The MuPix Pixel Sensors, the Mu3e DAQ and tracking in multiple scattering dominated environments

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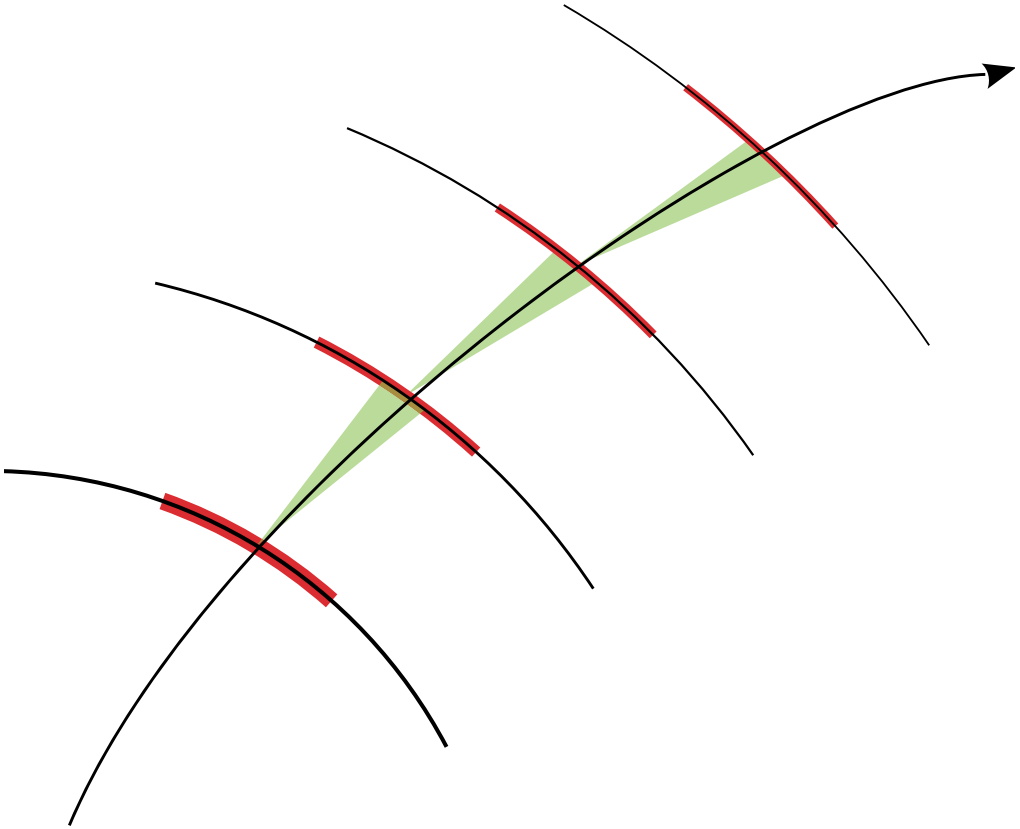
Overview

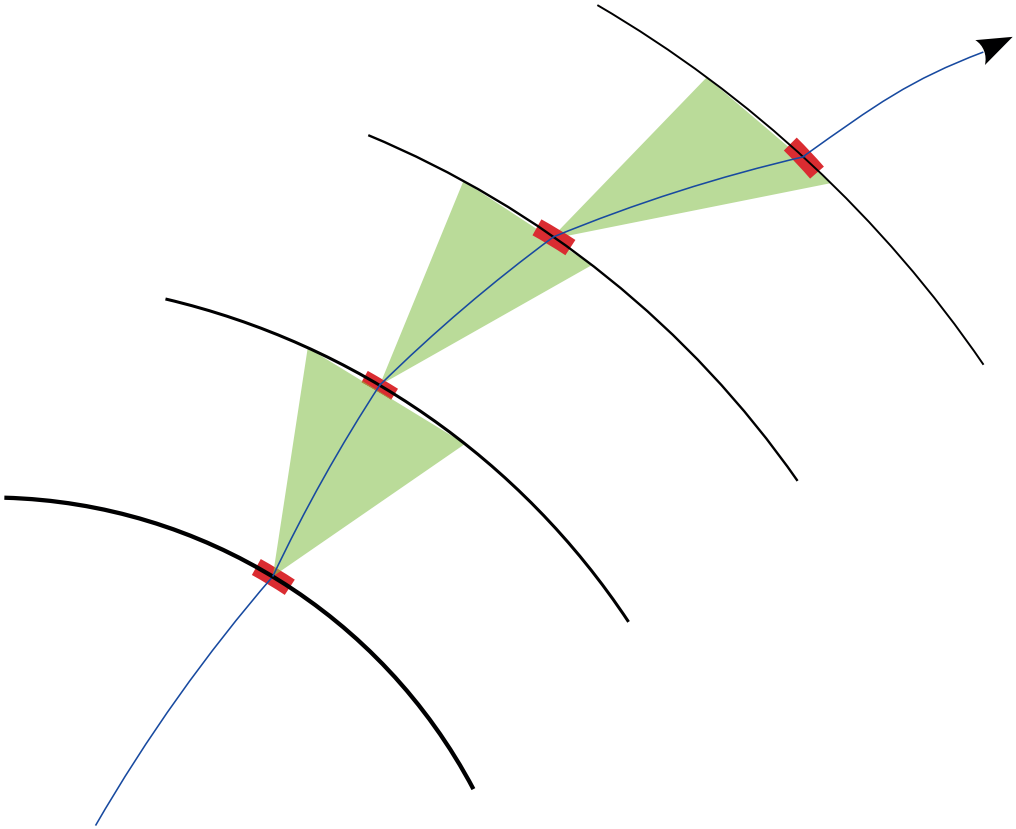
- Tracking in multiple scattering dominated environments
- The MuPix High-Voltage Monolithic Active Pixel Sensors
- Some Ideas from the Mu3e Data Acquisition
- Many Questions

Momentum measurement

- Apply magnetic field
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}} \left[1 + 0.088 \log_{10}\left(\frac{x\, z^2}{X_0 \beta^2}\right)\right]$$

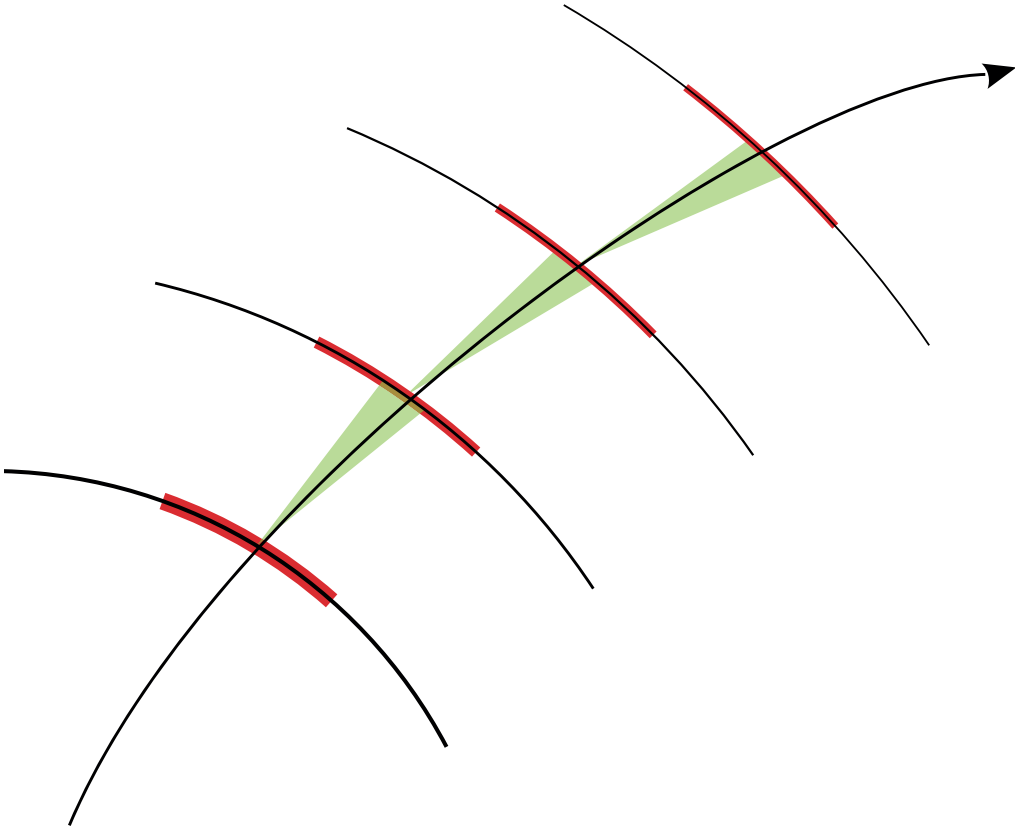


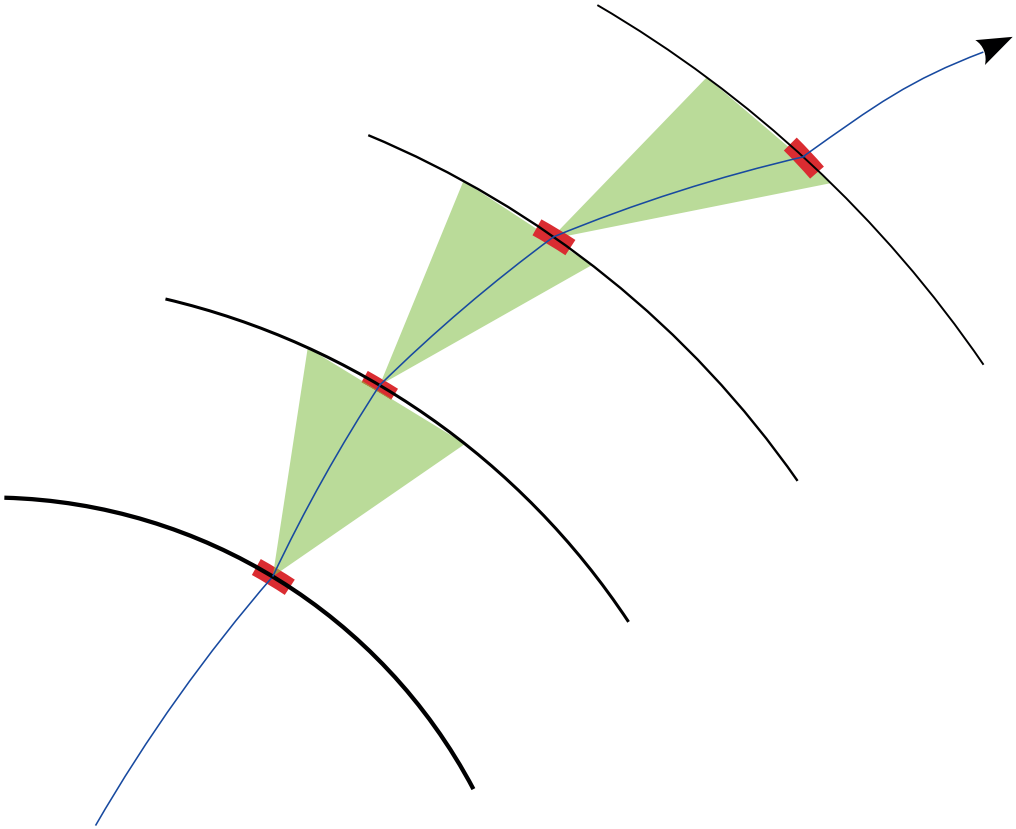


Momentum measurement

- Apply magnetic field
- Measure curvature of particles in field
- Limited by detector resolution and scattering in detector

- Below few 100 MeV/c momentum: Scattering completely dominates
- Large pixels (Mu3e: 80 μm)
- Very little material (0.1% X_0 per layer)





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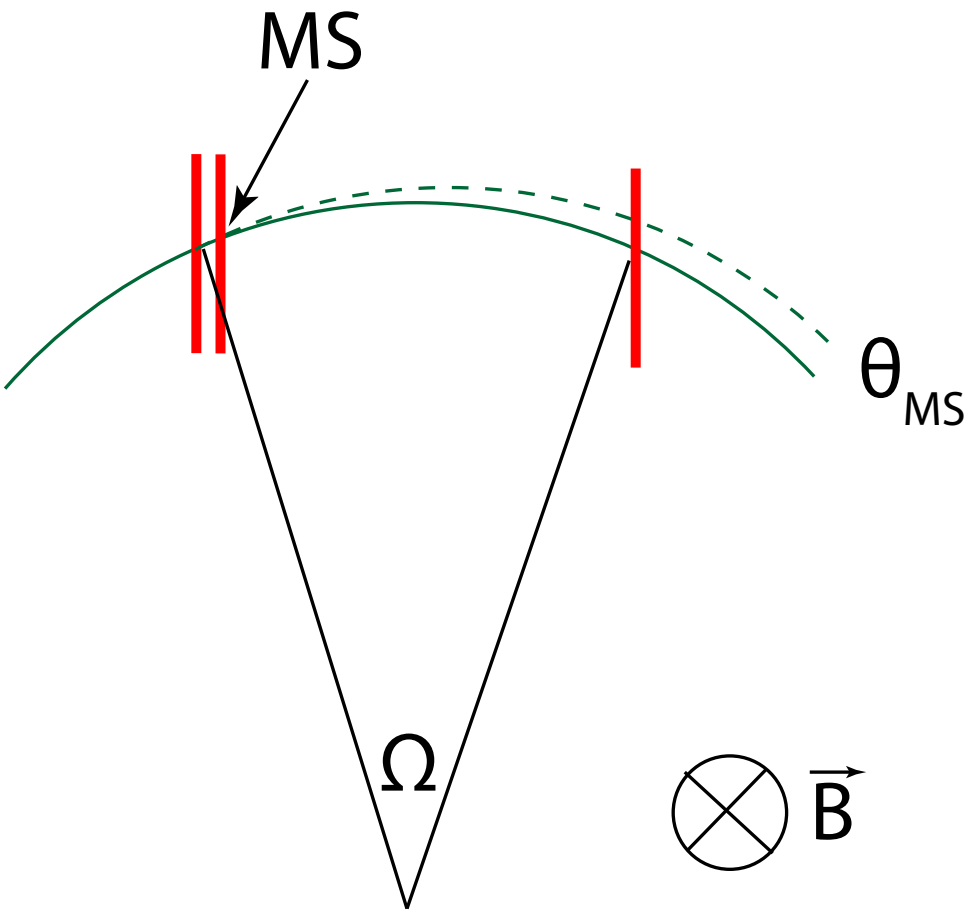
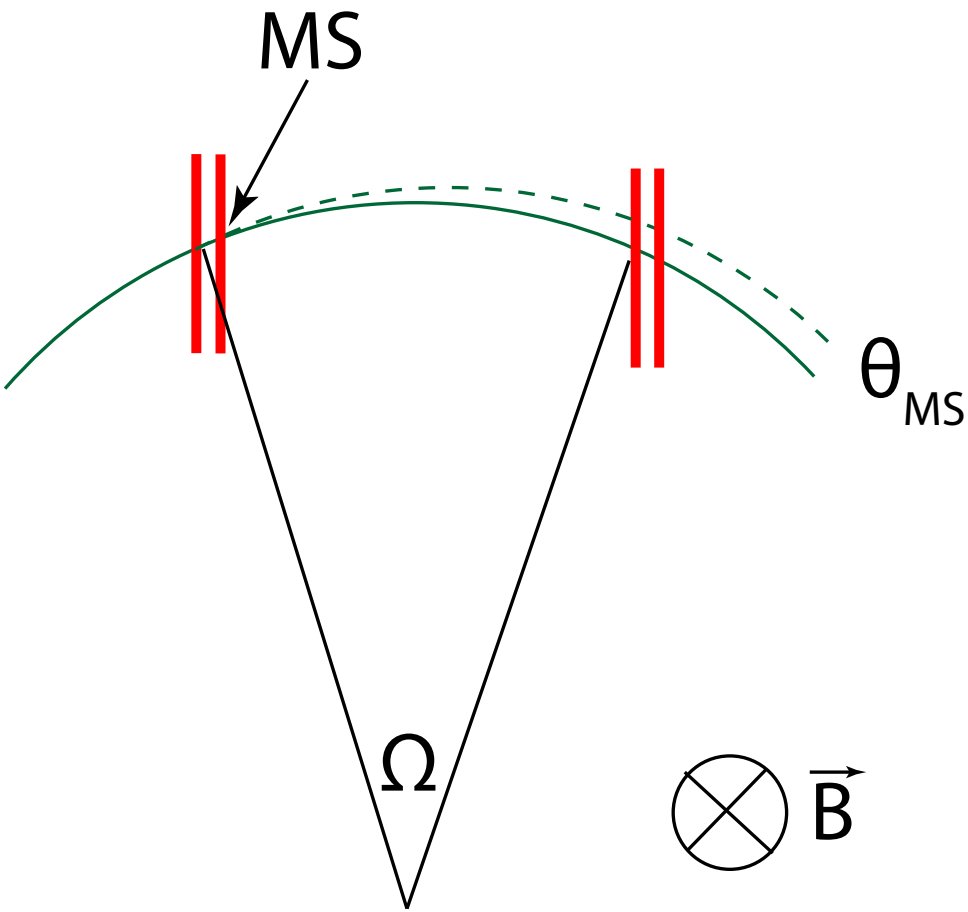


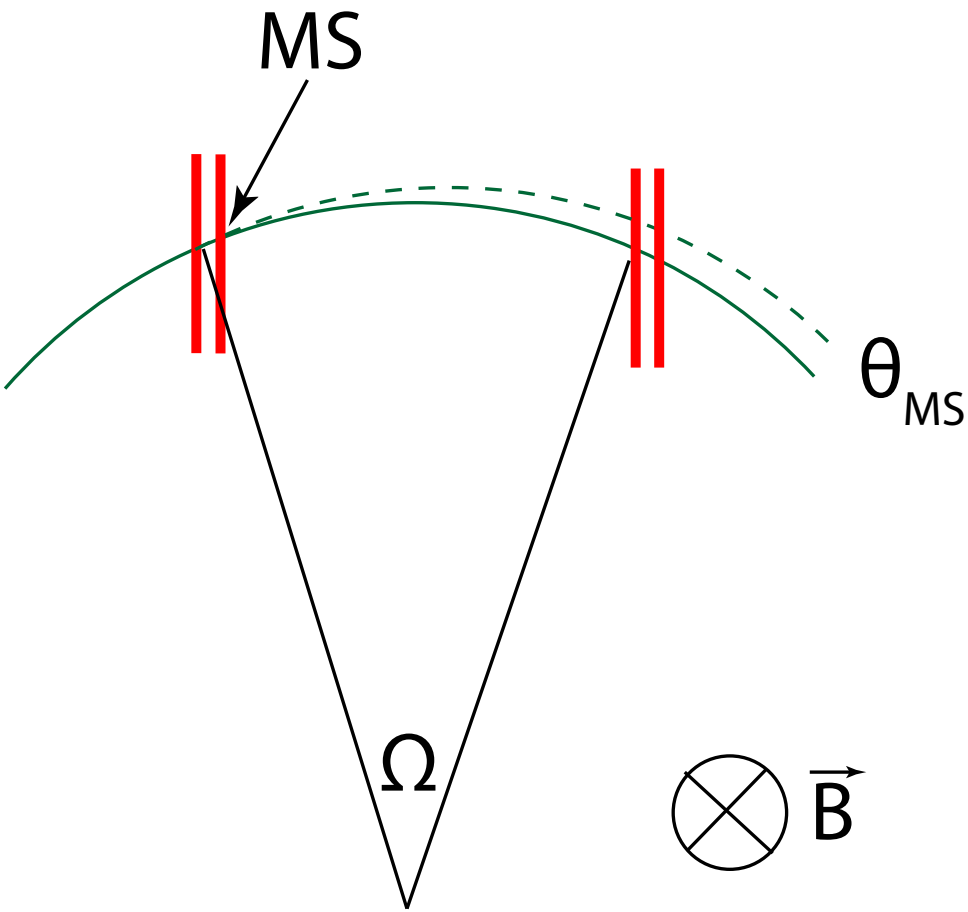
- Resolution dominated by multiple scattering
- Measure a direction (double plane) and then curvature over large drift distance

Momentum measurement



- Resolution dominated by multiple scattering
- Measure a direction (double plane) and then curvature over large drift distance (also works in the other direction)

Momentum measurement



- Resolution dominated by multiple scattering
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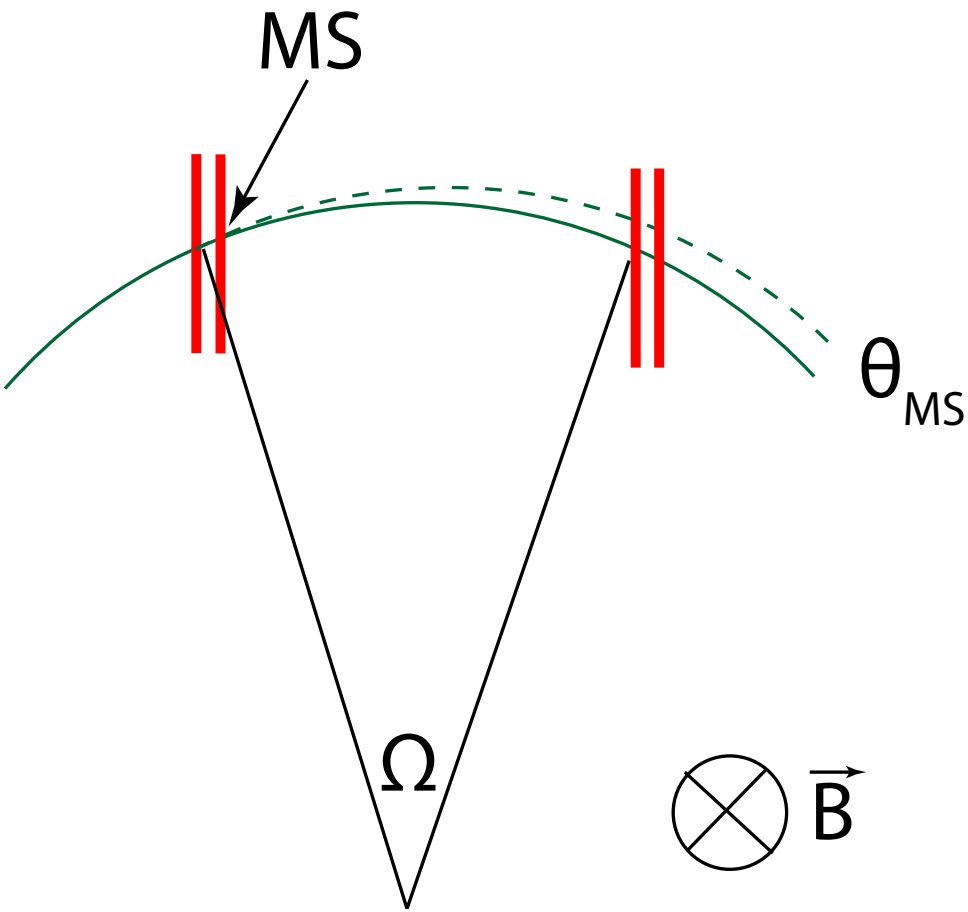
- Momentum resolution to first order:

