The High-Voltage Monolithic Active Pixel Sensor for the Mu3e Experiment

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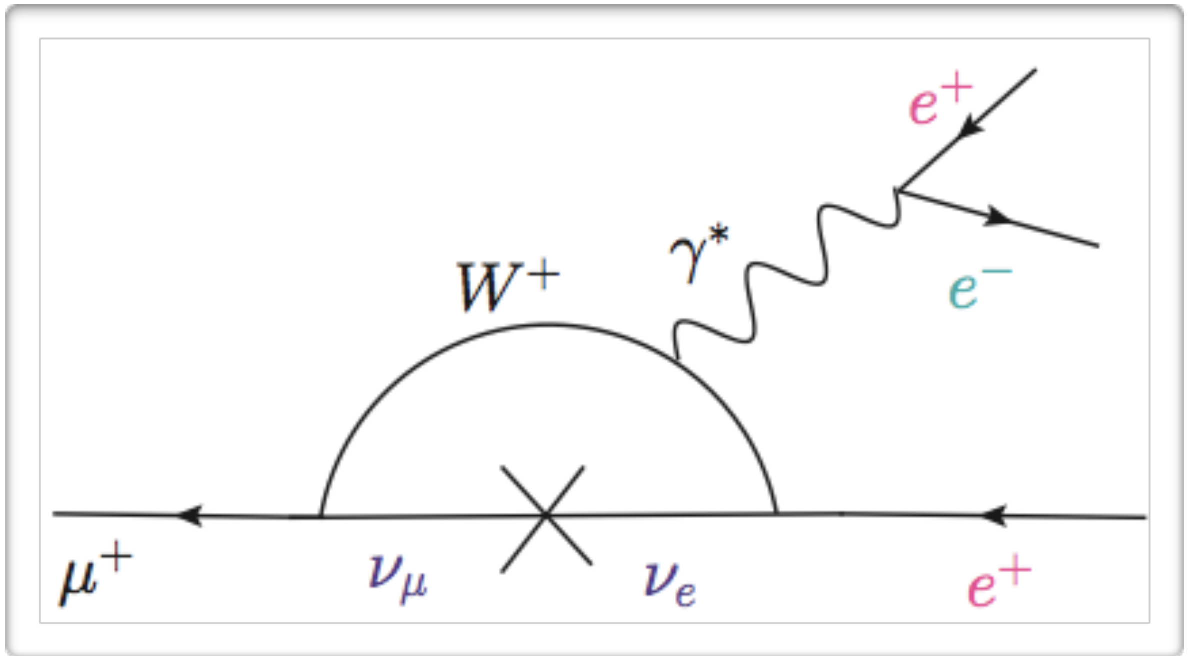
Outline

- The decay $\mu \rightarrow eee$
- The Mu3e Experiment
  - The Mu3e Pixel Detector based on HV-MAPS
  - Results from Test Beam at DESY 2013/2014

Motivation

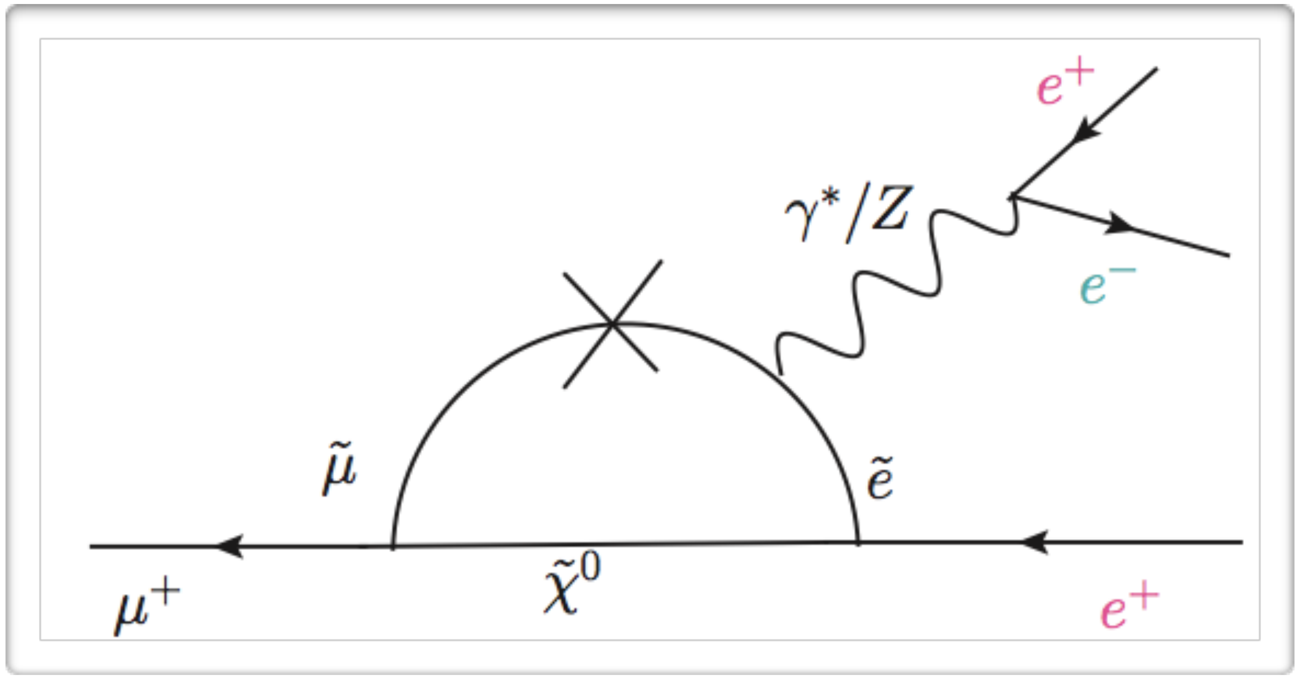
- The Mu3e experiment searches for :
  - Lepton flavor violation in the decay of $\mu^+ \rightarrow e^+e^+e^-$ with a sensitivity of BR < 10^{-16}
  - Four orders of magnitude improvement over the most stringent limit to date
- In the SM, the decay is suppressed to unobservable levels (BR< 10^{-54})



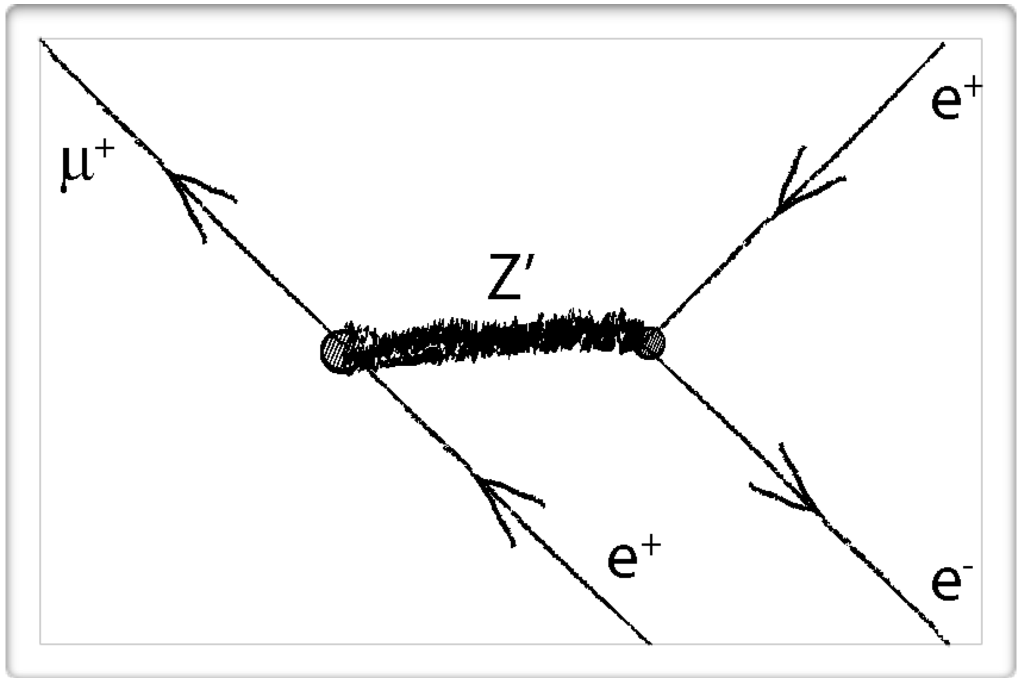
- Any observed signal event is a clear signature of new phenomena beyond the SM

