The Mupix Telescope
Towards a High Rate and Low Momentum Tracking Detector

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IMPRS Seminar
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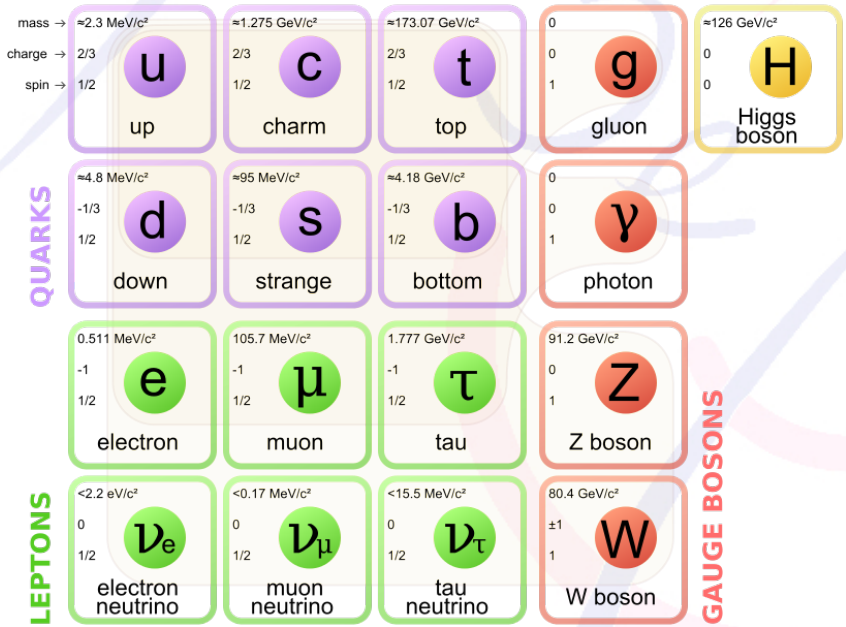
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS

FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Motivation



Standard Model

- Extremely successful model
- Three generations of matter
- Covering electromagnetic, weak and strong interactions
- Charged lepton flavor conserved

Missing

- Gravitation field
- Dark matter
- ...

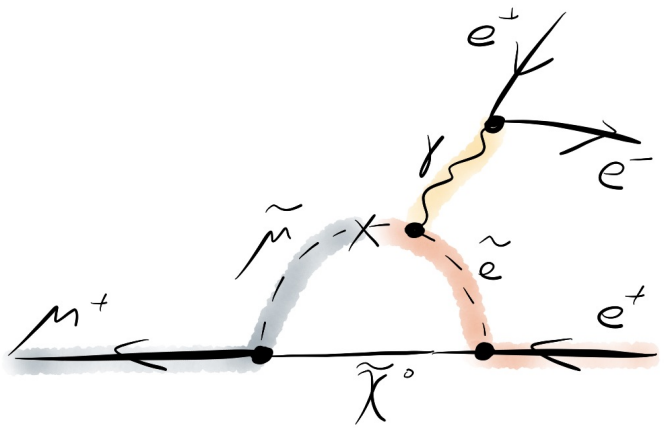
[https://upload.wikimedia.org/wikipedia/commons/1/1c/Standard_Model_of_Elementary_Particles-de.svg]

Physics beyond the SM and $\mu^+ \to e^+ e^- e^+$

Beyond the SM Theories

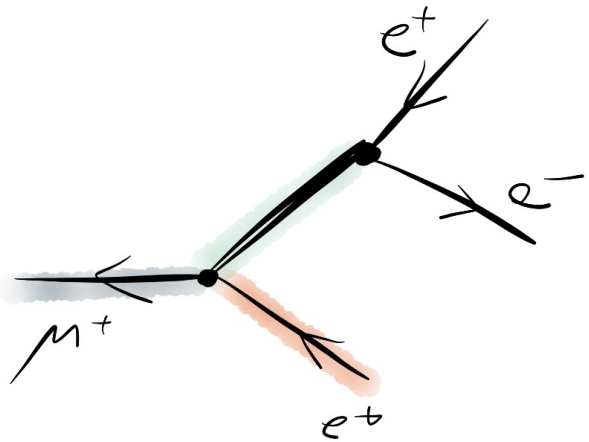
- Supersymmetry
- Extra heavy vector bosons (Z')
- Extended Higgs sector
- GUT models

→ Charged lepton flavor violation (cLFV)



SINDRUM: Searching $\mu^+ \to e^+ e^- e^+$

- Multiwire proportional chambers
- Limit set to BR $< 10^{-12}$ (1988)
- Statistically limited



Signal Decay

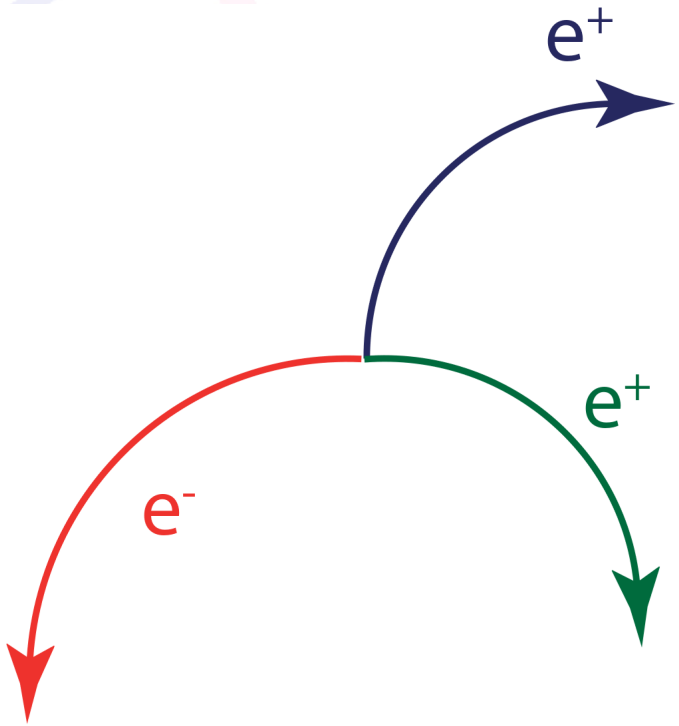
Goal: Search for cLFV decay: $\mu^+ \rightarrow e^+e^+e^-$ with sensitivity of 1 in 10^{16}

Signal decay characteristics

- $\sum p_i = 0$
- Coincident in time and space
- $E_{max} = 53$ MeV

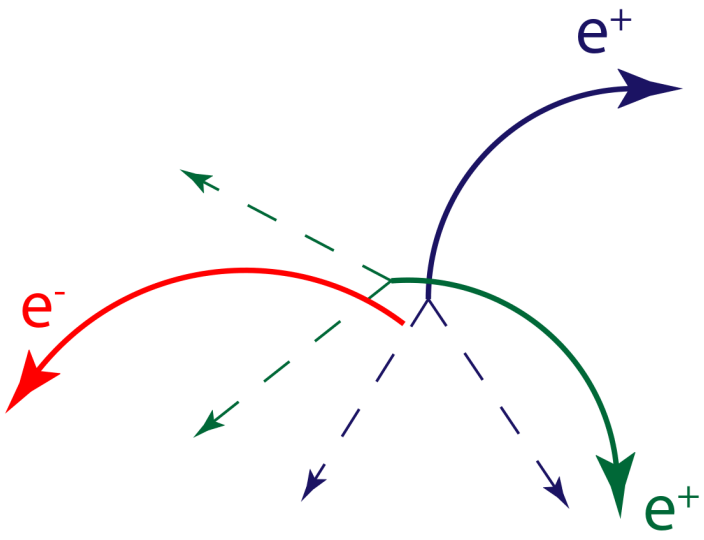
Experimental challenge

- Low momentum decay particles
  $\rightarrow$ Multiple Coulomb scattering
- High rate $\rightarrow$ combinatorics and timing
- Small BR $\rightarrow$ background suppression

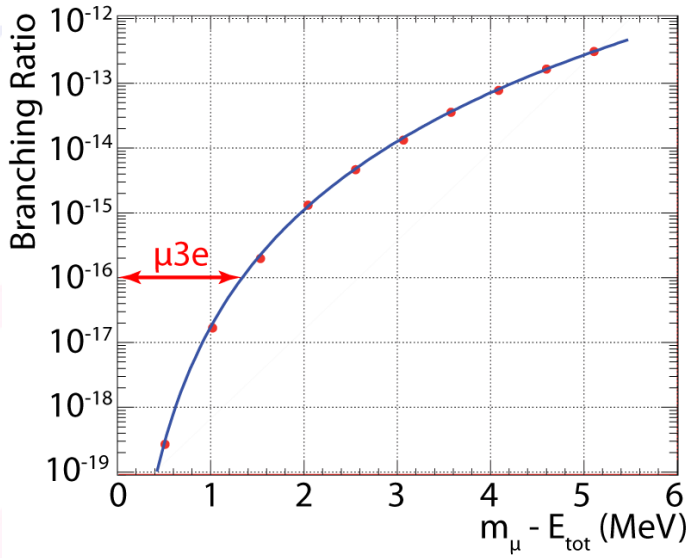


Background

Goal: Search for cLFV decay: $\mu^+ \to e^+ e^+ e^-$ with sensitivity of 1 in 10^{16}



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



Random Combinations

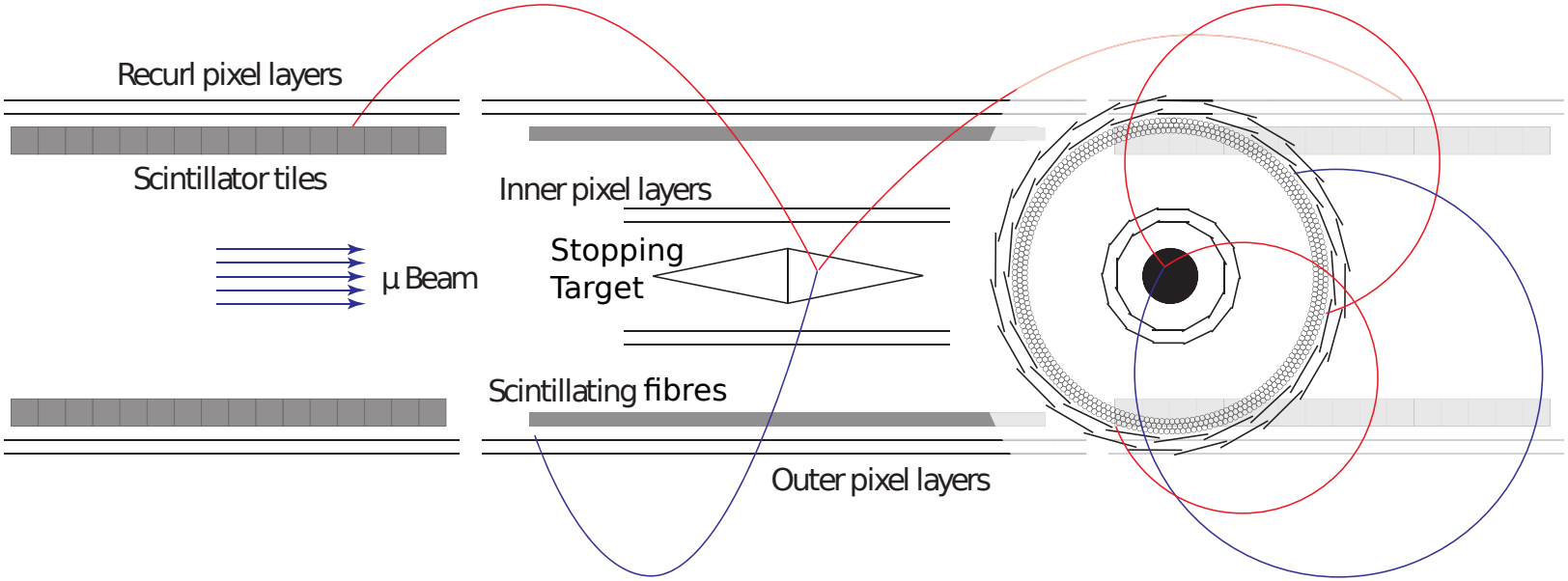
- High vertex resolution
- High time resolution

