High-Voltage
Monolithic Active Pixel Sensors for the
Mu3e Experiment

Niklaus Berger

Institut für Kernphysik, Johannes-Gutenberg Universität Mainz

October 2018

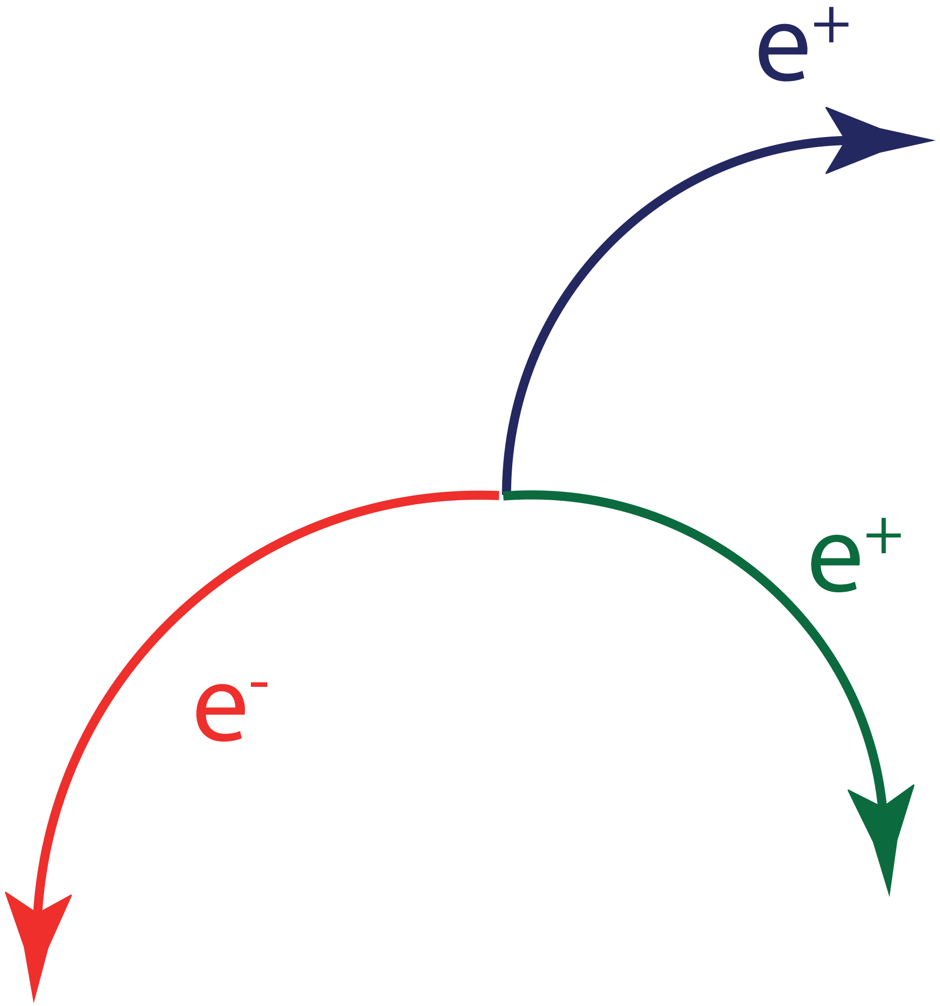
Overview

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

The Mu3e Experiment:

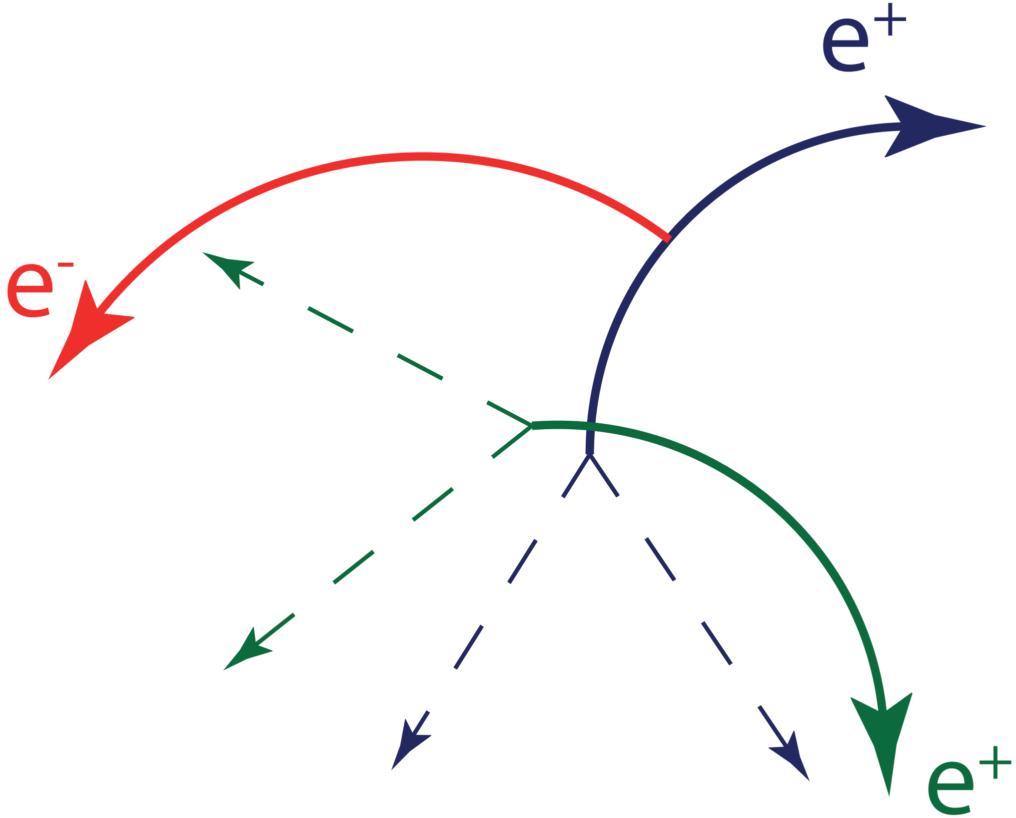
Searching for $\mu^+ \rightarrow e^+e^-e^+$
with a sensitivity of 10^{-16}
($2 \cdot 10^{-15}$ in phase I)

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

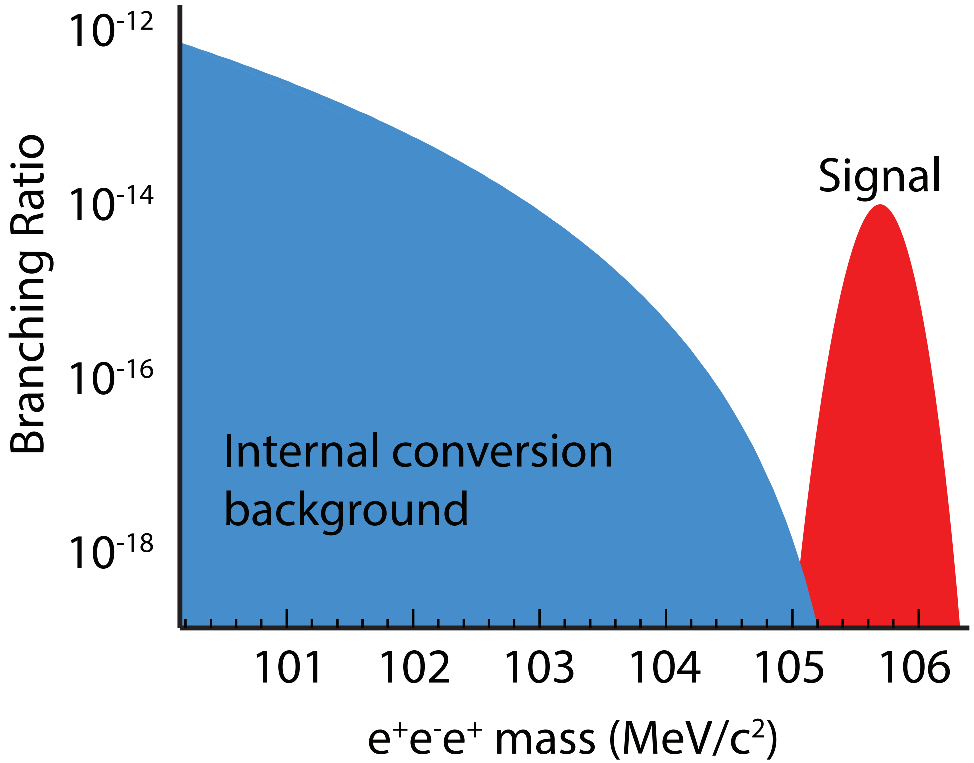
- Need very good timing, vertex and momentum resolution

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

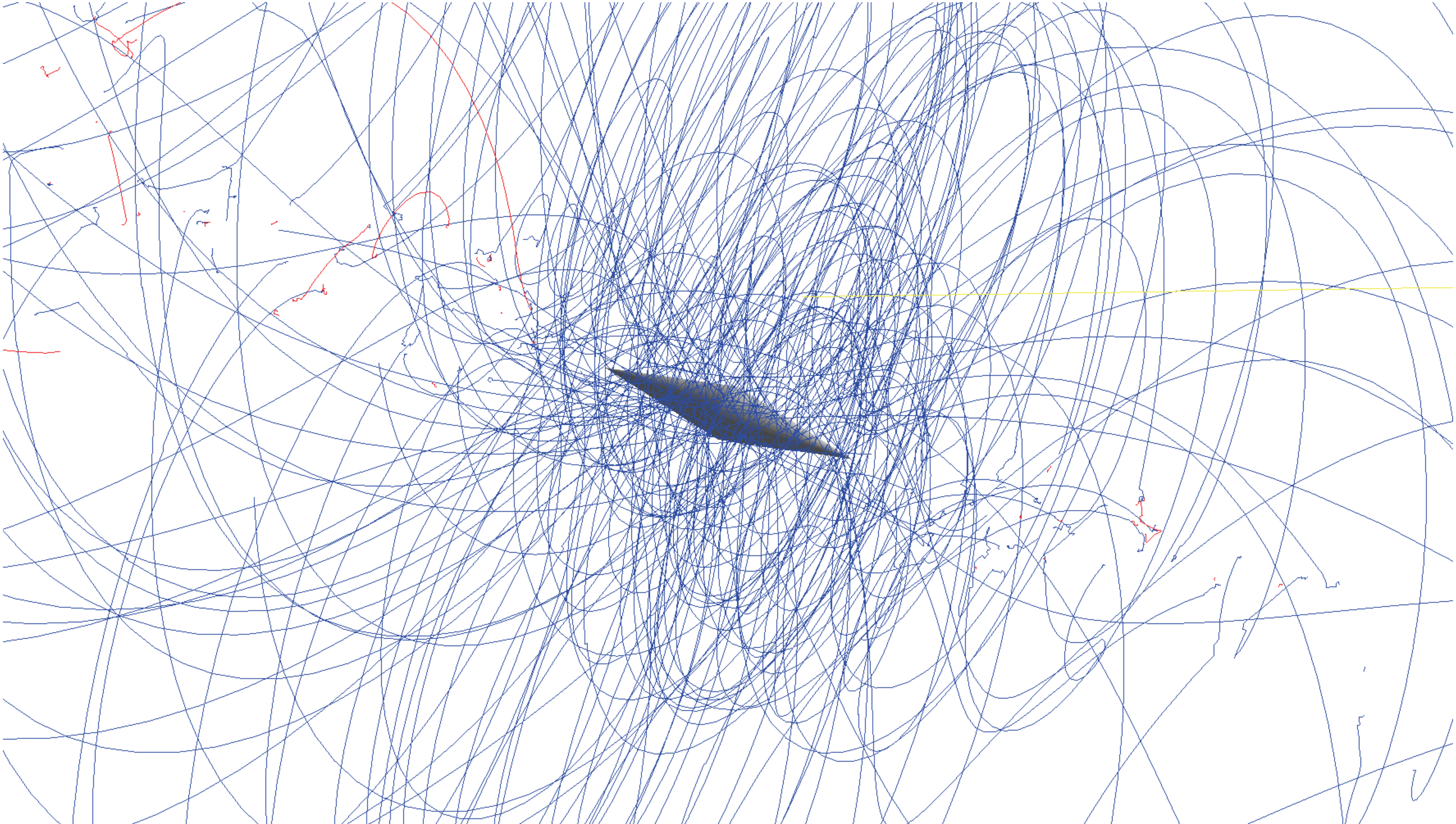
- New: NLO available from Matteo Fael and Signer et al. - now 10-20% easier

Building the
Mu3e Experiment

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

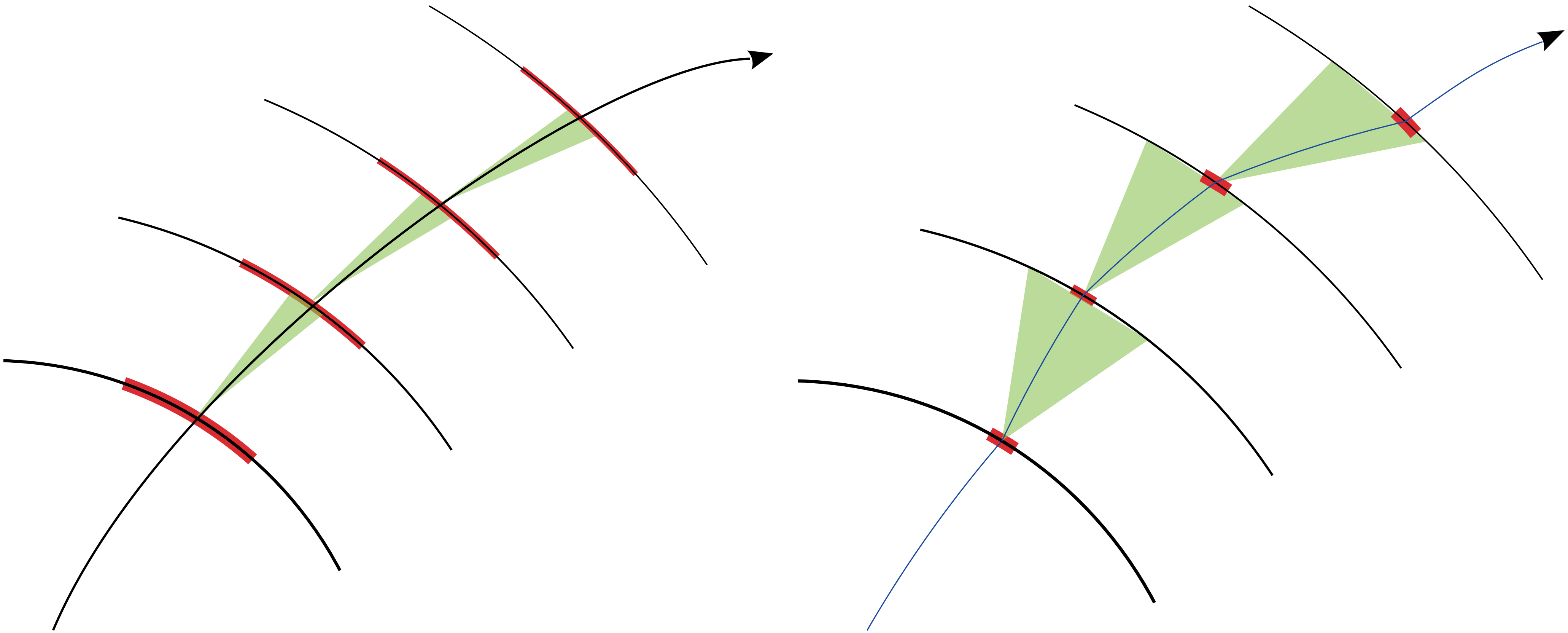
2 Billion Muon Decays/s

50 ns, 1 Tesla field



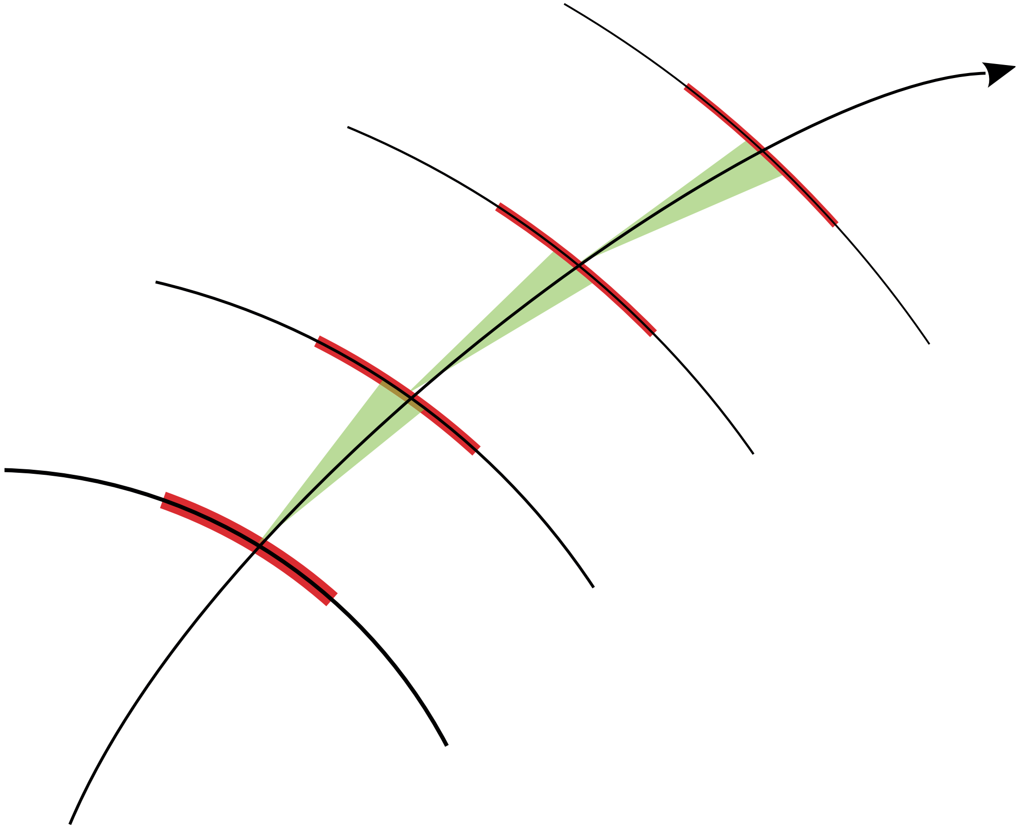
Momentum measurement

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

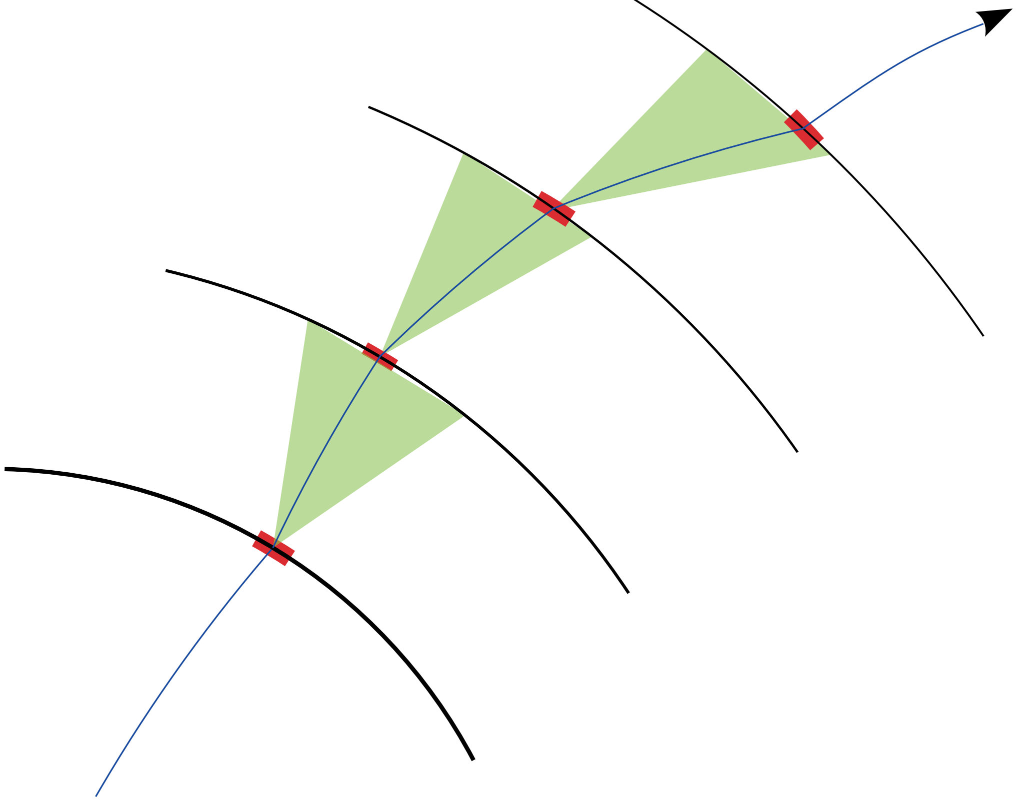


Momentum measurement

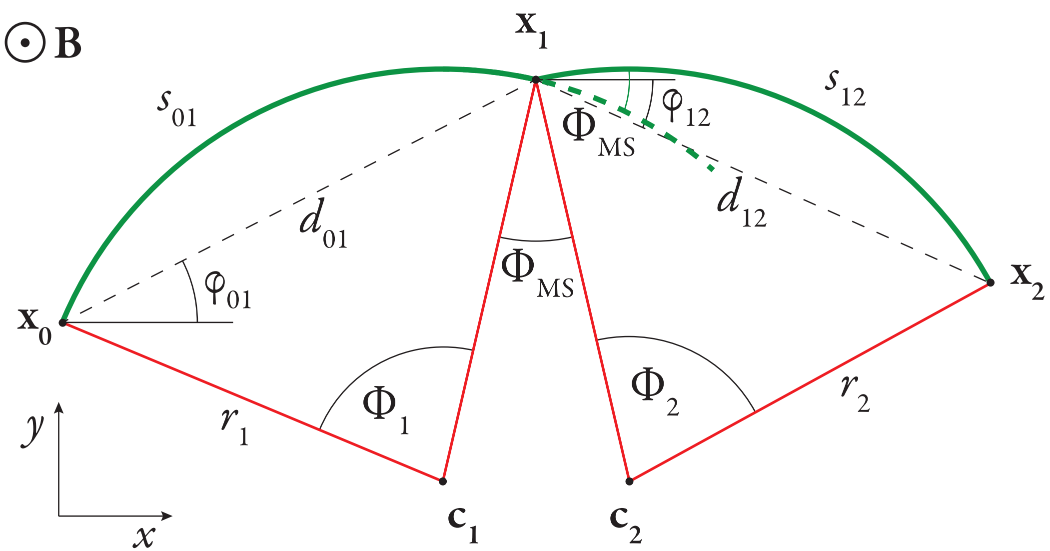
- Apply magnetic field (e.g. 1 Tesla)
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

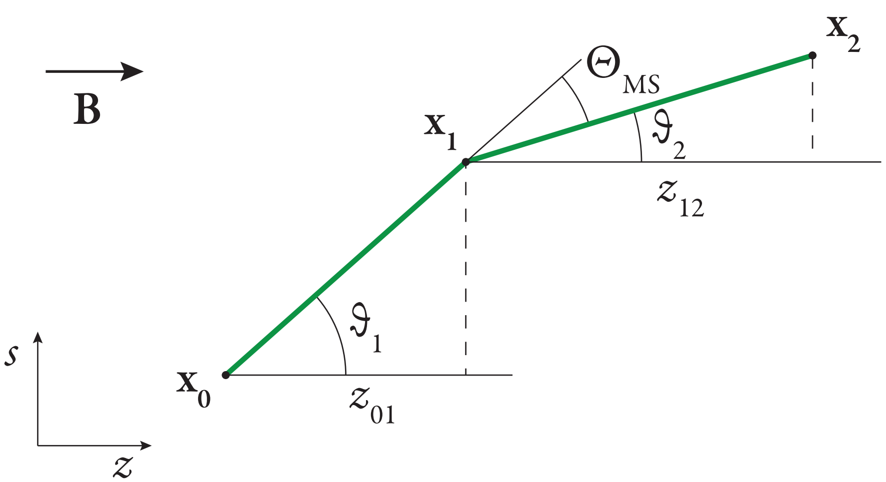


- At ~ 30 MeV/c momentum: Scattering completely dominates
- Large pixels: 80 µm
- Very little material: 0.1% X_0 per layer



Multiple Scattering Track Fit



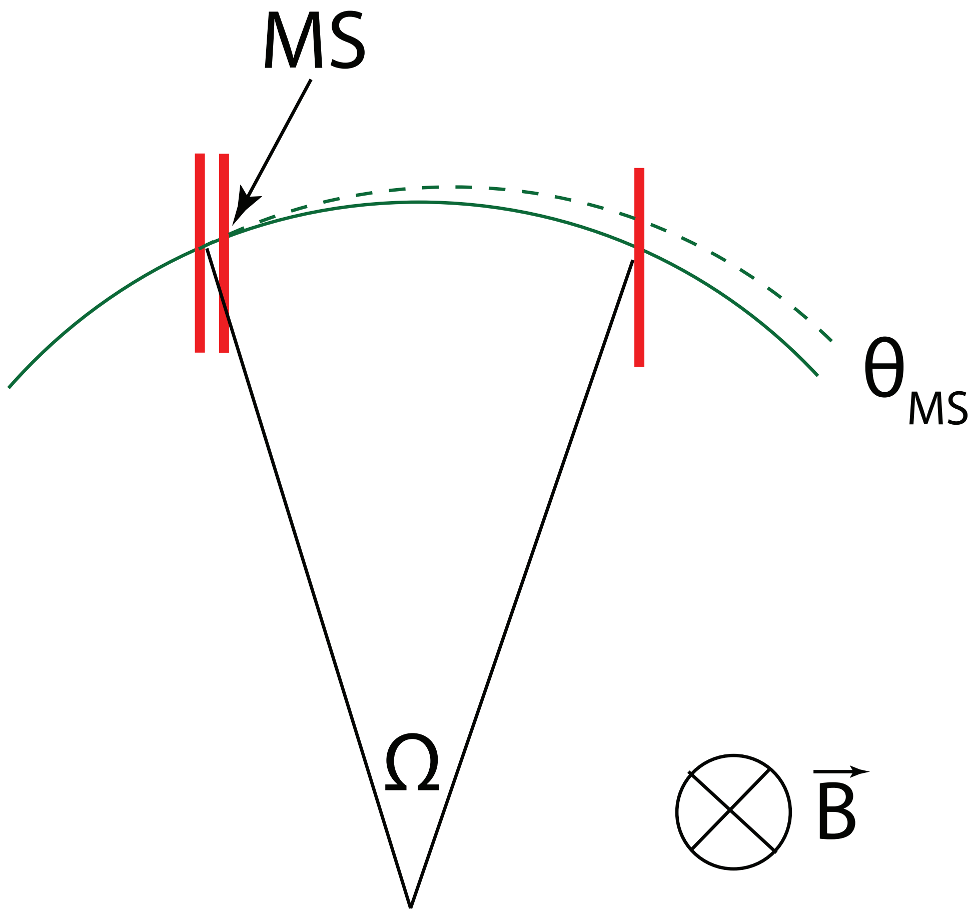


- Treat hit measurements as arbitrarily precise
- Consider scattering in each detector plane
- Two hits, two helices: Underconstrained problem

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

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

Momentum measurement

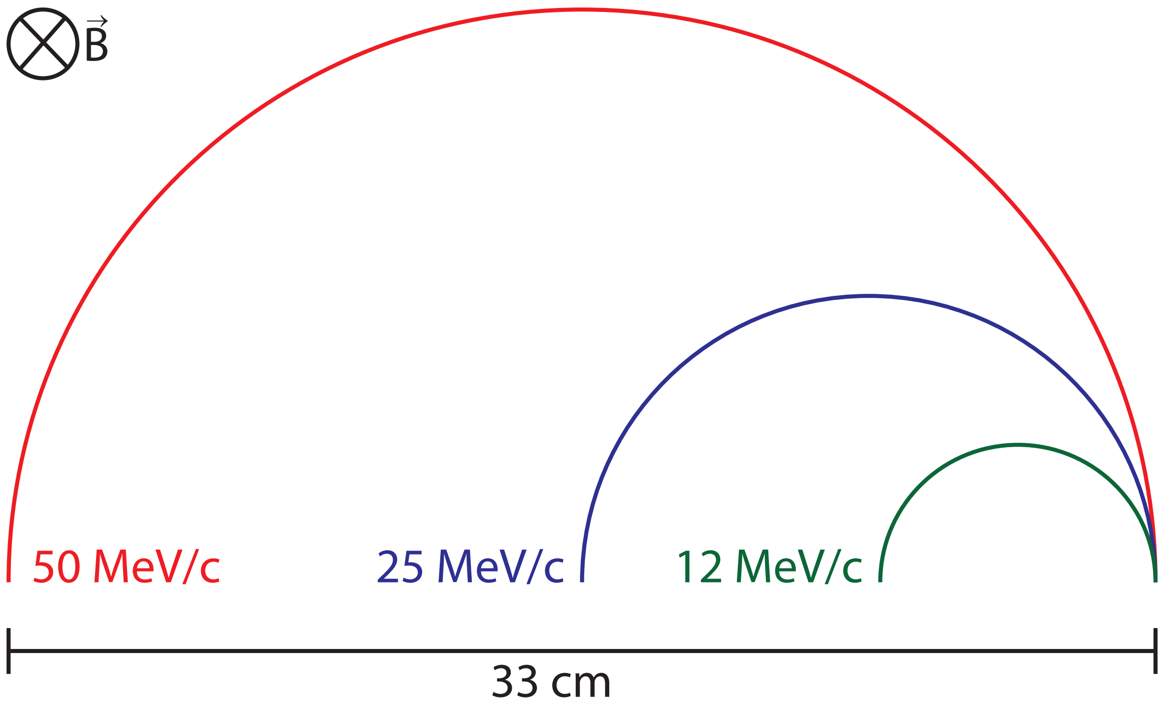


- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

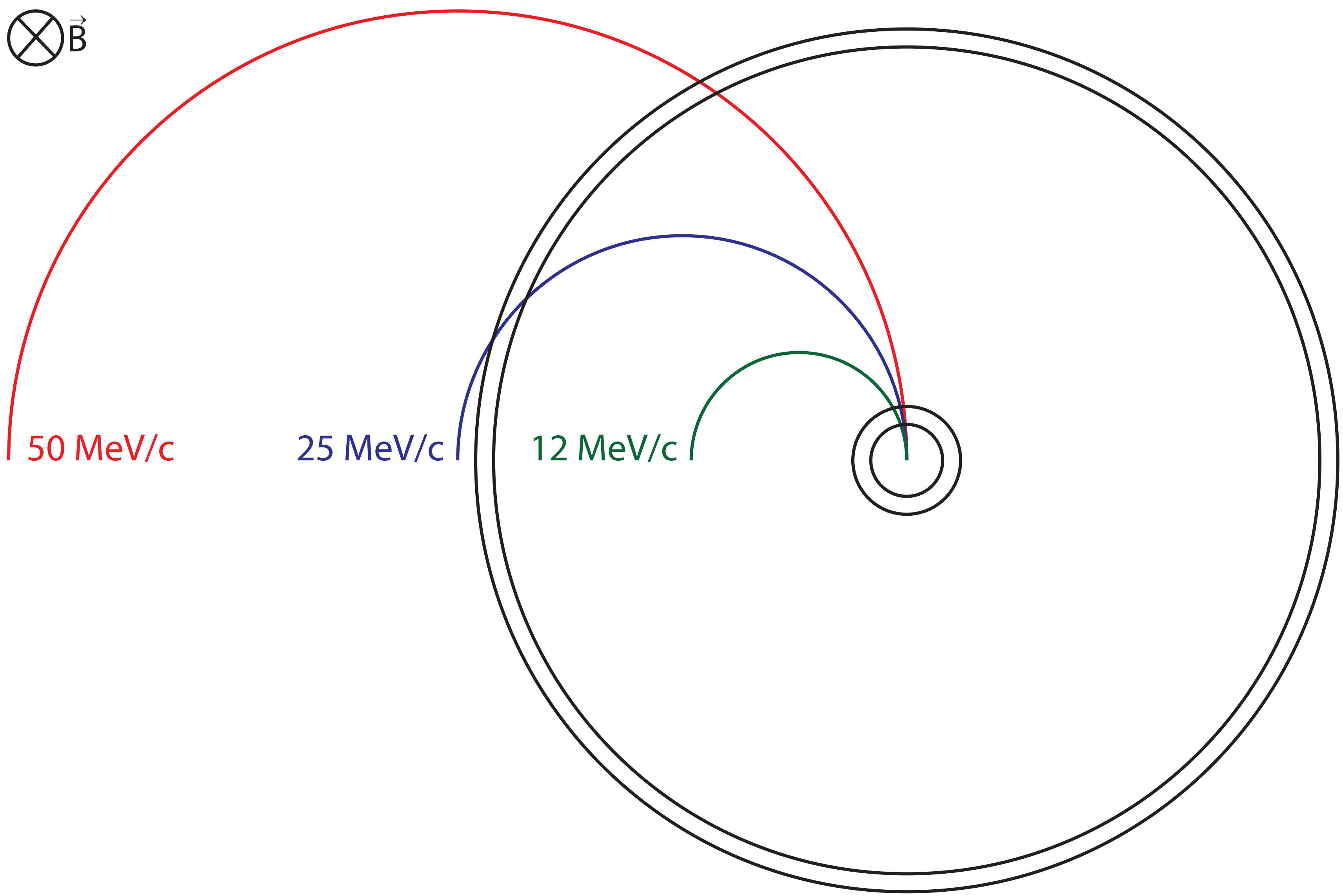
$$\sigma_P/_P \sim \theta_{MS}/_\Omega$$