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

Momentum measurement



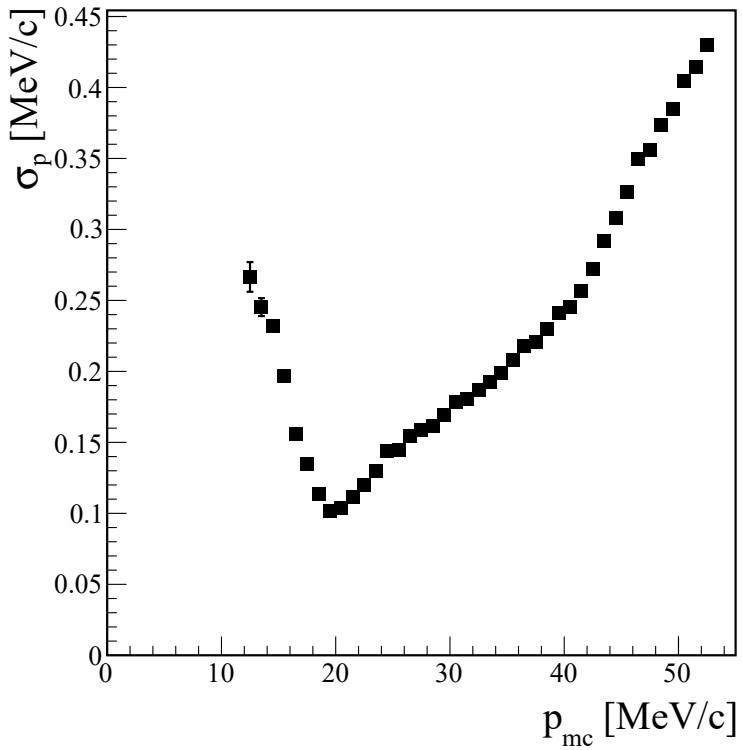
- Resolution dominated by multiple scattering
- Measure a direction (double plane) and then curvature over large drift distance (also works in the other direction)
- Momentum resolution to first order:

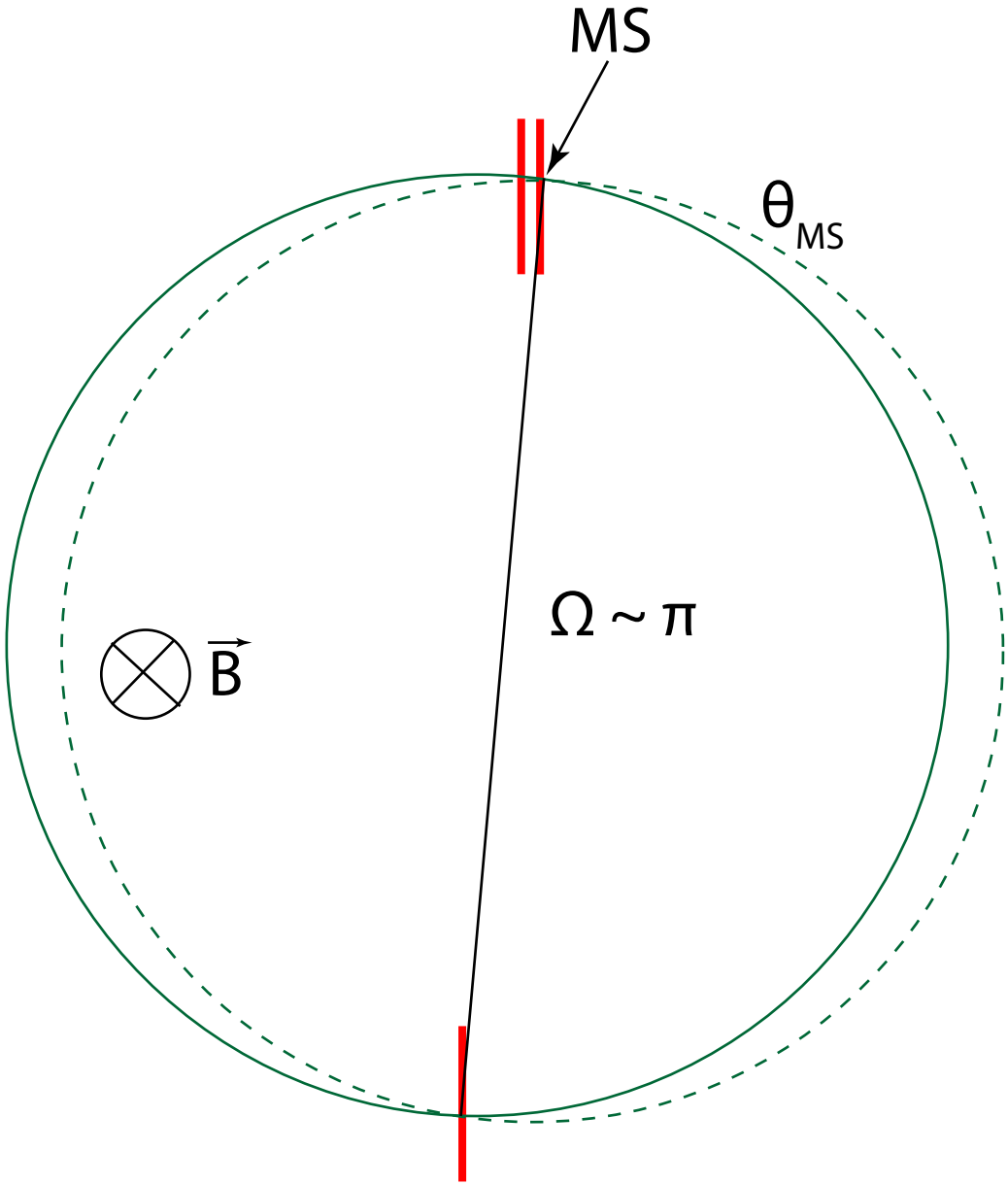
$$\sigma_P/P \sim \theta_{MS}/\Omega$$

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

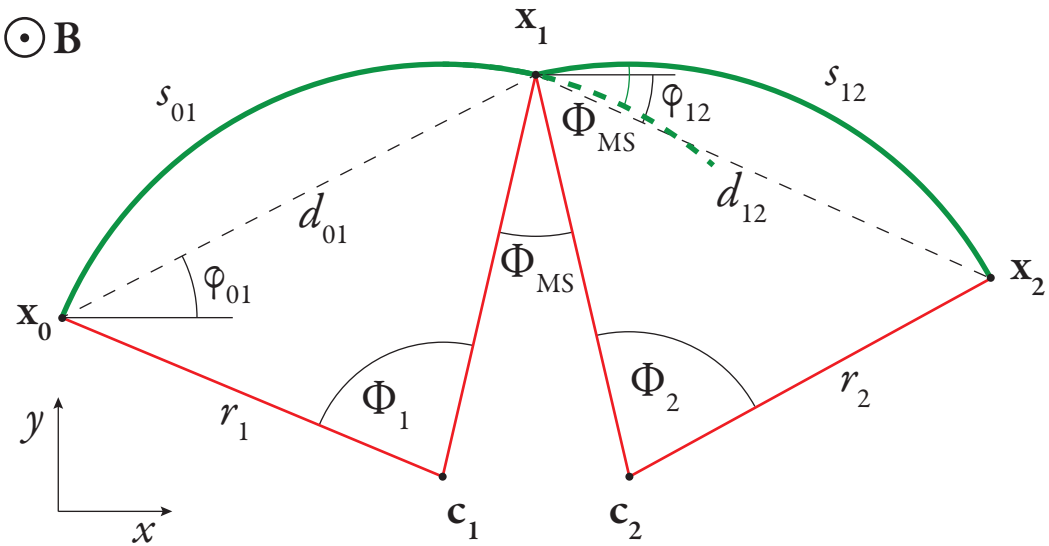
Precision vs. Acceptance

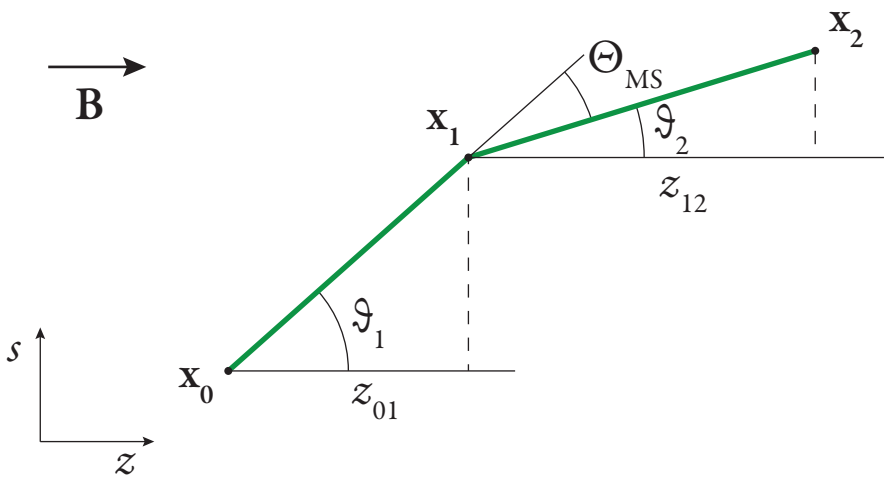
- Best resolution for semi-circles: Multiple scattering cancels to first order
- In Mu3e: Get to 100 keV/c resolution for ~20 MeV/c tracks





Multiple Scattering Track Fit



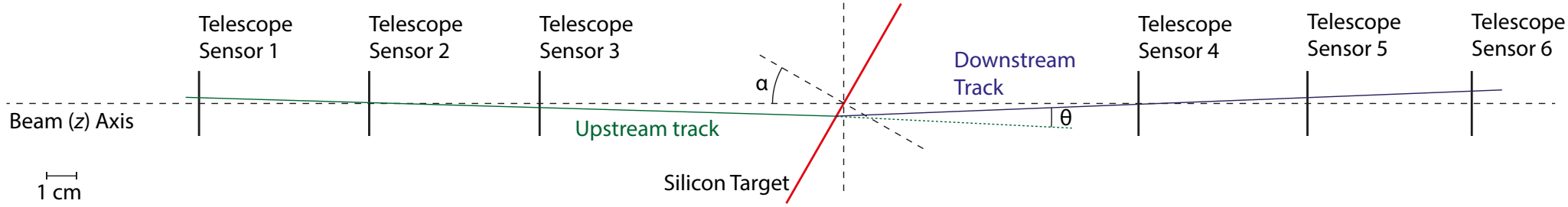


- Treat hit measurements as arbitrarily precise
- Consider scattering in each detector plane
- Two hits, two helices: Underconstrained problem

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

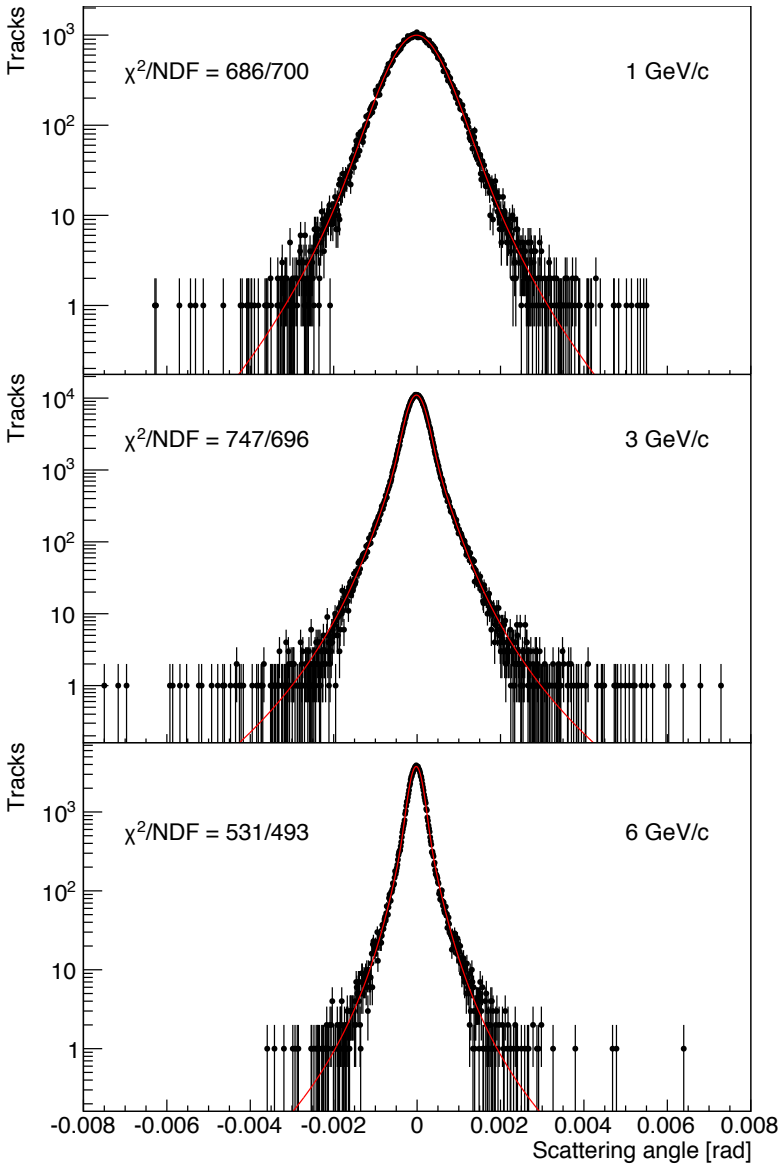
Nucl. Instrum. Meth. A 844C, 135 (2017)

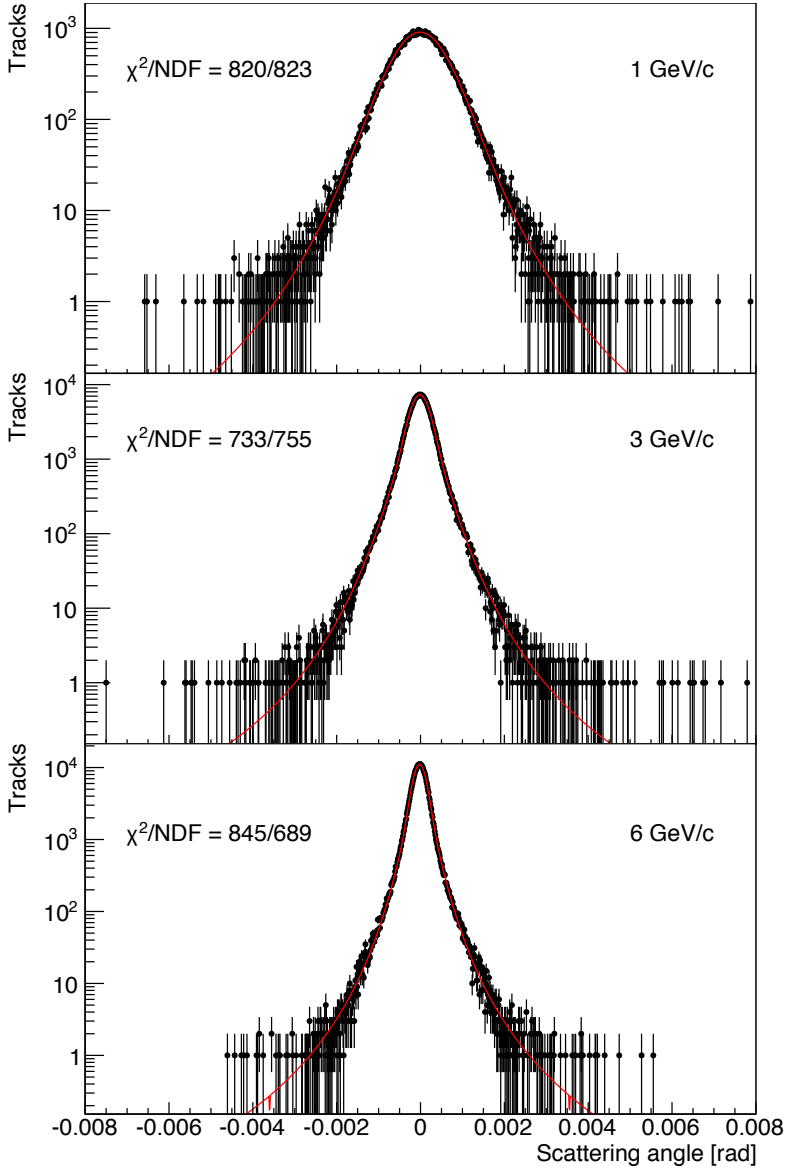
Measuring multiple scattering



- Study multiple Coulomb scattering in thin silicon wafers
- 1 day measurement at the DESY electron test beam
- Using the EUDET telescope

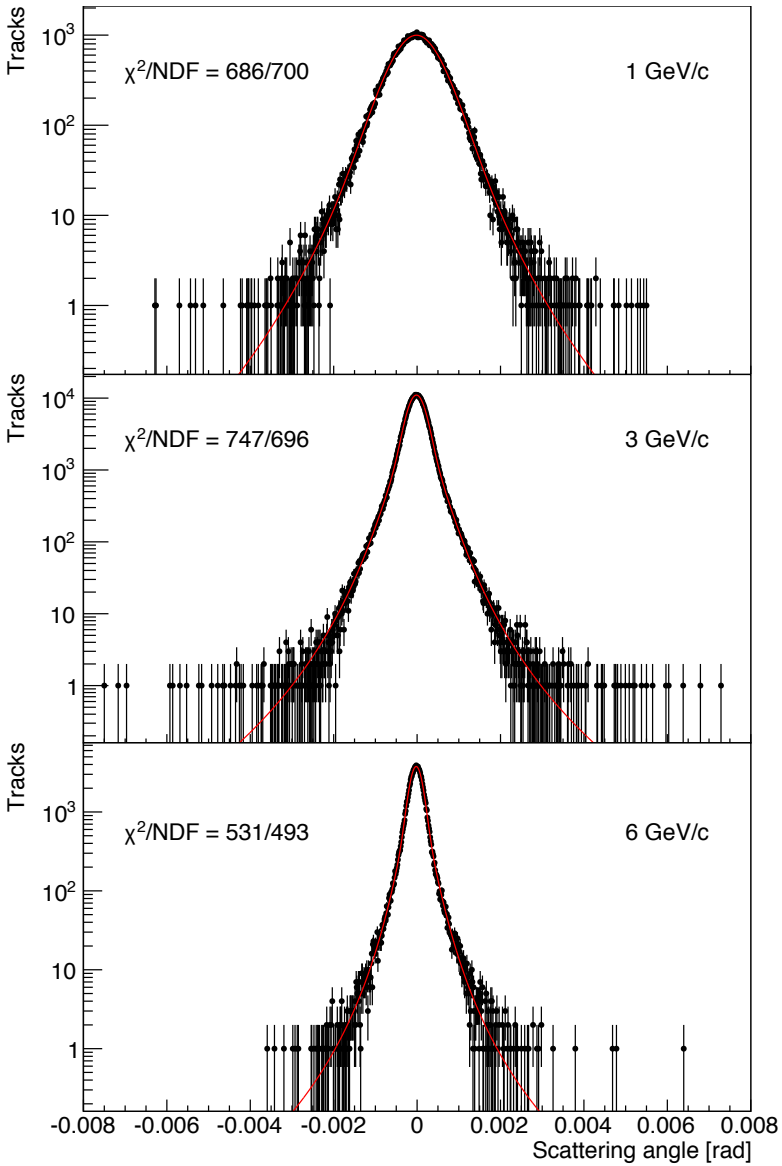
Measuring multiple scattering

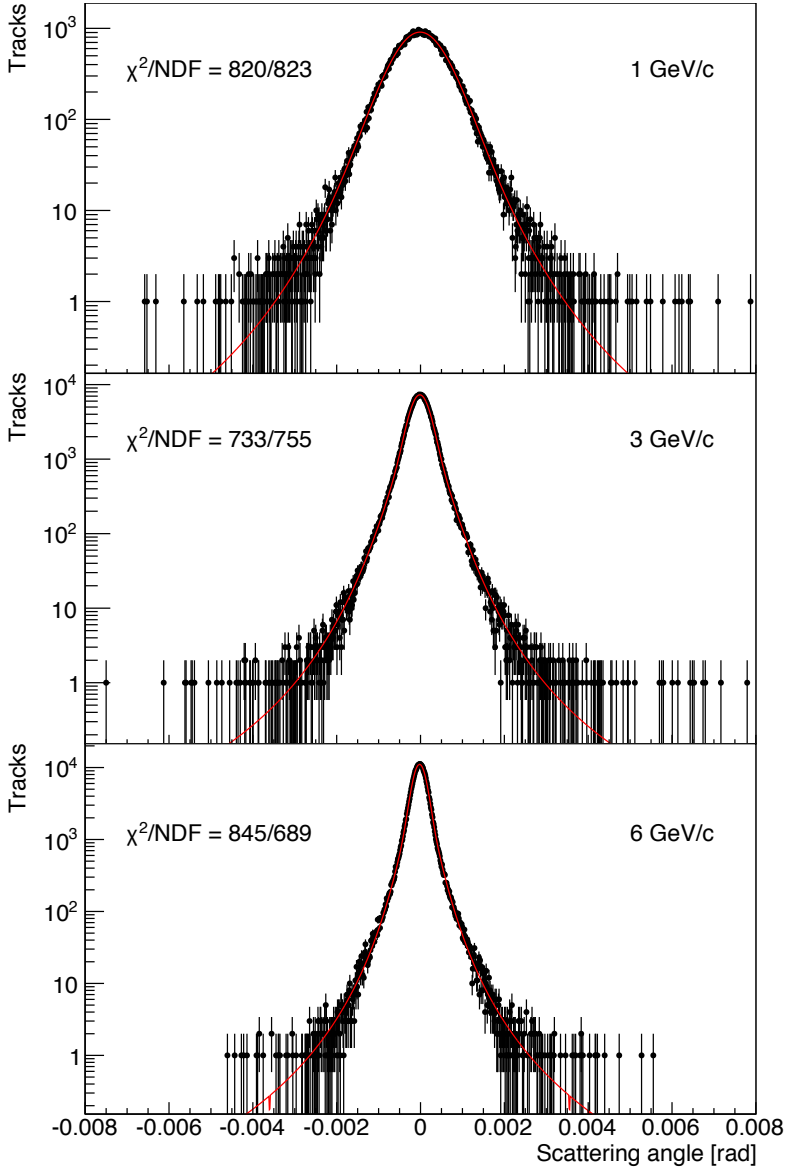




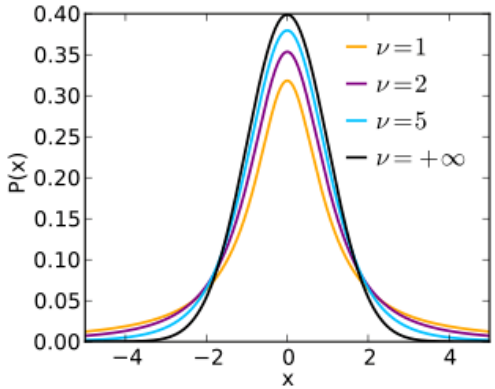
- Measure with and without silicon
- Fit distributions, difference is scattering in silicon

