A HV-MAPS Pixel Tracker for the Mu3e Experiment

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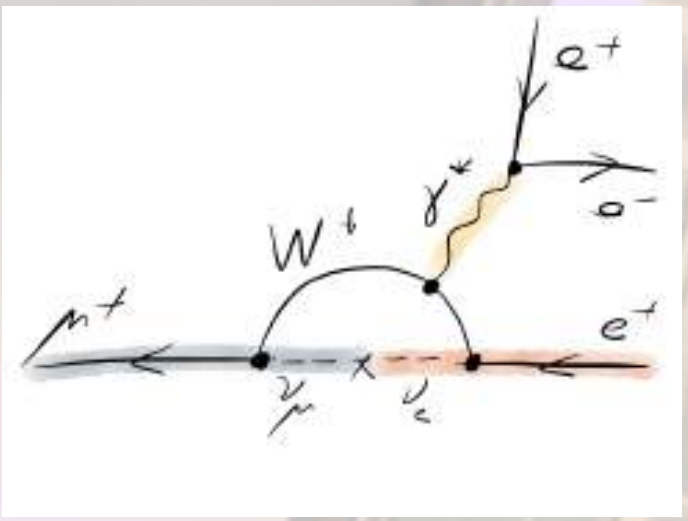
Physikalisches Institut Heidelberg

DPG Spring Meeting
T72.1
02. March 2016

Mu3e

The Physics Goal



- $\mu^+ \rightarrow e^+e^-e^+$ suppressed to a BR below 10^{-54} in the Standard Model
- Any observed signal is a sign for new physics
- Current limit BR $< 10^{-12}$ (SINDRUM)
- Aiming for sensitivity of 1 in 10^{16} decays

SINDRUM: "Search for the decay muto3e" Nucl. Phys.,B299 1, 1988

Mu3e

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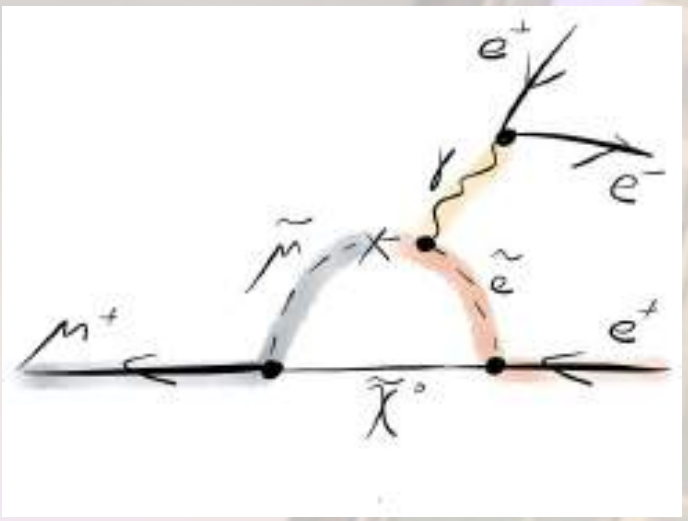

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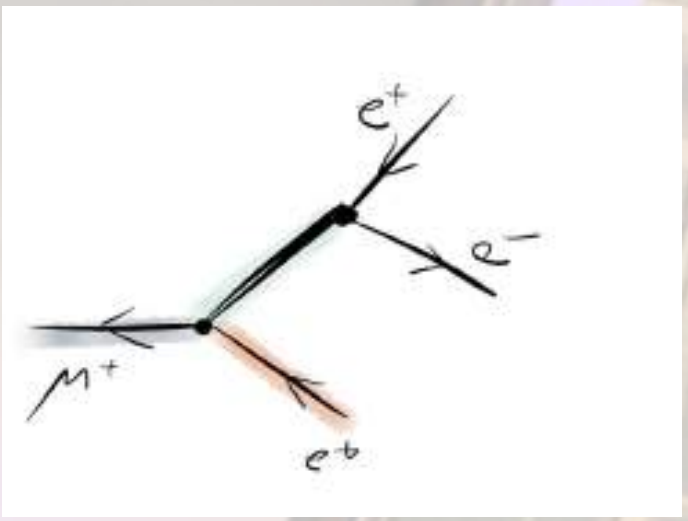

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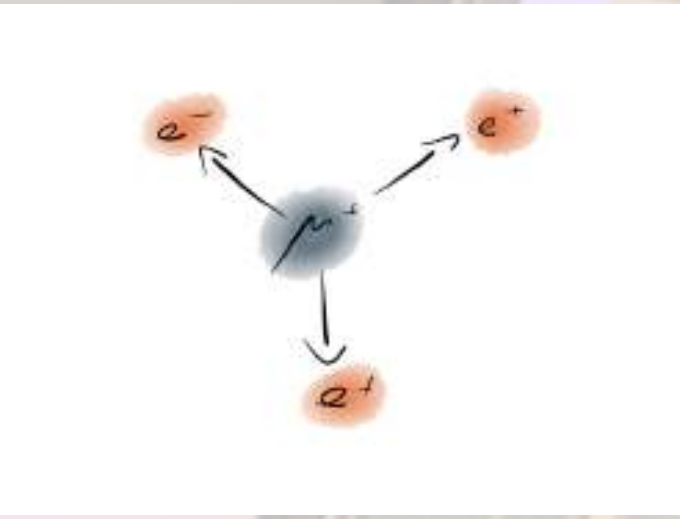
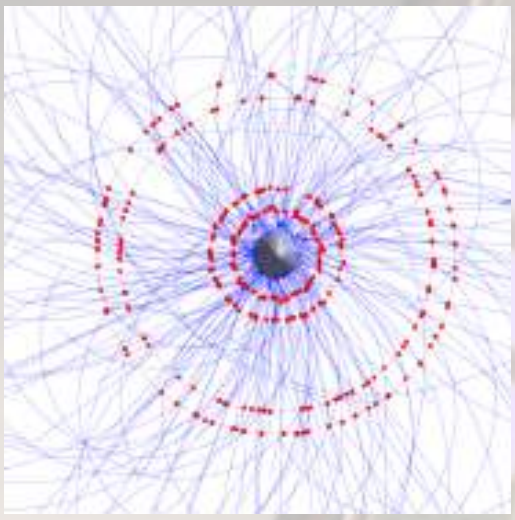
The Signal Decay

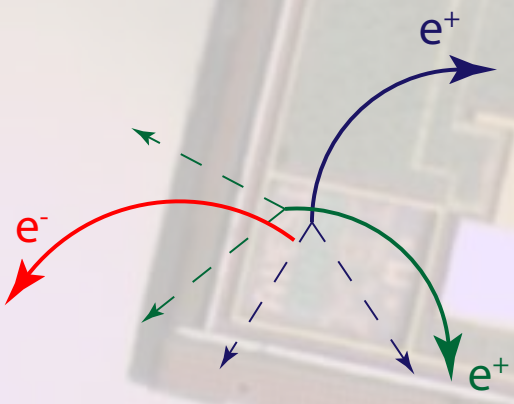


- Muons decay at rest: $\Sigma\vec{p} = 0$
- Common vertex and coincident in time
- Maximal momentum 53 MeV/c
- Reconstruct invariant mass from charged particle tracks ($E_{tot} = m_\mu$)

The Background

Accidental & Combinatorial

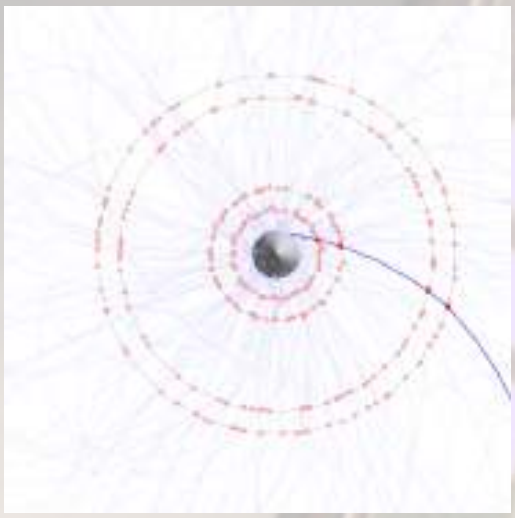


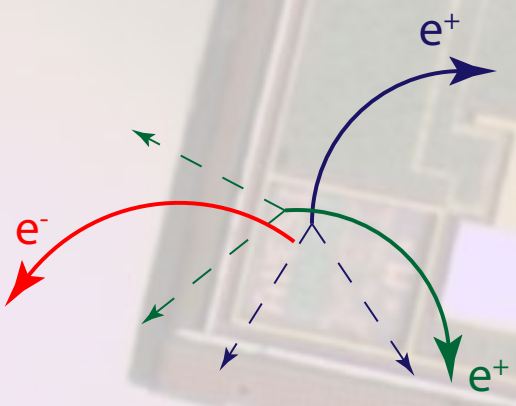


- 10^9 decays per second
- Gives rise to accidental & combinatorial background
- Good time and vertex resolution needed

The Background

Accidental & Combinatorial





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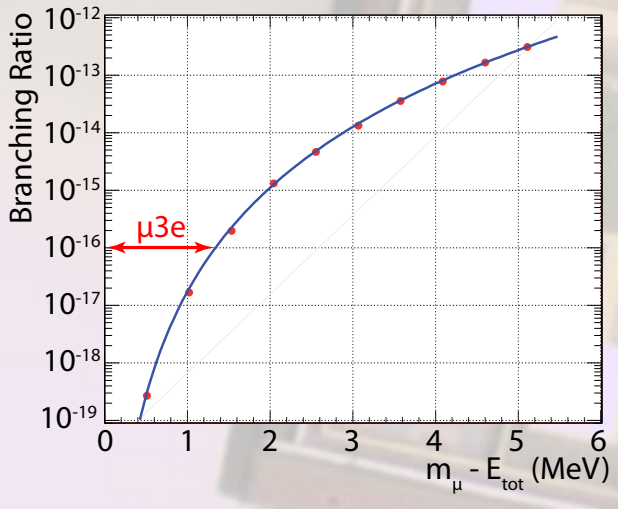
The Background

Irreducible



R.M.Djilkibaev and R.V.Konoplich, Phys.Rev., D79 073004, 2009

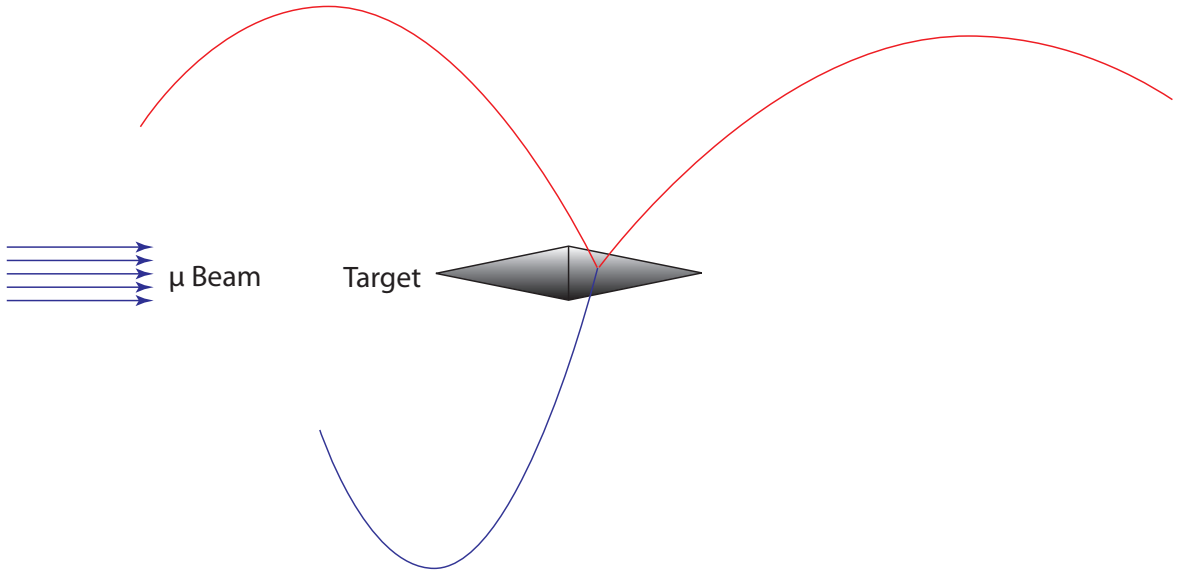
- Irreducible background from radiative decays with internal conversion: $\mu^+ \rightarrow e^+e^-e^+\bar{\nu}_\mu\nu_e$
- Good momentum resolution needed to suppress SM background
- Momentum resolution is dominated by multiple scattering $\propto \sqrt{x}/p$