Motivation

- The experiment allows to test models involving new particles
- Supersymmetry
- Extended Higgs models
- Heavy vector bosons



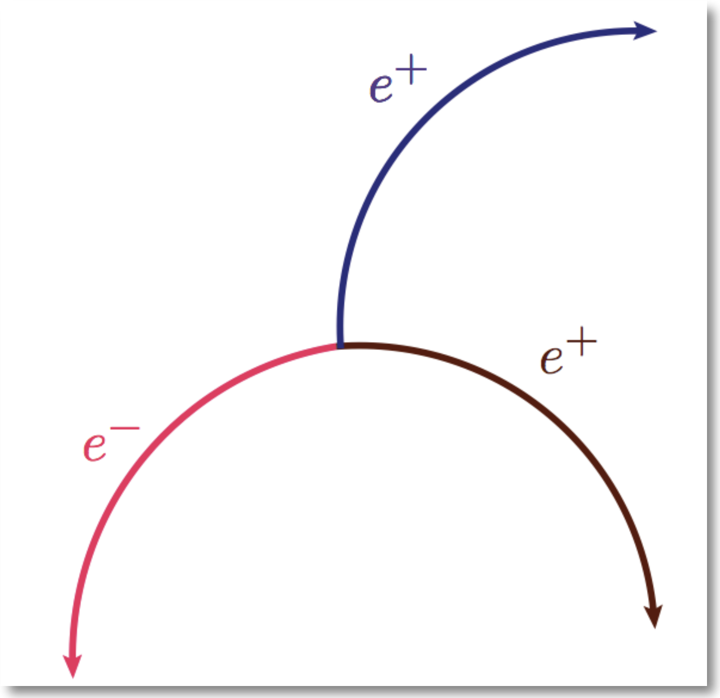
Supersymmetry



LFV at tree level

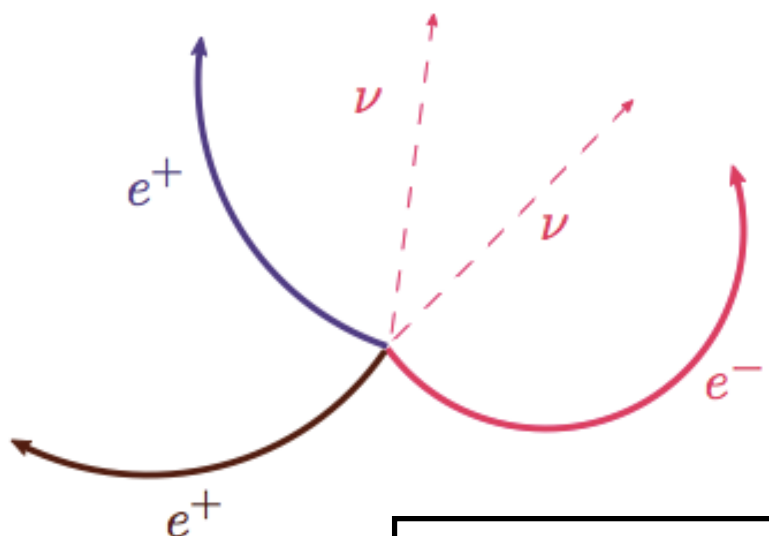
Signal and Backgrounds

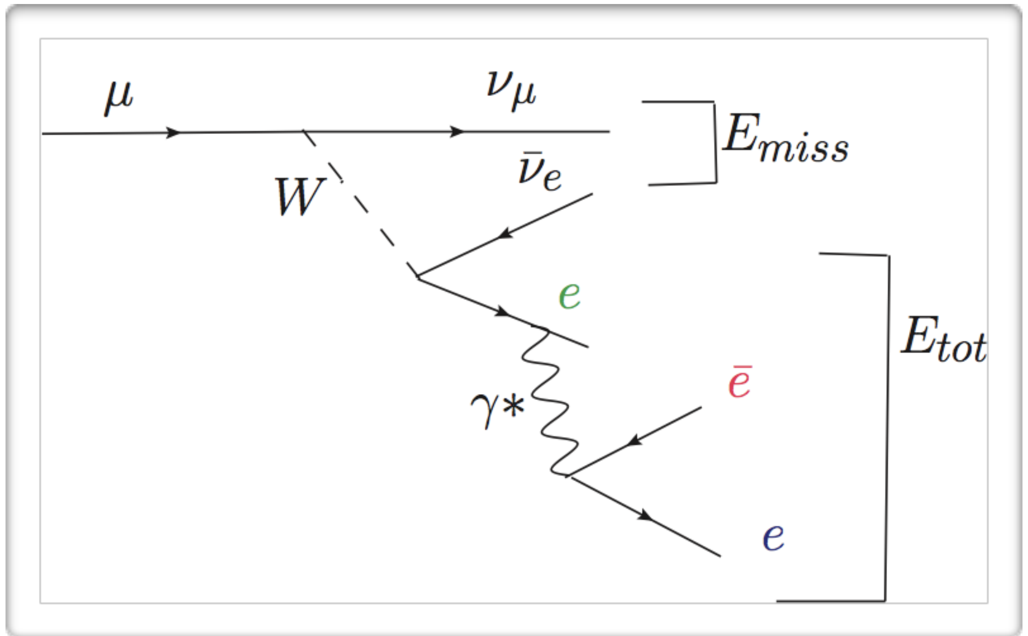
- Decay signature: Muon decays at rest
- Two positrons and an electron
- Opposite curvature in magnetic field
- Coincident in time, originating from same vertex
- Momentum conservation: $|\vec{p}_{tot}| = |\Sigma \vec{p}_i| = 0$
- Energy conservation: $E_{tot} = \Sigma E_i = m_\mu c^2$
- Individual energies are below 53 MeV



Signal and Backgrounds

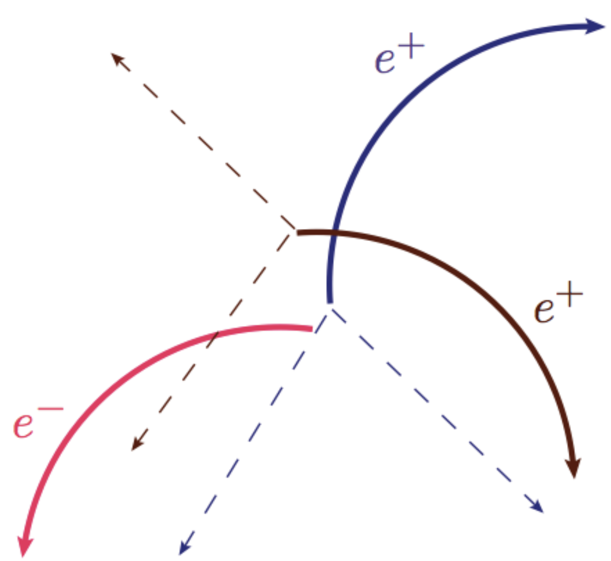
- Internal Conversion (Radiative muon decay)