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

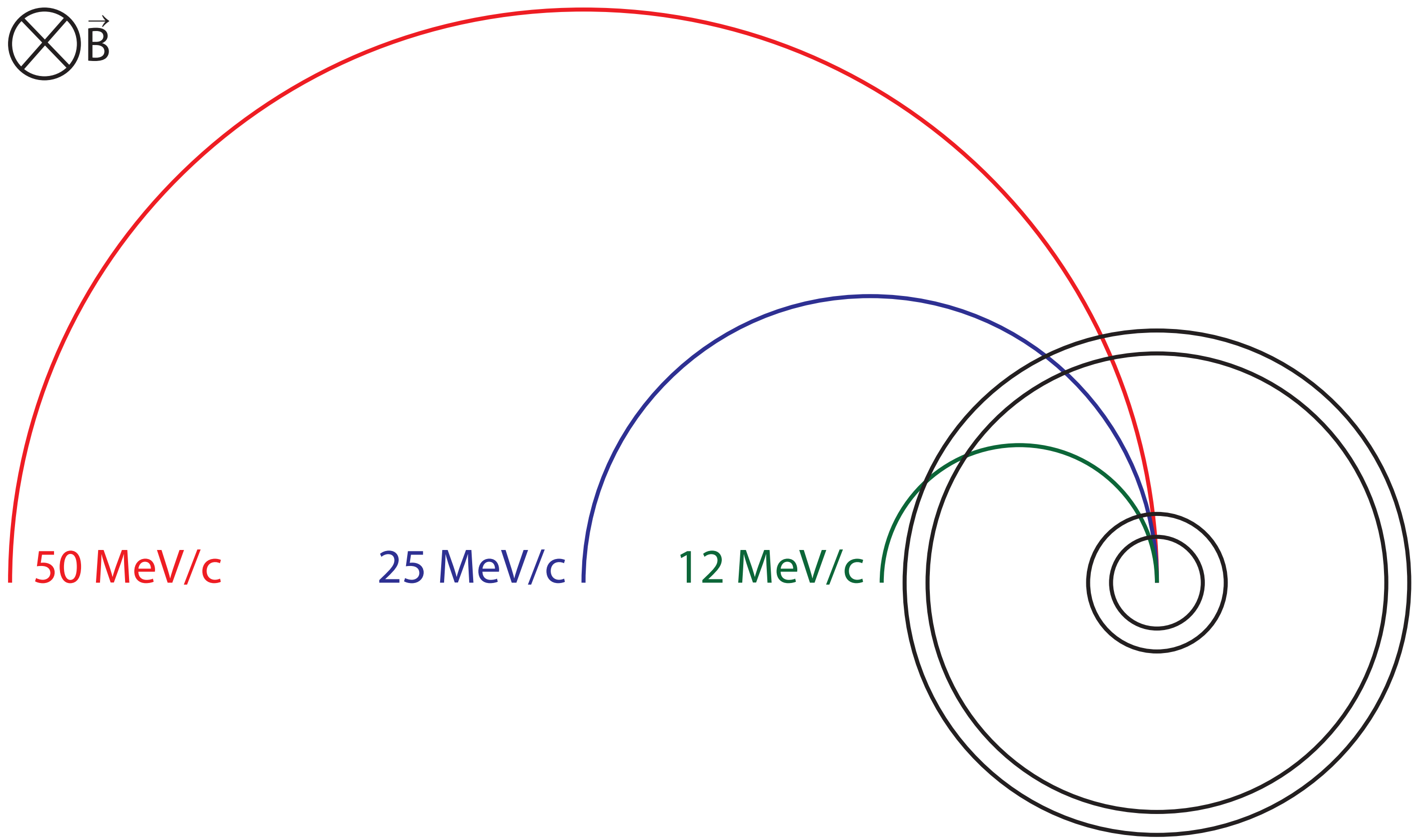
Precision vs. Acceptance



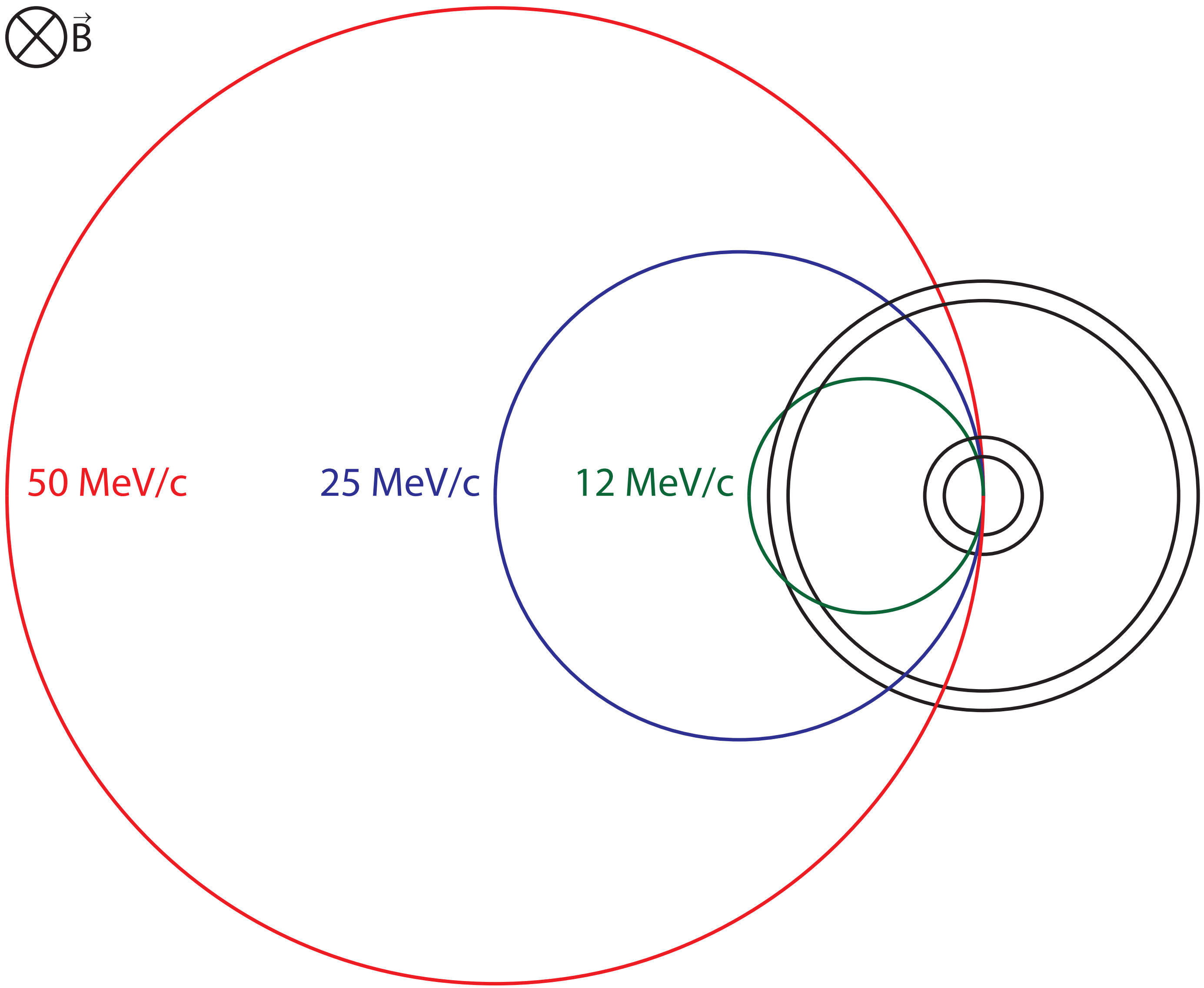
Precision vs. Acceptance



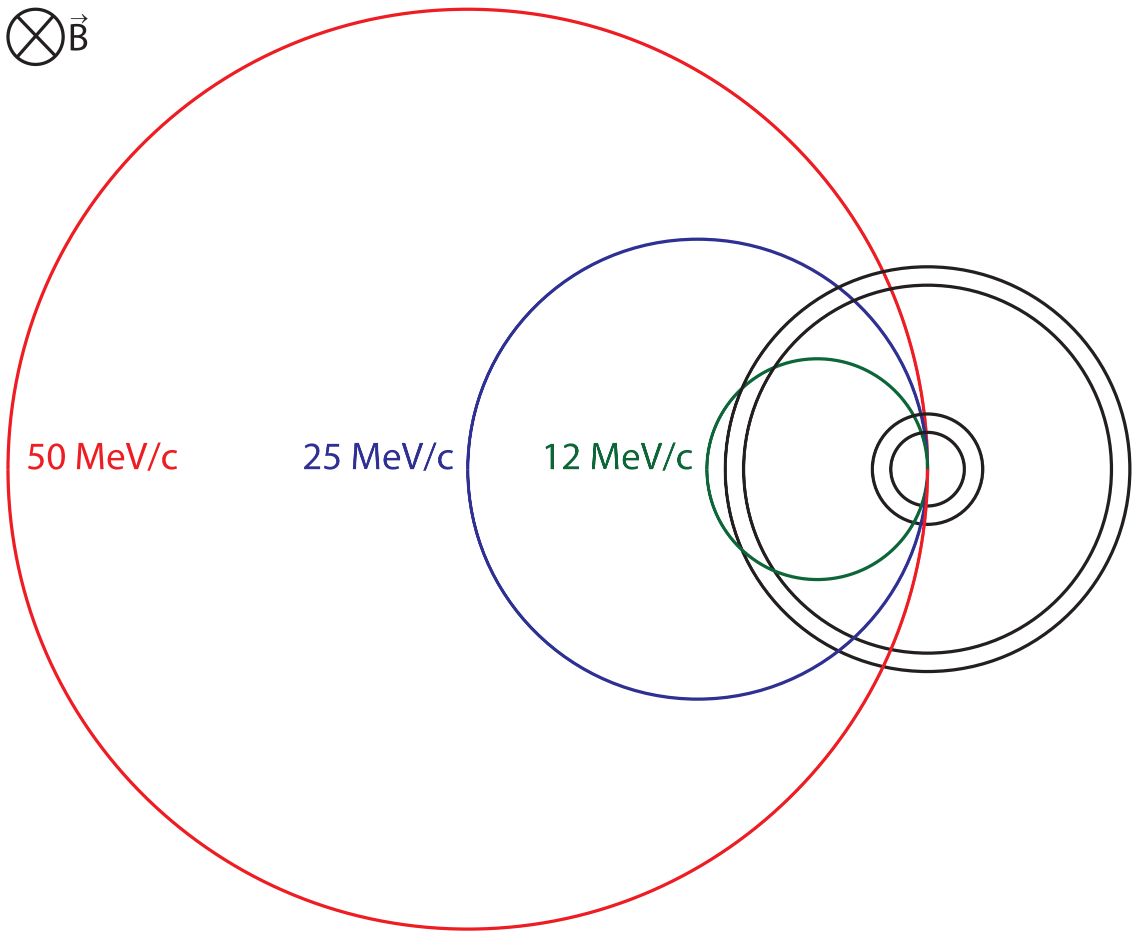
Precision vs. Acceptance

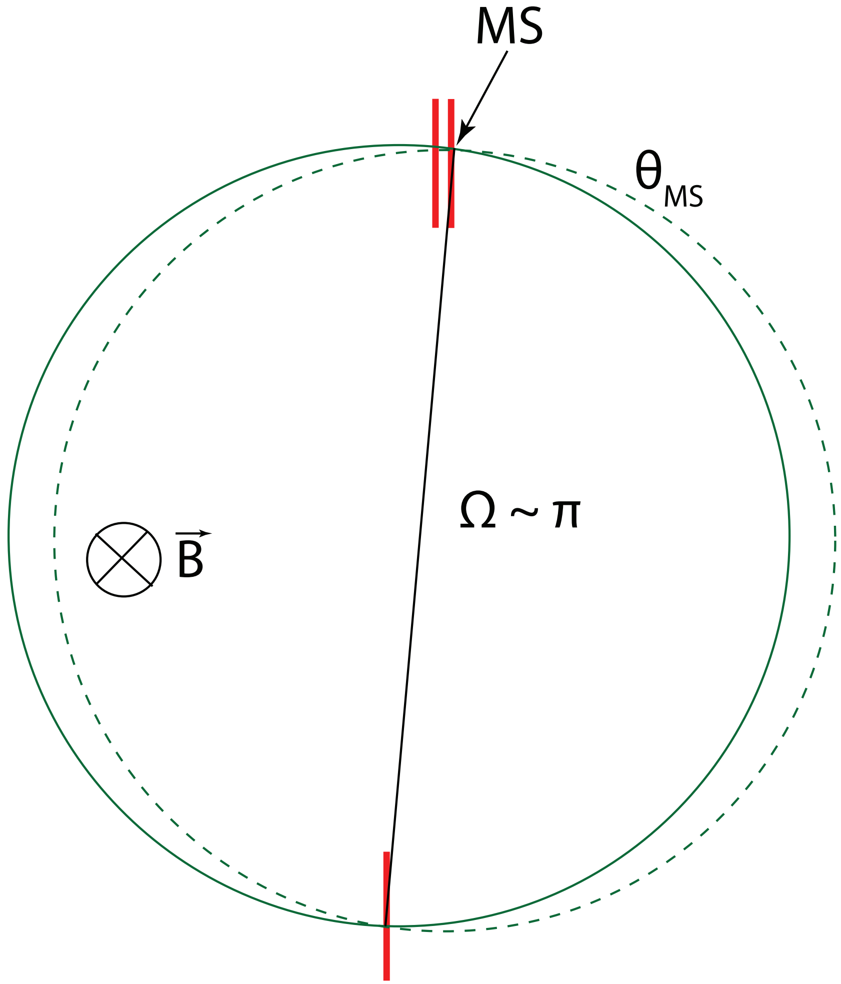


Precision vs. Acceptance

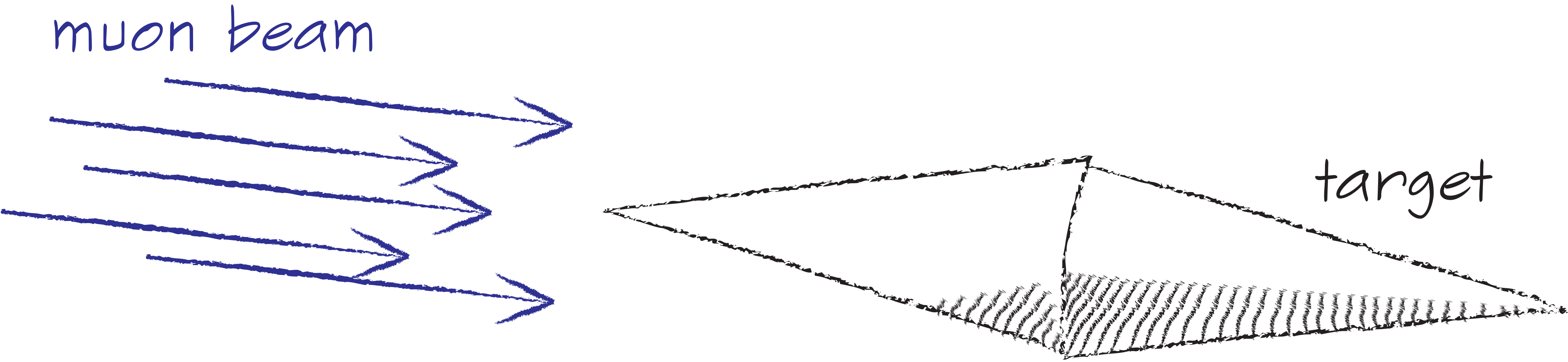


Precision vs. Acceptance

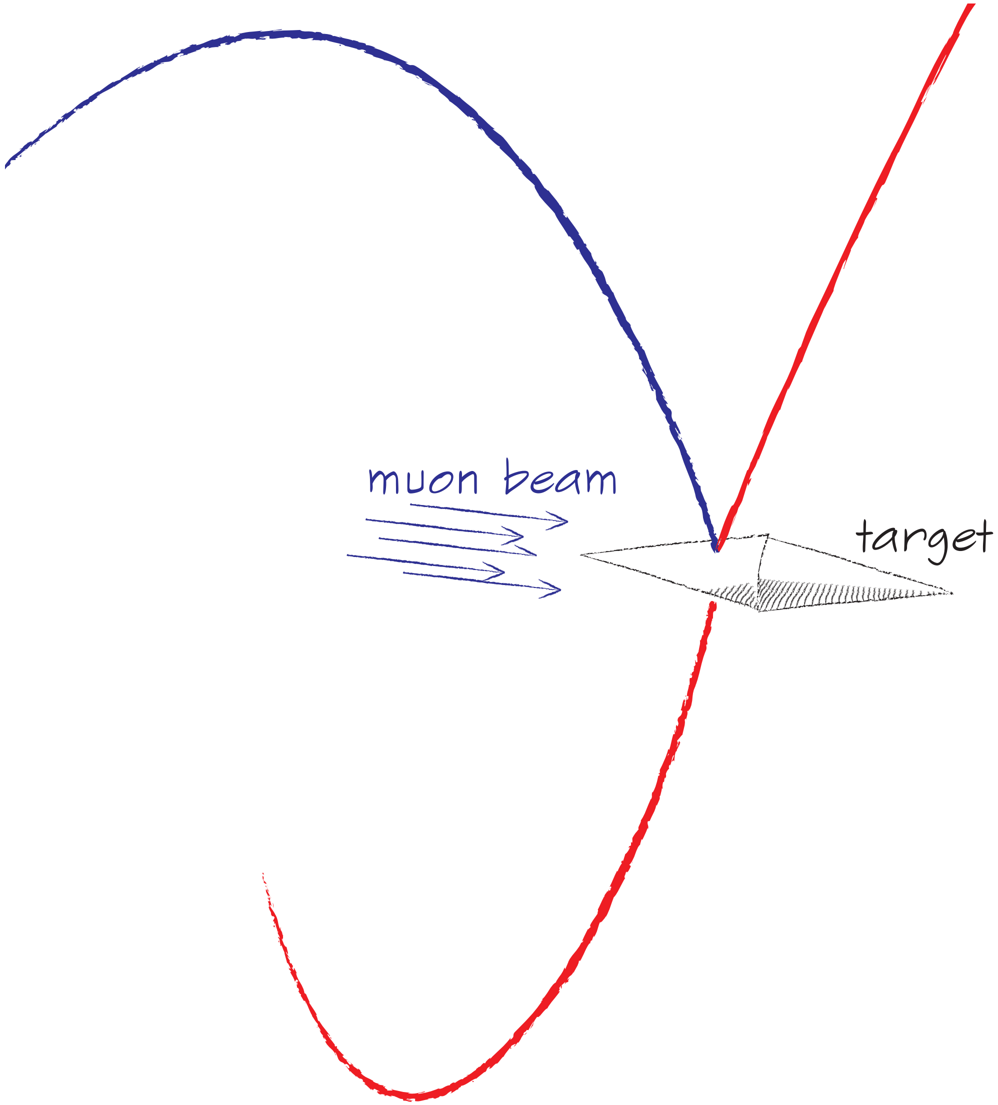




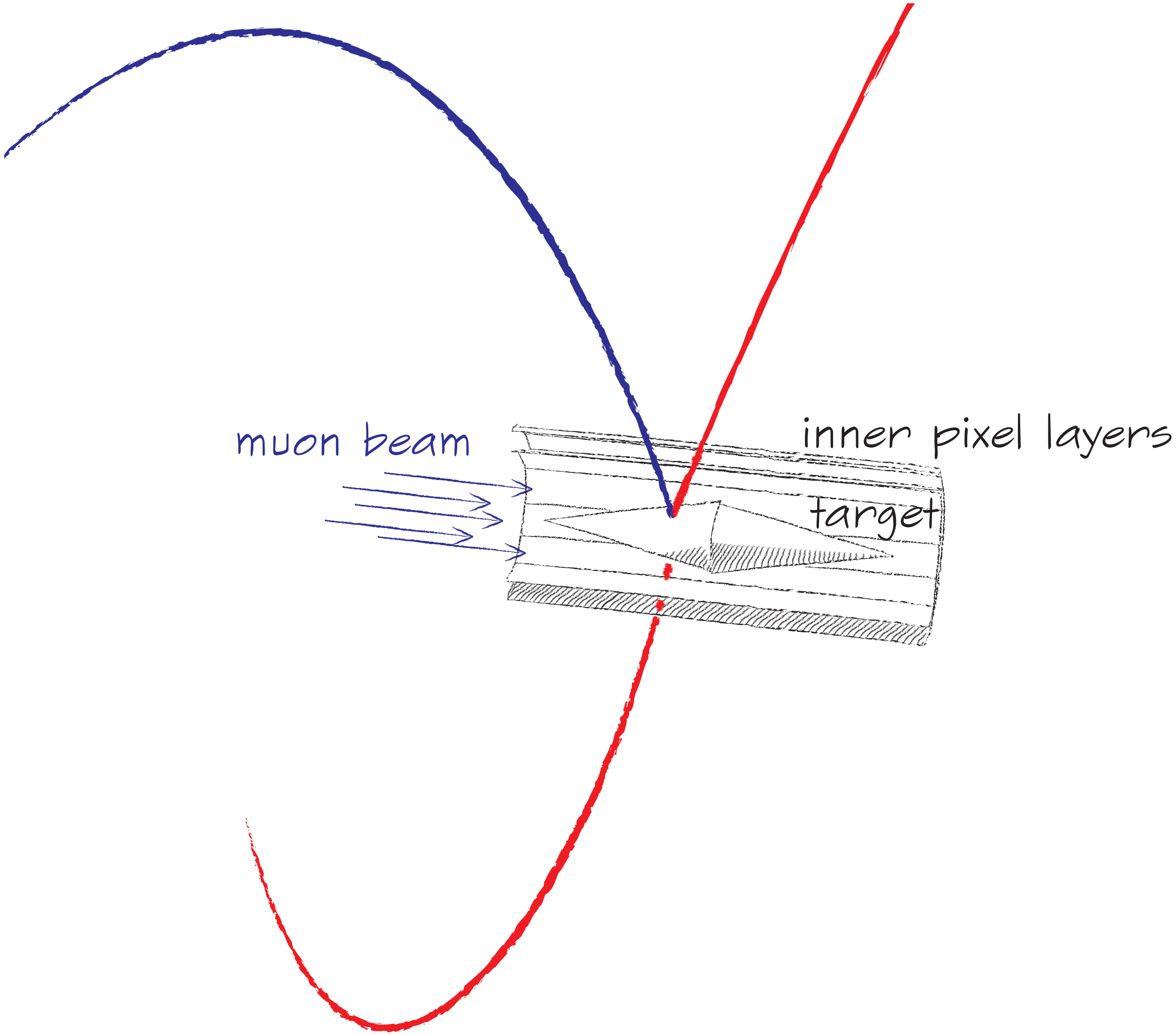
Detector Design



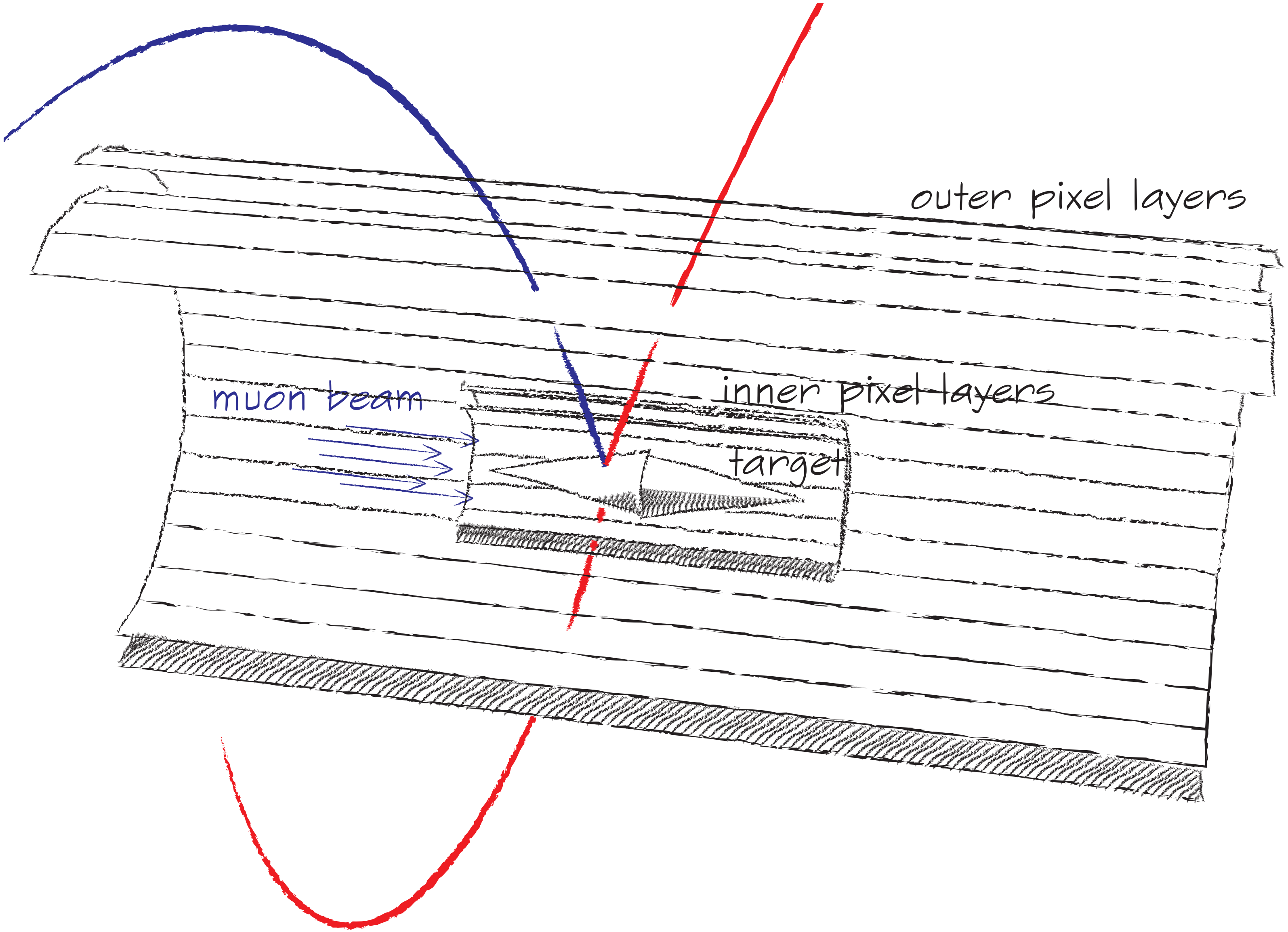
Detector Design



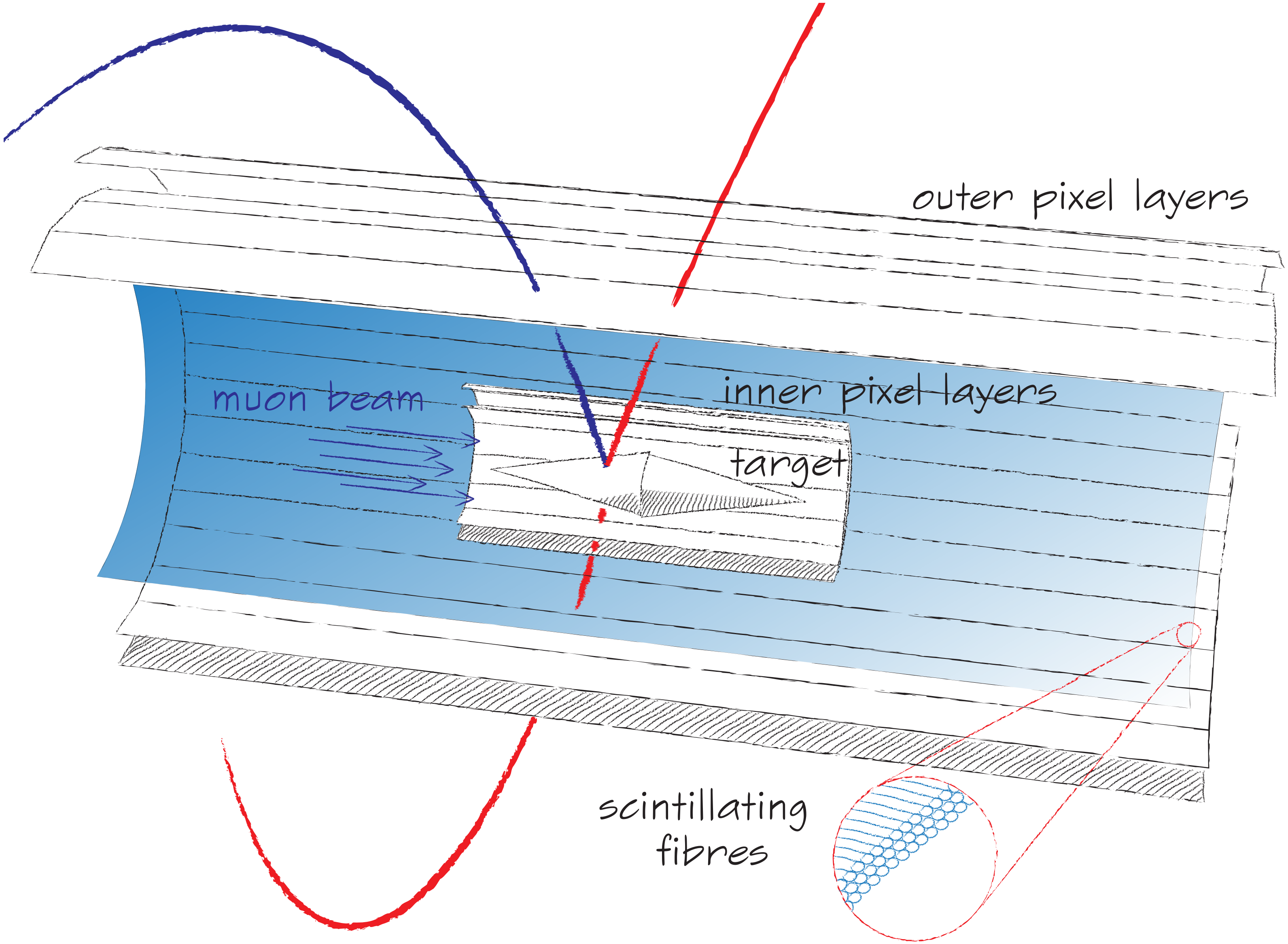
Detector Design



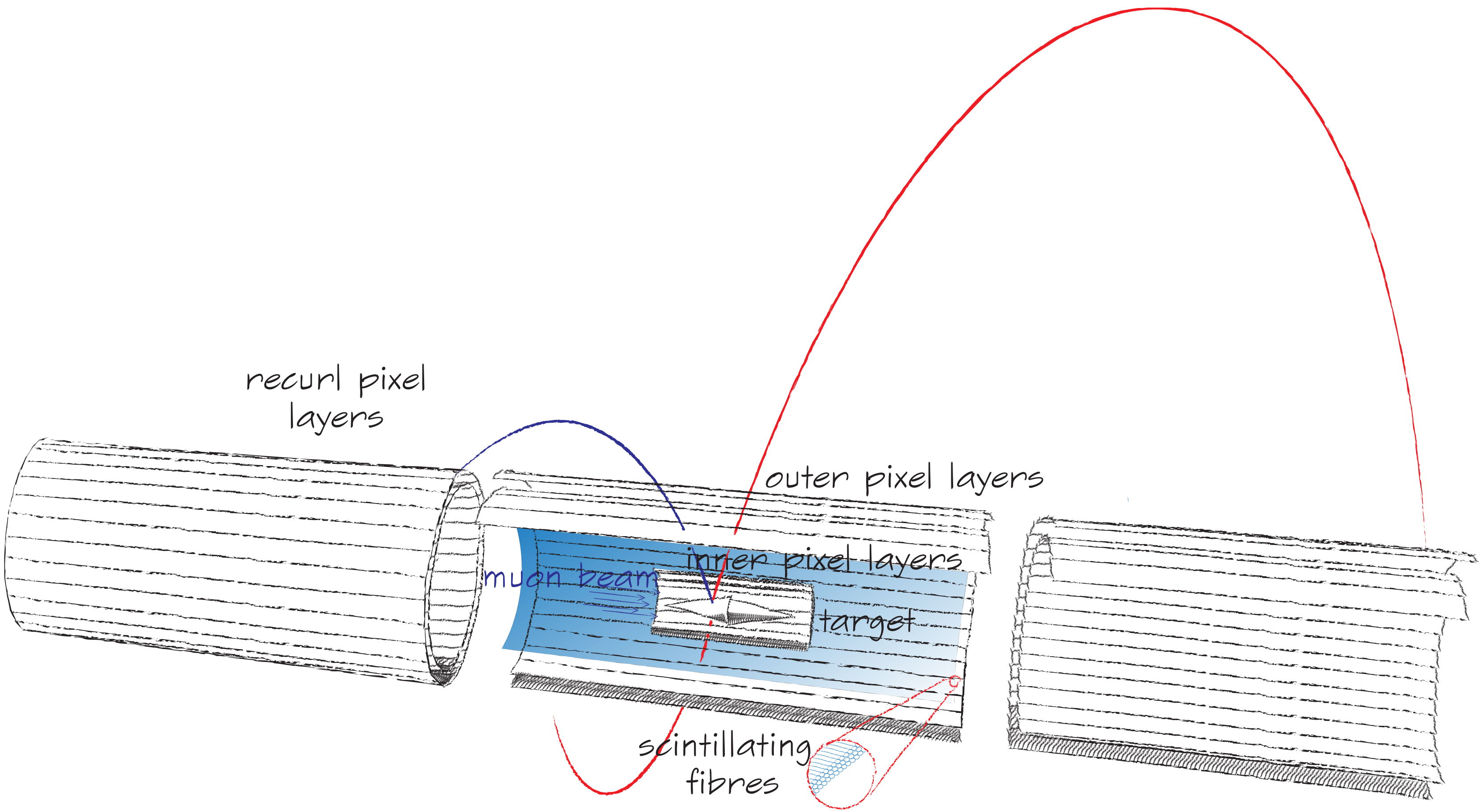
Detector Design



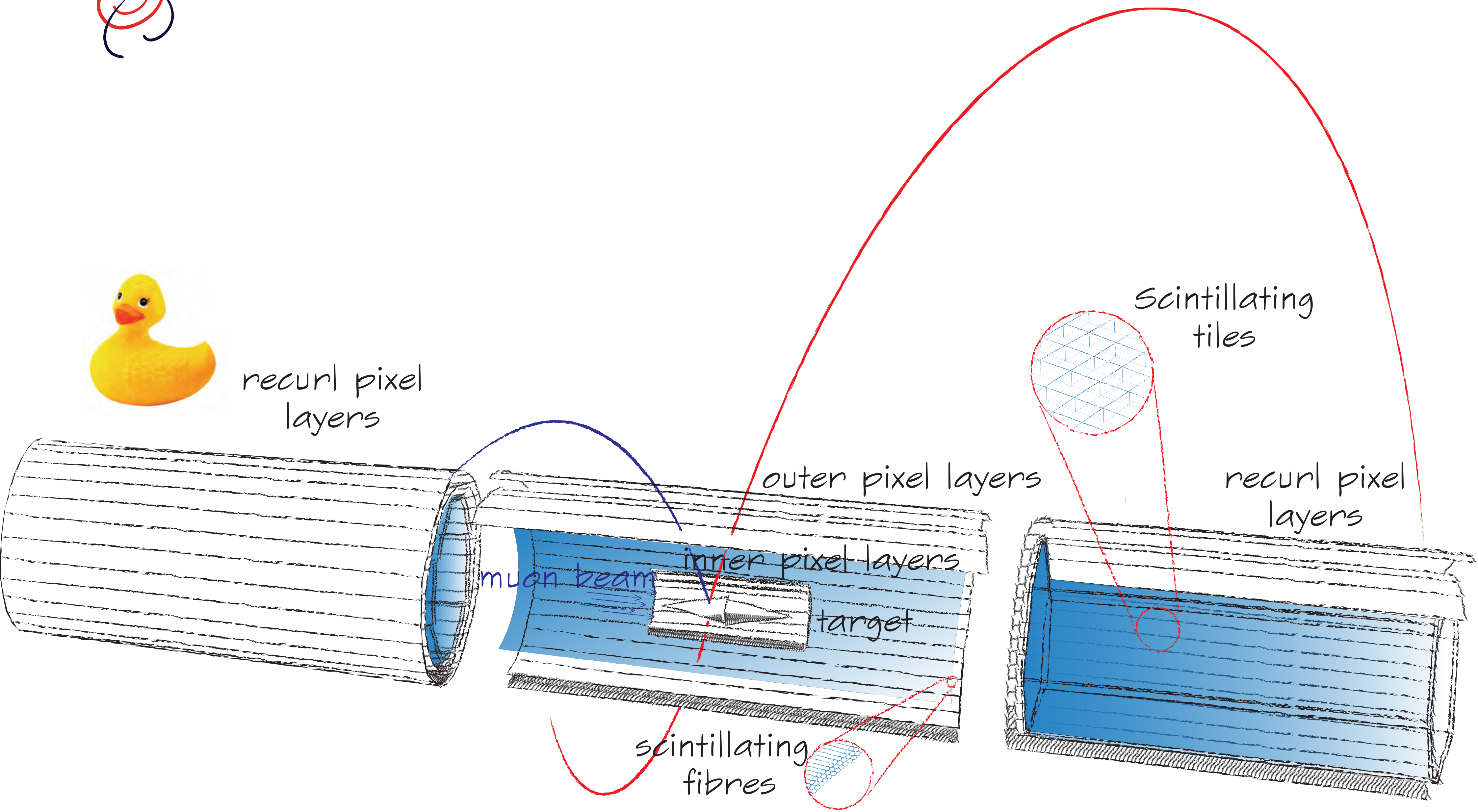
Detector Design



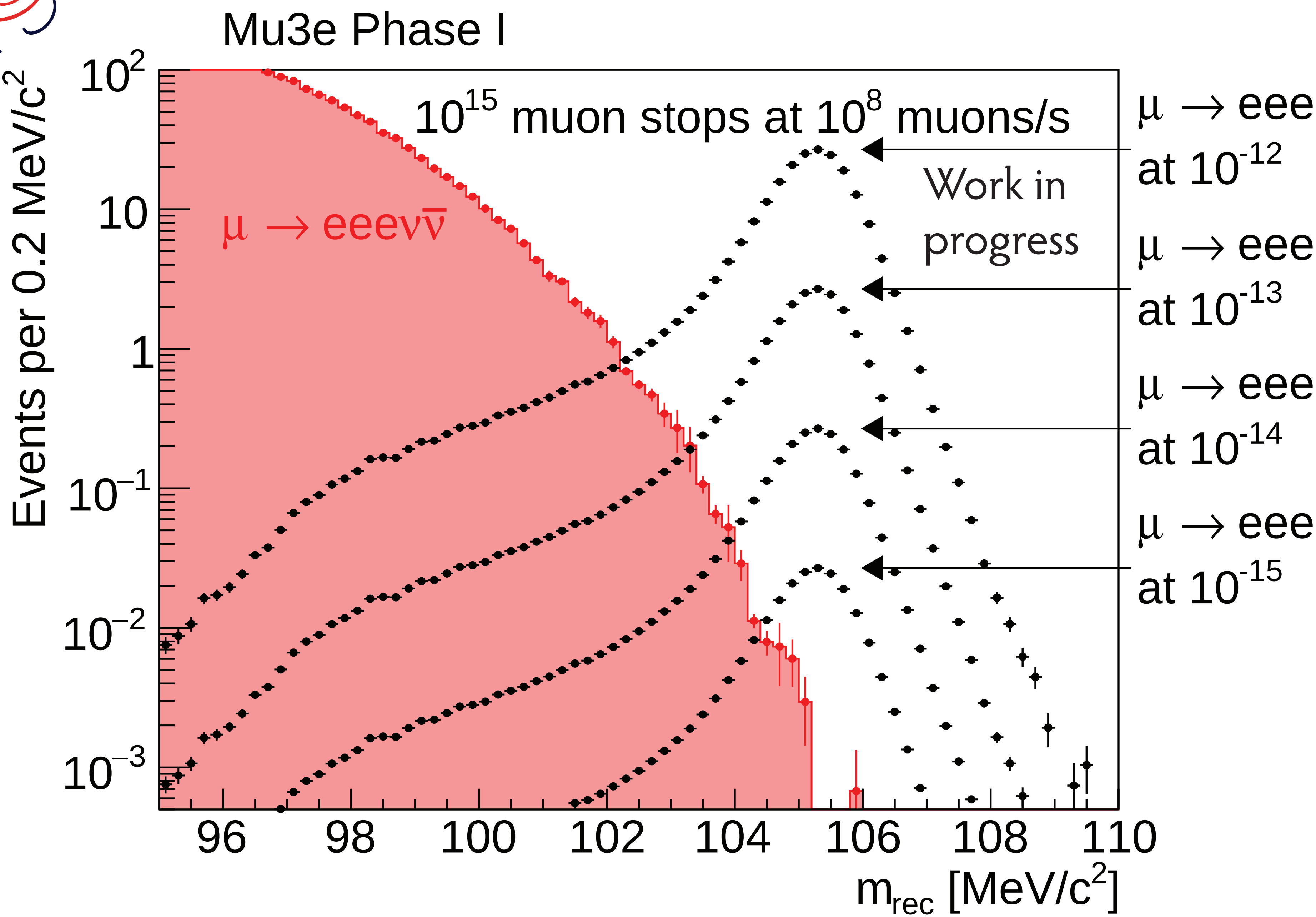
Detector Design



Detector Design



Performance Simulations: Mass reconstruction

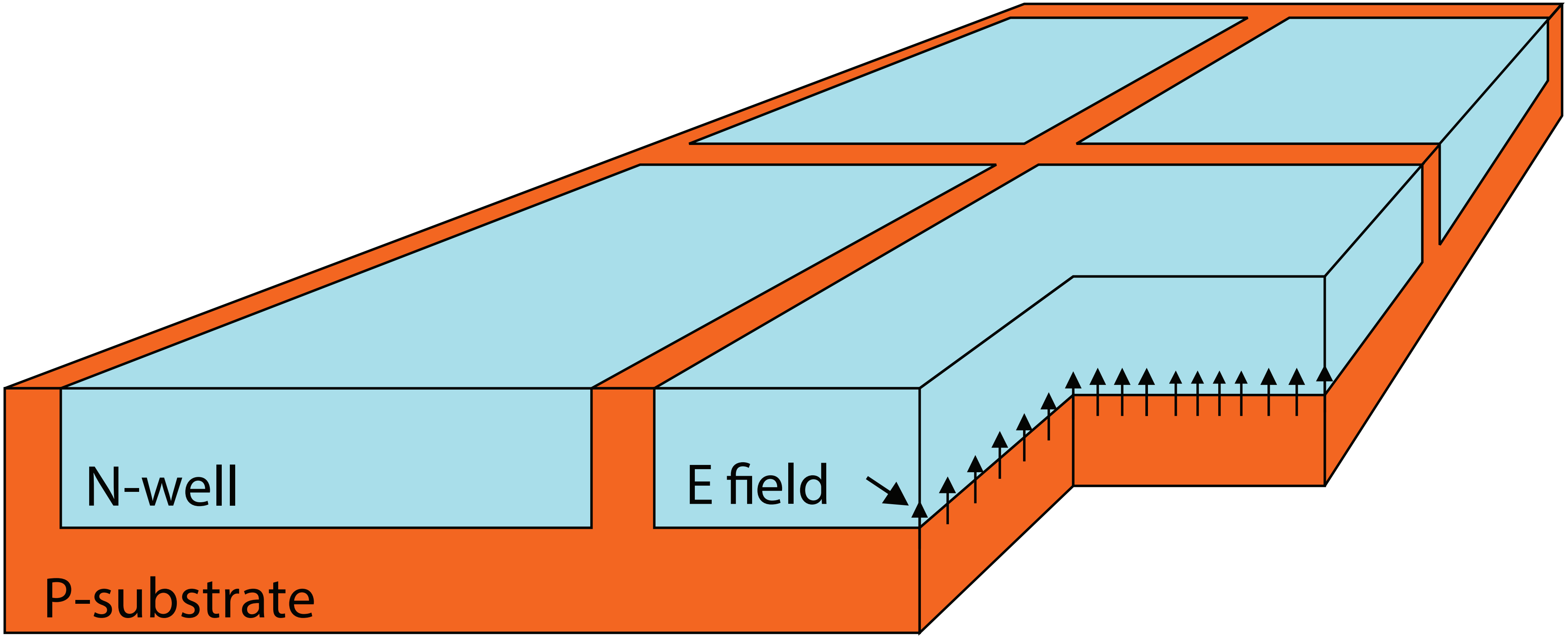


High-Voltage
Monolithic Active Pixel Sensors

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

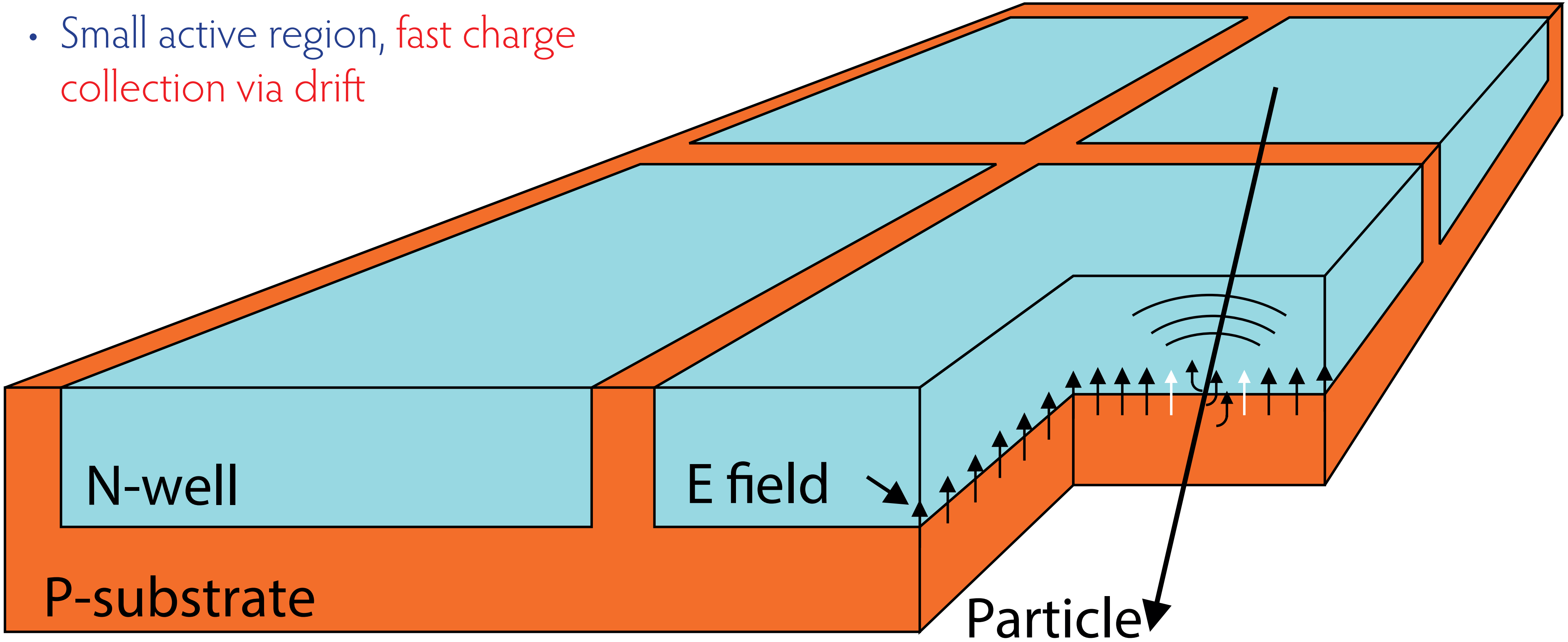
- Use a high voltage commercial process (automotive industry)