Internal Conversion

- $\mu^+ \to e^+ e^- e^+ \nu_e \bar{\nu}_\mu$
- High momentum resolution

The Detector

Concept: Stop 10^9 muons per second on target and measure decay particles

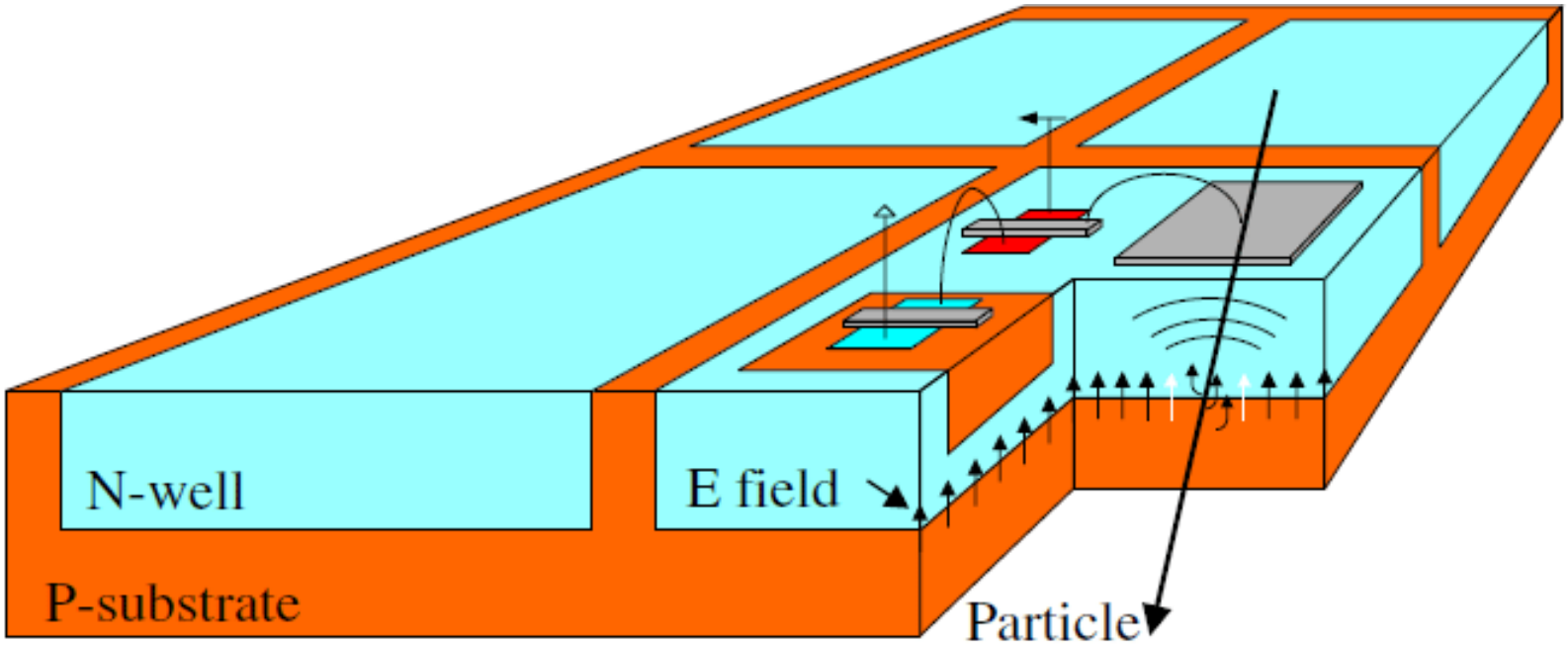


Build everything as thin as possible

→ Use thin and fast pixel sensors

HighVoltage - MonolithicActivePixelSensors (HV-MAPS)

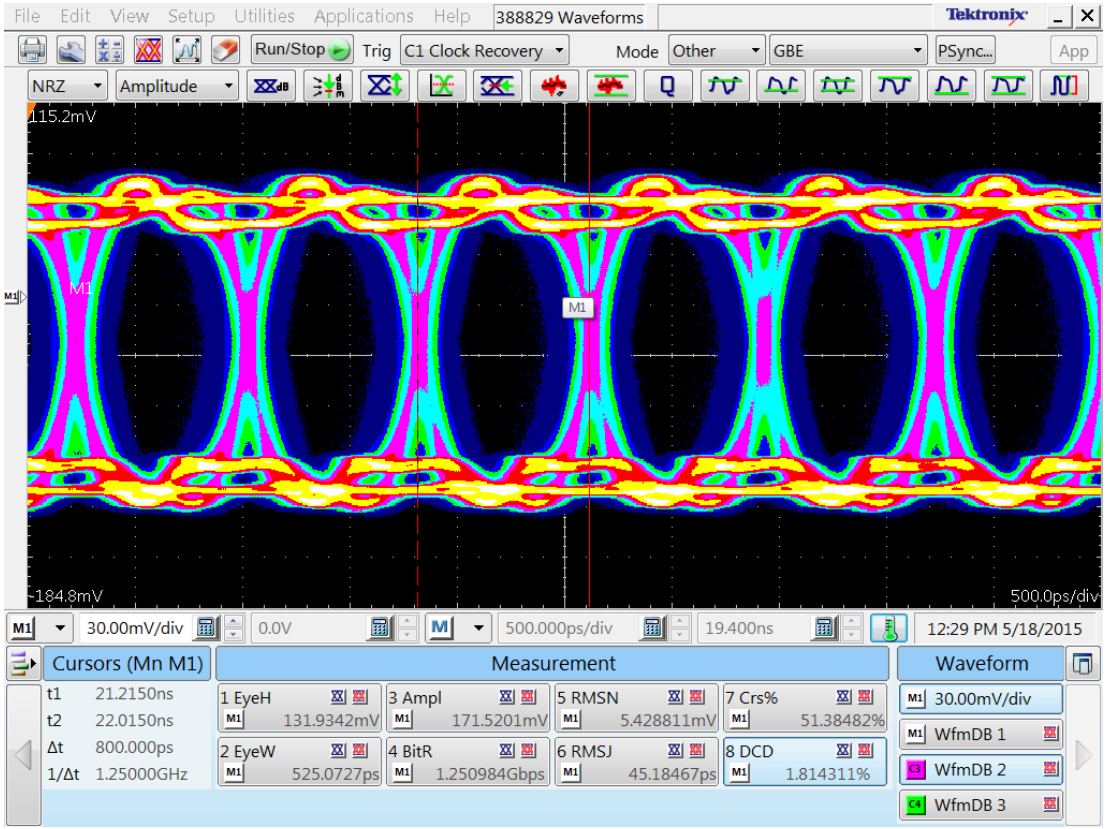
(I.Peric, P. Fischer et al., NIM A 582 (2007) 876)

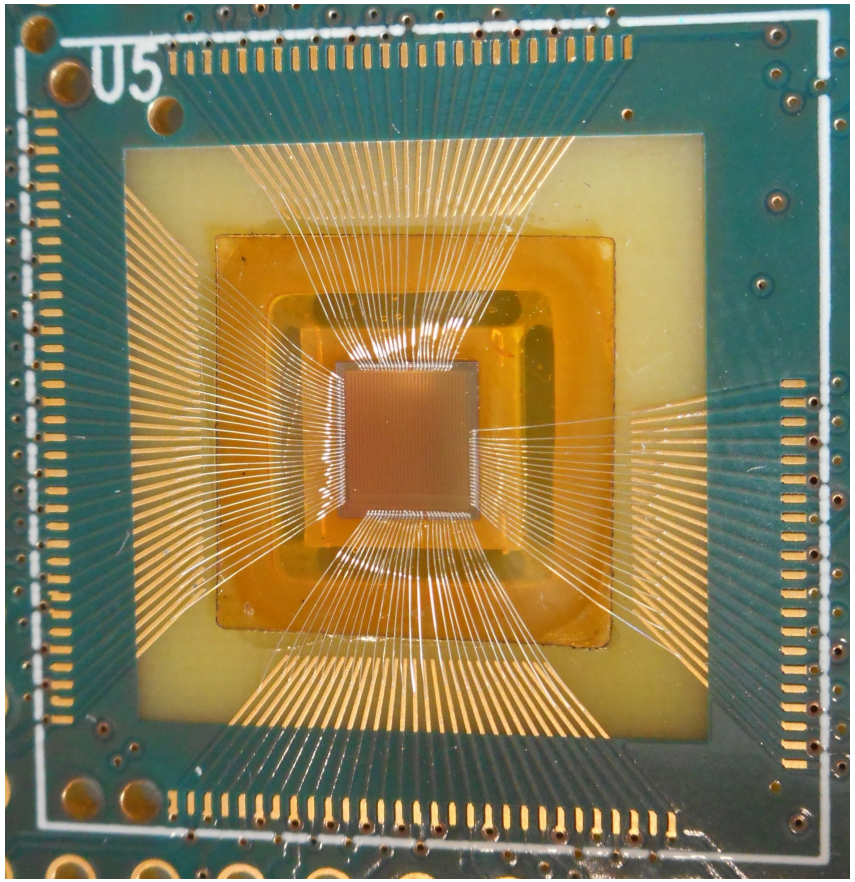


- Hit position and time read out
- 80 x 80 μm^2
- 256 x 256 pixel
- Time resolution < 11 ns
- Efficiency > 99.5 %
- 50 μm thin $\approx 0.05\%$ radiation length

The MuPix 7

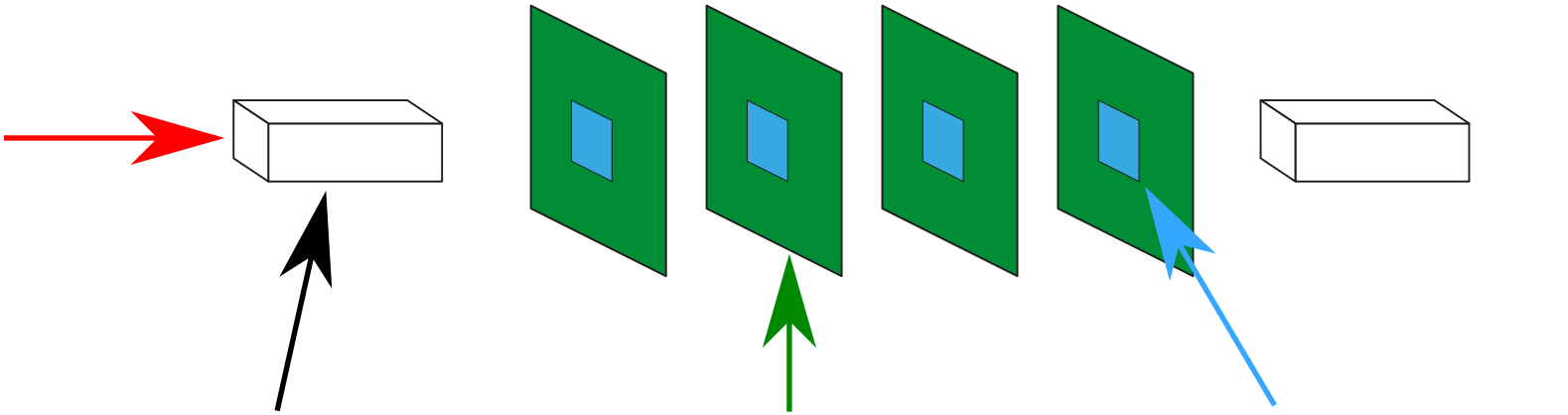
- Fully integrated readout on the chip
- On chip PLL & VCO
- 1.25 GBit/s data ≈ 33 MHits/s

