The MuPix CMOS Tracker for Mu3e

Heiko Augustin

Physikalisches Institut Heidelberg

UK CMOS Meeting
10. March 2016
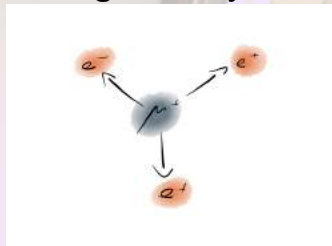
Motivation - Mu3e

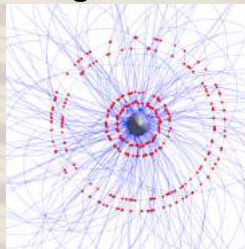**The Search for New Physics**

- Immeasurable in SM ($BR < 10^{-54}$)
- Sensitive to new physics
- Improve sensitivity $BR < 10^{-12} \rightarrow 10^{-16}$

The Signal Decay

Background

- $> 10^9$ decays/s
- Combinatorial & Accidental
- $\rightarrow$ Good time and vertex resolution

SINDRUM: "Search for the decay muto3e" Nucl. Phys., B299 1, 1988
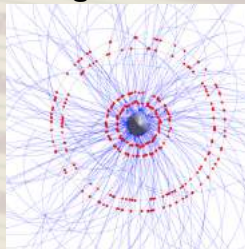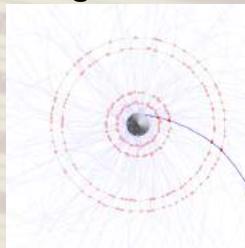
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- Decay at rest: $\Sigma \vec{p} = 0$
- Common vertex and coincident in time
- Maximal momentum $53\,\text{MeV}/c$
- Reconstructed invariant mass ($E_{tot} = m_\mu$)

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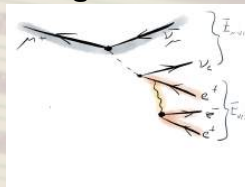
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- Radiative decay
- Good momentum resolution required
- $\rightarrow$ Reduce multiple scattering

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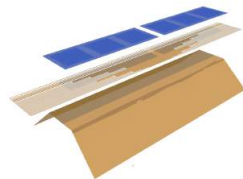
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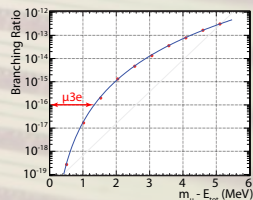
R.M.Djilkibaev and R.V.Konoplich,

Phys.Rev., D79 073004, 2009

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The Requirements for the Silicon Pixel Tracker
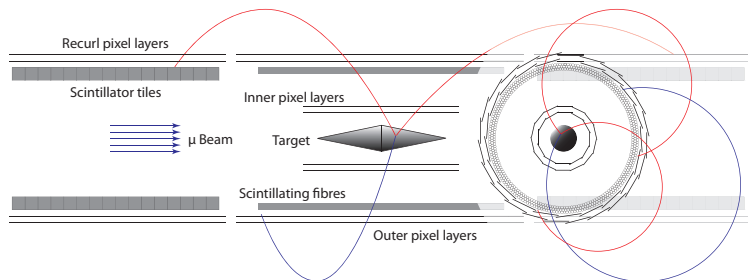
- High rate
→ Good time resolution
- Good momentum resolution
→ Low material budget

The Requirements for the Silicon Pixel Tracker

Pixel Sensor Requirements

Pixel Size	Time Resolution	Material Budget	Efficiency
$80 \times 80\,\mu m^2$	$< 20\,ns$	$\approx 1\,\%_0\ X_0/layer$	$> 99\%$

- High rate
- $\rightarrow$ Good time resolution
- Good momentum resolution
- $\rightarrow$ Low material budget
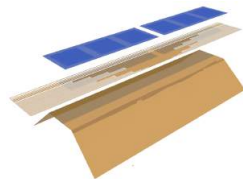
High Voltage Monolithic Active Pixel Sensors

N-well

E field

P-substrate

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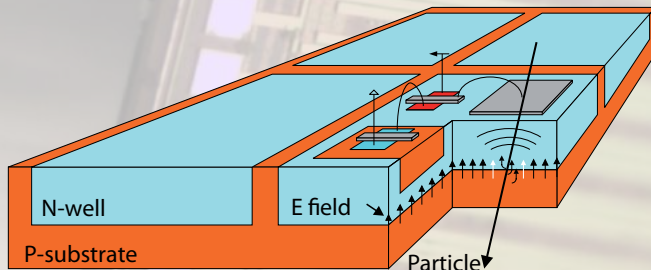
I.Peric, P. Fischer et al., NIM A 582 (2007) 87

- Deep n-well in p-doped substrate
- Depleted area is the active detector volume $10 - 20\,\mu m$
- Fast charge collection via drift $< 1\,ns$
- Sensor can be thinned to $< 50\,\mu m$

The MuPix7 Prototype
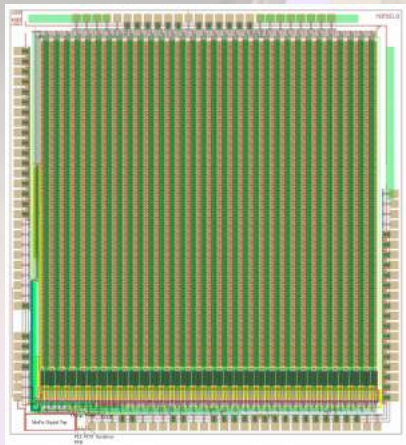
- Commercial 180 nm HV-CMOS process
- Thinned to 50 μm