The Detector

1T magnetic field

The Detector

1T magnetic field



The Detector

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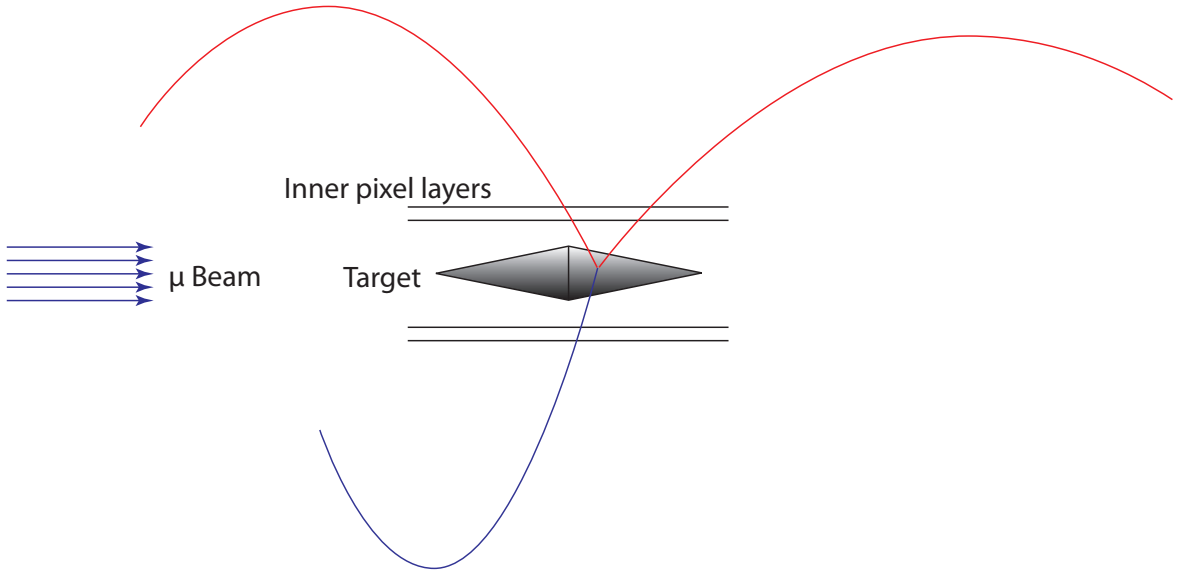

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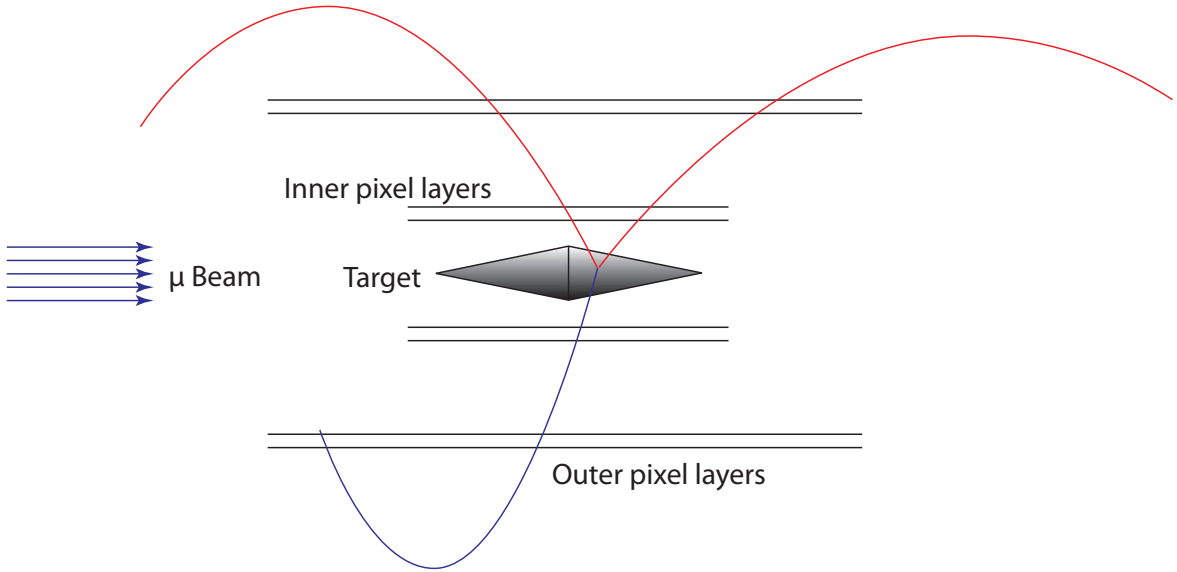

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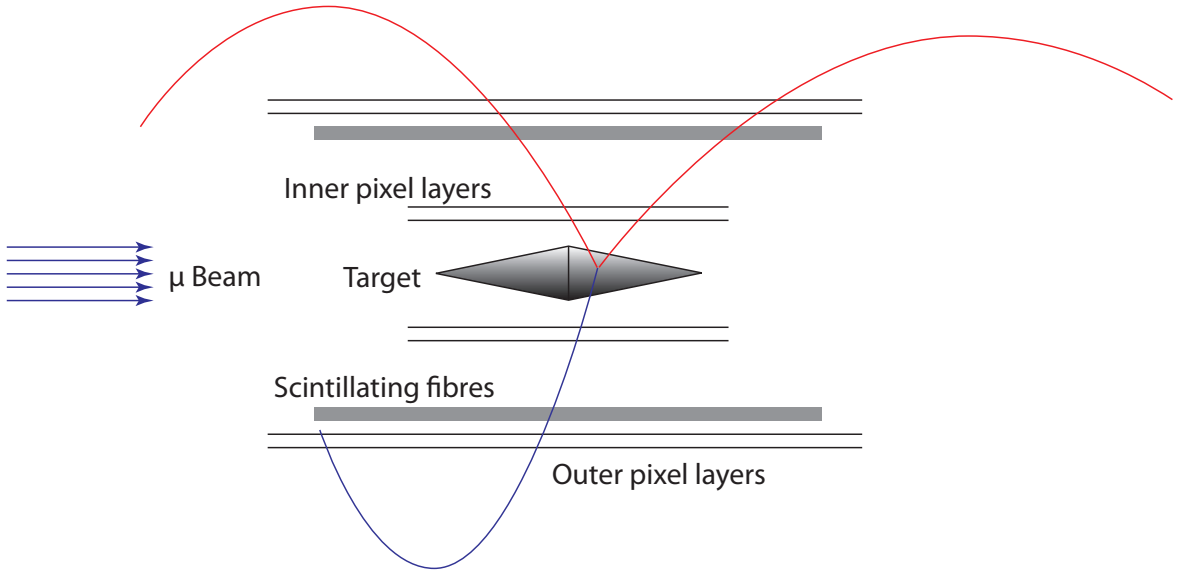
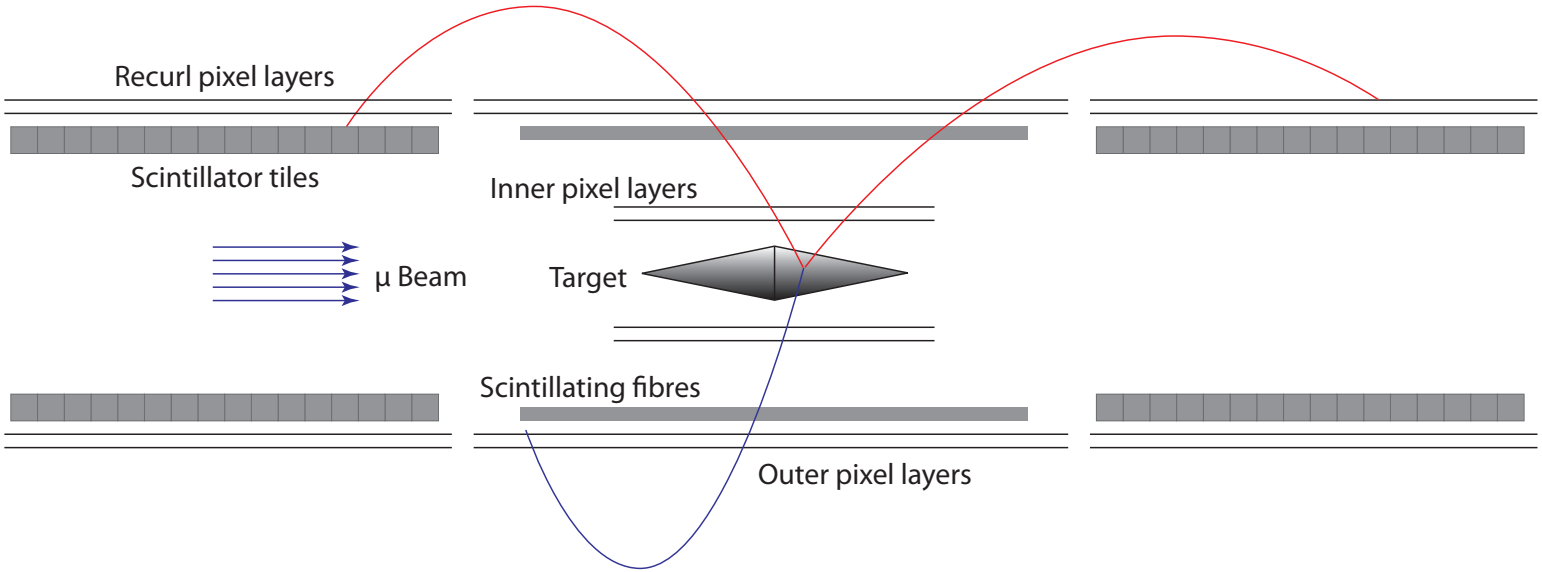
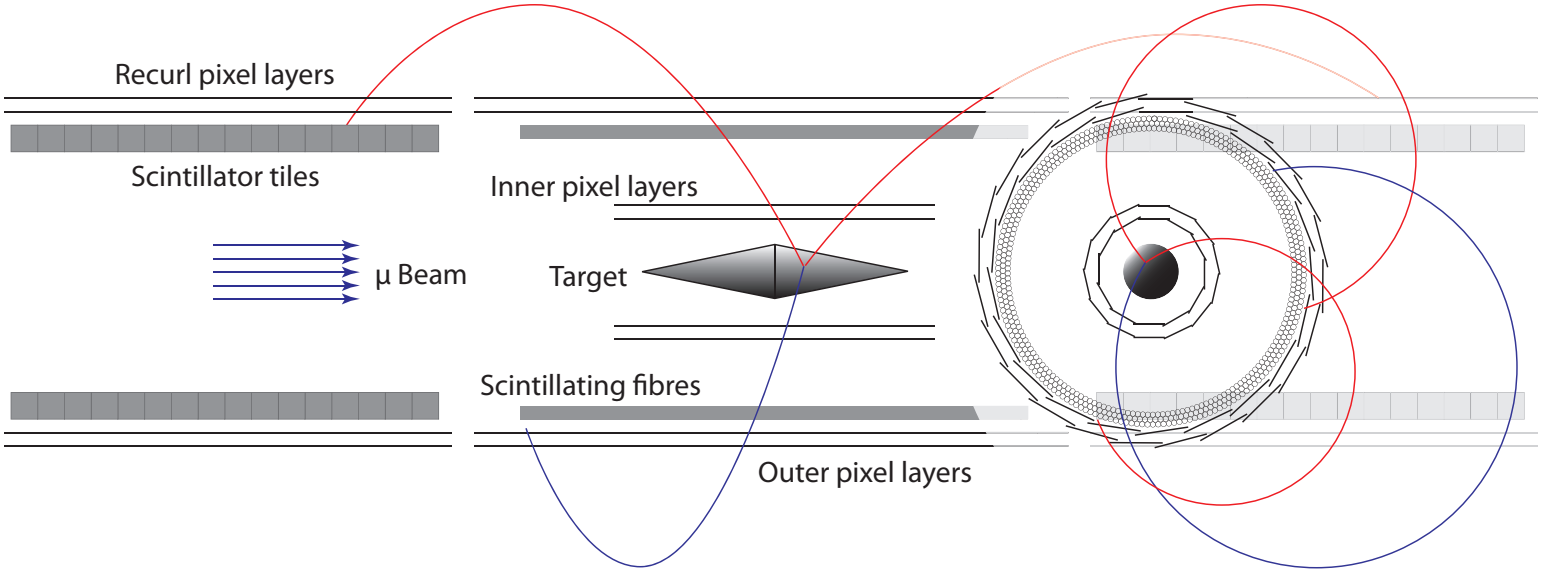


The Detector

1T magnetic field



The Requirements for the Silicon Pixel Tracker



- Good vertex resolution
- Good time resolution & low dead time
  $\rightarrow$ fast signal generation & shaping
- Good momentum resolution $\rightarrow$ low material budget

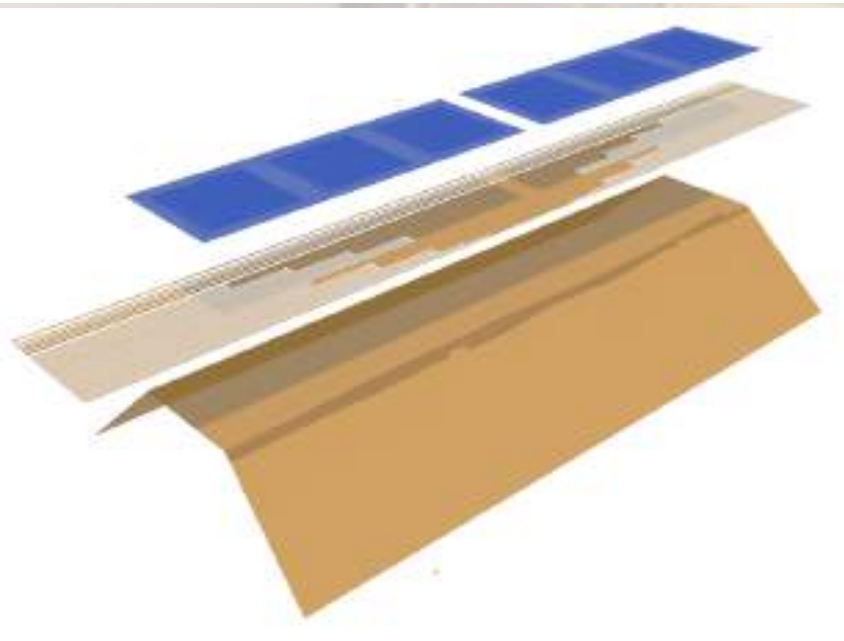
The Requirements for the Silicon Pixel Tracker

Pixel Sensor Requirements

Pixel Size	Time Resolution	Material Budget	Efficiency
$80 \times 80\,\mu m^2$	$< 20\,ns$	$< 1\,‰\ X_0$/layer	$> 99\%$