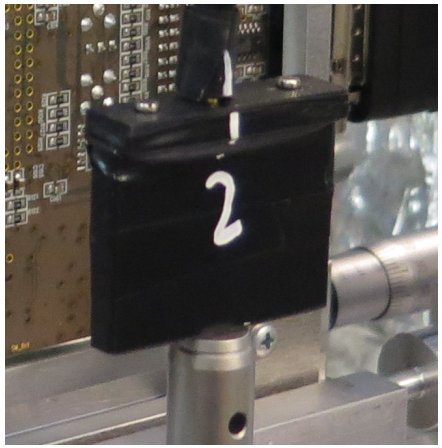




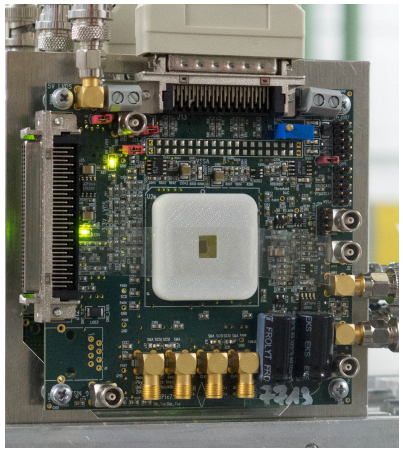
The MuPix Telescope

Idea: Build a tracking detector out of Mu3e parts as integration test and fill a gap in the choice of existing beam telescopes:

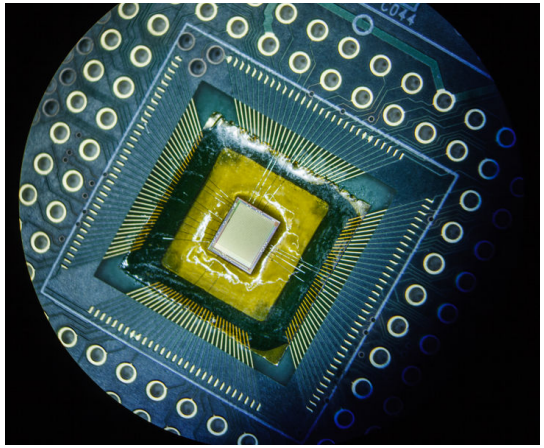




Scintillating Tiles



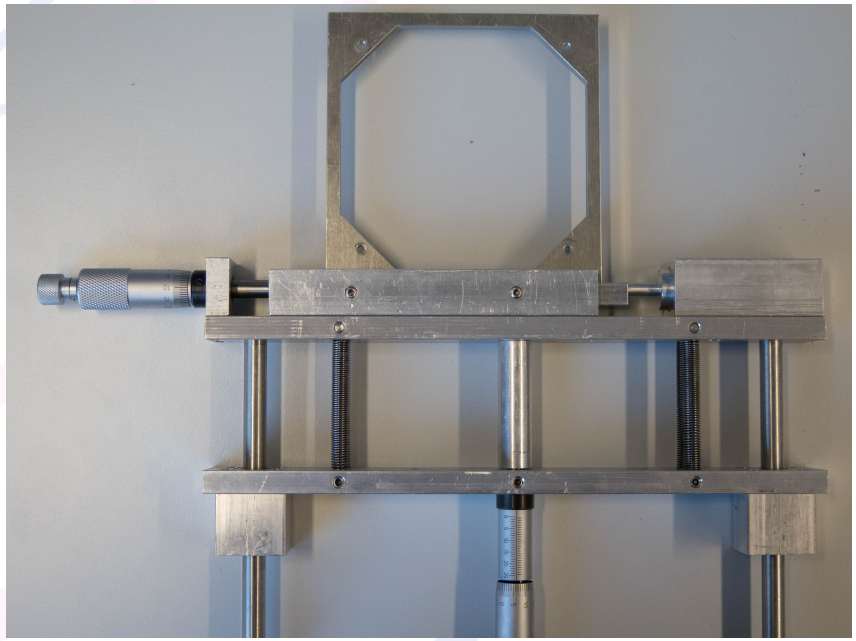
MuPix PCB



MuPix sensor

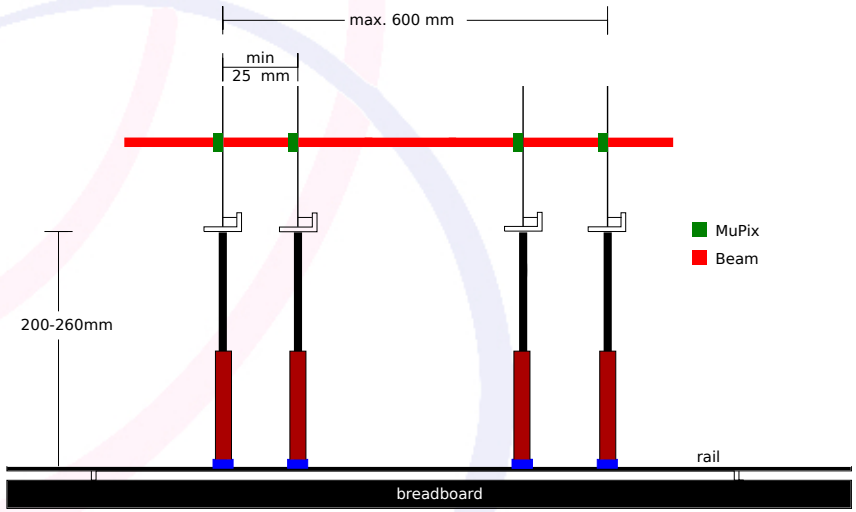
Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision



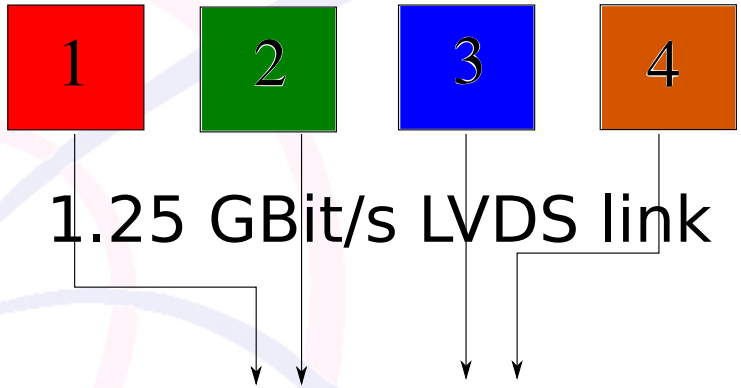
Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support



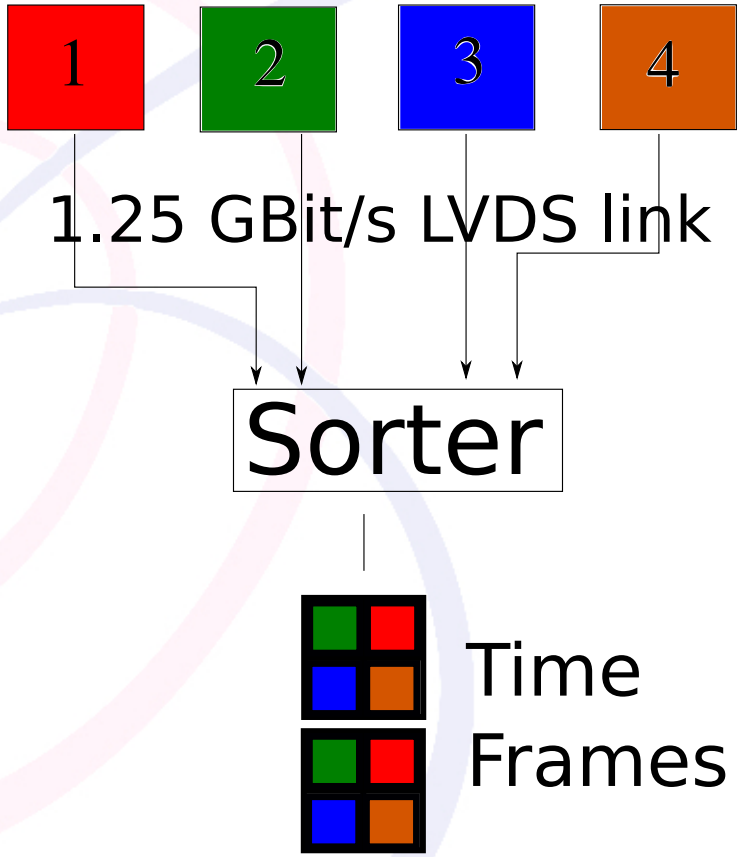
Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting



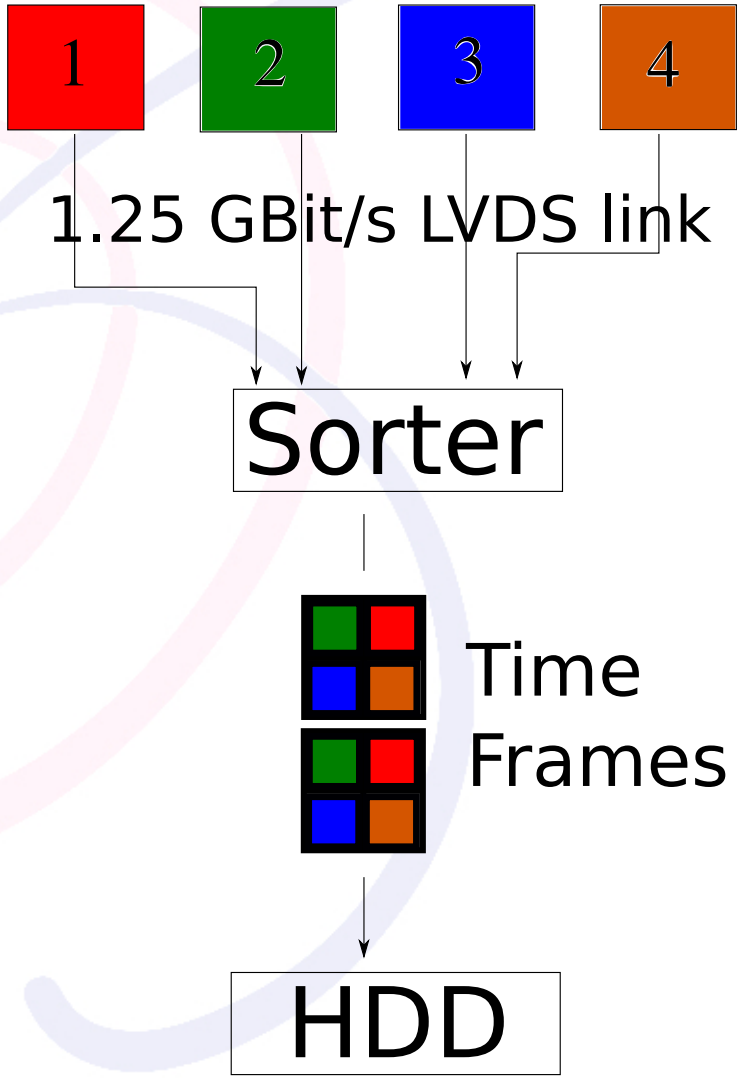
Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting
- GByte/s data transfer to PC



Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage



Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
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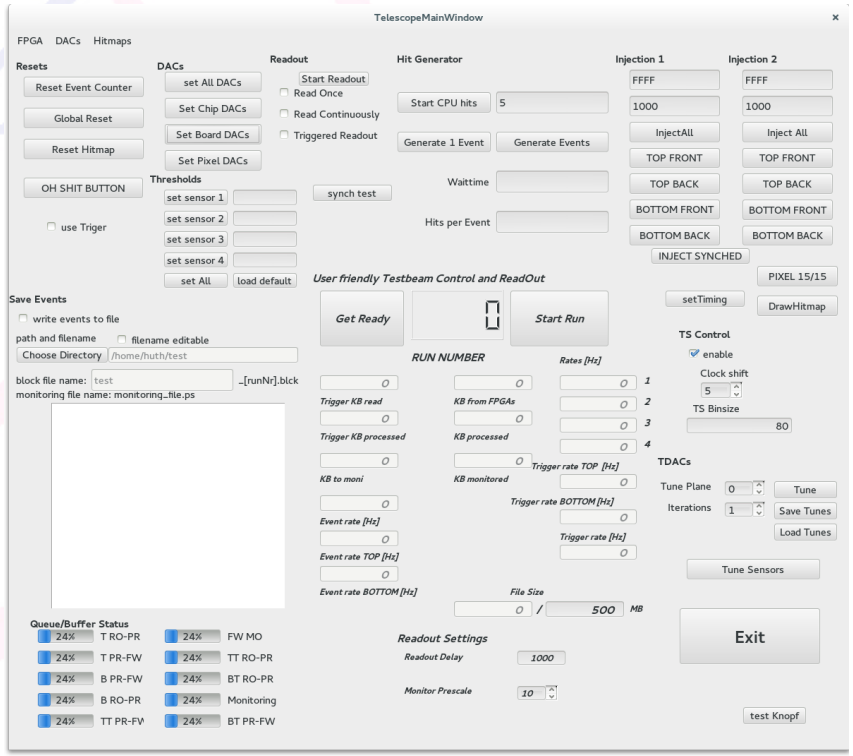
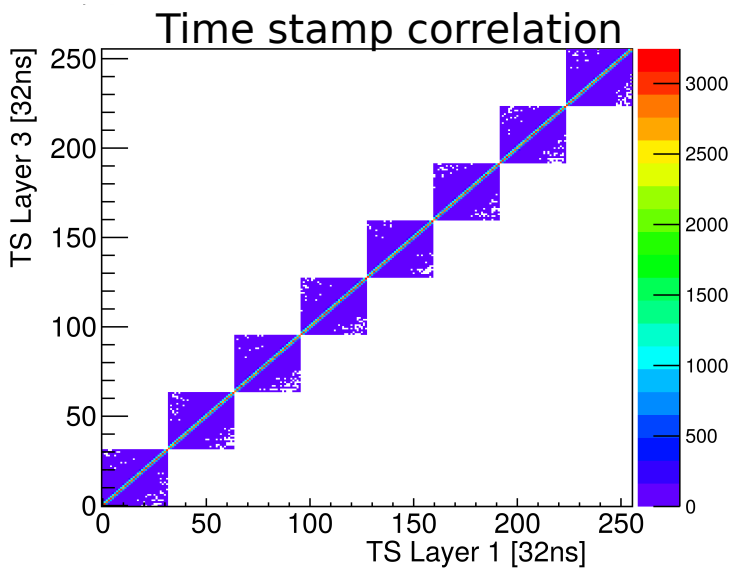
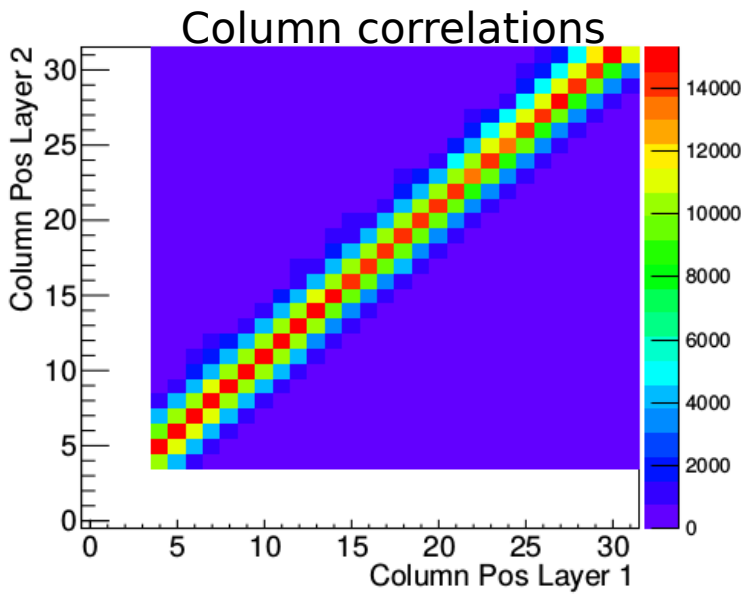
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage
- User friendly control interface



Concept, Readout & DAQ

- Custom PCB holder with 10 μm precision
- Commercial mechanical support
- Differential high speed links: 1.25 GBit/s
- Online time sorting
- GByte/s data transfer to PC
- Up to 60 MByte/s final data storage
- User friendly control interface
- Online monitoring, tracking and efficiency calculation





DESY Testbeam

Goals: Measure

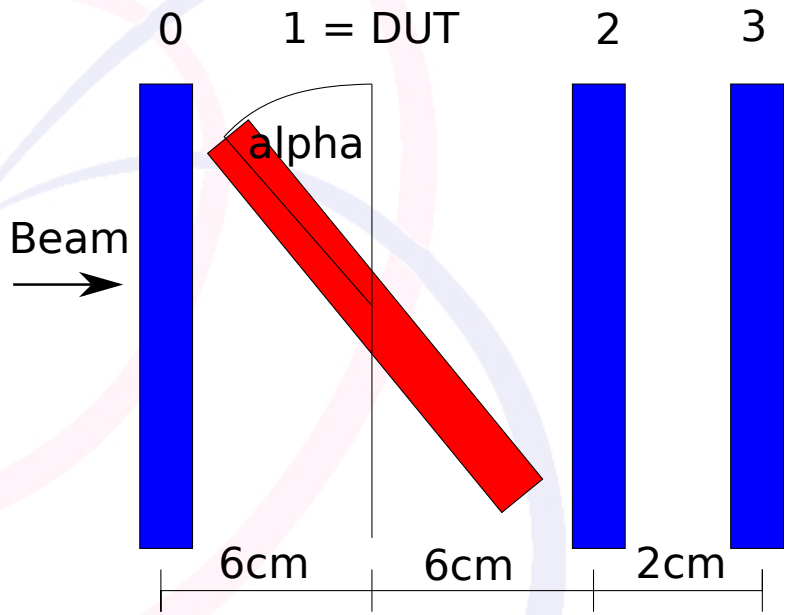
- Efficiency
- Noise
- Time resolution

Beam:

- Positrons
- 4-6 GeV/c
- Rate $<$ 10 kHz

Setup:

- Rotated device under test
- DMA and GPU tests

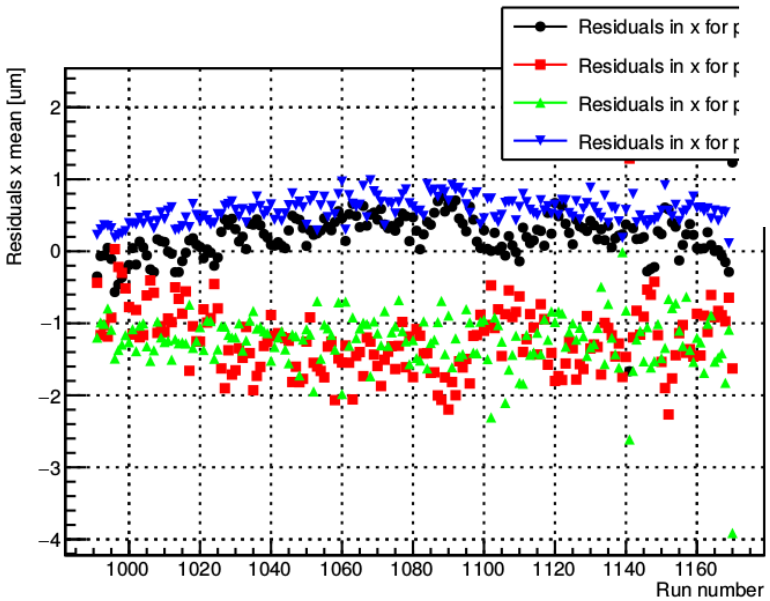


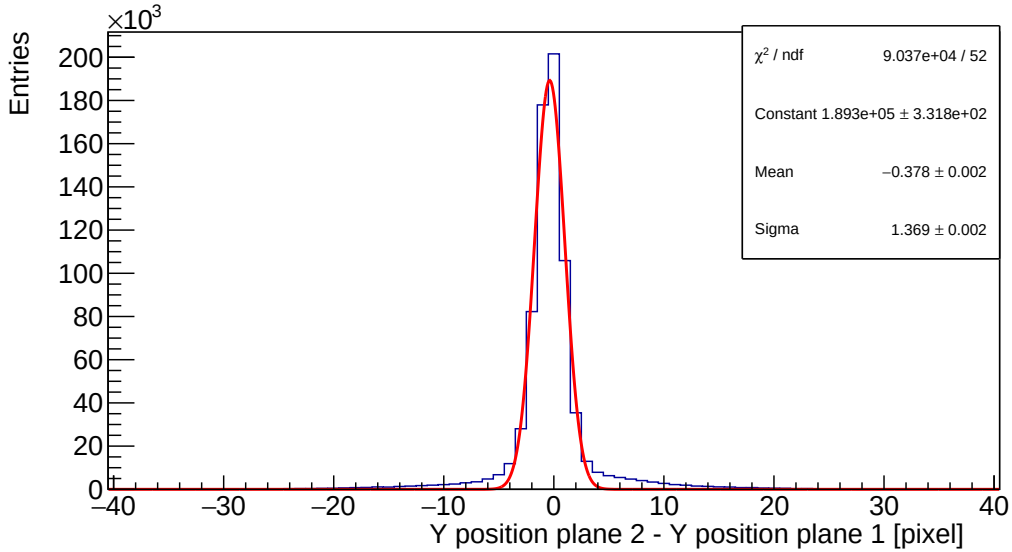
High rate facilities we also use:

- HIPA at PSI
- SPS at CERN

Performance and Alignment

- Track rate $\mathcal{O}$ (500Hz)
- Precise mechanical alignment $\mathcal{O}(100\,\mu m)$
- Very stable over time
- Z distances $\mathcal{O}$ (5 cm)





- Automatic track based alignment
- Software alignment precision $\mathcal{O}(1\,\mu m)$

Track Model

Trackmodel: Straight track without scattering

$$\vec{x}(z) = \vec{x_0} + \vec{a} \cdot z$$

$\rightarrow \mathcal{X}^2$ can be analytically minimized

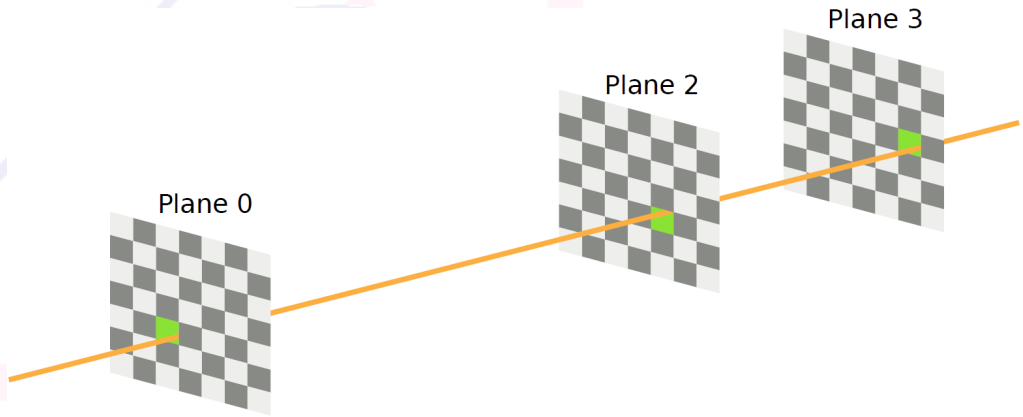
$$\mathcal{X}^2 = \sum_{i=1}^{n} \left(\frac{(x_i - (x_0 + a_x \cdot z_i))^2}{\sigma^2_{x_{m_i}}} + \frac{(y_i - (y_0 + a_y \cdot z_i))^2}{\sigma^2_{y_{m_i}}} \right)$$

$$\text{assuming } \sigma_{x/y_{m_i}} = \text{pixel resolution} = \frac{\text{pixel size}}{\sqrt{12}}$$

$\rightarrow$ Fast and robust track model!