Good momentum and total energy resolution required

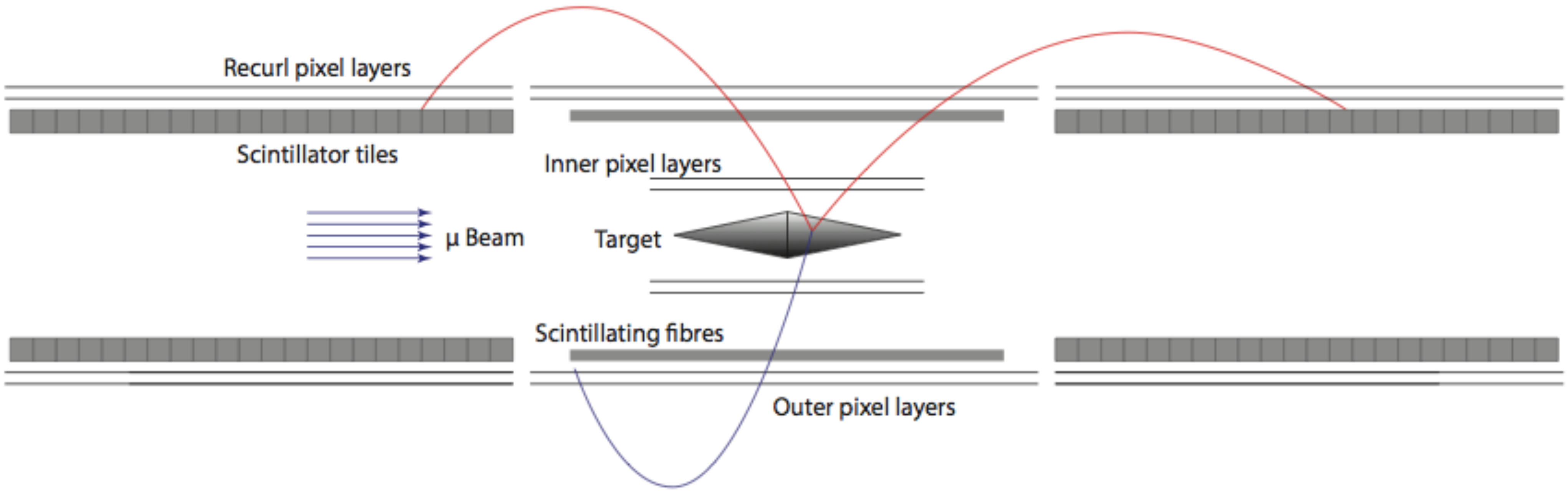
- Combinatorials



Precise timing, good momentum and vertex resolution required

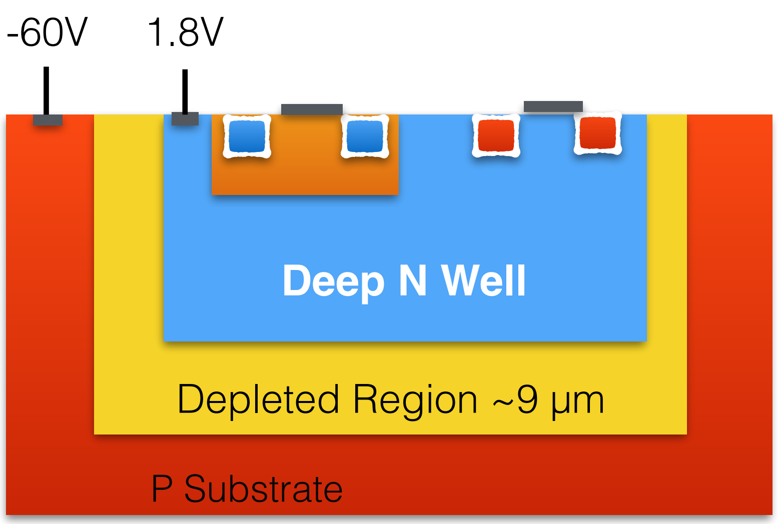
$$\sigma_p < 0.3\ MeV, \quad \sigma_t < 100\ ps$$

Mu3e Experiment



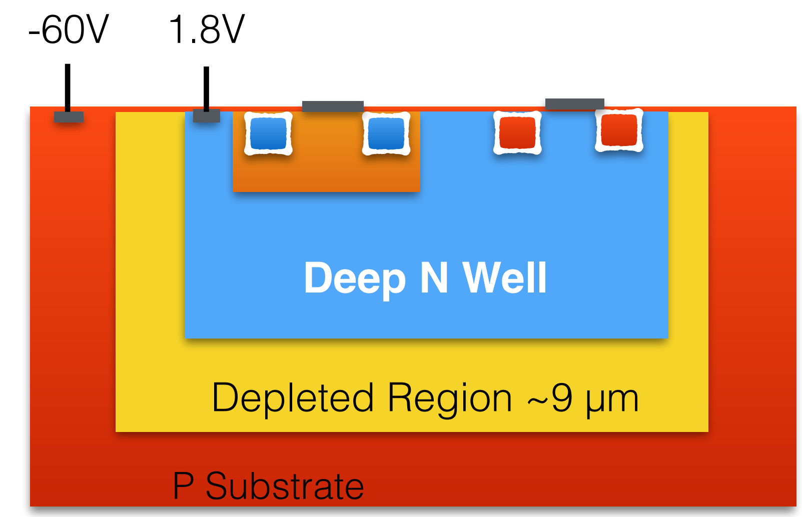
- To achieve sensitivity goal:
  - 10^9 muon decays/s
  - excellent vertex resolution
  - excellent time resolution
- Low p_T < 53 MeV/c decay product, track resolution dominated by multiple scattering.
- High granularity Si- based tracking detector made of HV-MAPS

HV-MAPS

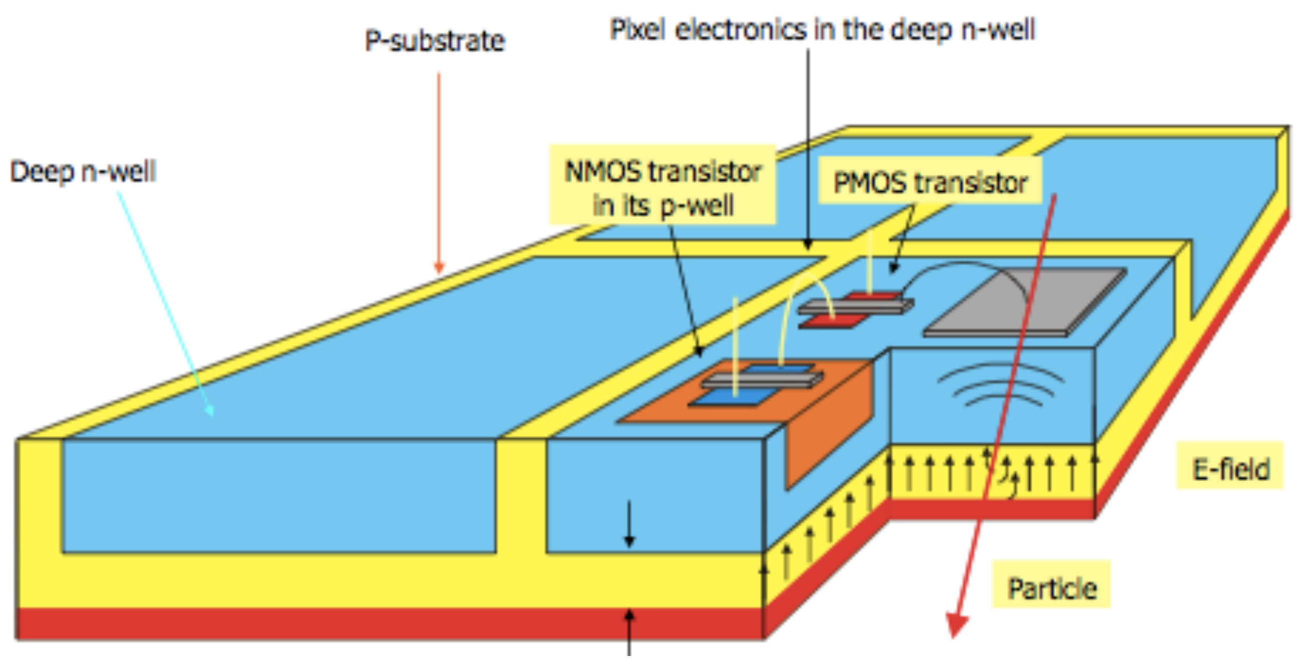


- HV-MAPS as a particle detector
- Based on 180 nm HV-CMOS technology
- Fast charge collection (<100 ps) via drift, results in high radiation tolerance
- Thinning to < 50 µm
- Power consumption ~ 7.5 µW/pixel
- Relatively cheap due to use of commercial process