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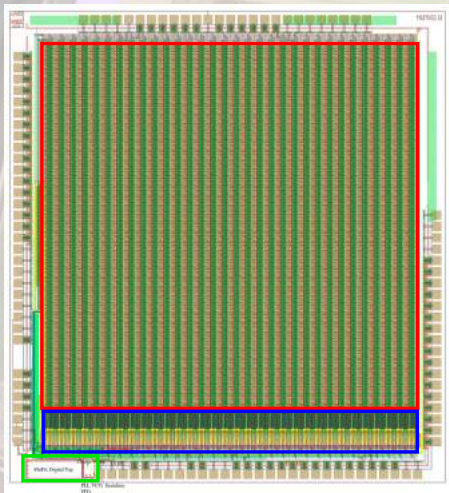
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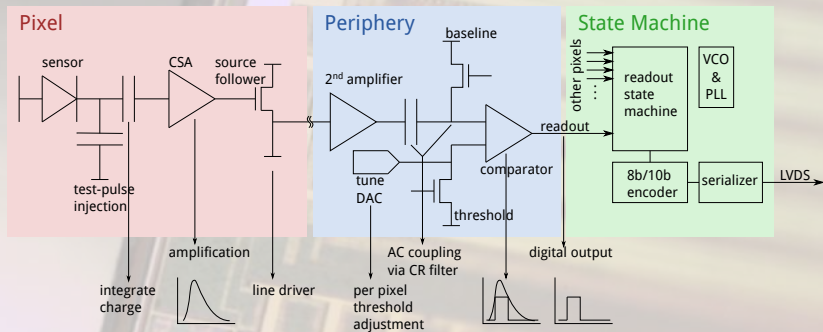
The Pixel
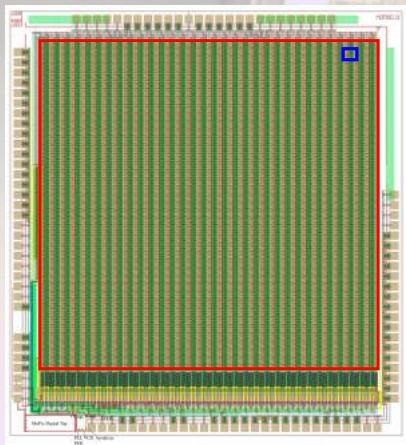
- $3.2 \times 3.2\,\text{mm}^2$ active area
- 32×40 pixels
- 3×3 diode structure
- In-pixel amplifier

80 µm

103 µm
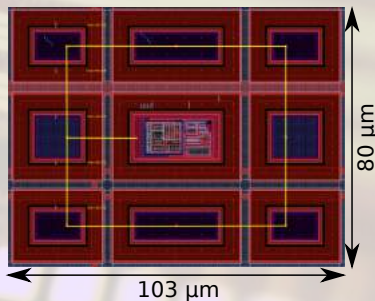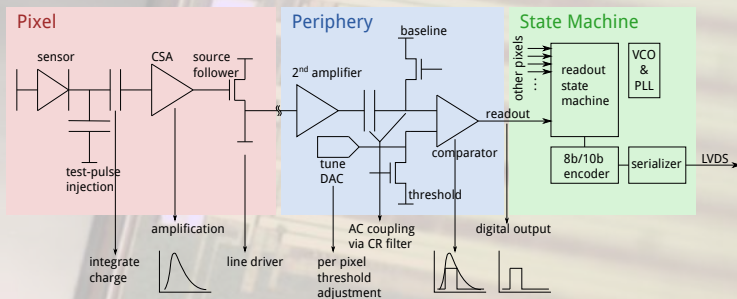
The Pixel

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

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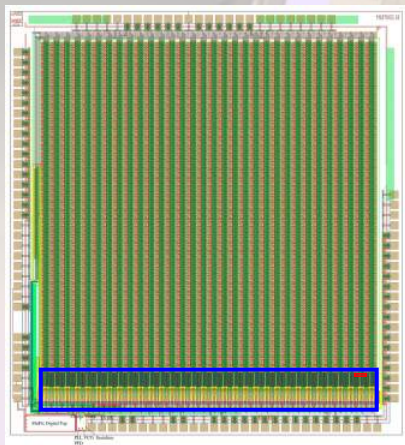
- Additional amplification stage
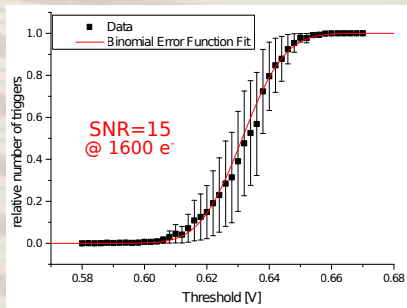- Signal digitisation
- 8-bit time stamps
- Zero-suppressed readout

7 μm, 51 μm
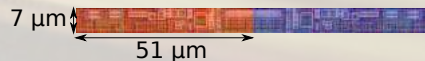
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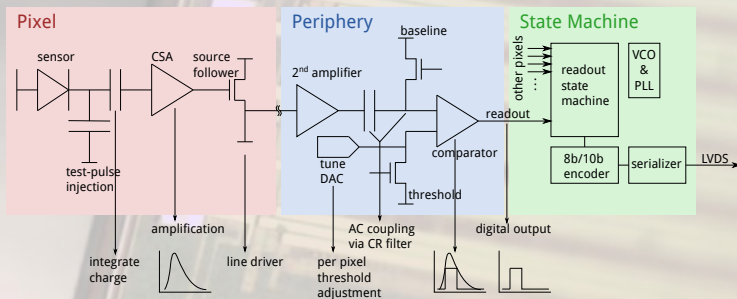
- Individual pixel tuning
- Characterise analogue behaviour

The Analogue Behaviour

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

Sensor Tuning

Untuned
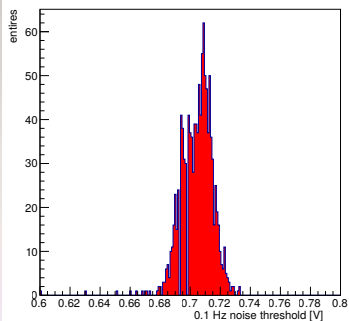
- equalize chip response
- tuning on per pixel noise
- enhancement of sensitivity to small signals
- routinely used in test beam measurements