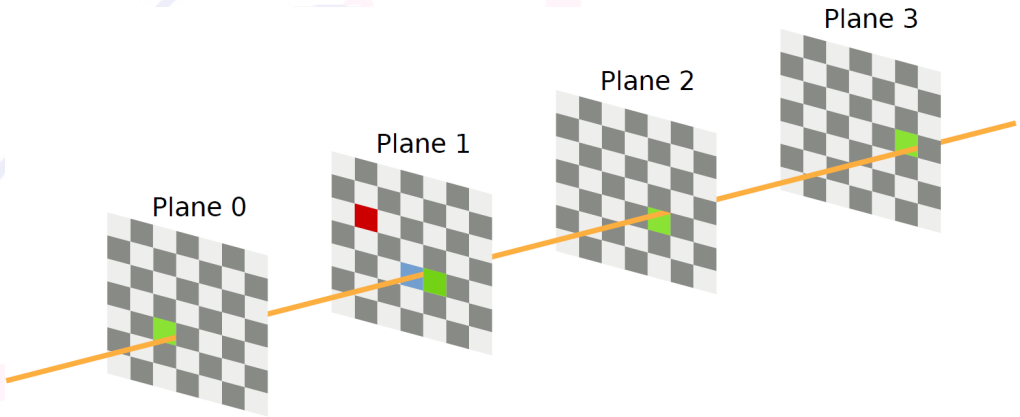
Analysis Procedure

- Define coordinate system and fit track



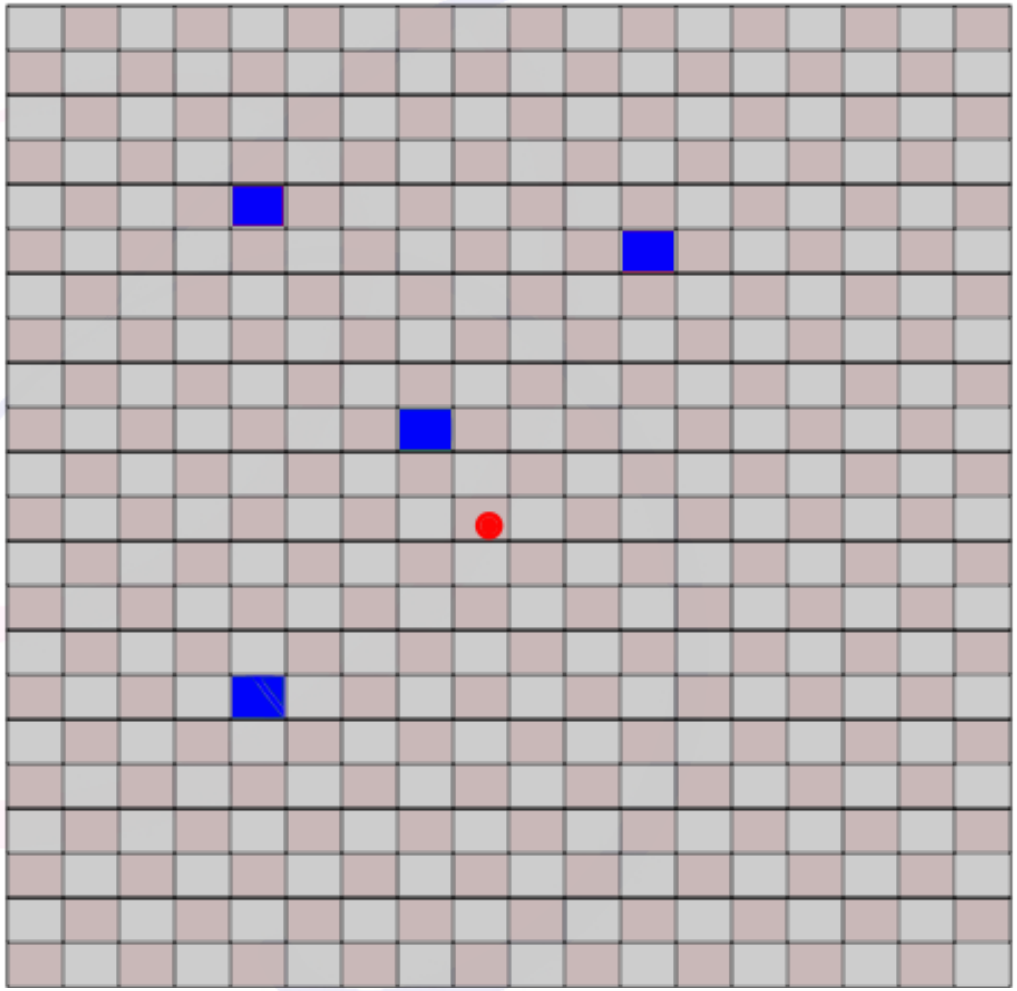
Analysis Procedure

- Define coordinate system and fit track
- Define device under test



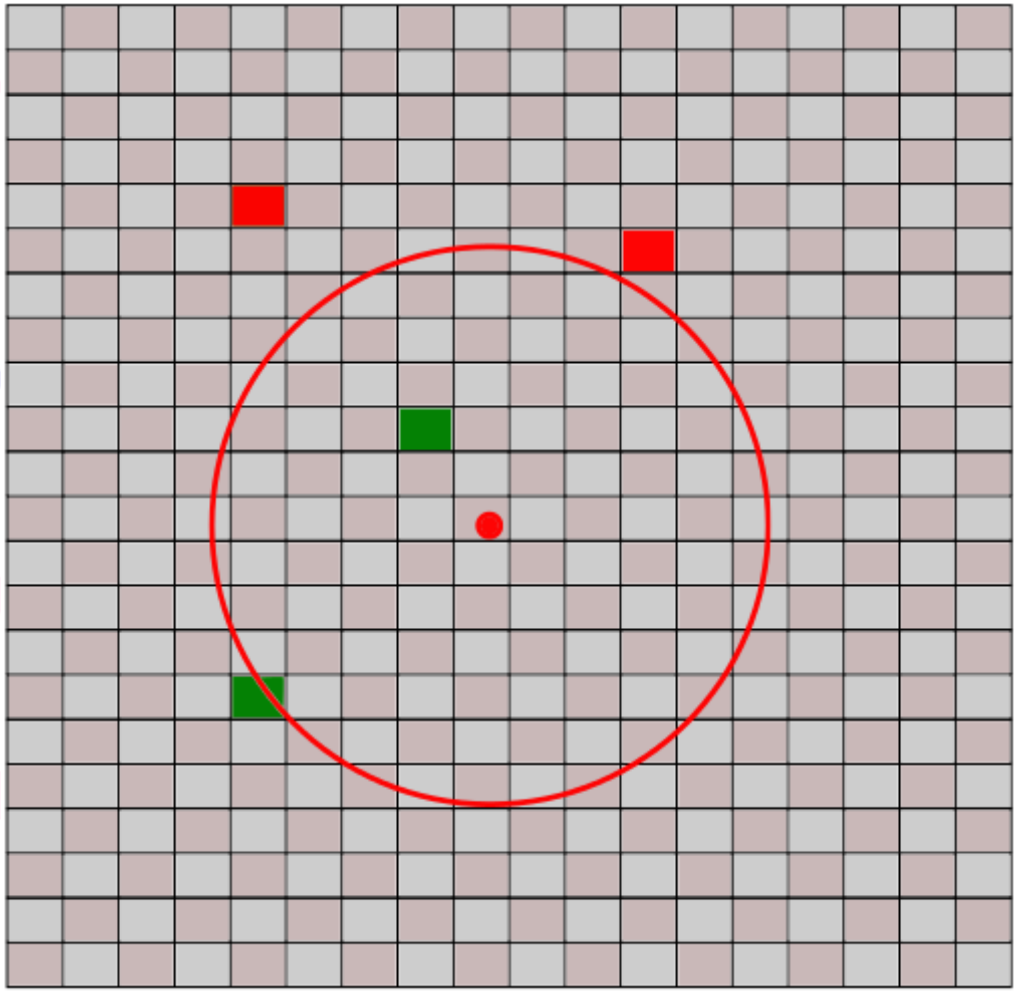
Analysis Procedure

- Define coordinate system and fit track
- Define device under test
- Extrapolate track and check hits



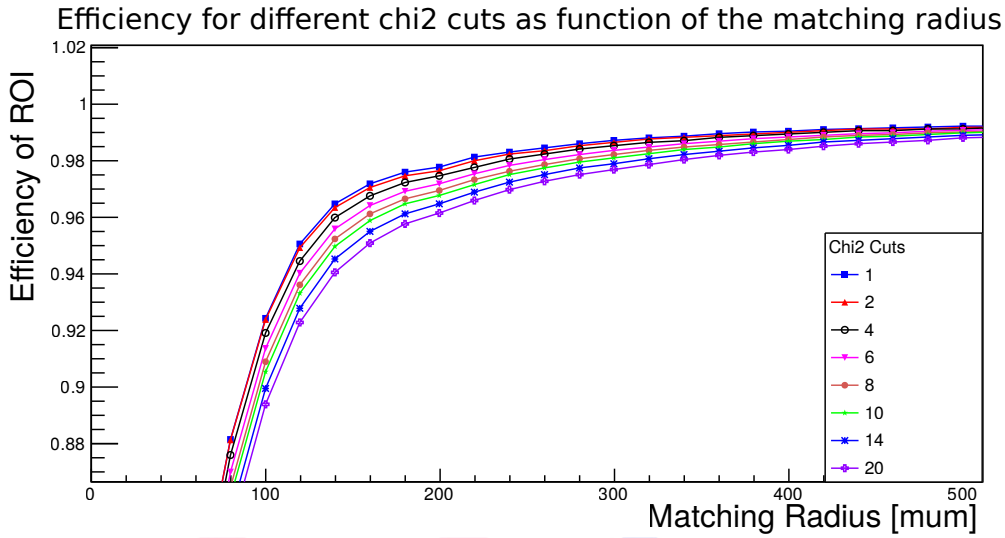
Analysis Procedure

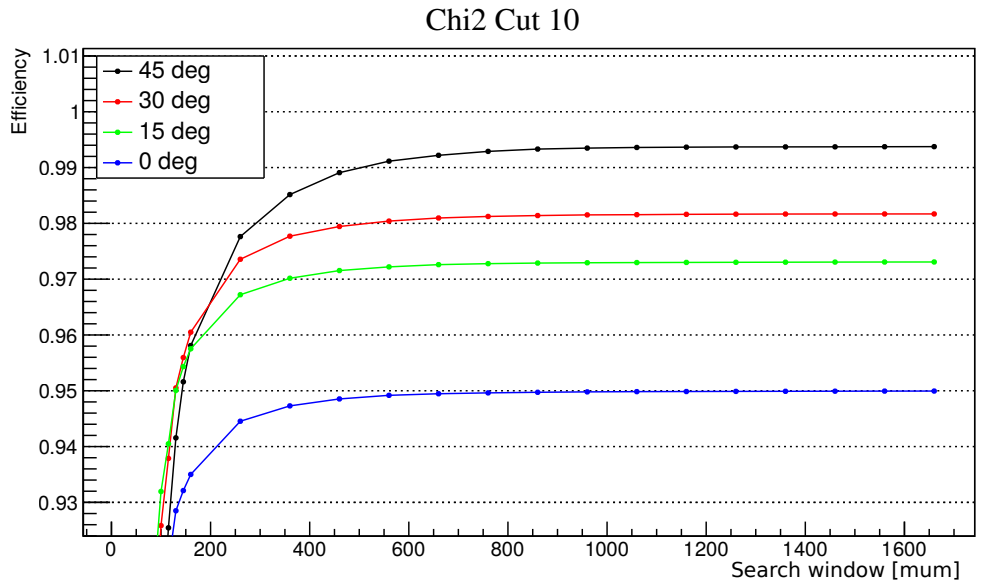
- Define coordinate system and fit track
- Define device under test
- Extrapolate track and check hits
- Define a search window and match closest hit



