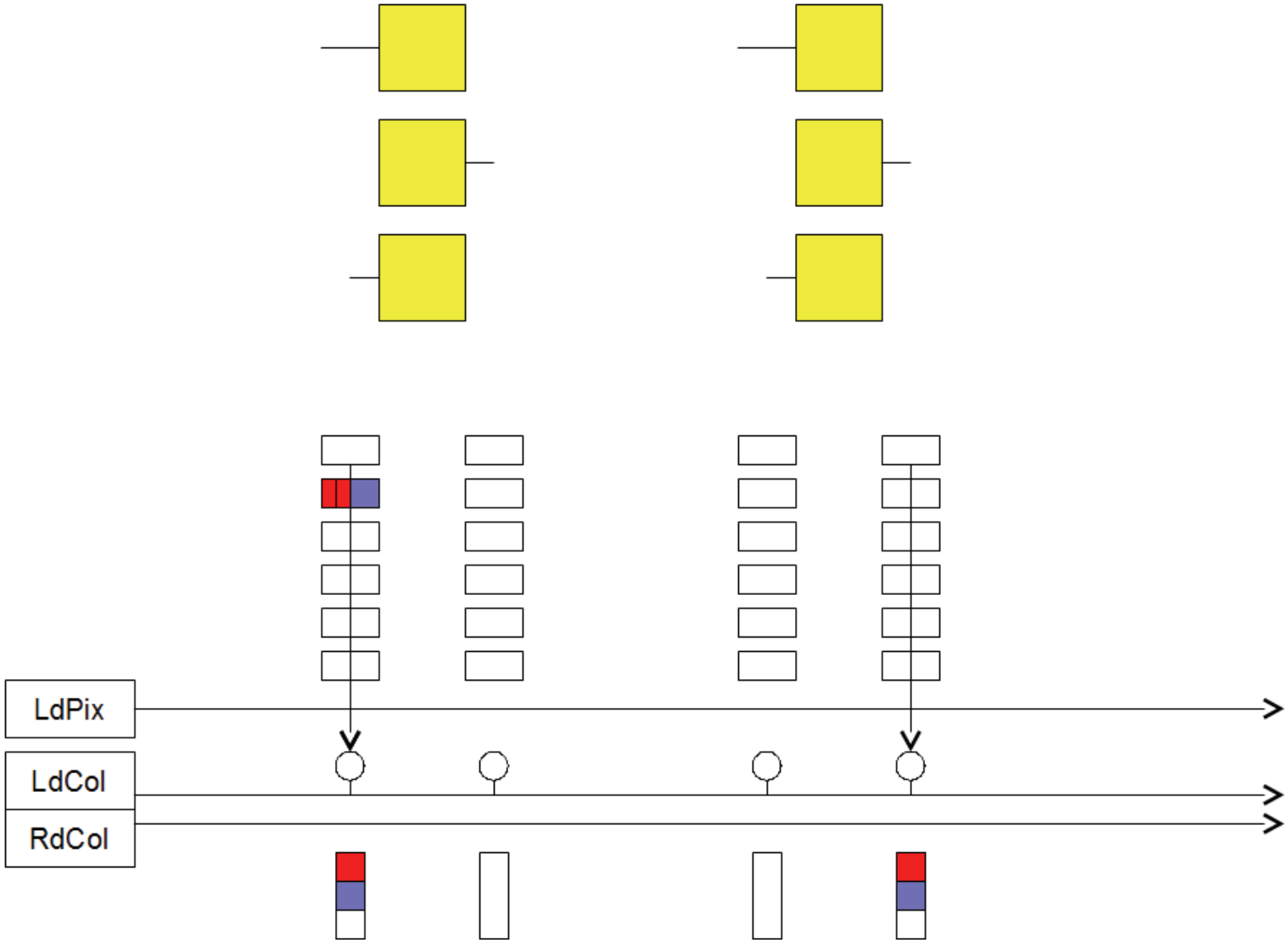

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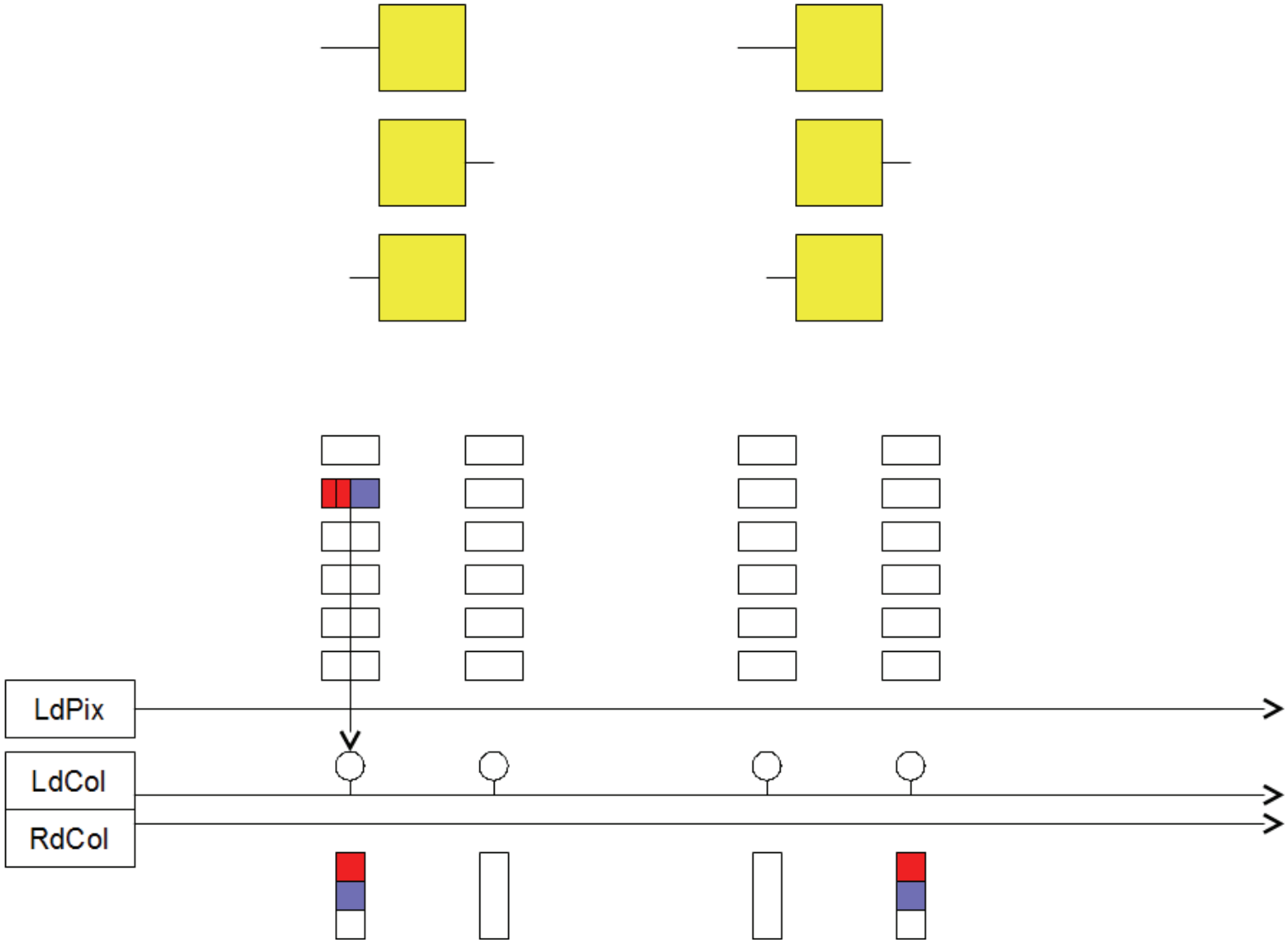

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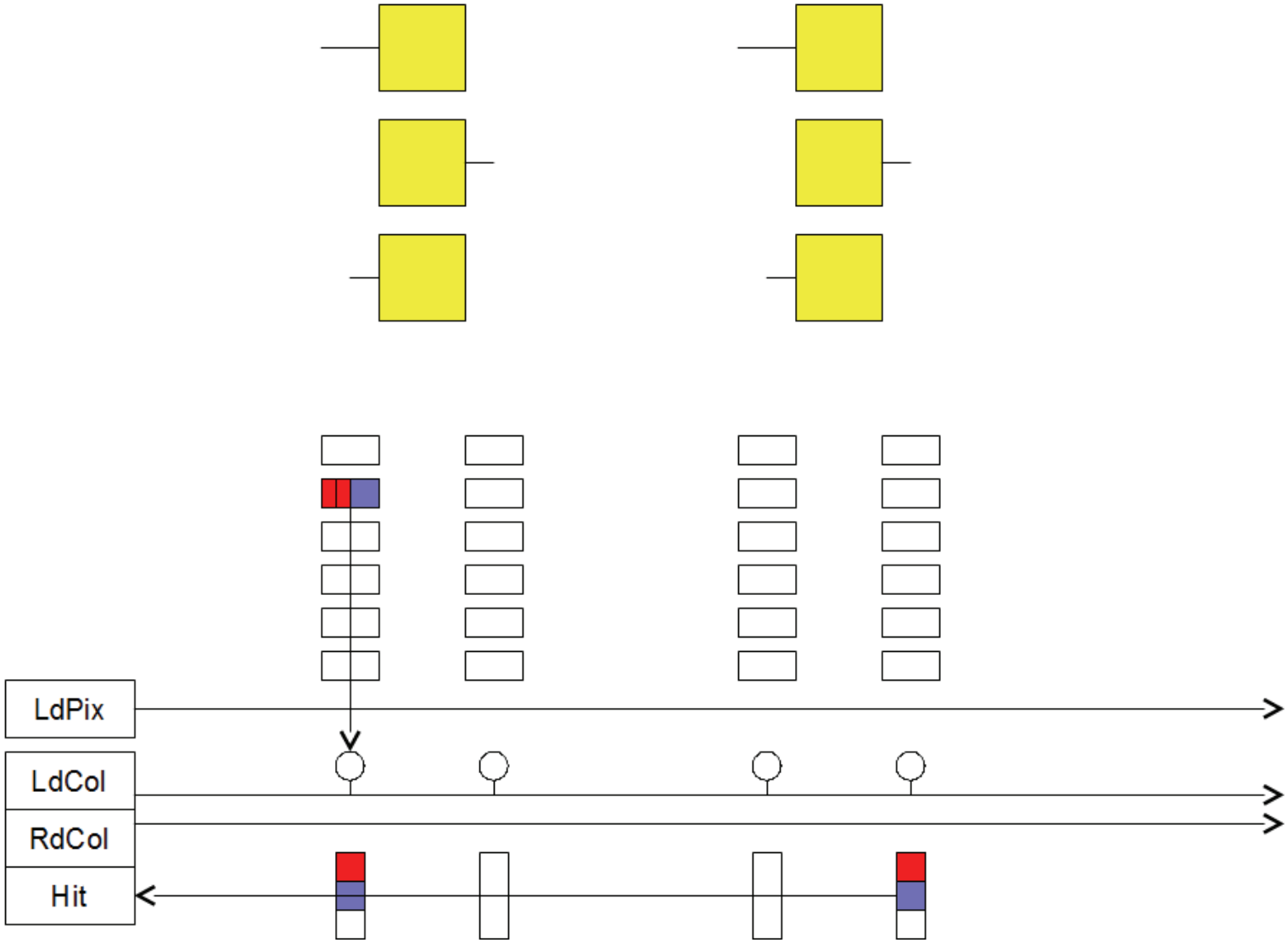