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



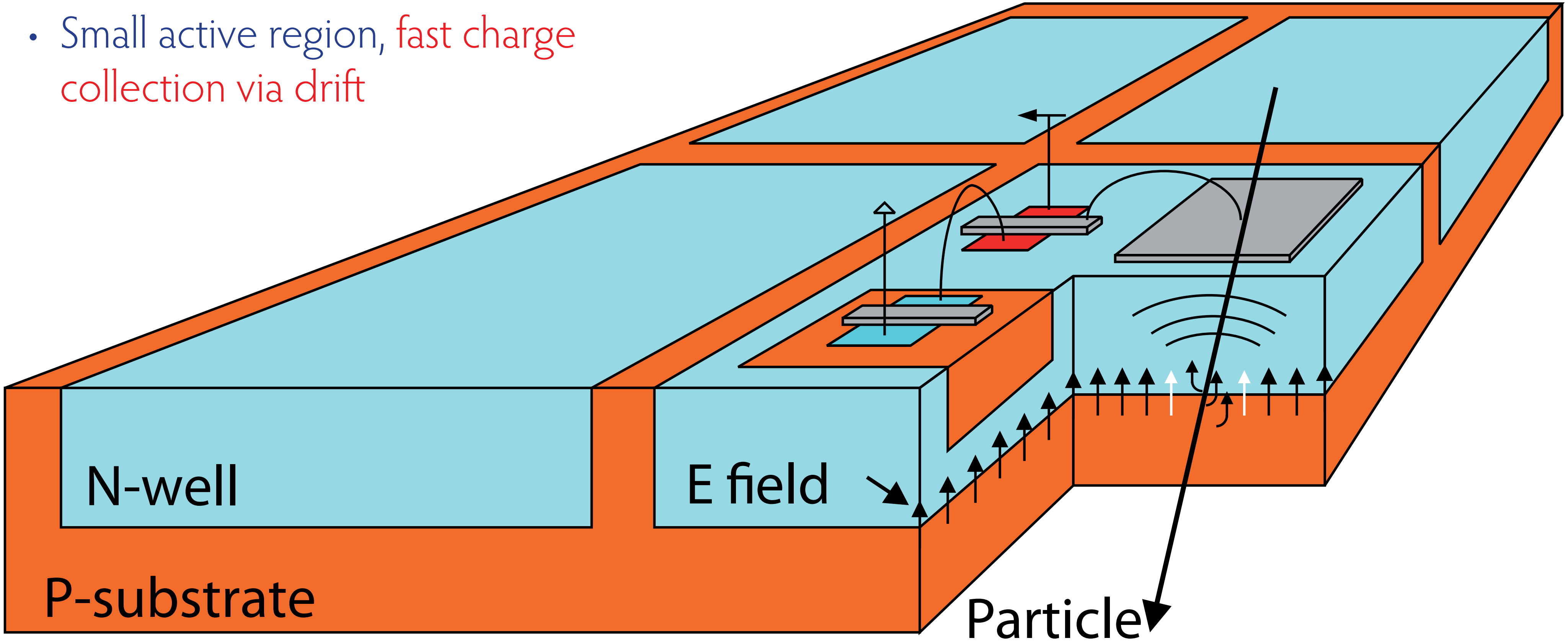
Fast and thin sensors: HV-MAPS

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

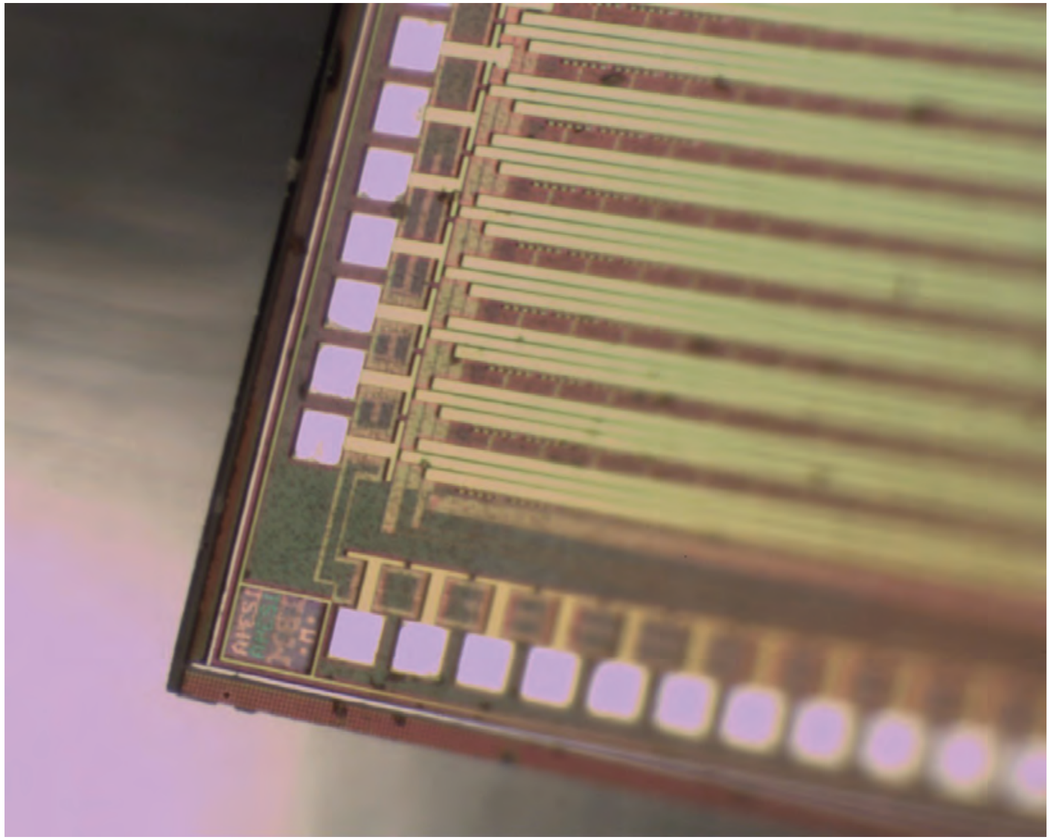
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



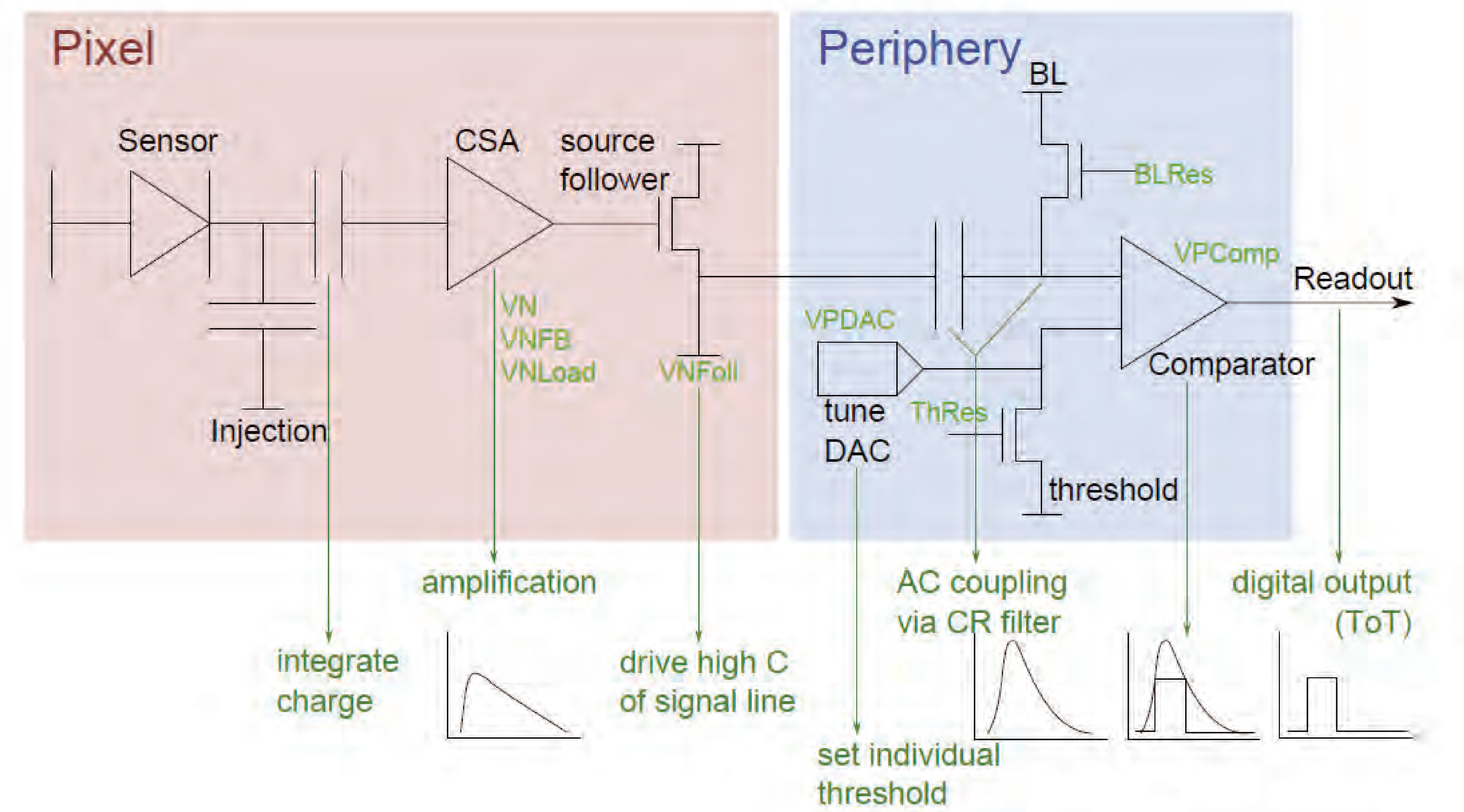
The MuPix Prototypes

Developed a series of HV-MAPS prototypes

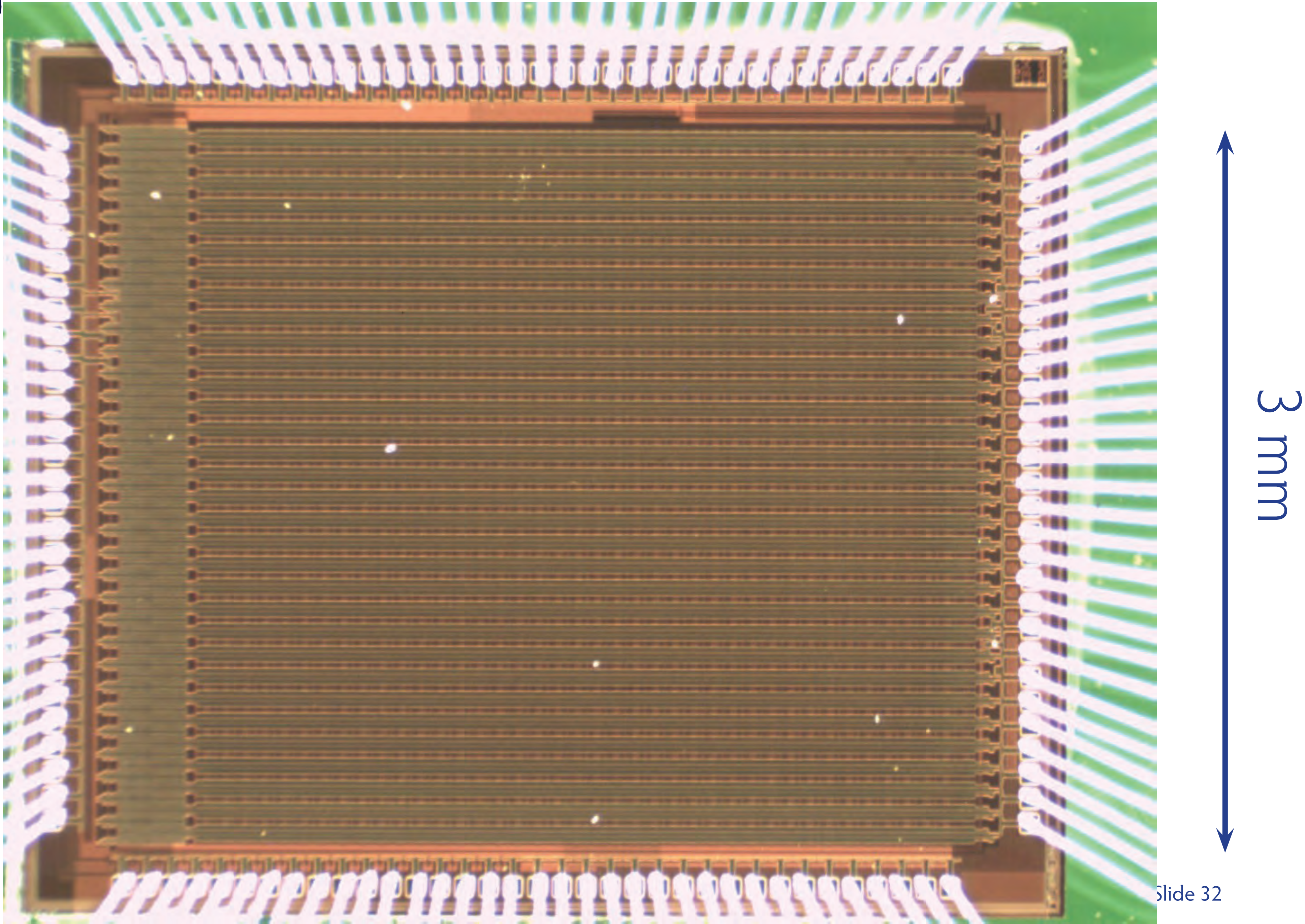
- Goal: Detection and signal processing with just 50 µm silicon
- 6th chip, MuPix7, is a full system-on-a-chip
- Well characterized, working very nicely
- Next step is going big: 2 x 1 cm^2 MuPix8 under test



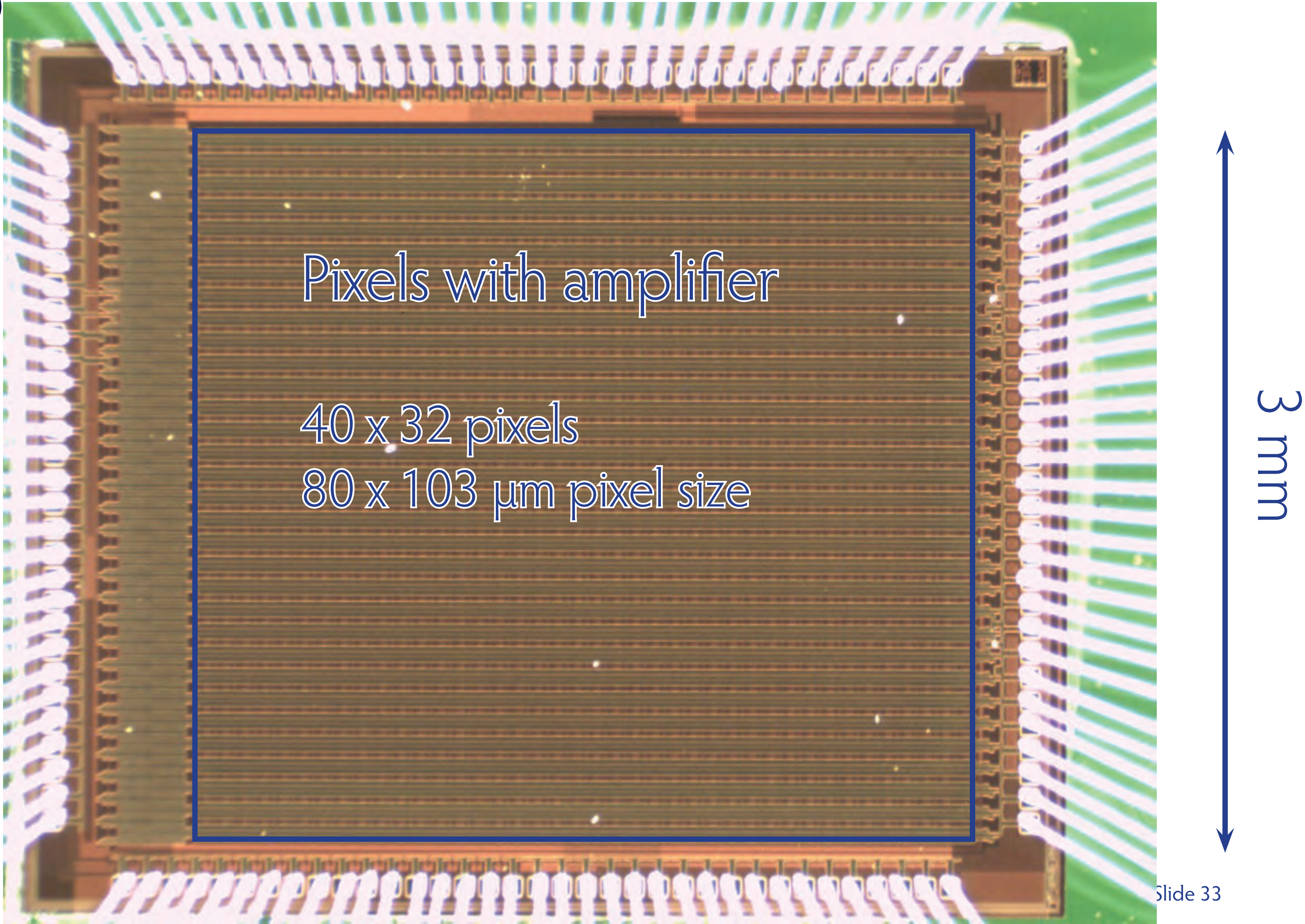
MUPIX electronics (MuPix7)



MuPix7

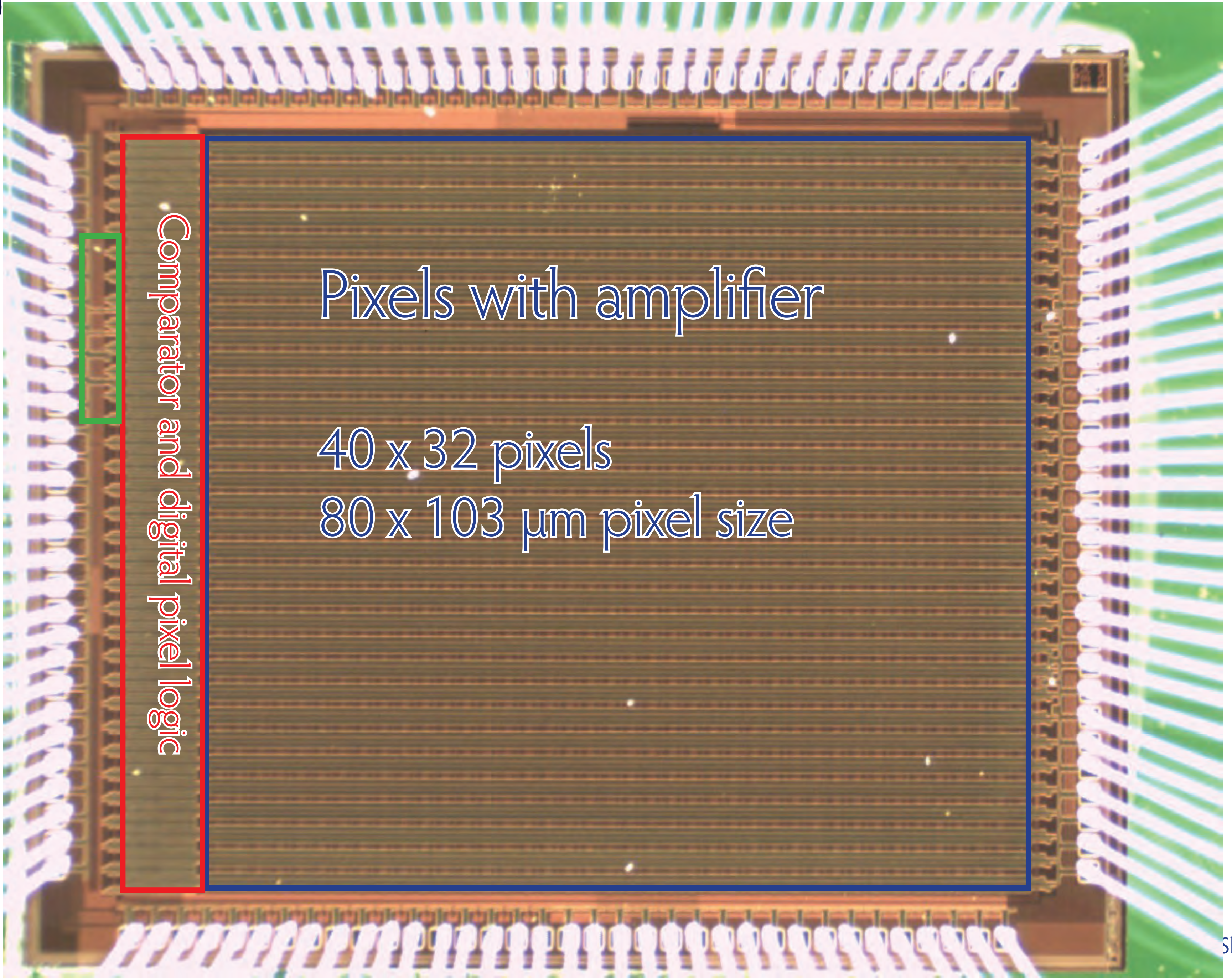


MuPix7



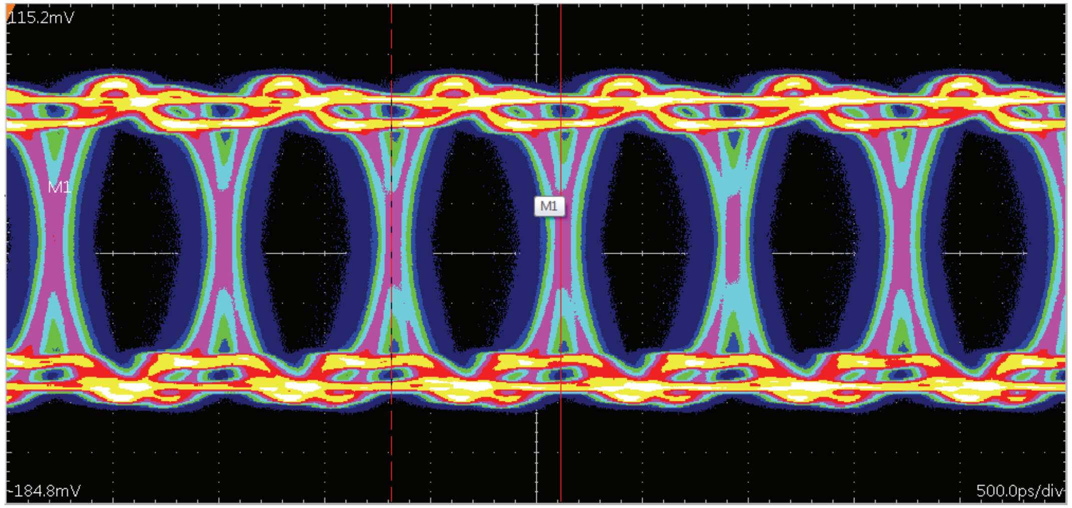
Pixels with amplifier
40 x 32 pixels
80 x 103 µm pixel size
3 mm

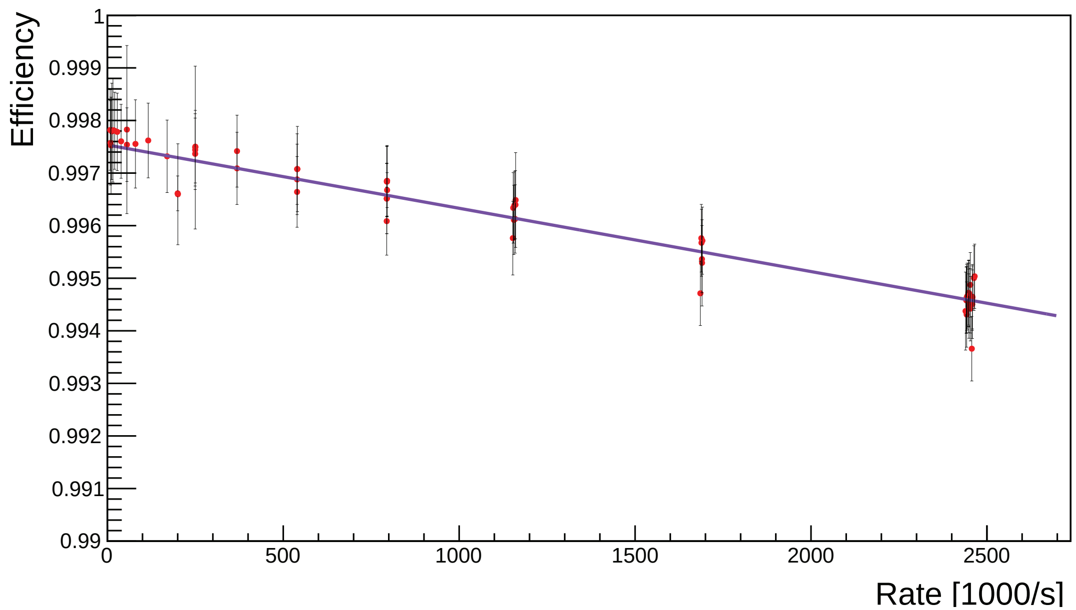
MuPix7


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

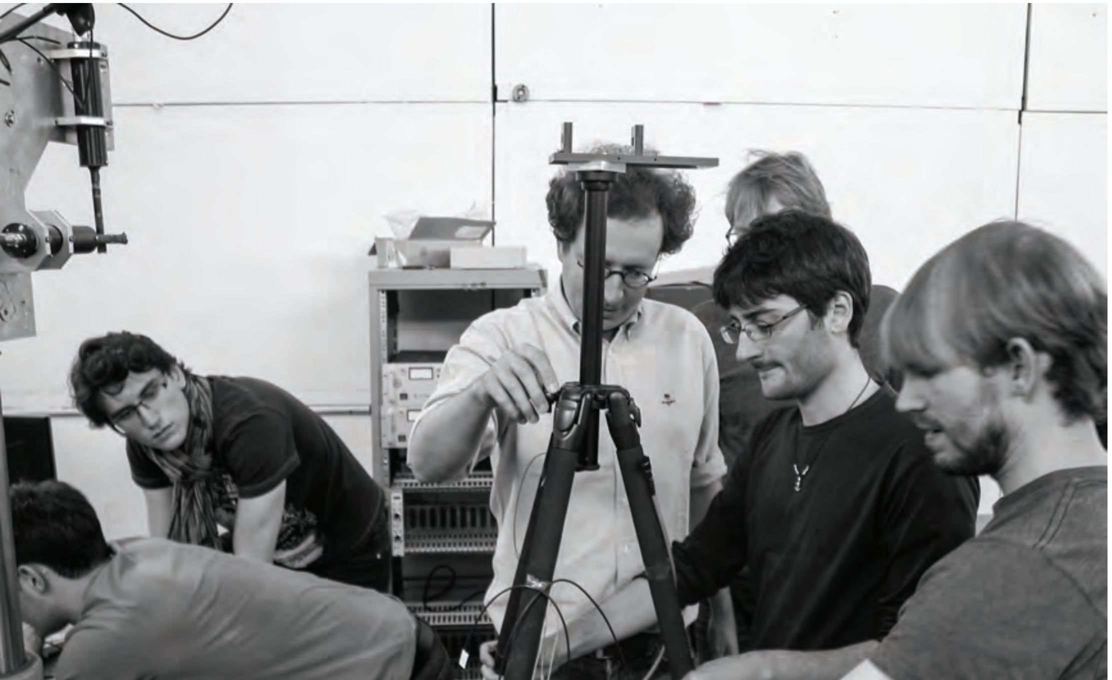
Fully digital output

- 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)





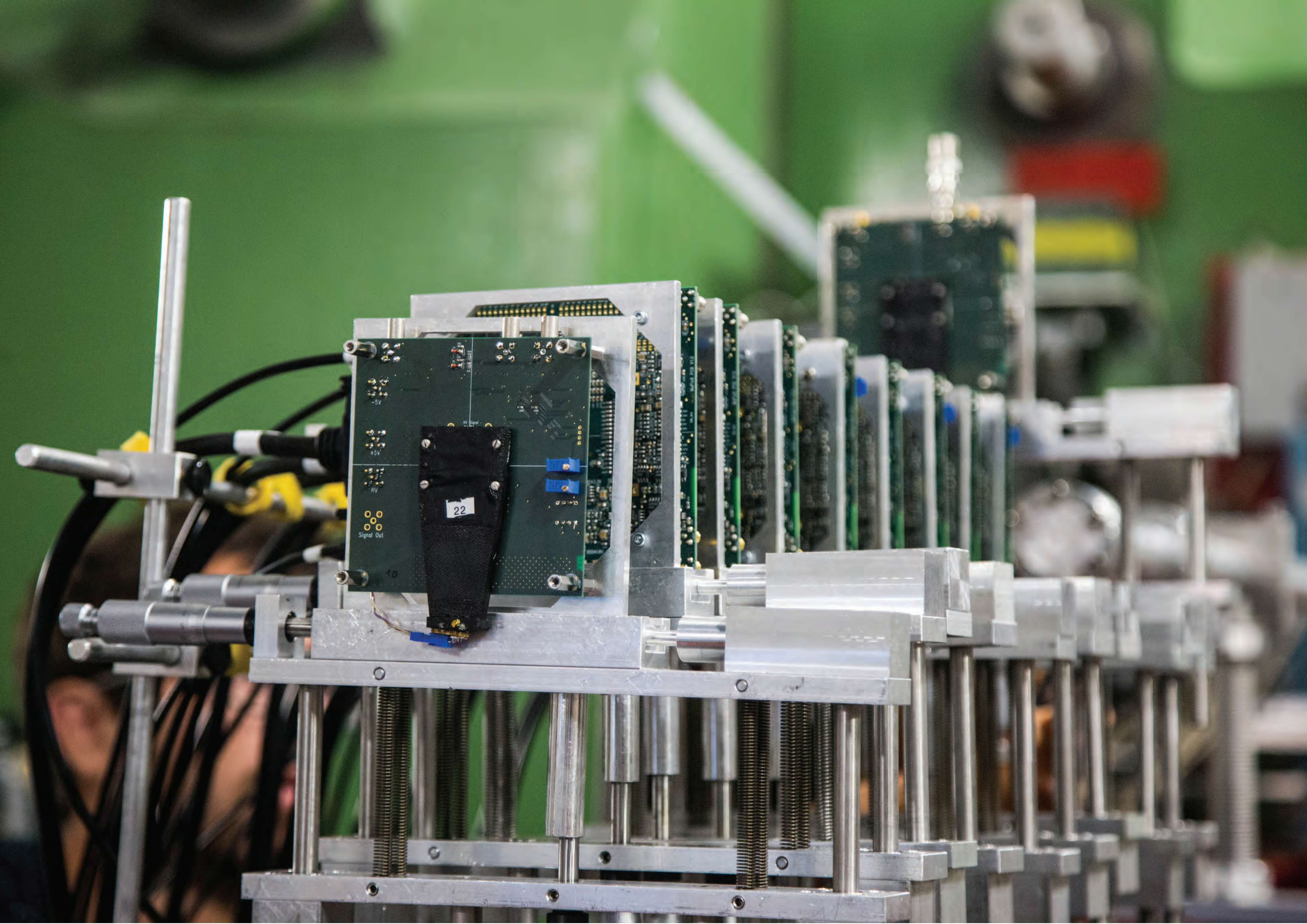
Beam tests



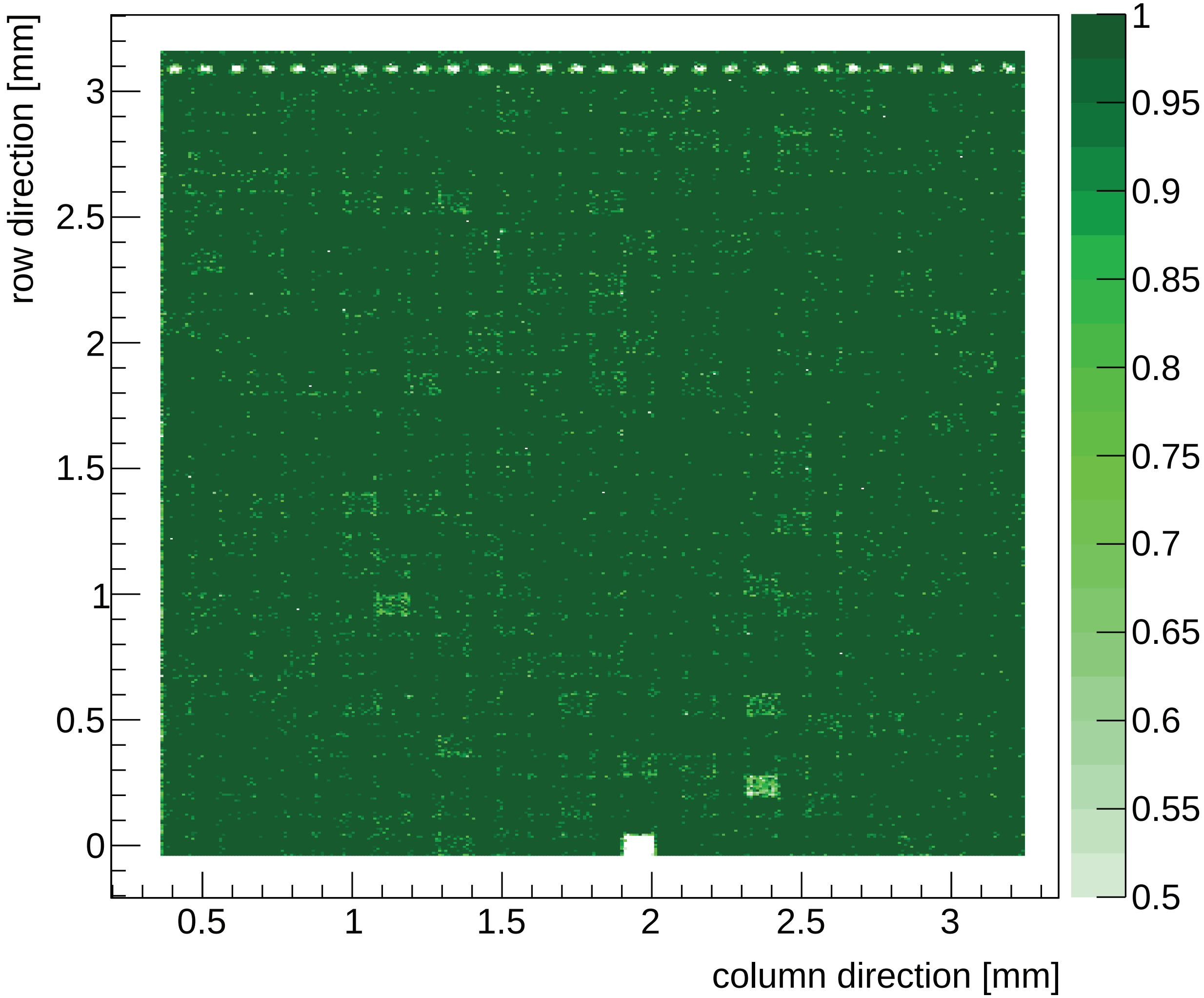
Tests done at

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

- Thanks for all the beam time and support!