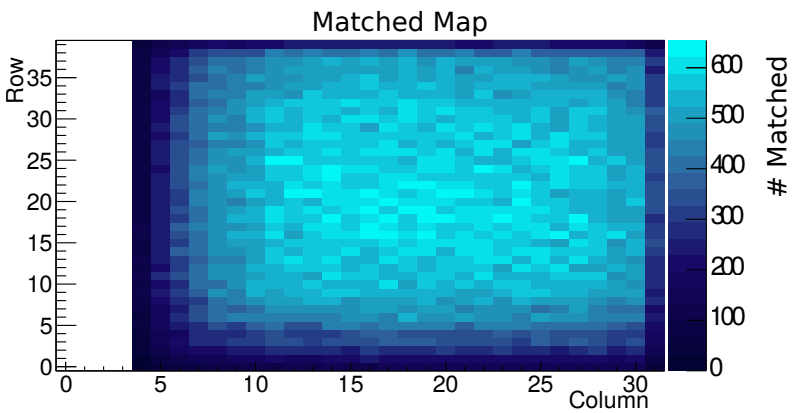
Analysis Procedure

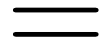
- Define coordinate system and fit track
- Define device under test
- Extrapolate track and check hits
- Define a search window and match closest hit
- Analyze effects

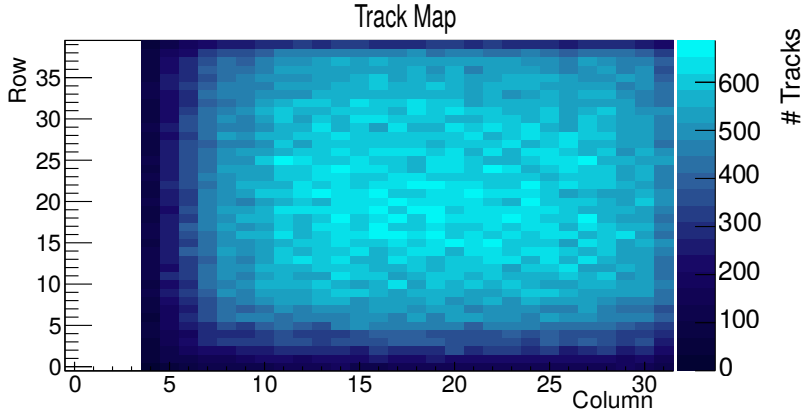




Efficiency Analysis







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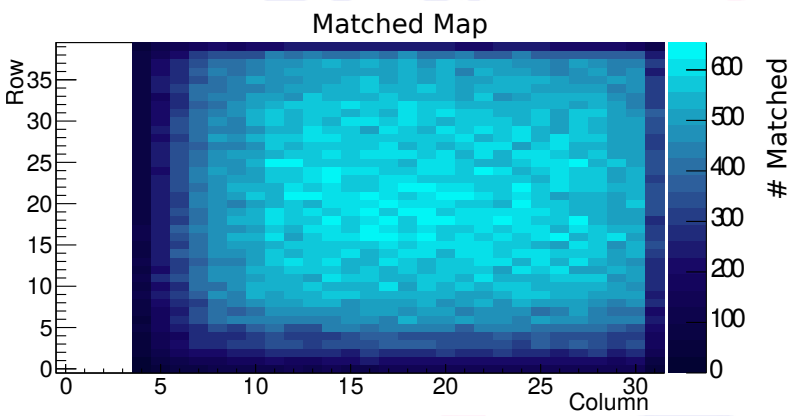

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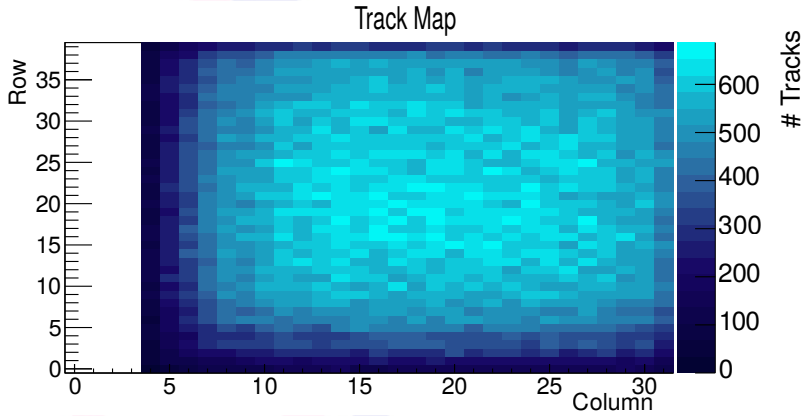

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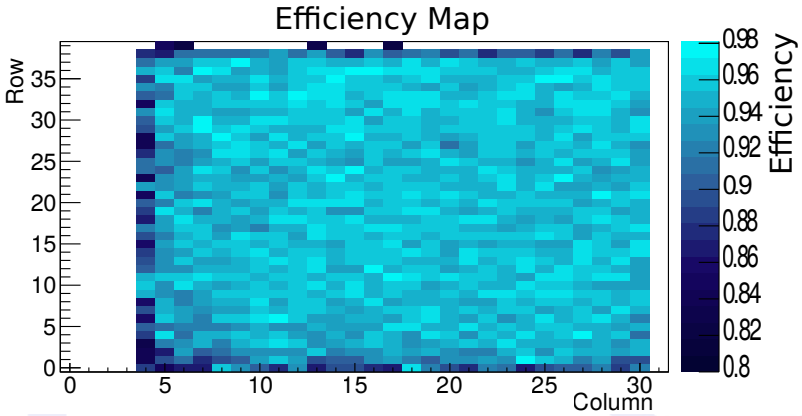
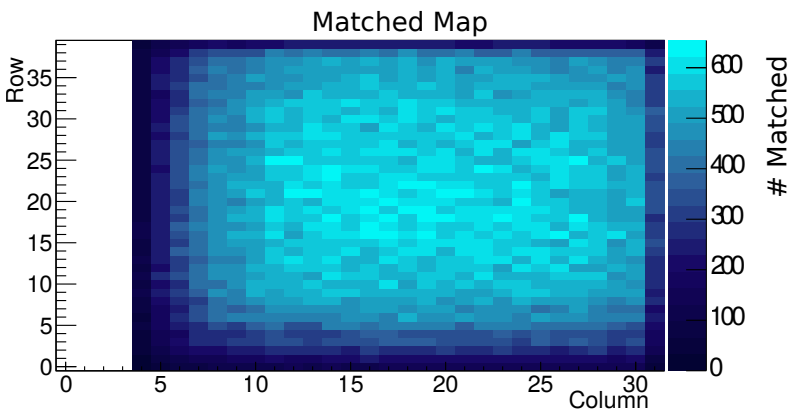


$$\text{Eff} = \frac{\#\text{ matched}}{\#\text{ tracks}}$$

$$\text{Noiserate}_{\text{pixel}} = \frac{\#\text{hits} - \#\text{ matched}}{\#\text{ runtime} \cdot \#\text{ pixel}}$$

Efficiency Analysis



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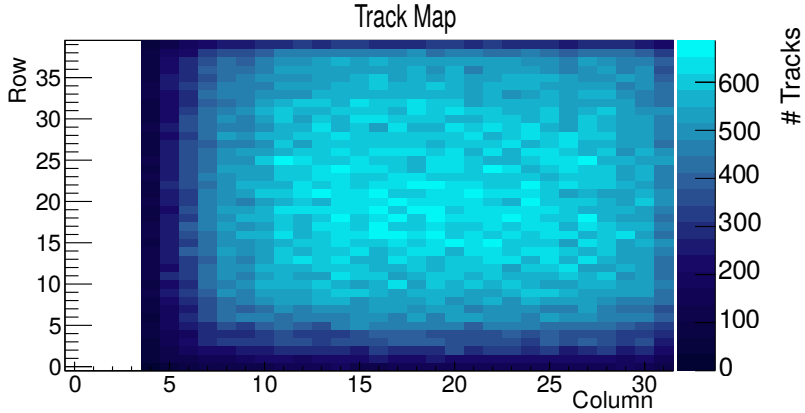

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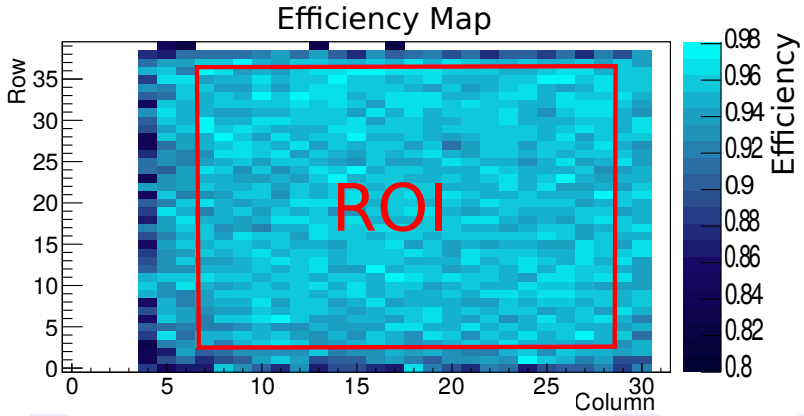
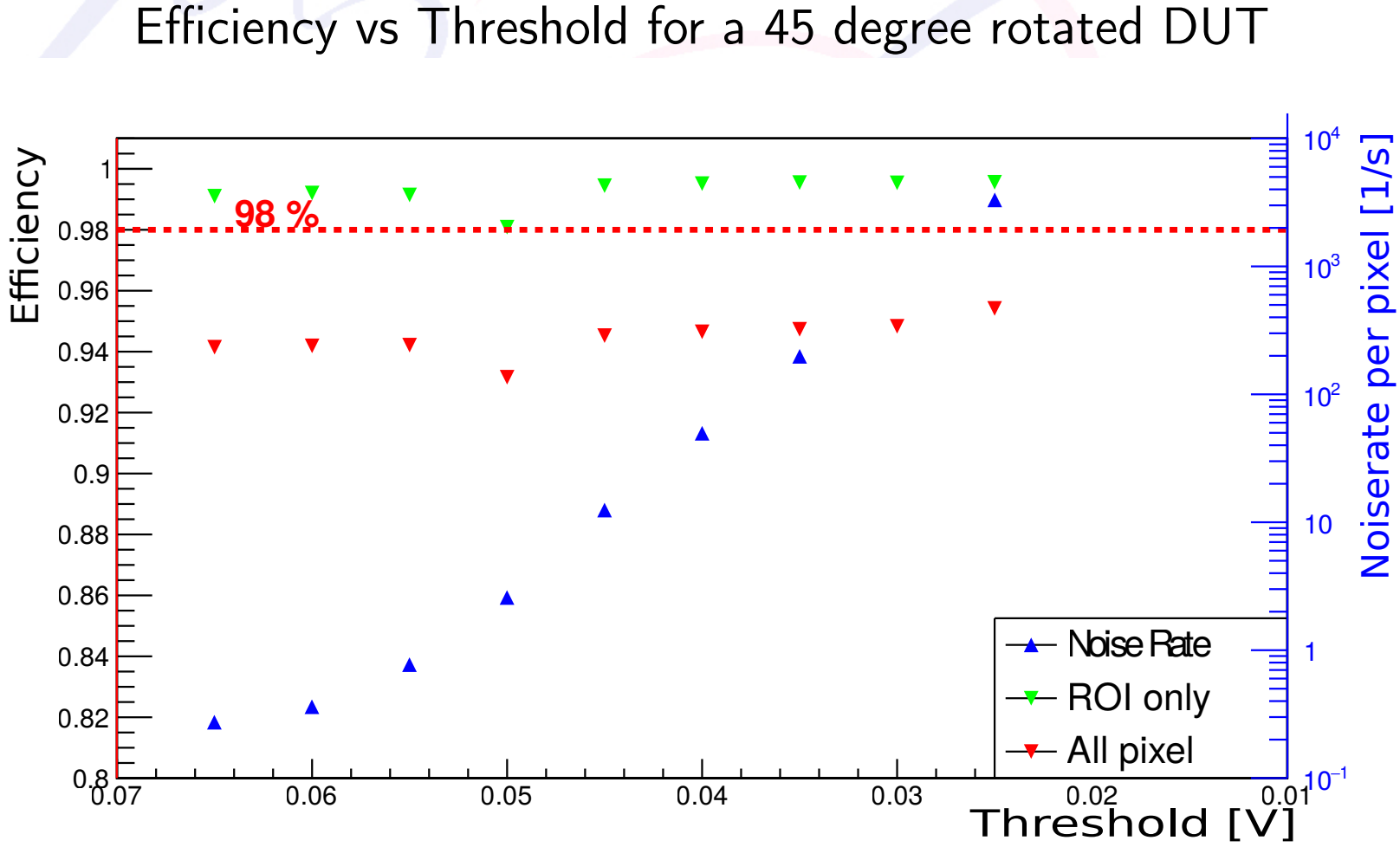