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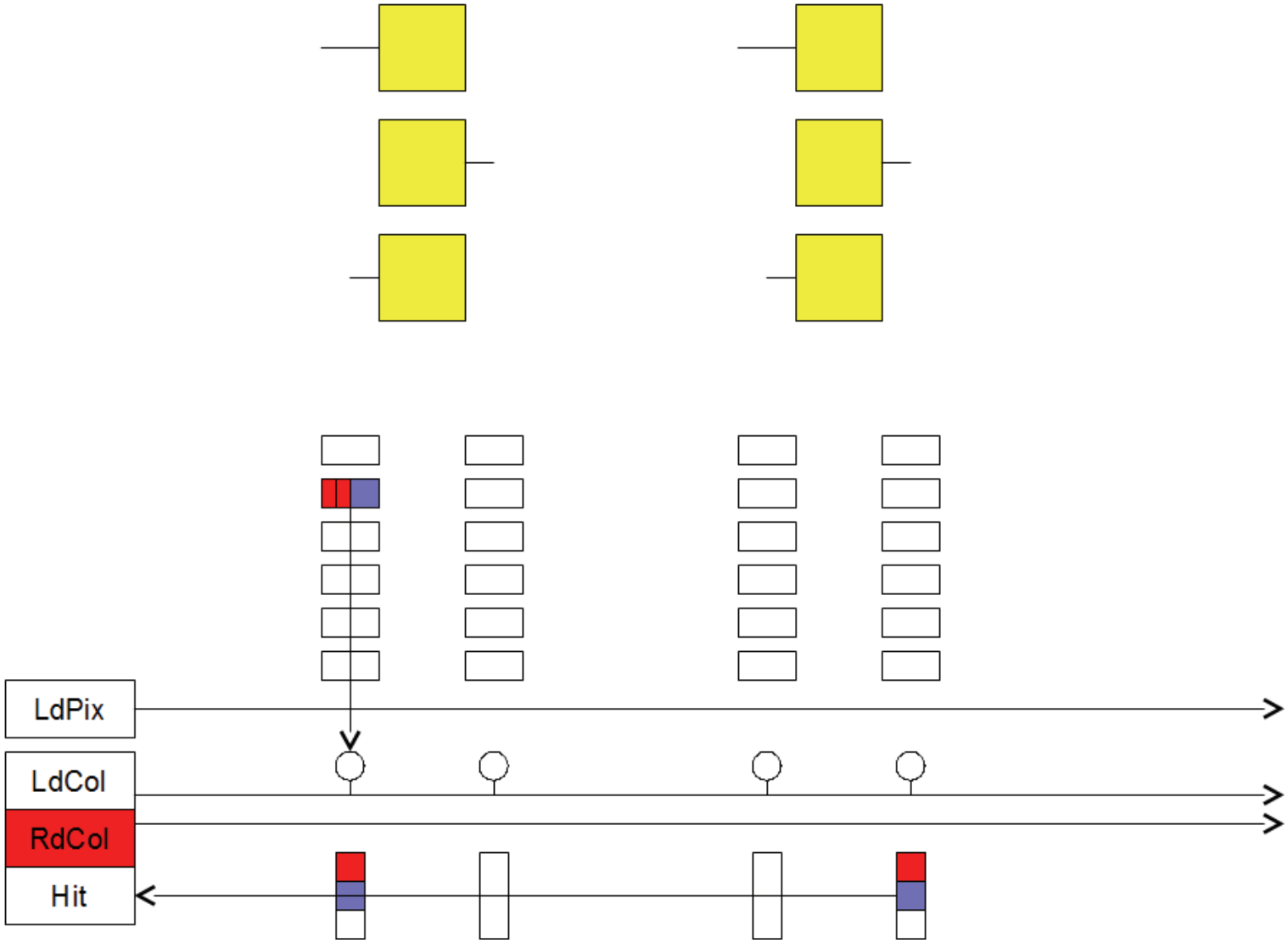

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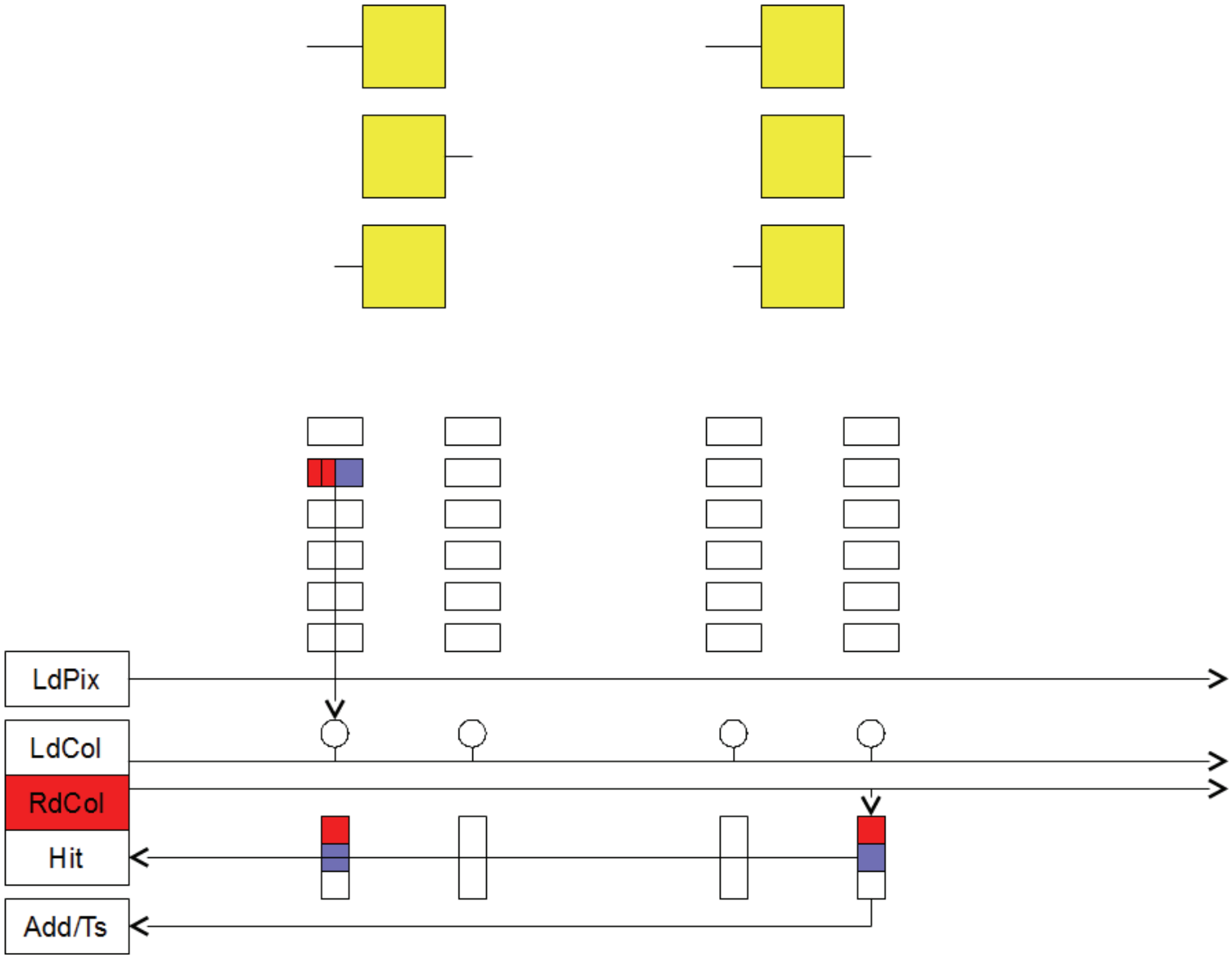

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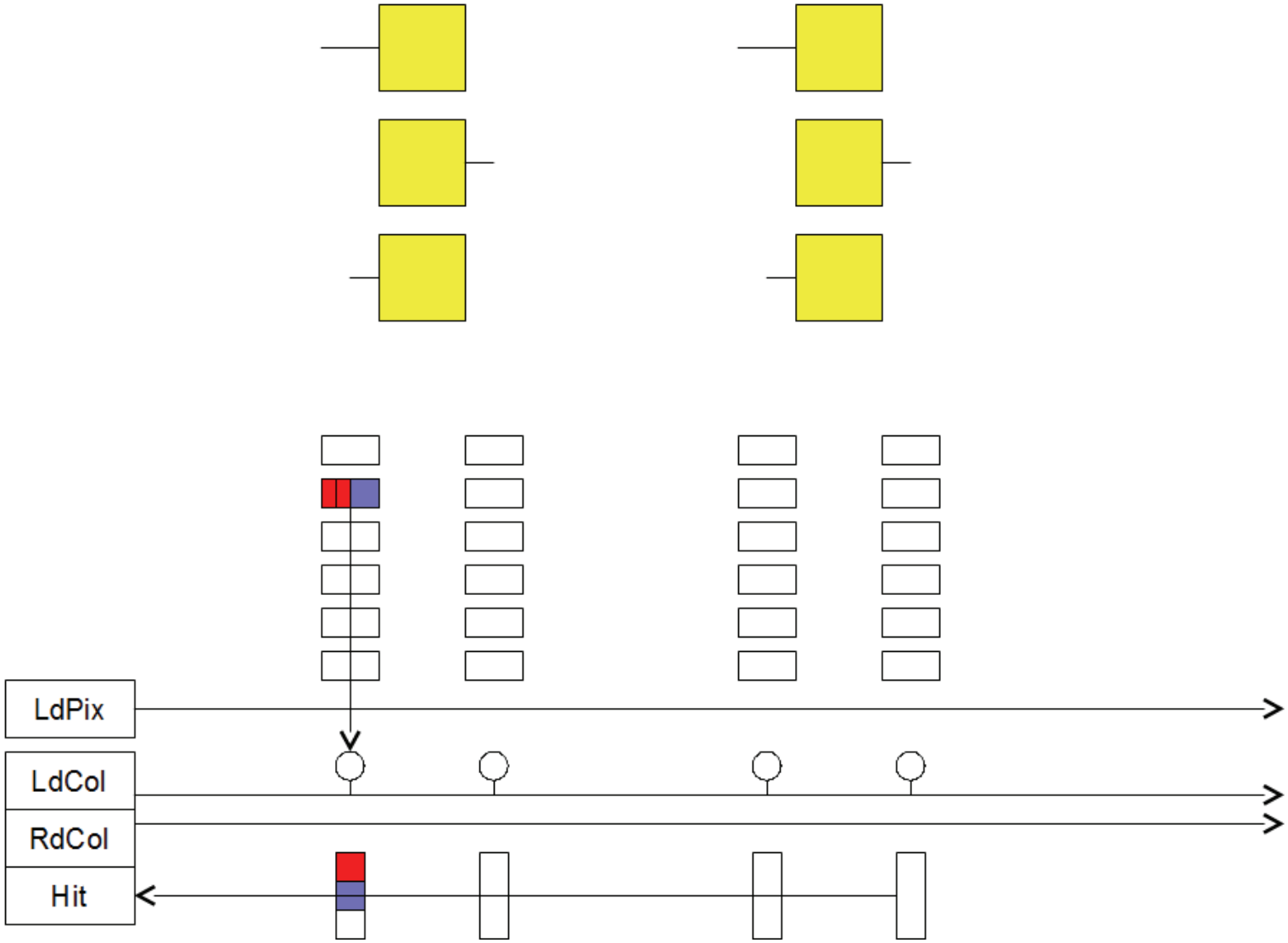