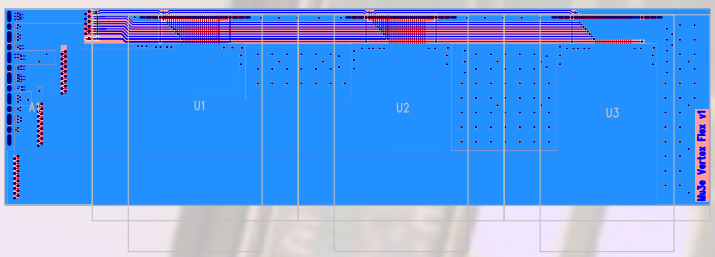
- Good vertex resolution
- Good time resolution & low dead time
  $\rightarrow$ fast signal generation & shaping
- Good momentum resolution $\rightarrow$ low material budget

The Pixel Tracker



- Readout & Powering via Flexprints: T42.7
- Cooling in Helium atmosphere: T75.2

The Pixel Tracker



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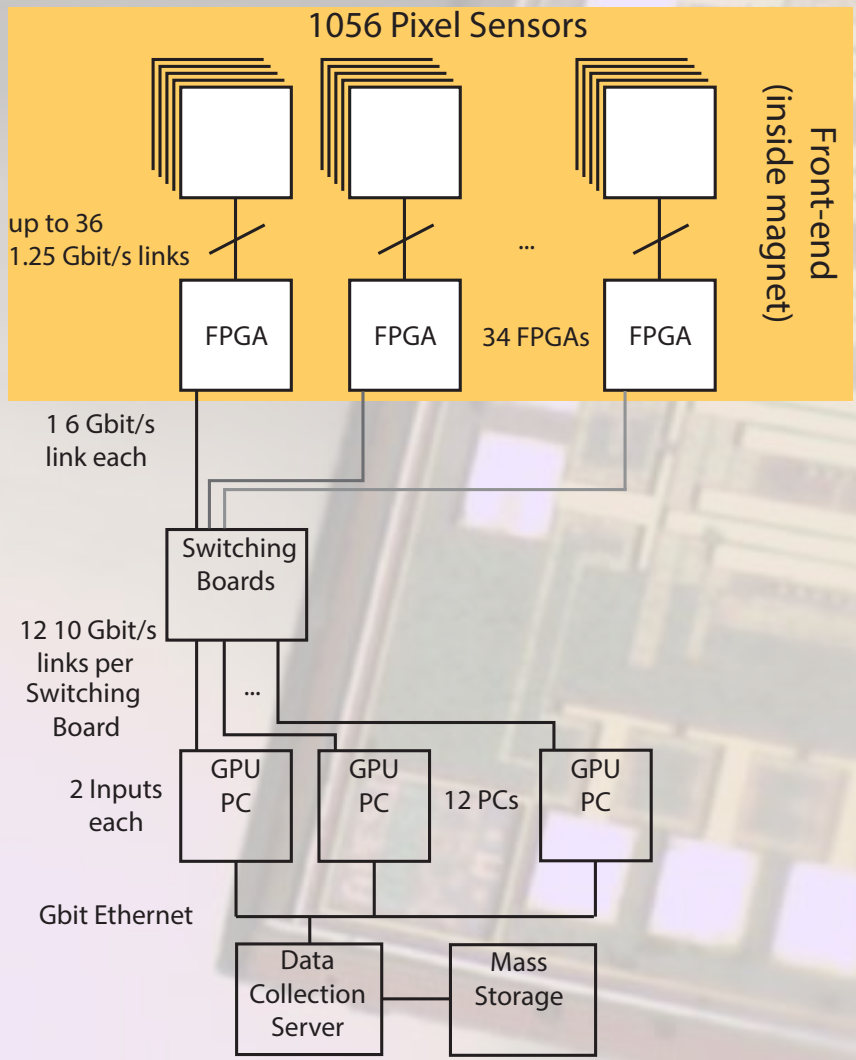
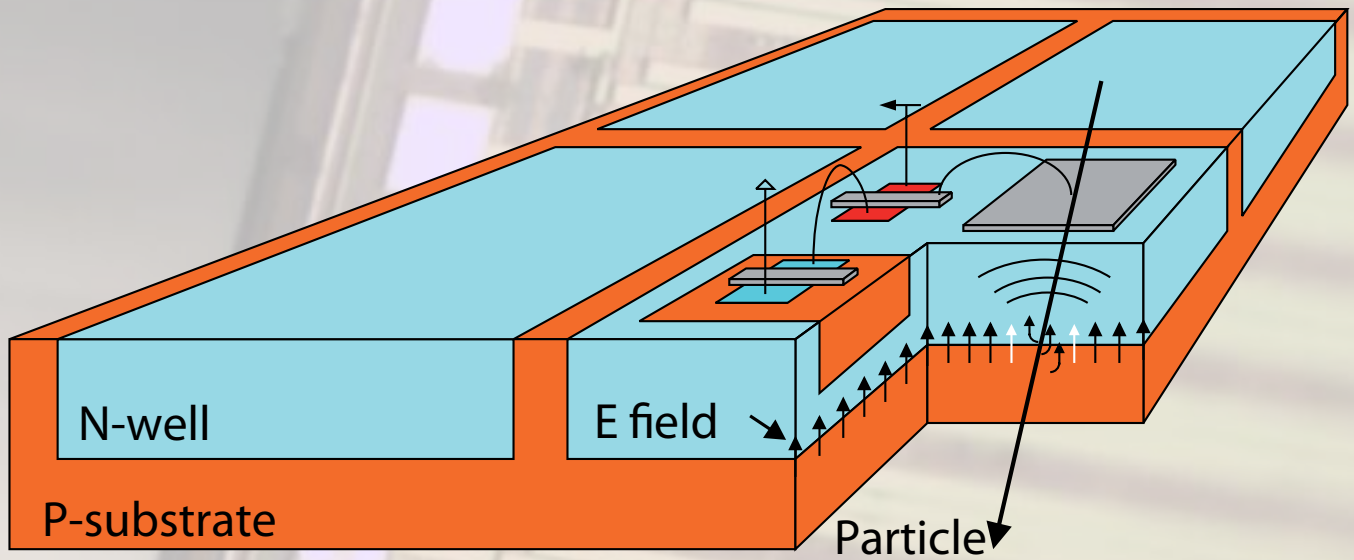
The Pixel Tracker

Readout



- Untriggered readout
- 1 Tbit/s raw data rate
- GPU based online reconstruction
- Sessions:
  T42.5, T42.6, T22.5, T22.4, T98.1, T98.5

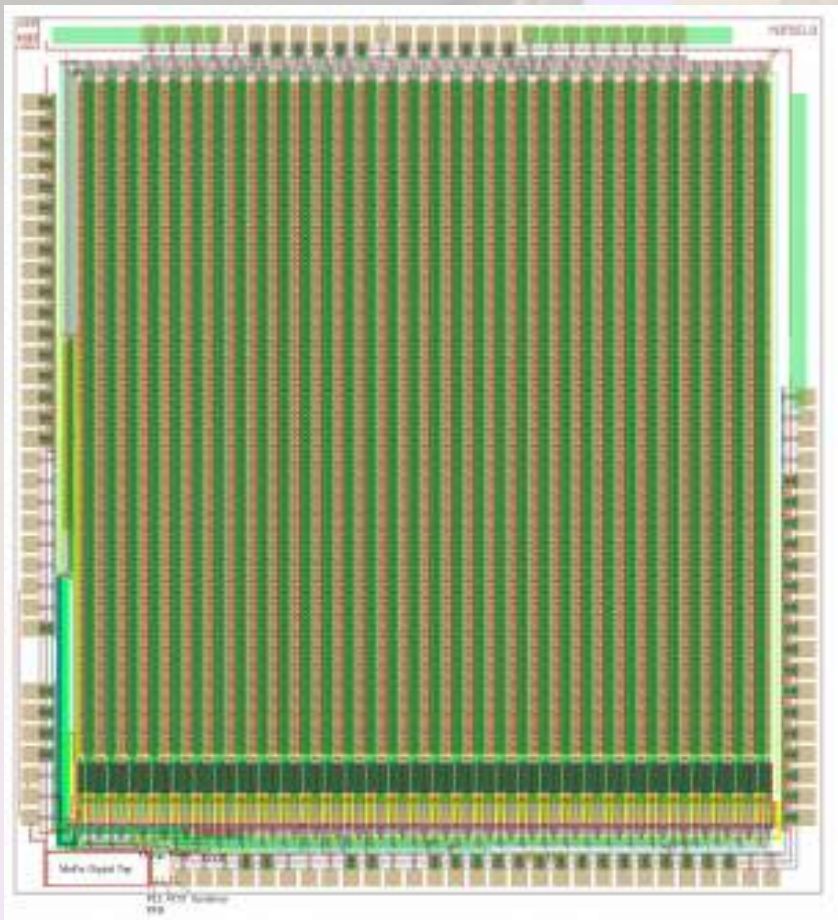
High Voltage Monolithic Active Pixel Sensors



I.Peric, P. Fischer et al., NIM A 582 (2007) 87

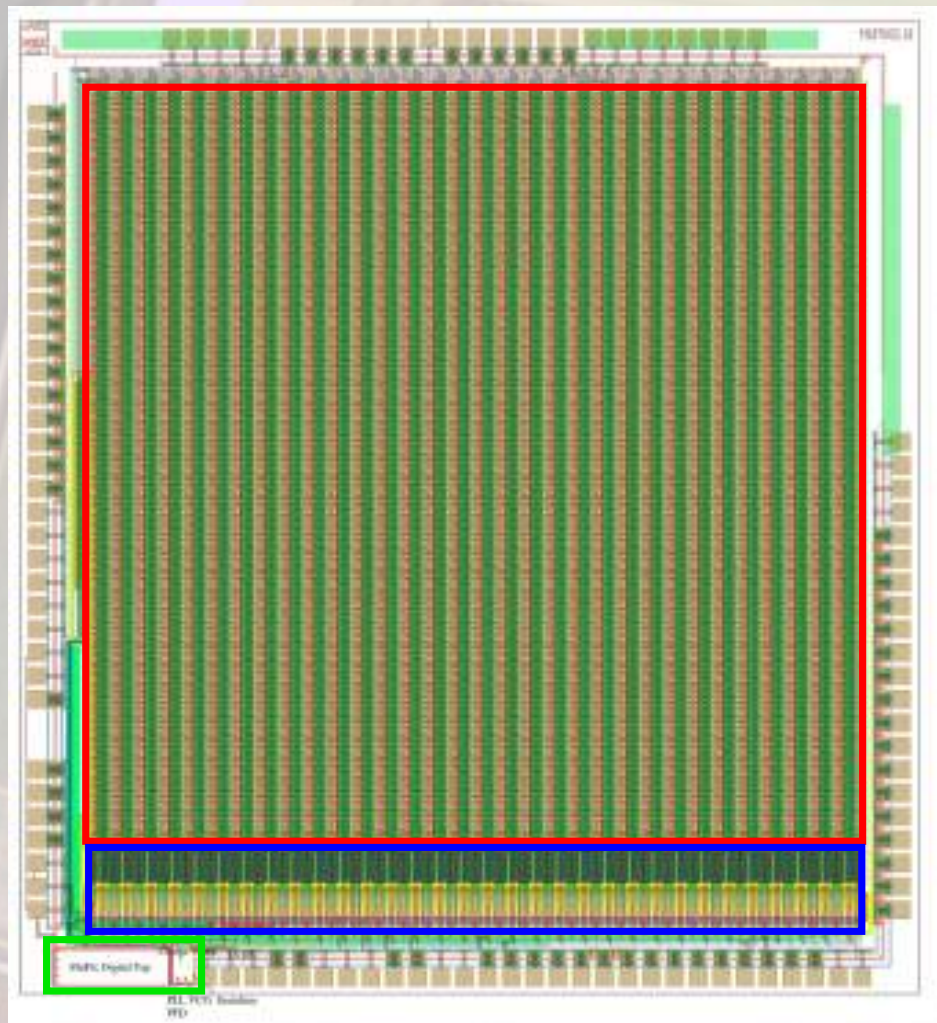
- Deep n-well in p-doped substrate
- Depleted area is the active detector volume $\approx 15\,\mu m$
- Fast charge collection via drift
- Sensor can be thinned to $< 50\,\mu m$