22
Signal Out
+5V
HV

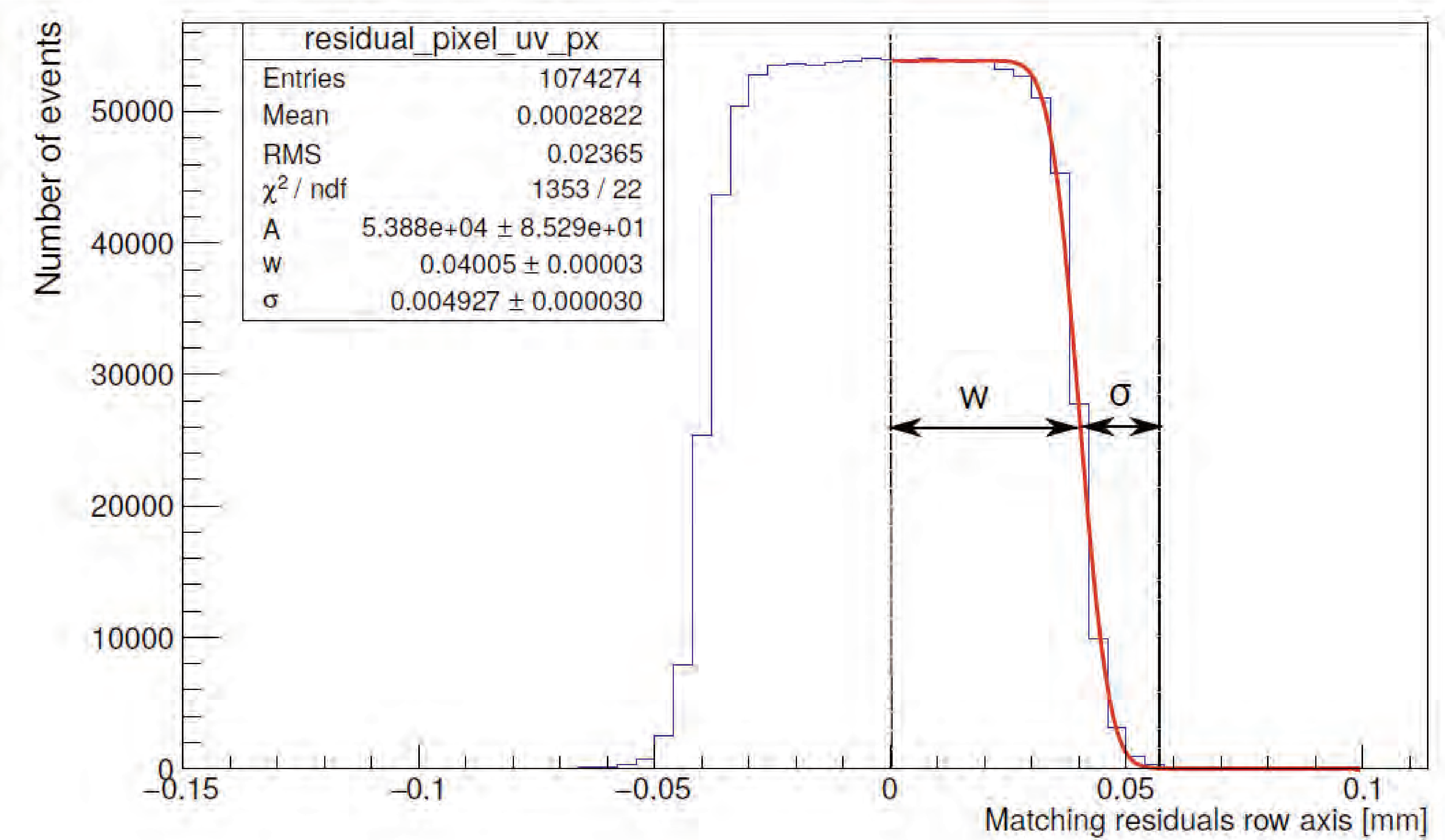
MuPix7 Performance: Efficiency



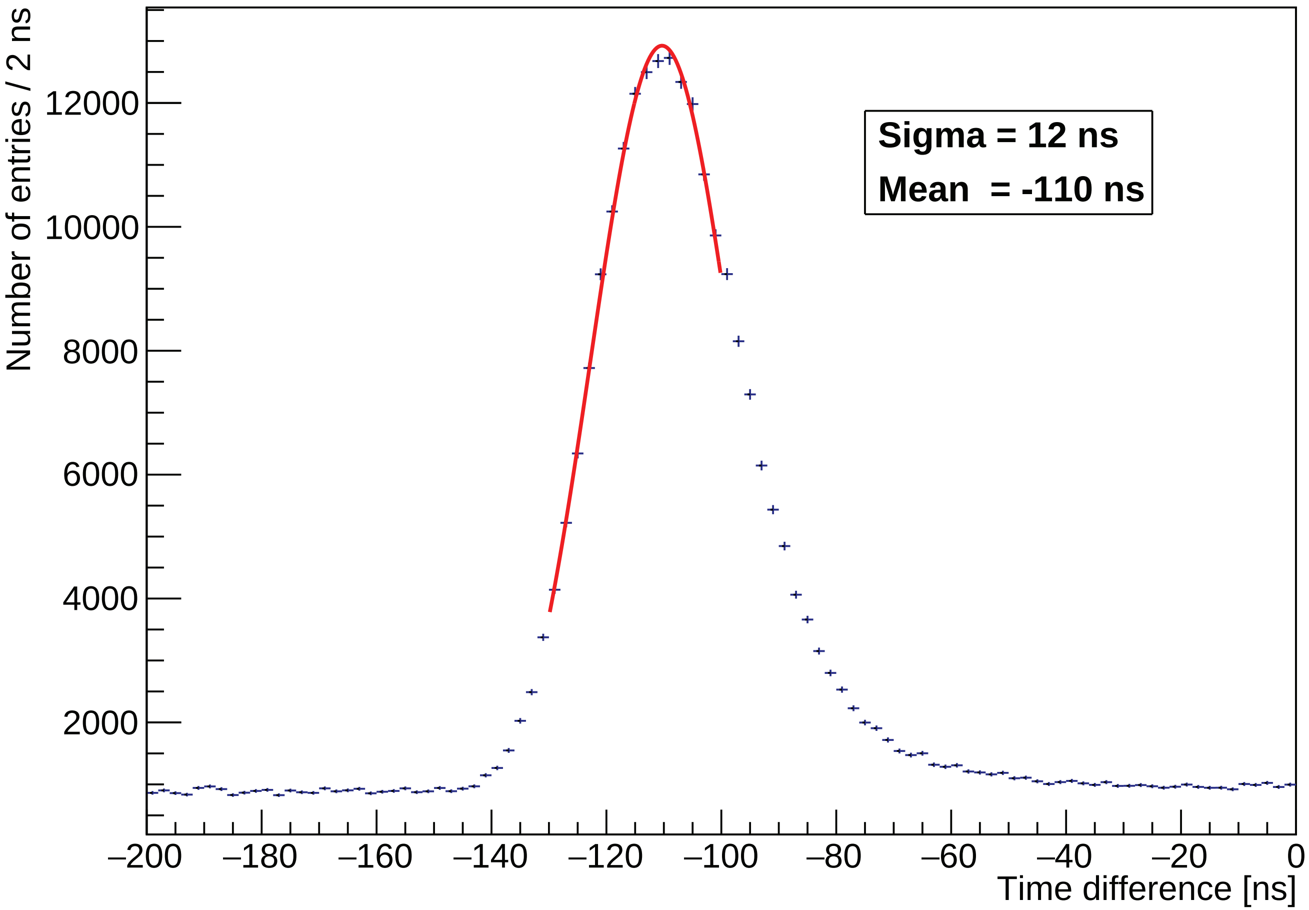
- Beam test at DESY with 4 GeV electrons
- 50 µm sensor, 90° incidence
- Using high-resolution EUDET-Telescope as reference
- All features well understood

MuPix7 Performance: Spatial Resolution

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



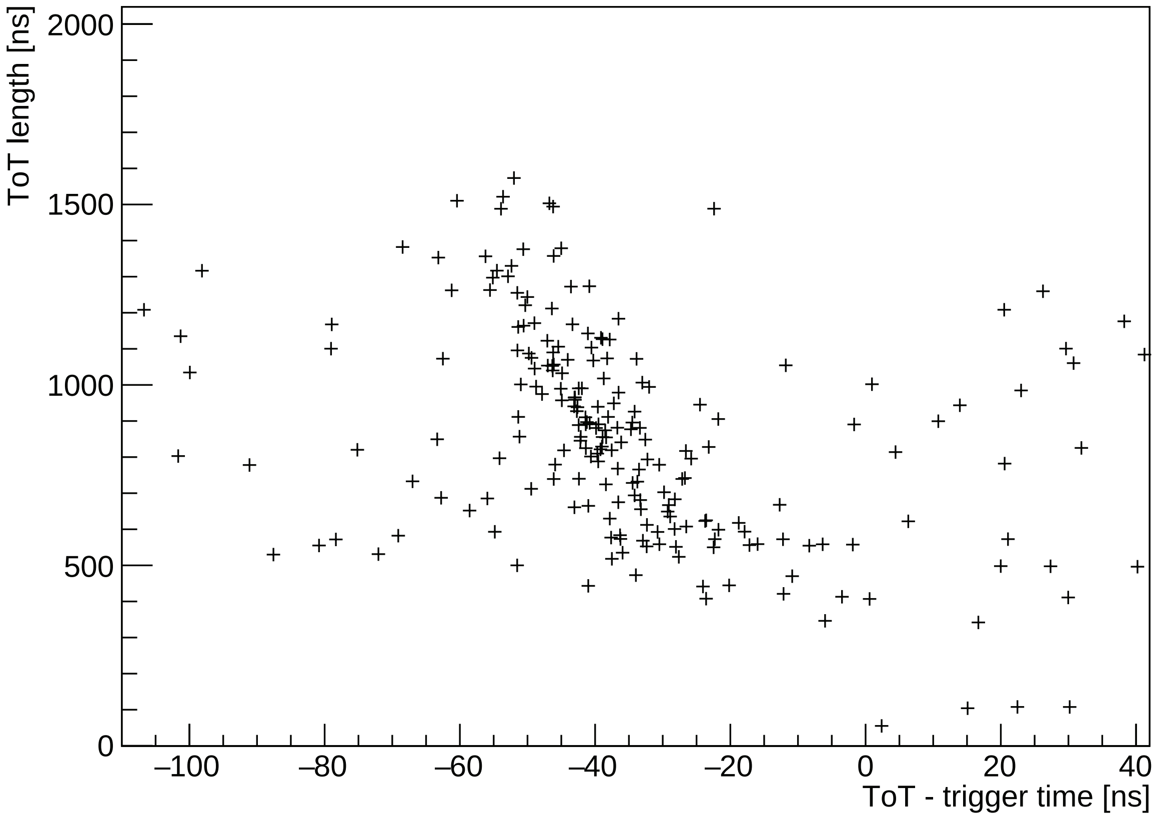
MuPix7 Performance: Time Resolution



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

MuPix7 Performance: Time resolution

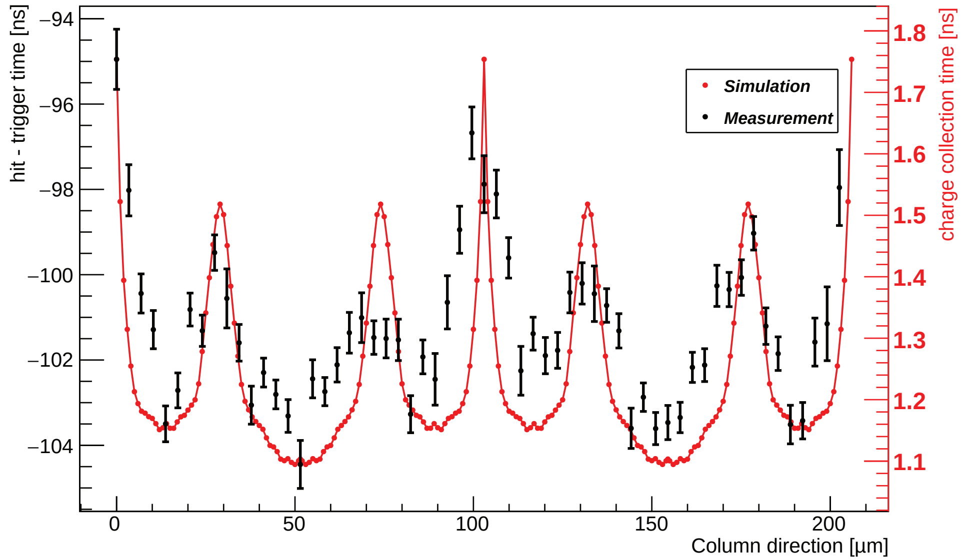
- Single pixel with time-over-threshold signal (~ signal size)
- MuPix8 has signal size for all pixels and finer timestamps
- Can do time-walk correction

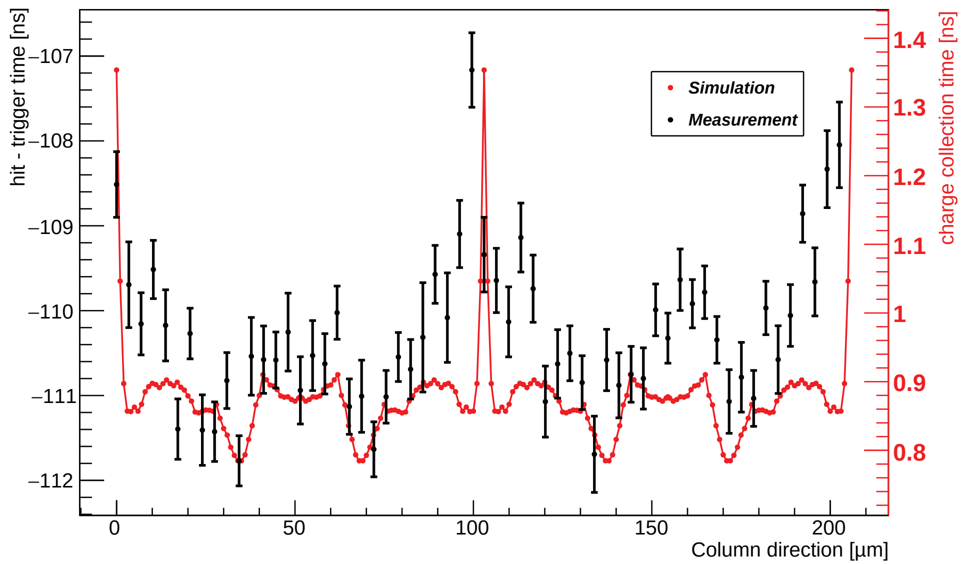


MuPix7 Simulation and Data

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

- Simulation using TCAD: All features can be reproduced

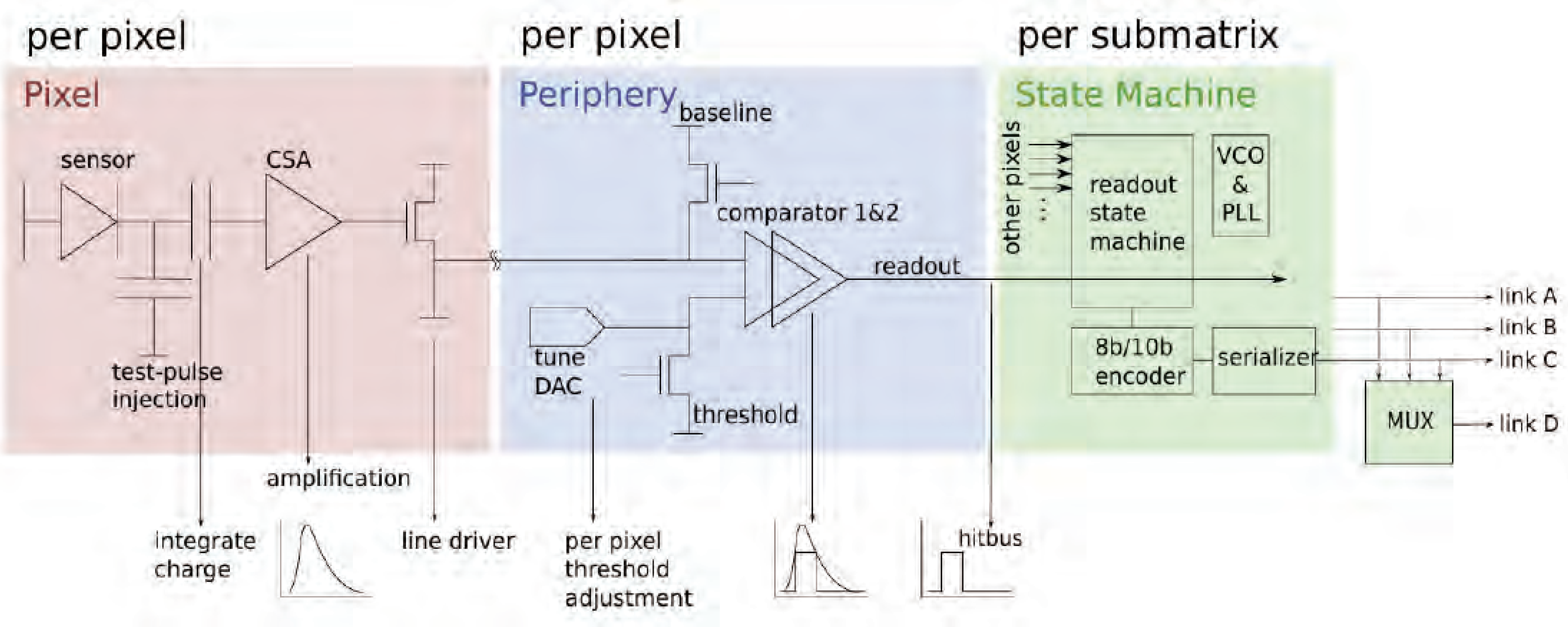




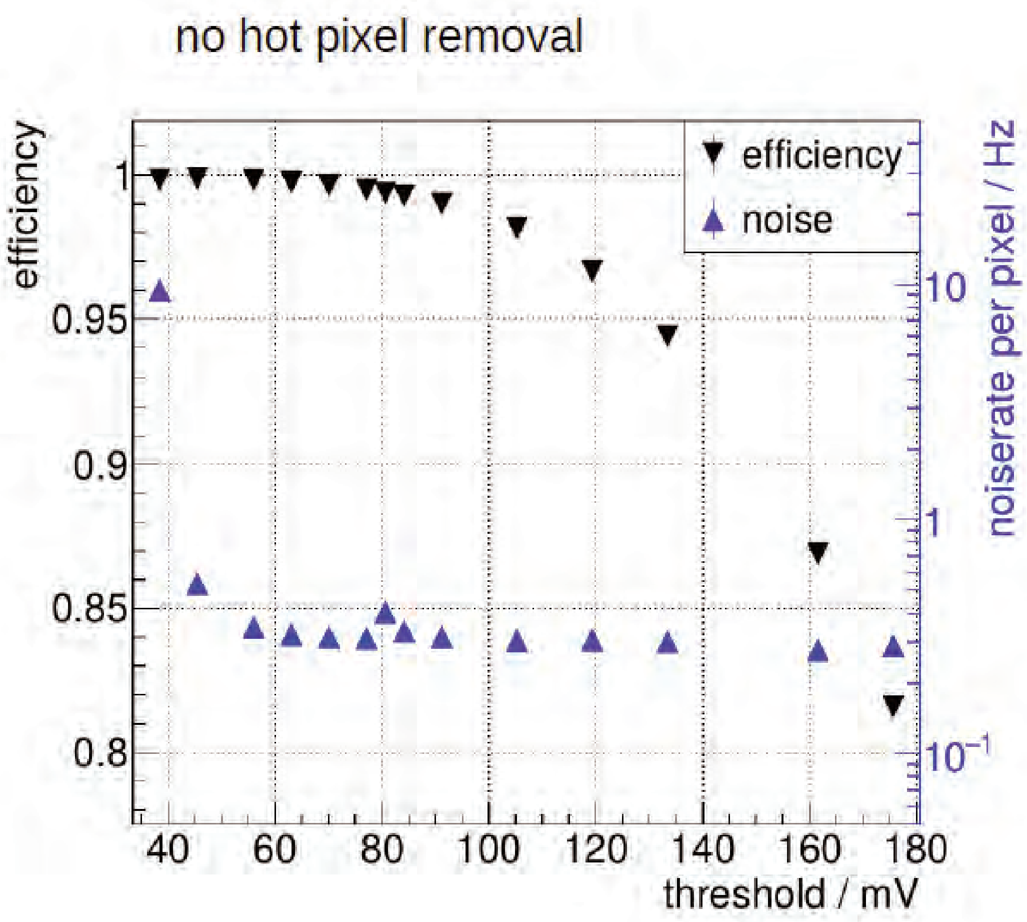
MuPix8

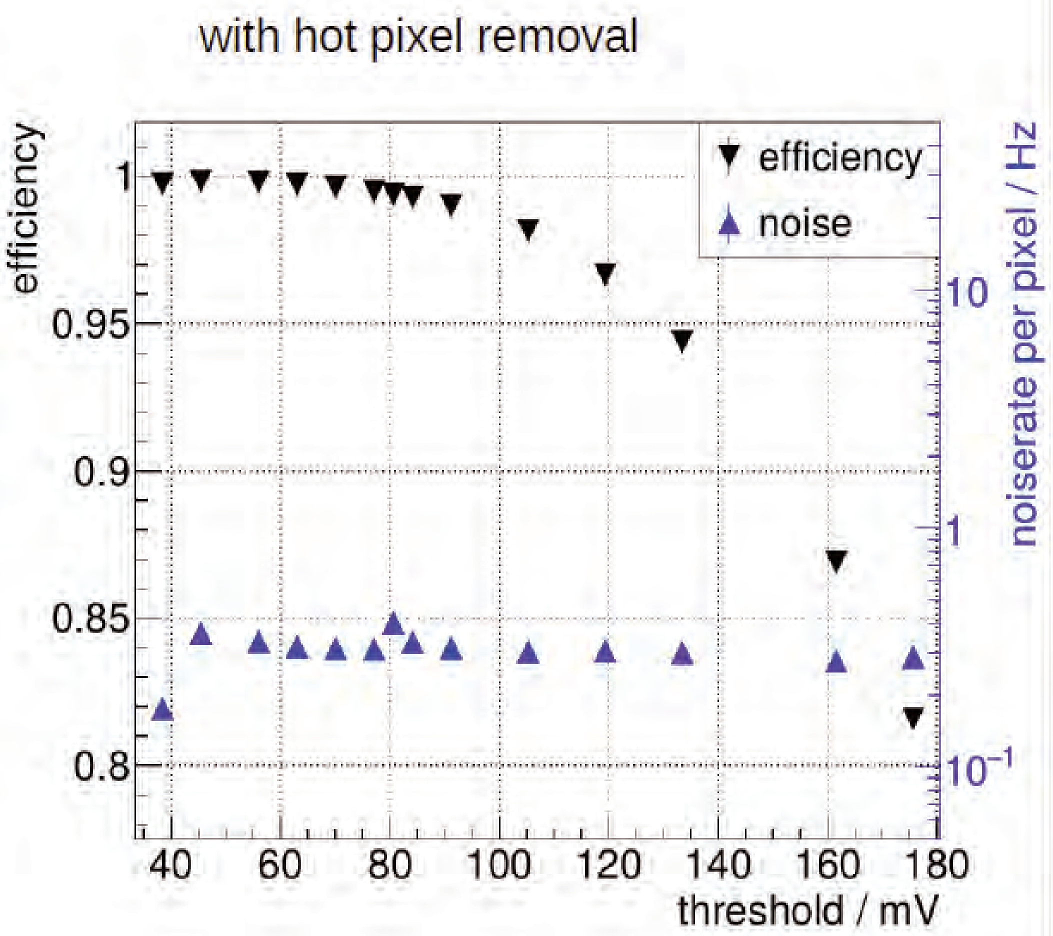
- MuPix8, the first large sensor (2 cm x 1 cm) now available
- Currently under test
- Three sub-matrices with different signal transmission to periphery
- Results from matrix A with the Mupix7-like source follower