Measuring multiple scattering

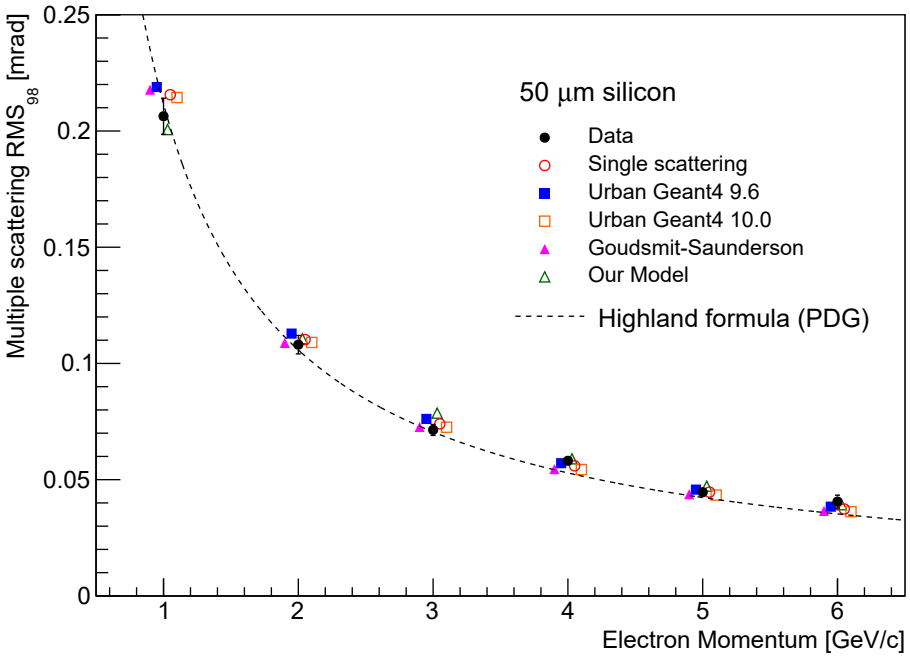




- Measure with and without silicon
- Fit distributions, difference is scattering in silicon
- Shape well described by Student's t distribution

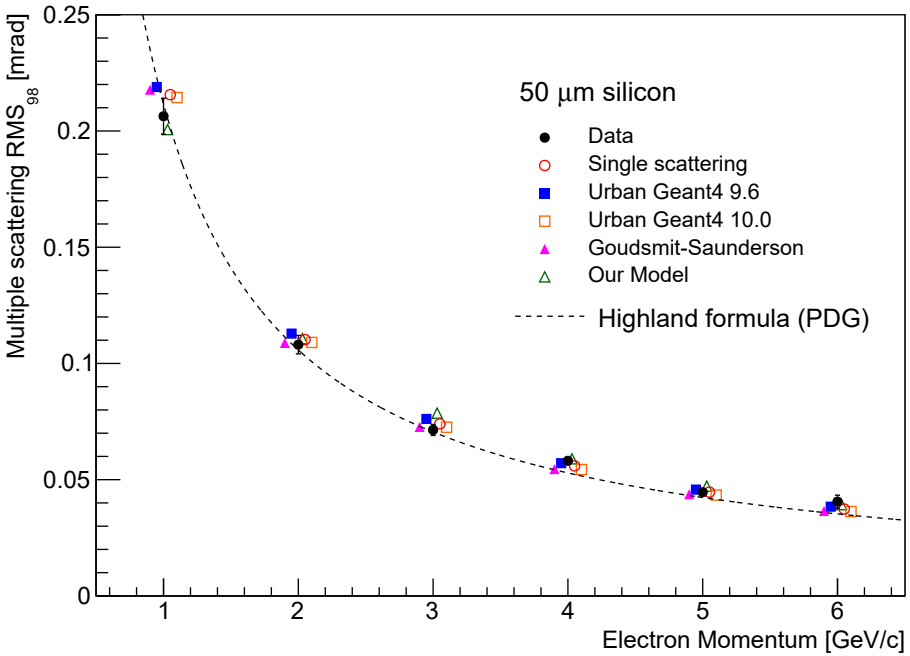


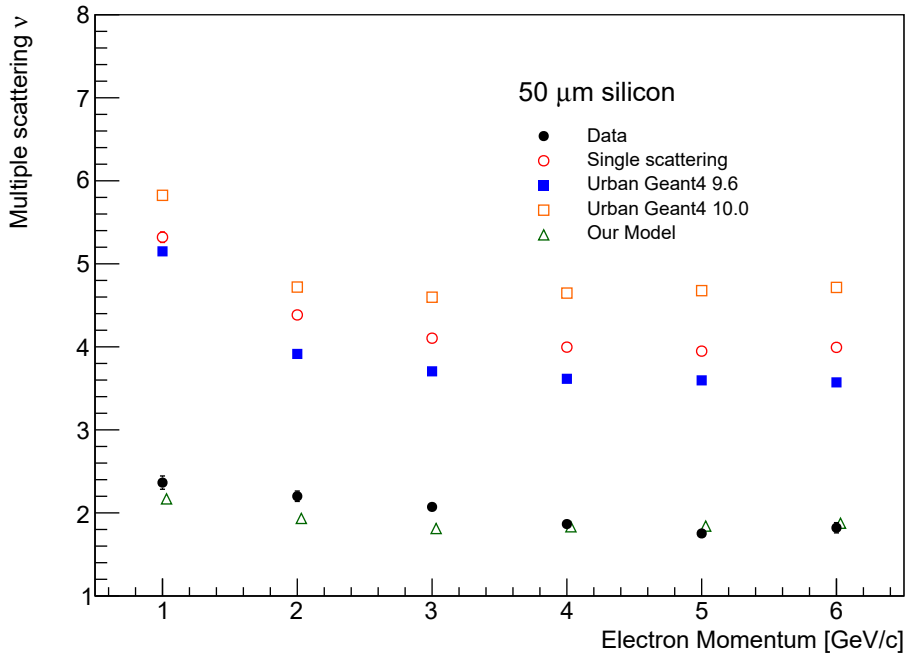
Measuring/simulating multiple scattering



- RMS of the central 98% of the distribution well described by Highland formula and Geant4 models

Measuring/simulating multiple scattering



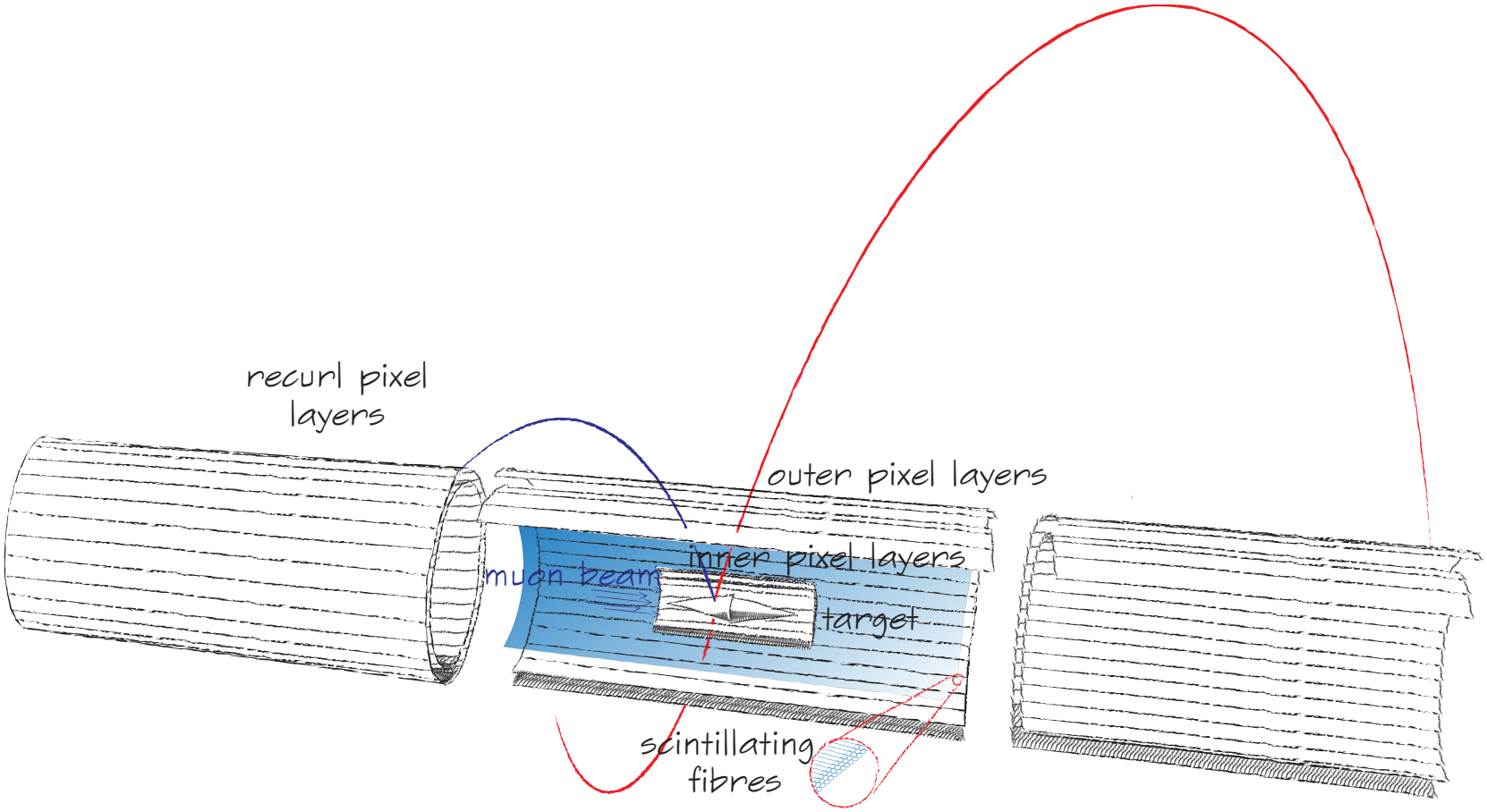


- RMS of the central 98% of the distribution well described by Highland formula and Geant4 models

N. Berger et al. Multiple Coulomb Scattering in Thin Silicon JINST 9 P07007(2014), arxiv:1405.2759

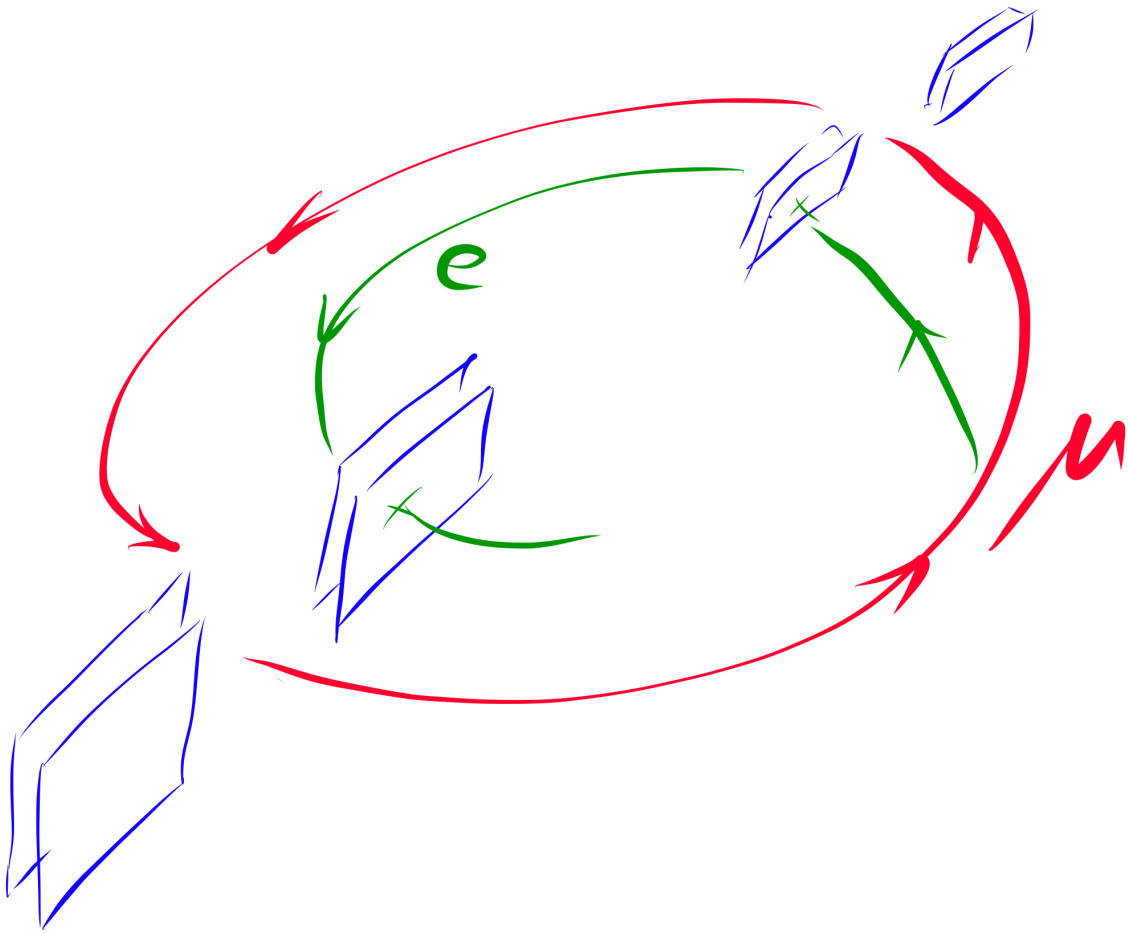
- Models do not have enough tails ($\nu \rightarrow \infty$: Gaussian)
- Would like to extend this to lower momenta

Mu3e Detector Design



EDM Momentum Resolution Detector

- A double plane of detectors
- Optimum momentum resolution for circling positrons
- Likely loose some positrons



Questions:

- What momentum resolution do we need?
  Few MeV/c?
- Acceptance should be close to 100%?
- What will dominate the systematic uncertainty?
  Tracking efficiency?
  Up-/down differences in tracking efficiency?

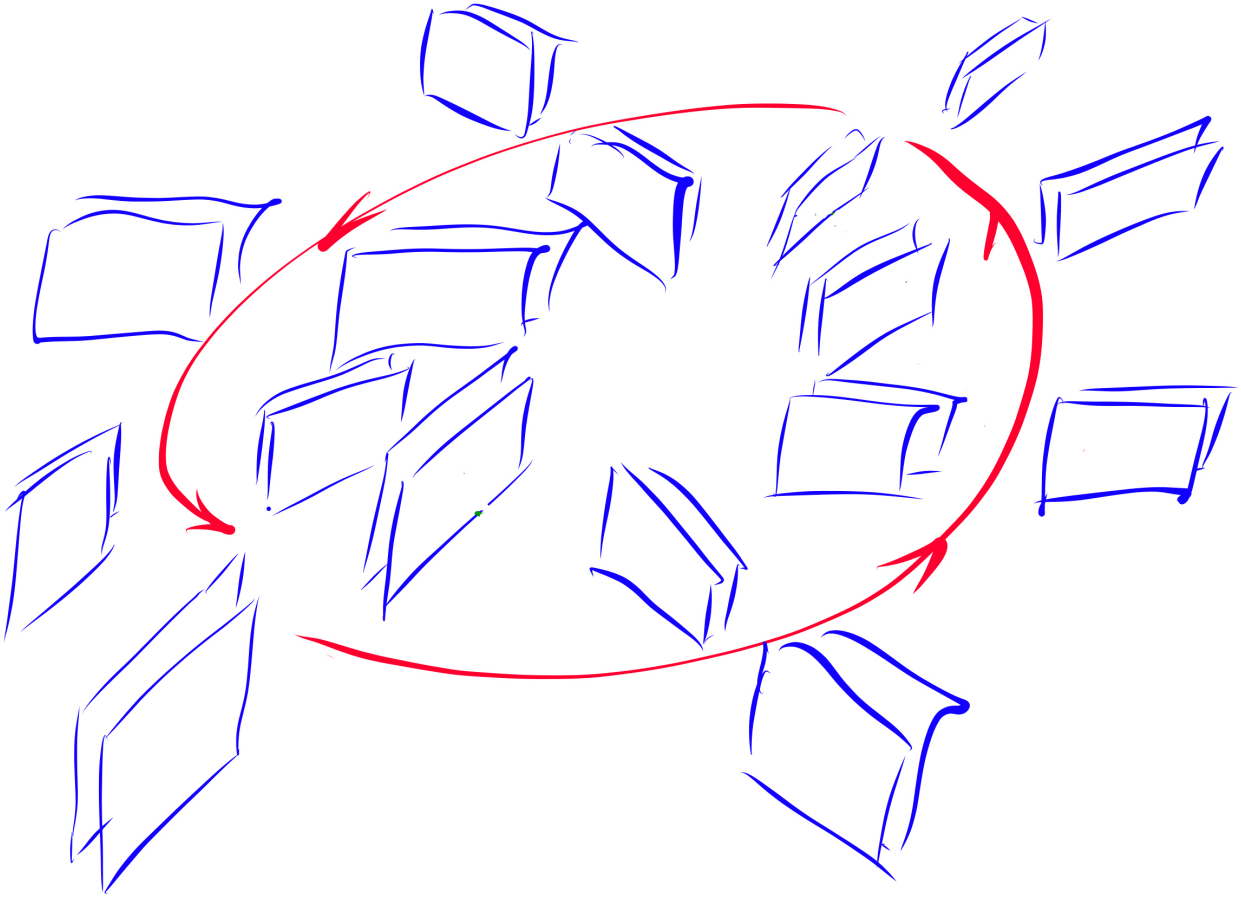
Efficiency:

- Use highly efficient sensors
- Be highly redundant

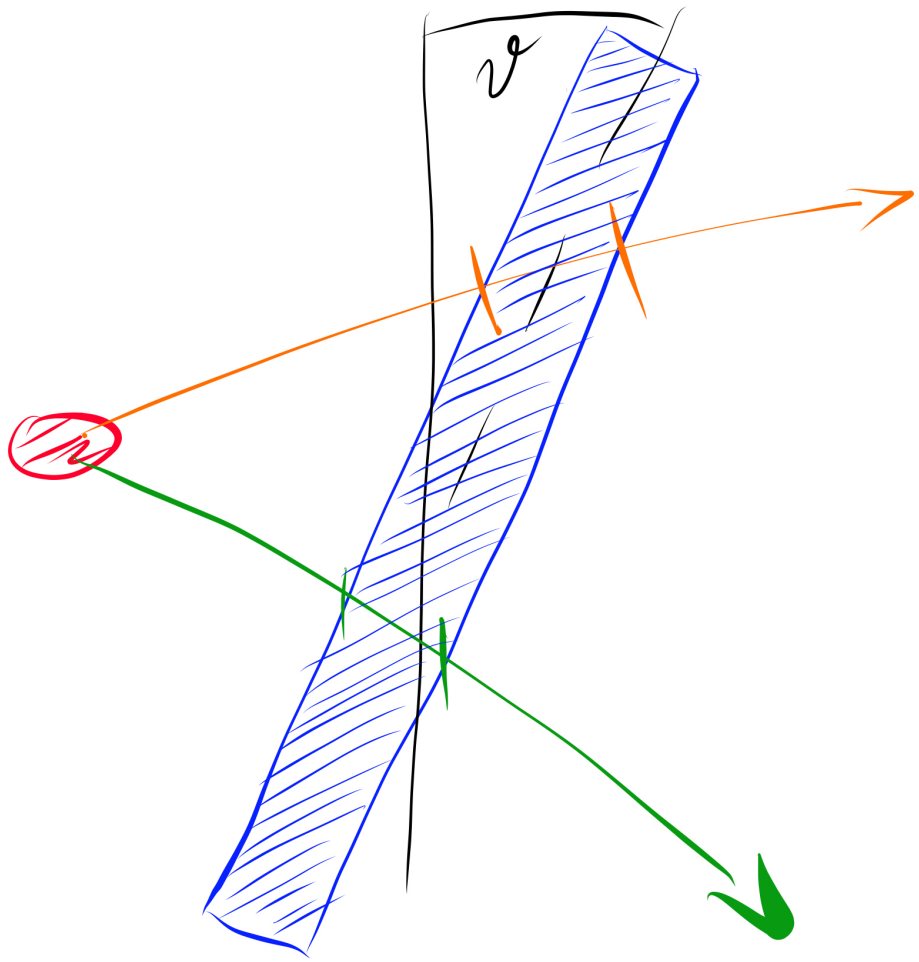
More redundancy means more material means less momentum resolution - one of the trade-offs for this experiment

EDM Tracking Detector?

- How many blades?
- Inside orbit?
- Vertical dimension?
- Trigger?
- Services?
- Cooling?
- What sensors?