The MuPix7 Prototype



- Commercial 180 nm HV-CMOS process
- Thinned to 50 µm

The MuPix7 Prototype



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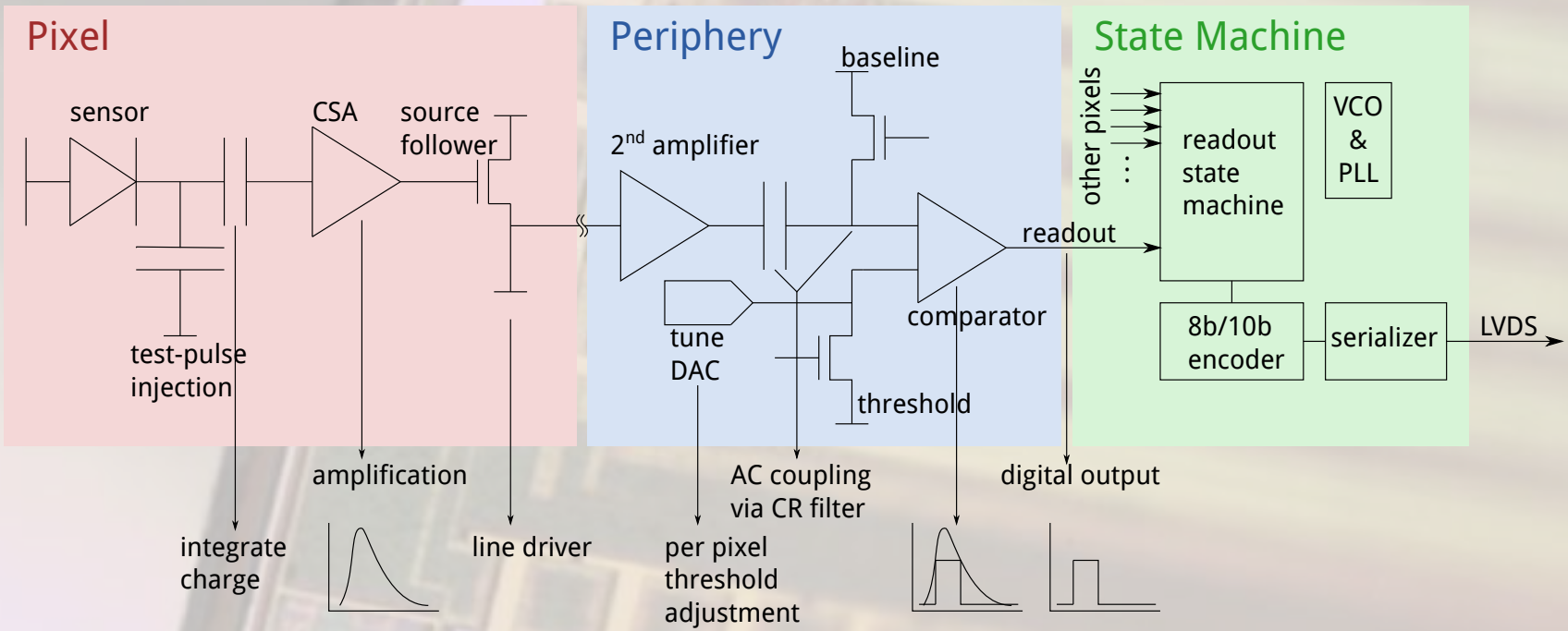
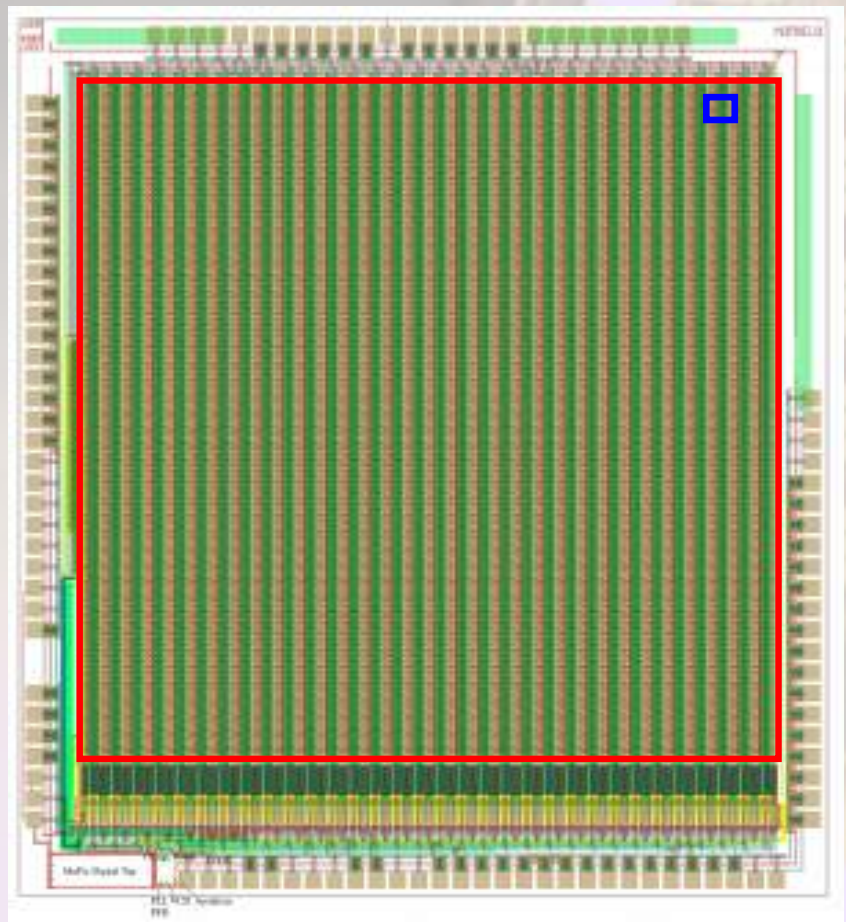
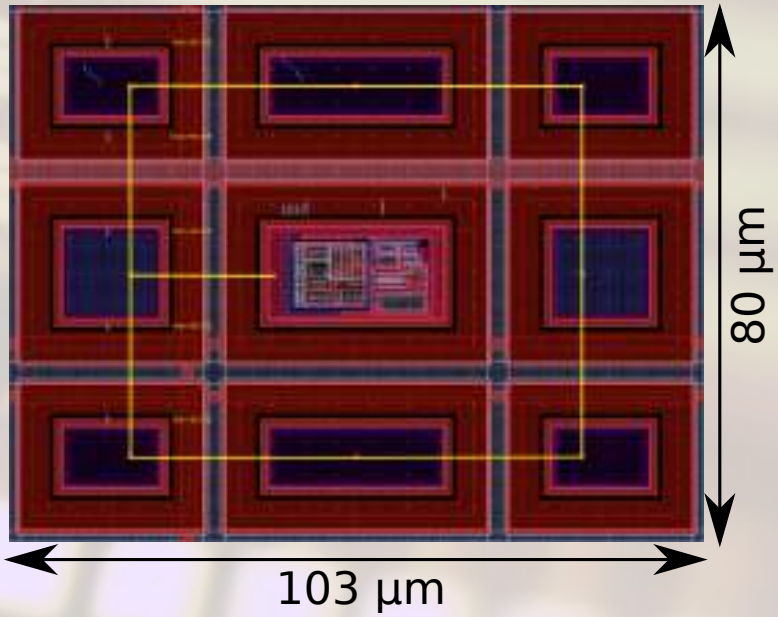


The Pixel



- $3.2 \times 3.2\,\mathrm{mm}^2$ active area
- 32×40 pixels
- 3×3 diode structure
- In-pixel amplifier



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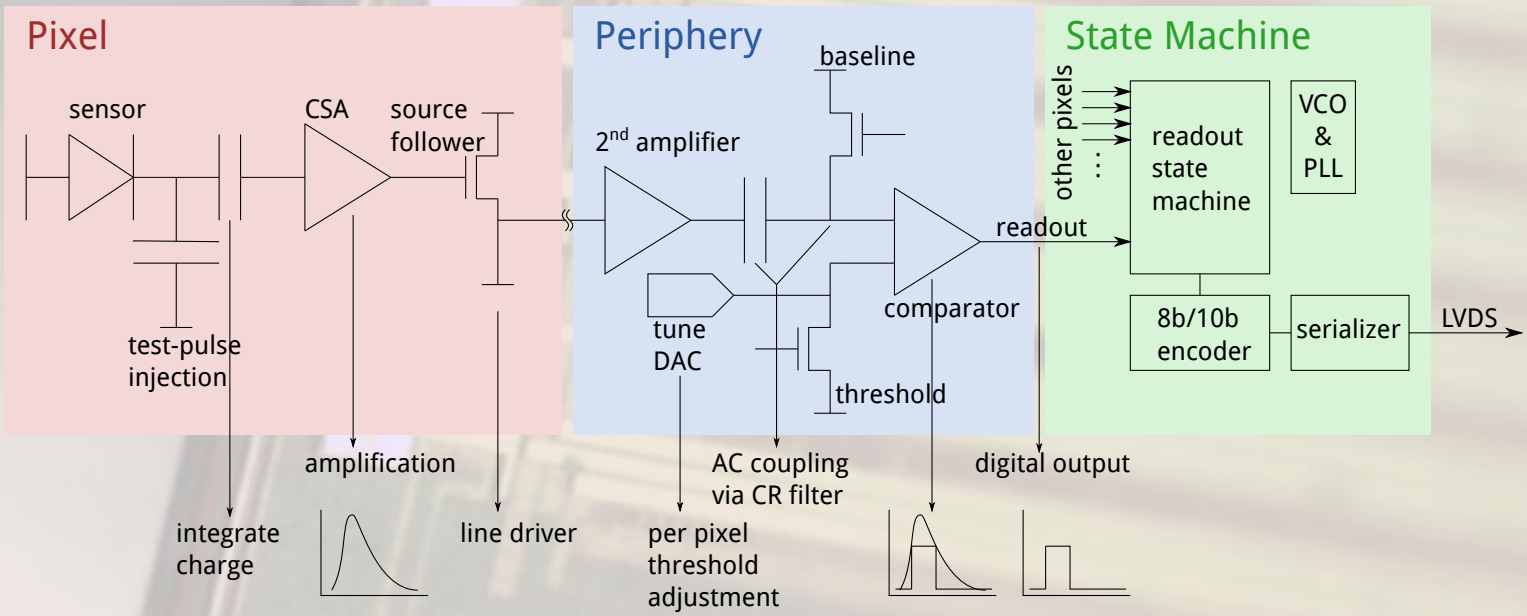
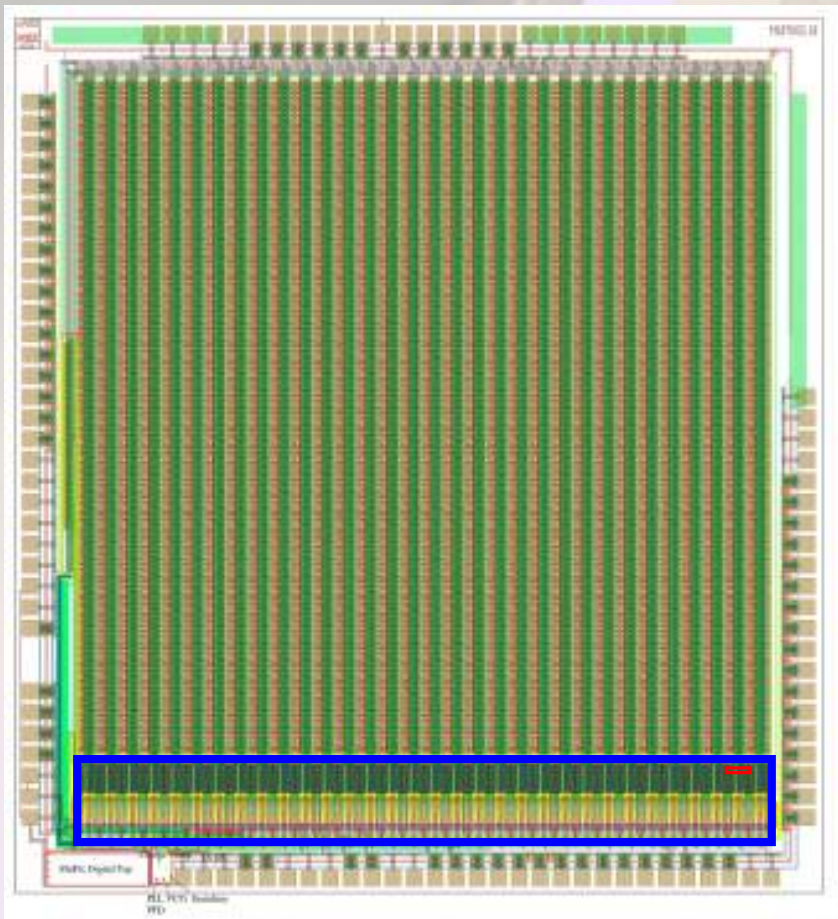
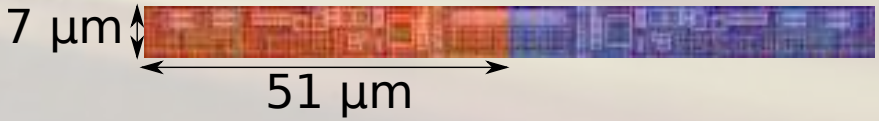


- In-pixel amplifier
- Point-to-point connection to periphery

The Periphery



- Additional amplification stage
- Signal digitisation
- 8-bit time stamps
- Zero-suppressed readout