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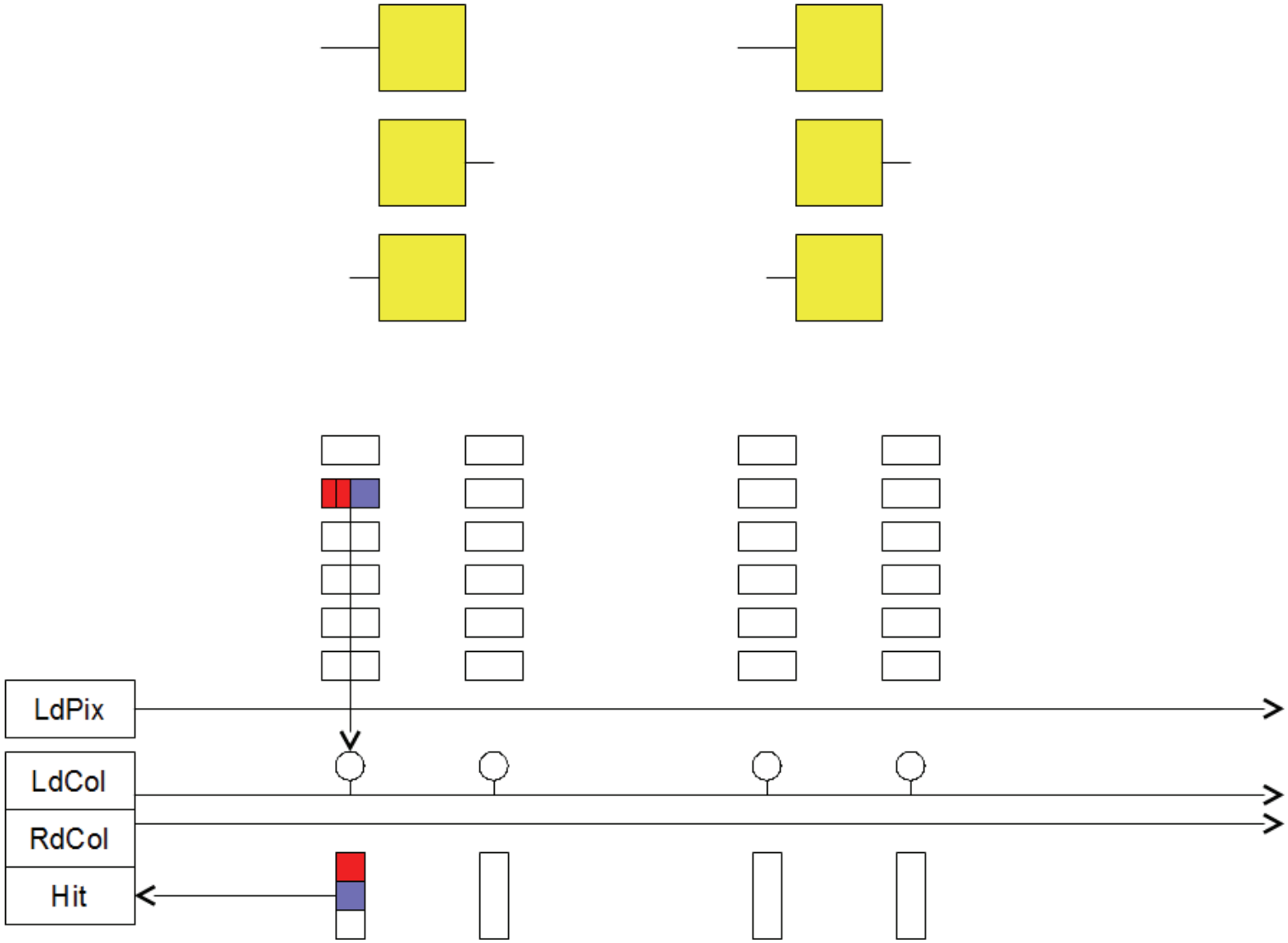

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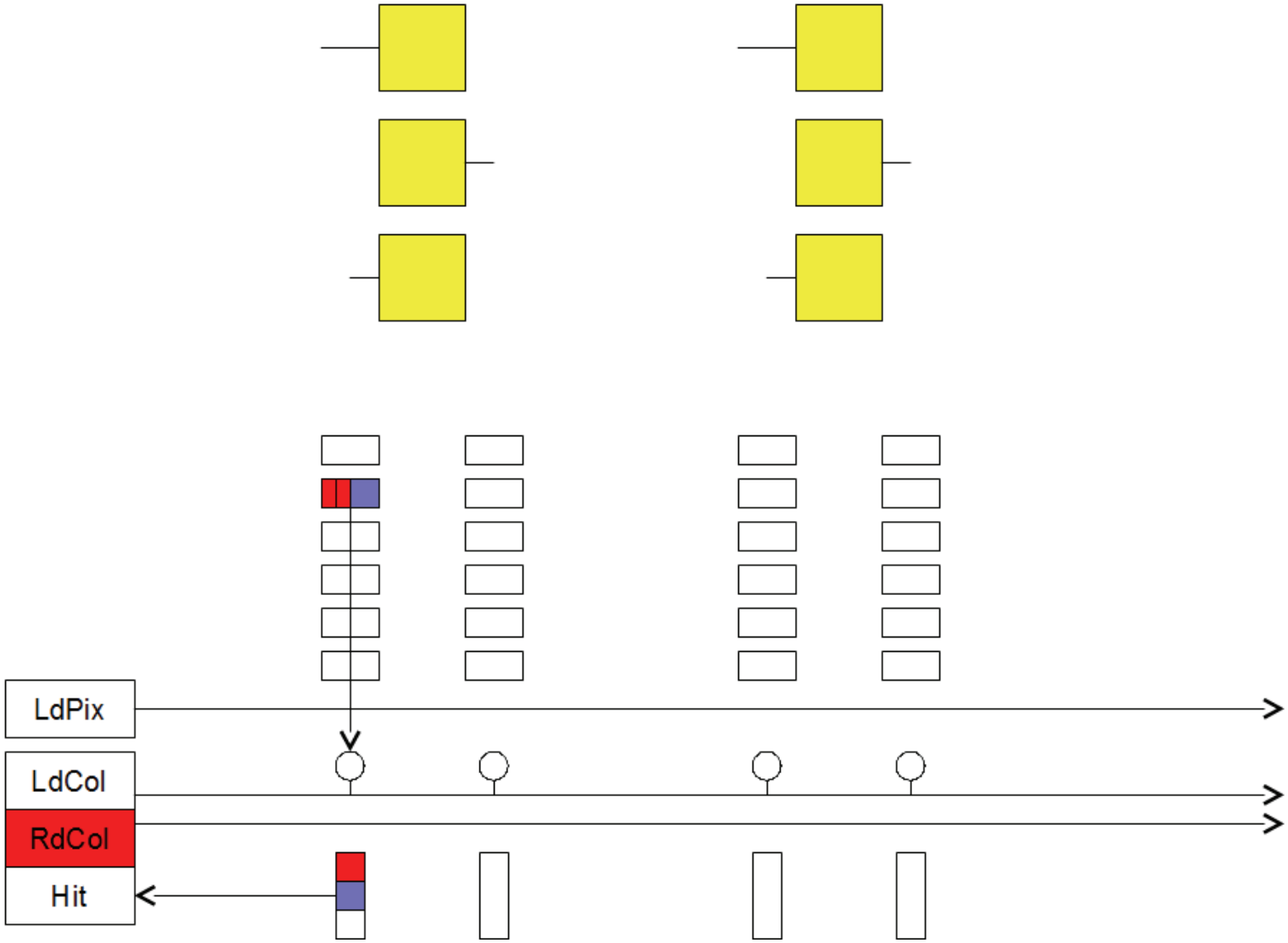

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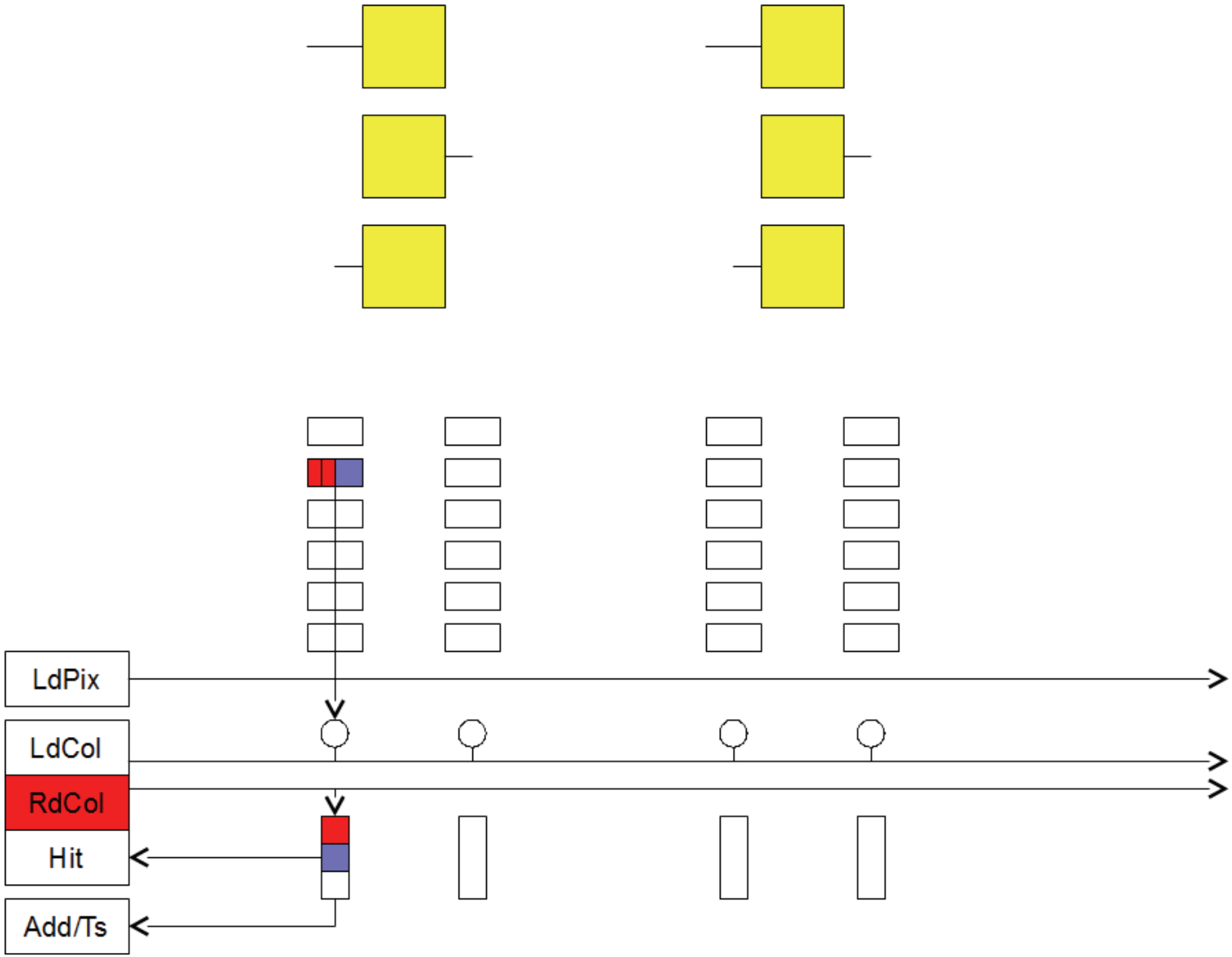