Sensor Tuning

Tuned
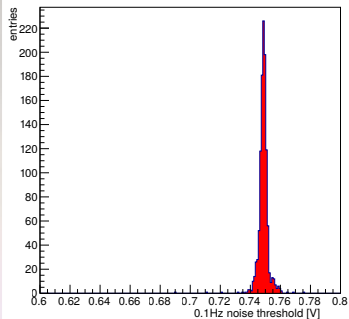
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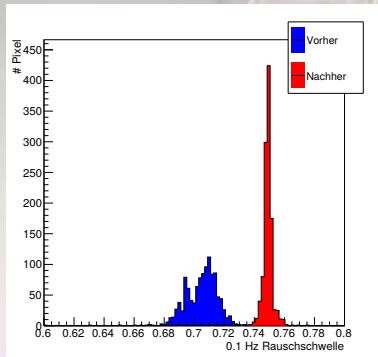
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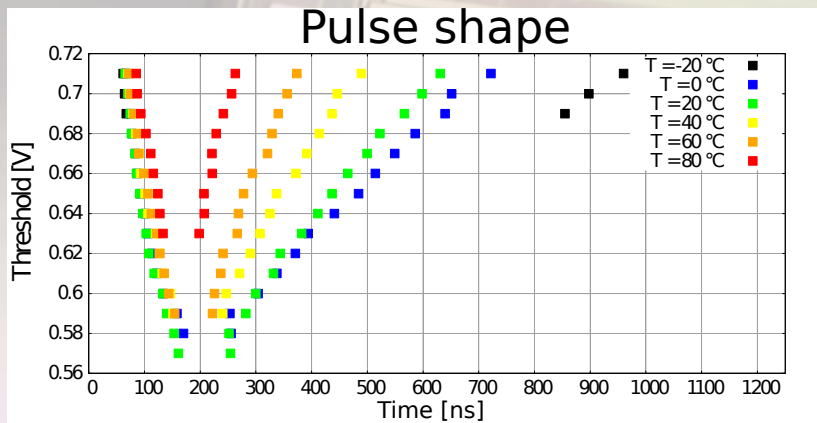- tuning on per pixel noise
- enhancement of sensitivity to small signals
- routinely used in test beam measurements

Power Consumption & Temperature Dependence
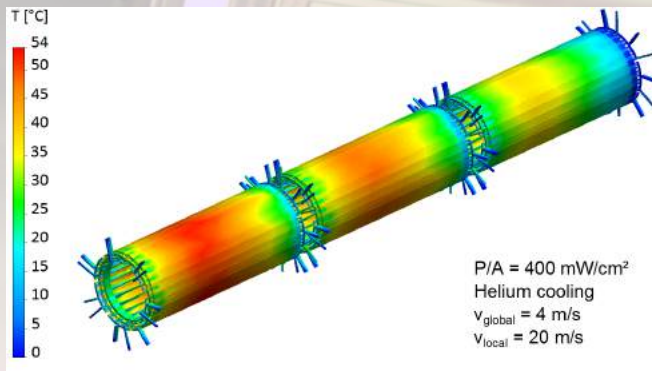
- Upper limit of $400\,\mathrm{mW\,cm^{-2}}$
- Temperature gradient of $50\,\mathrm{K}$
- Investigation of temperature dependence

Temperature Dependence - Pulse Shape
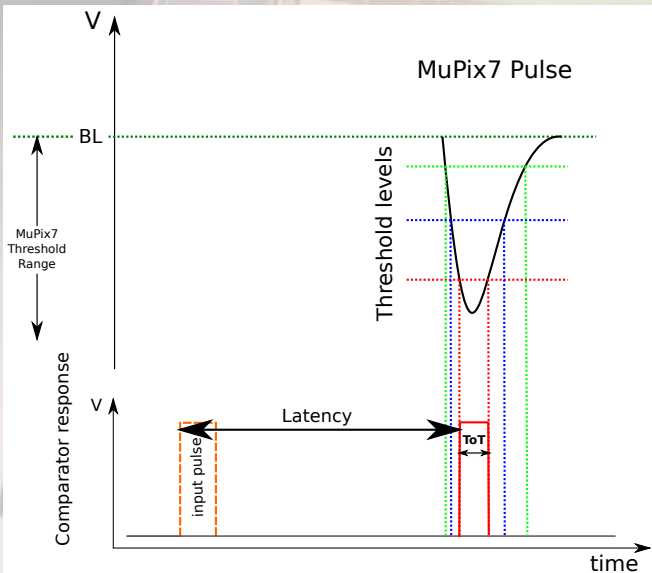
Temperature Dependence - Pulse Shape

- Temperature dependence observed
- Effect reproduced with bias current

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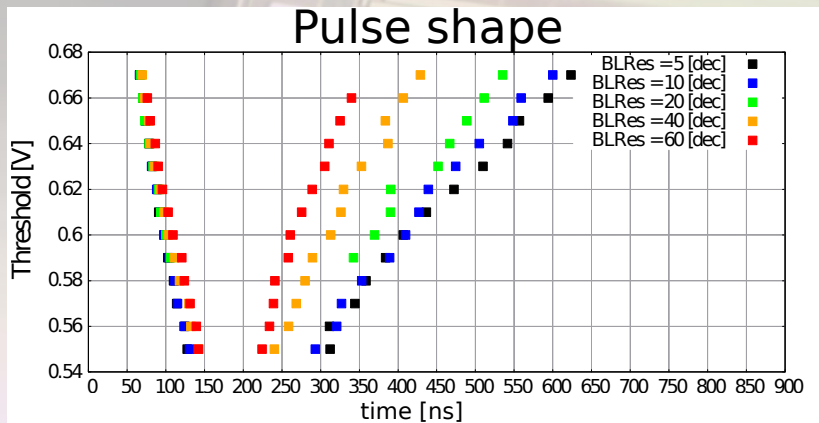
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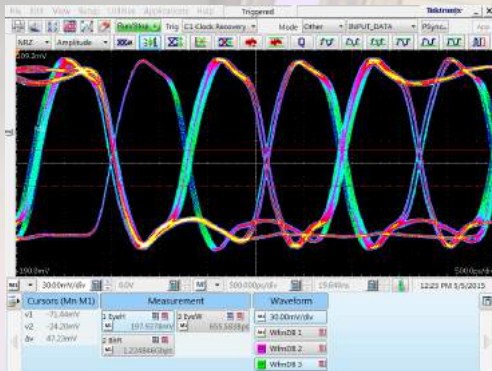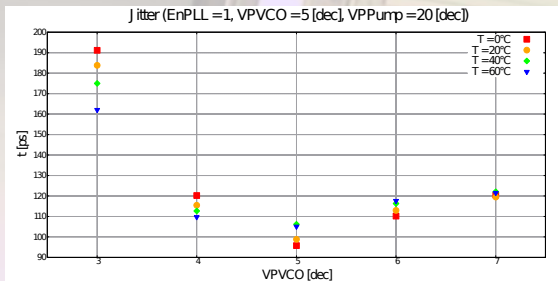- Effect reproduced with bias current