HV-MAPS

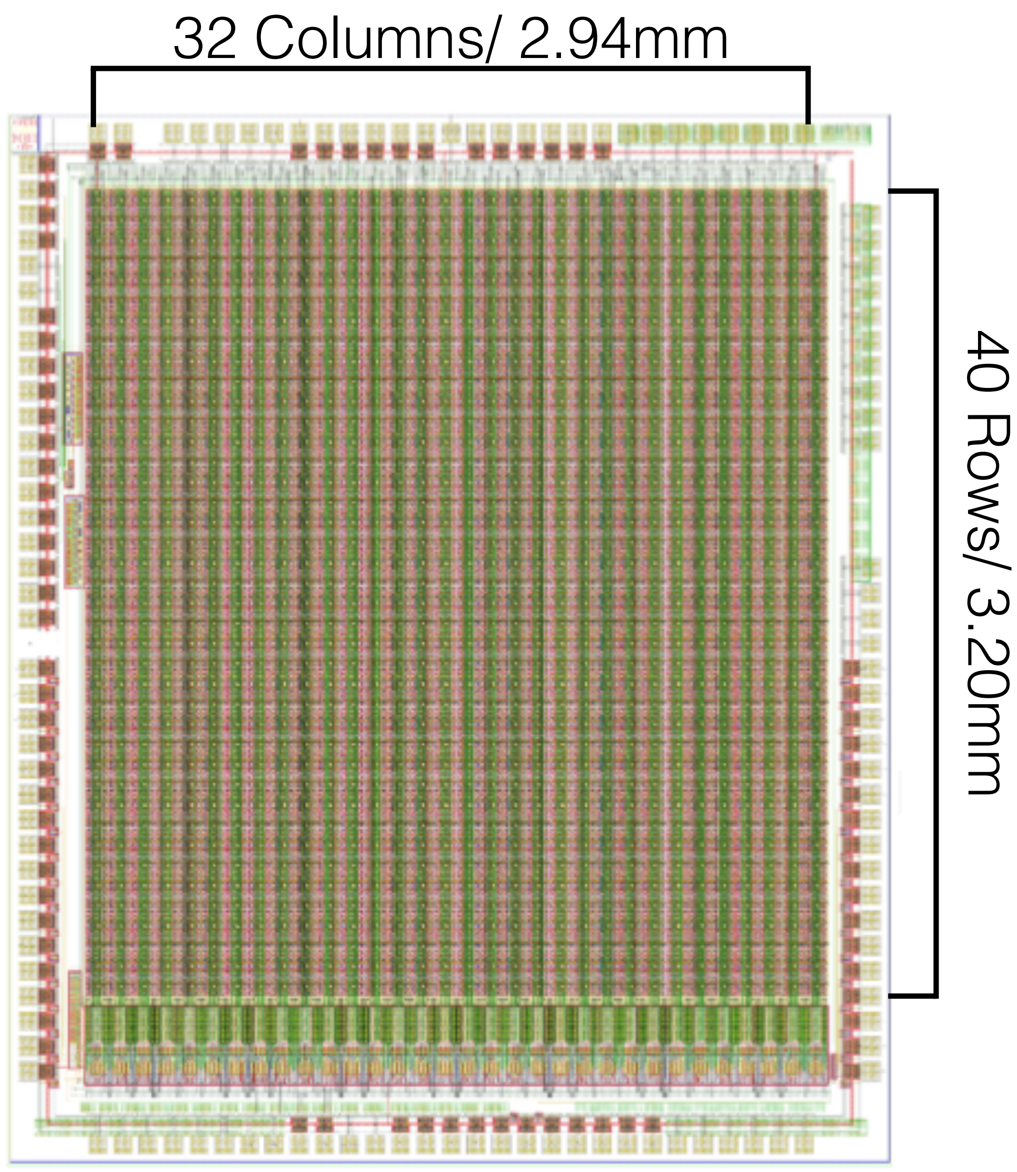


- Low doped deep N- well as signal collecting region
- Depleted p-n junction as a sensor ~ 9 µm
- The charge collected by drift ~625 e in depleted region using Sr^{90} as a source
- Entire pixel electronics CMOS transistors inside the deep N-well
- Integrated readout electronics
- N- well are in matrix, depleted zones overlapped ~ 100% fill factor