$$\text{Eff} = \frac{\#\text{ matched}}{\#\text{ tracks}}$$

$$\text{Eff}_{\text{ROI}} = \frac{\#\text{ matched}_{\text{ROI}}}{\#\text{ tracks}_{\text{ROI}}}$$

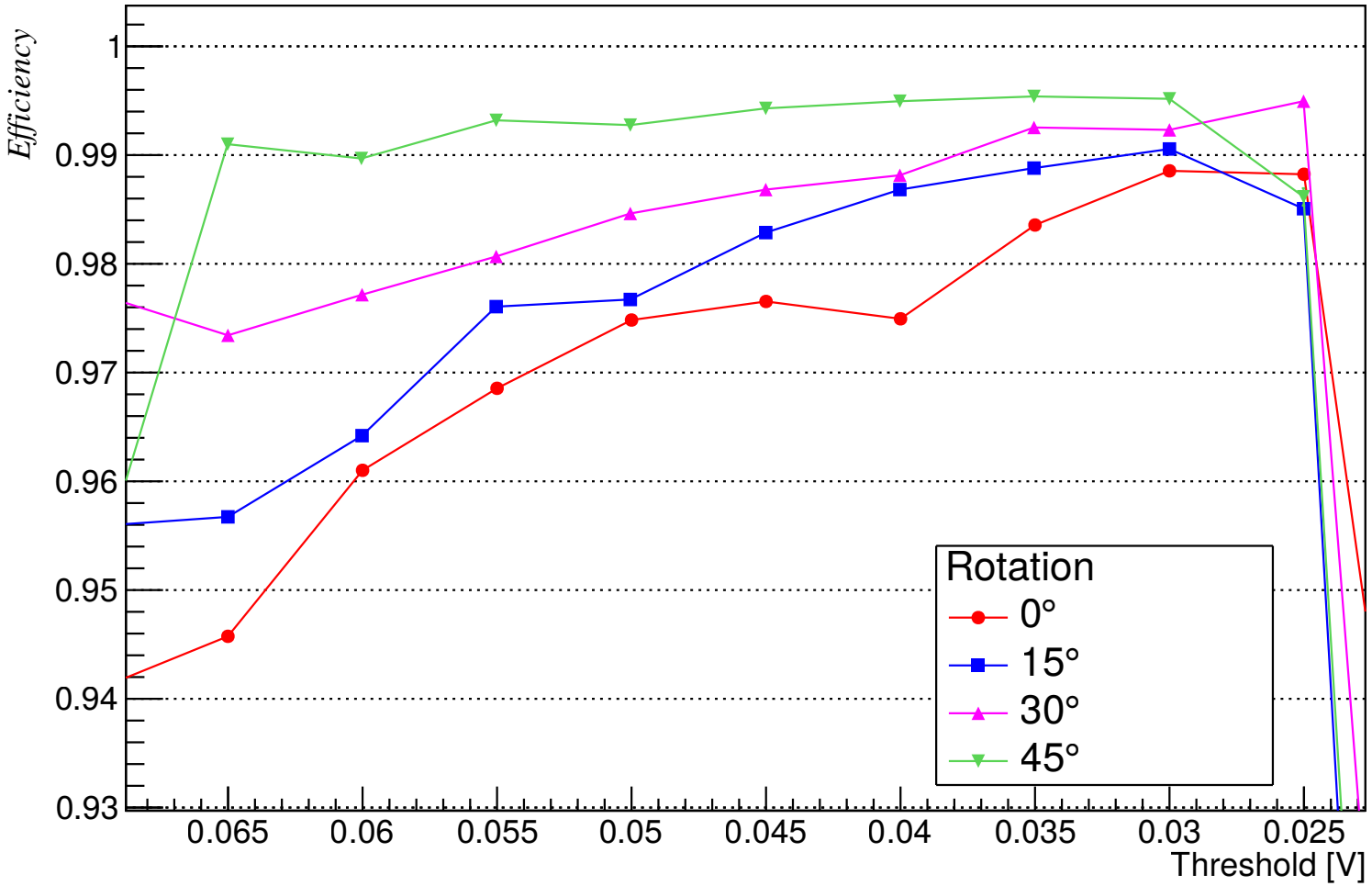
$$\text{Noiserate}_{\text{pixel}} = \frac{\#\text{hits} - \#\text{ matched}}{\#\text{ runtime} \cdot \#\text{ pixel}}$$

Efficiency Scan



Efficiency Summary

Efficiency vs Threshold for a 800 μm search window



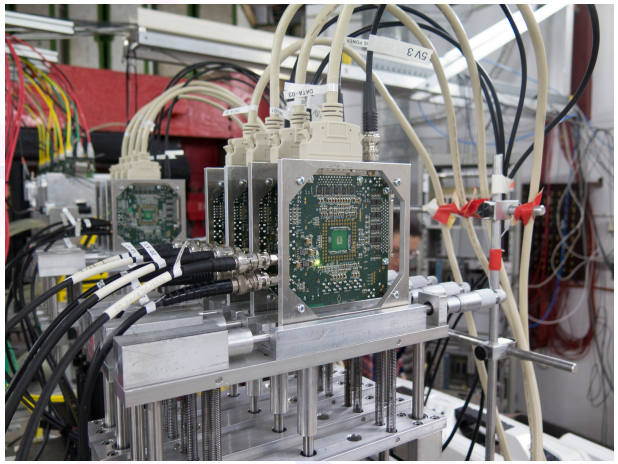
Conclusion

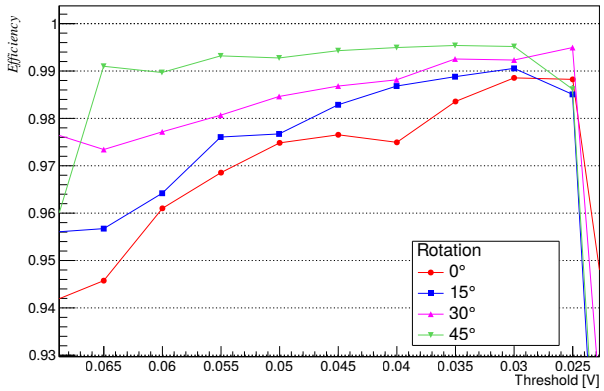
- First running integrated HV-MAPS System
- High Rate capabilities $\mathcal{O}$ (1MHz)
- Important tool to test scaling
- High system efficiency > 99 %

Outlook

- 8 planes
- Improve DUT integration
- Use existing DAQ to develop module tests and readout
- Next prototype with a size of $> 1 \times 1$ cm^2
- Better timing: timestamps created by faster clock

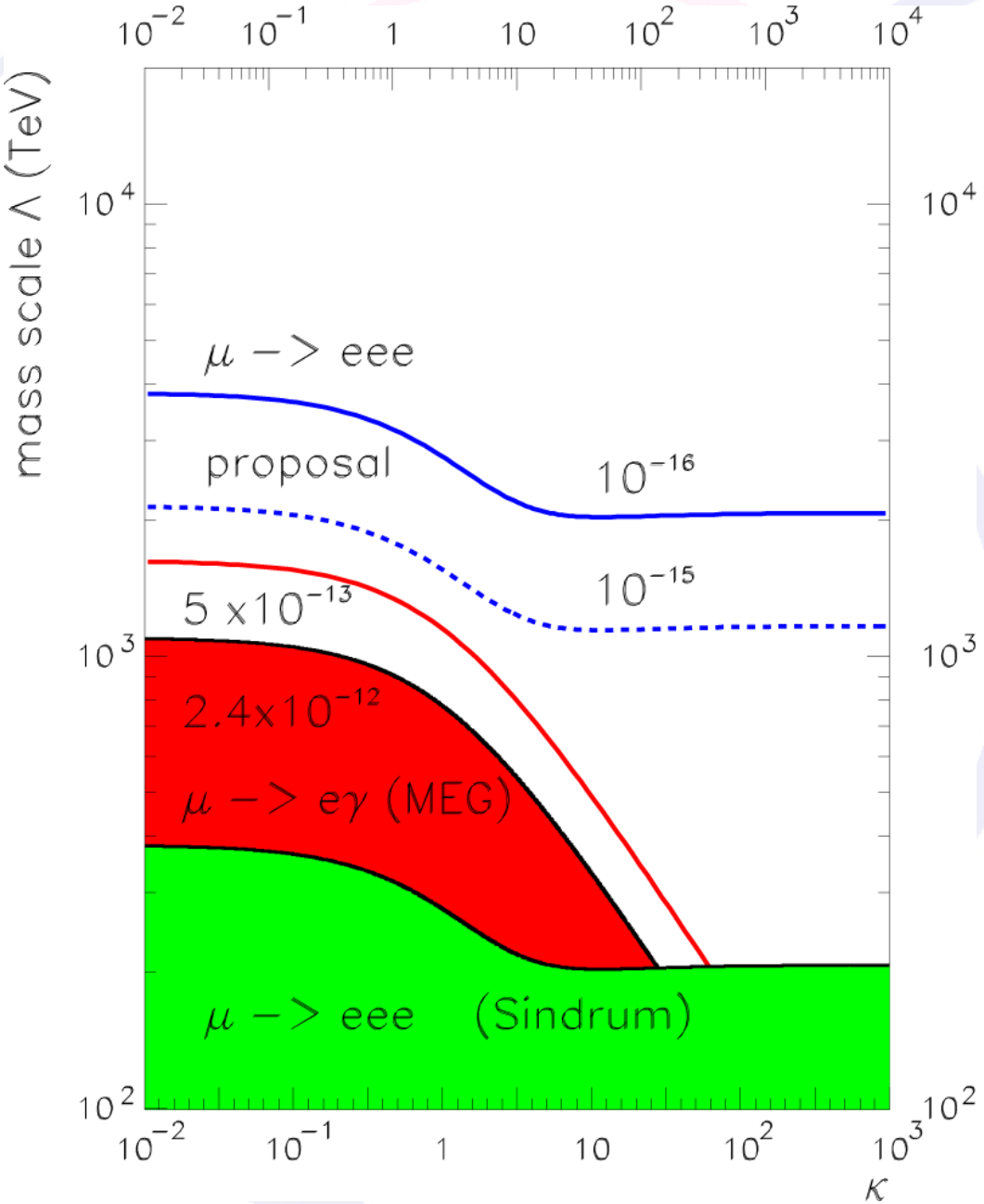
Thanks to the Helmholtz alliance for providing beam time!