The MuPix State Machine
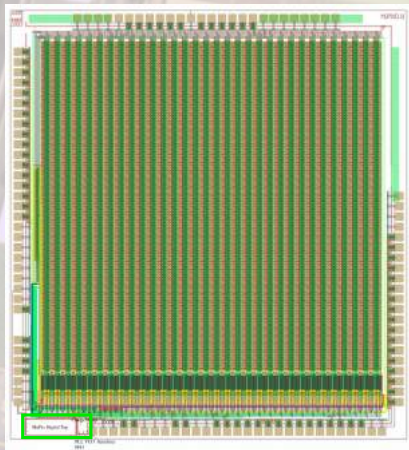
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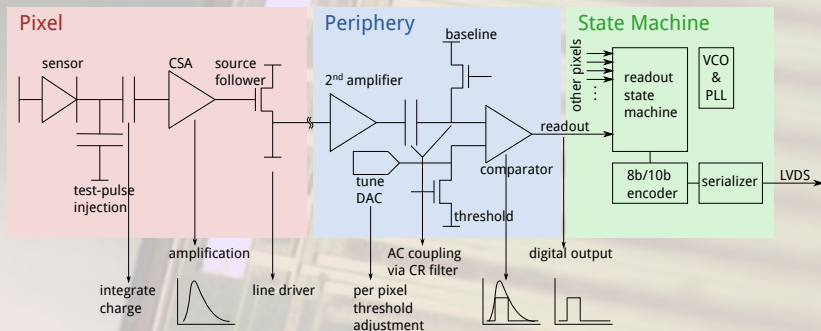
- On-chip readout state machine
- VCO & PLL
- LVDS Gbit data link

Voltage Controlled Oscillator & Phase Locked Loop

- Stable working point
- Jitter <100 ps
- Chip as line driver
- 1.25 Gbit/s 8b10b encoded data
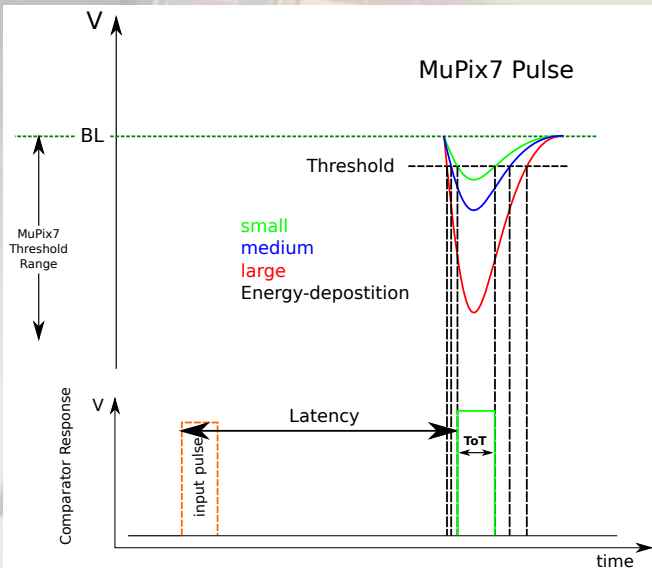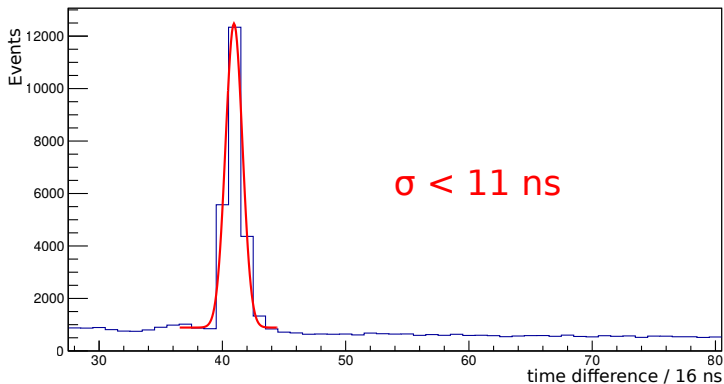- Up to 30 MHits/s possible

Voltage Controlled Oscillator & Phase Locked Loop

Jitter (EnPLL =1, VPVCO =5 [dec], VPPump =20 [dec])