MuPix8 Architecture

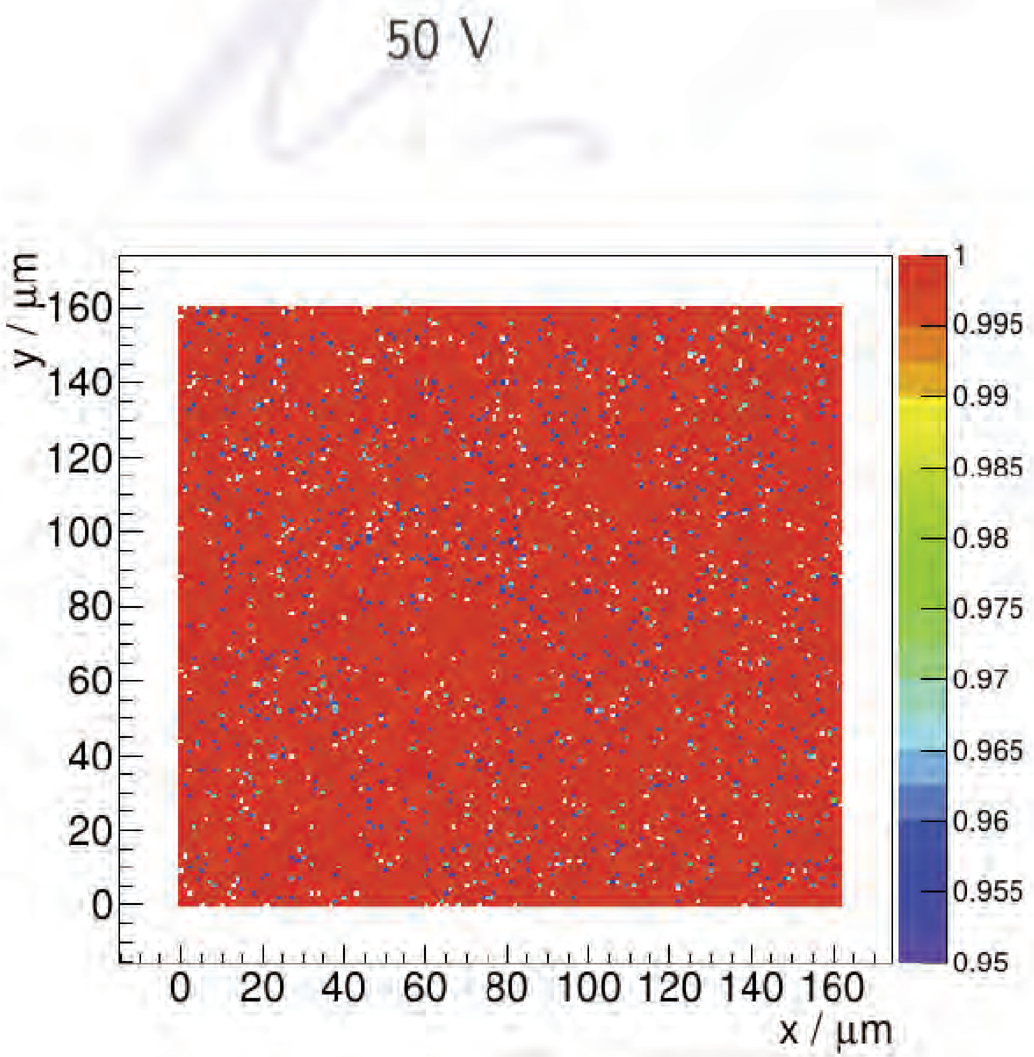


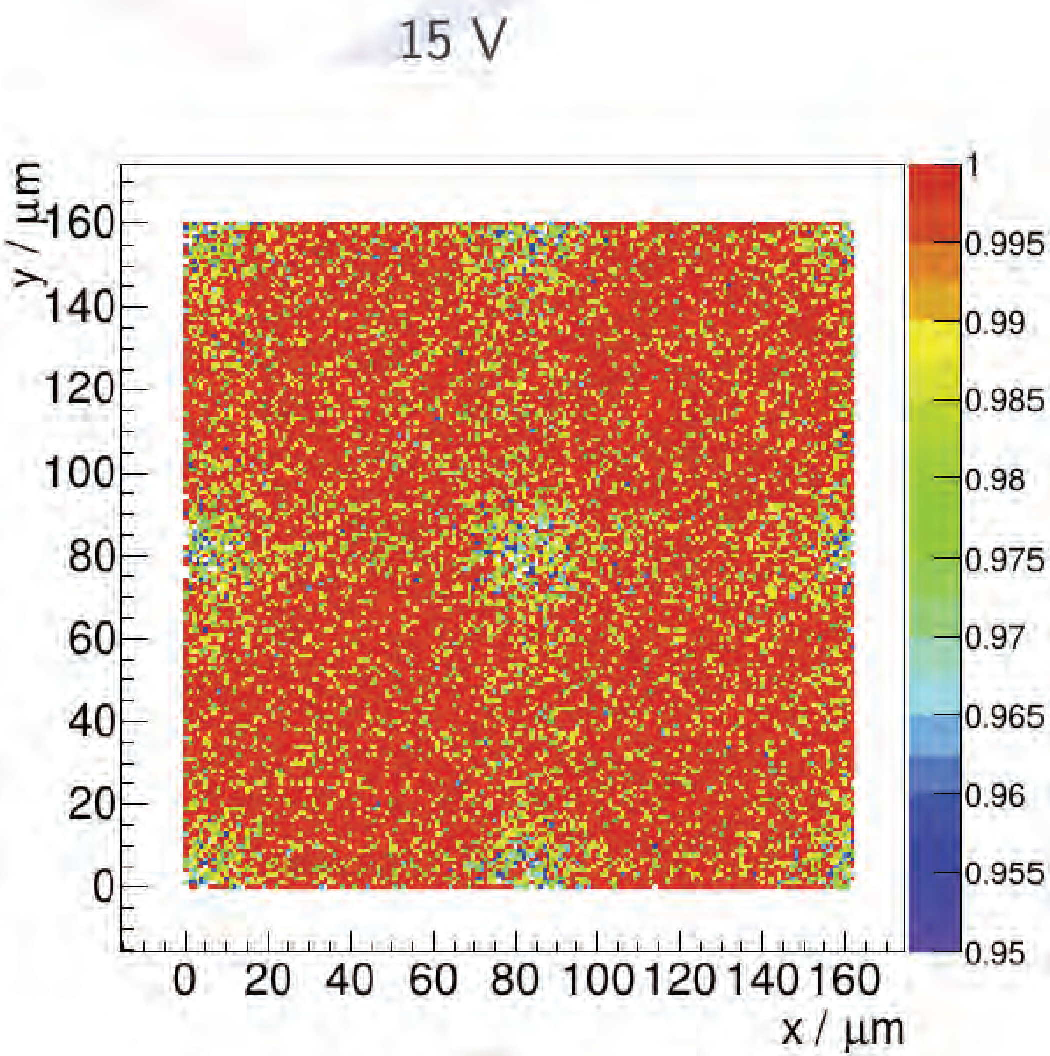
MuPix8 Performance





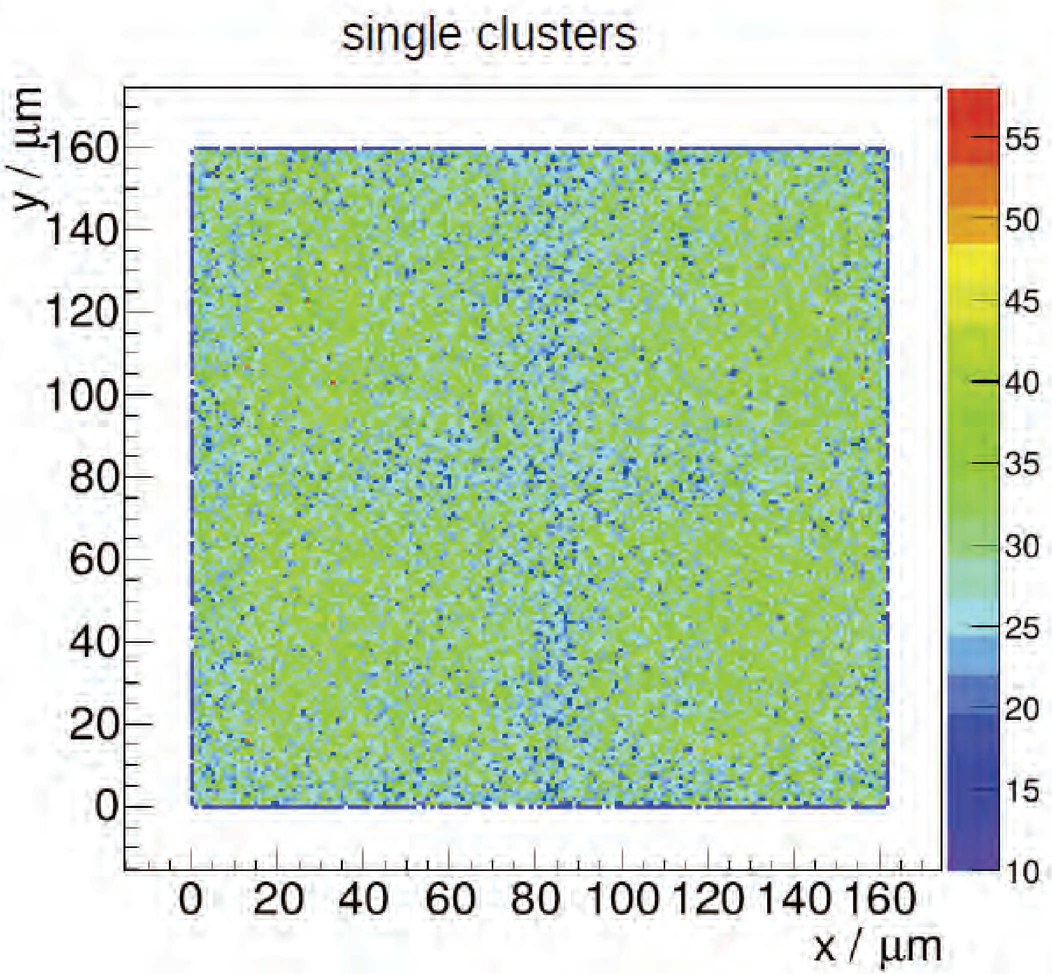
MuPix8 Performance

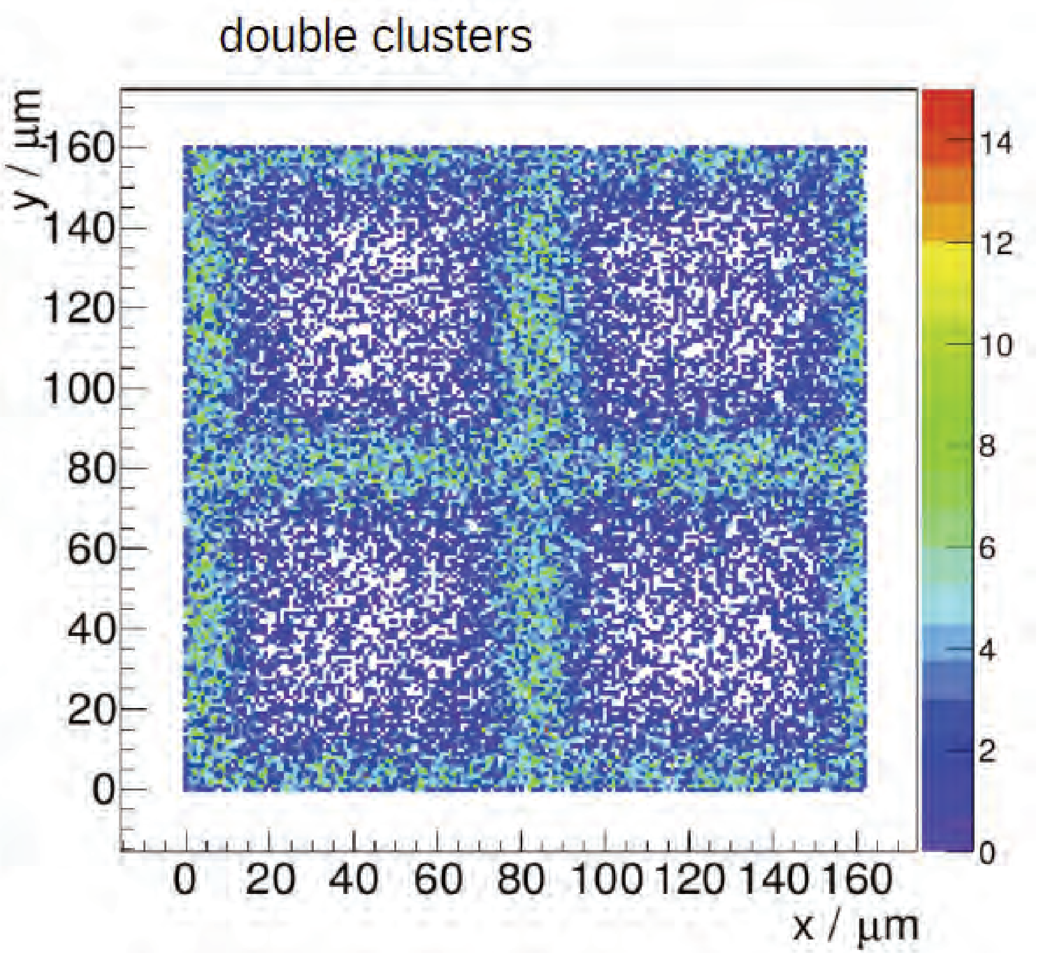




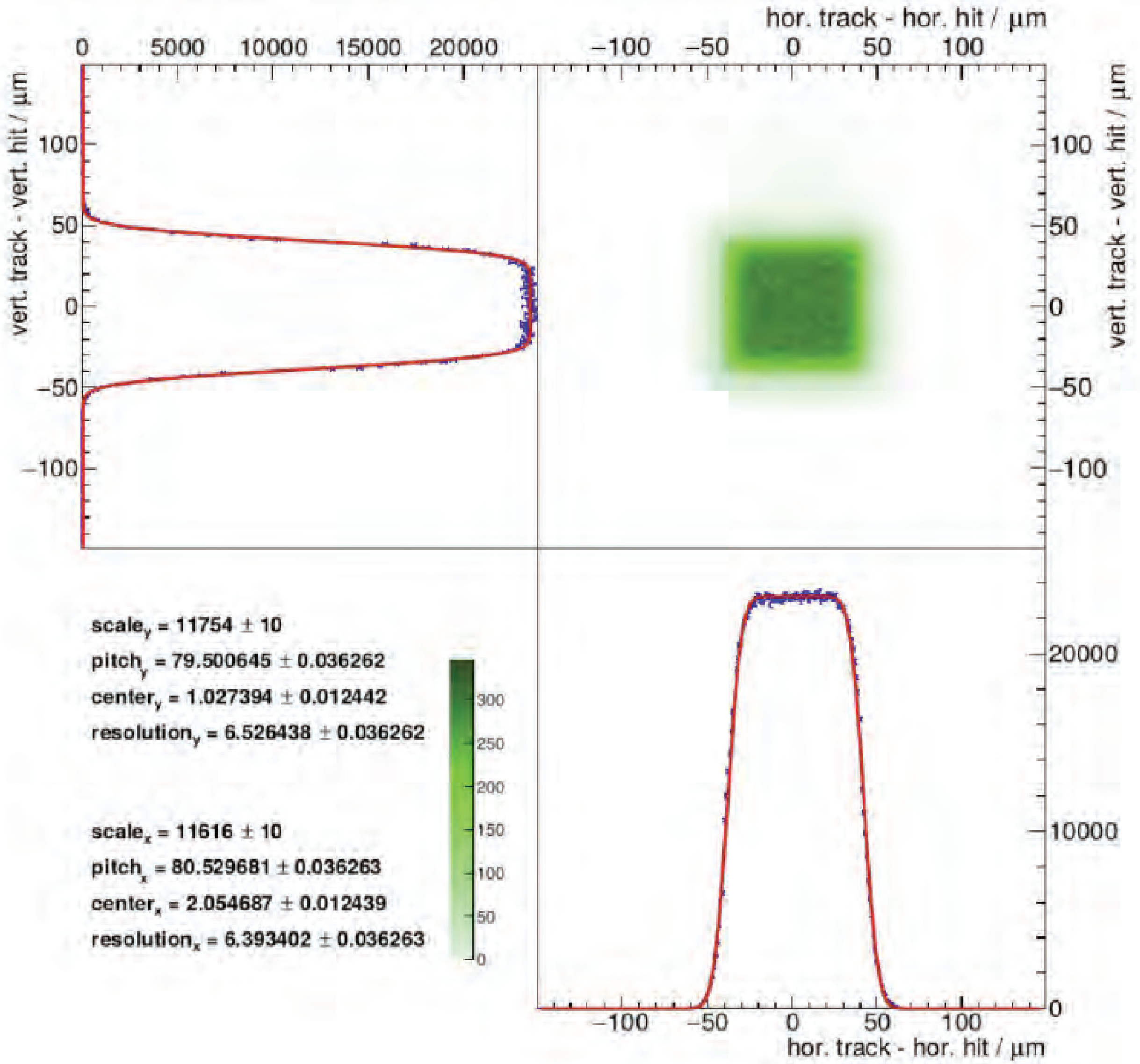
MuPix8 Performance

- Charge sharing only at pixel edges



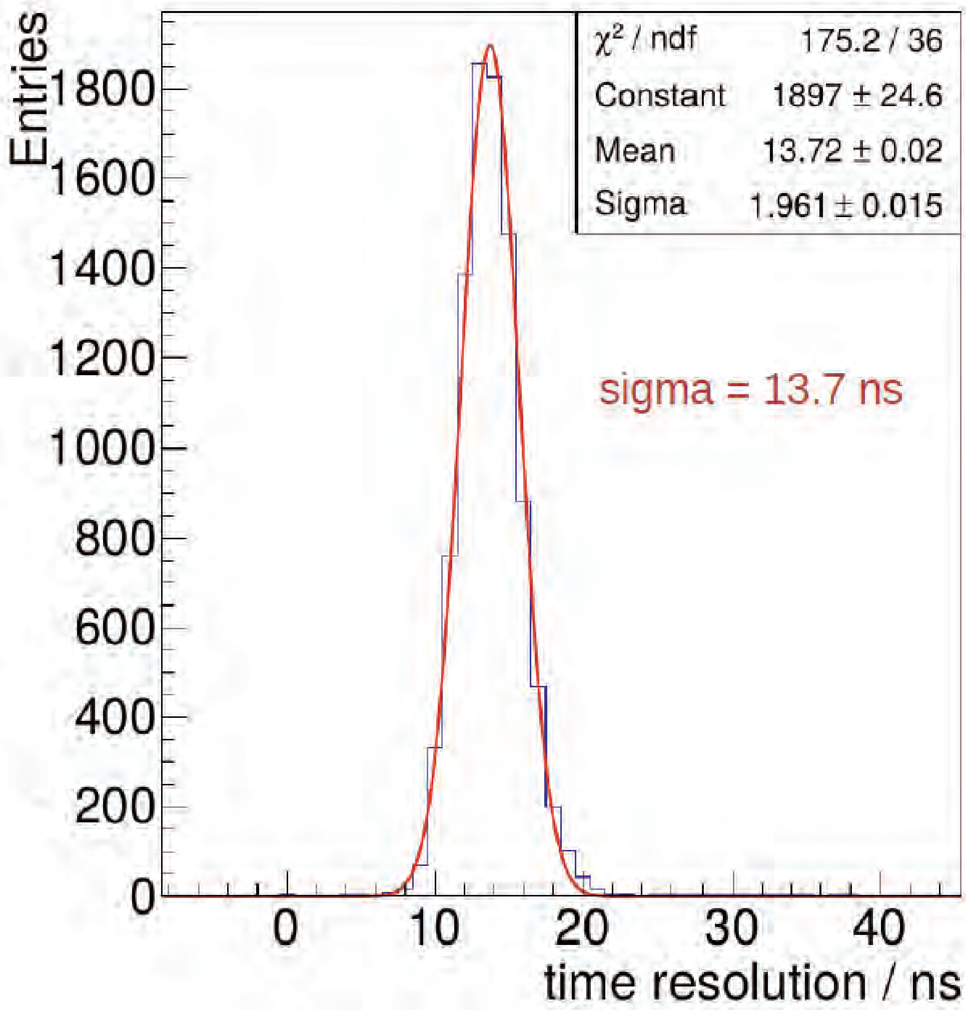


MuPix8 Performance



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

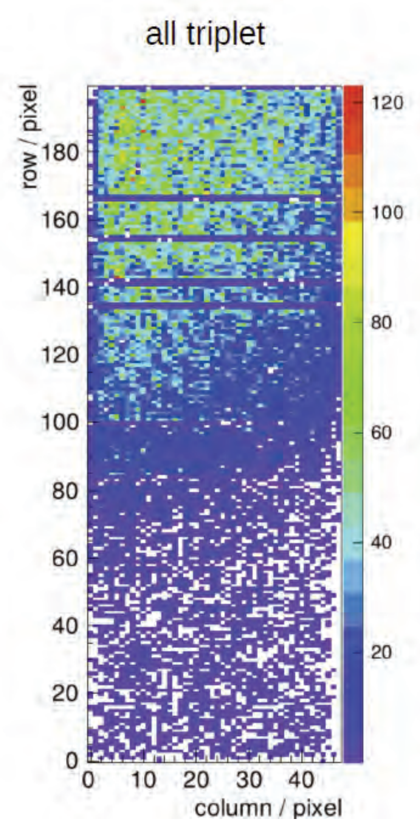
MuPix8 Performance

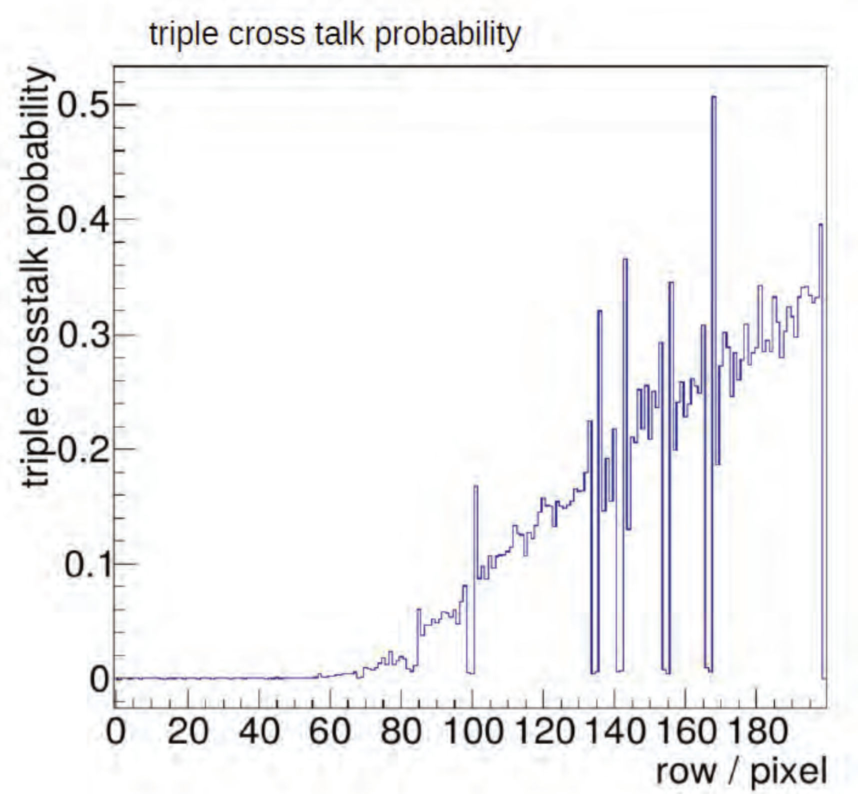


- 8 ns timestamps
- Some delays over the chip, large pixel-to-pixel variations: Need correction
- Further improvements possible, for matrix subset, 6 ns were obtained

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

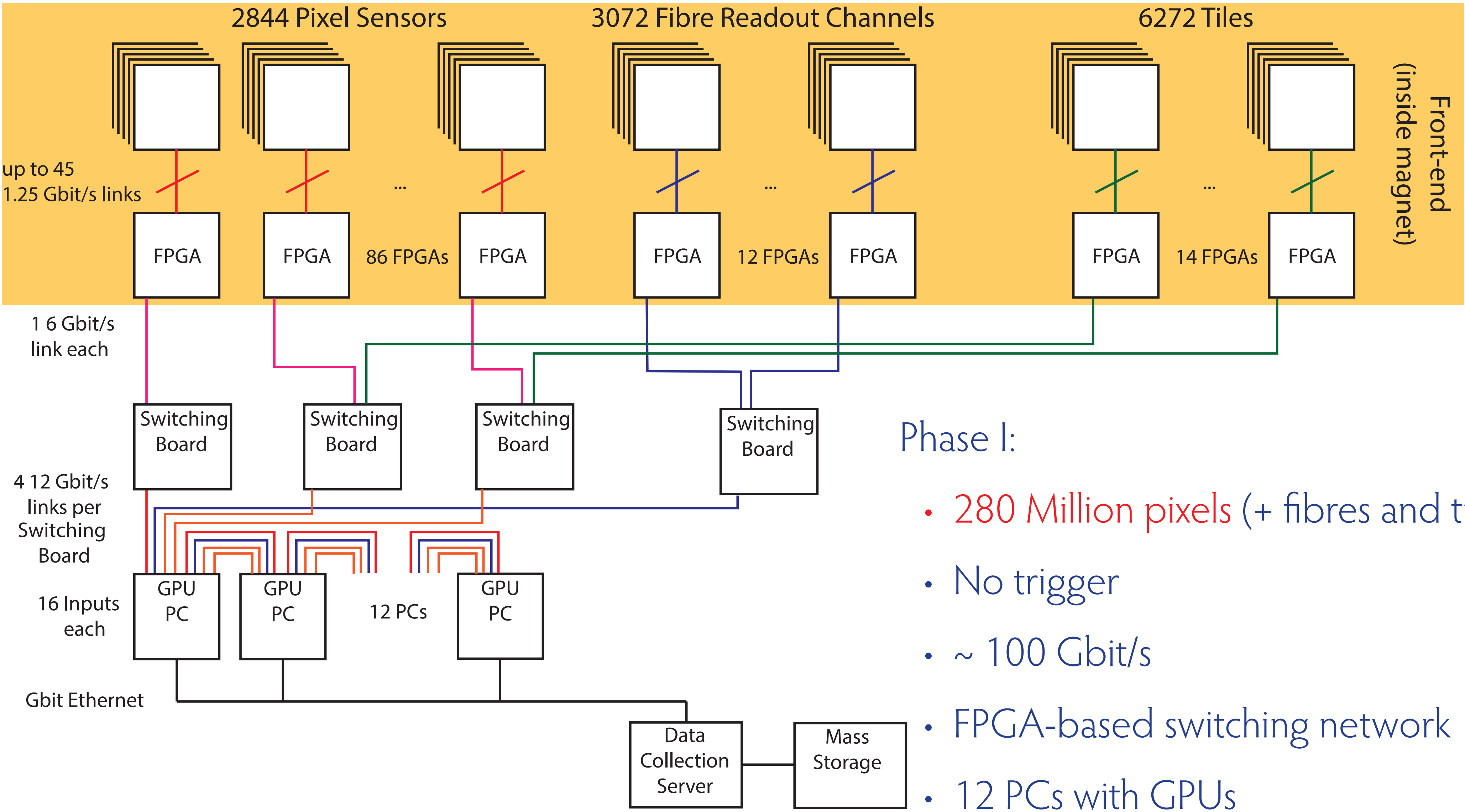
- Note: The PANDA luminosity detector will operate MuPix in vacuum: Cooling via diamond wafers

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

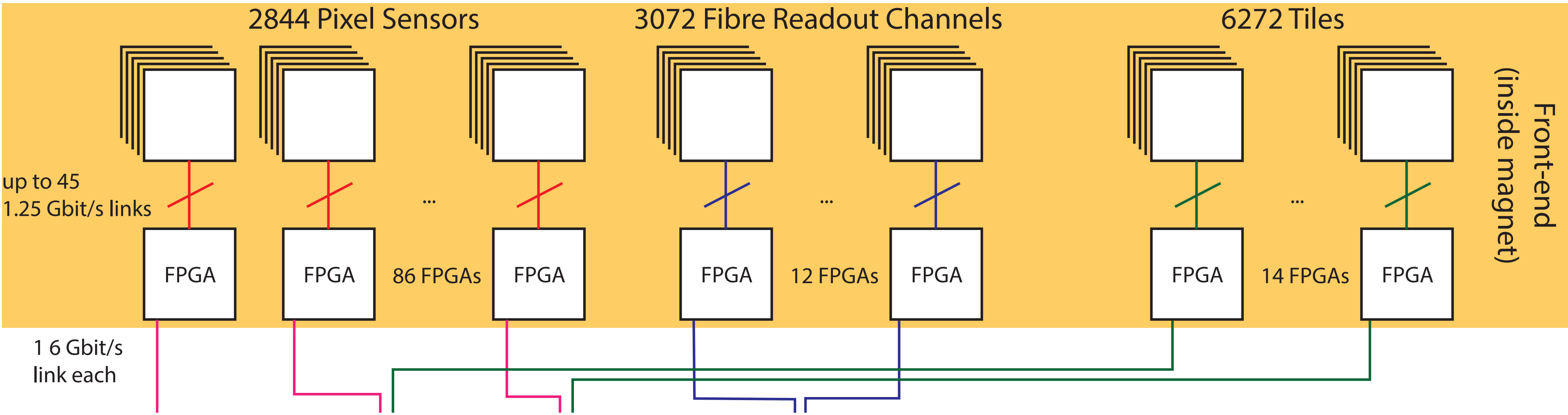
Data Acquisition



Phase I:

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

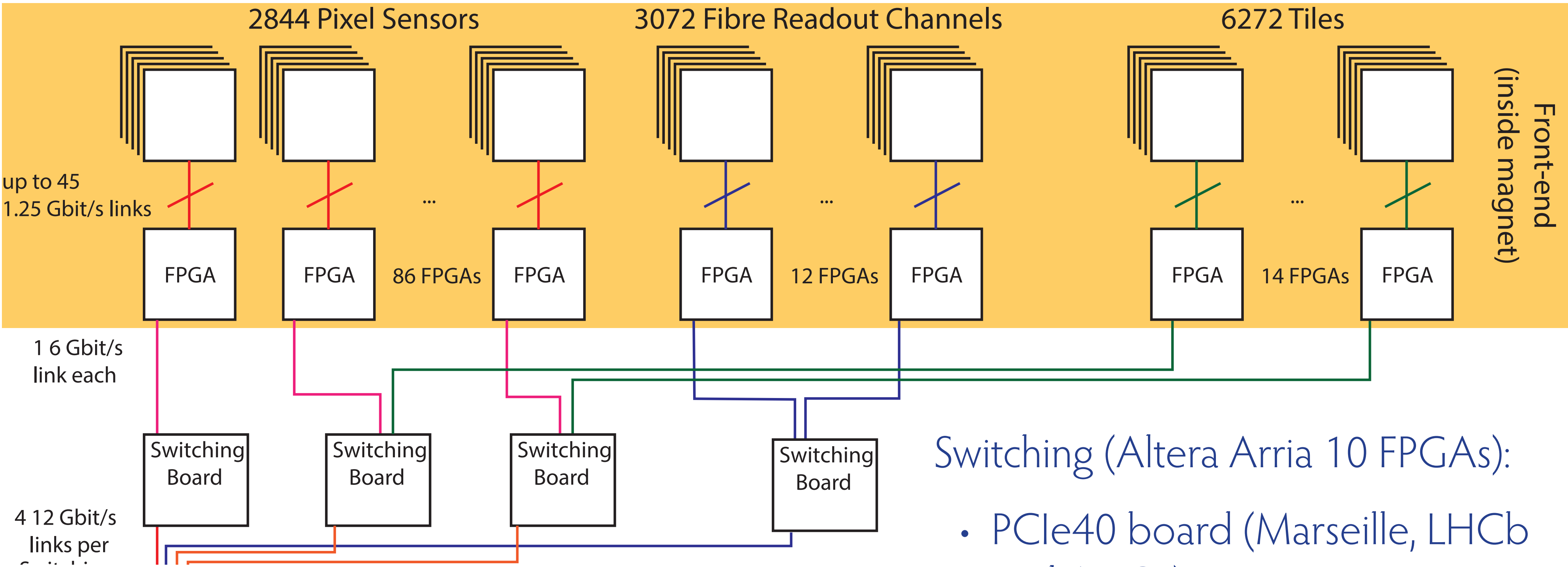
Data Acquisition



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

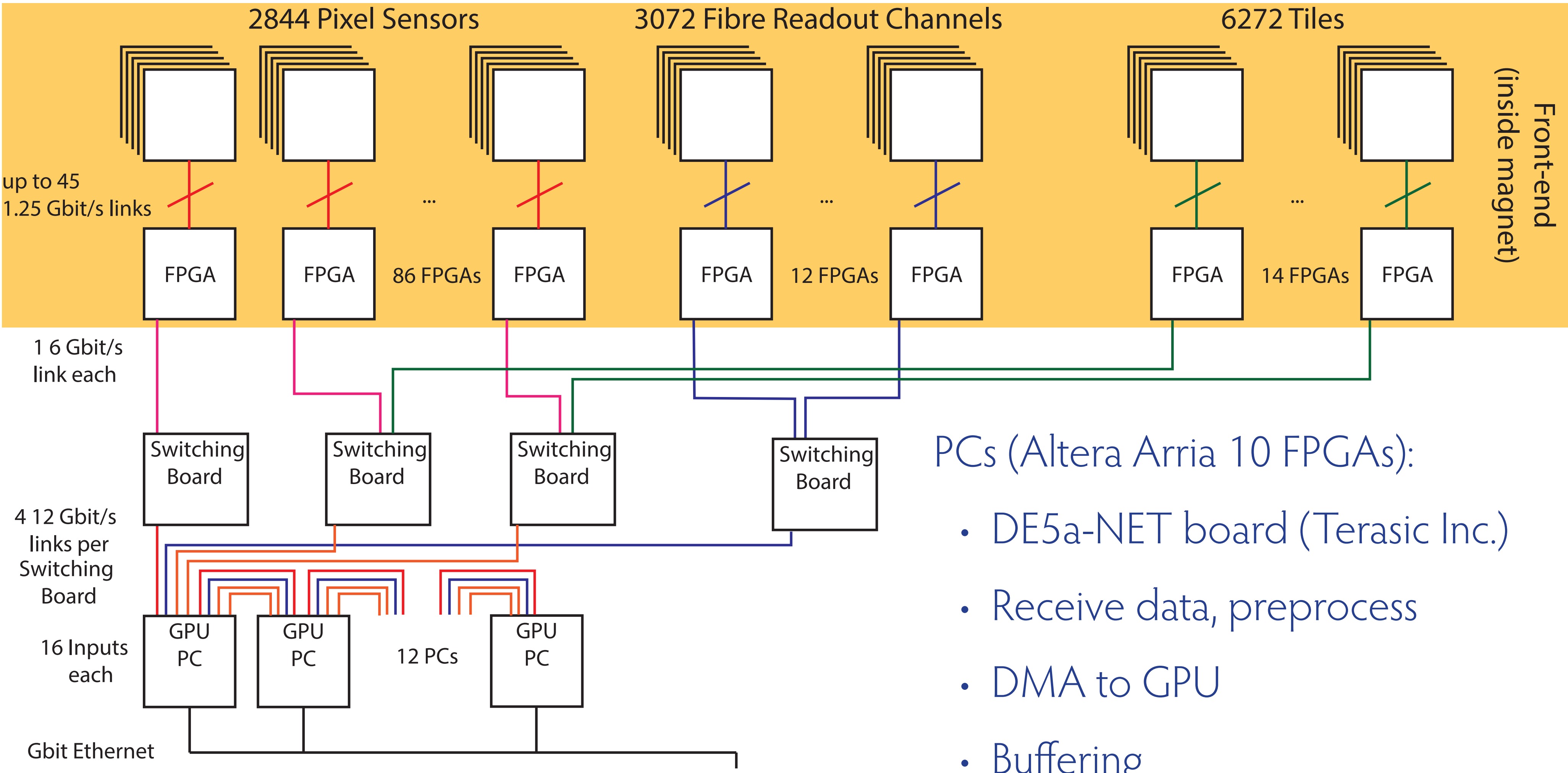
Data Acquisition



Switching (Altera Arria 10 FPGAs):

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

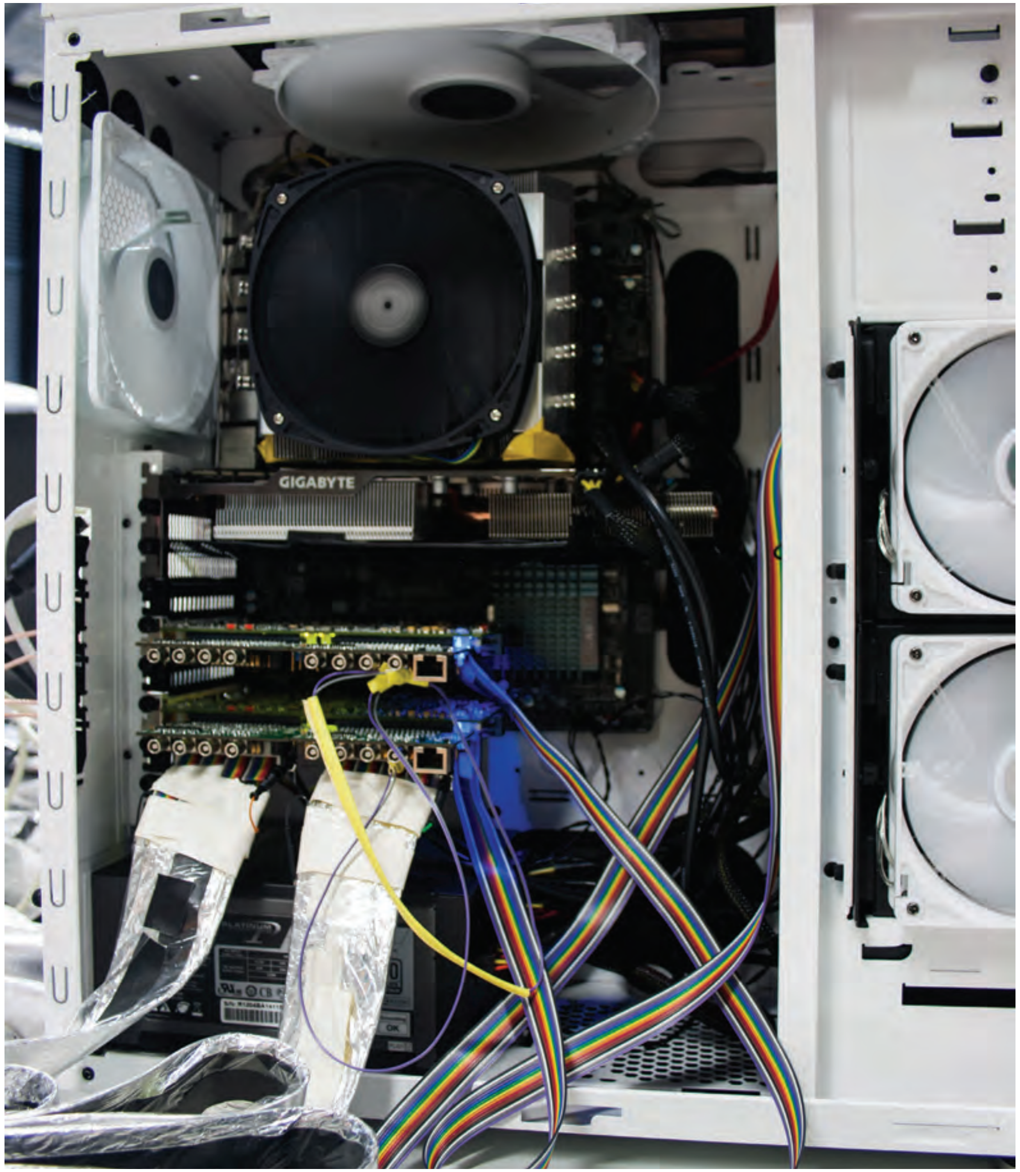
Data Acquisition



PCs (Altera Arria 10 FPGAs):

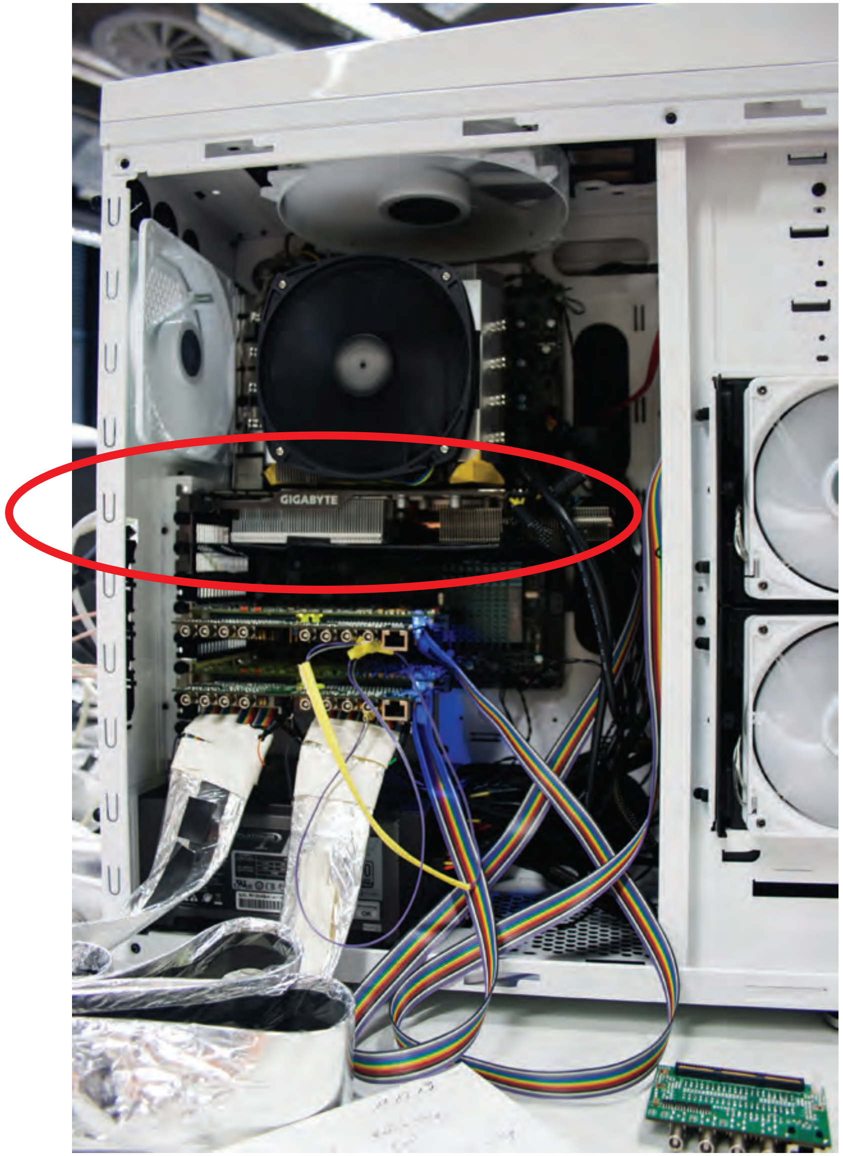
- DE5a-NET board (Terasic Inc.)
- Receive data, preprocess
- DMA to GPU
- Buffering

Online reconstruction



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

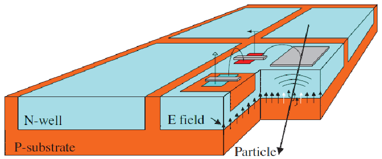
Online filter farm



- 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

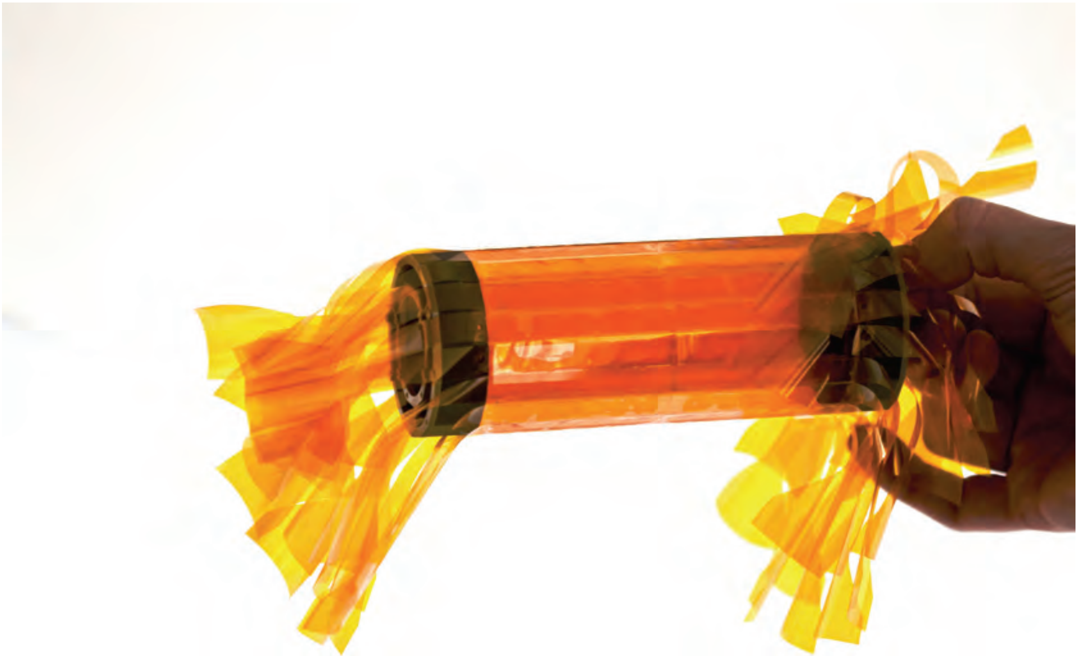
- Mu3e aims for $\mu \rightarrow eee$ at the 10^{-16} level
- First large scale use of HV-MAPS



- 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

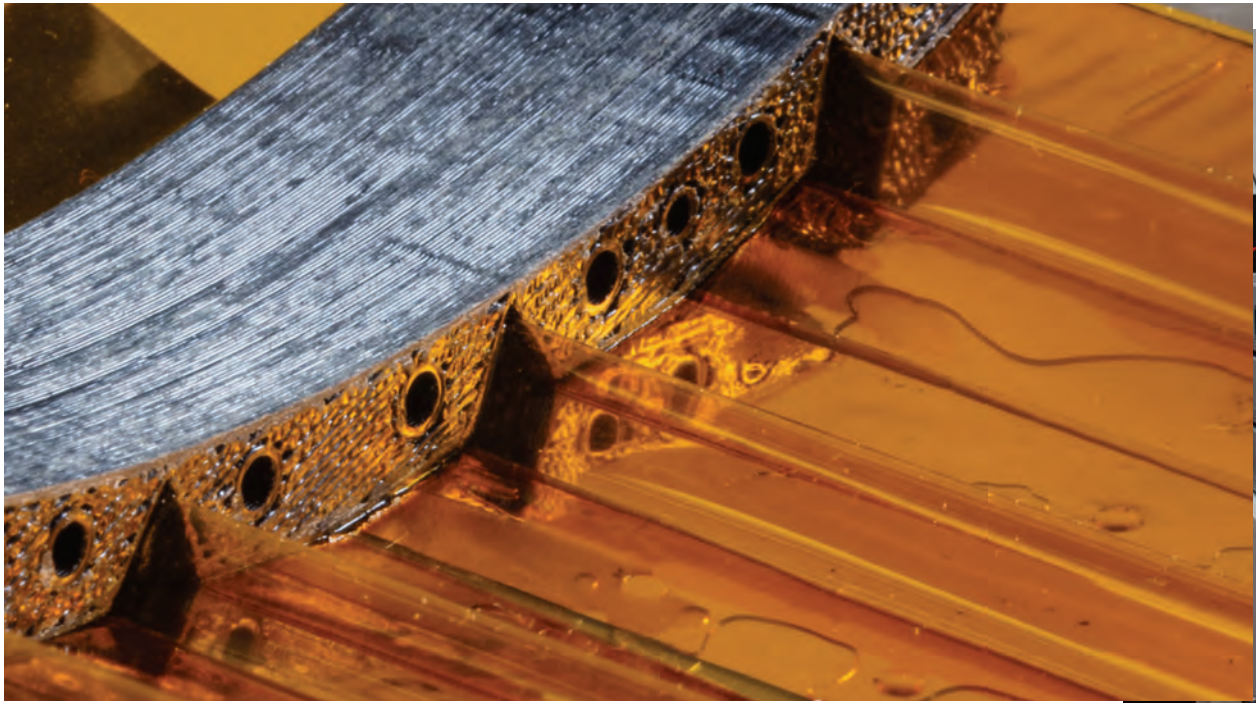
Backup Material

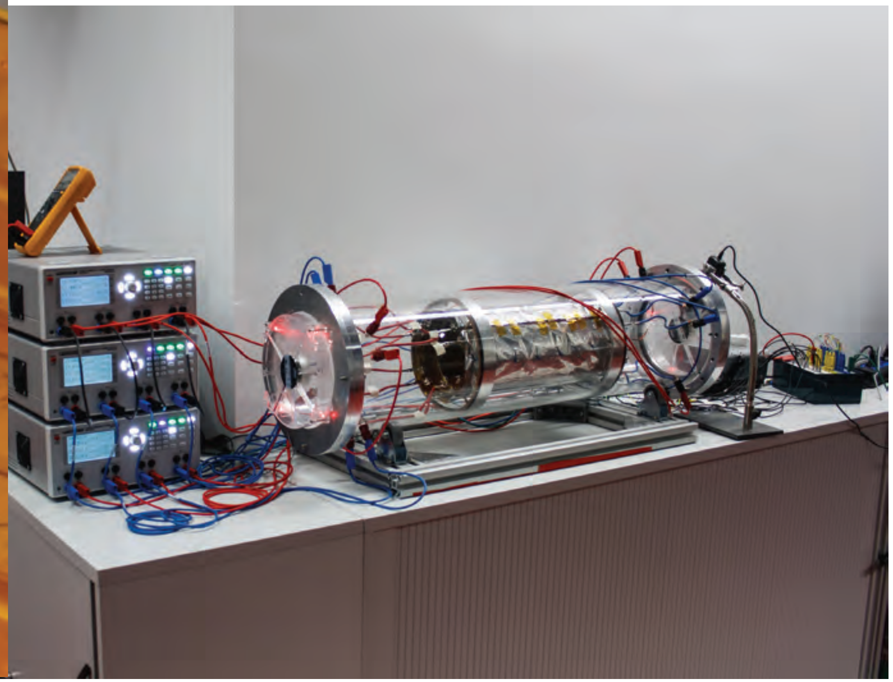


Cooling

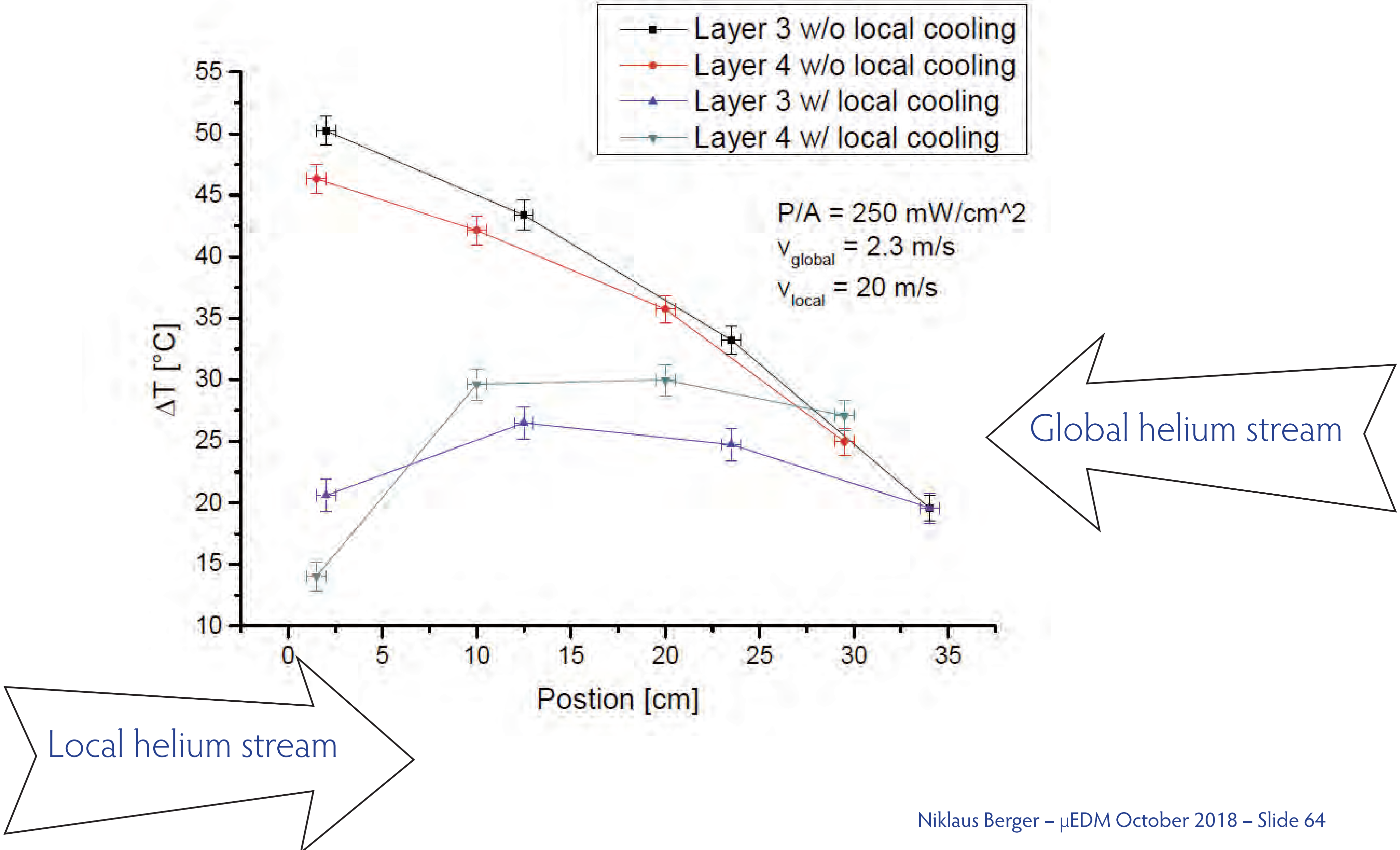
- Add no material:
  Cool with gaseous Helium
  (low scattering, high mobility)
- ~ 250 mW/cm^2 - total ~3 kW
- Simulations: Need ~ several m/s flow