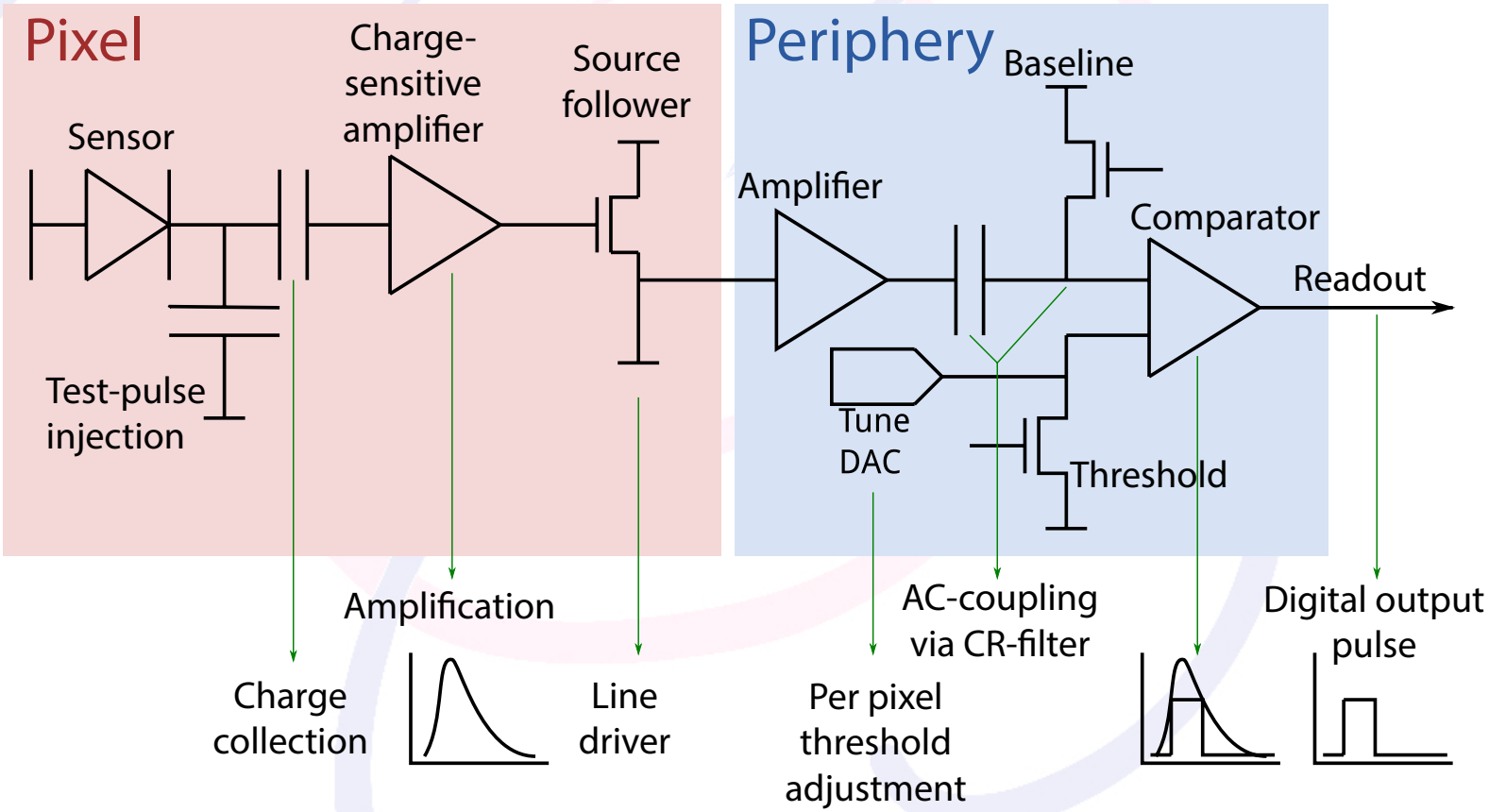



Thank
you!

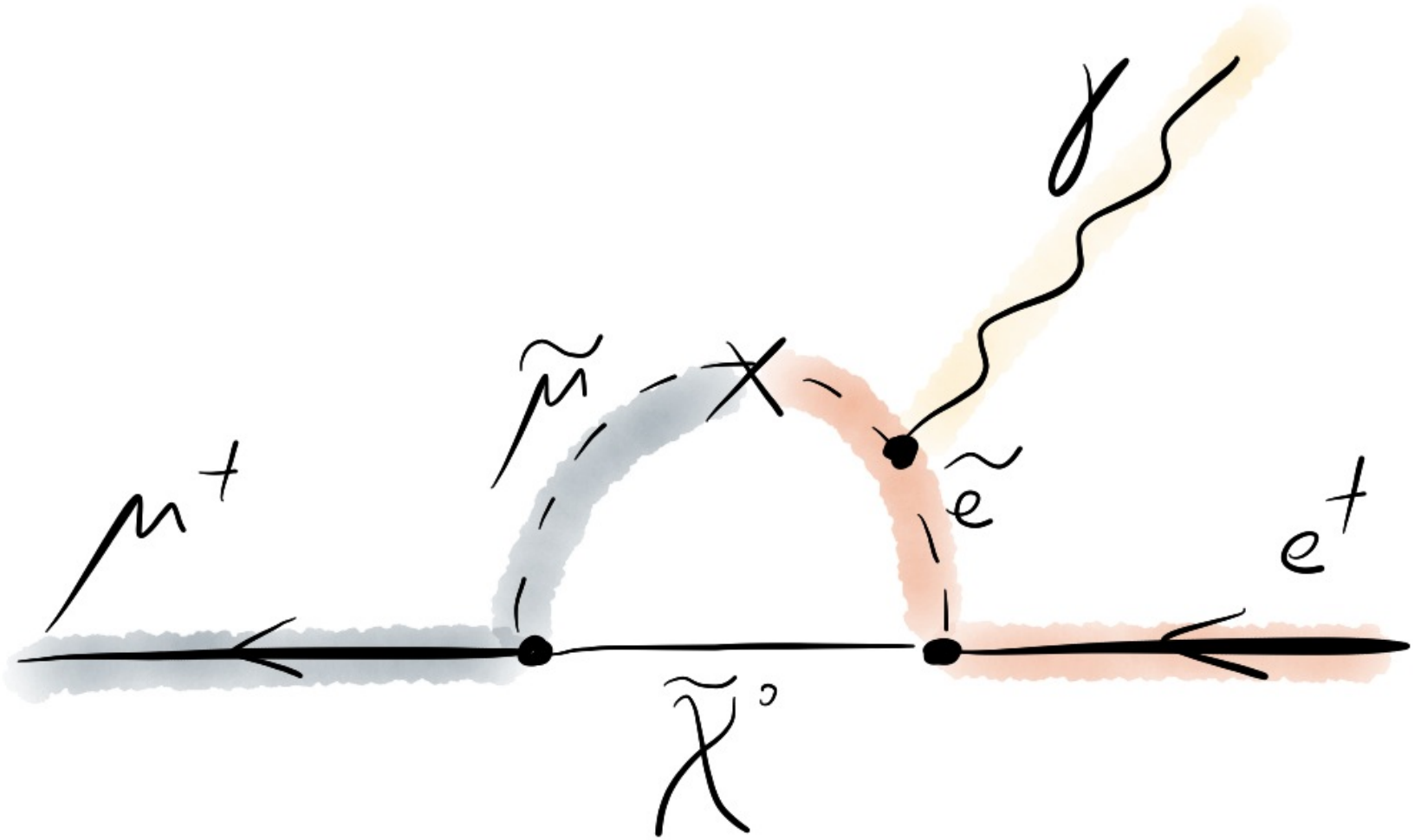
Mass Scale Sensitivity



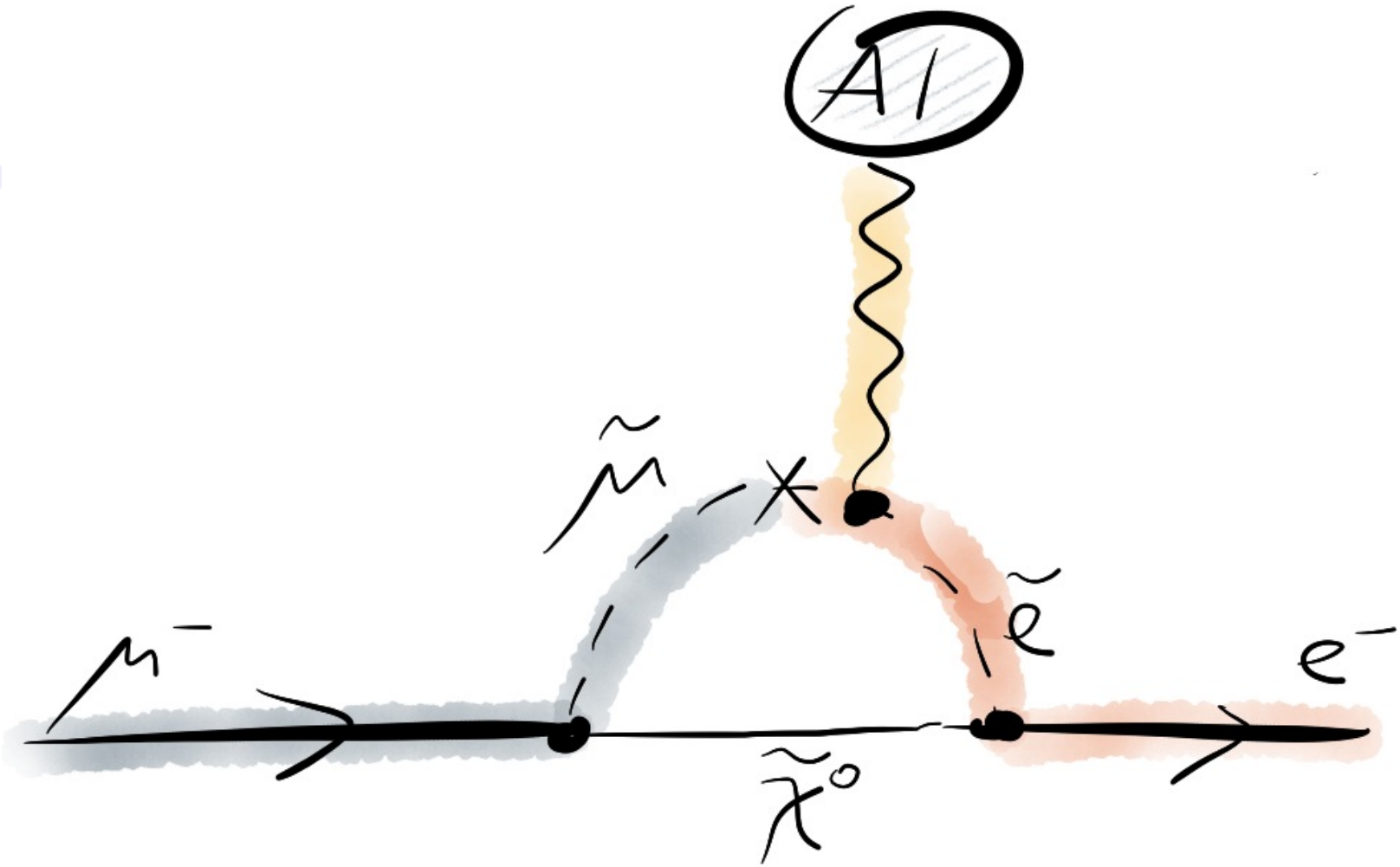
Pixel Electronics



$\mu \to e\,\gamma$



$\mu \to e$



Muon decays history