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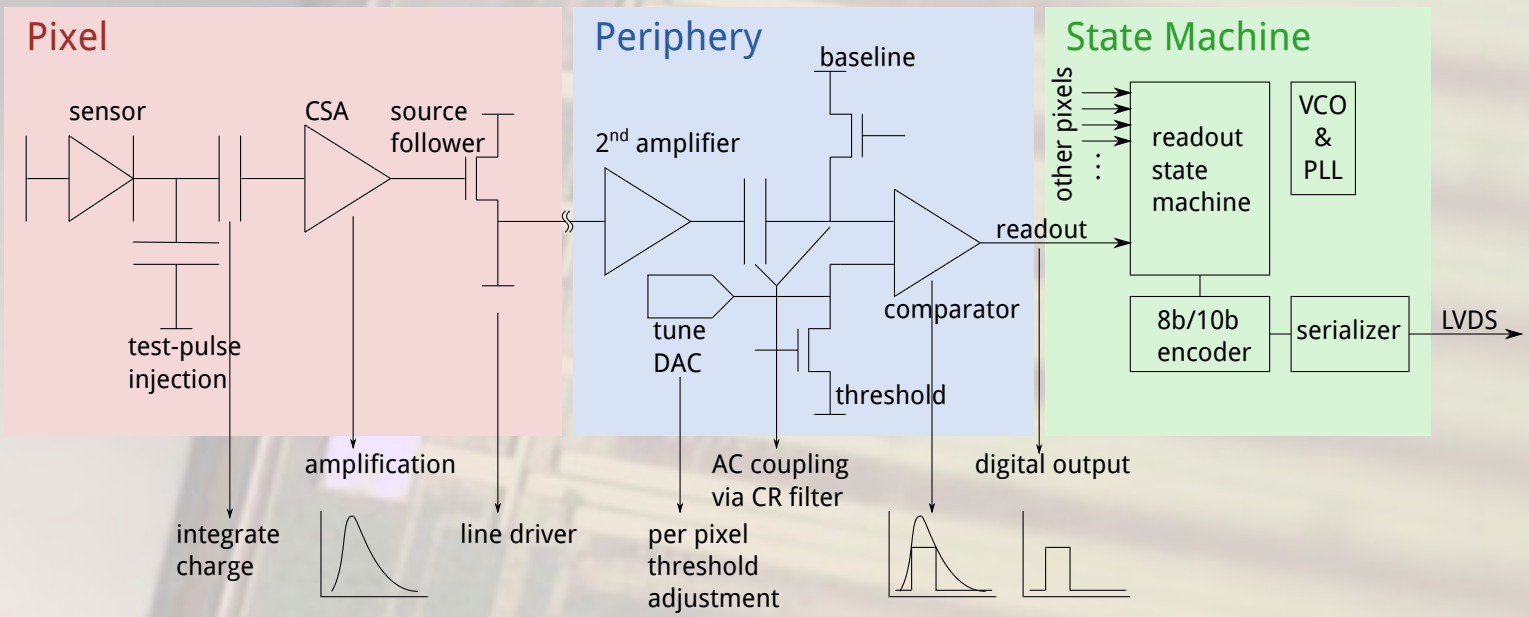


- Individual pixel tuning
- Characterise analogue behaviour

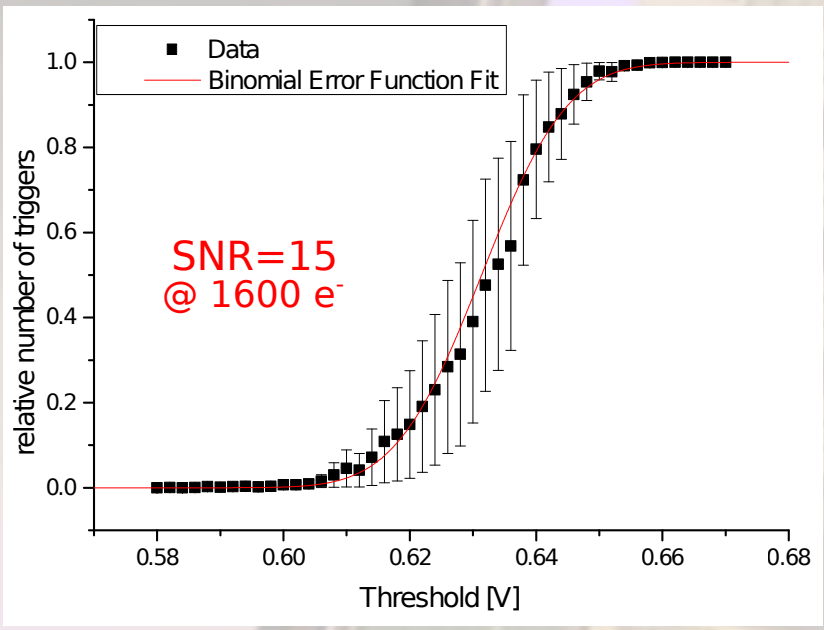
→ T72.2 & 3

The Analogue Behaviour

- Test of general functionality
- HV-dependence
- Analogue performance
- Pulse shape reconstruction
- SNR determination

More Details: T72.2, T72.3

The Analogue Behaviour



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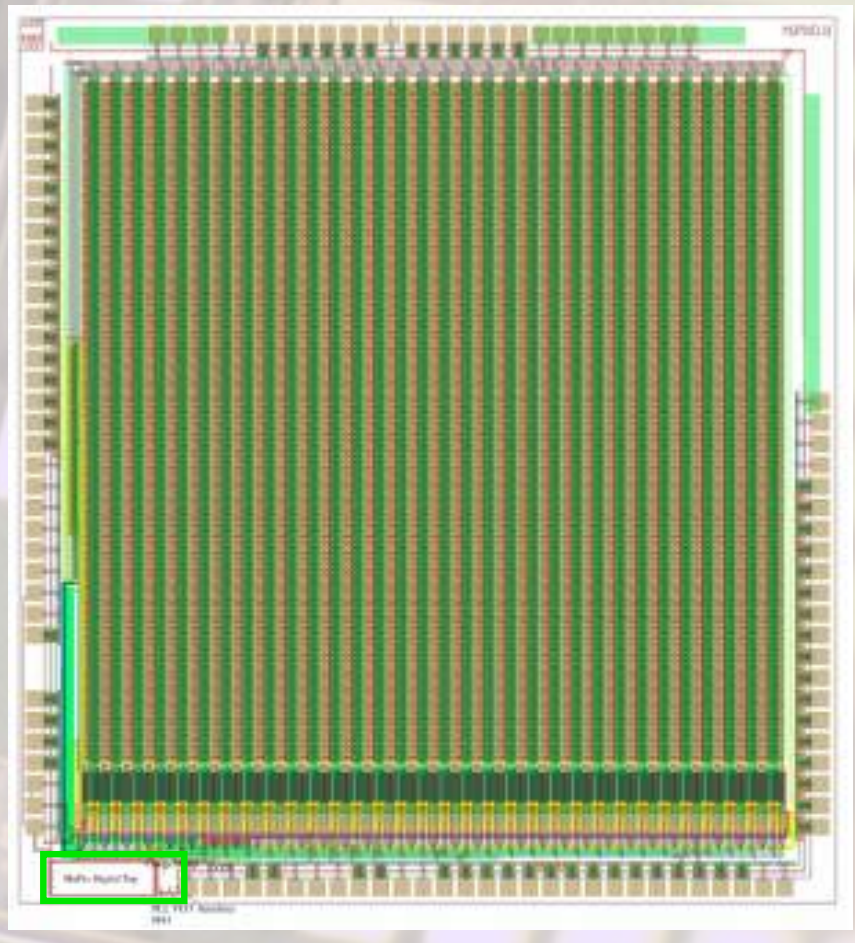
More Details: T72.2, T72.3

The MuPix State Machine



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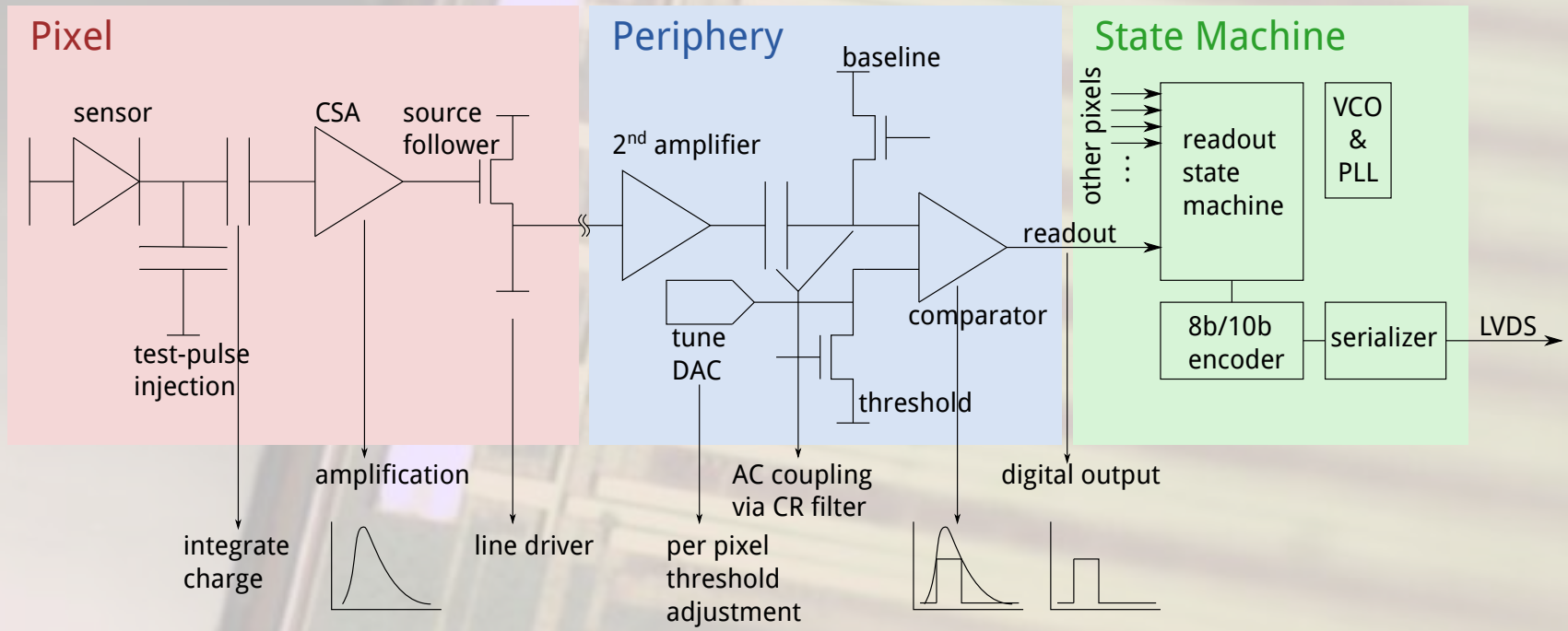
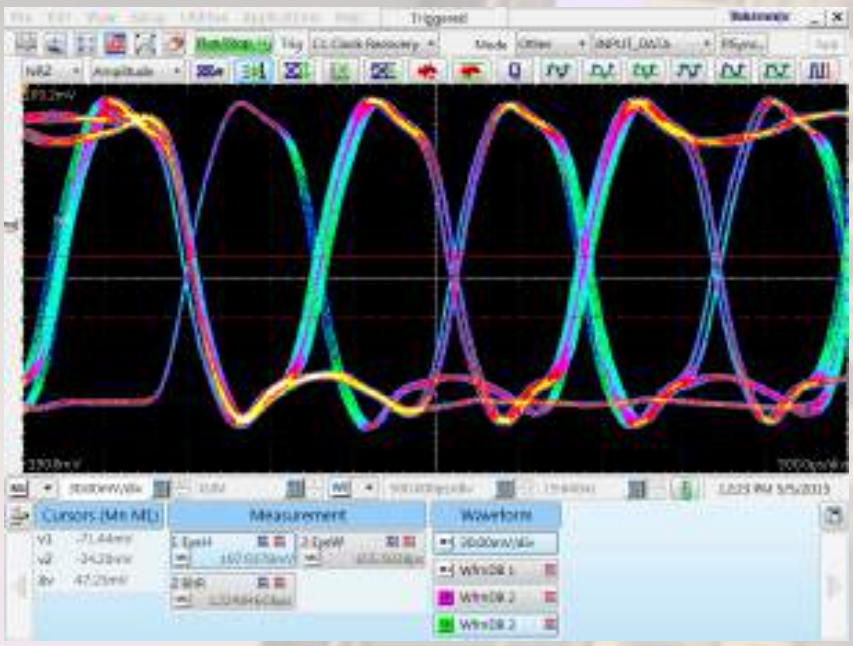


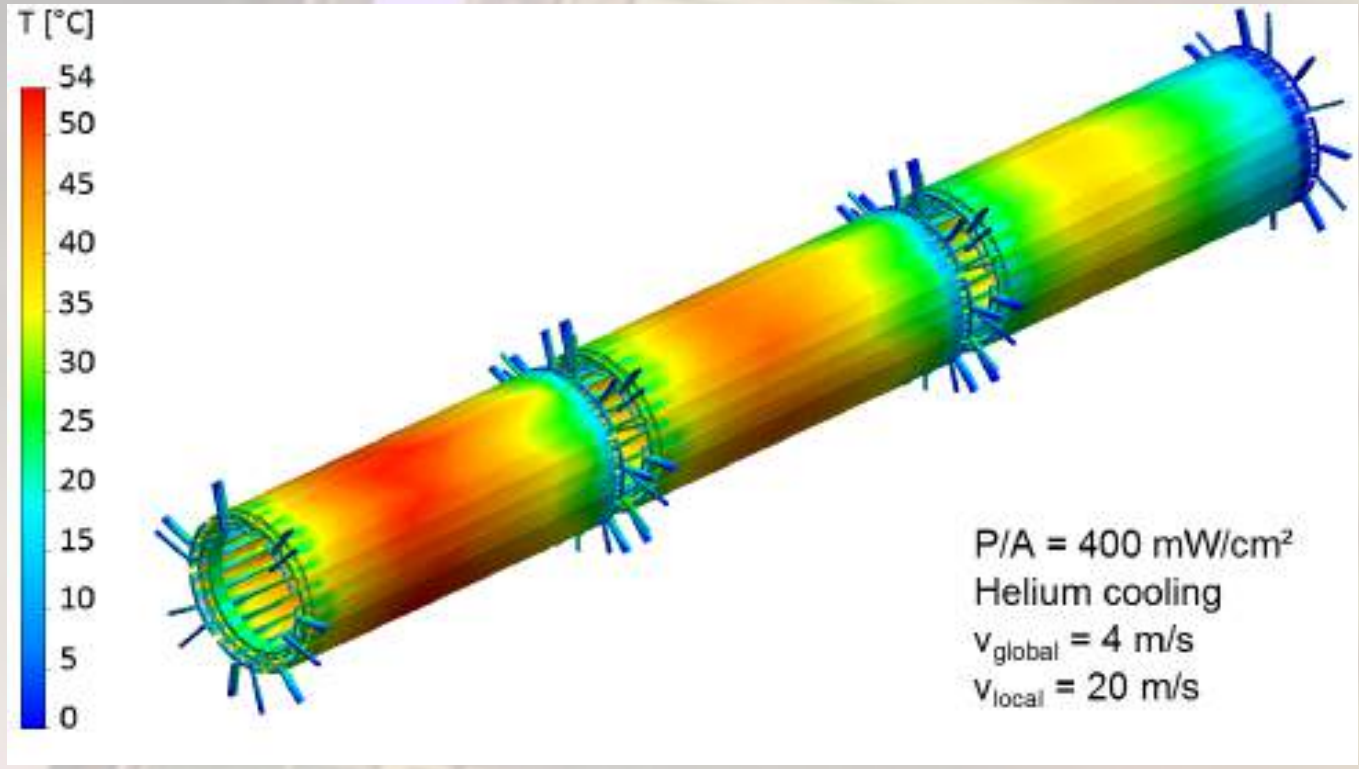
- On-chip readout state machine
- VCO & PLL
- LVDS Gbit data link