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- Jitter <100 ps
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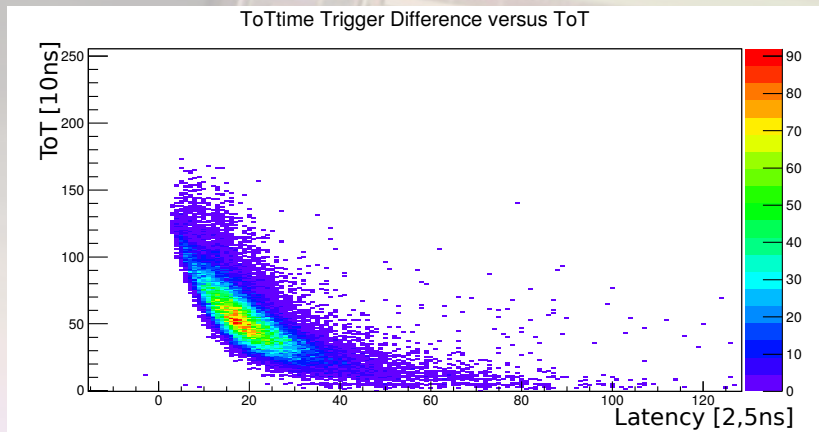
Testbeam Measurements
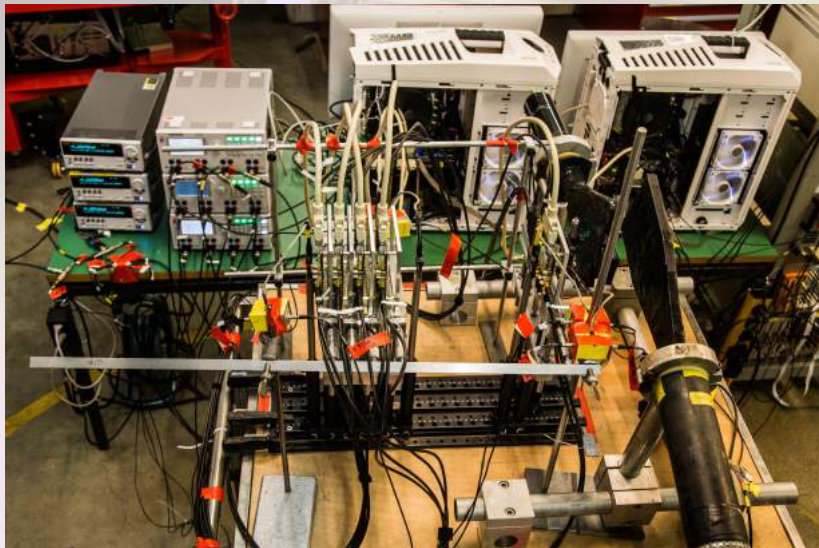
Time Resolution

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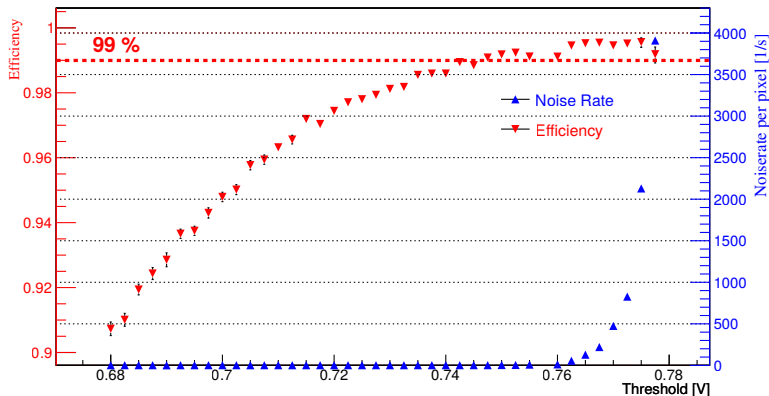
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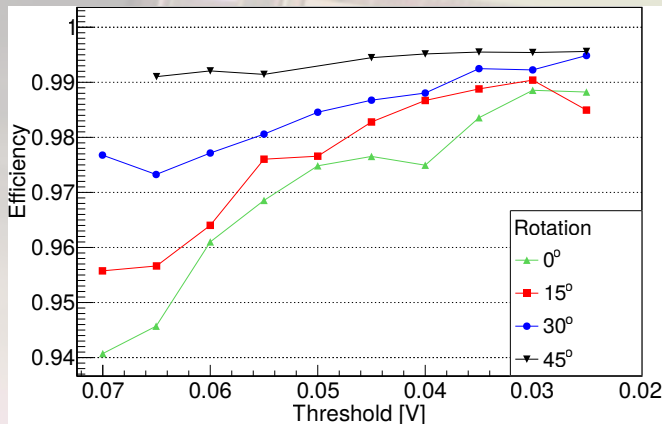- Time walk observed for pixel analogue behaviour

The MuPix Telescope
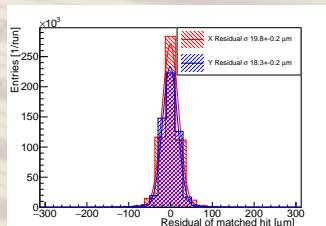
- 4 layers MuPix7
- Use one as DUT
- Time sorted data
- Resolution <30 μm
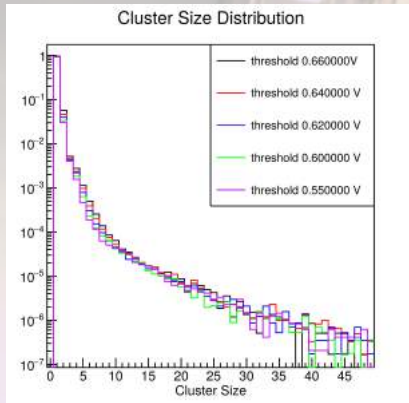- Position resolved analysis

Efficiency Measurements

- 220 MeV mixed pion beam provided by PSI
- Efficiencies above 99 % observed
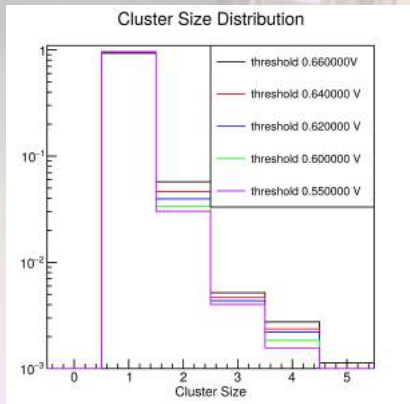- Tuning results in sharp noise edge

Rotation Measurements

- 4 GeV electrons at DESY
- Increased signal $\propto (cos\alpha)^{-1}$
- $\rightarrow$ Larger high efficiency plateau
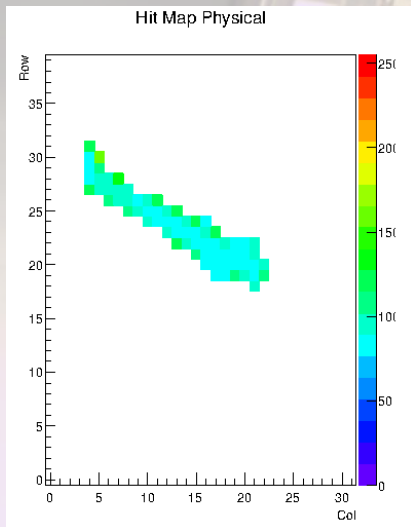- Increase of resistivity advantageous