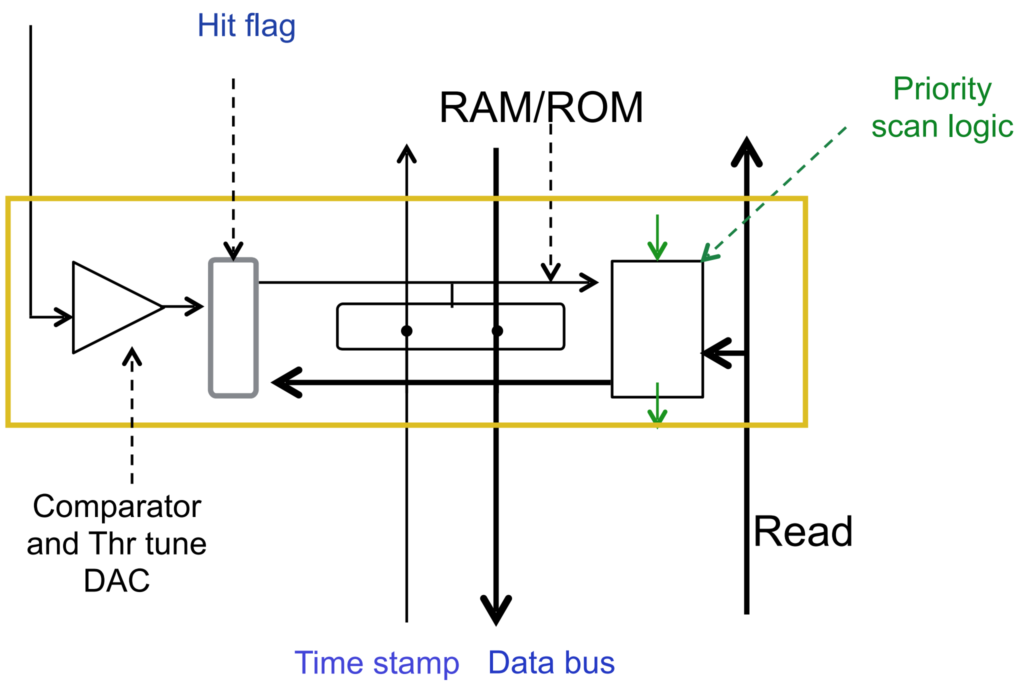
MUPIX4

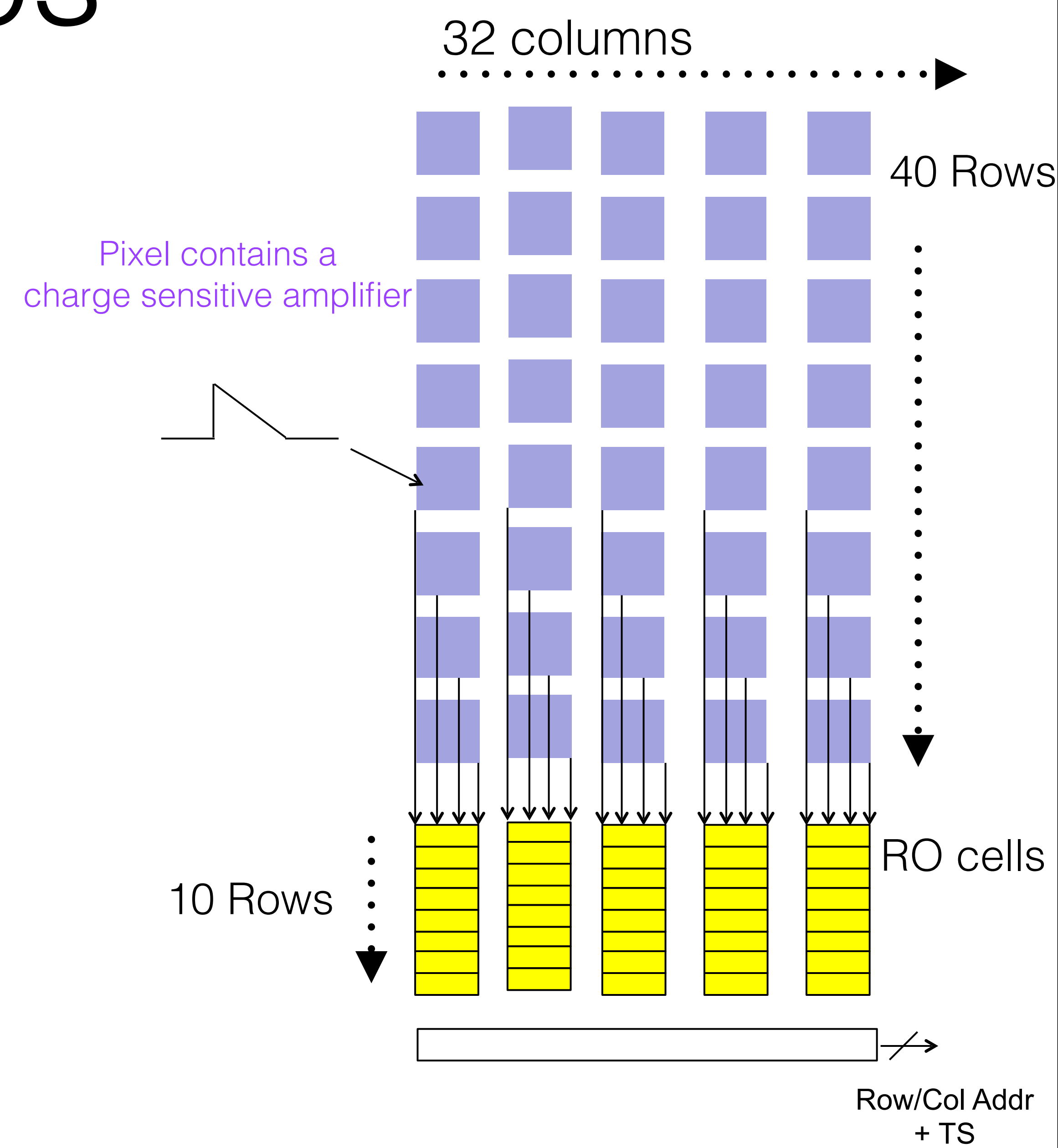
- Features : AMS 180nm process
- Pixel Matrix: 40x32 pixels, 80x92 μm^2 (pixel size)   Active area : 9.4 mm^2
- Moderate substrate resistivity ~10 Ω cm
- Designed by Ivan Peric (U. Heidelberg Institute for Computer Science (ZITI)
- Analog part: Small pixel capacitance
  Temperature tolerance
- Digital part: Zero suppression
  Mostly Ready
  Feature: pixel address problem in half column
  Fixed in MUPIX6 using inverters



HV-MAPS: Integrated readout electronics

Concept: Each pixel has its own read out (RO) cell placed on the chip periphery



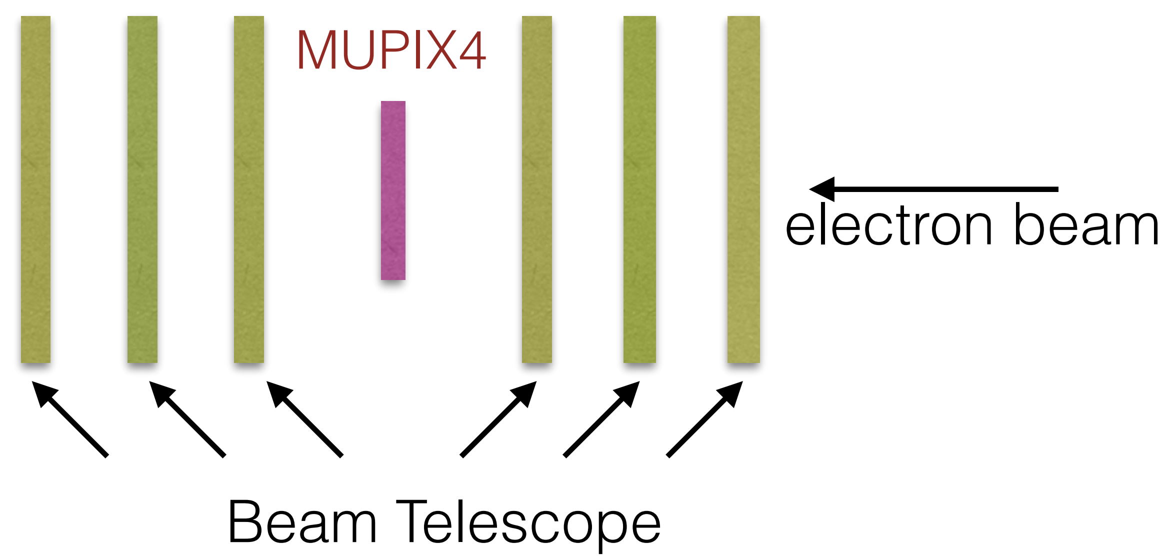


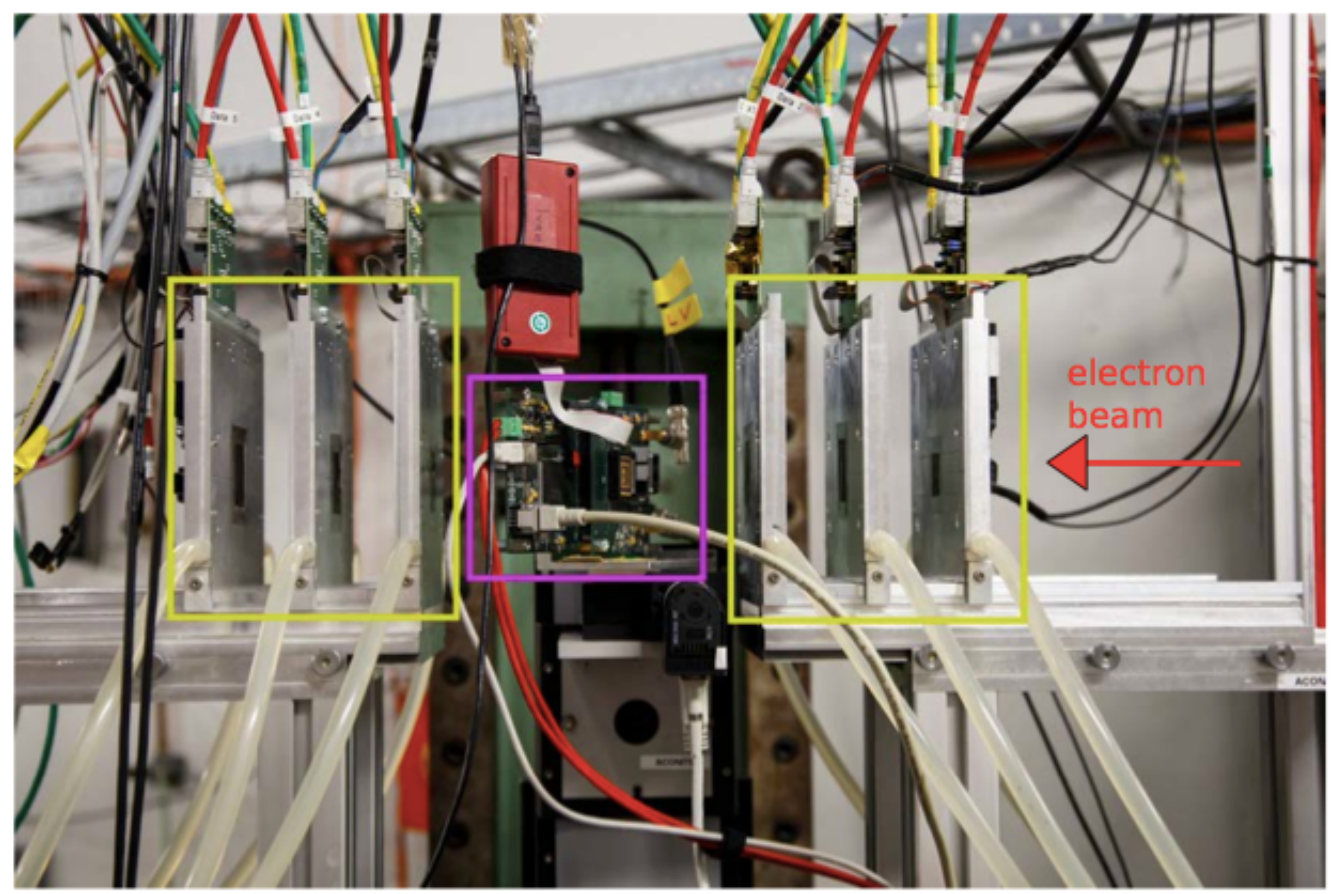
Readout cell function:
Time stamp
Hit data
Priority logic
Binary Suppressed read out