Voltage Controlled Oscillator & Phase Locked Loop



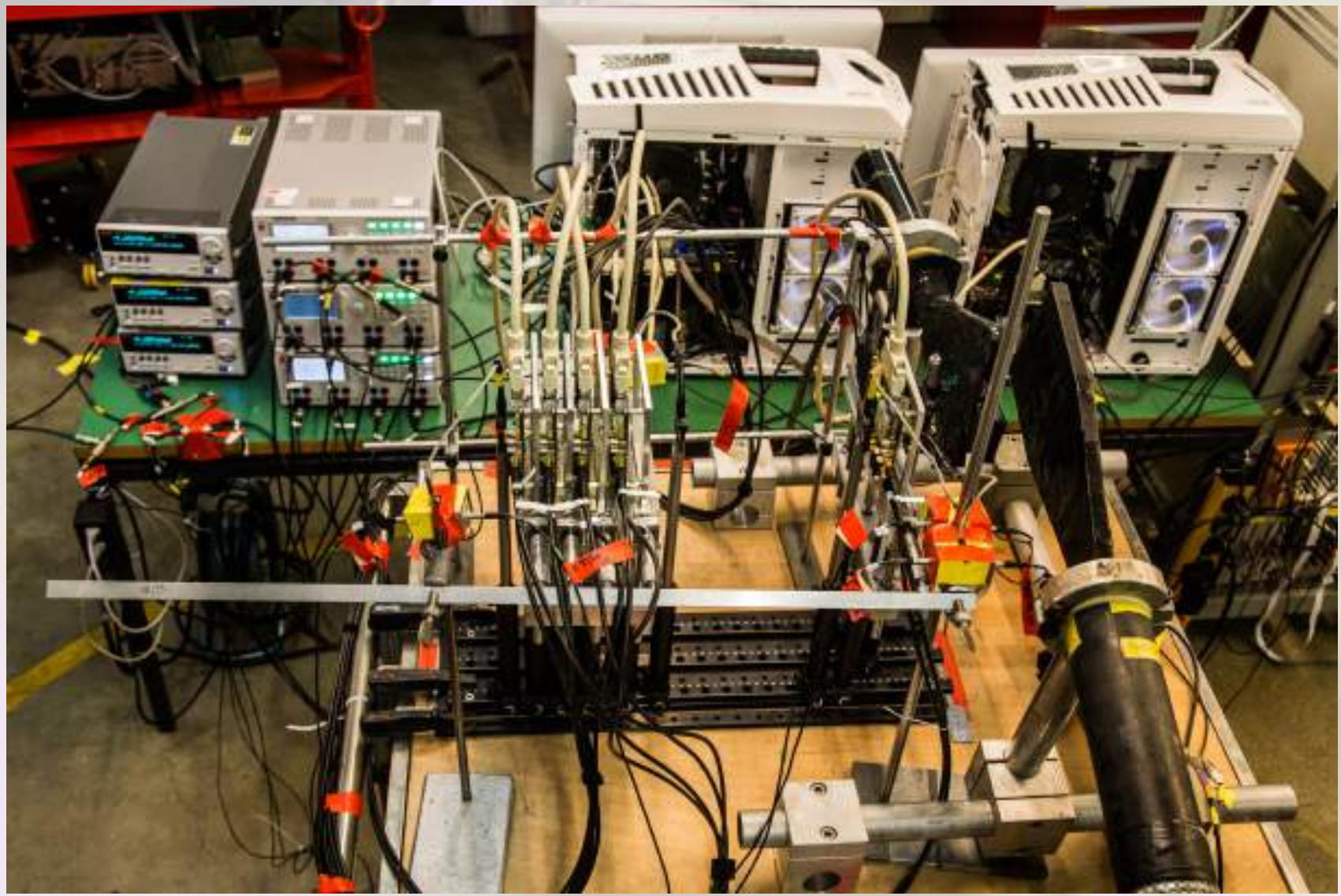
- Stable working point
- Chip as line driver
- Jitter <100 ps ($\rightarrow$ T72.2)
- 1.25 Gbit/s 8b10b encoded data
- Up to 30 MHits/s possible

Power Consumption



- Upper limit of 400 mW cm^{-2}
- Temperature gradient of 50 K ($\rightarrow$ T75.7)
- Investigation of temperature dependence ($\rightarrow$ T72.2)

Testbeam Measurements



Time Resolution

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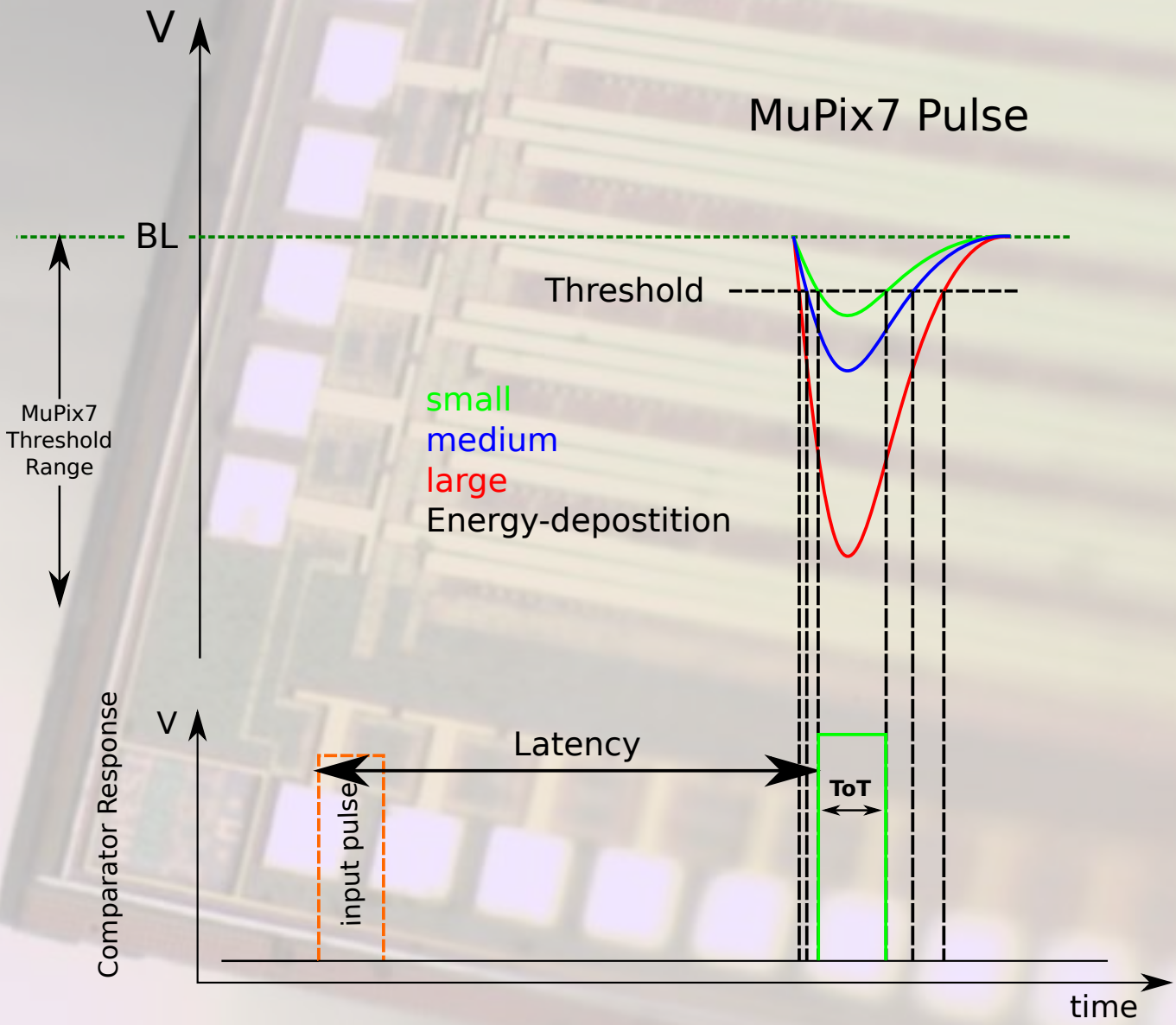

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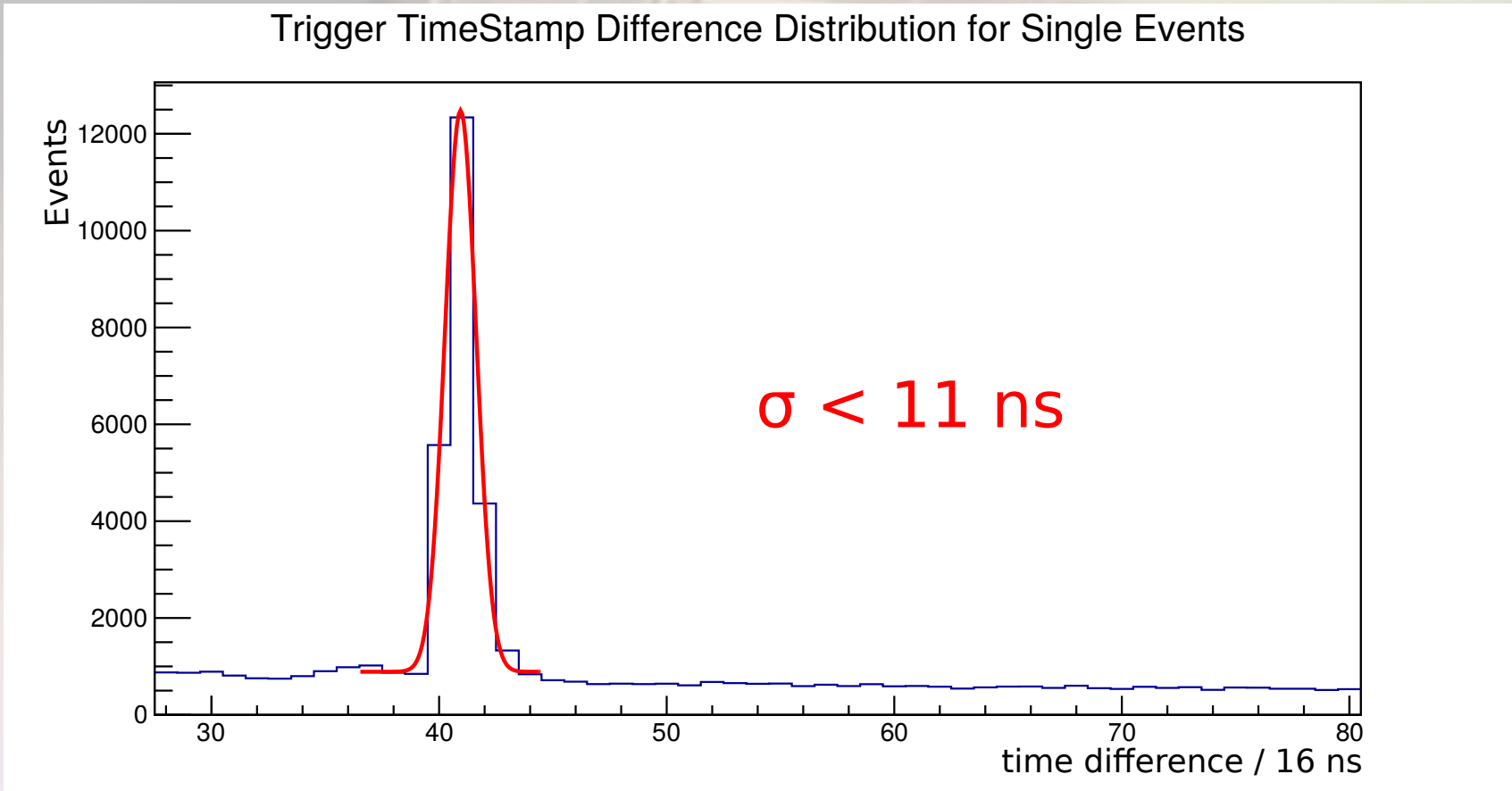
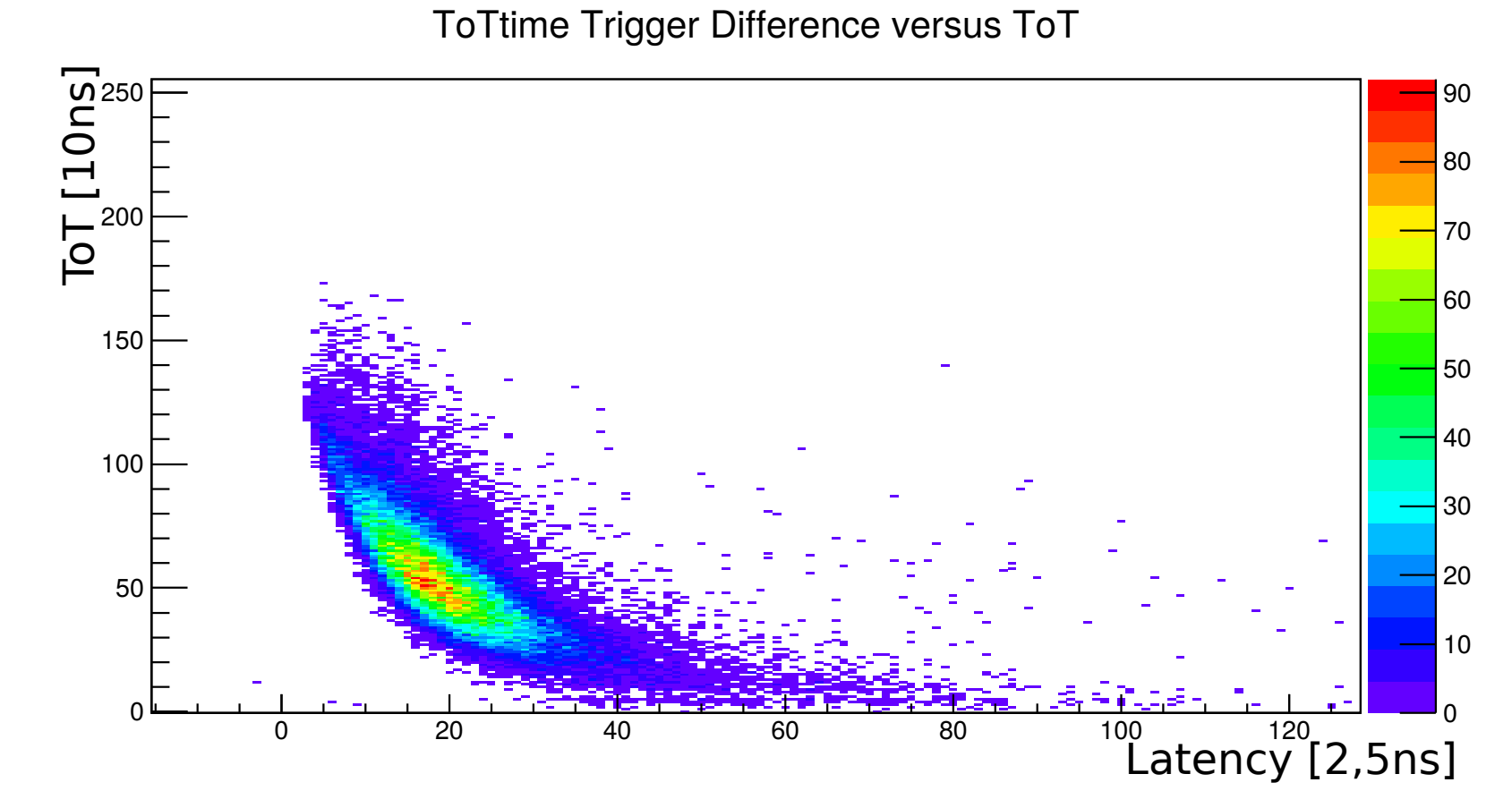