Clustering

- More than 90 % single hits
- Small clusters due to charge sharing
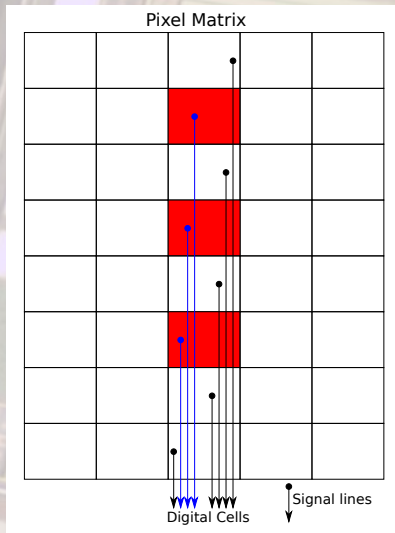- Tails from delta events

Clustering

Cluster Size Distribution

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- Tails from delta events

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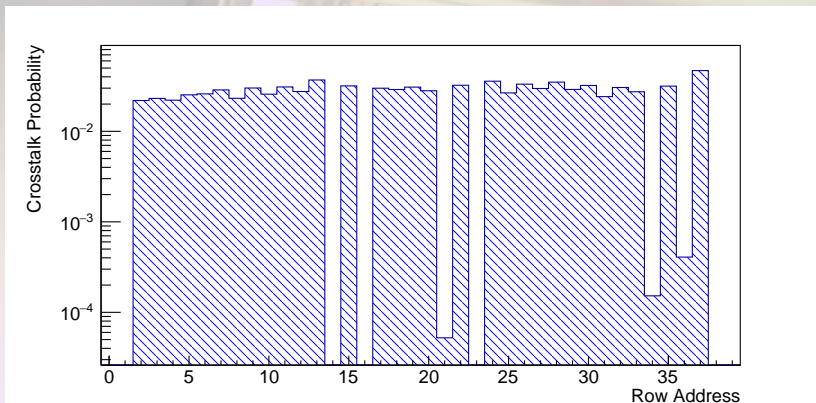- Small clusters due to charge sharing
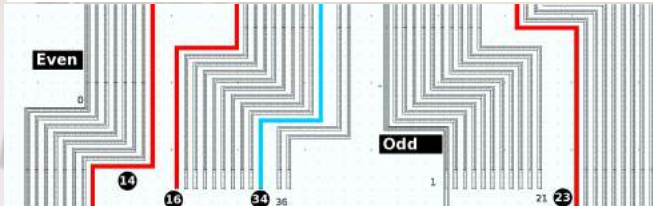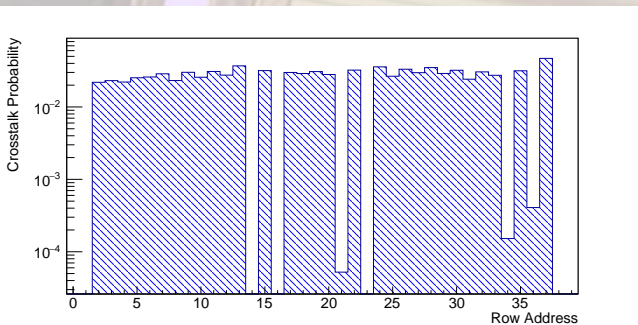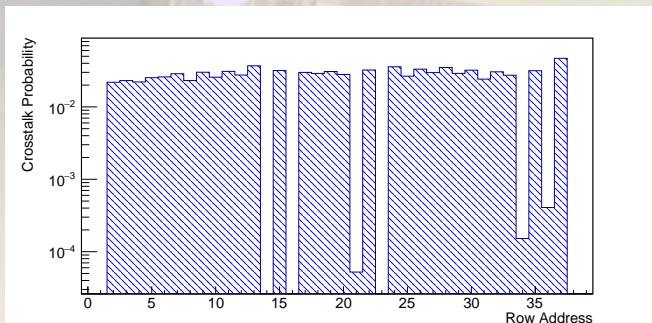- Tails from delta events

Crosstalk
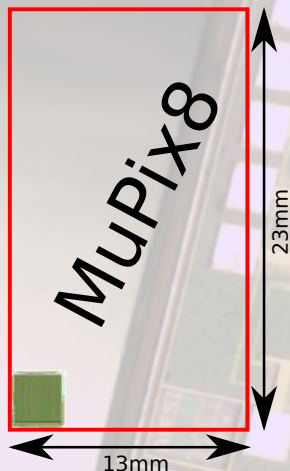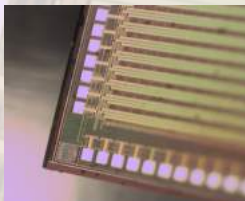
Crosstalk

Crosstalk

Crosstalk

- Crosstalk observed
- Matches signal routing

MuPix8 Prototype

23mm

13mm

- Submission planned for June 2016
- First big chip $2.3 \times 1.3\,\mathrm{cm}^2$
- Pixel size $80 \times 80\,\mathrm{\mu m}^2$
- Higher resistivity substrate ($20\,\Omega\,\mathrm{cm} \rightarrow 80\,\Omega\,\mathrm{cm}$)
- 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

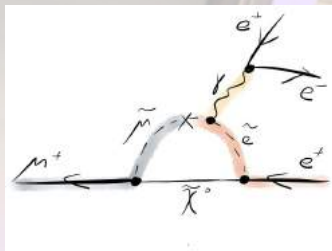BACKUP

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

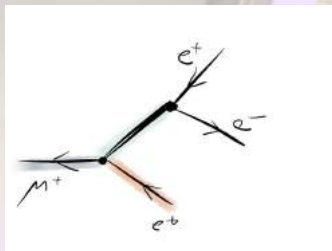SINDRUM: "Search for the decay muto3e" Nucl. Phys.,B299 1, 1988

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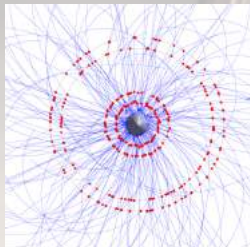SINDRUM: "Search for the decay muto3e" Nucl. Phys.,B299 1, 1988