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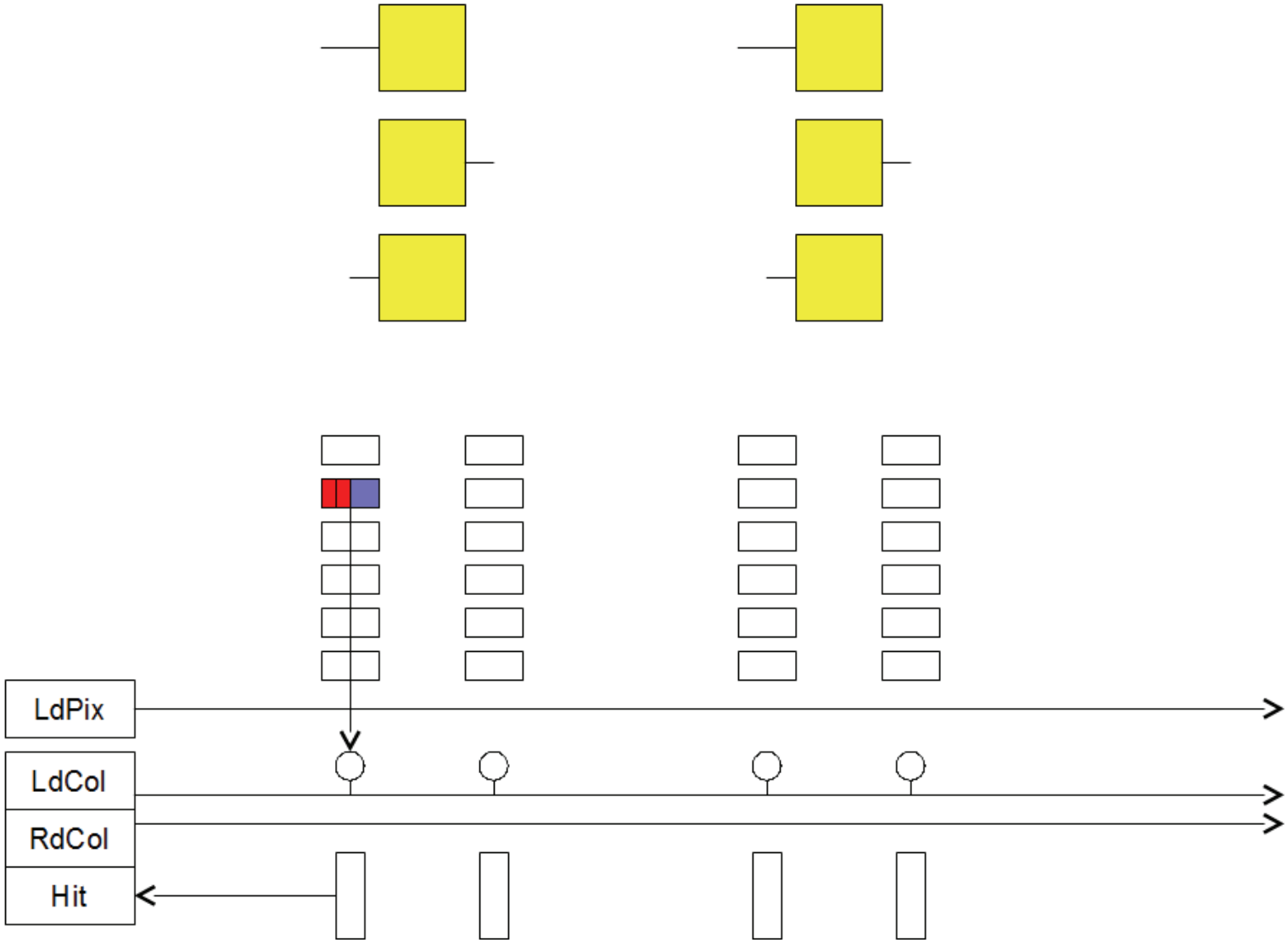

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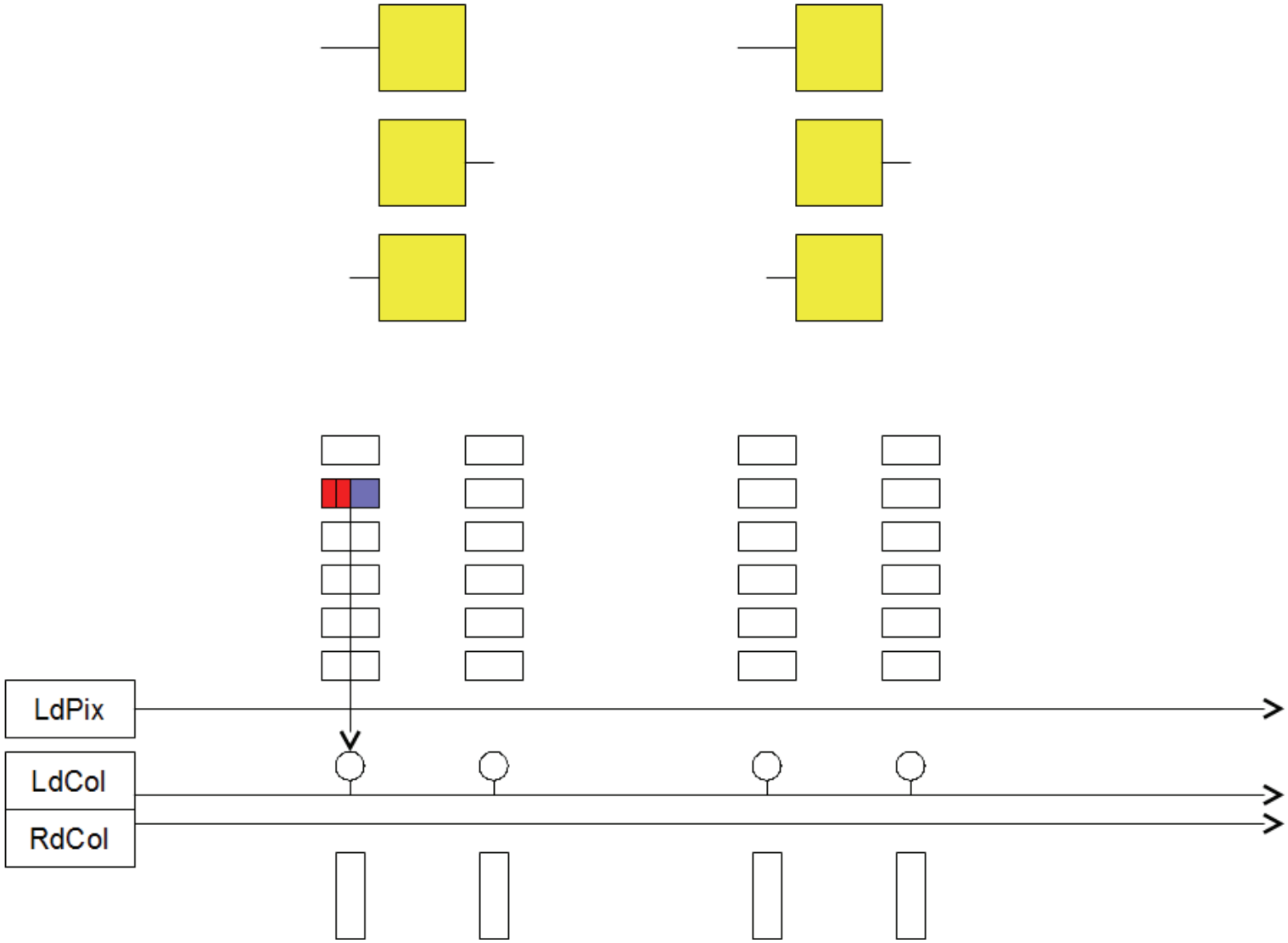

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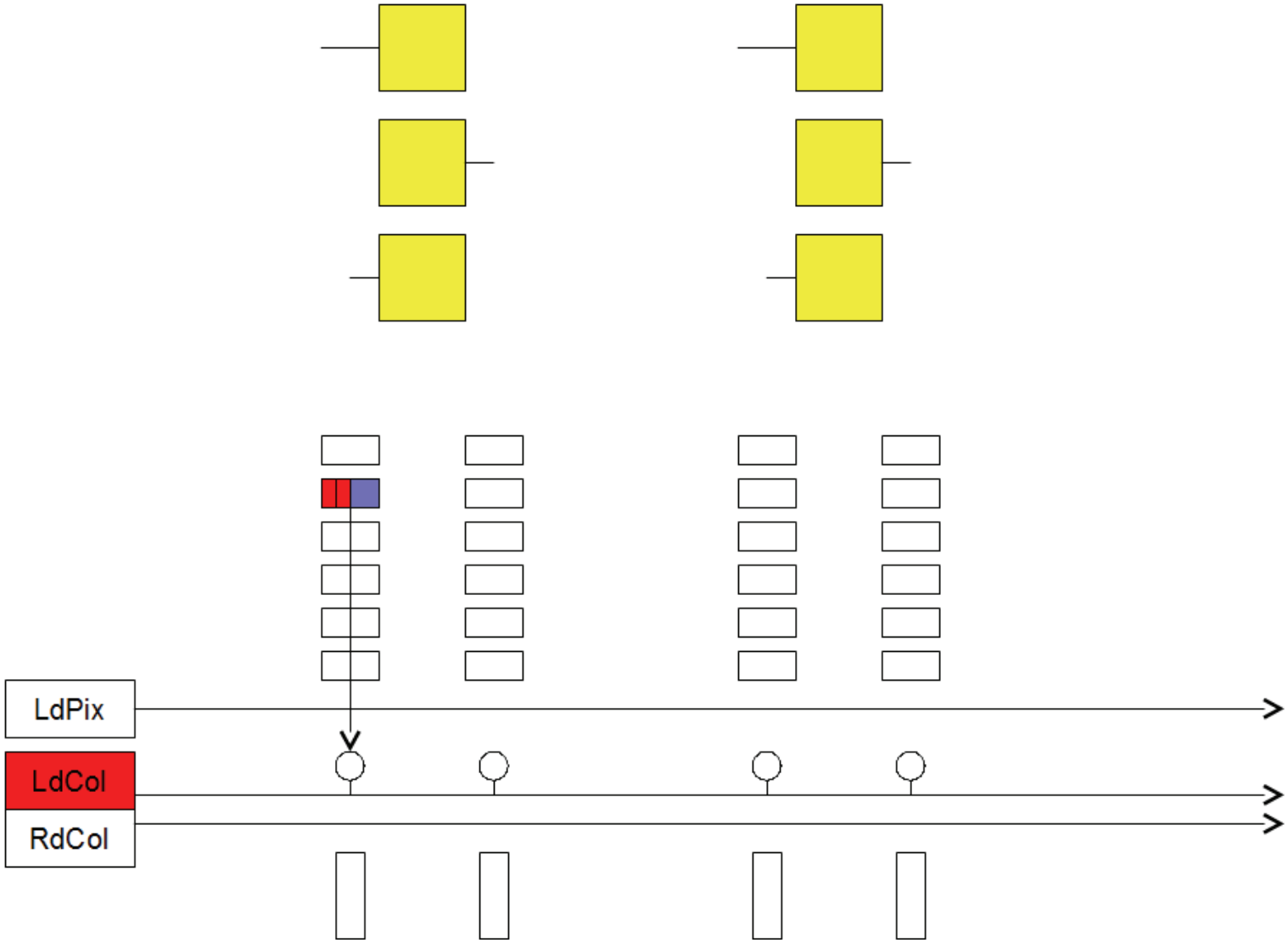