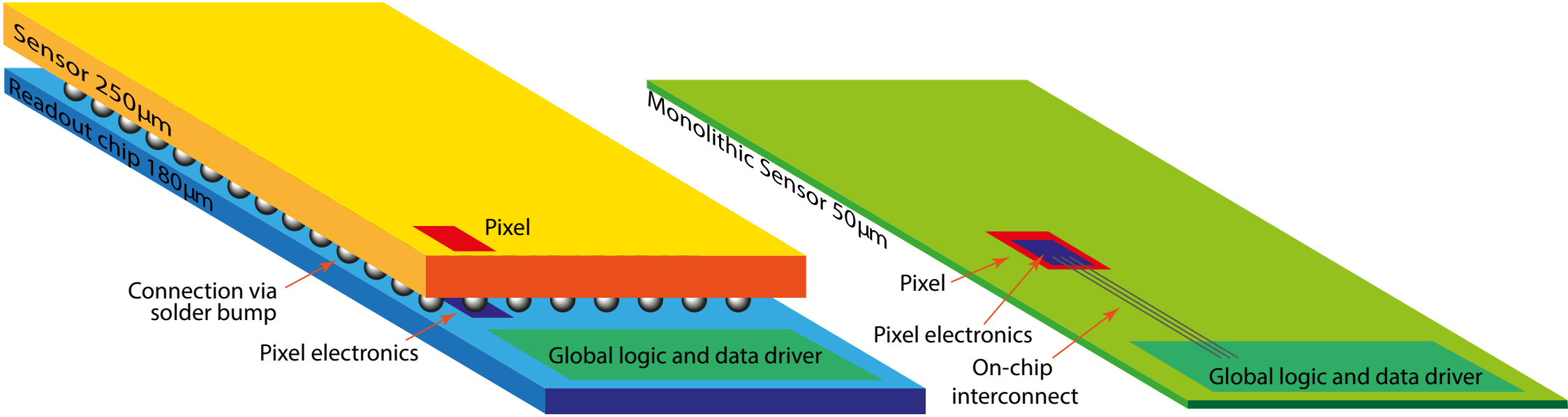
Misalignment systematic



- Tilt of any sensors relative to the horizontal will lead to different path-lengths for up- and down-going positrons
- Different efficiency
- Different scattering

High-Voltage
Monolithic Active Pixel Sensors

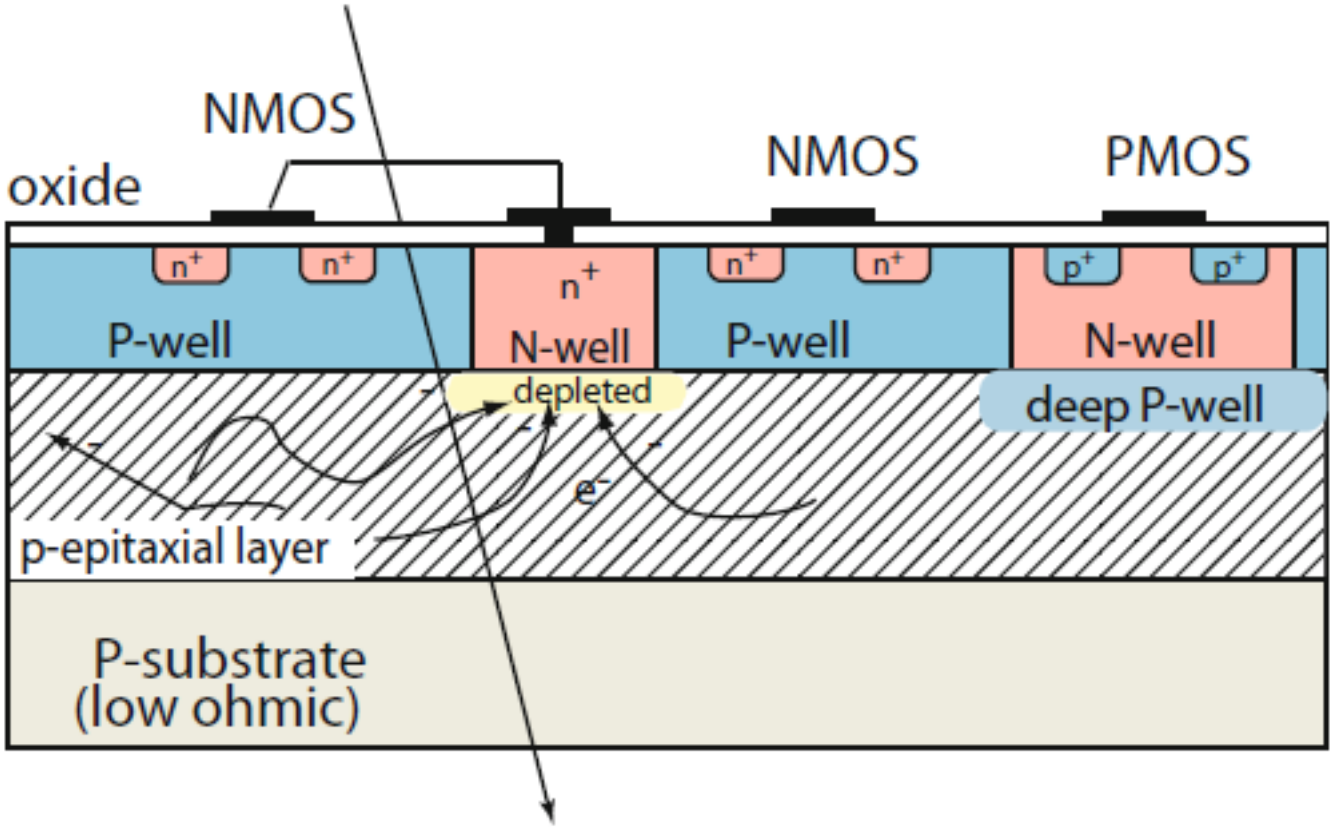
Hybrid vs. monolithic detectors



MAPS: Monolithic Active Pixel Sensors

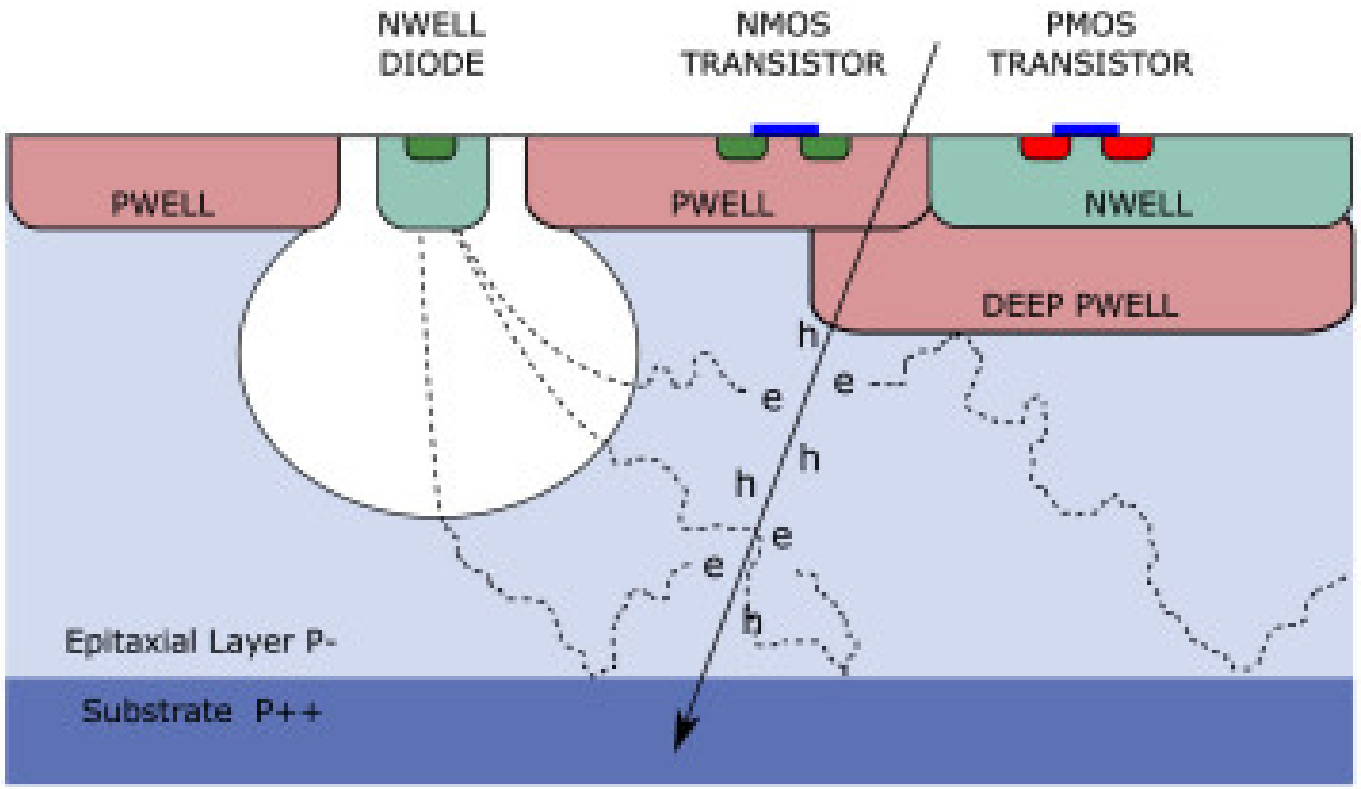
Use commercial CMOS processes

- Charge collection from epitaxial layer
- No electrical field
- Diffusion: Slow
- Substrate does not contribute: Can be made thin: 50 µm
- PMOS transistors act as parasitic charge collection diodes: Need to be shielded: More complex manufacturing



MAPS: Monolithic Active Pixel Sensors

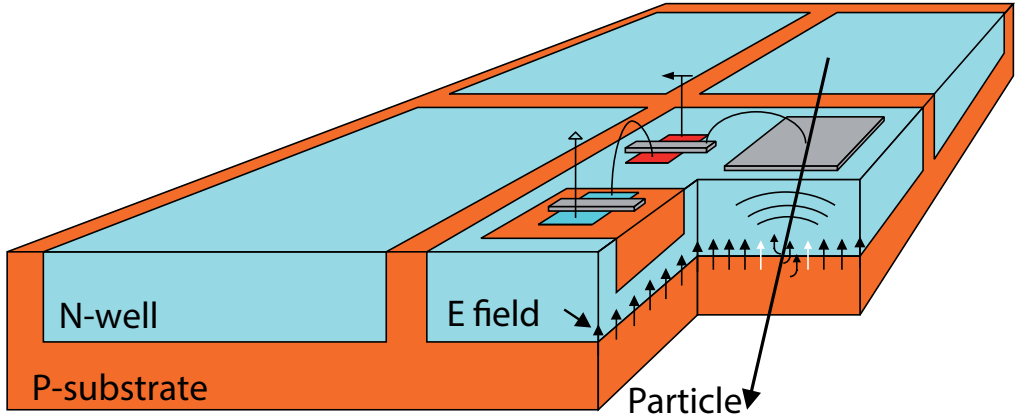
- Current state: ALPIDE sensor for ALICE pixel detector
- 180 nm TowerJazz imaging process
- Partial depletion (white)
- Low power (< 40 mW/cm^2)
- Still slow: ~2 μs peaking time

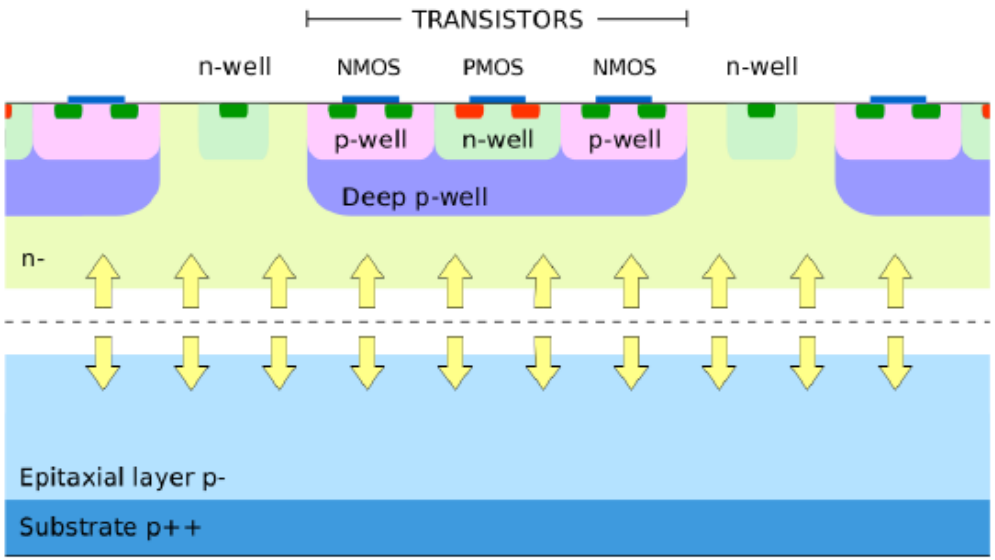


Nuclear Instruments and Methods in Physics Research A 824 (2016) 434–438

Faster sensors: Depleted MAPS

- Fully deplete the active volume
- Either via high voltage
  (high voltage processes, MuPix)
  Large collection electrodes
- High resistivity substrate and modified
  imaging processes (afternoon)
  Small collection electrodes

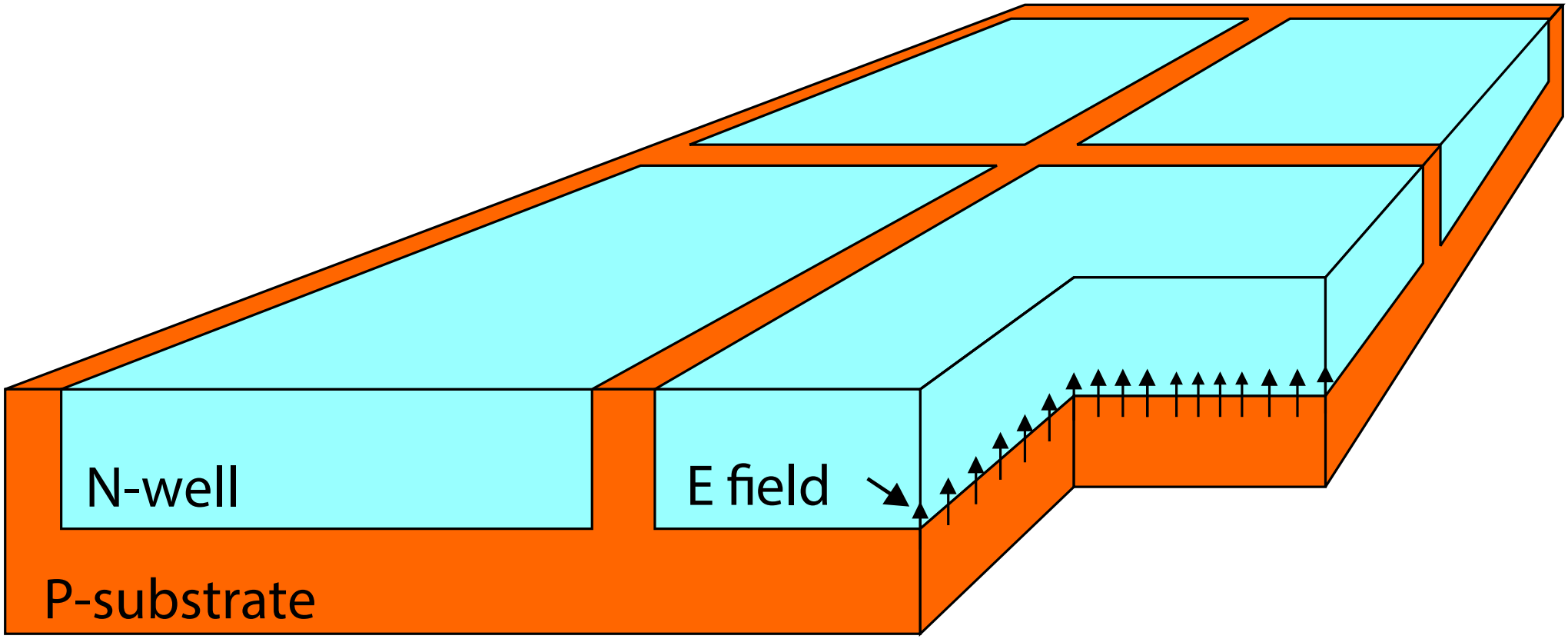




Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)



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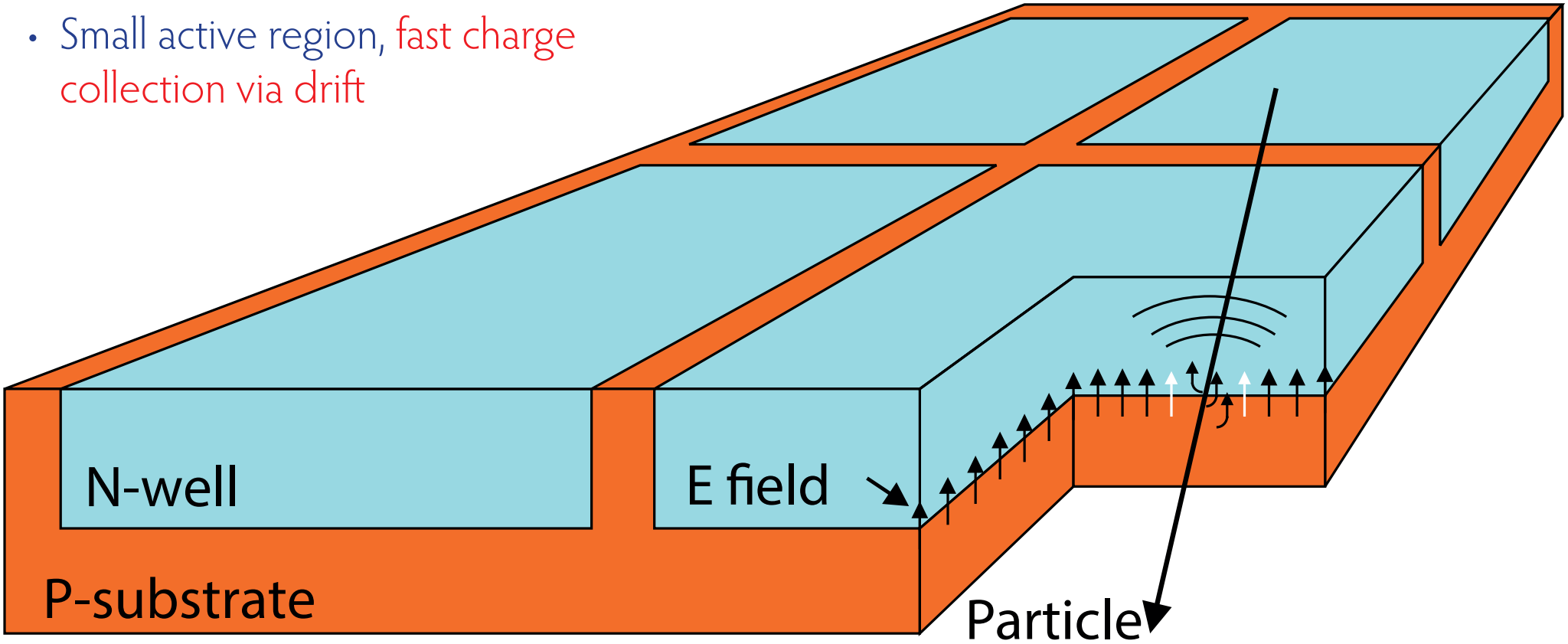

Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors - Ivan Perić

- Use a high voltage commercial process (automotive industry)
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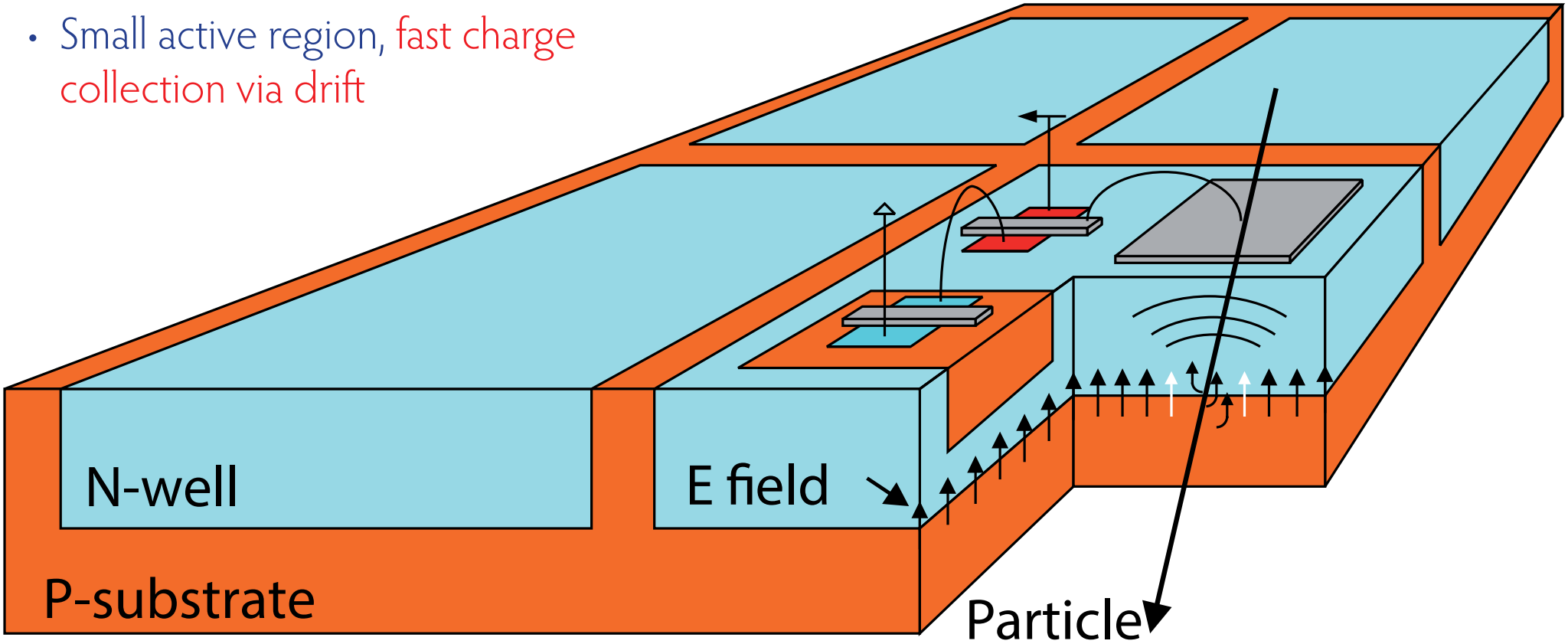
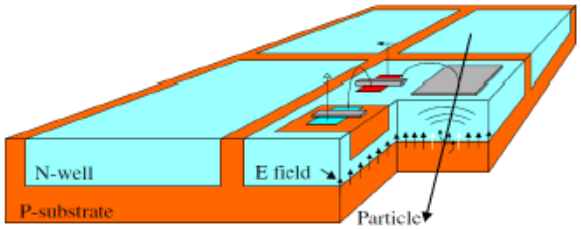
- Implement logic directly in N-well in the pixel - smart diode array
- Can be thinned down to < 50 μm

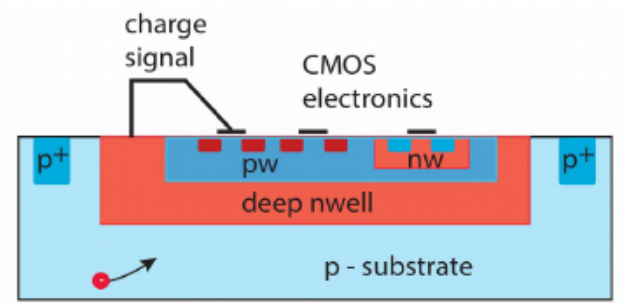
(I.Perić, P. Fischer et al., NIM A 582 (2007) 876)



HV-MAPS Prototypes - History

I. Peric et al (2007)





Mupix7 was the first small scale prototype integrating all relevant features of a **fully monolithic chip** (VCO, PLL, state machine, ...)