RO cell size is 7µm x 40 µm in 180nm AMS process (with comparator and threshold tune DAC)

Test Beam set up at DESY

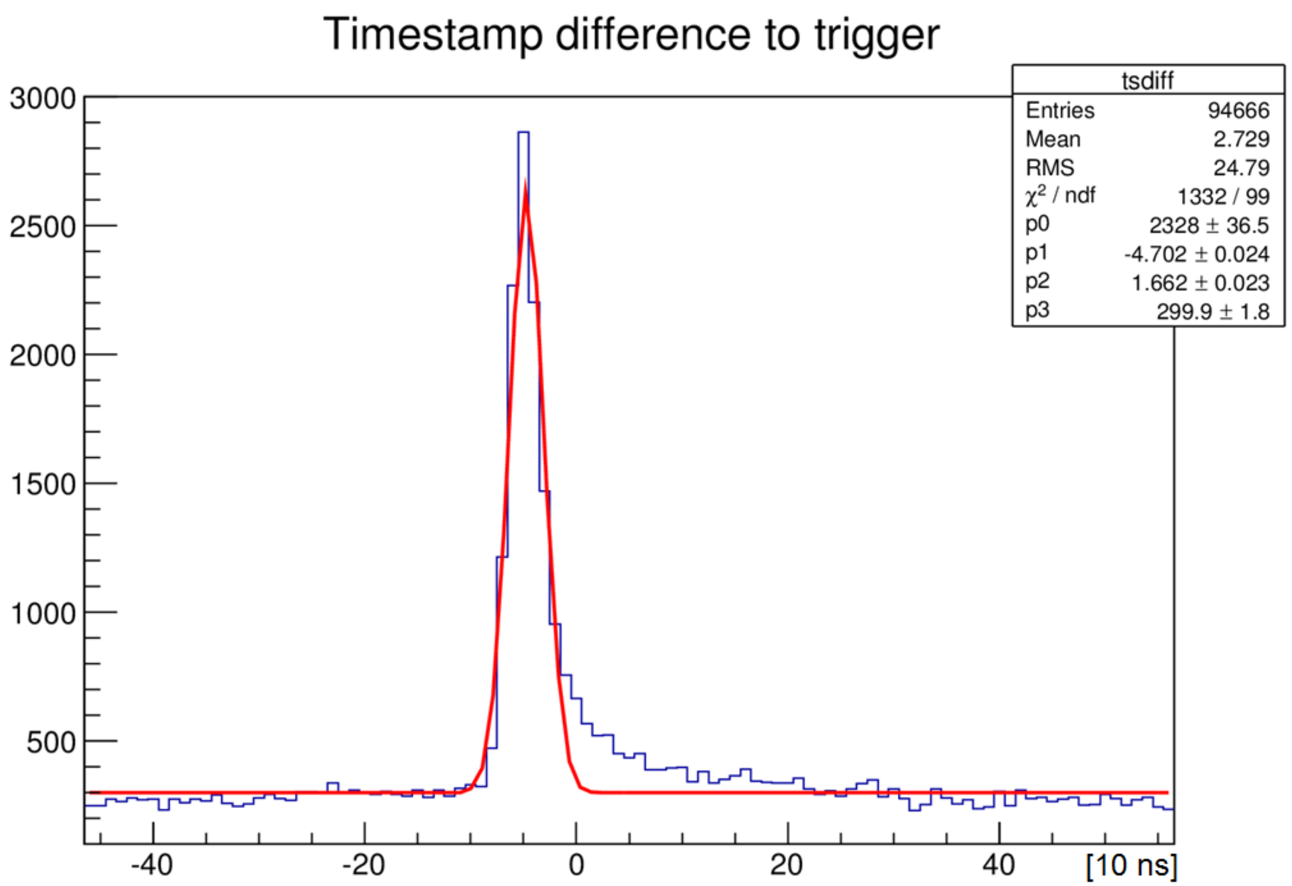
- DESY Test Beam set up
  - Beam-line T22
  - 1 GeV to 6 GeV electrons
  - EUDET Telescope
  - MUPIX4 prototype