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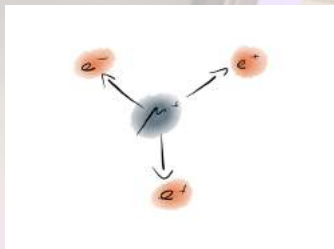
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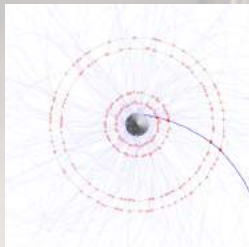
The Background
Accidental & Combinatorial

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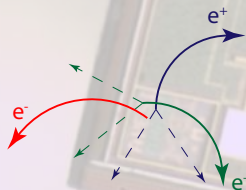- Good time and vertex resolution needed
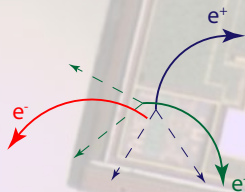
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The Background
Irreducible

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

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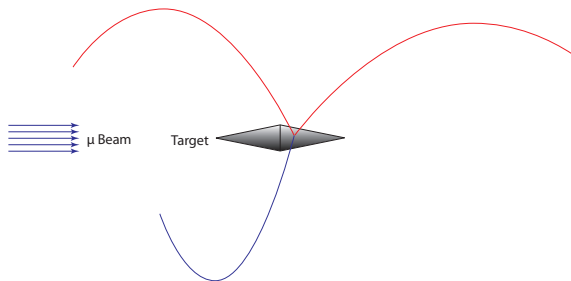- Momentum resolution is dominated by multiple scattering $\propto \sqrt{x}/p$
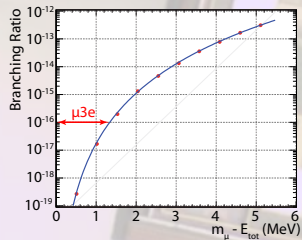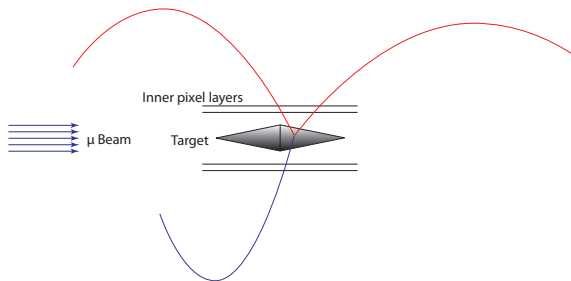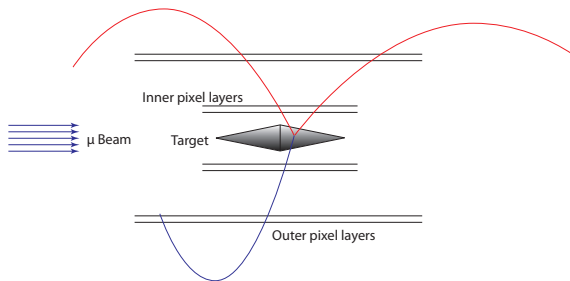
The Detector

1T magnetic field

The Detector

1T magnetic field

The Detector
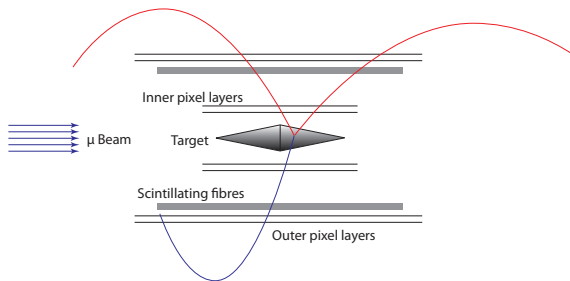
1T magnetic field

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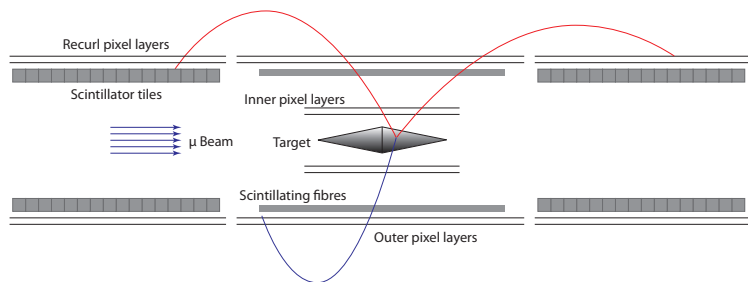
1T magnetic field

The Detector

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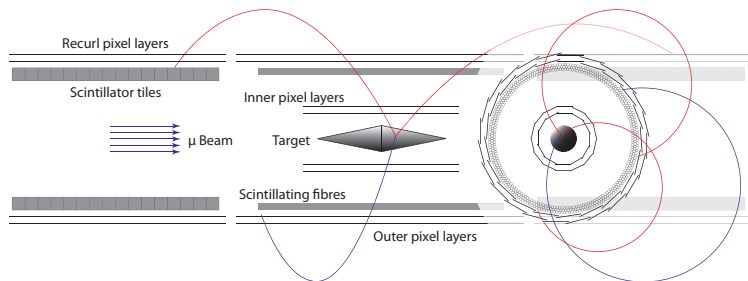## The Detector

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

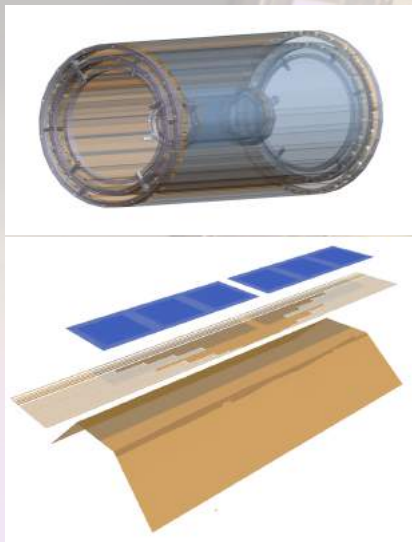# The Requirements for the Silicon Pixel Tracker

Pixel Sensor Requirements

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

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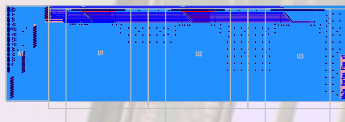
The Pixel Tracker