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

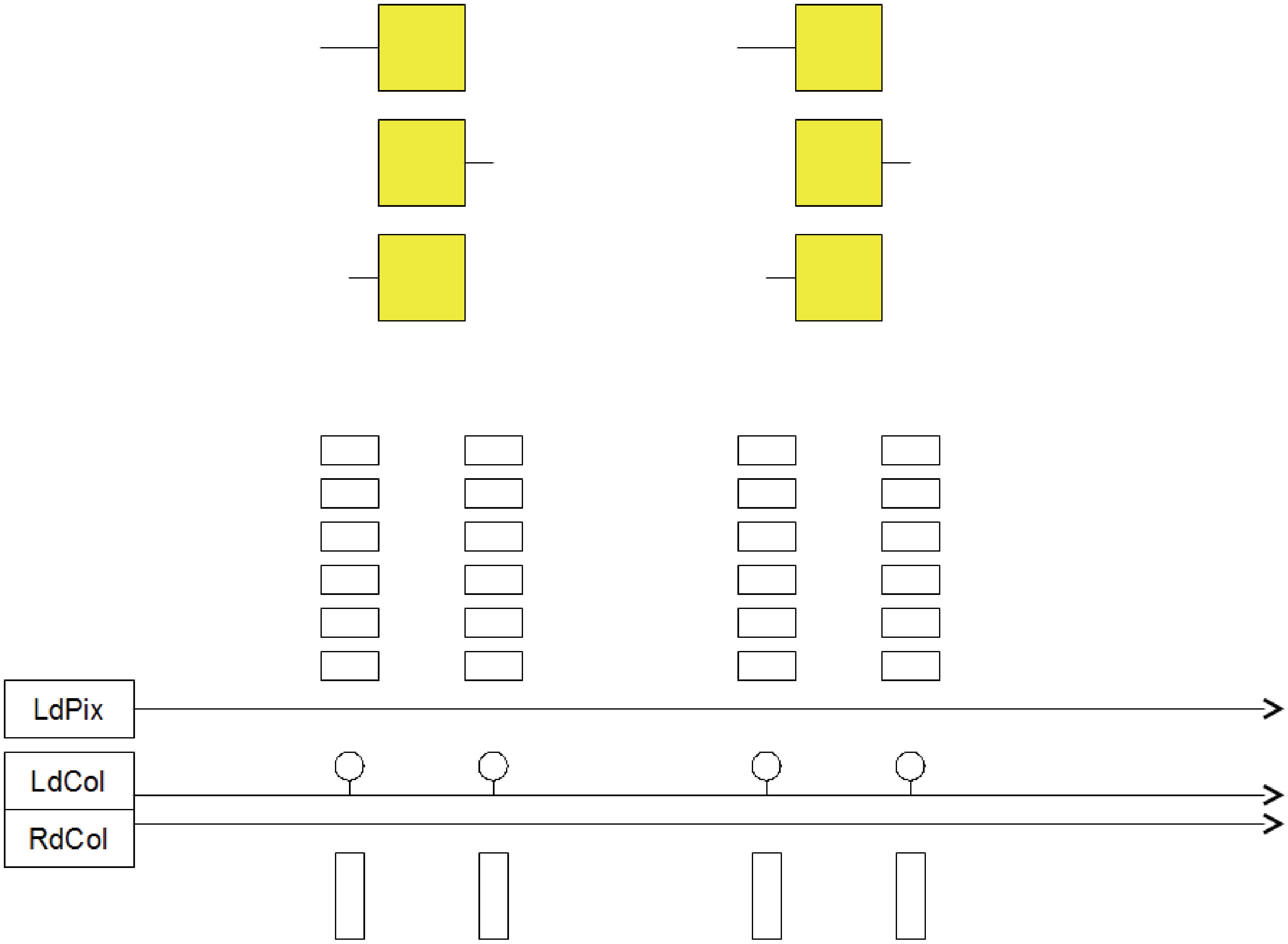




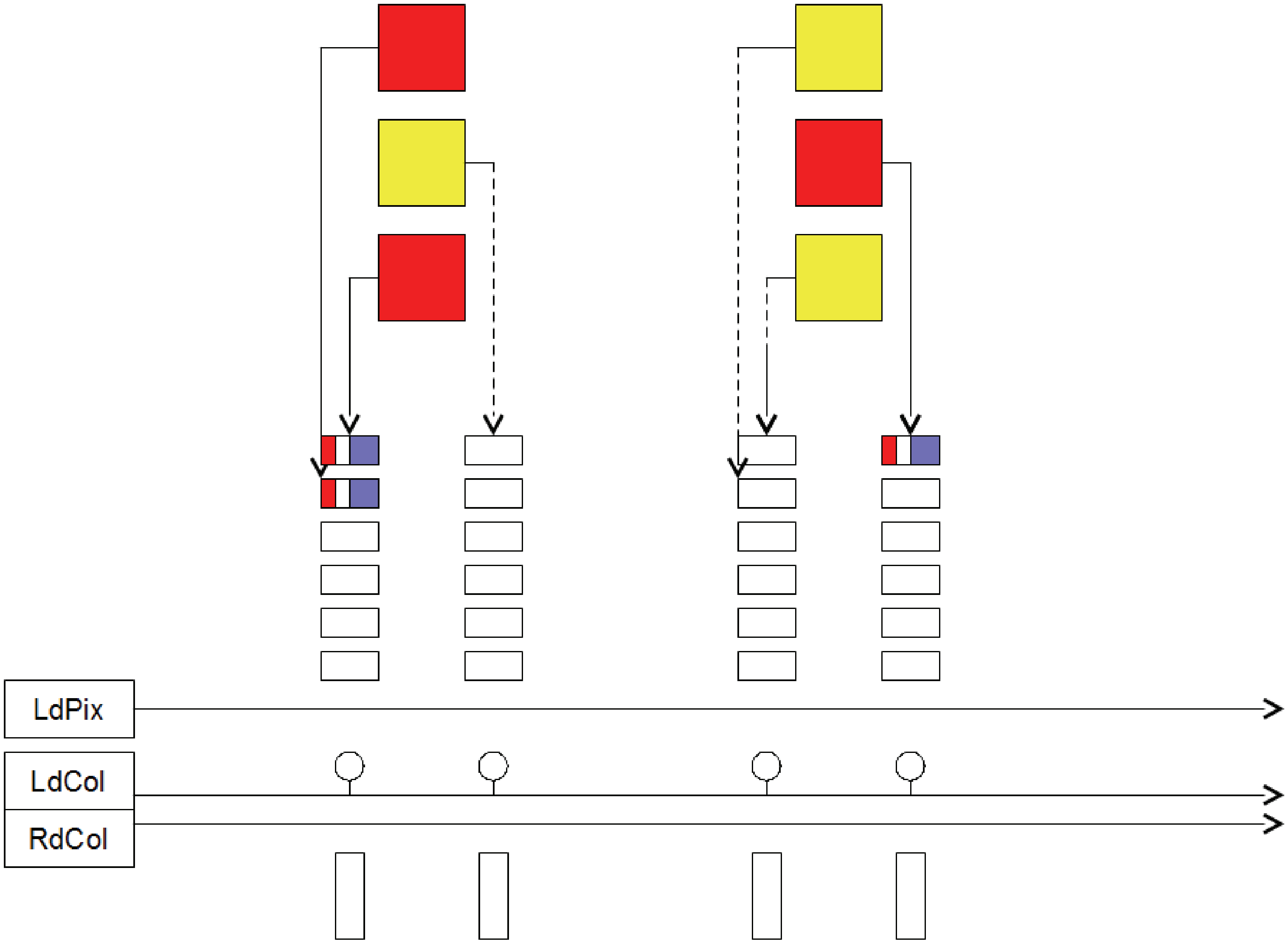
Cooling tests



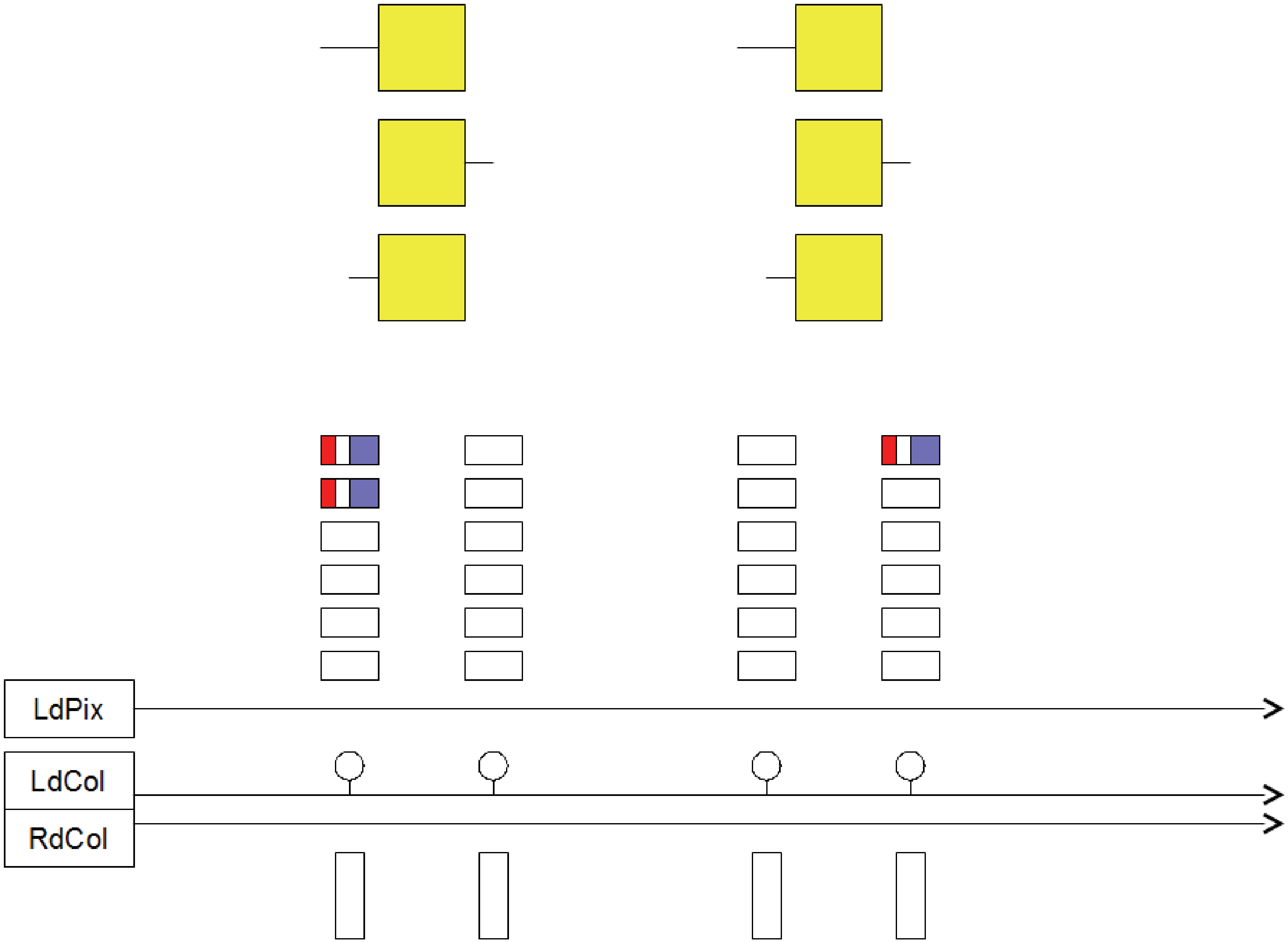
Readout



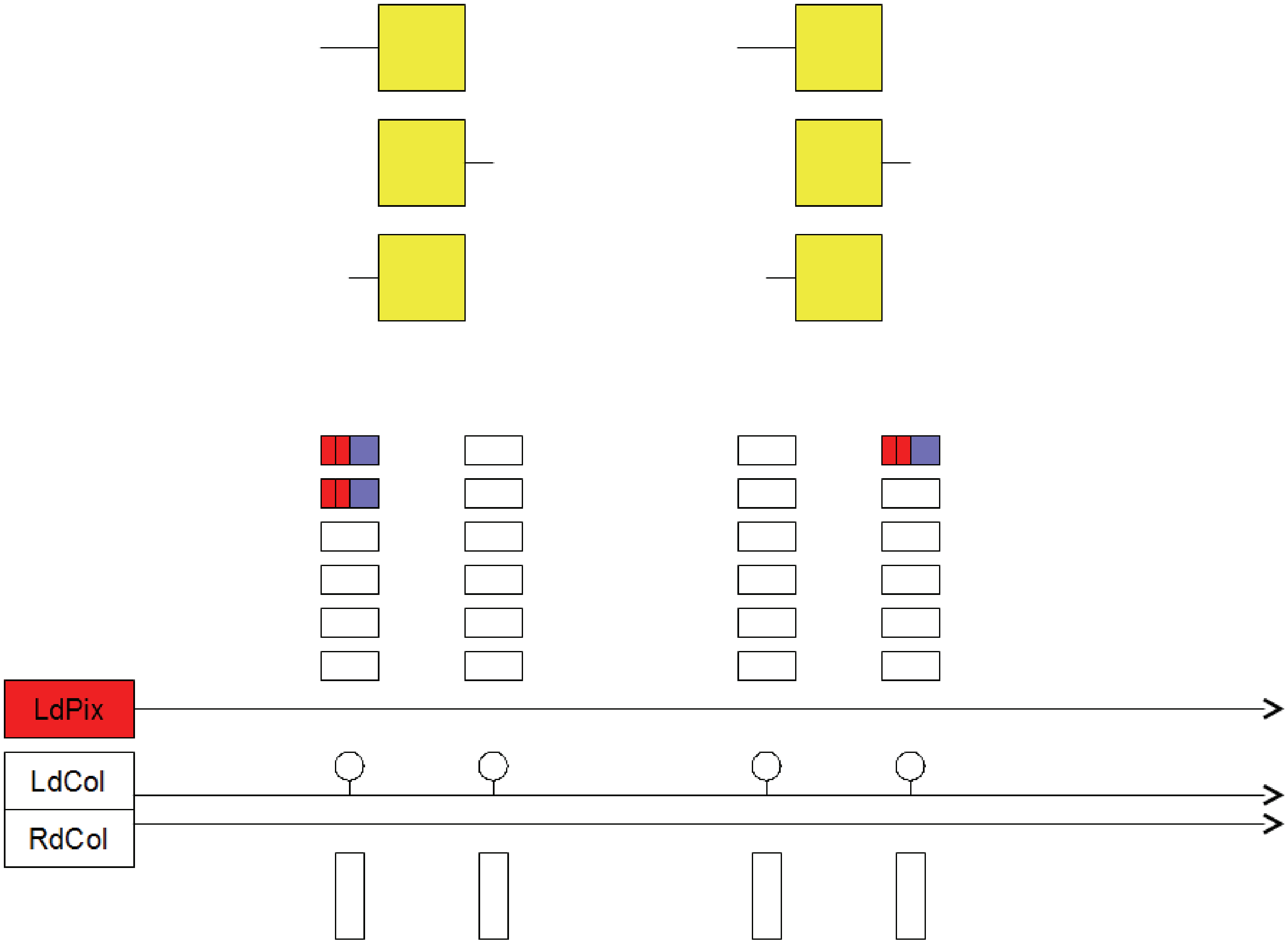
Readout



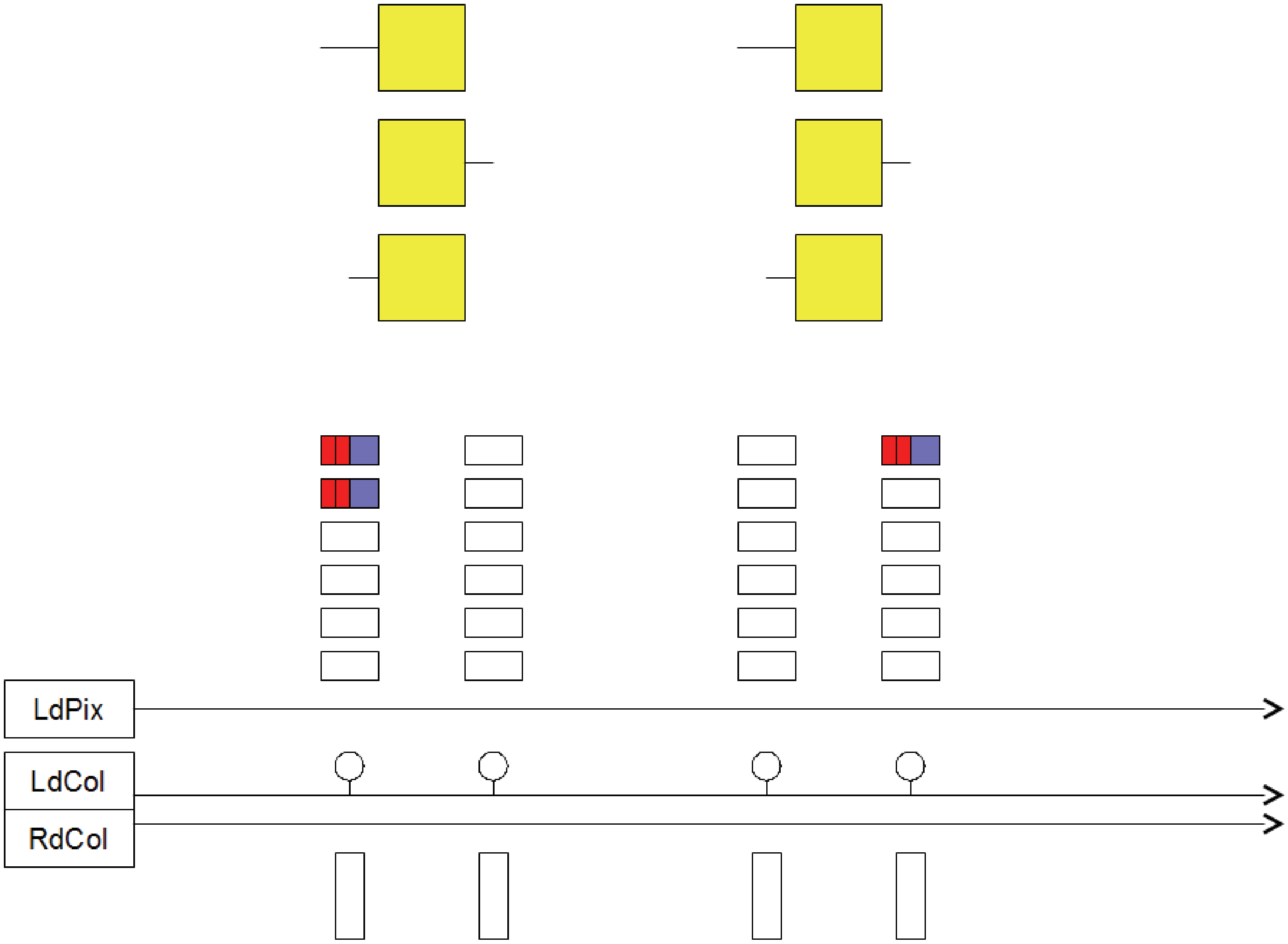
Readout



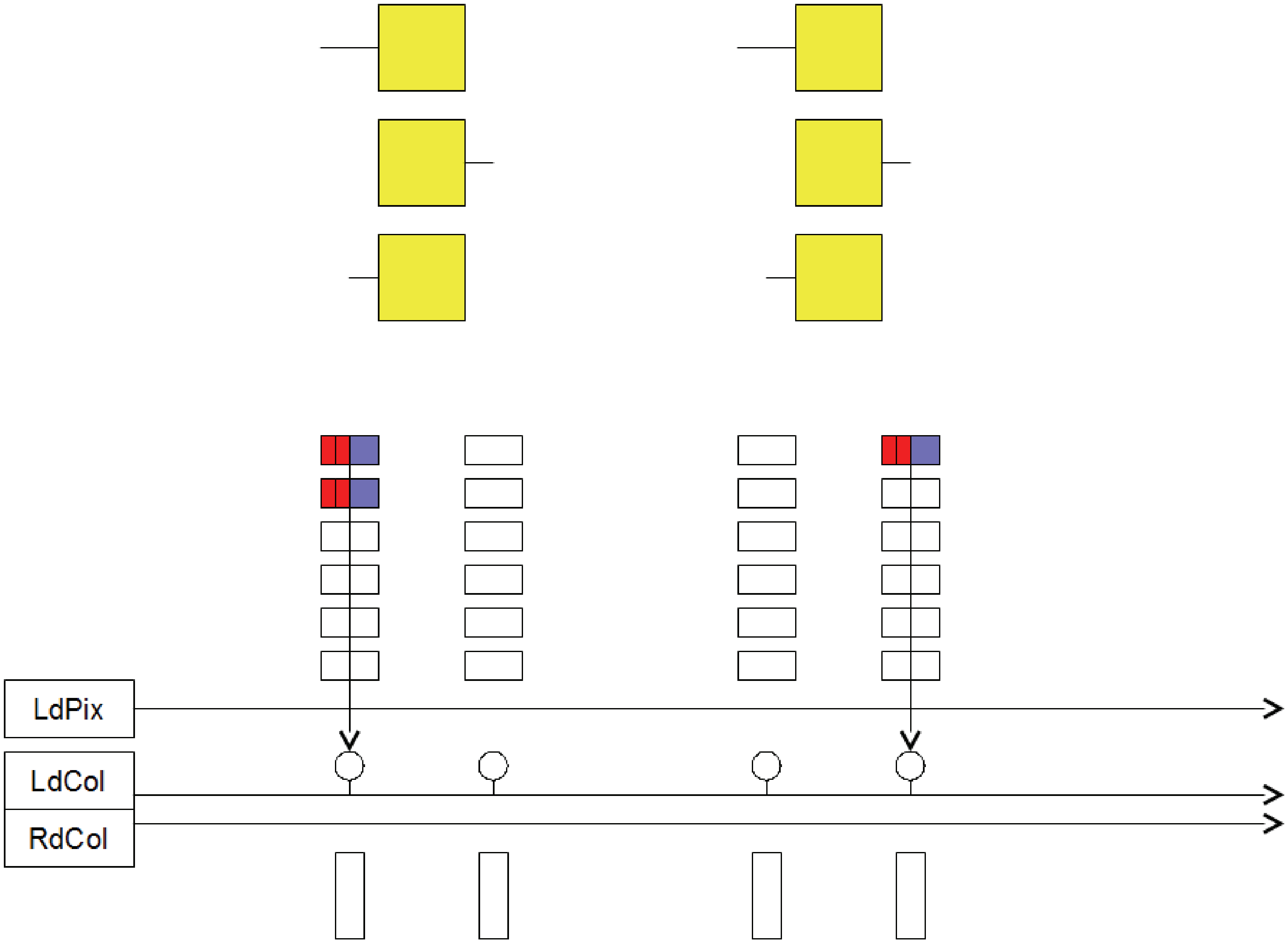
Readout



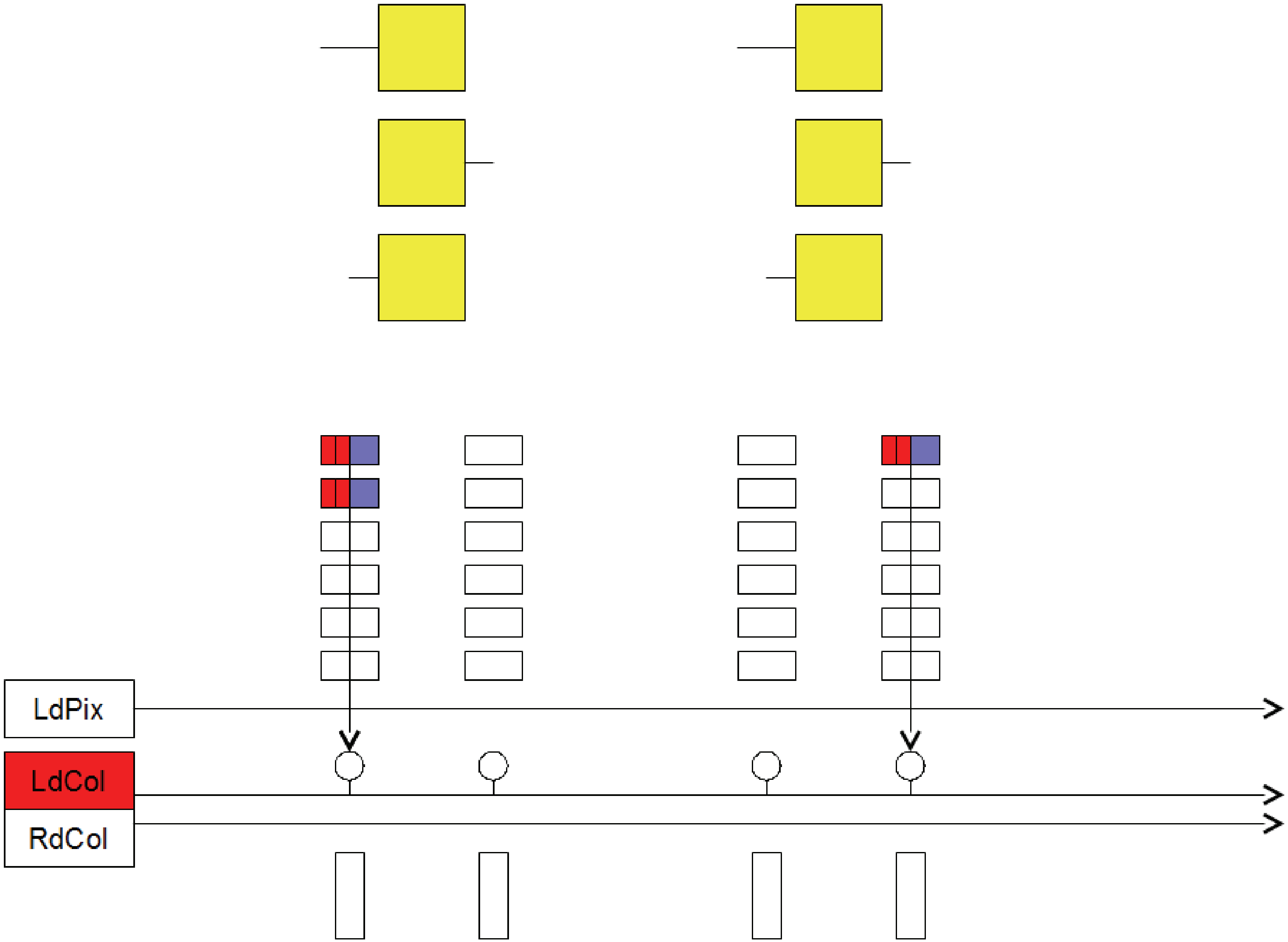
Readout



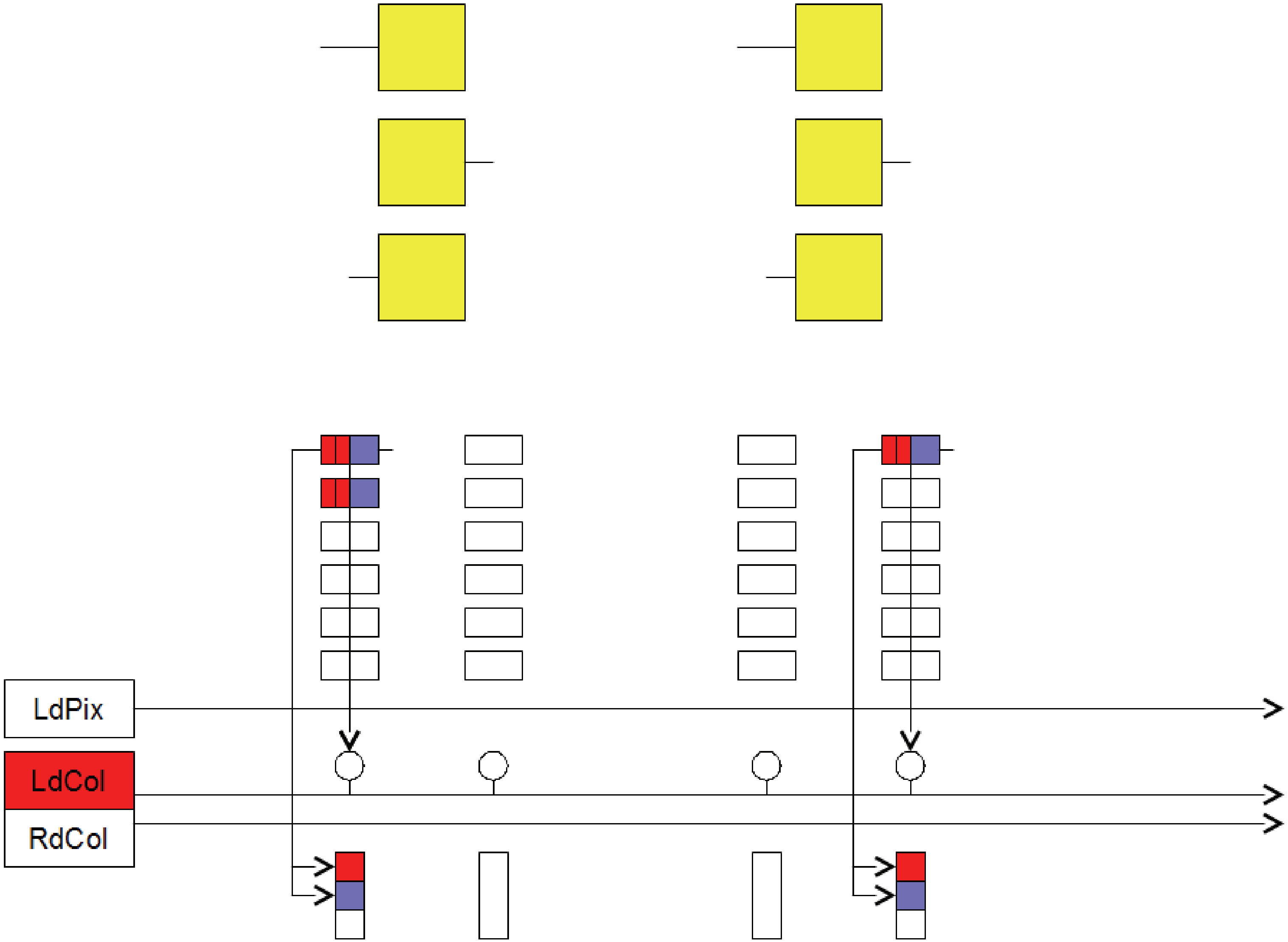
Readout



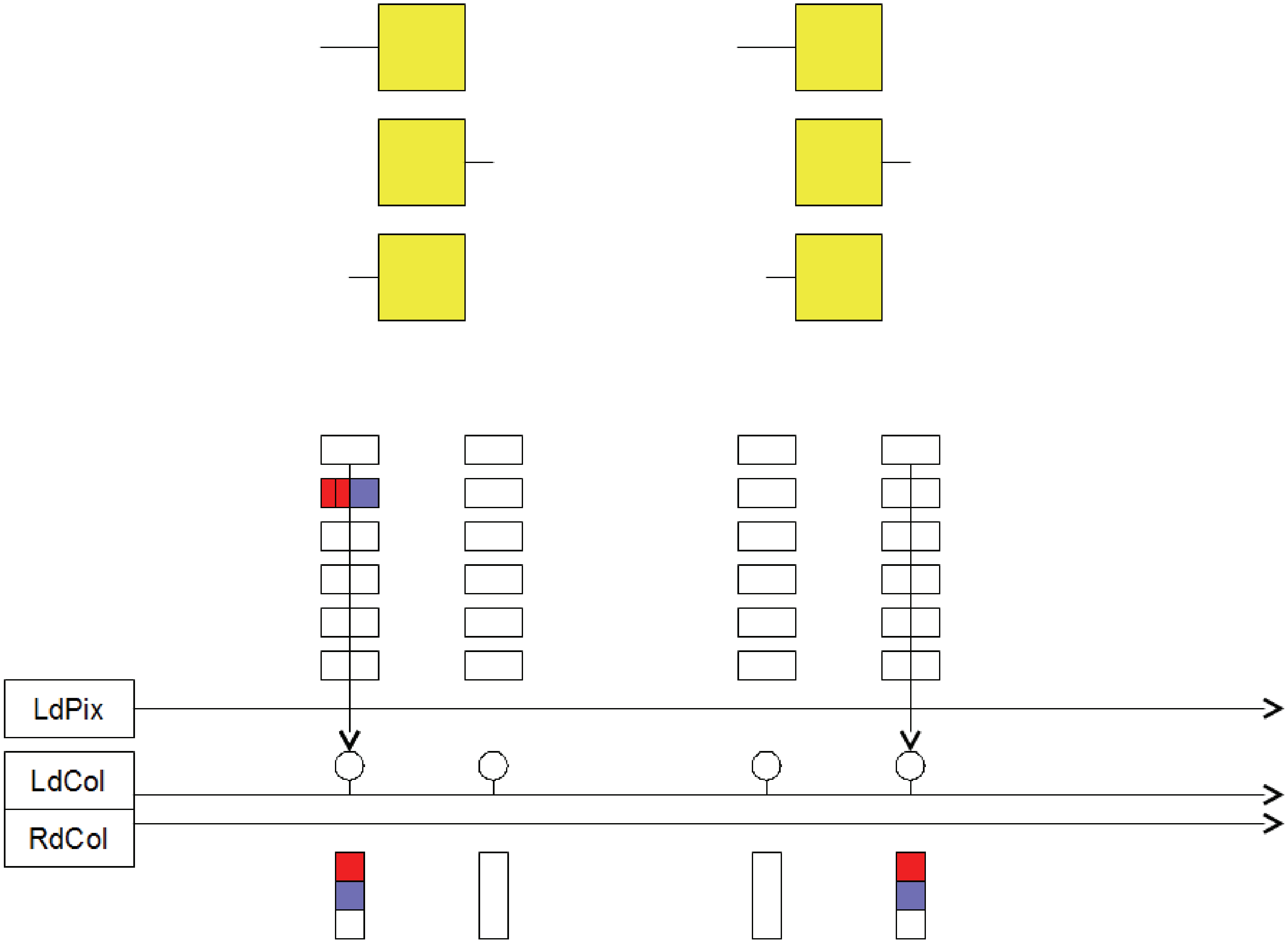
Readout



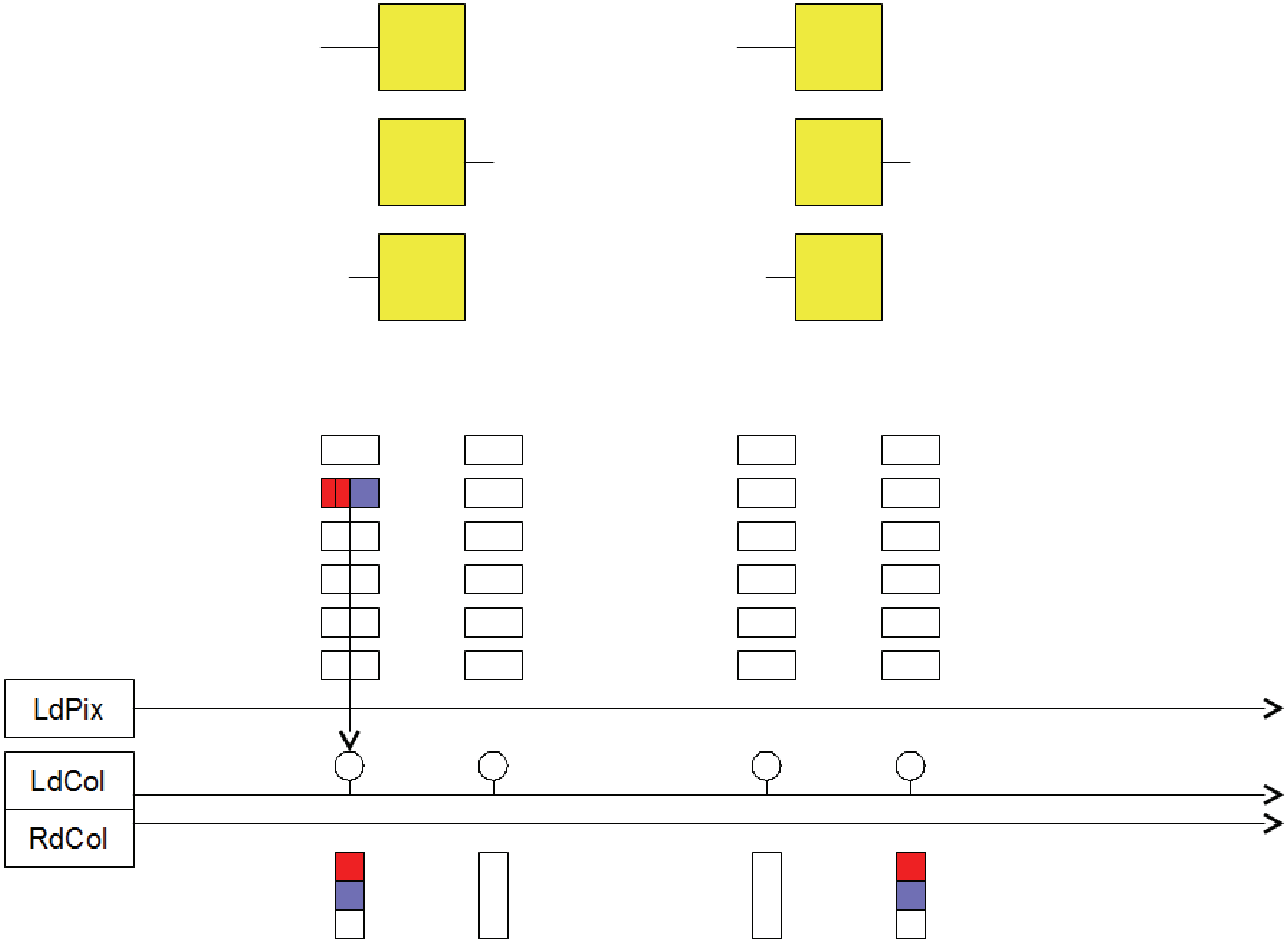
Readout



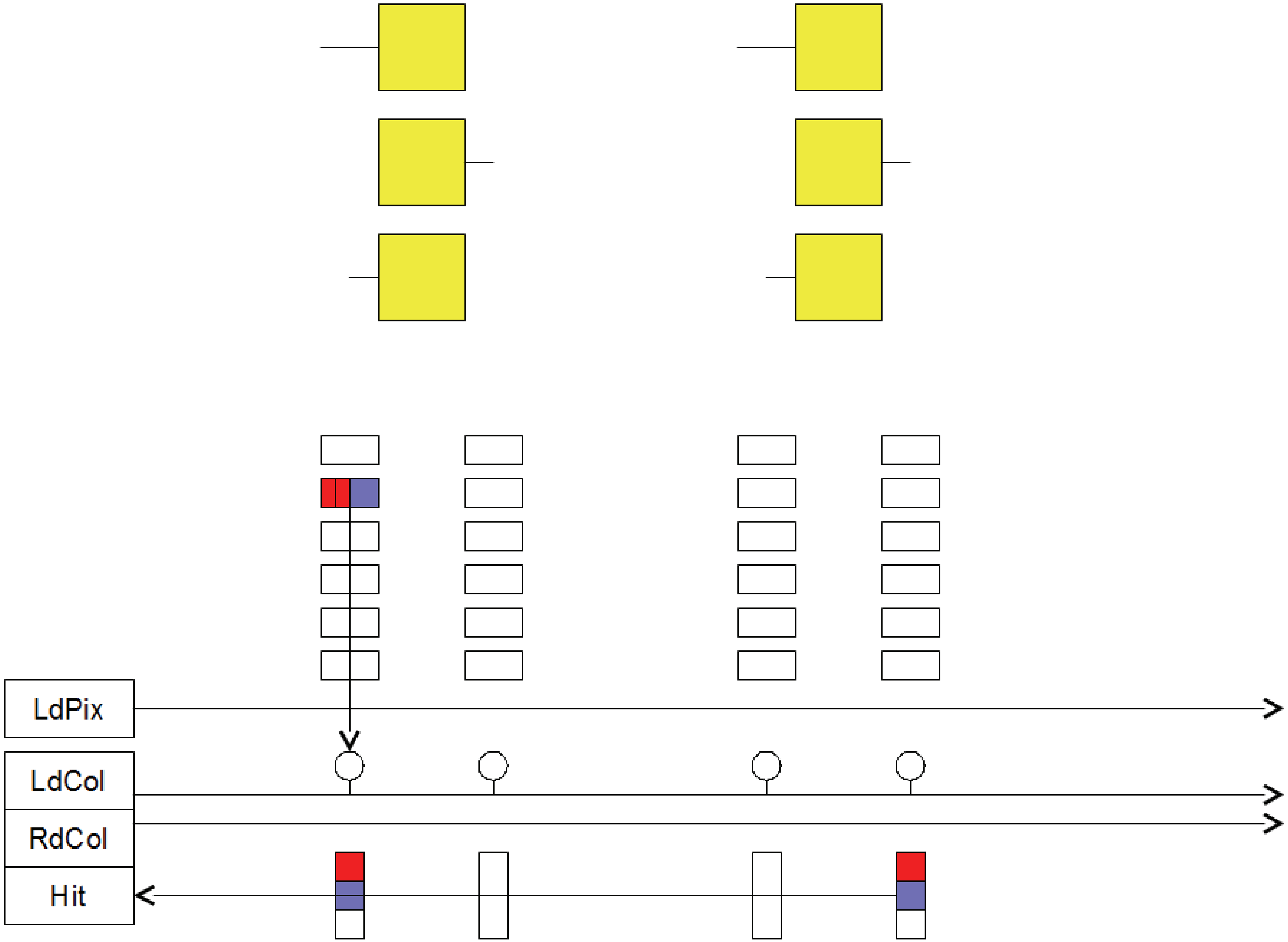