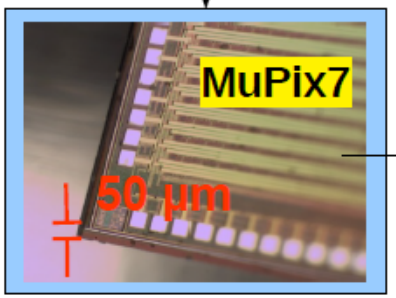
Mu3e-Experiment

MuPix1

MuPix2

.....

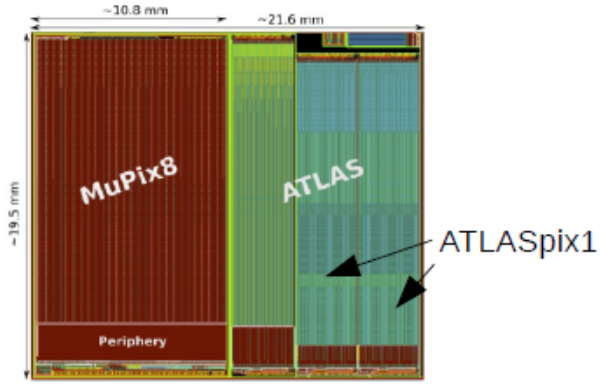
MuPix6



AMS H18 (IBM)

Mu3e & ATLAS (HL-LHC)

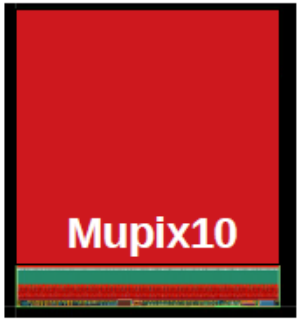
AMS AH18



Mupix9

ATLASpix2

TSI H18



Mar 2020

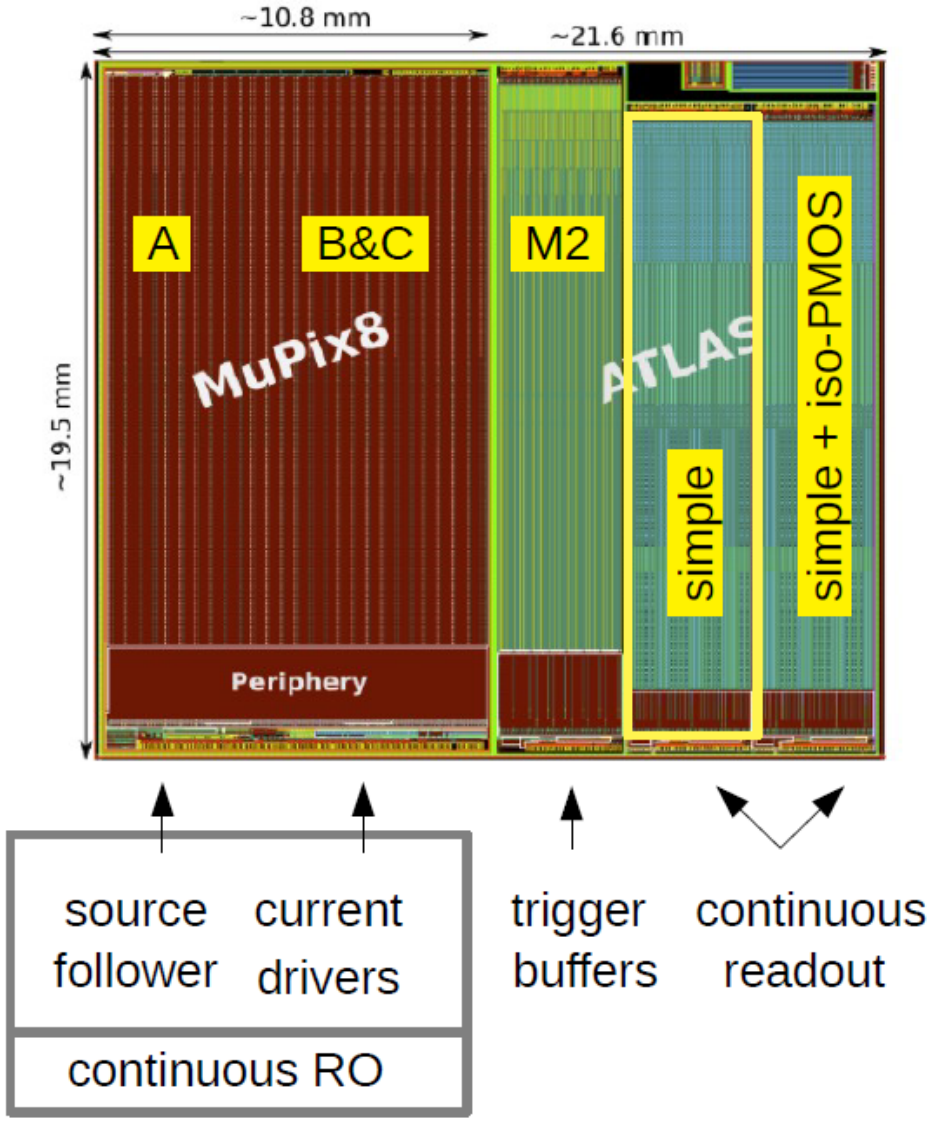
Sep 2019

Slide by A. Schöning

MuPix8 & ATLASpix1

Mupix8

- pixel: 80 x 81 µm²
- 200 rows x 48 cols
- amplifier in pixel cell
- **discriminators in periphery**
- 6 bit ToT
- state machine
- serial link up to 1.6 Gbit/s



ATLASpix

- pixel: 40 x 130 µm²
- 400 rows x 25 cols
- amplifier in pixel cell
- **discriminators in active pixel cell**
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Slide by A. Schöning

MuPix8 & ATLASpix1

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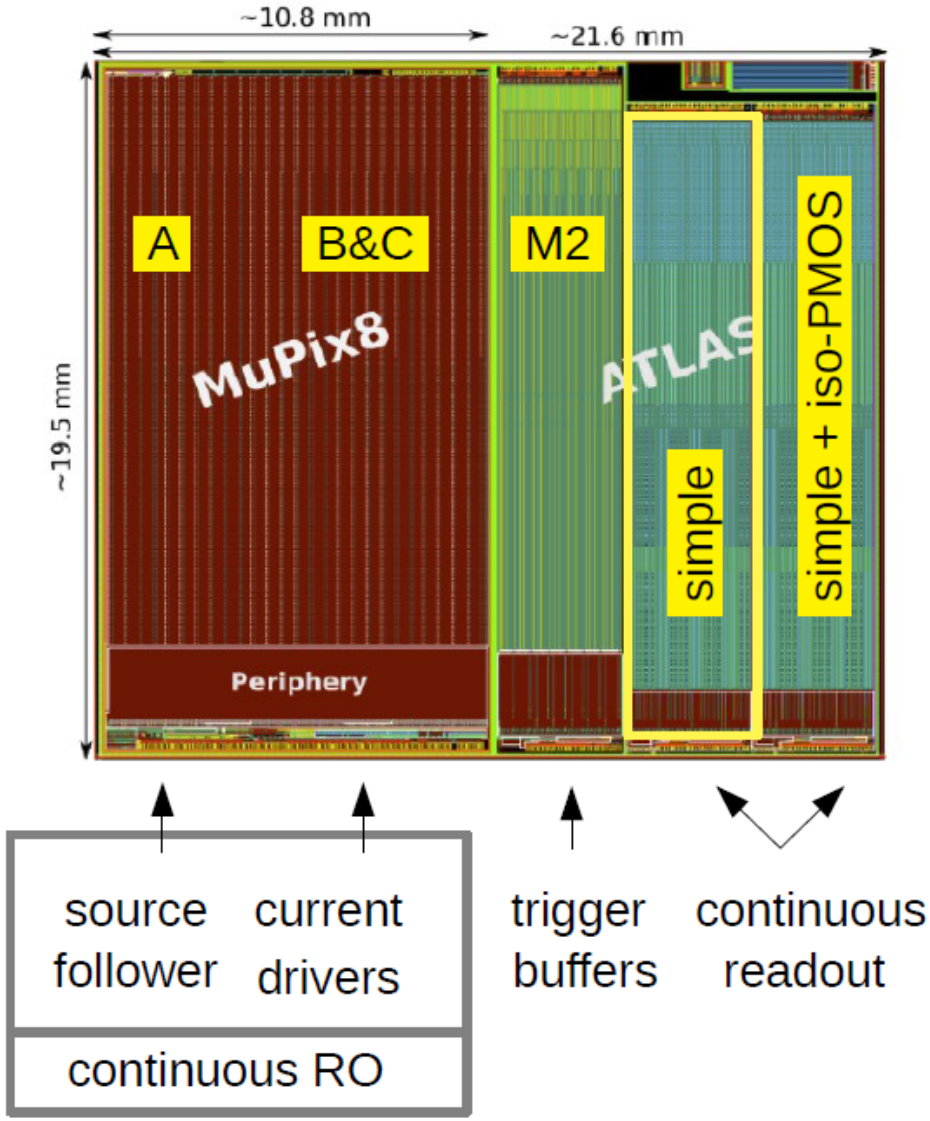

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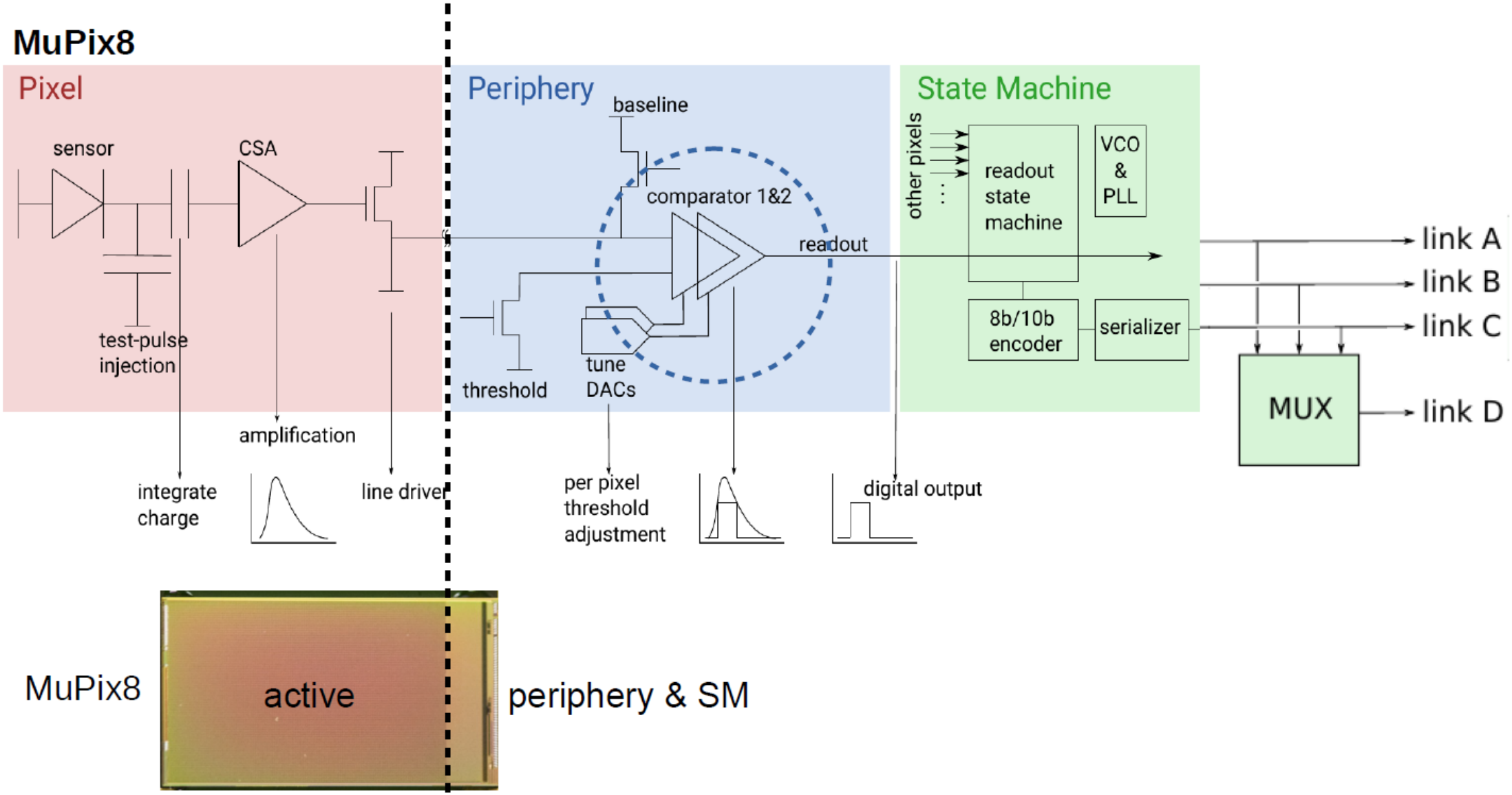
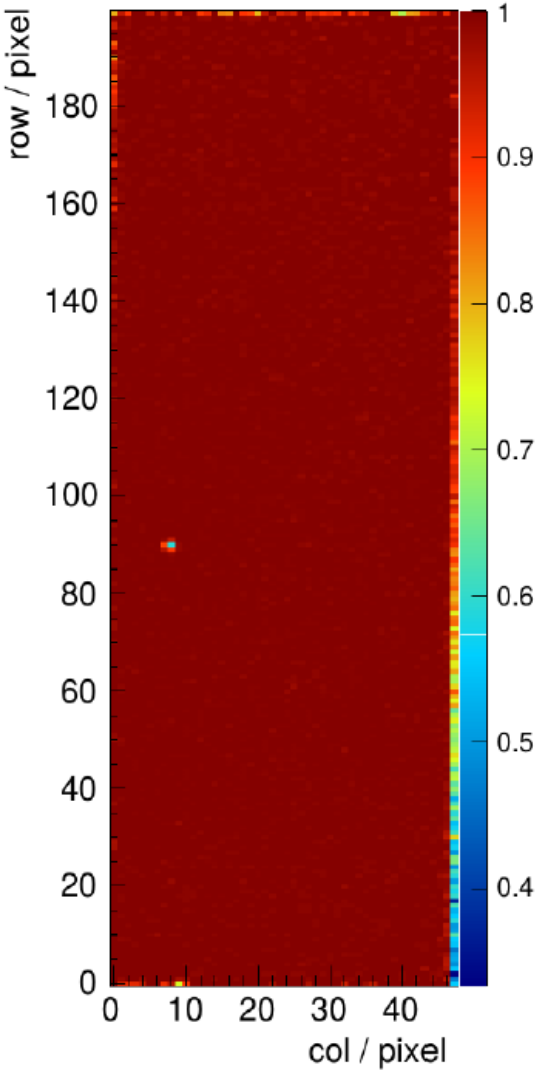
Slide by A. Schöning