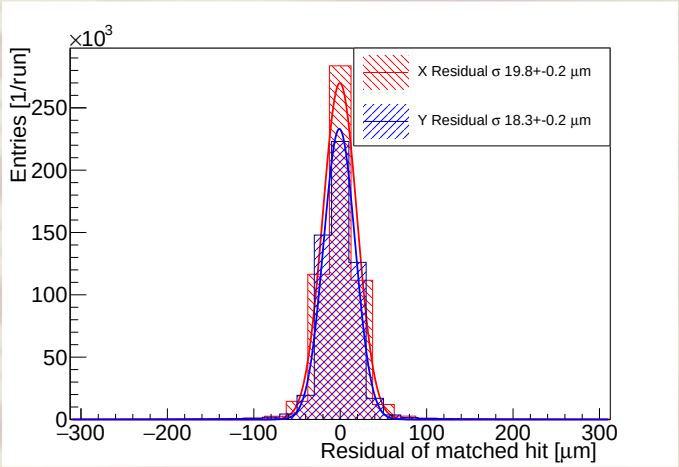
- Sandwich scintillator setup
- Time resolution measured to <11 ns

Time Resolution



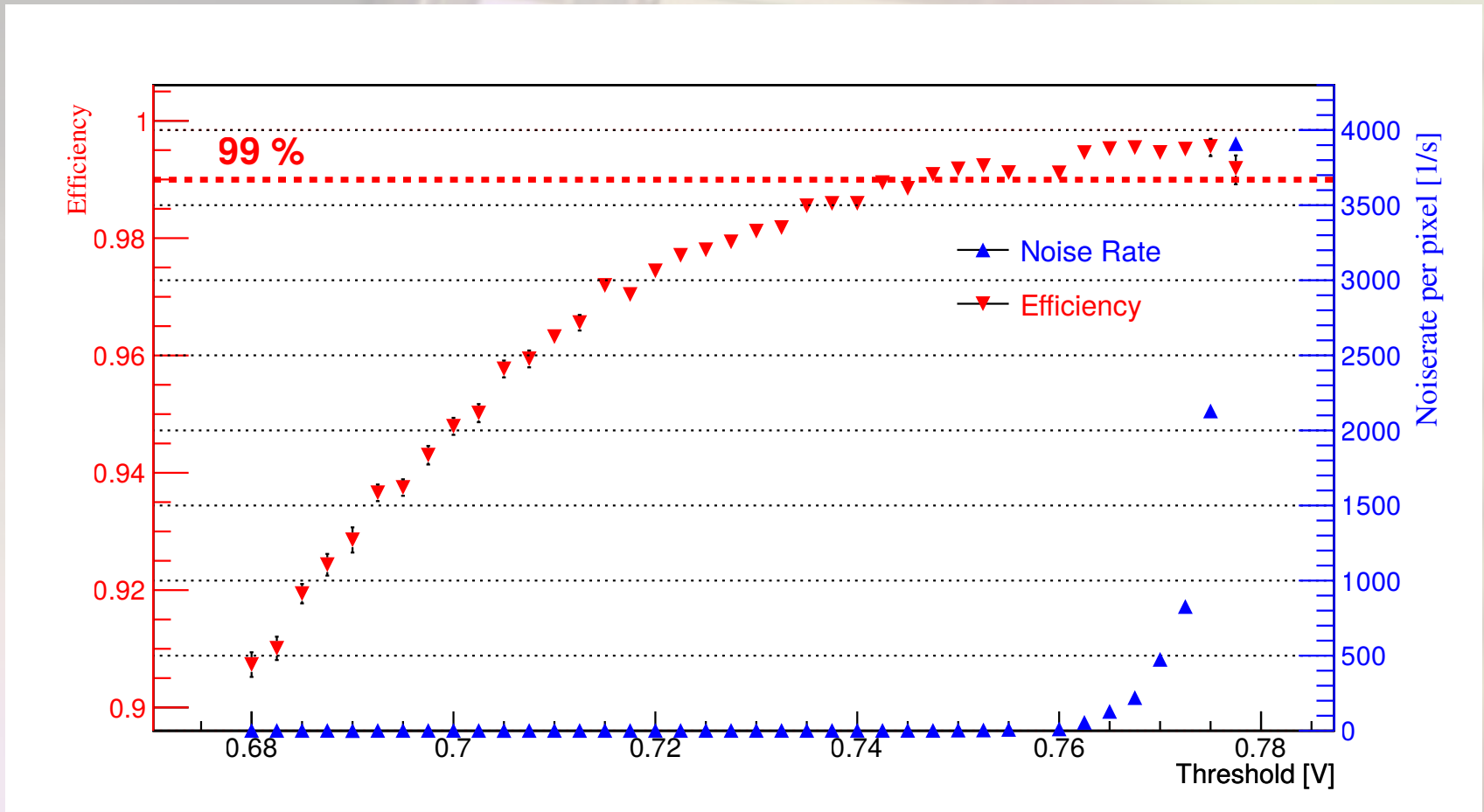
- Sandwich scintillator setup
- Time resolution measured to <11 ns
- Time walk observed for pixel analogue behaviour

The MuPix Telescope (T99.5)



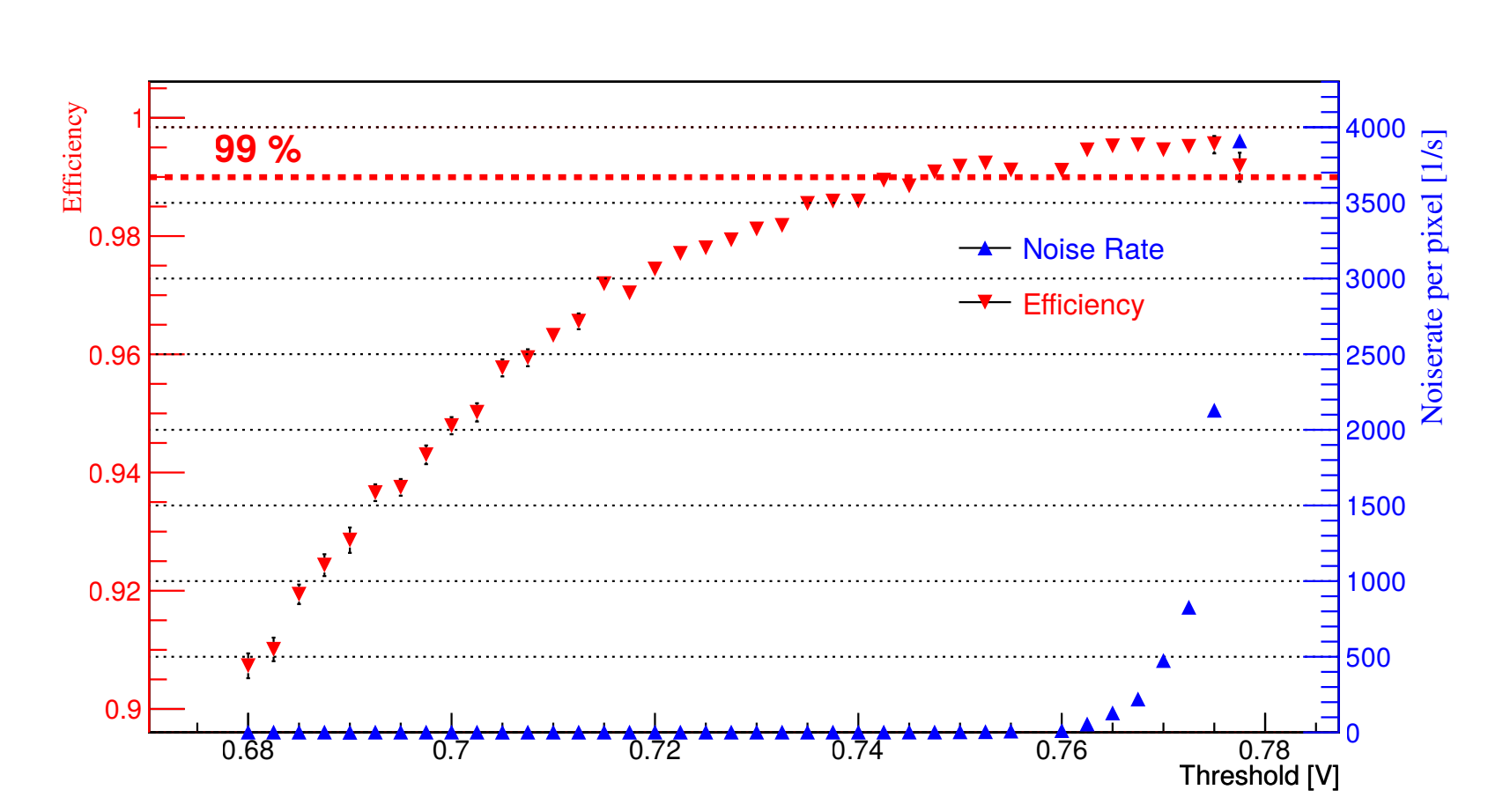
- 4 layers MuPix7
- Use one as DUT
- Time sorted data (T22.4)
- Resolution <30 µm
- Position resolved analysis