Readout



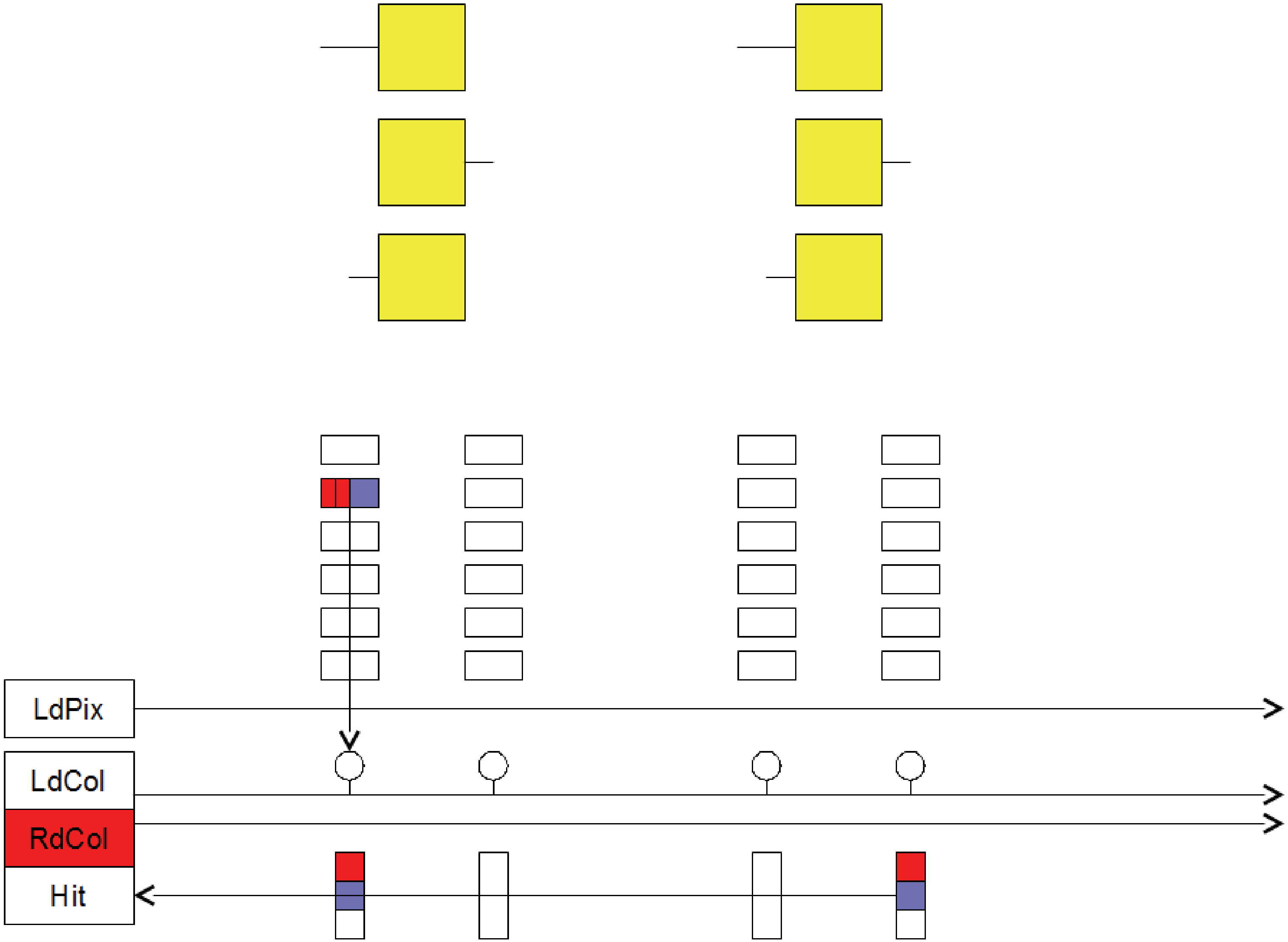
Readout



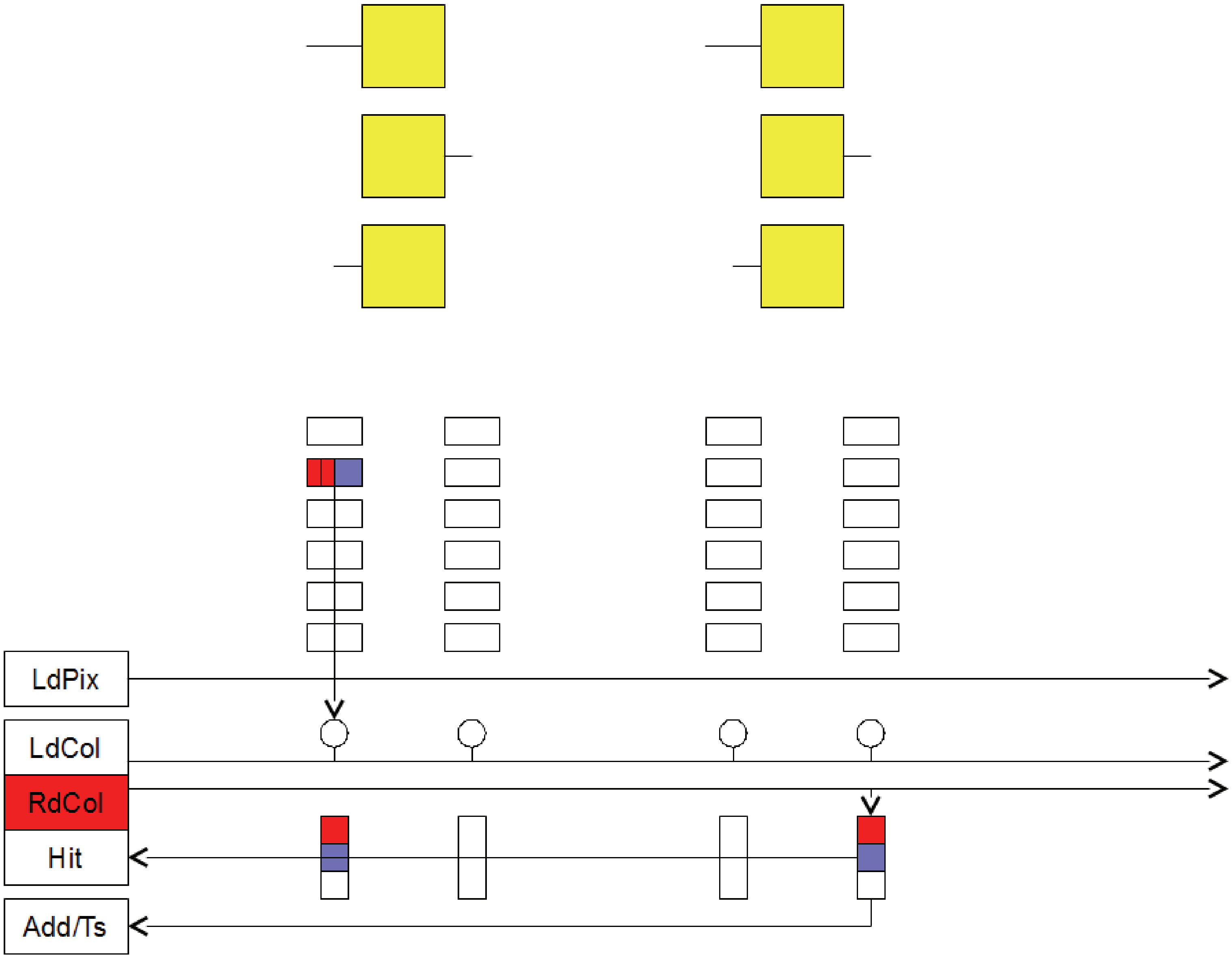
Readout



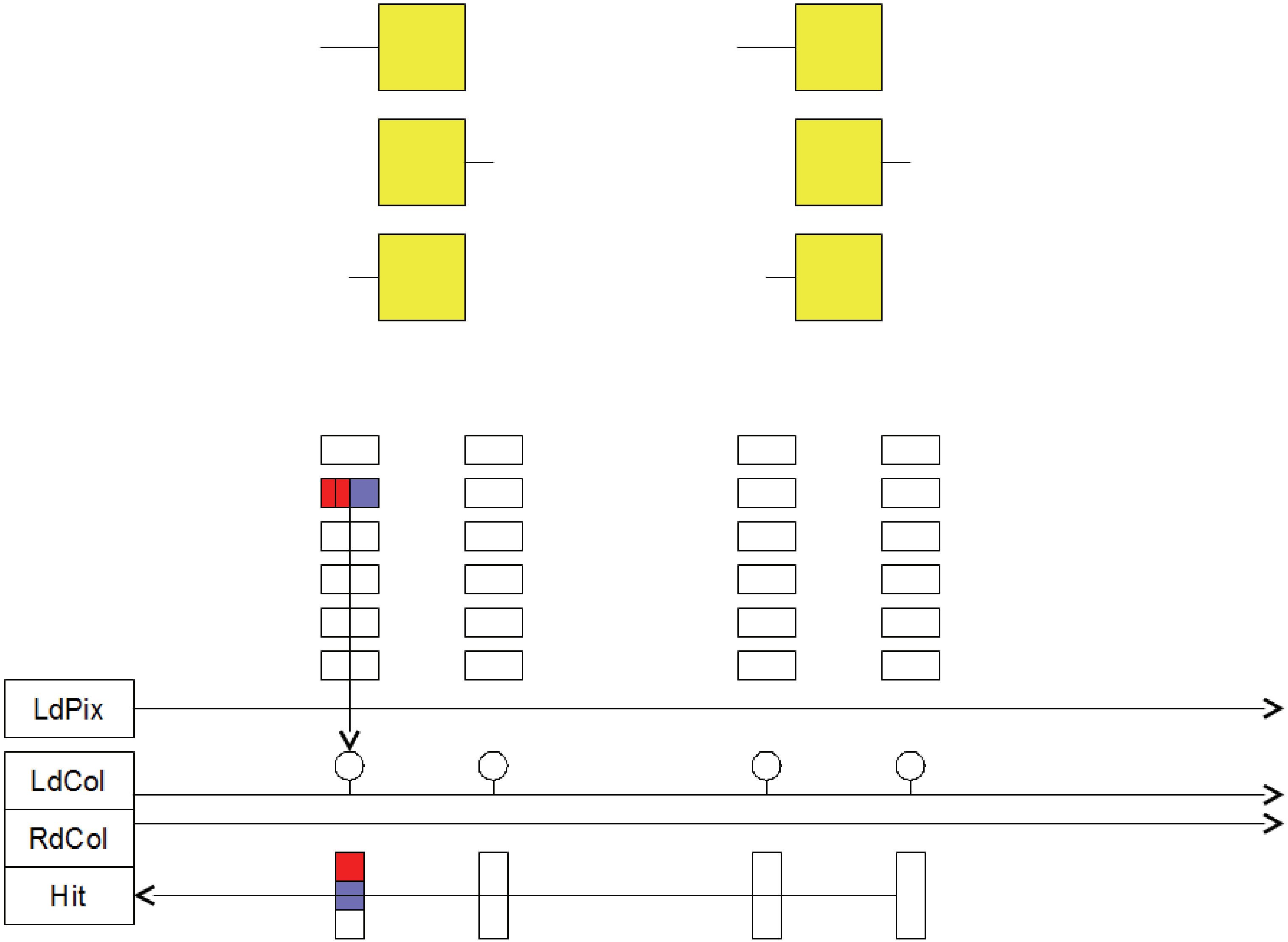
Readout



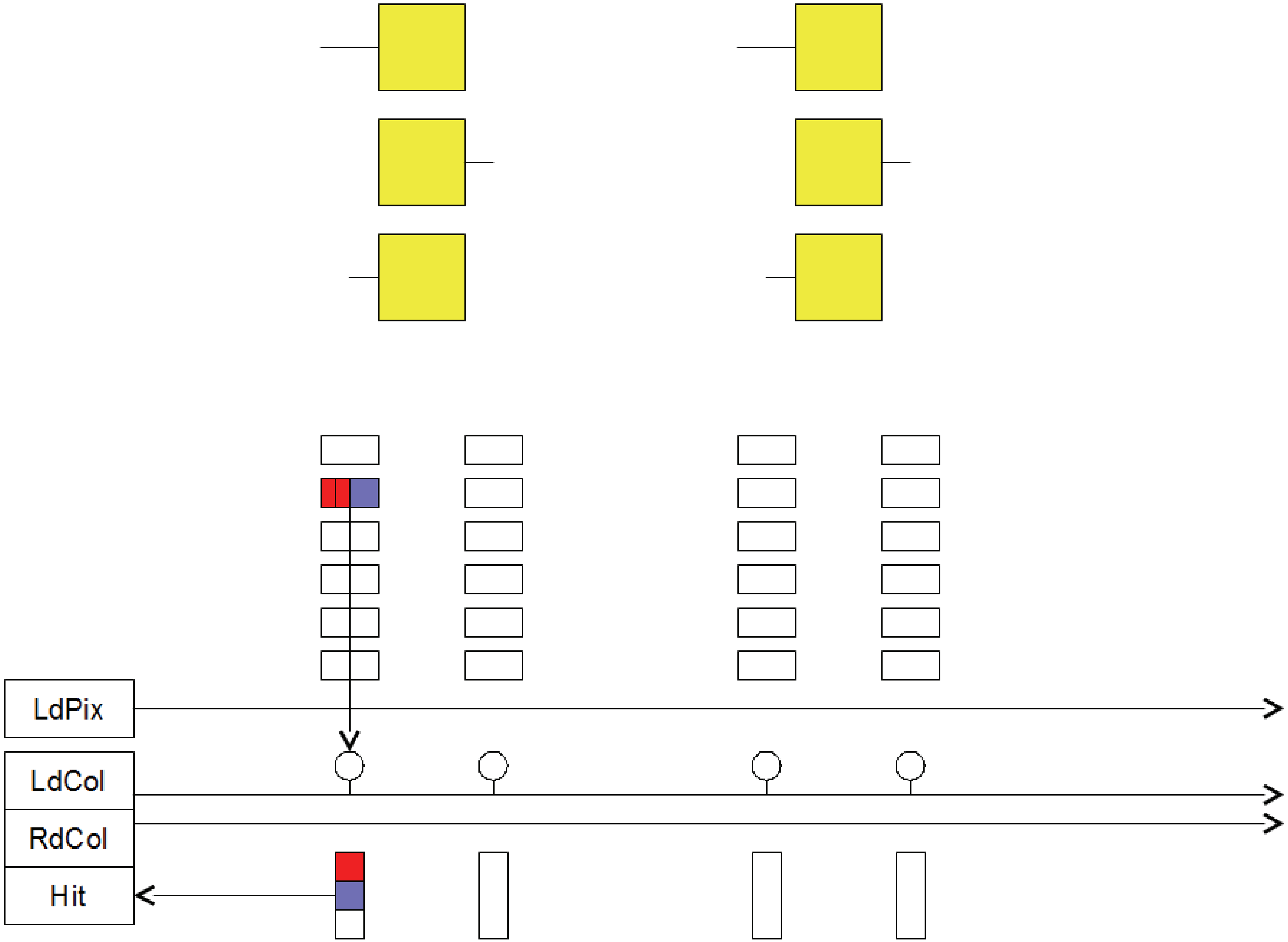
Readout



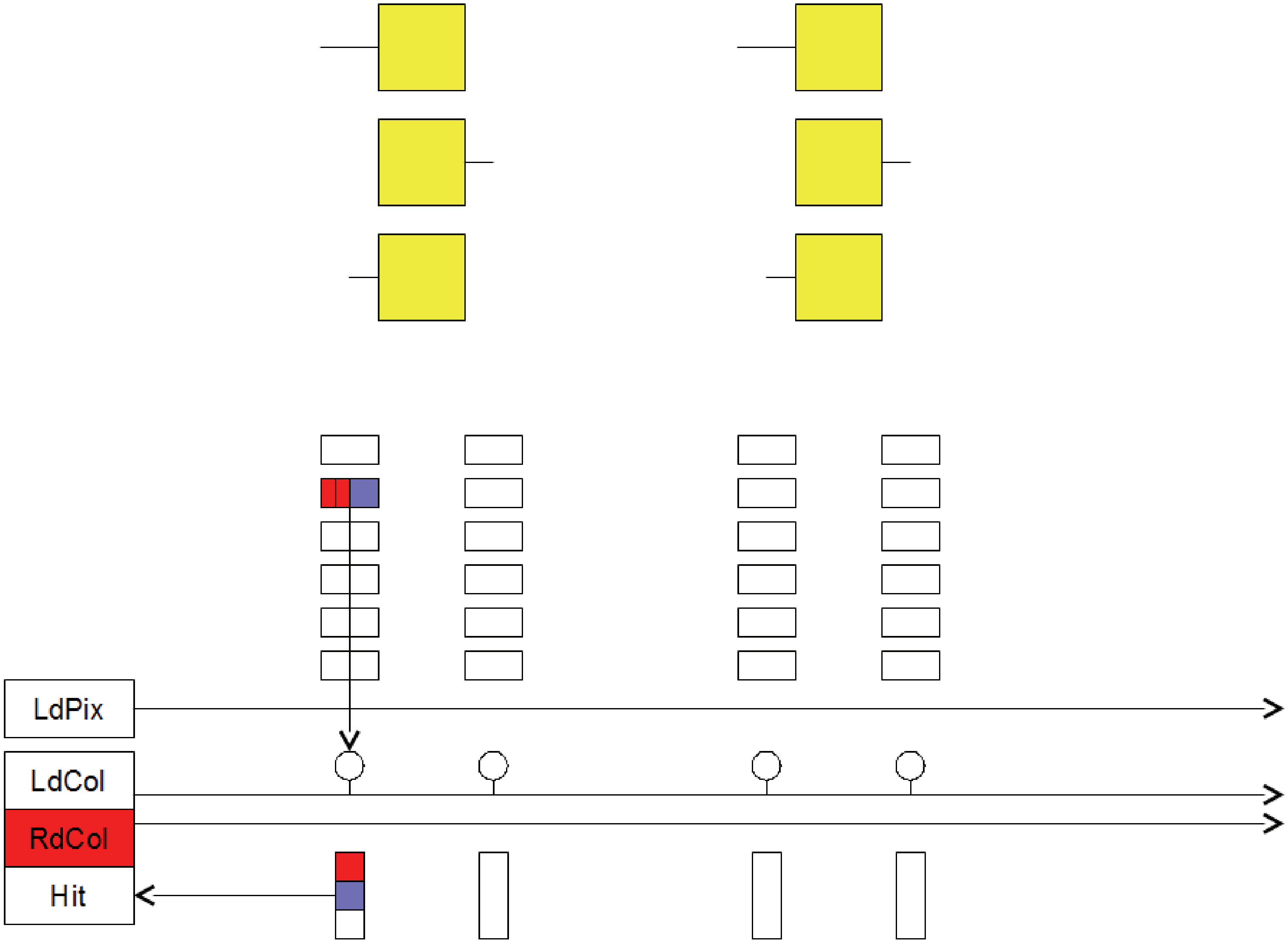
Readout



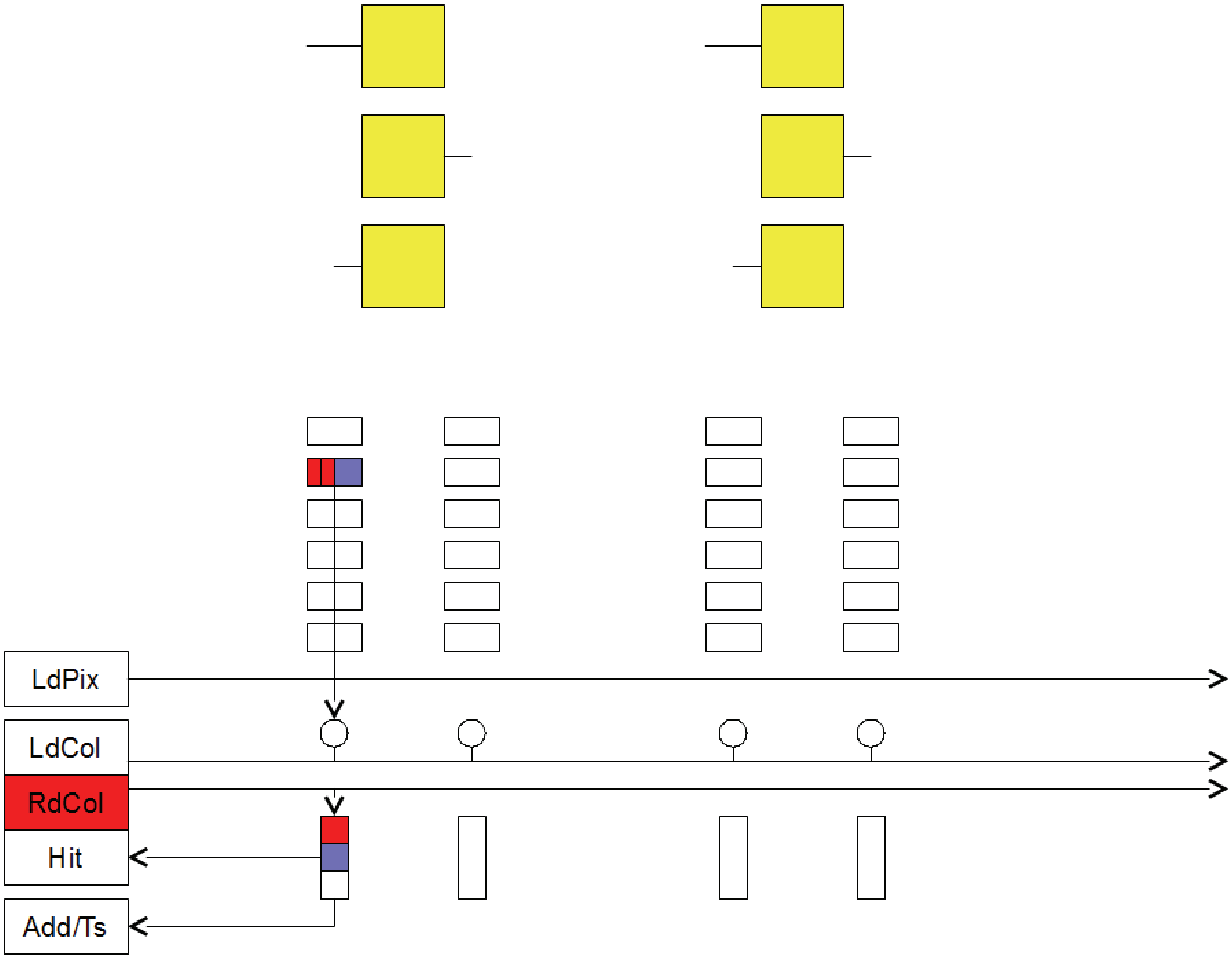
Readout



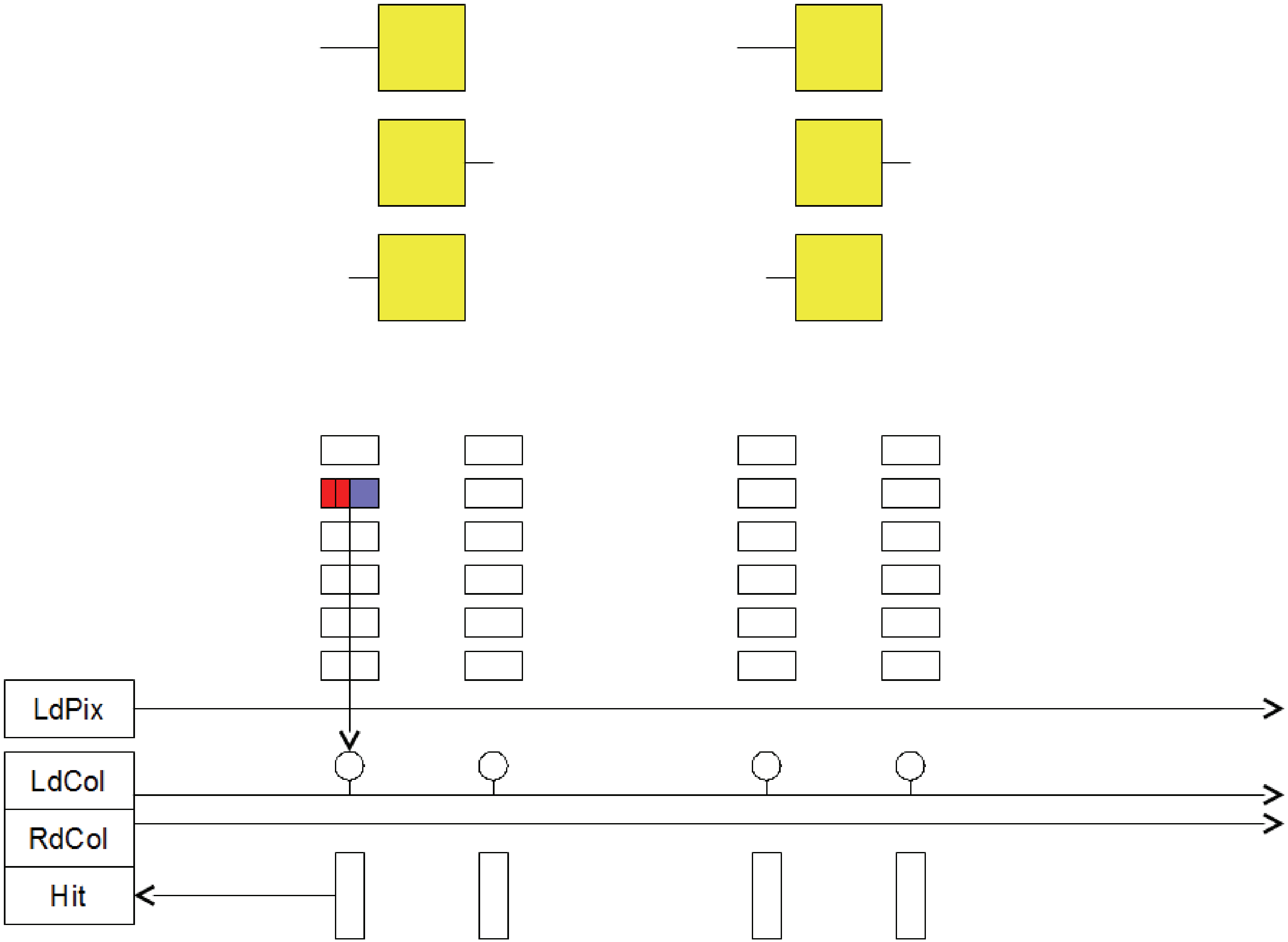
Readout



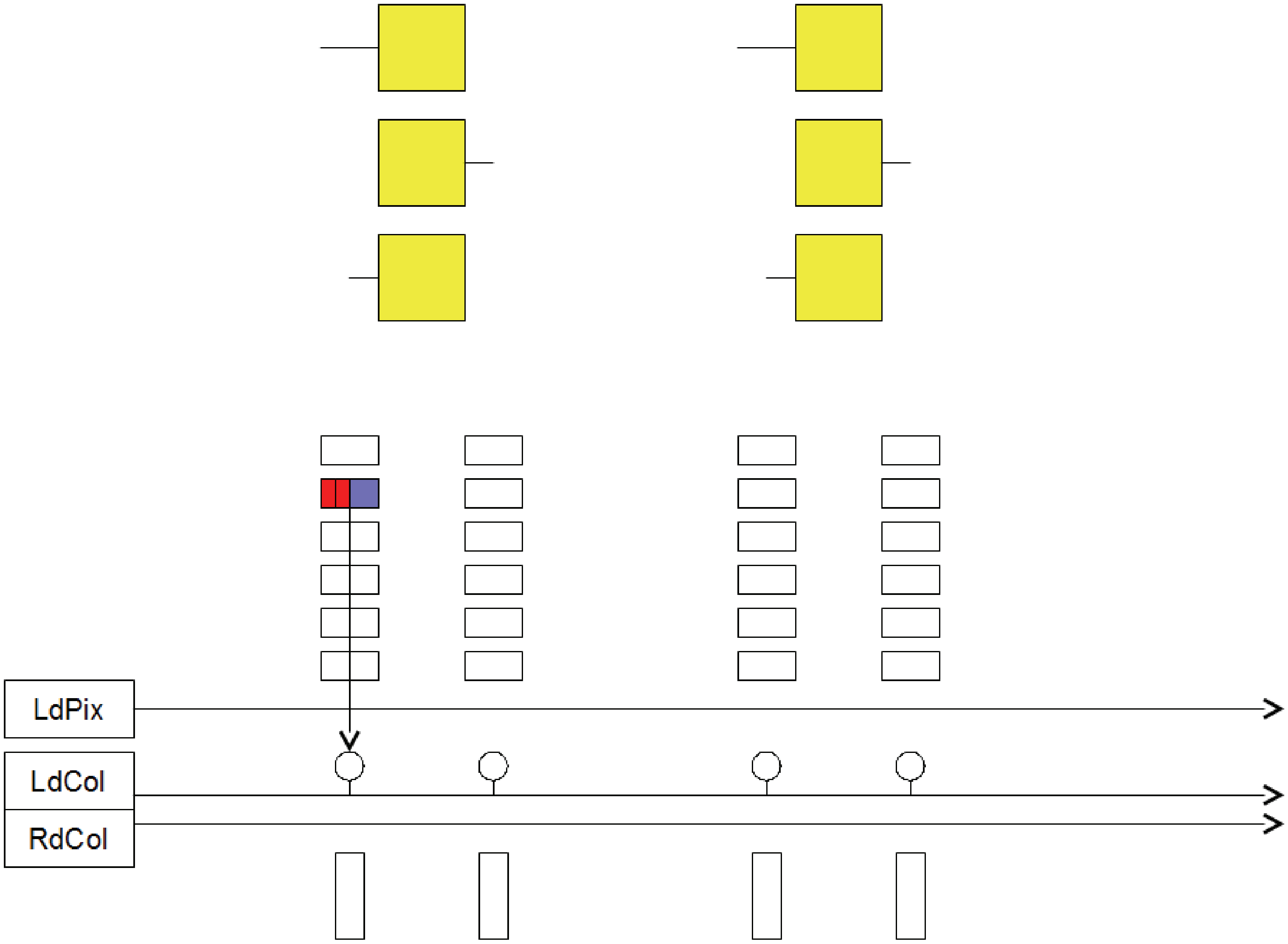
Readout



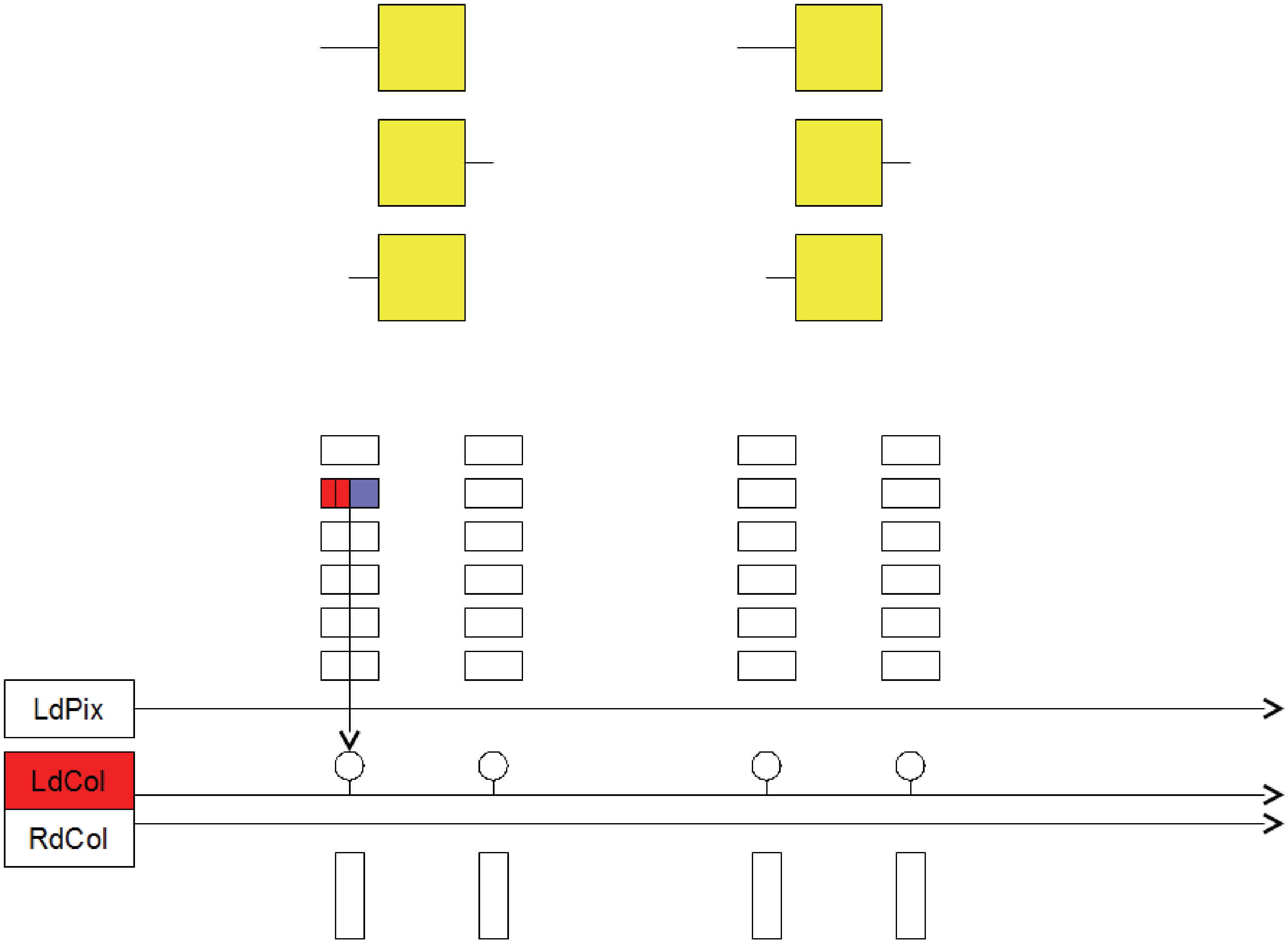
Readout



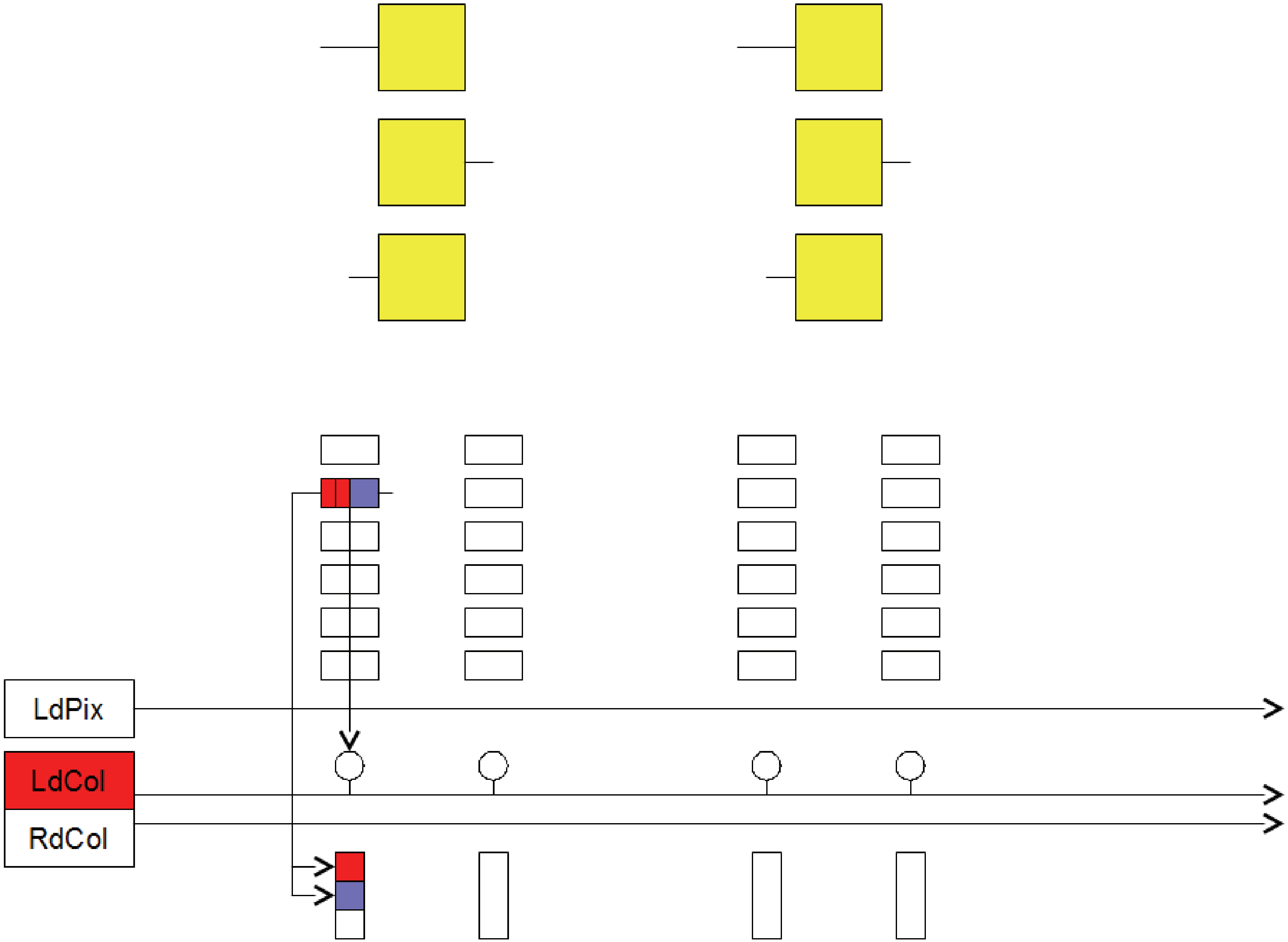
Readout



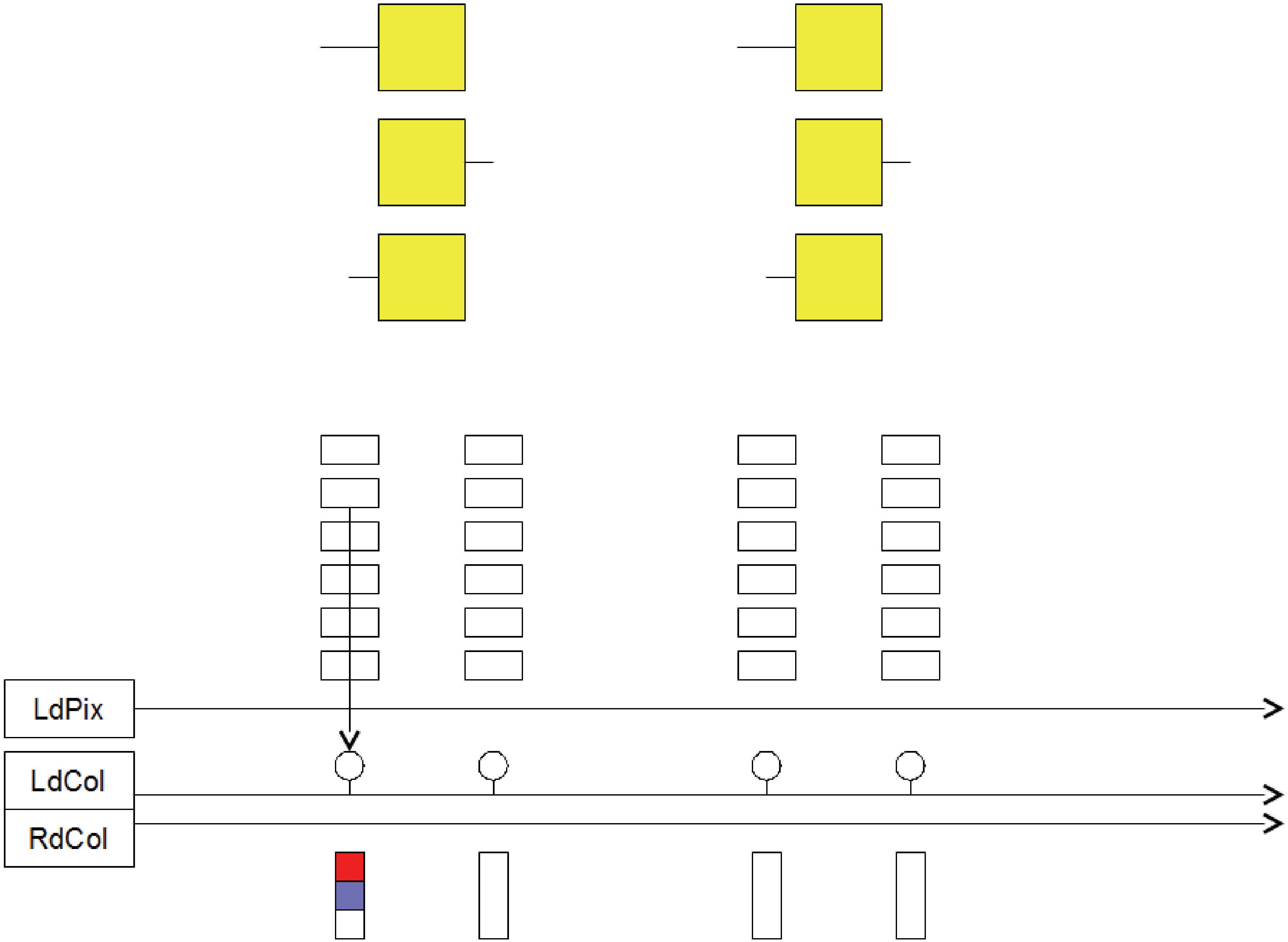
Readout