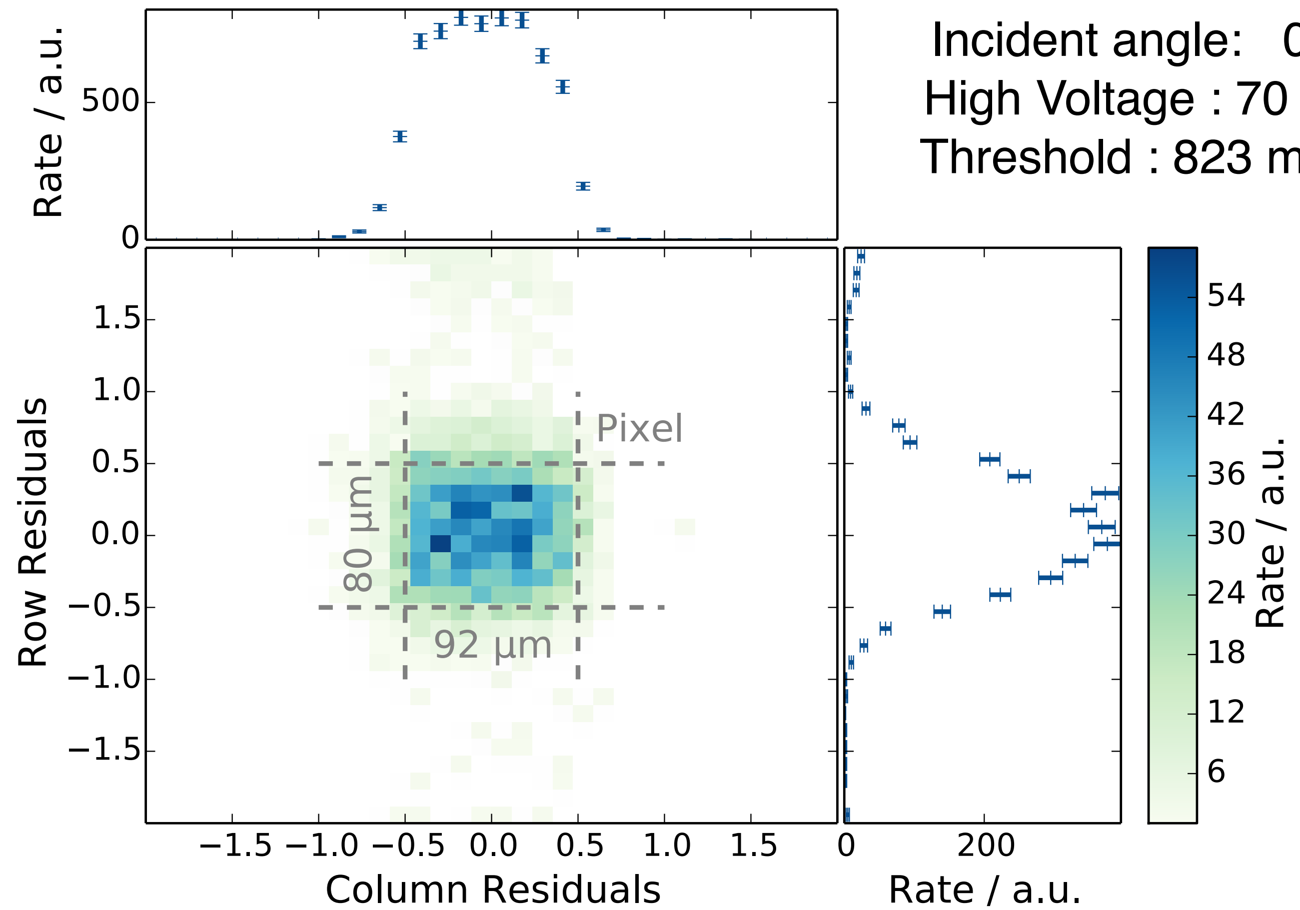




Test Beam Results

Time and Single Hit Resolution





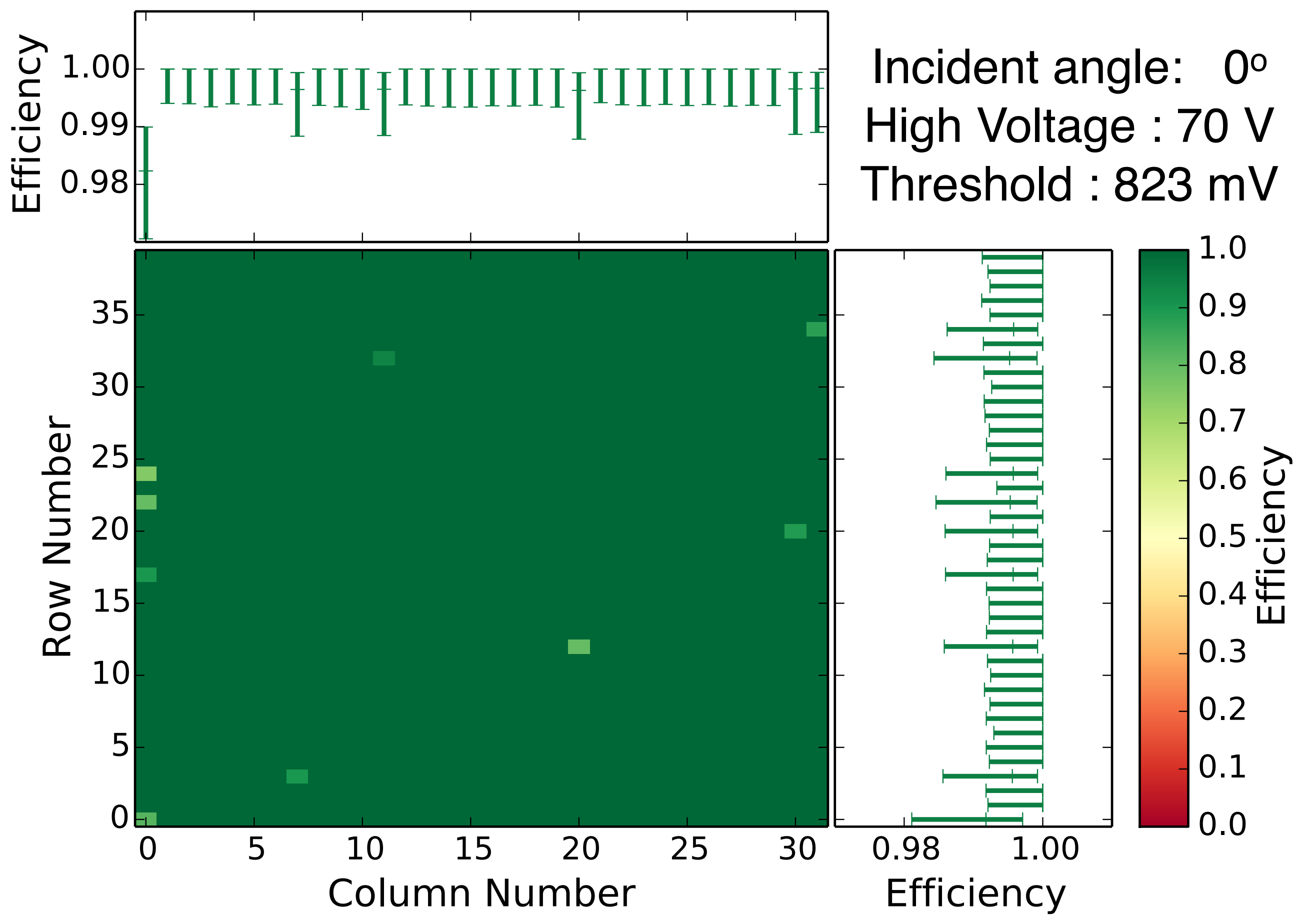
Incident angle: 0°
High Voltage : 70 V
Threshold : 823 mV

Result: Time Resolution : 17 ns
(Sensor and DAQ)
External Gray counter at 100 MHz

Result: Resolution given by pixel size
Measured track residuals:
RMS x = 28 µm, RMS y = 29 µm

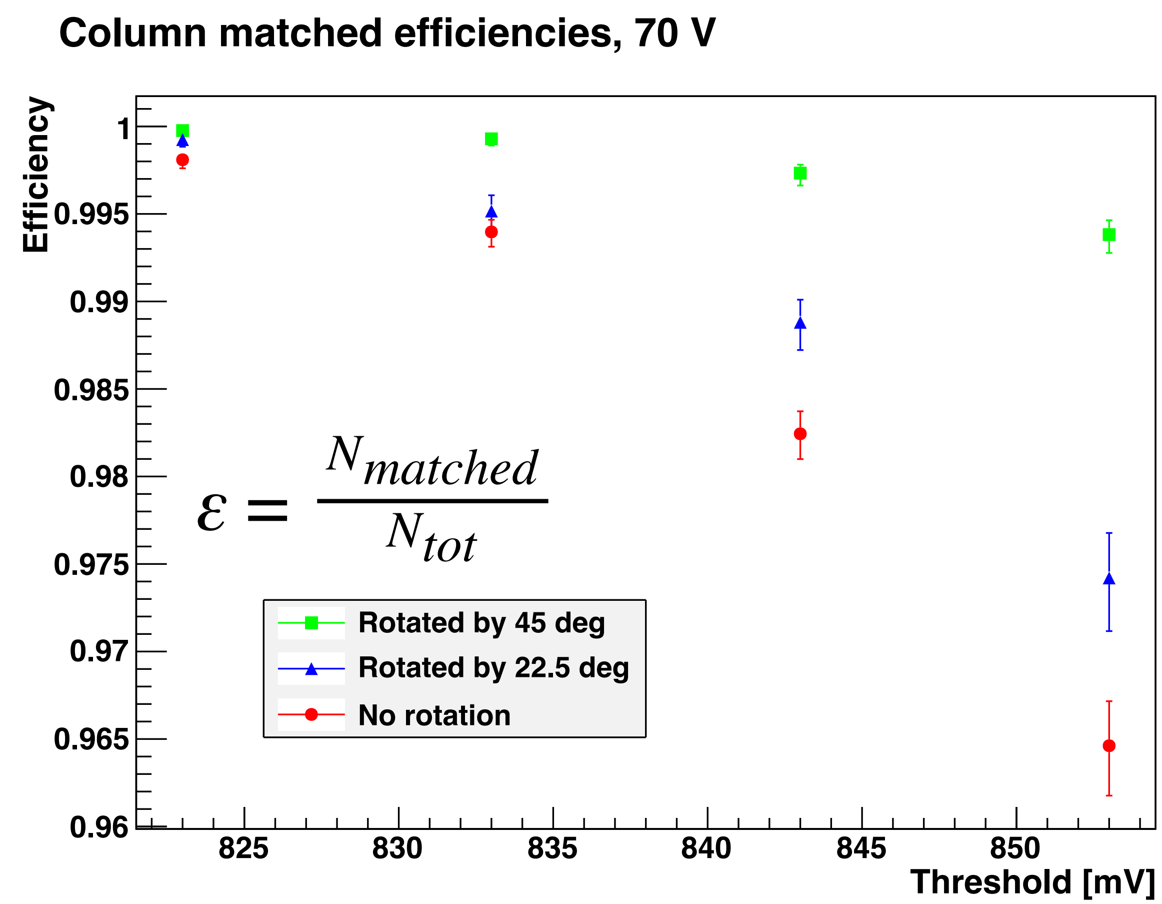
Pixel Efficiency

Pixel Efficiency



Result: First working prototype
Efficiency > 99% for untuned DAC

Pixel Efficiency



Result: Rotated chip with 45 degree angle, higher efficiency

Conclusion

- Mu3e experiment aims for $\mu \rightarrow e^+e^+e^-$ with sensitivity of BR < 10^{-16}
- HV-MAPS has been implemented for fast charge collection efficiency, radiation hardness, and minimum material
- Looking forward to integrate full digital electronics in the Mu3e pixel prototype by end of this year
- The MUPIX4 has already the required analog performance
- Currently, the performance of MUPIX6 is being tested at PSI