Example: Mupix8 Architecture

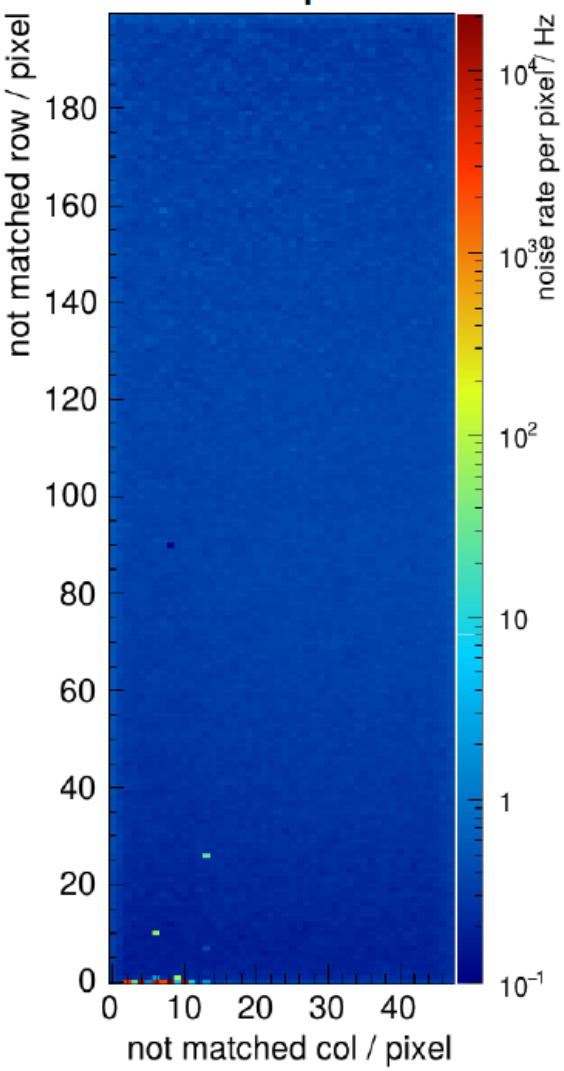


Mupix8 Performance Plots

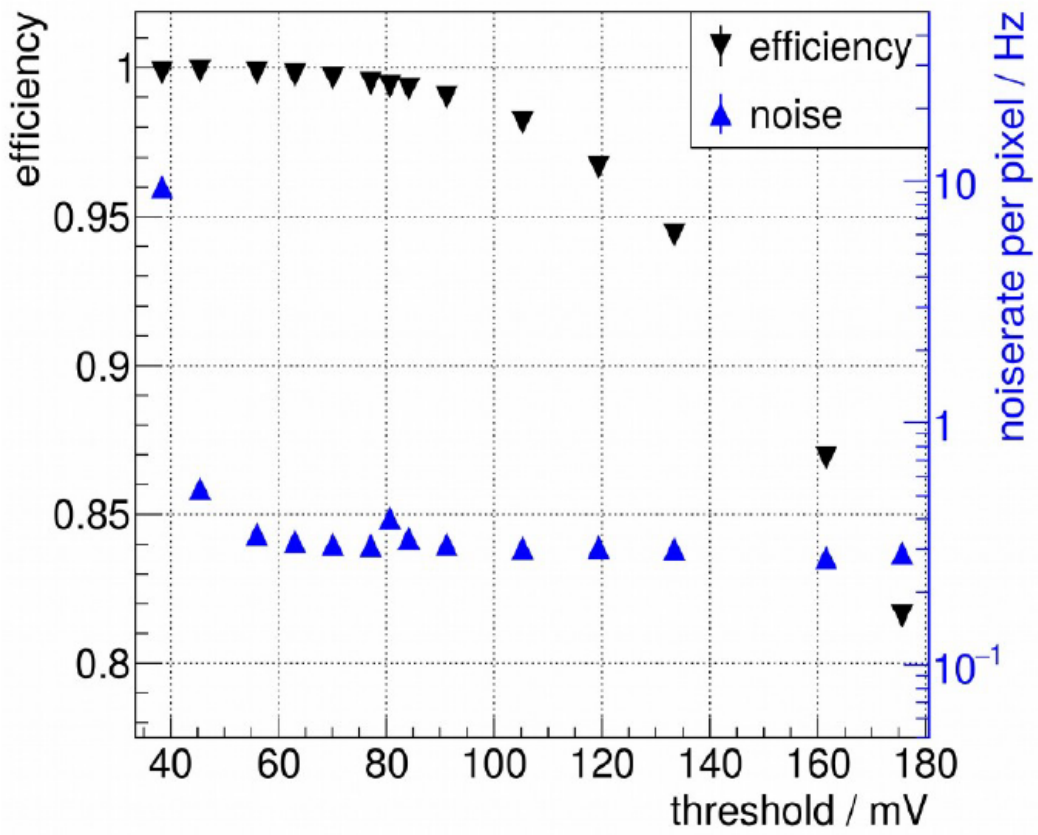
efficiency
~99.9%



noise
~1Hz/pixel

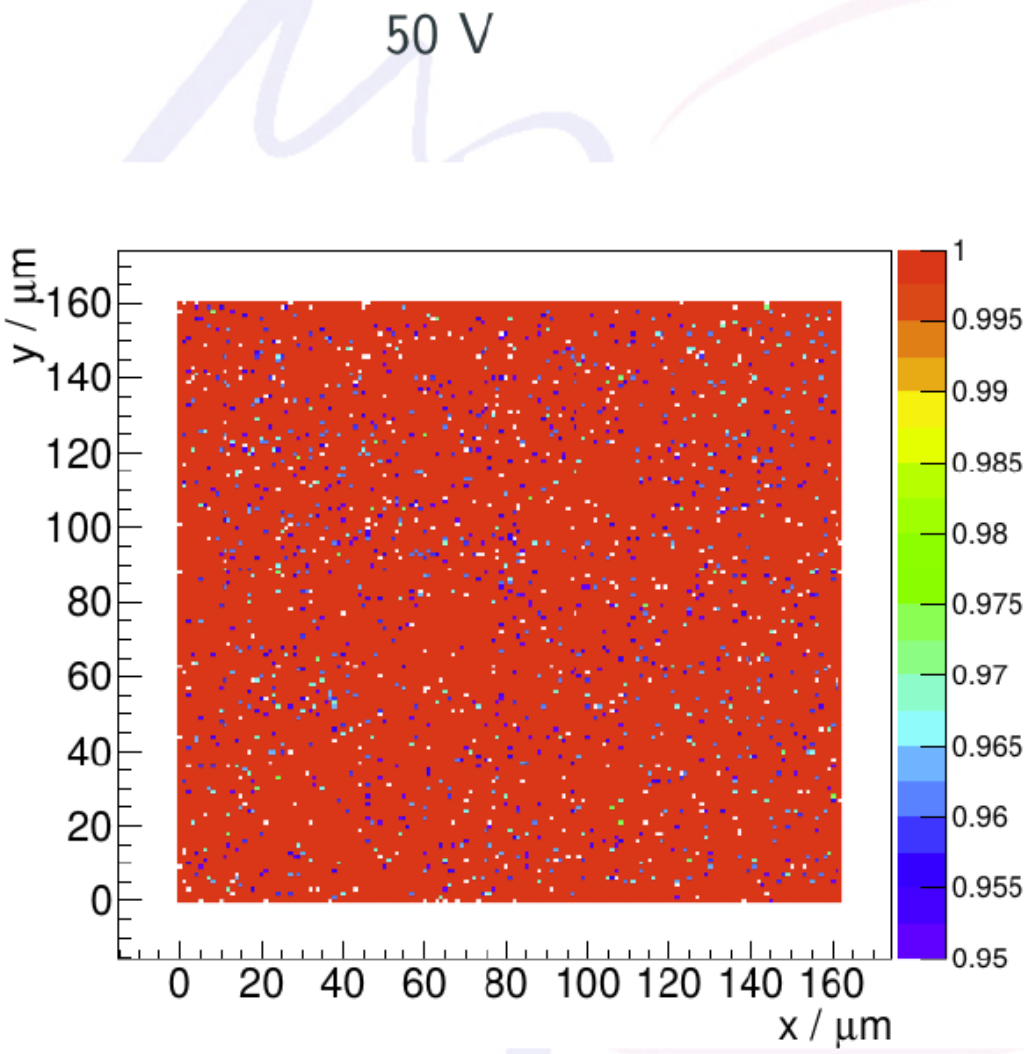


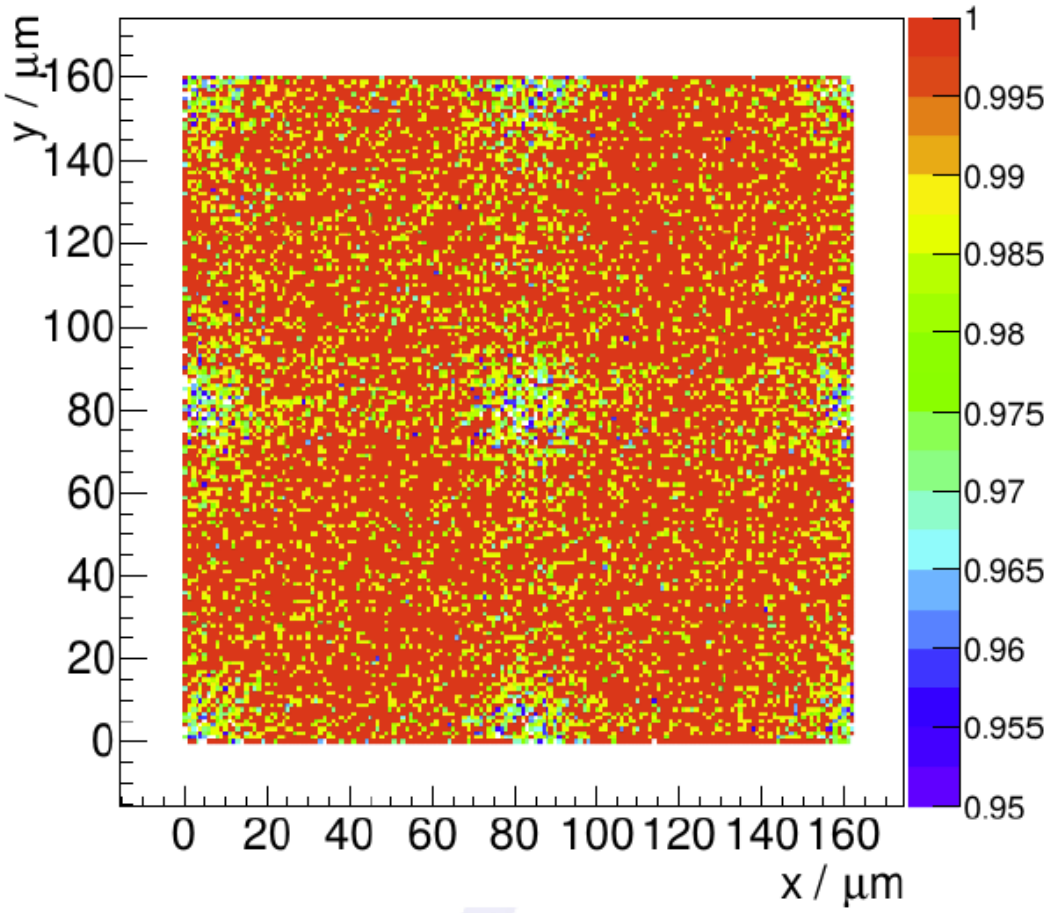
80 Ω cm



100mV ~ 1300 e-

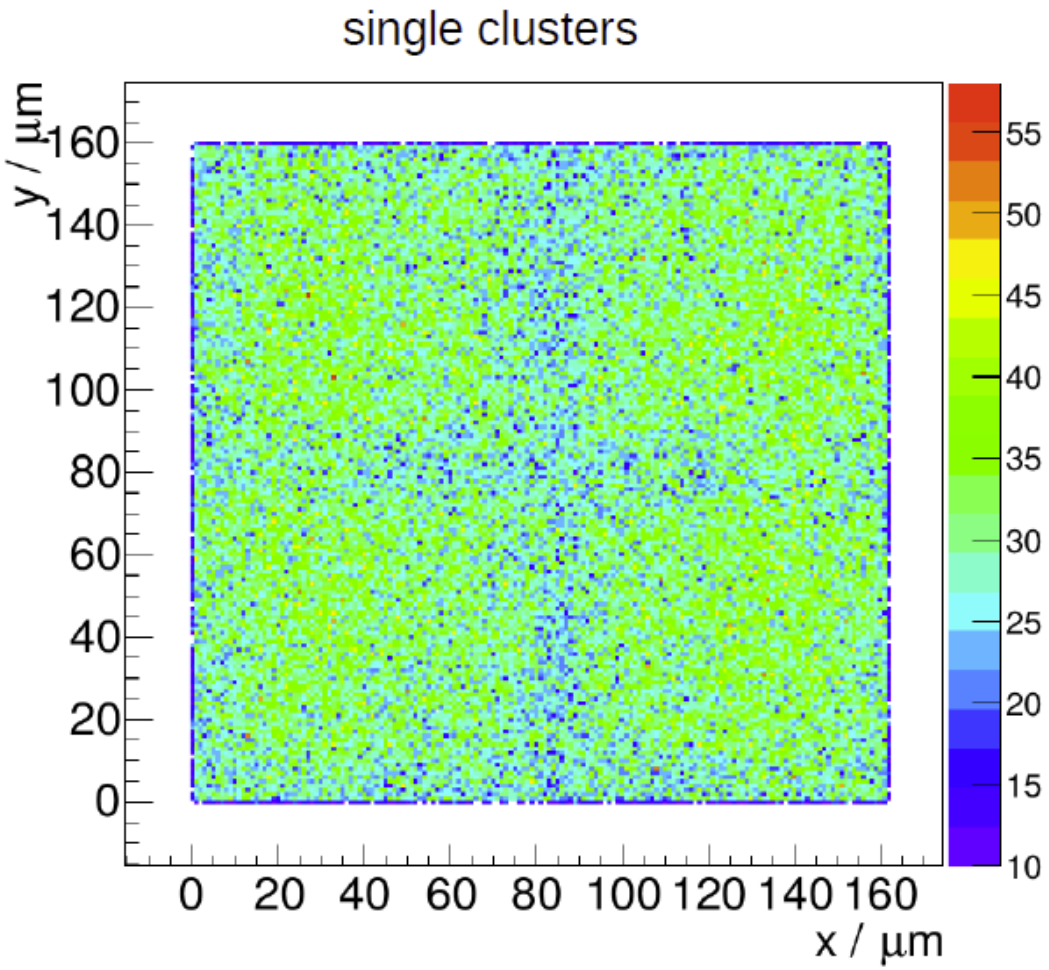
MuPix8 Performance

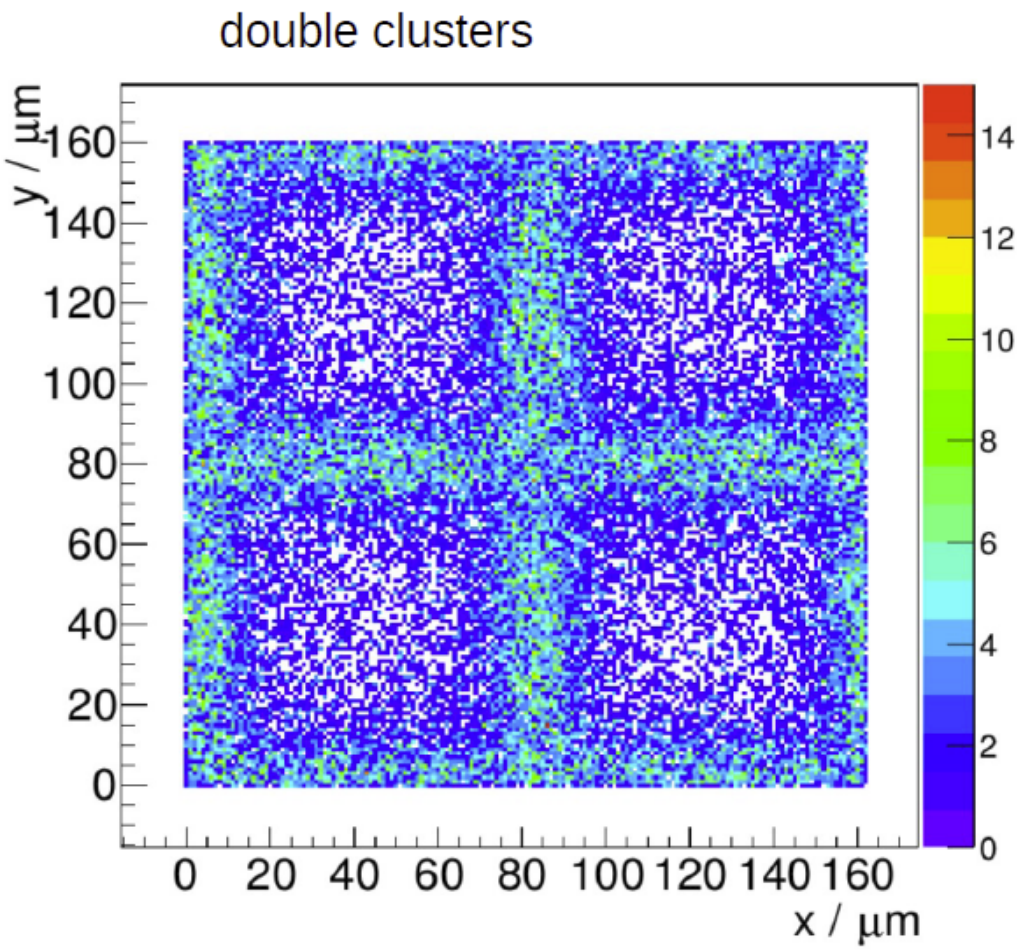




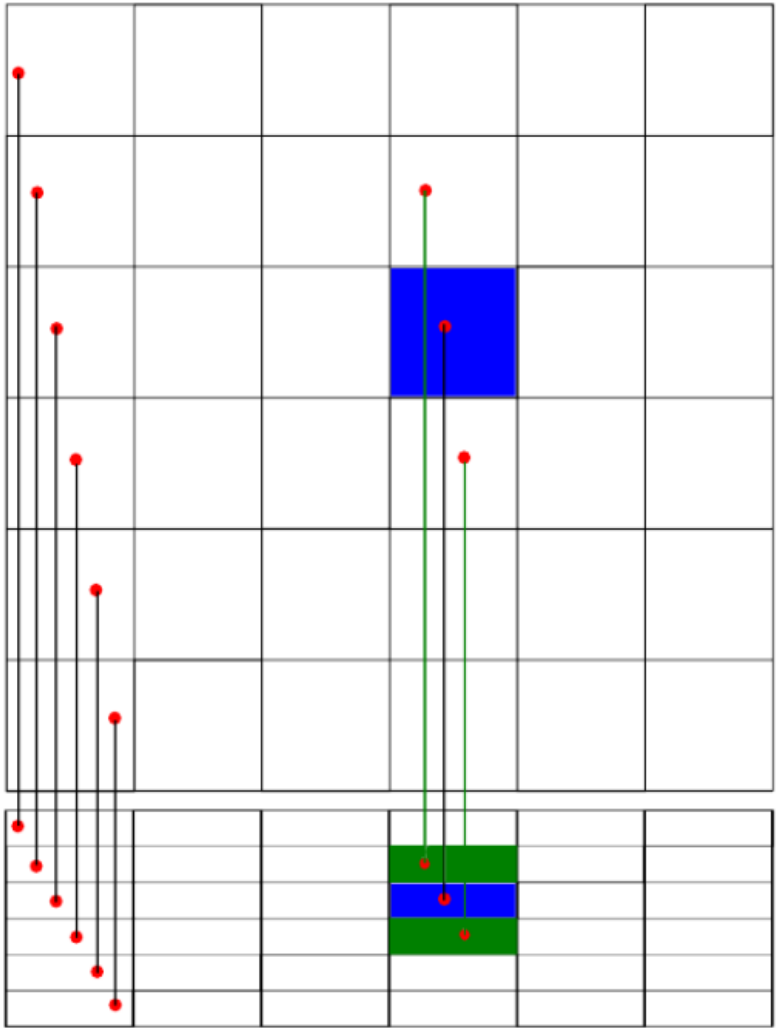
MuPix8 Performance

- Charge sharing only at pixel edges





Mupix/ATLASpix Readout Architecture



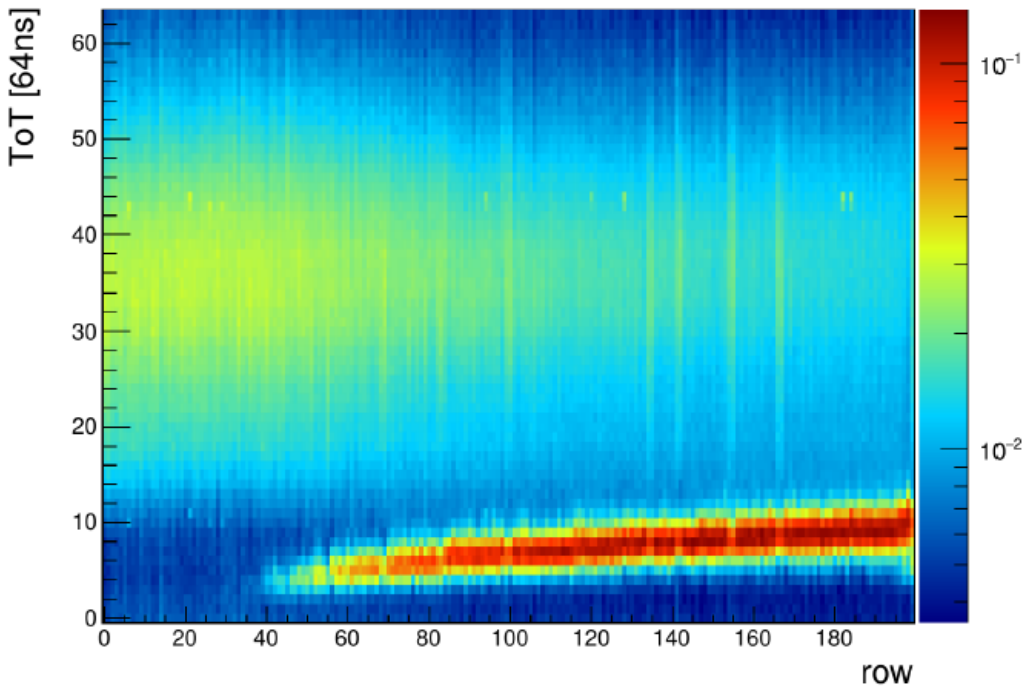
Problem:
→ capacitive coupling between RO lines

ATLASpix (discriminator in cell)
✔ binary(discriminated) RO

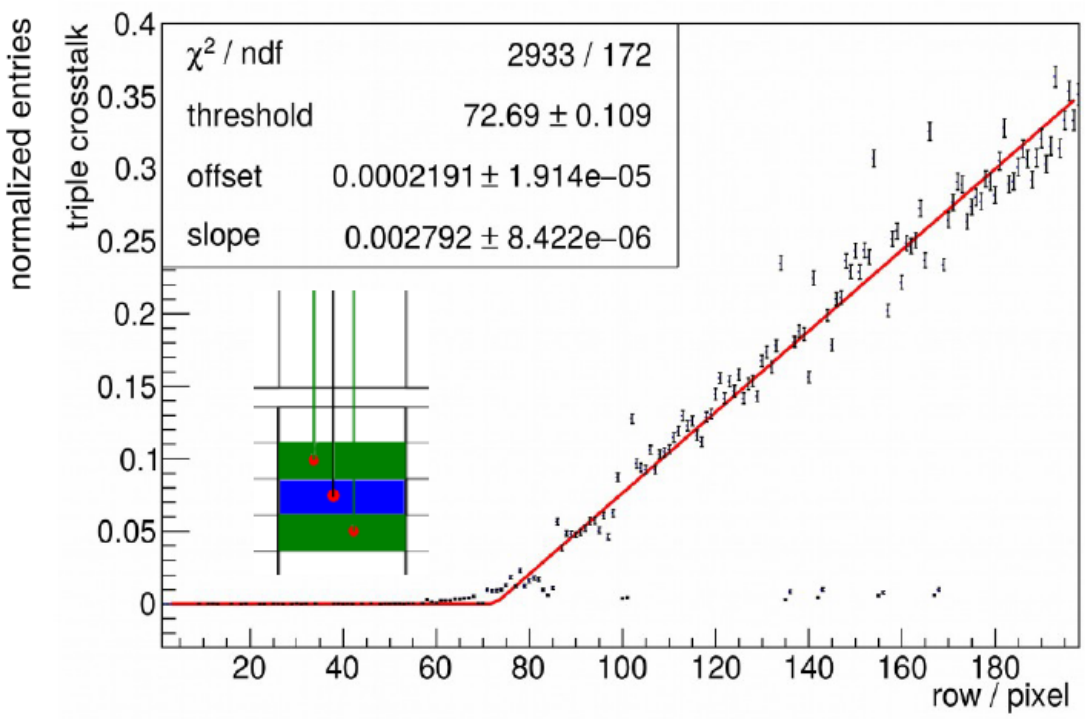
MuPix (analog amplified signal)
✗ source follower (A) → cross talk
✗ current driver (B+C) → in principle ok,
but design issues with Mupix8

Mupix8 Cross Talk (Source Follower)

Time over Threshold (dE/dx)



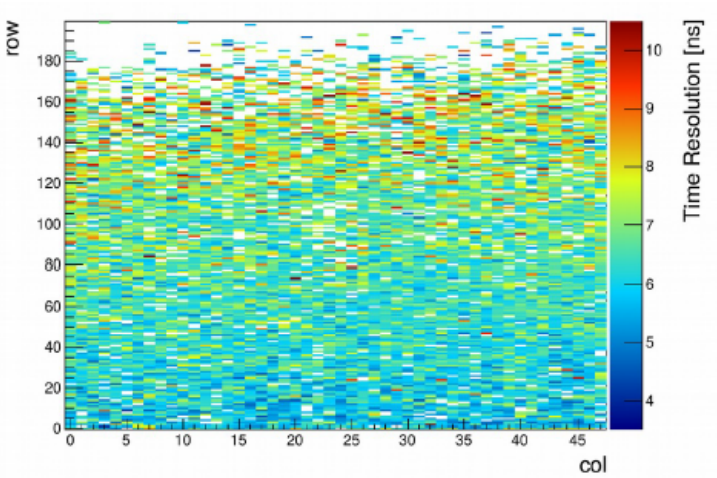
"Triplet" Probability



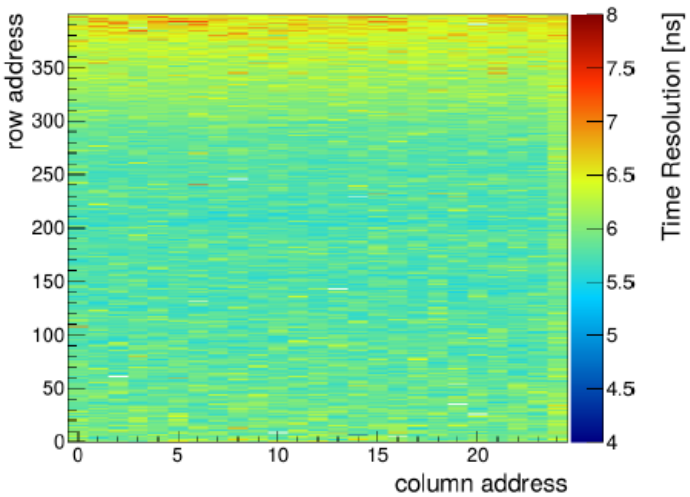
row number is proportional to length of trace!