- Readout & Powering via Flexprints
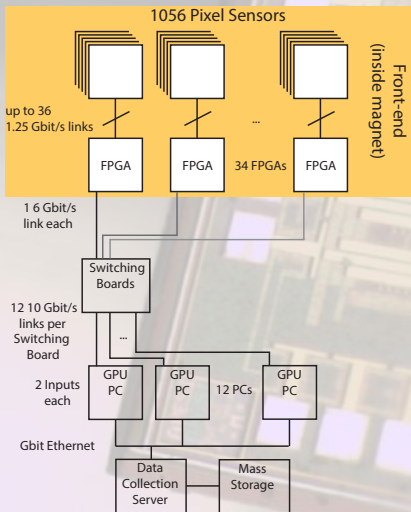- Cooling in Helium atmosphere

The Pixel Tracker

- Readout & Powering via Flexprints
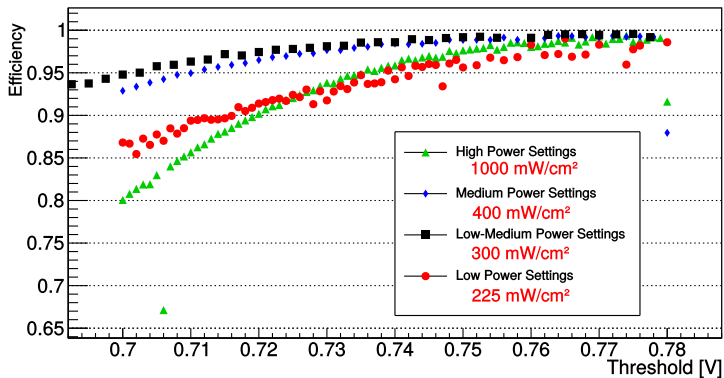- Cooling in Helium atmosphere
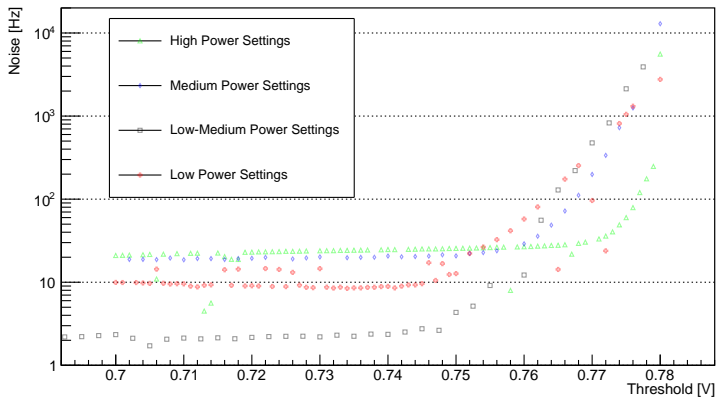
The Pixel Tracker
Readout

- Untriggered readout
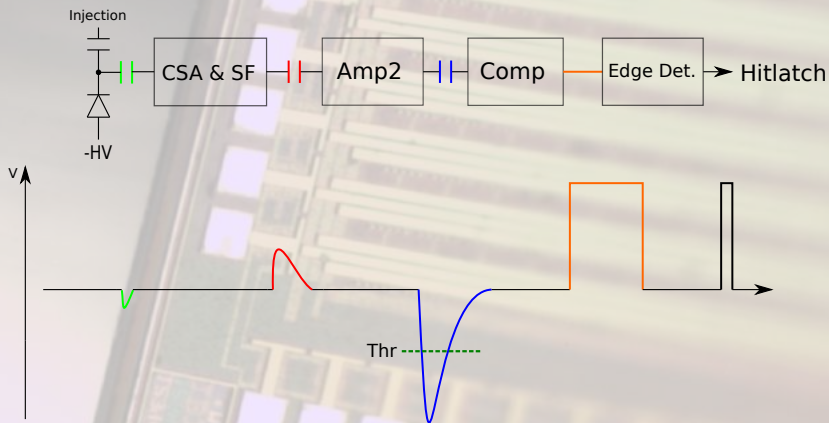- 1 Tbit/s raw data rate
- GPU based online reconstruction

Power Consumption

Power Consumption
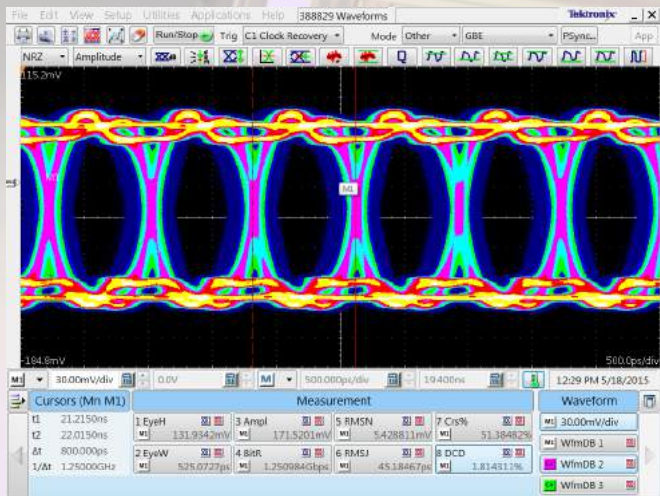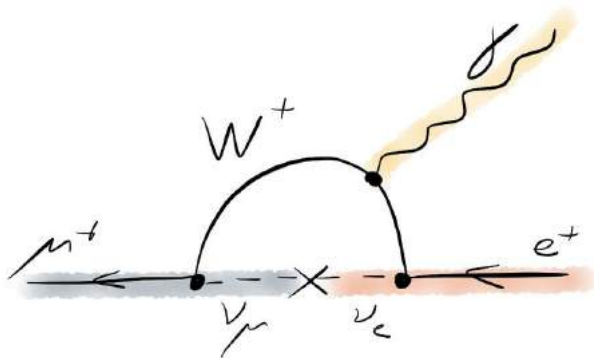
Pulse shape

Eye Diagram

MEG $\mu \to e\gamma$

LFV Landscape