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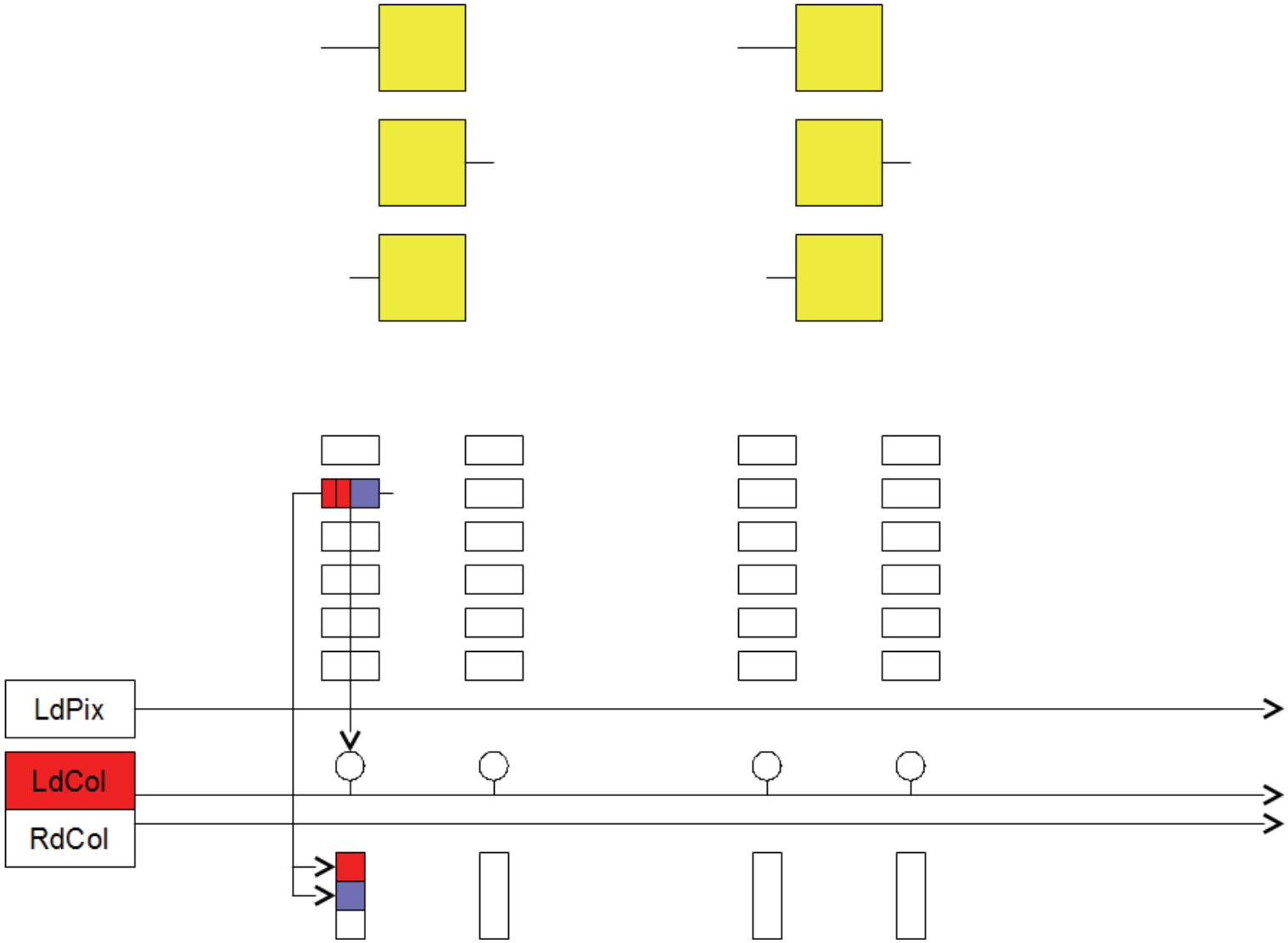

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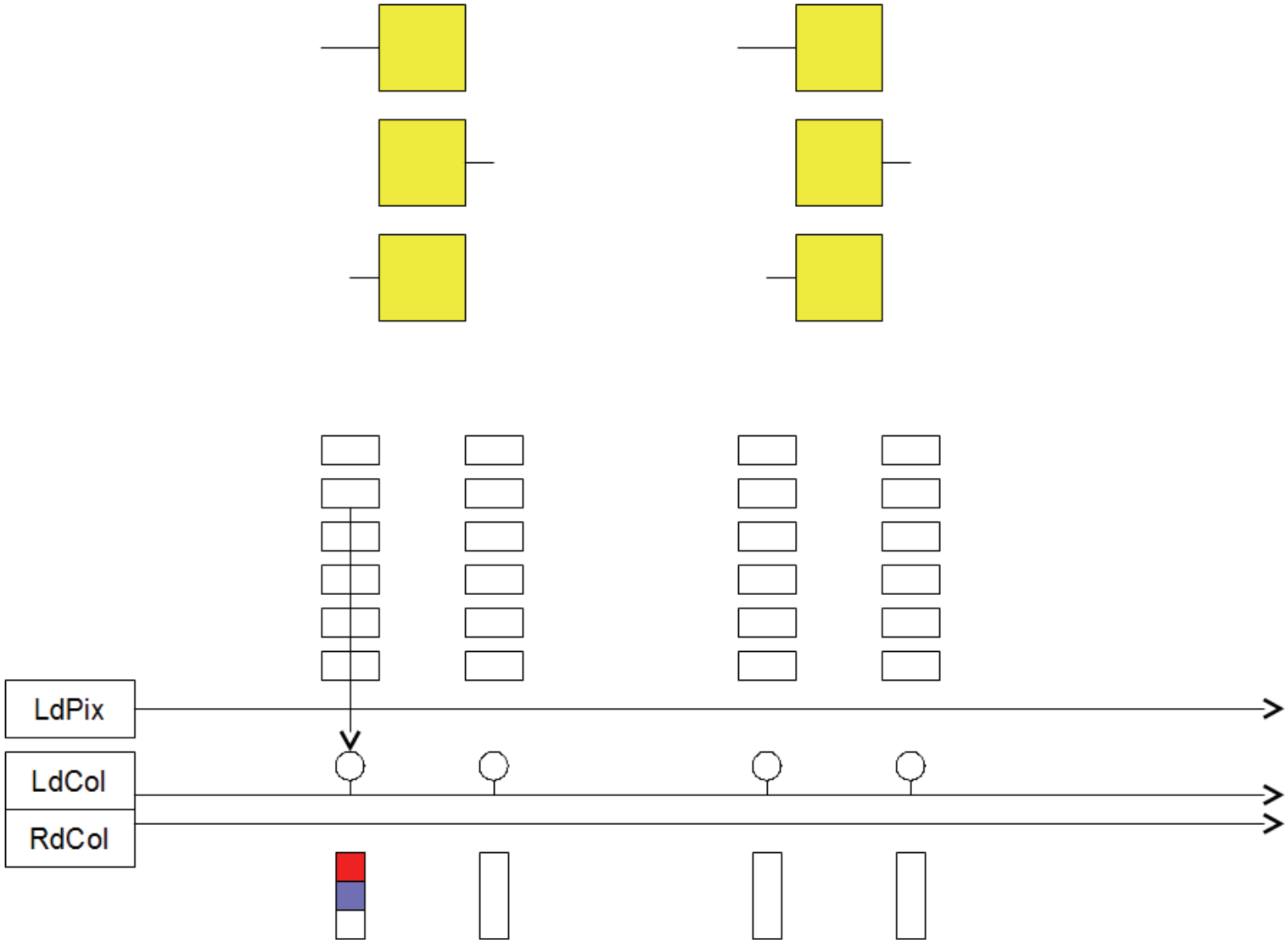

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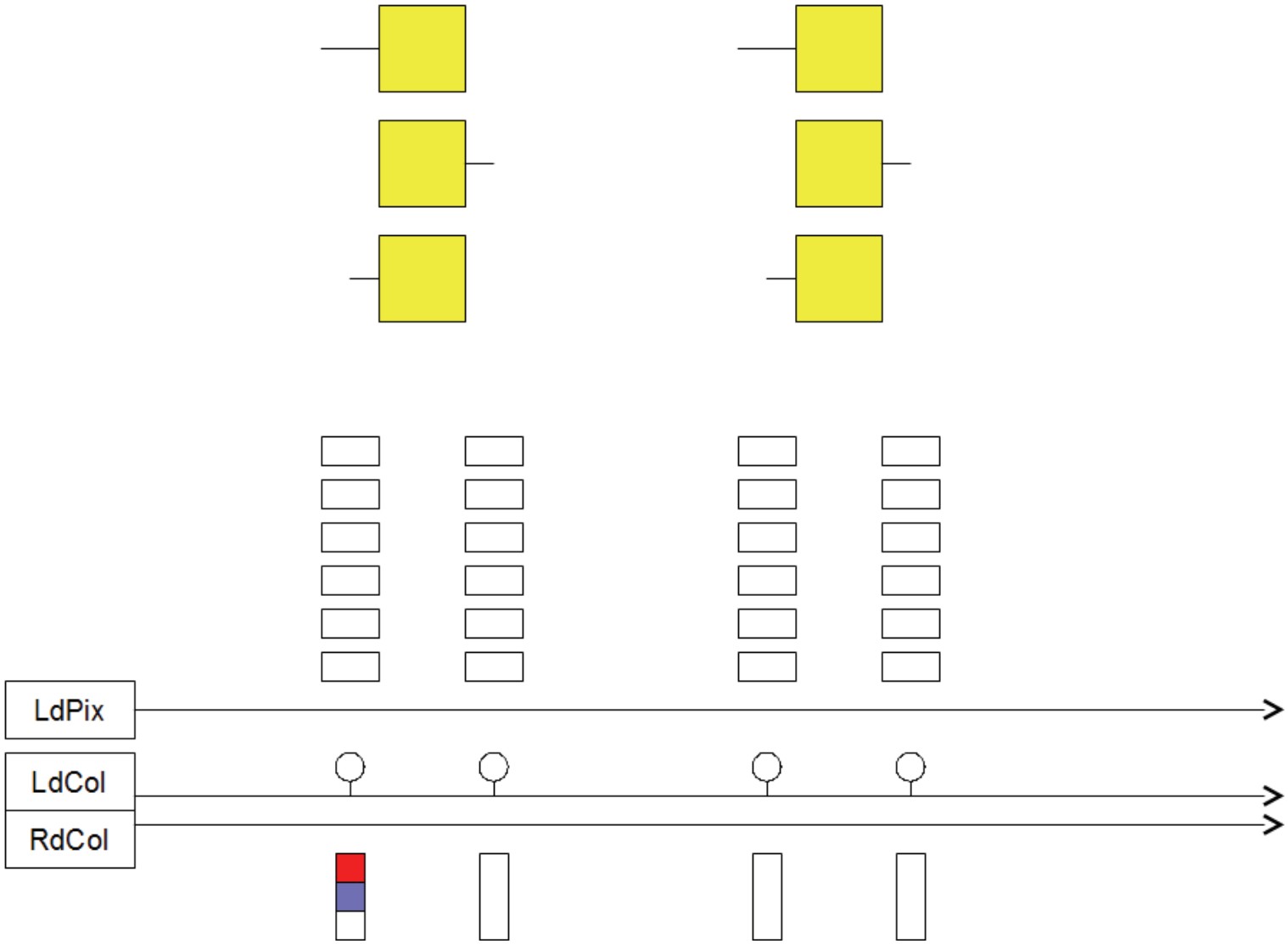