Time Resolution with and w/o TWC

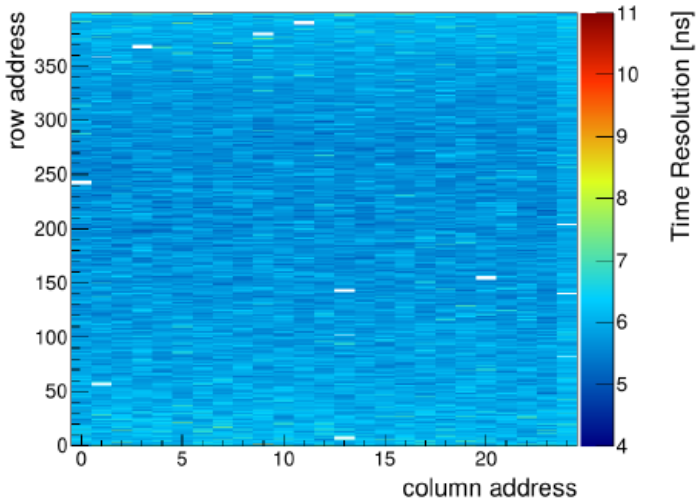
MuPix8



ATLASpix_simple
(NMOS comparator)



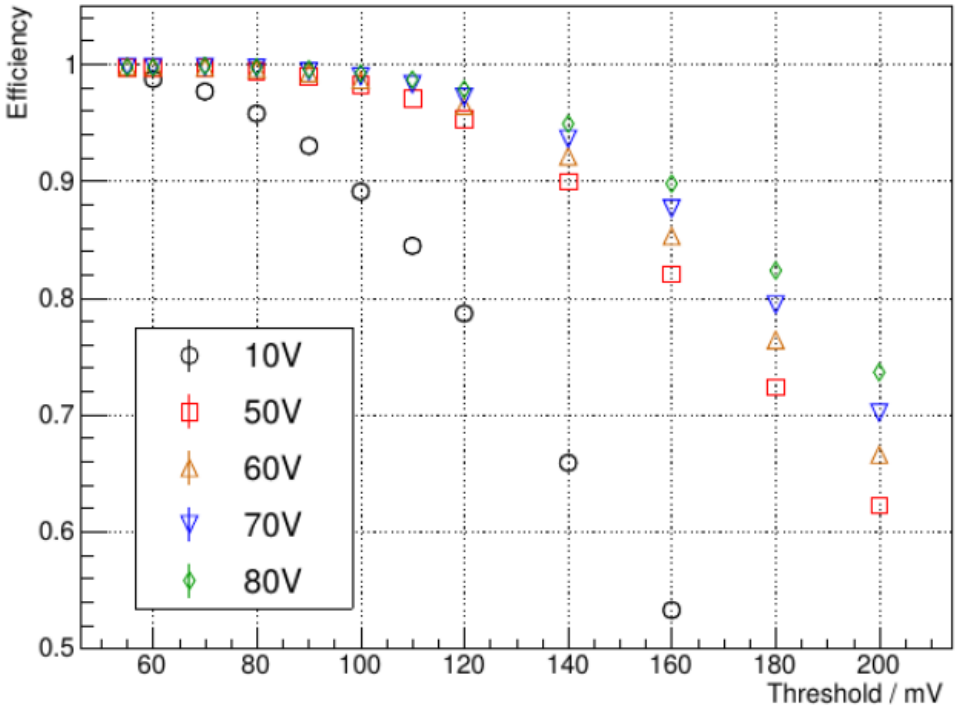
ATLASpix_simple_iso
(CMOS comparator)



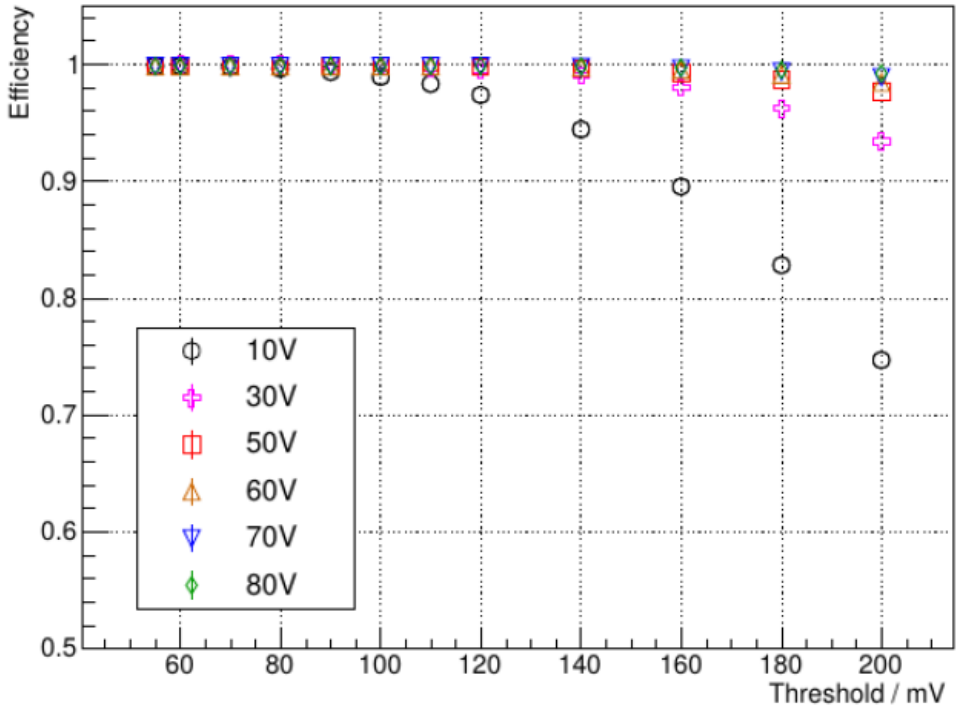
	MuPix8	ATLASpix_simple	ATLASpix_simple_iso
	[sampling 8 ns]	[sampling 16 ns]	[sampling 16 ns]
w/o TWC:	8.8 ns	8.1 ns	6.8 ns
with TWC:	6.5 ns (6.2 ns)	5.9 ns	5.8 ns
internal res.:	6.1 ns (5.8 ns) (short traces)	3.7 ns	3.6 ns

Substrate Resistivity Dependence ATLASpix1

80 Ω cm

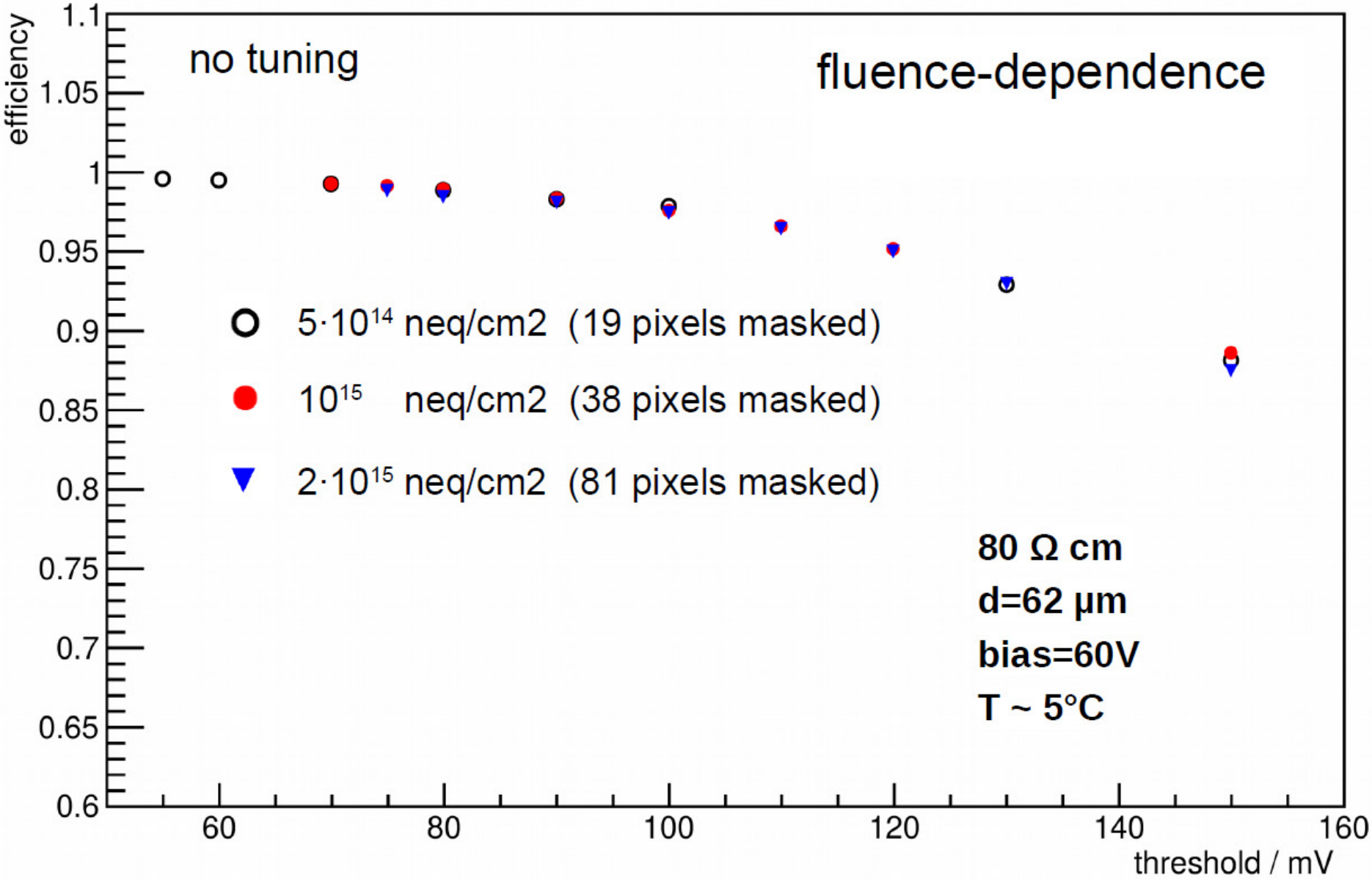


200 Ω cm



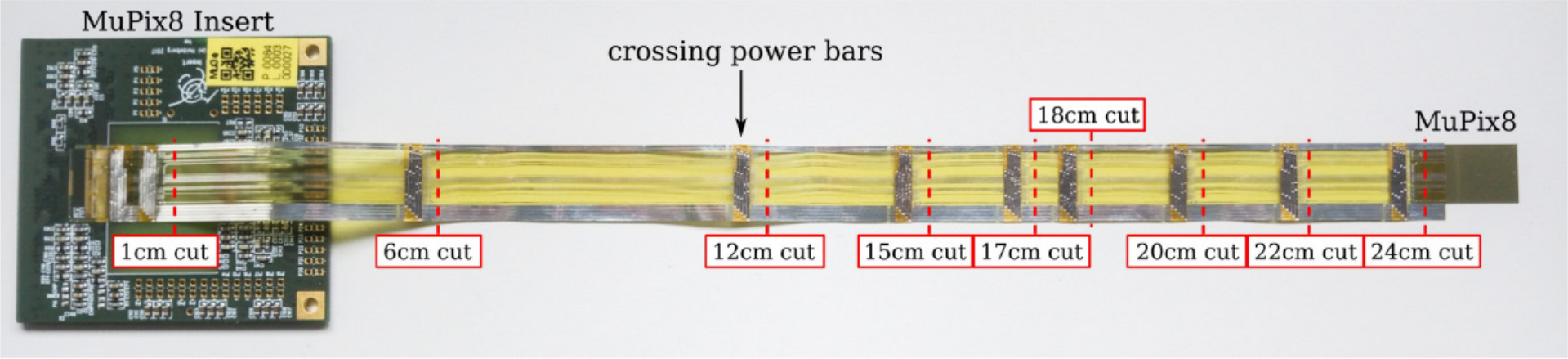
significant larger depletion with higher resistivity!

Neutron Irradiated 80 Ωcm ATLASpix1 @ 60V



Pixel Sensor Integration Highlight I

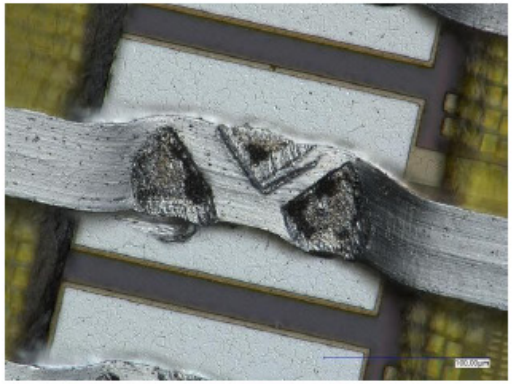
Mupix8 successfully operated on LTU flexprint!

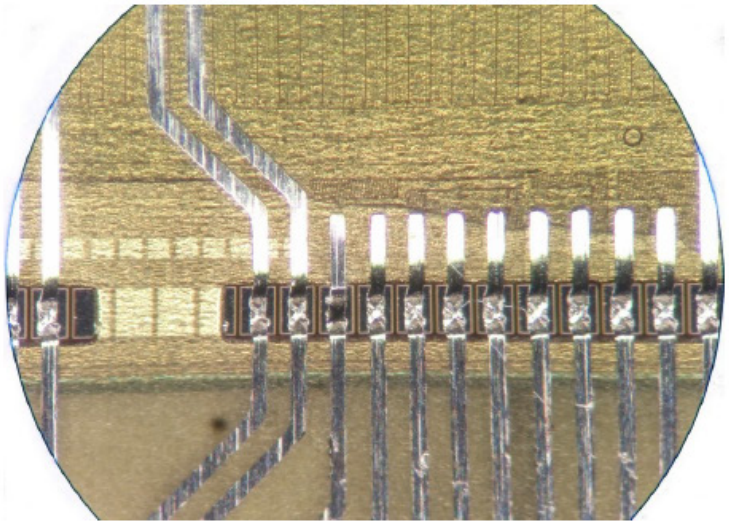


- no decoupling capacitors
- common VDD and VDDA supply

→ low noise

→ no LVDS bit errors



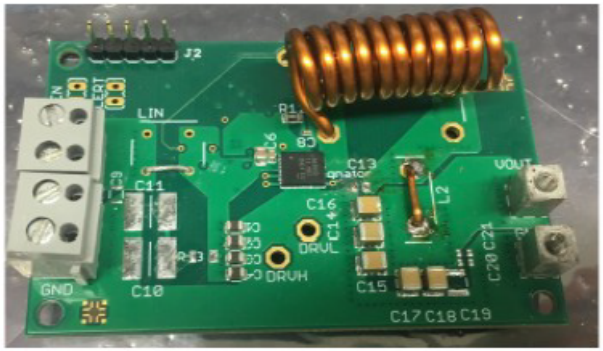


Slide by A. Schöning

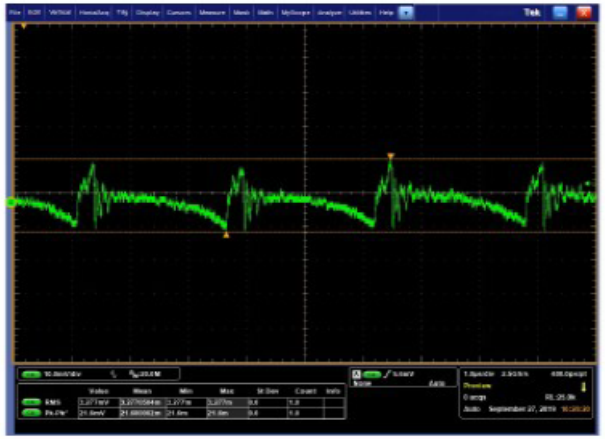
Pixel Sensor Integration Highlight II

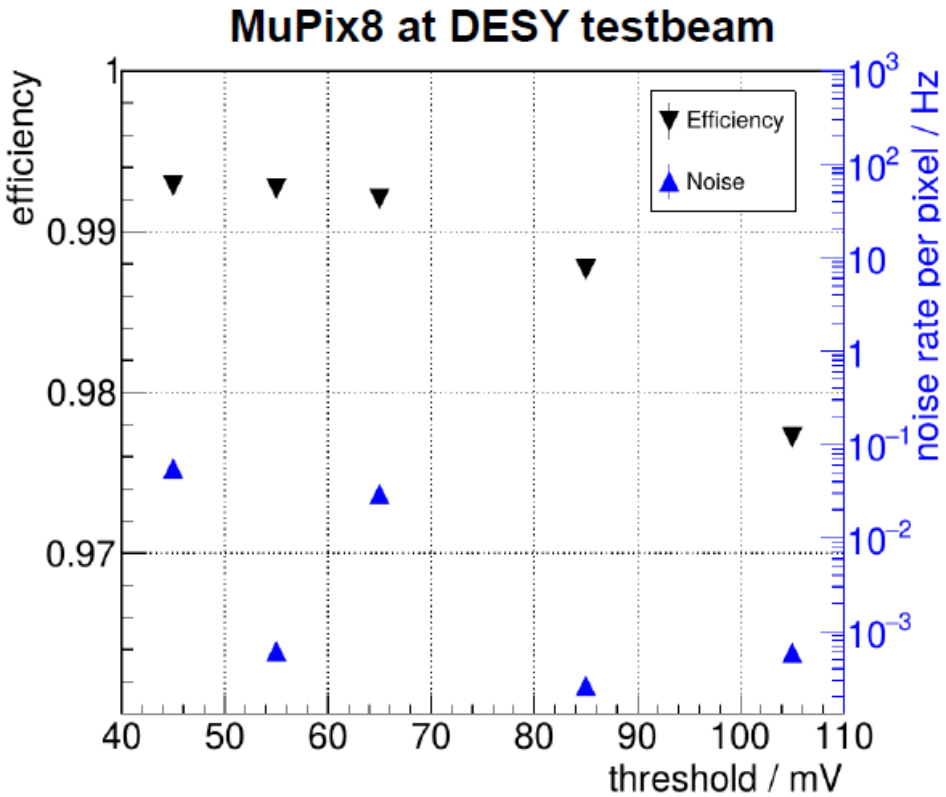
Mupix8 operated with DC/DC converters developed for Mu3e
w/o decoupling capacitors (common VDD and VDDA) → milestone!

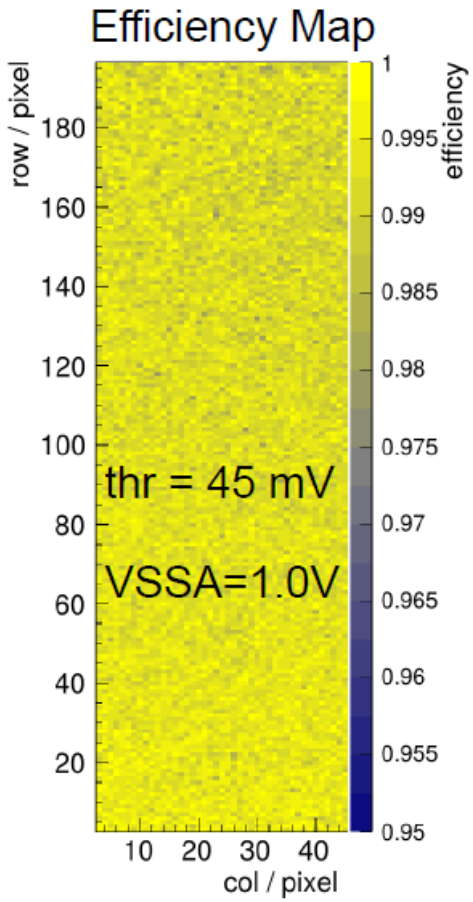
Expected for MuPix10: ~200 mW/cm^2



With filtering: 20 mV Pk-Pk



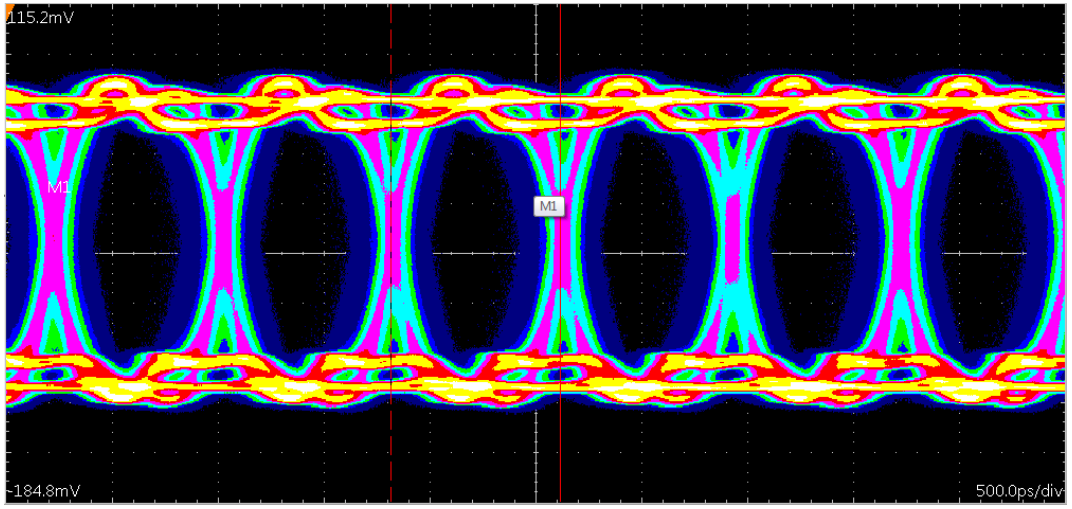


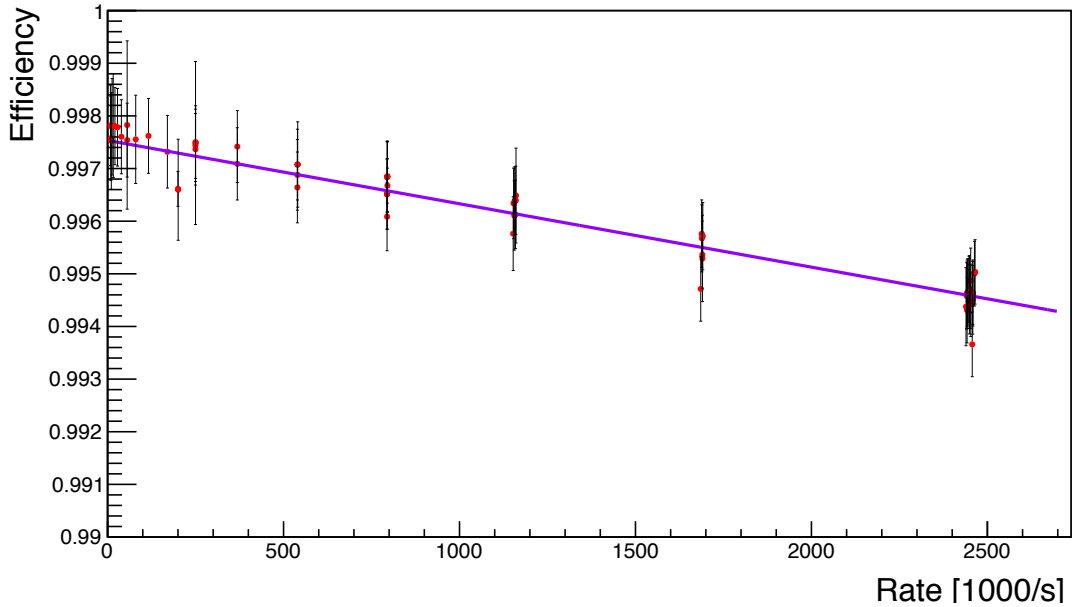


Slide by A. Schöning

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)

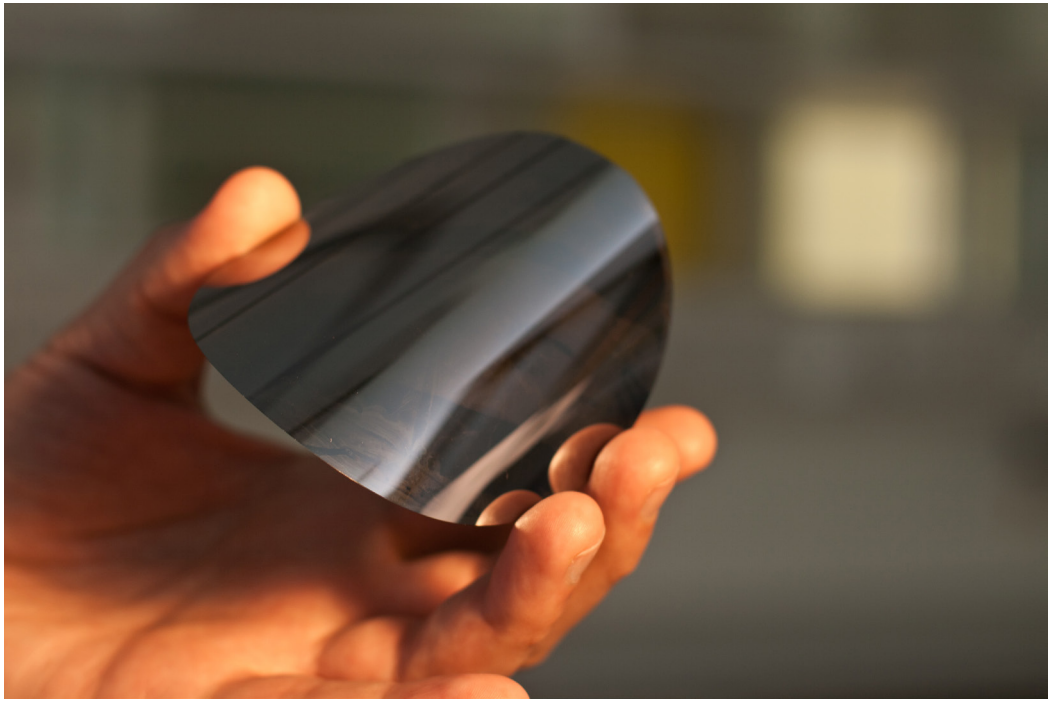




How to get to ~0.1 X_0 per layer

50 µm silicon is not self-supporting

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



Chips are active: ~ 200 mW/cm^2

- Need "no-mass" cooling
- Gaseous helium at very high flow speeds for Mu3e - challenging project
- Prototype tests so far successful, full mock-up under construction

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

Questions:

- How much sensor area is needed?
- Can we operate the sensors in a cooling gas?
- How much access do we have for services?
- FPGAs in magnet? DC/DC in magnet?
- Do the pixels have to generate an injection trigger?
  (short latency?)