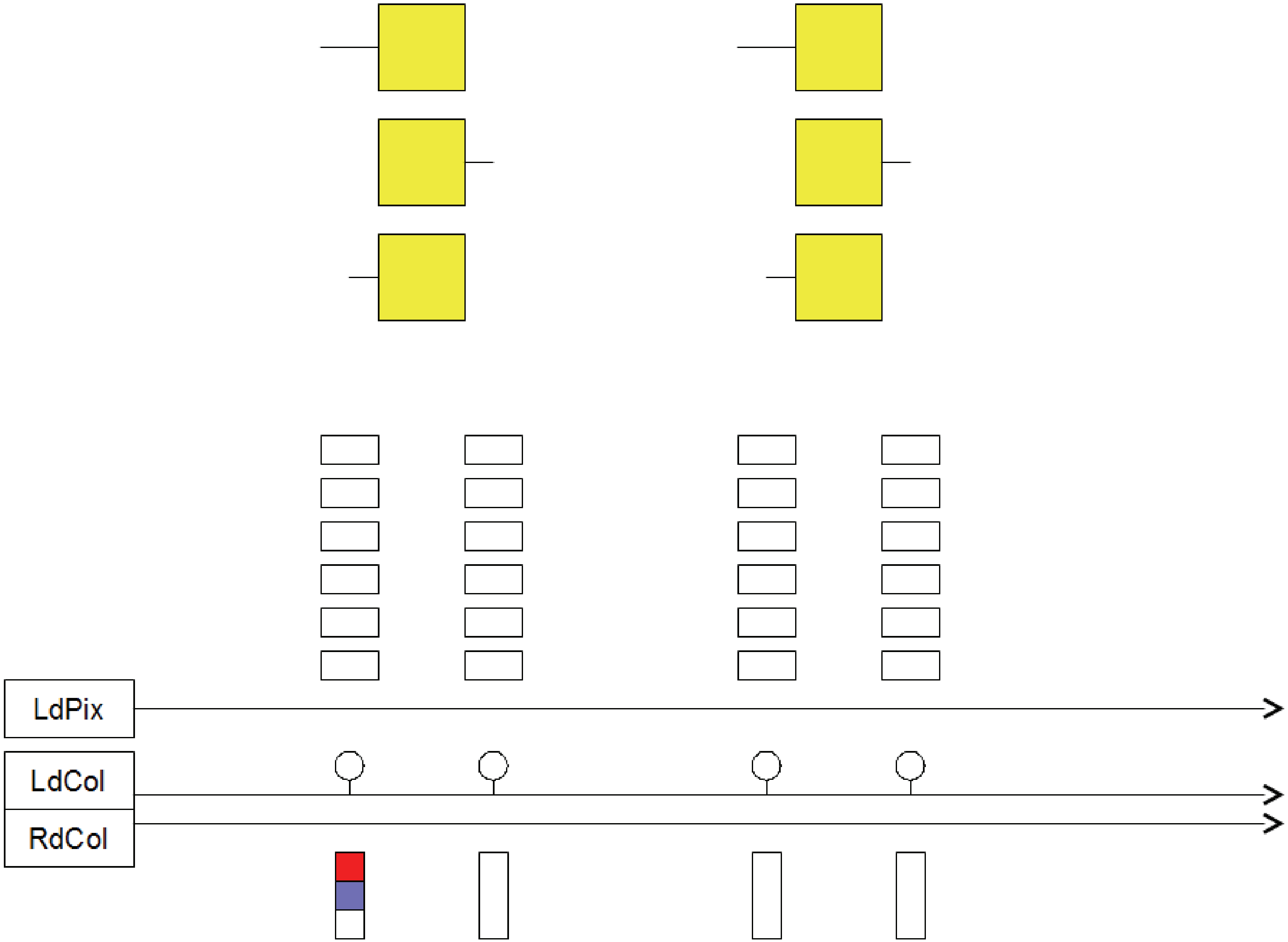
Readout



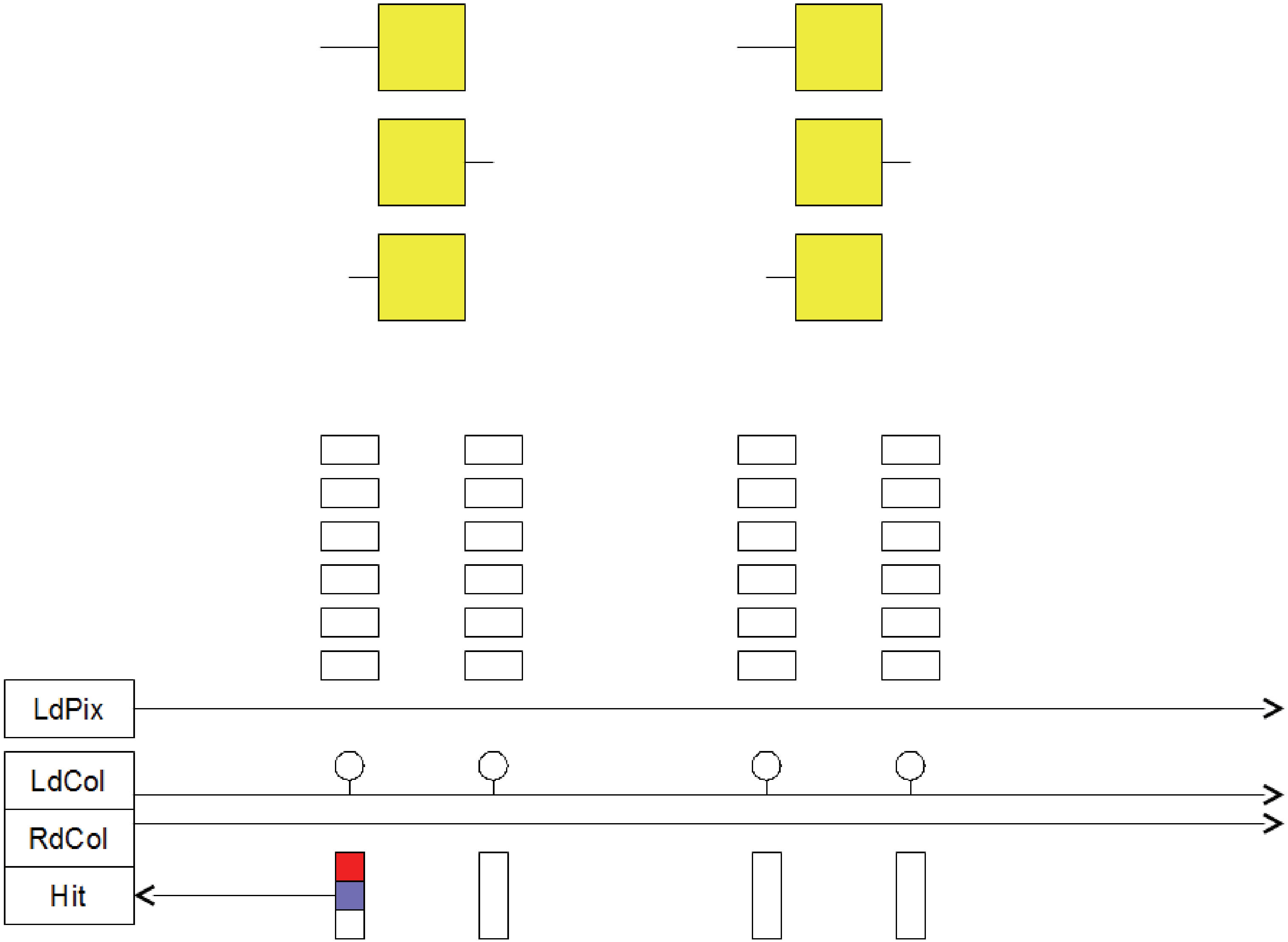
Readout



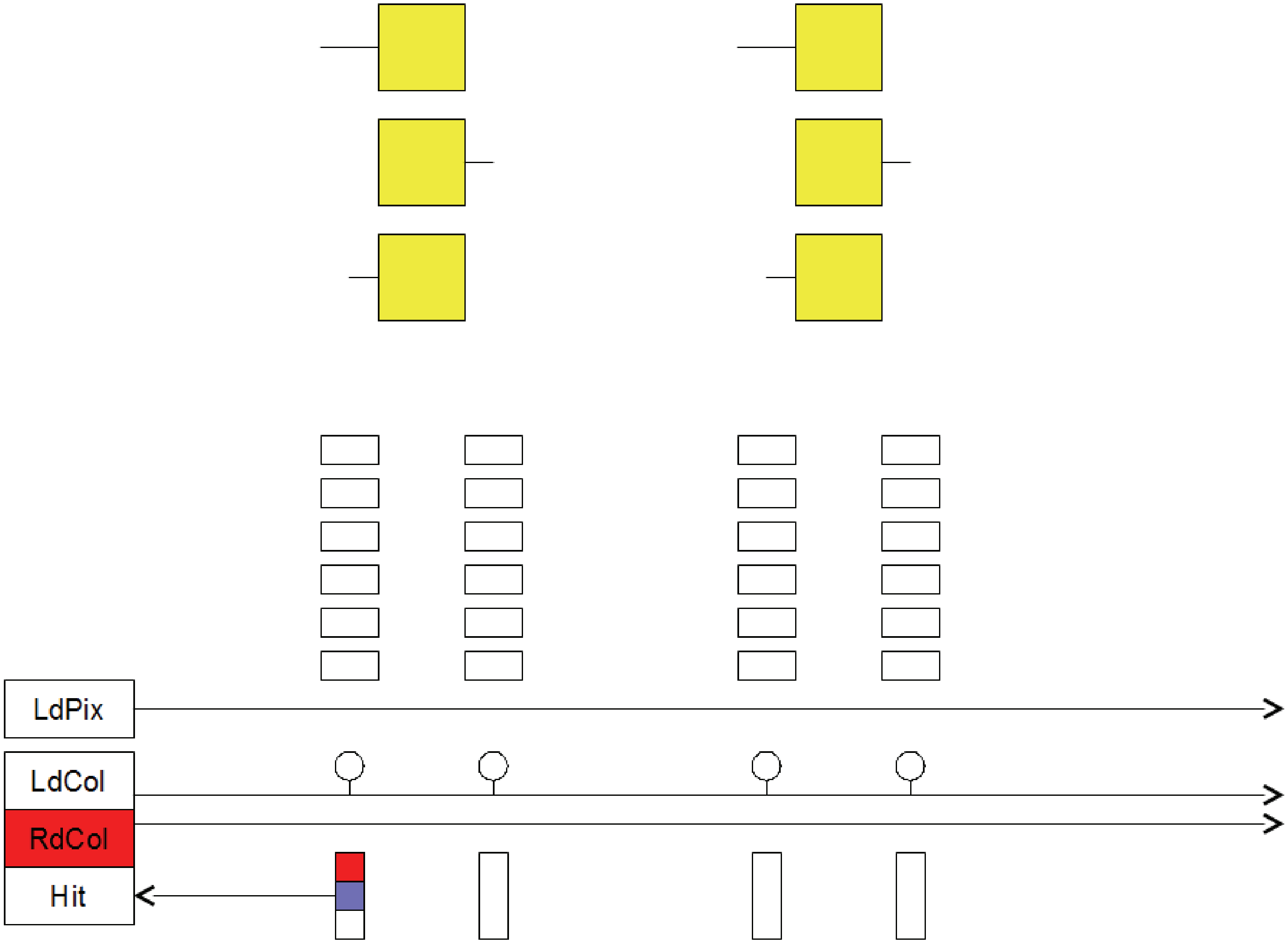
Readout



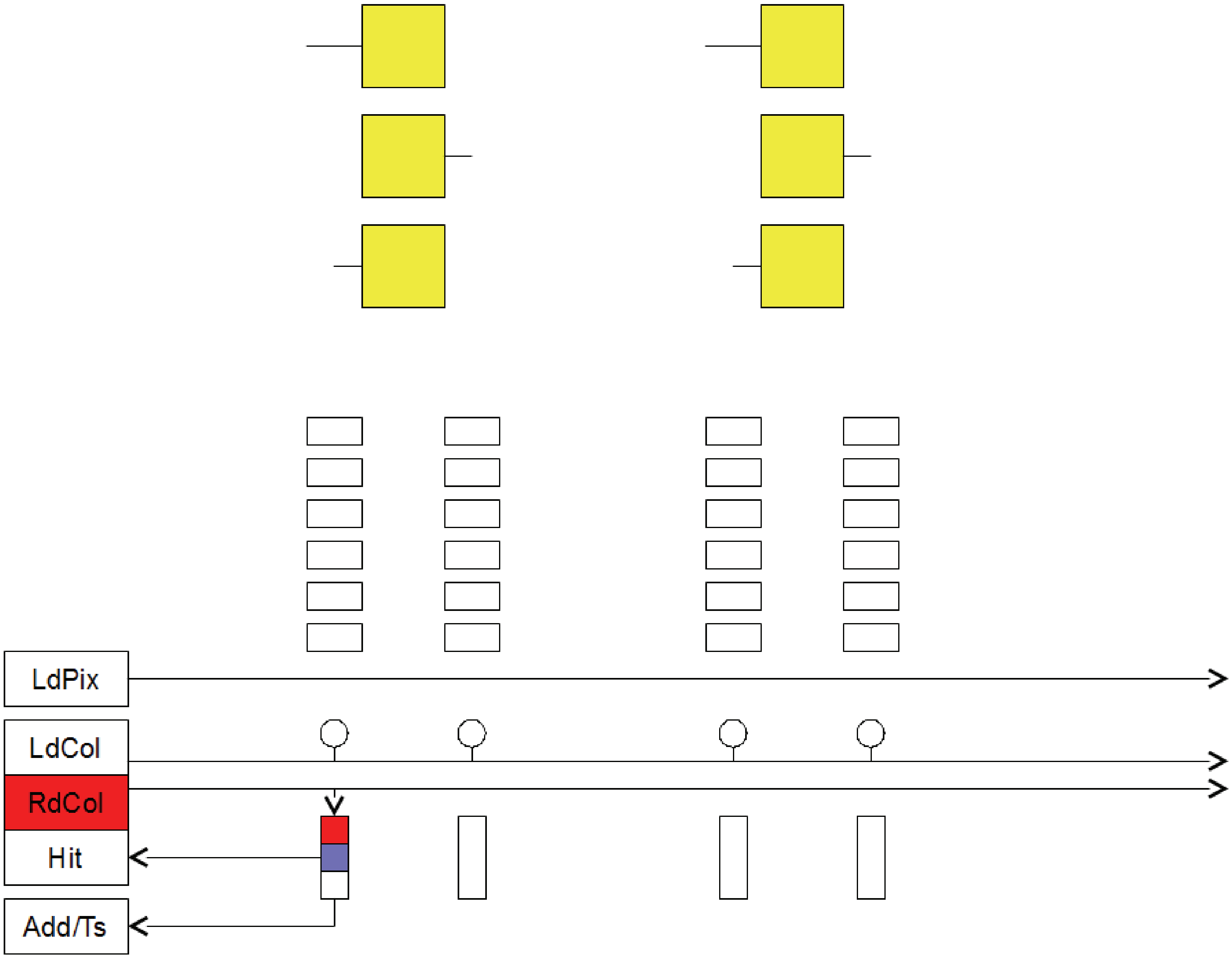
Readout



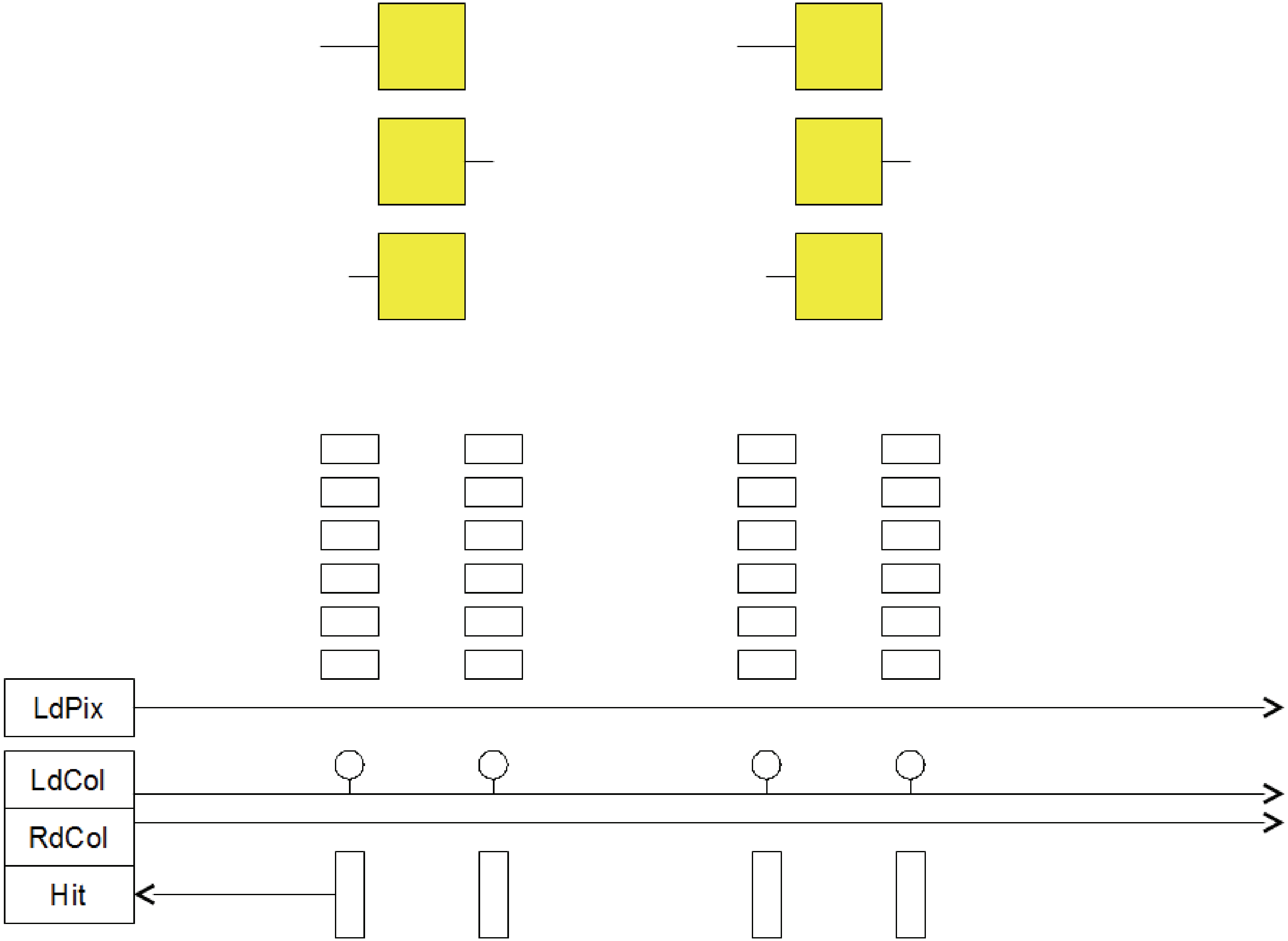
Readout



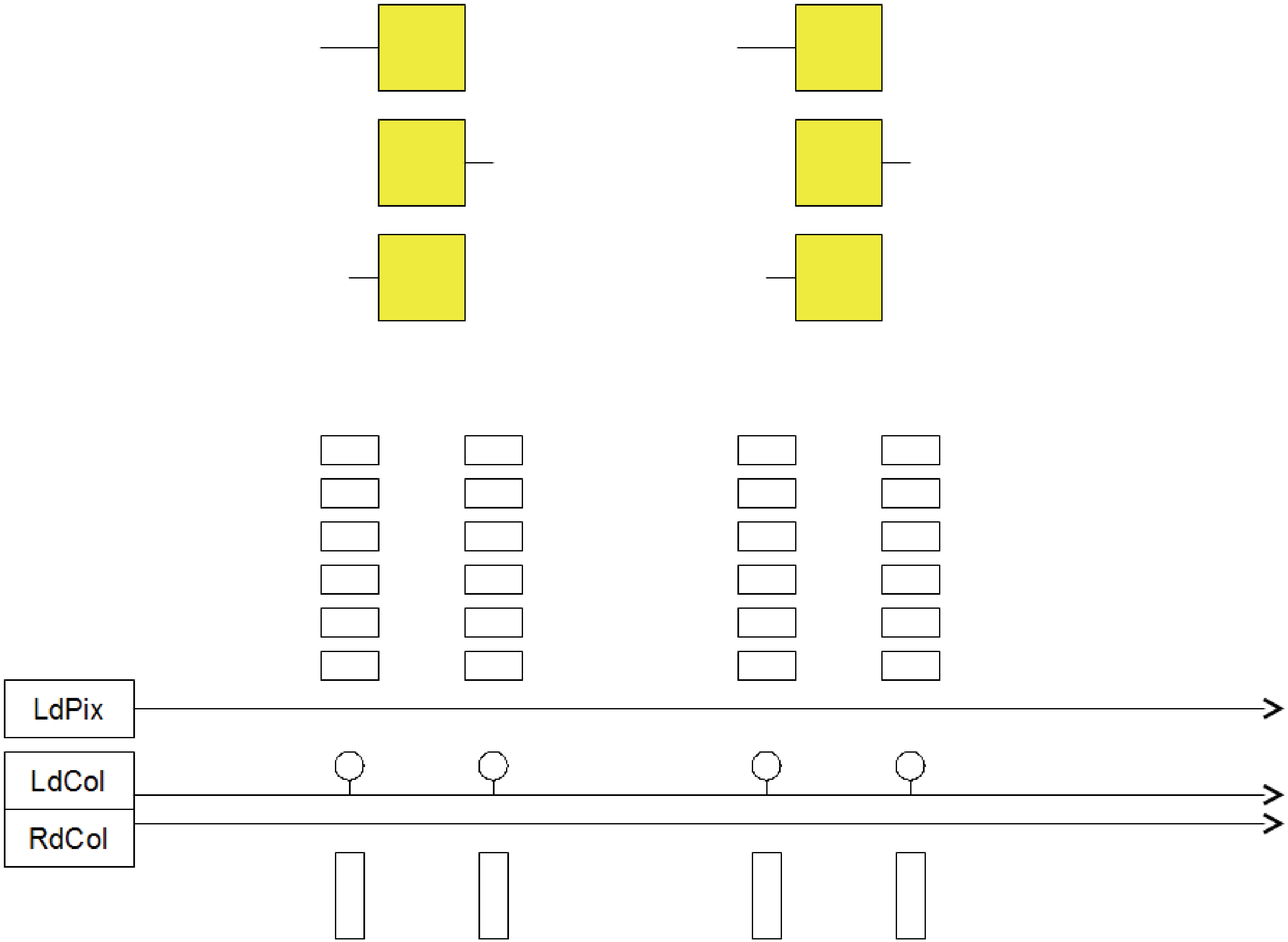
Readout



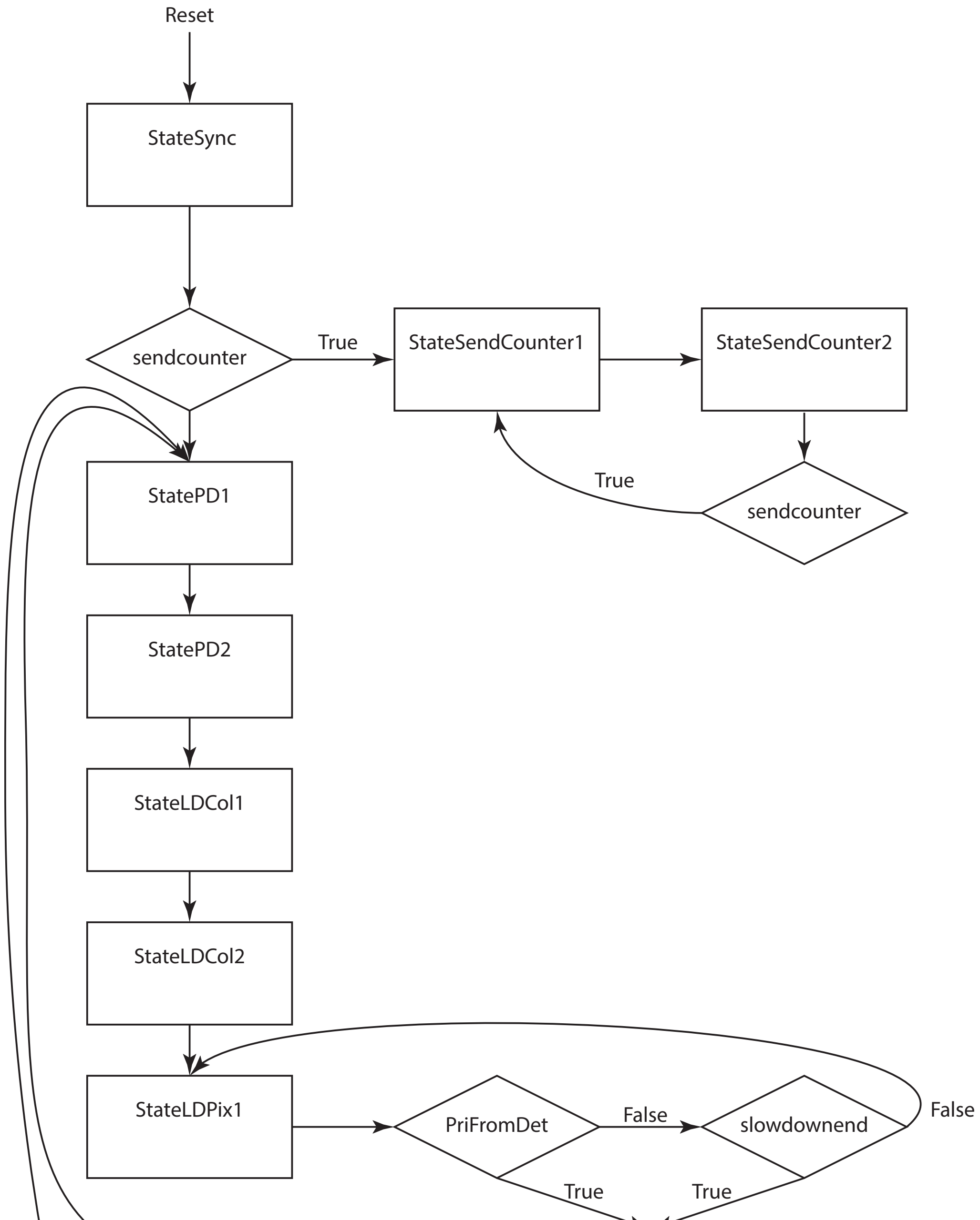
Readout

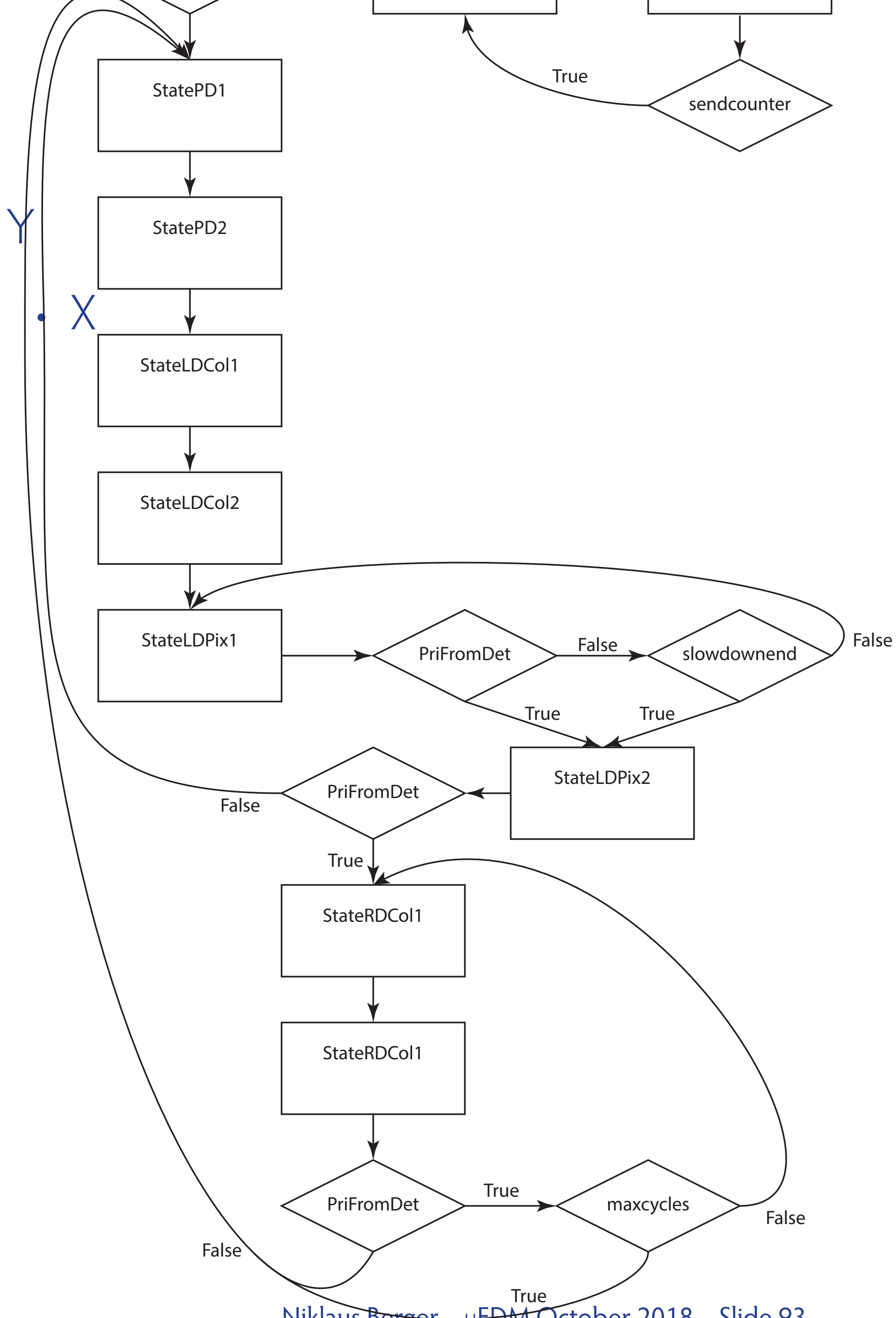


Readout



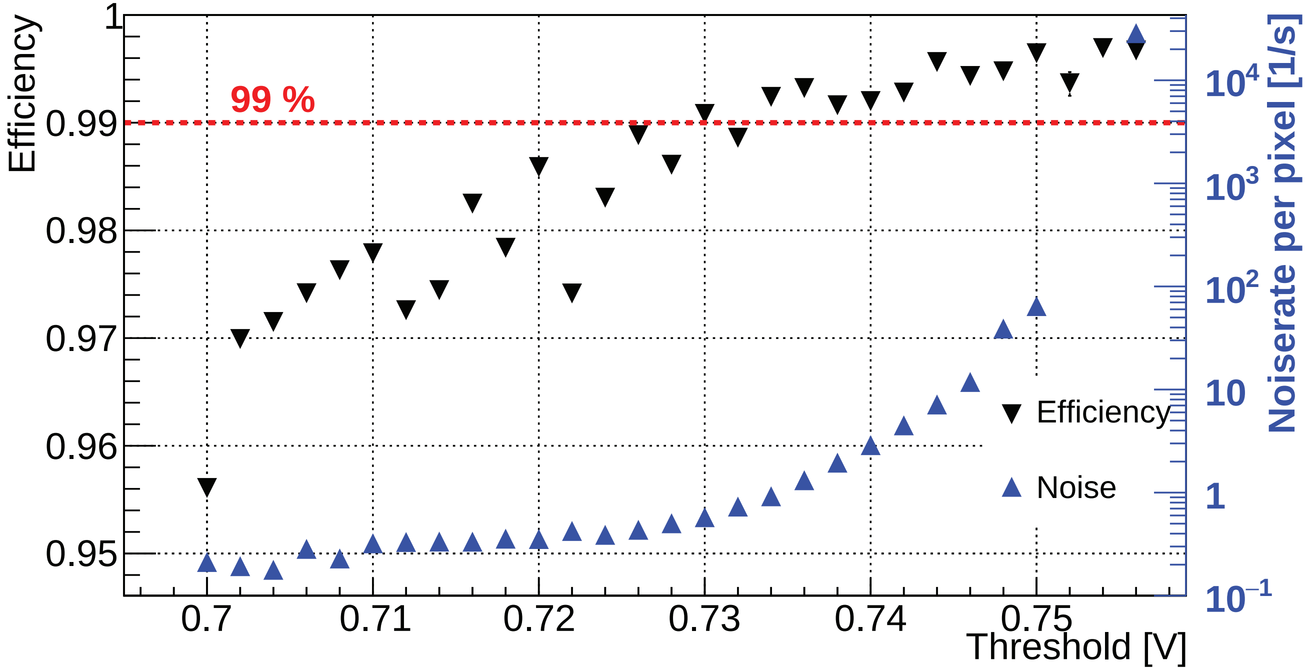
State Machine





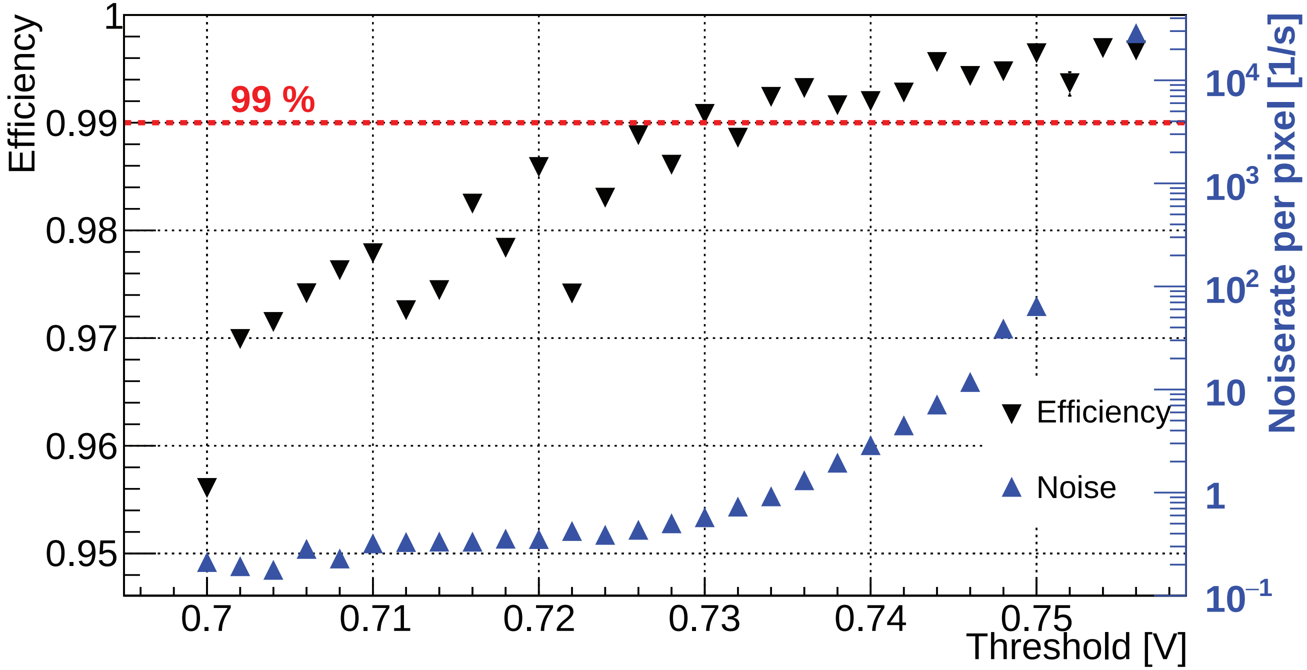
MuPix7 Performance: Efficiency vs. Noise

- 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°