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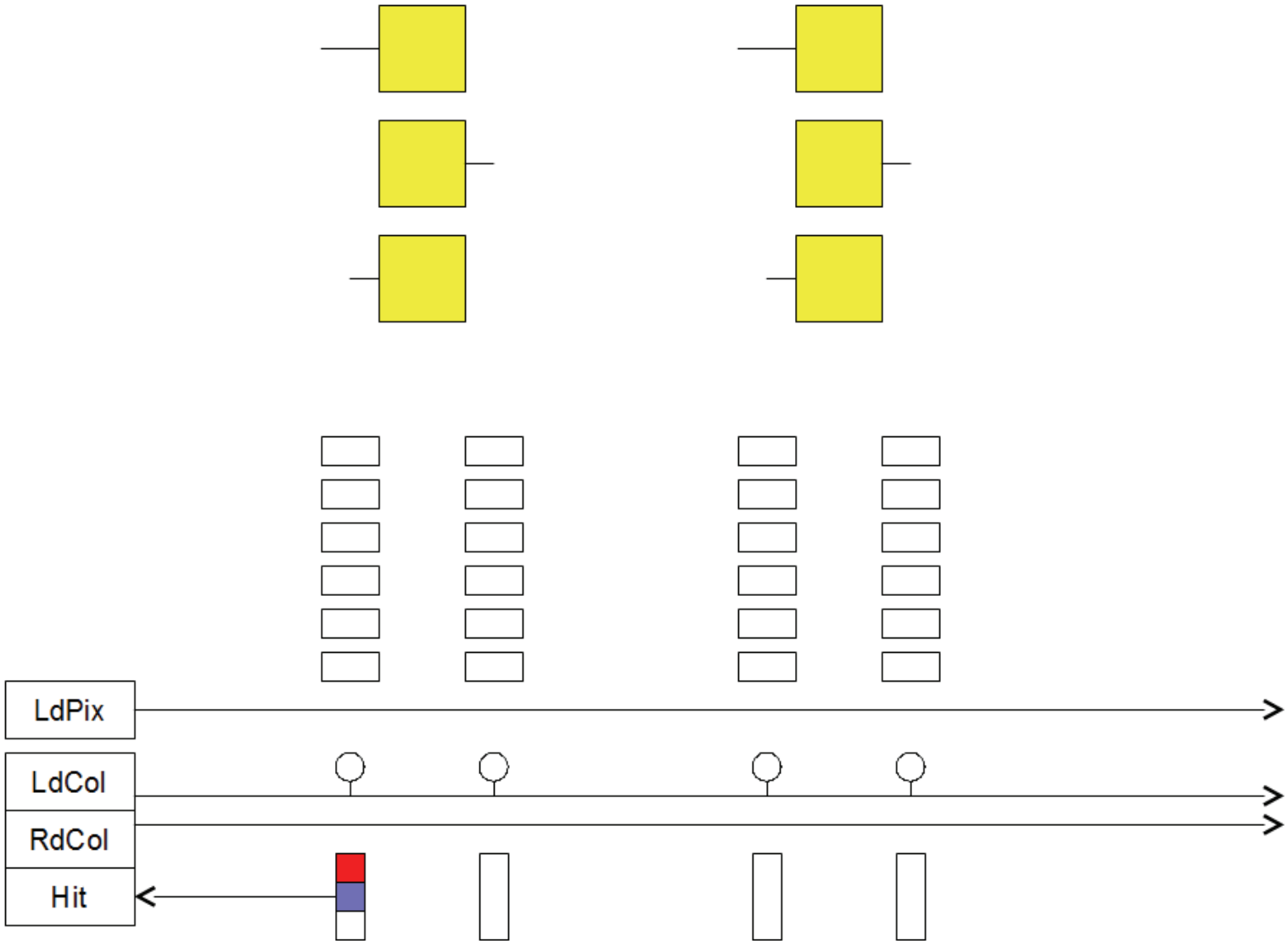

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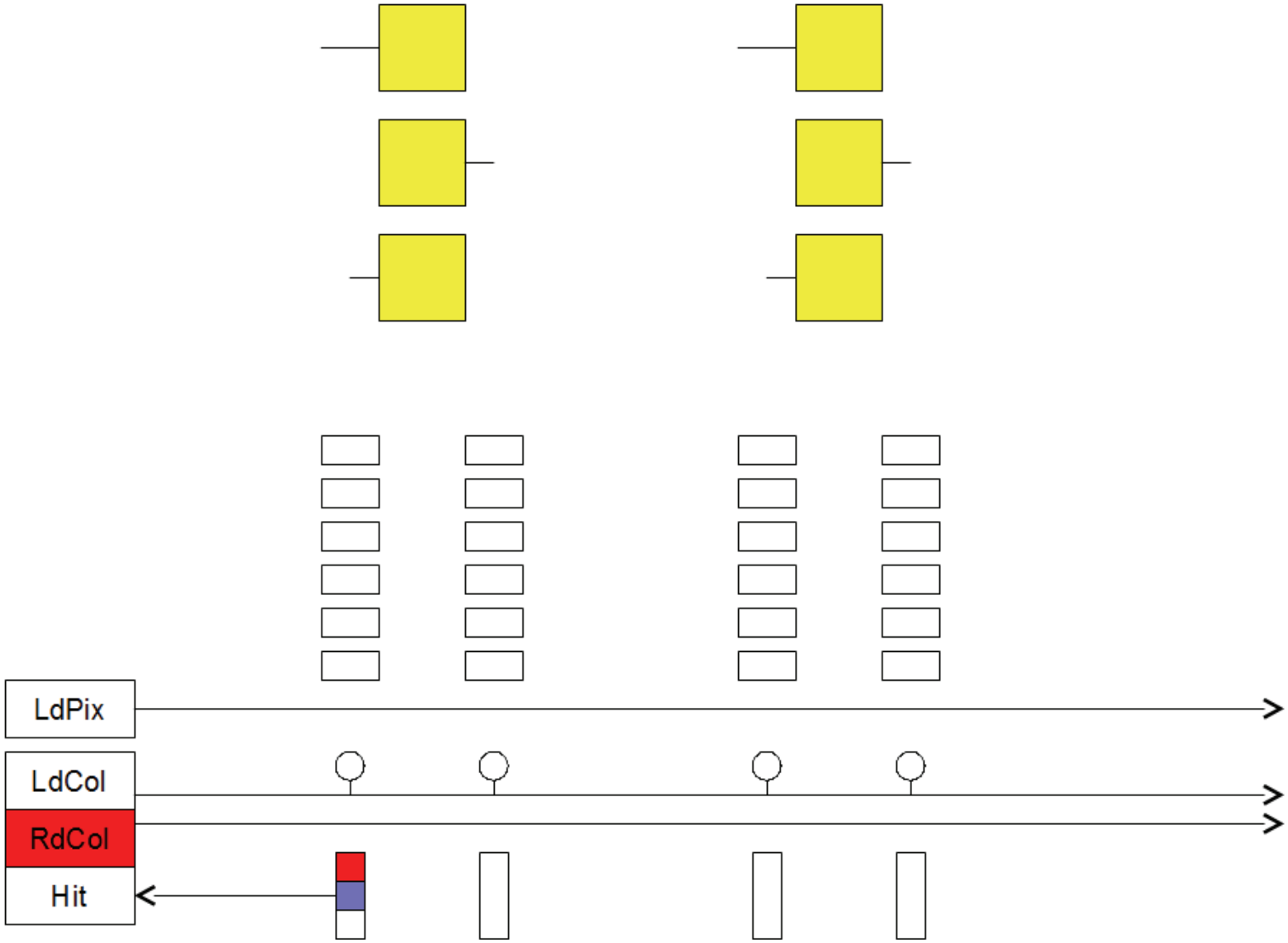

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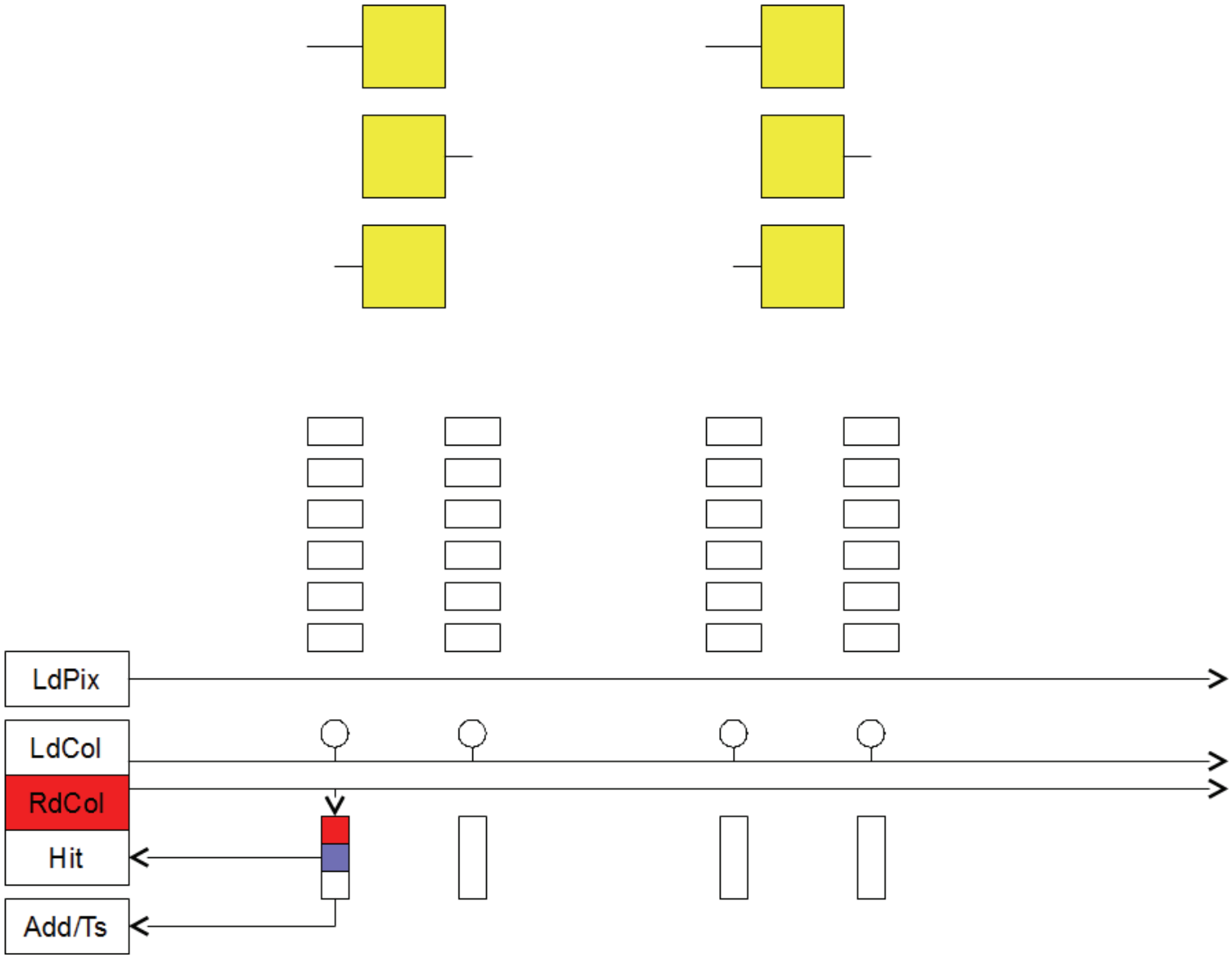