Efficiency Measurements



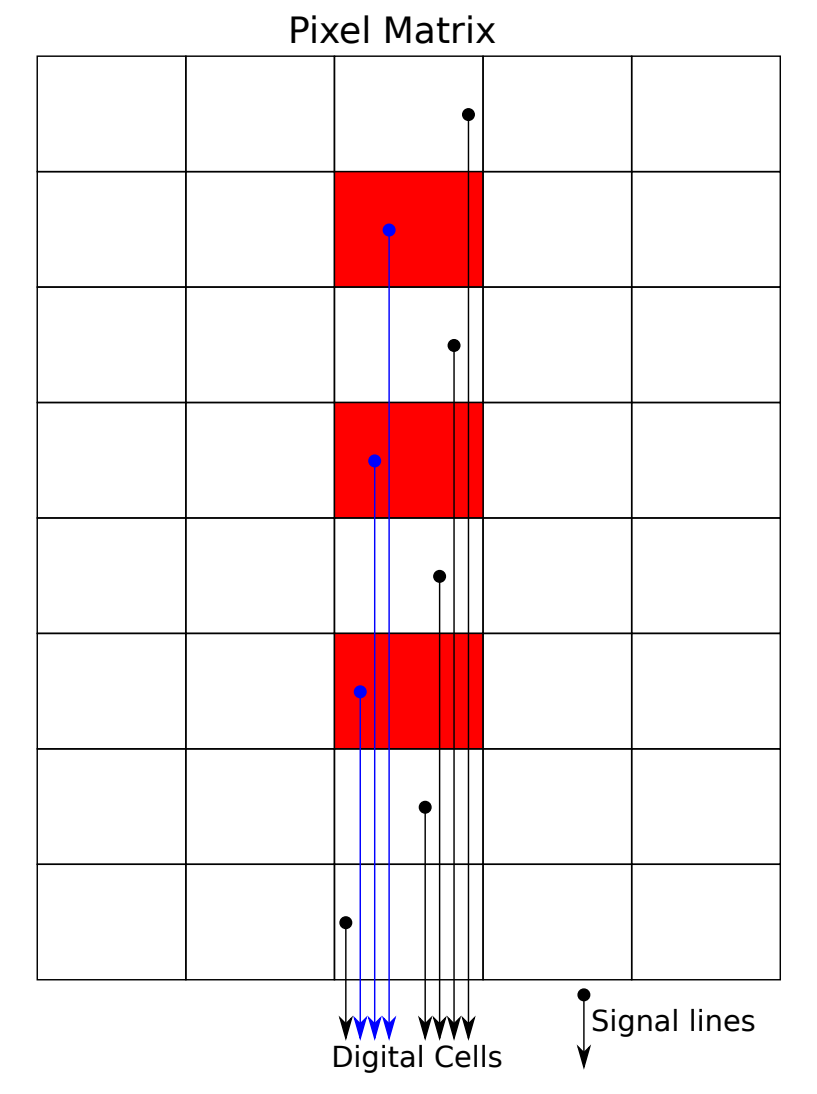
- Use telescope setup
- 220 MeV mixed pion beam provided by PSI

Efficiency Measurements

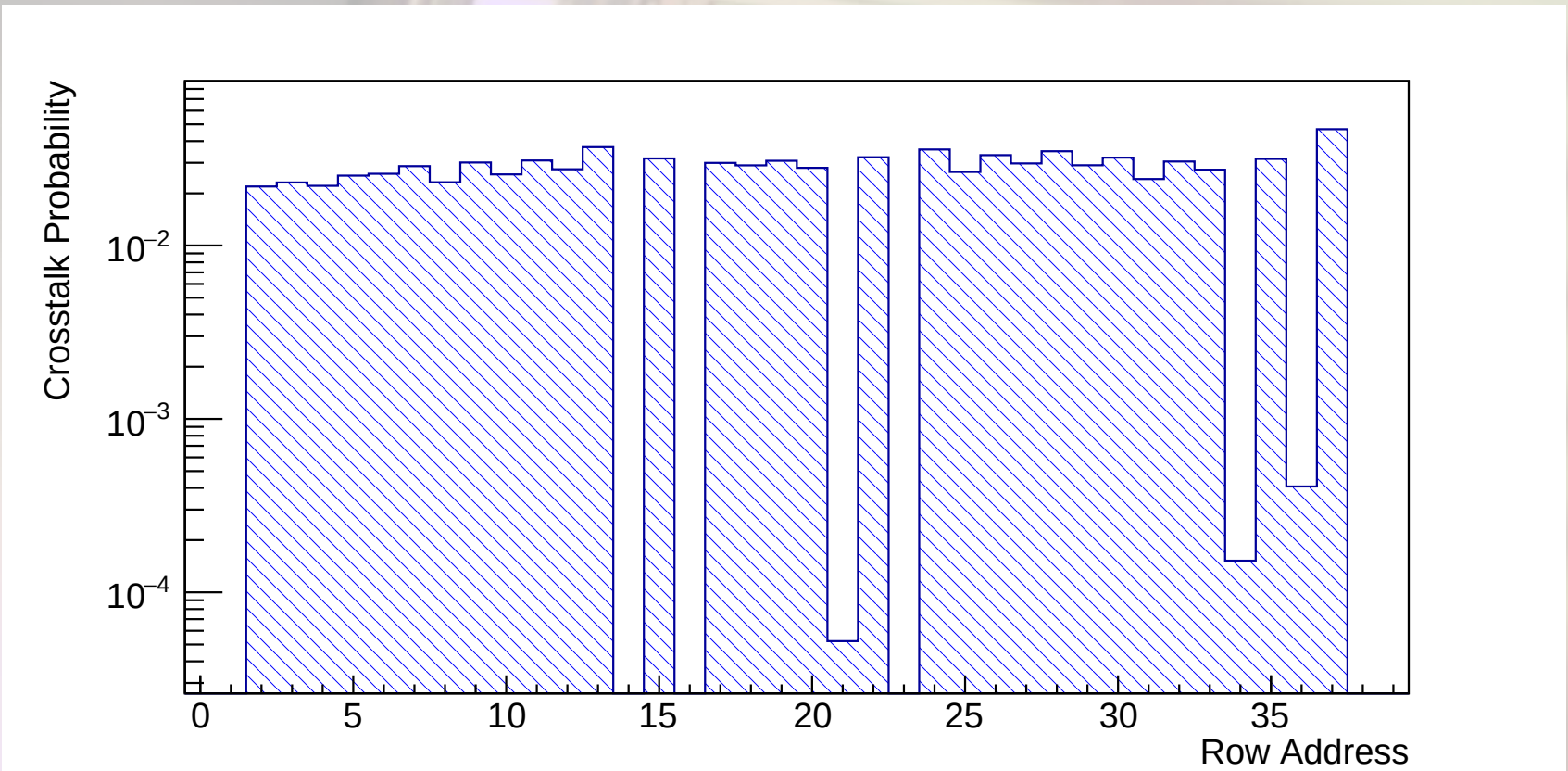


- Efficiencies above 99 % observed
- Tuning results in sharp noise edge
- Power consumption: $\approx 300\,\mathrm{mW\,cm^{-2}}$

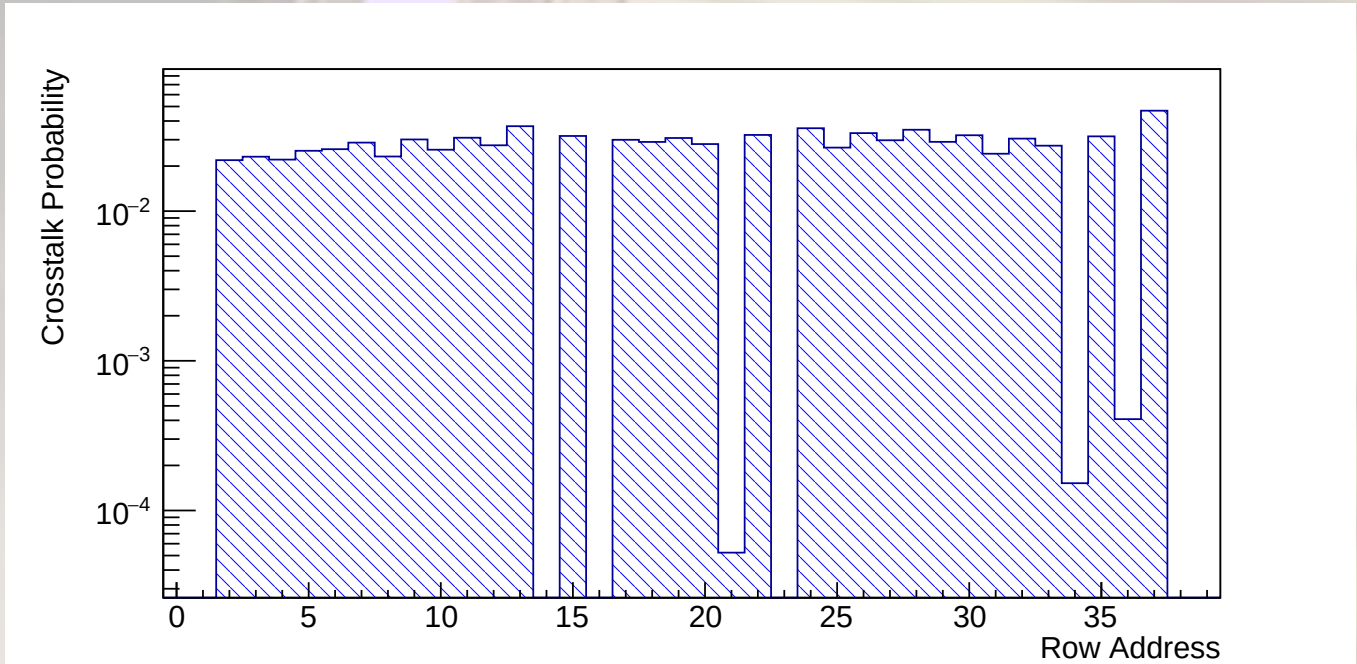
Crosstalk



Crosstalk


Crosstalk Probability
10^{-2}
10^{-3}
10^{-4}
0
5
10
15
20
25
30
35
Row Address

Crosstalk


Crosstalk Probability
10^{-2}
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0
5
10
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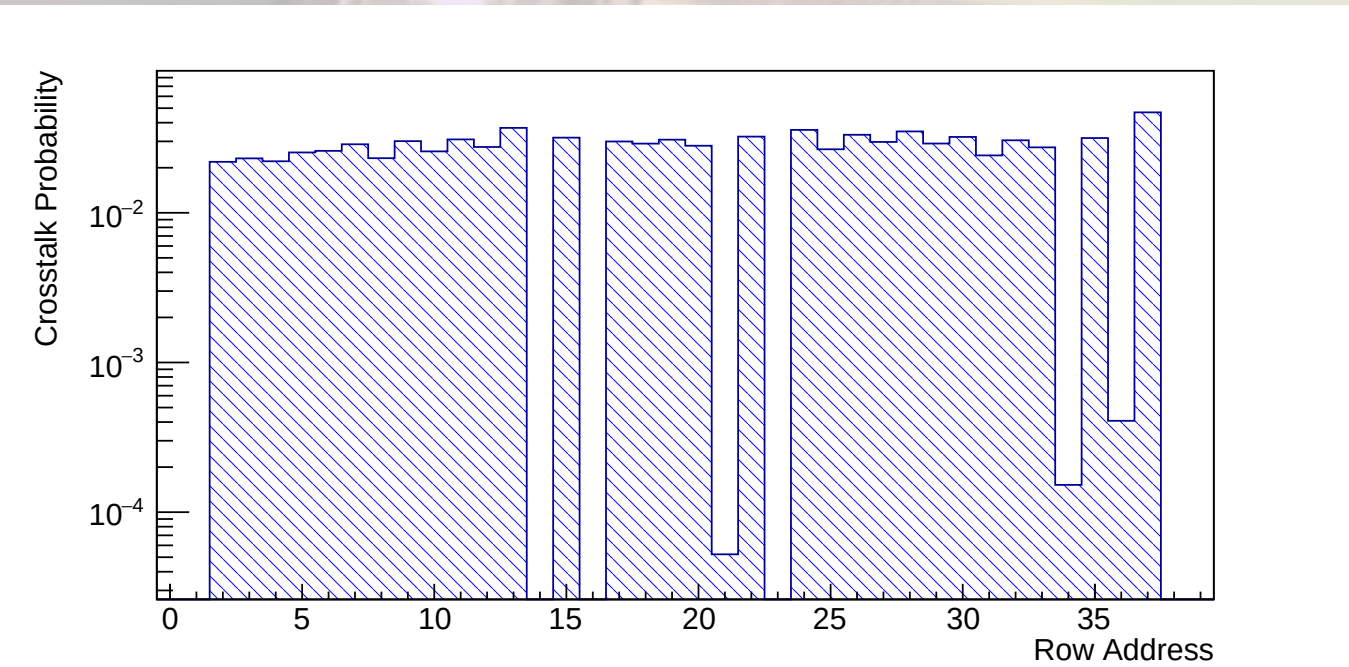
20
25
30
35
Row Address
Even
0
14
16
34
36
Odd
1
21
23

Crosstalk

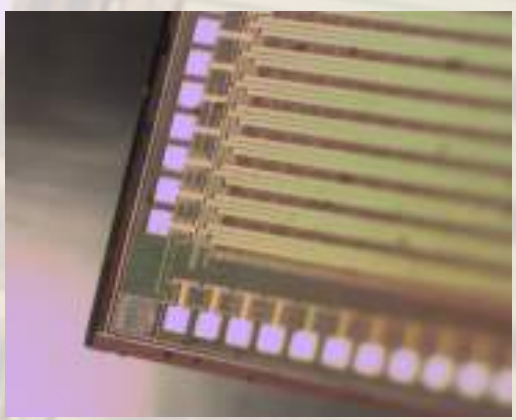


- Crosstalk observed
- Matches signal routing

MuPix8 Prototype

- Submission planned for June 2016
- First big chip $2.3 \times 1.3\,\mathrm{cm}^2$
- Pixel size $80 \times 80\,\mu\mathrm{m}^2$
- Higher resistivity substrate
- First module prototypes

Summary



- Reliable characterisation setup & frame work
- Very well performing chip technology
- First HV-MAPS prototype with integrated readout
- Many design goals already satisfied

Acknowledgments

The efficiency measurements for several power settings have been performed at the Test beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

We would like to thank the PSI for providing high rate test beams under excellent conditions.

We owe our SPS test beam time to the SPS team and our LHCb colleagues, especially Heinrich, Kazu and Martin.

We thank the Institut für Kernphysik at the JGU Mainz for giving us the opportunity to take data at MAMI.

Mu3e Talks

- Front-End Board: T22.4
- Switching Board: T22.5
- GPU-Online Reconstruction: T42.5
- GPU-Telescope Reconstruction: T42.6
- Flexprints: T42.7
- MuPix T-Dependence: T72.2
- MuPix Tuning: T72.3
- Mechanic & Cooling: T75.7
- Track reconstruction: T98.1
- Detector alignment: T98.5
- MuPix7 Telescope: T99.5