More questions:

- How to control for up/down differences in efficiency?
- How to align the sensors without calibrating away an EDM? Track-based alignment? Optical system? What are possible weak modes?

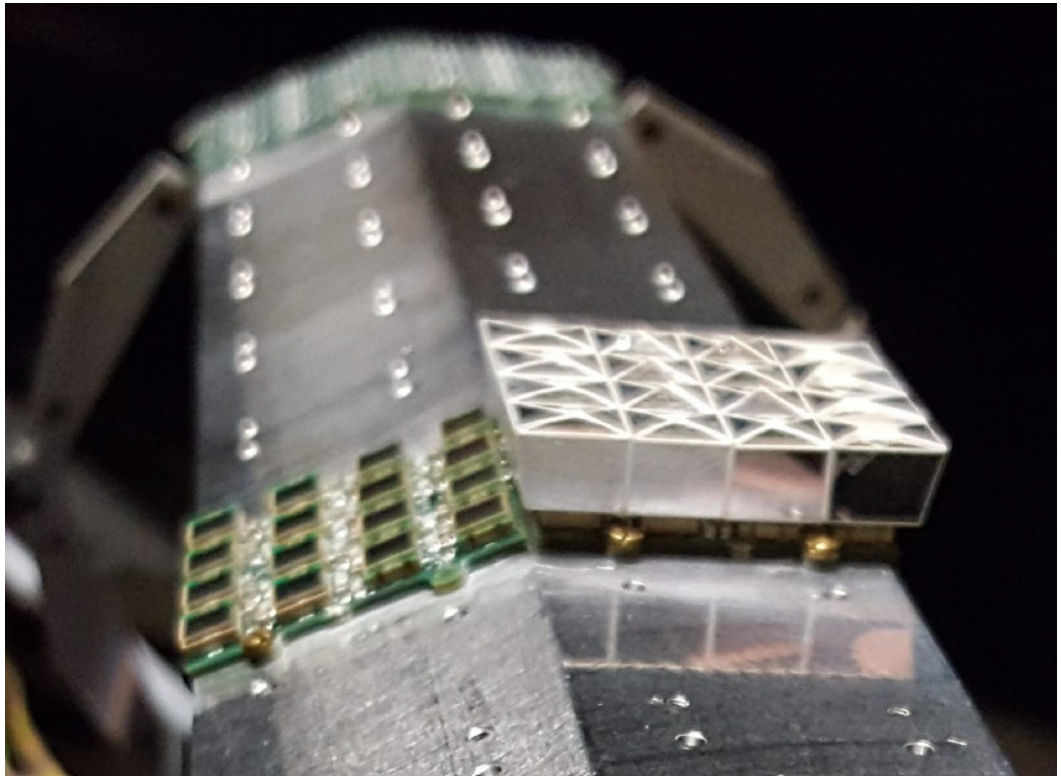
Data Acquisition
(the Mu3e Example)

MuPix output

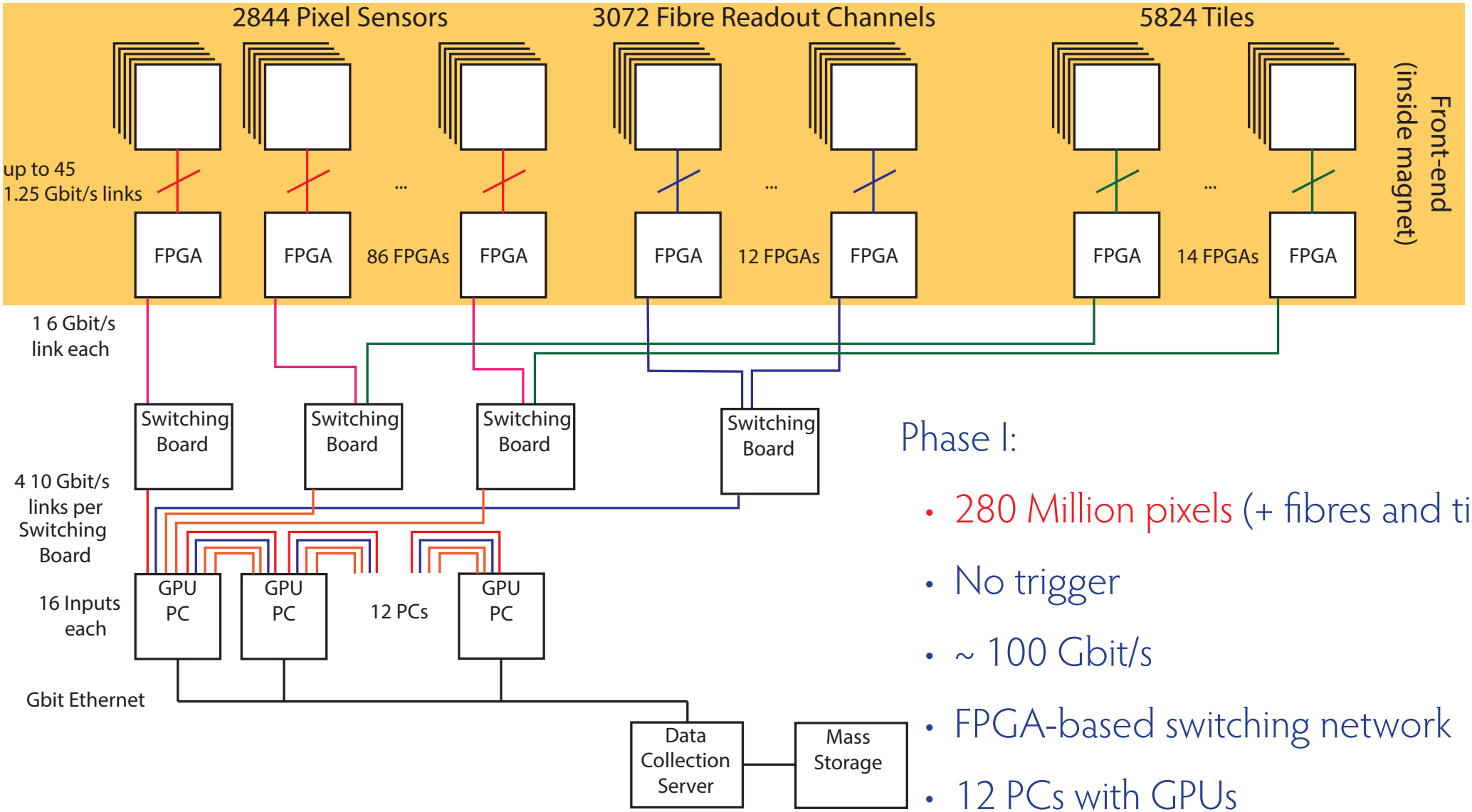
- 1.25 Gbit/s 8b10b encoded LVDS links
- Either three submatrices with a link each
  or
  one link multiplexing the sub-matrices
- Roughly 30 MHits/s per link maximum
- Hits are 32 bit: column, row, time, charge
- Hits are not strictly time sorted on link

Timing detectors

- Mu3e also has scintillating fibres and tiles for improved timing
- SiPMs read out via a custom ASIC, the MuTrig (KIP Heidelberg)
- Output also 1.25 GBit/s LVDS link
- Allows for very uniform DAQ



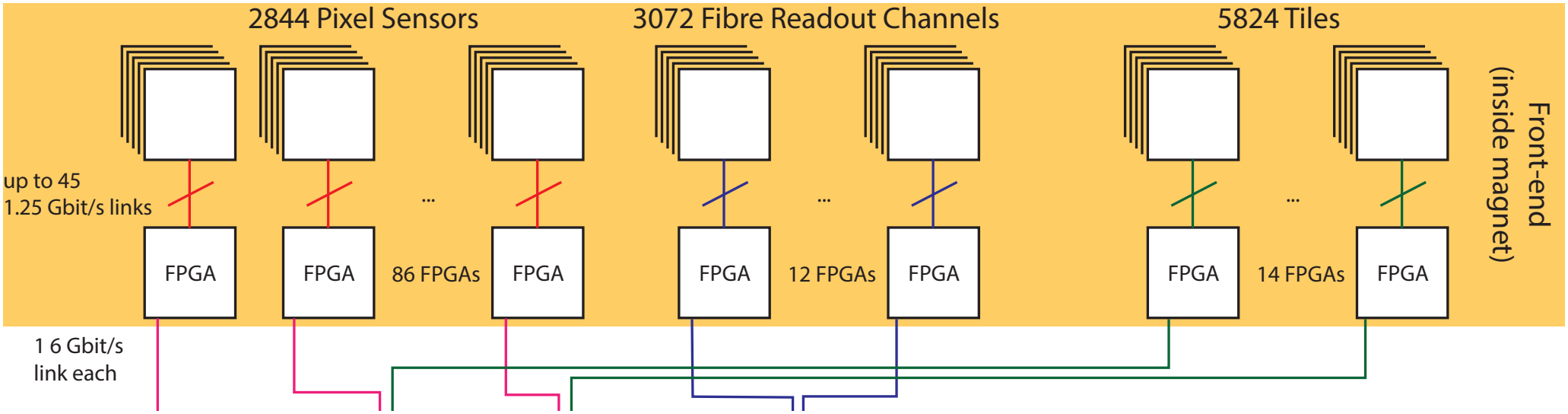
Data Acquisition

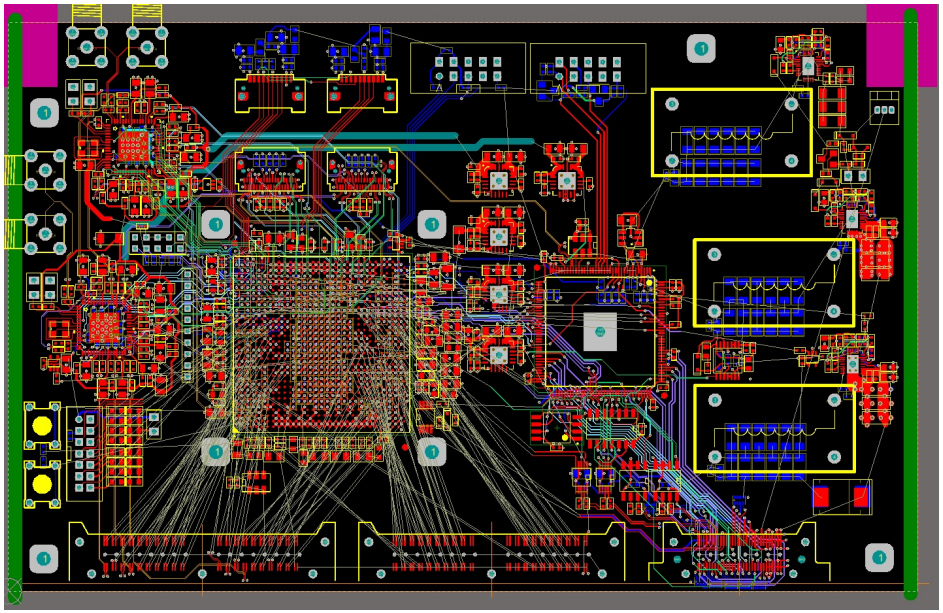


Phase I:

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

Data Acquisition

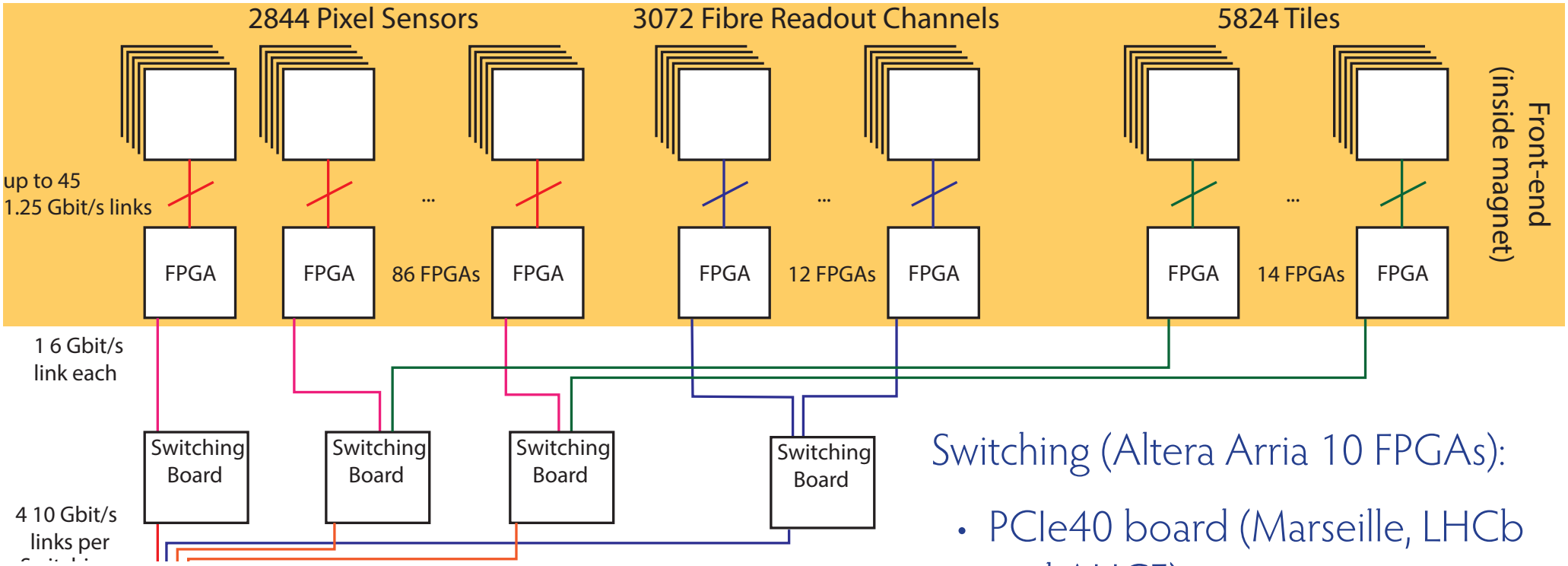


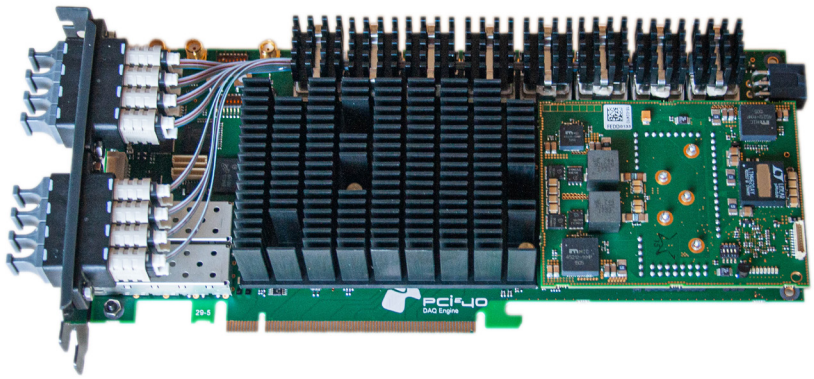


Front end (Altera Arria V FPGAs):

- 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

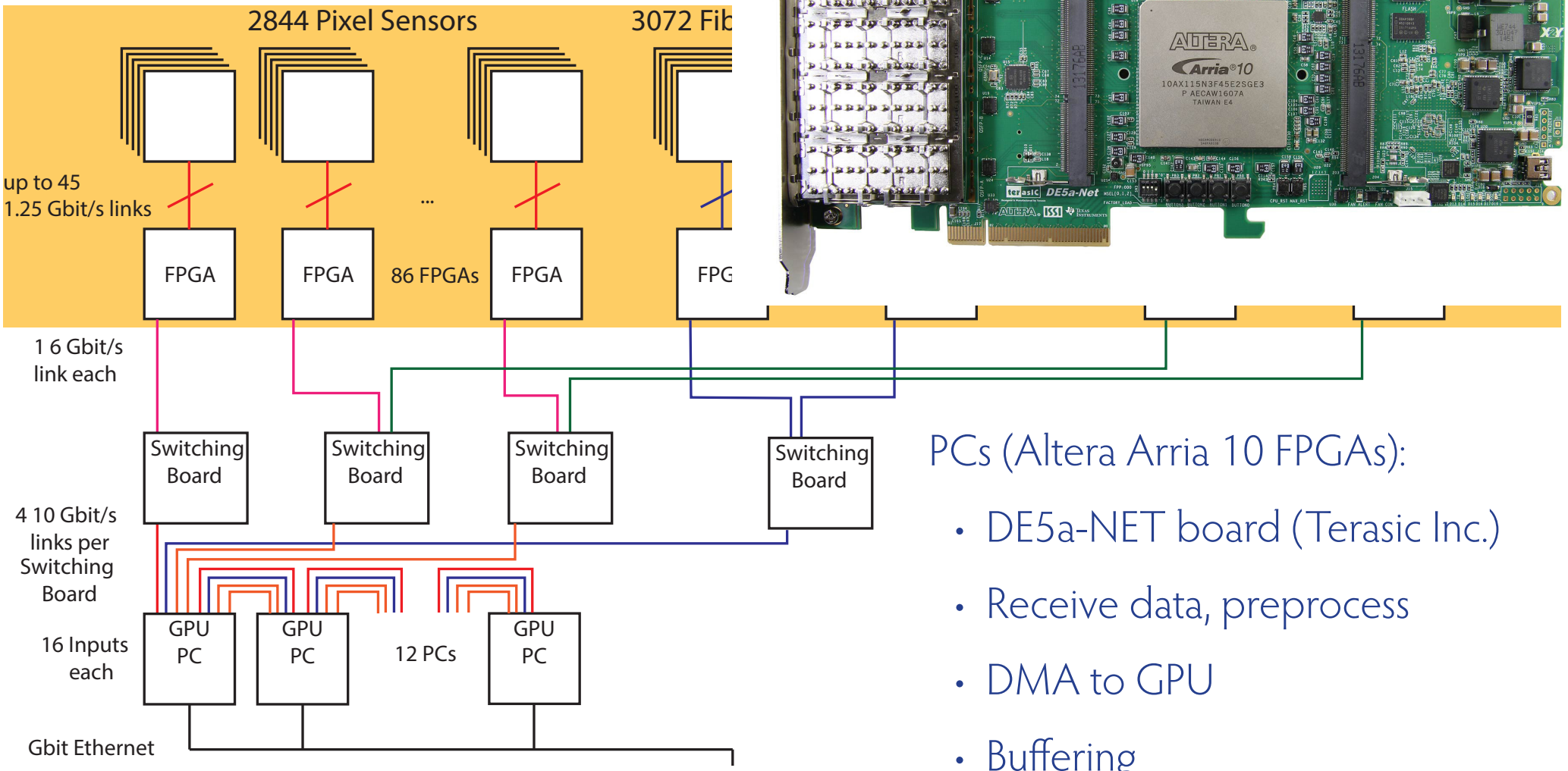




Switching (Altera Arria 10 FPGAs):

- 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
- MIDAS software (S. Ritt & Co.) for data and slow control handling

Some things we like

- LVDS links to FPGAs on detector, everything else optical
  (galvanic decoupling, no cross-talk, space-efficient, commercial components)
- PCIe as the interface between custom and PC logic
  (fast, operating system support, have our own well-debugged firmware and drivers)
- Using commercial FPGA evaluation boards wherever possible
  (cheap, well debugged)
- GPUs allow for handling very large reconstruction loads on a budget

Final Questions

- Momentum resolution/redundancy trade-off?
- Can we cool sensors in the active volume? (how much? vacuum or gas?)
- What is limiting the result? Momentum? Timing? Efficiency? What does this mean for the sensor?
- What are the challenges for the DAQ?
- Are there ideas on how to go beyond single muons at a time?