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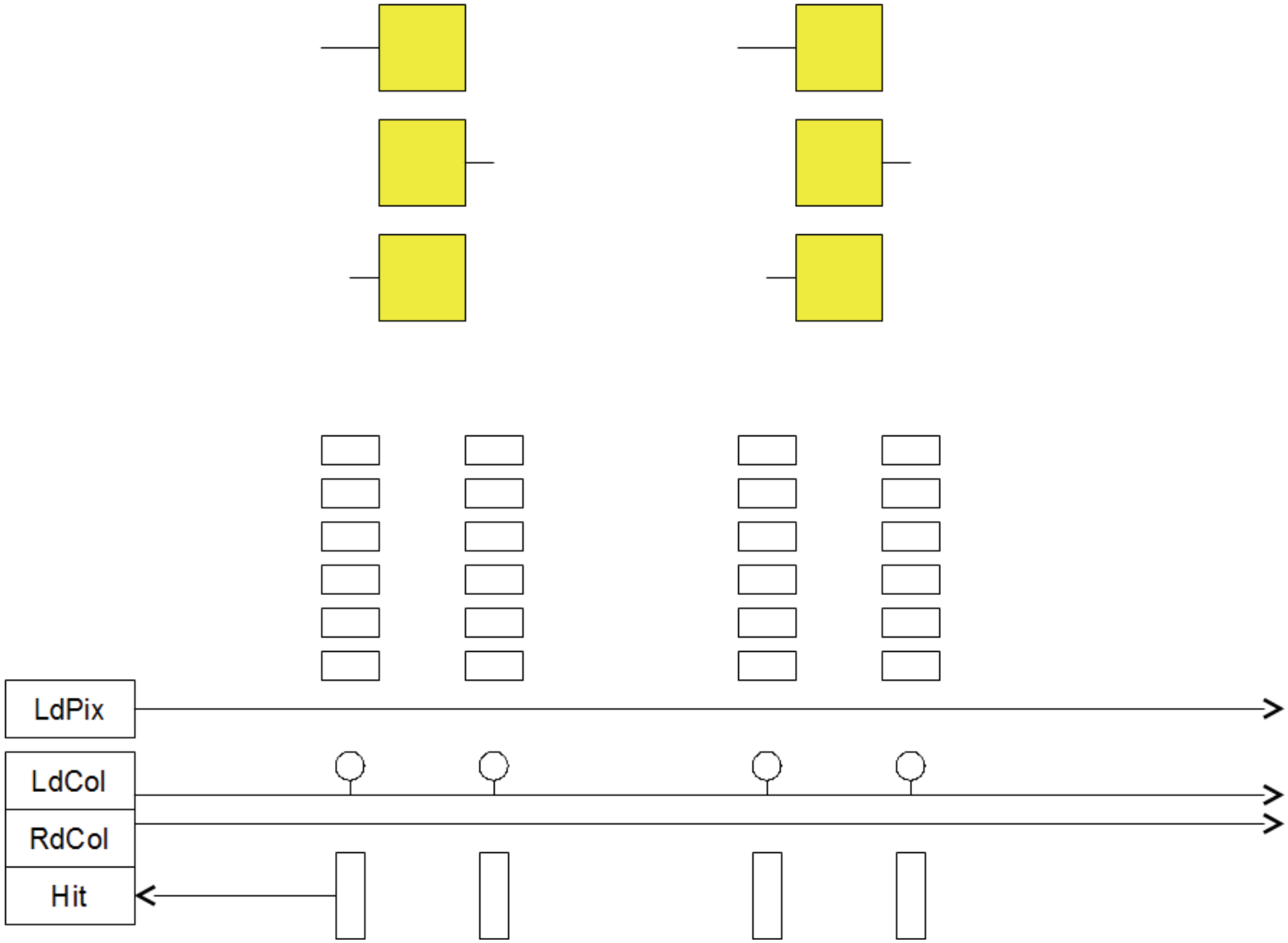

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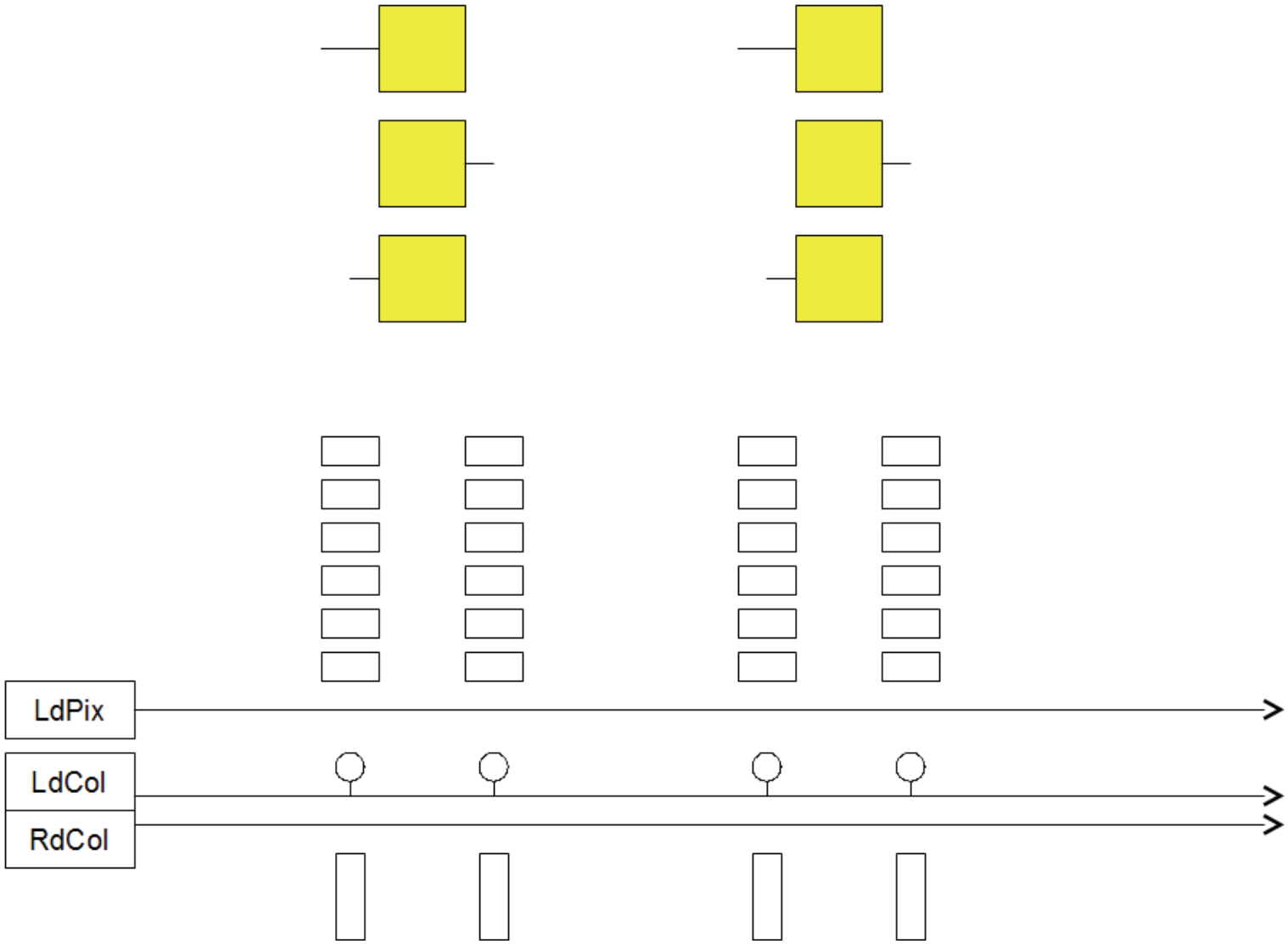
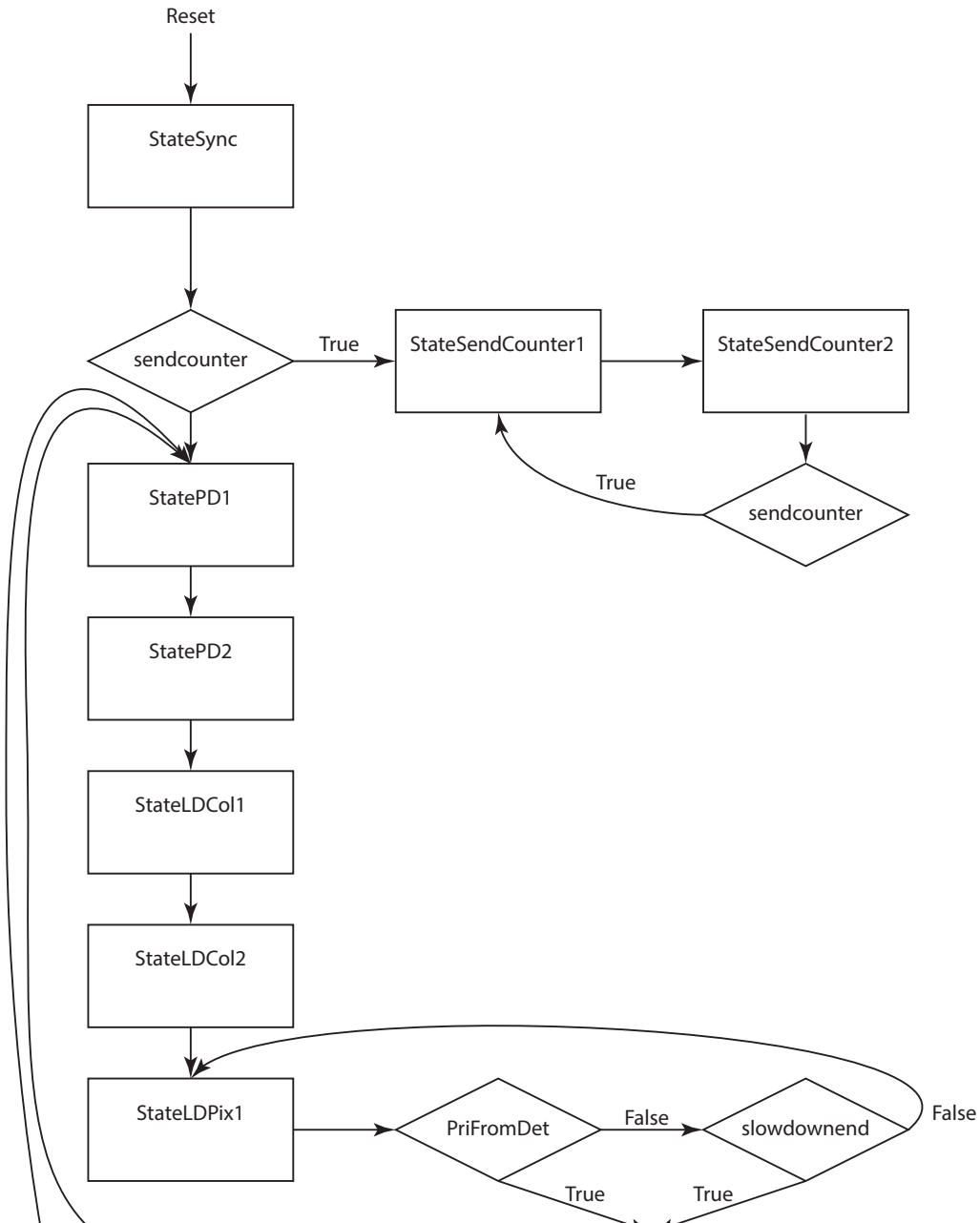
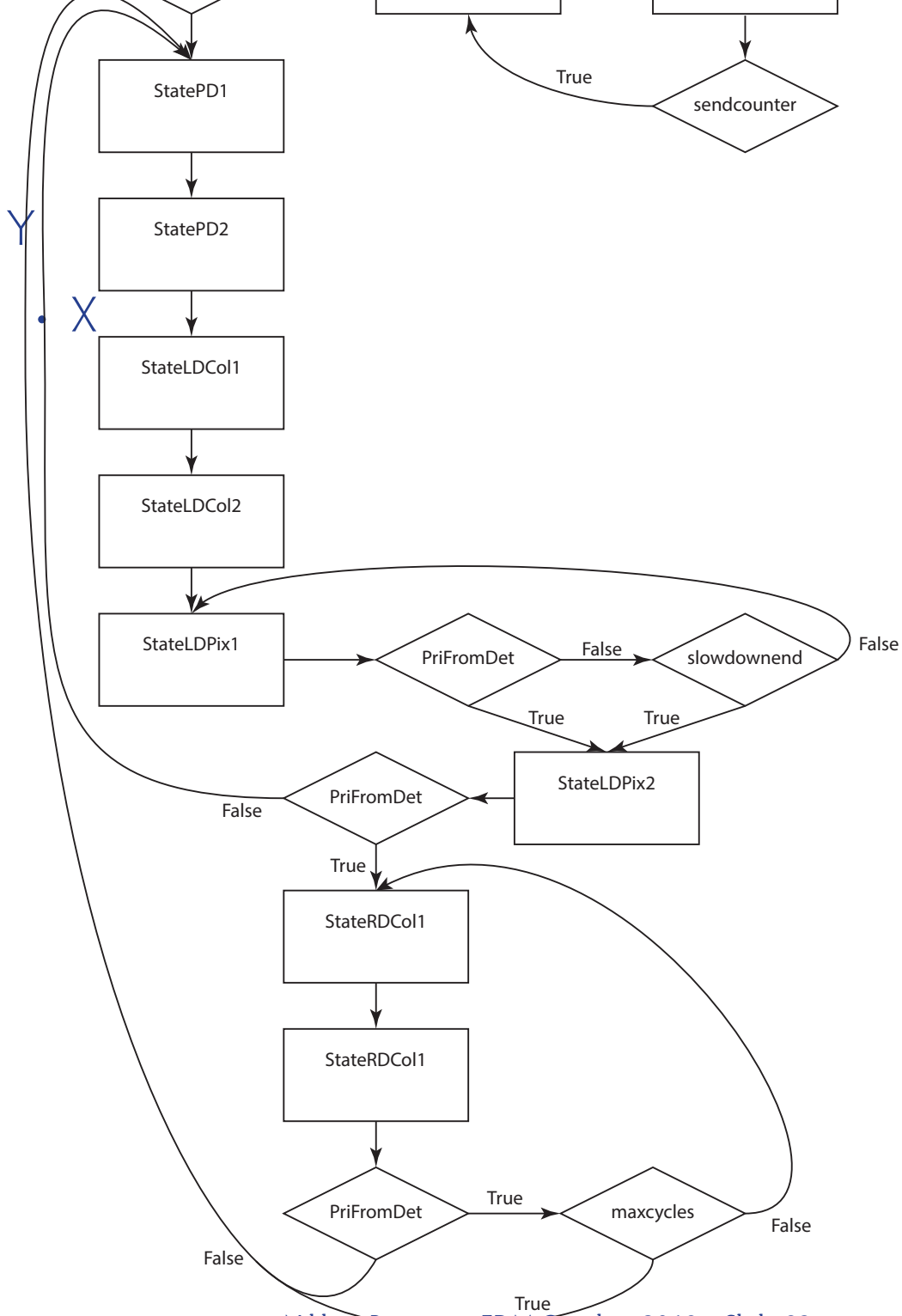


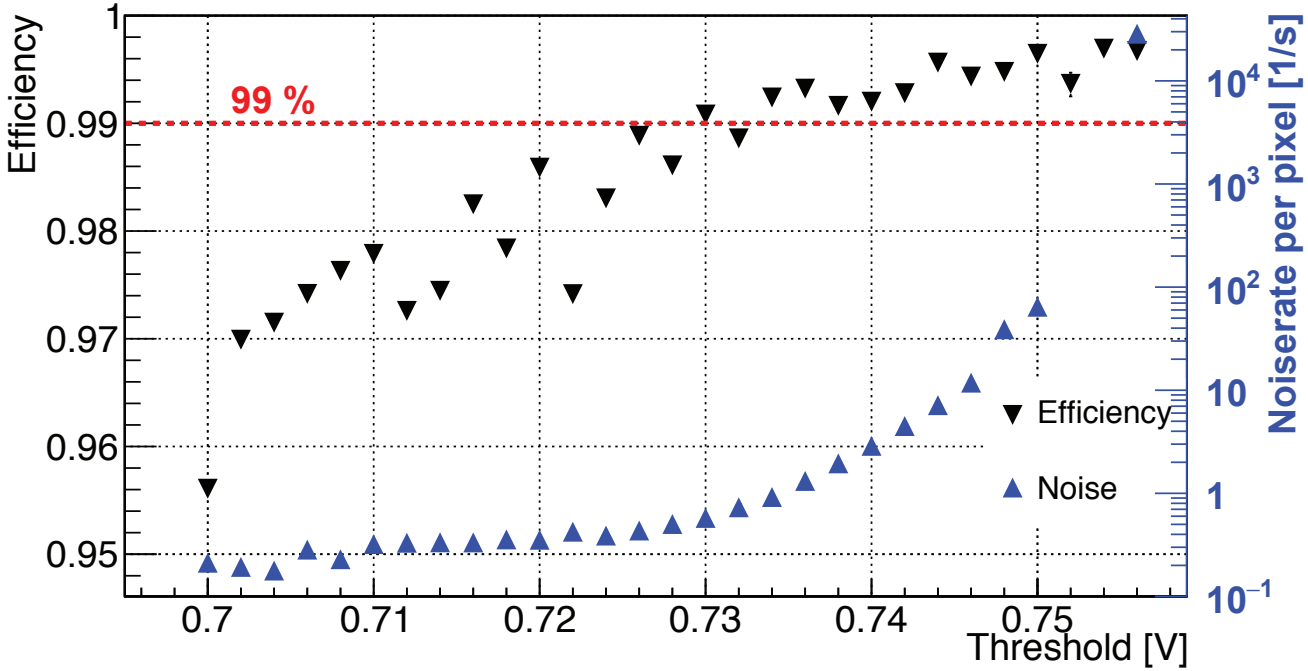
StateMachine





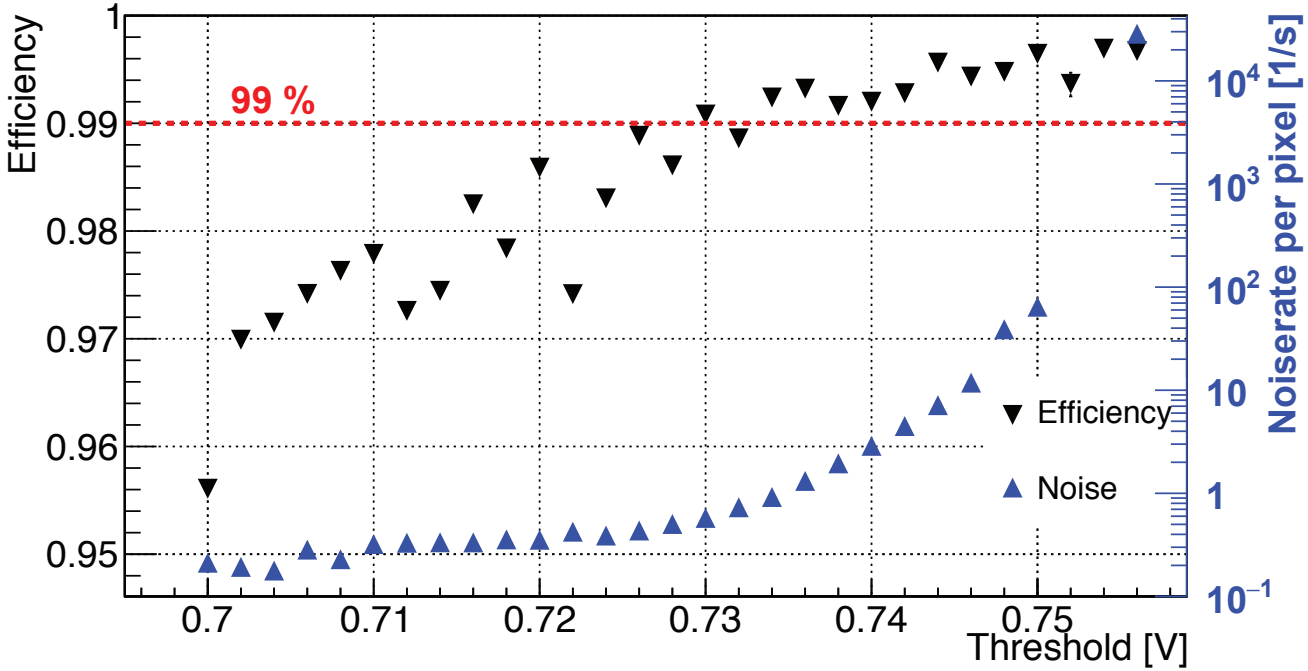
MuPix7 Performance: Efficiency vs. Noise

- 90° incidence angle
- 99% efficient for less than 10 Hz noise per pixel

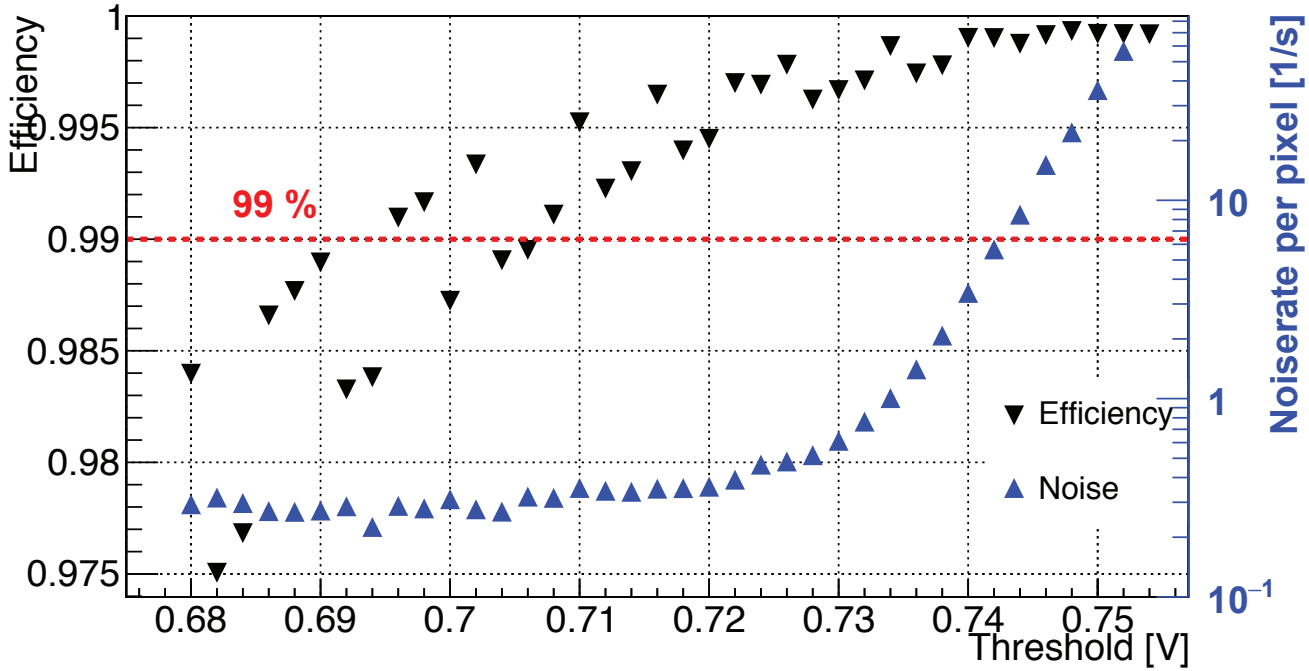


MuPix7 Performance: Efficiency vs. Noise

- 90° incidence angle
- 99% efficient for less than 10 Hz noise per pixel



- 45° incidence angle
- 99% efficient for less than 1 Hz noise per pixel



- MuPix8 has higher resistivity substrate: 45° signal at 90°