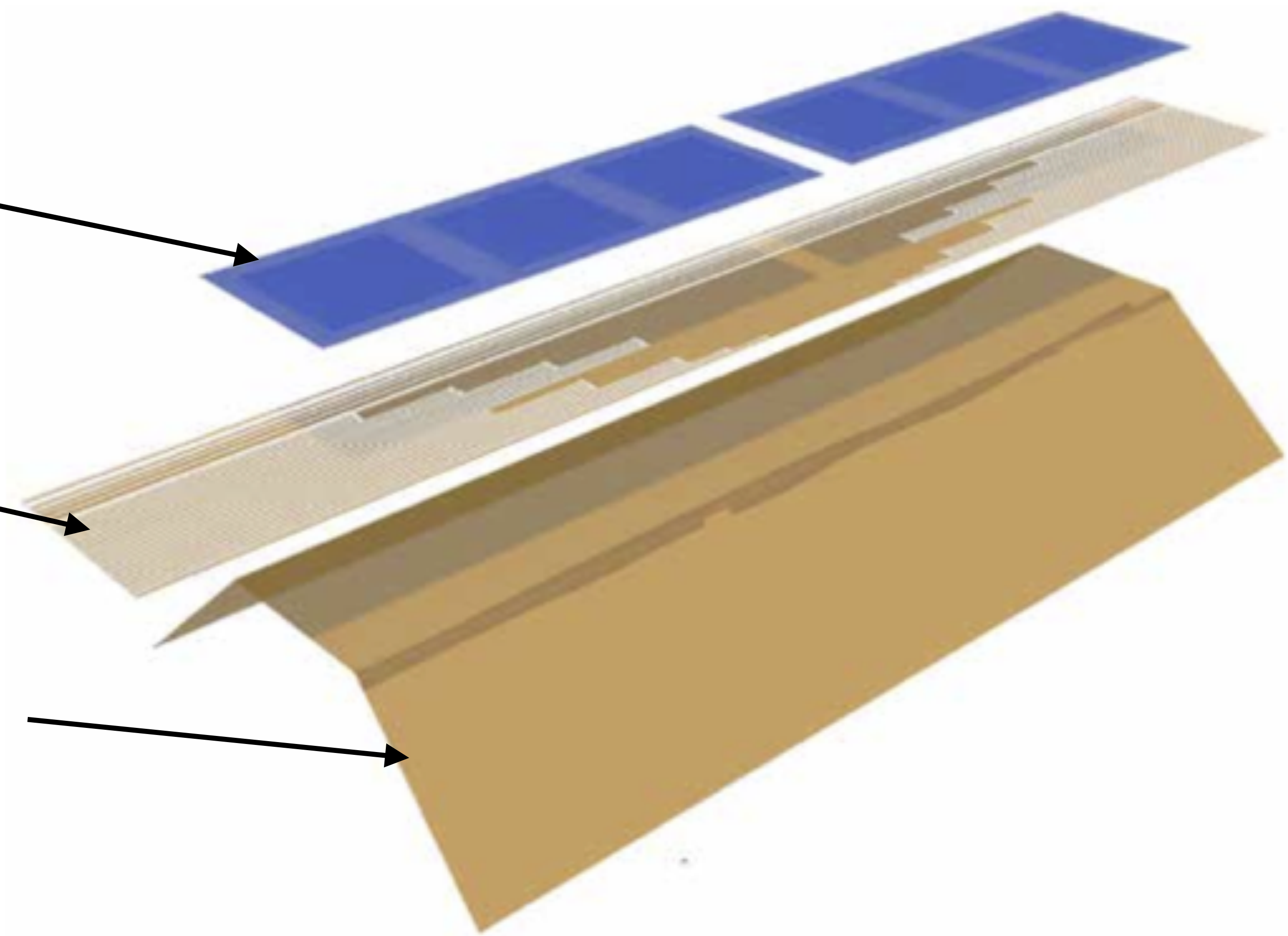
Backup slides

Mechanical prototype and sandwich Design

HV-MAP
Thinned to 50 µm
sensor size 1 x 2 cm^2 or 2x2 cm^2

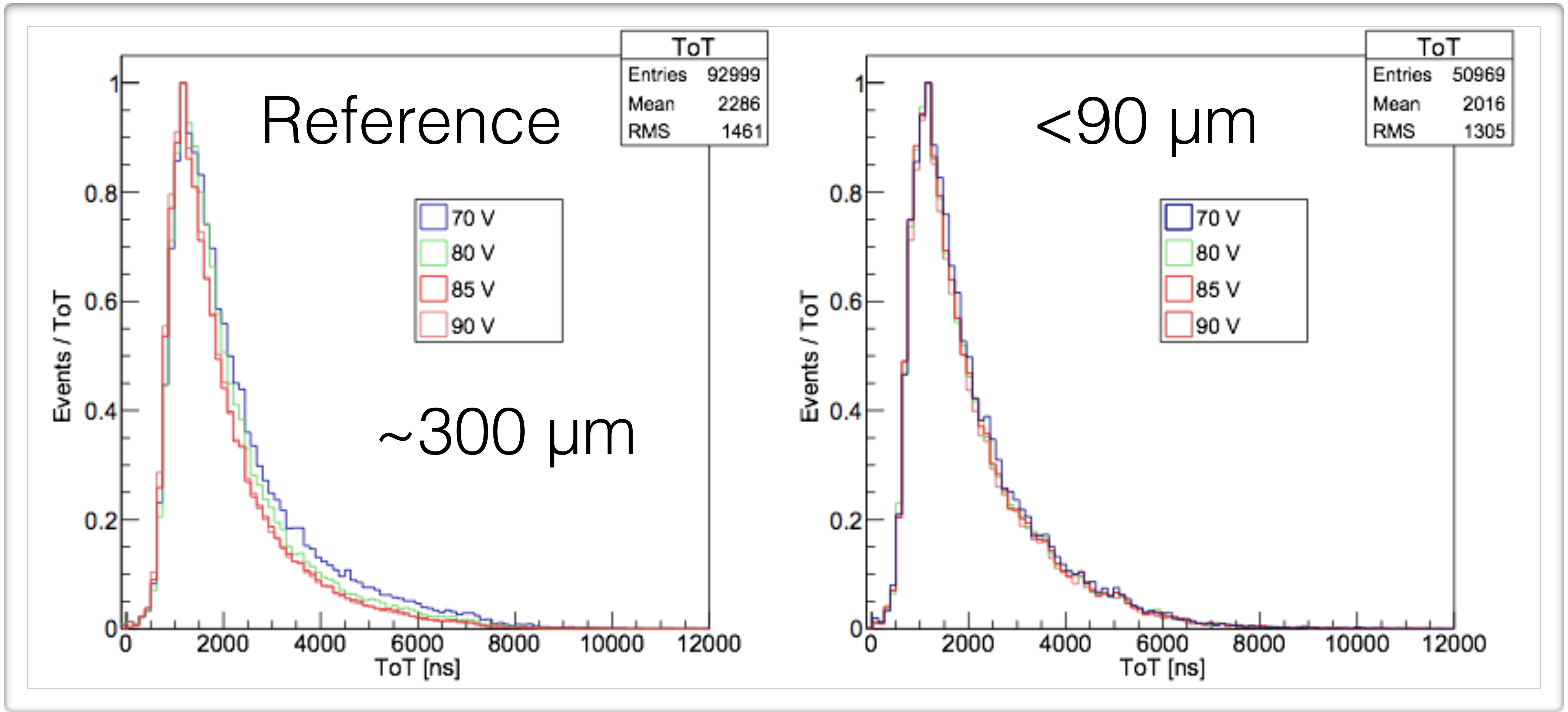
Kapton™ flex print
25 µm Kapton™
12.5 µm Al traces

Kapton™ Frame Modules
25 µm foil
self support



$<0.1\%$ X_0 per layer

Thinned sensor

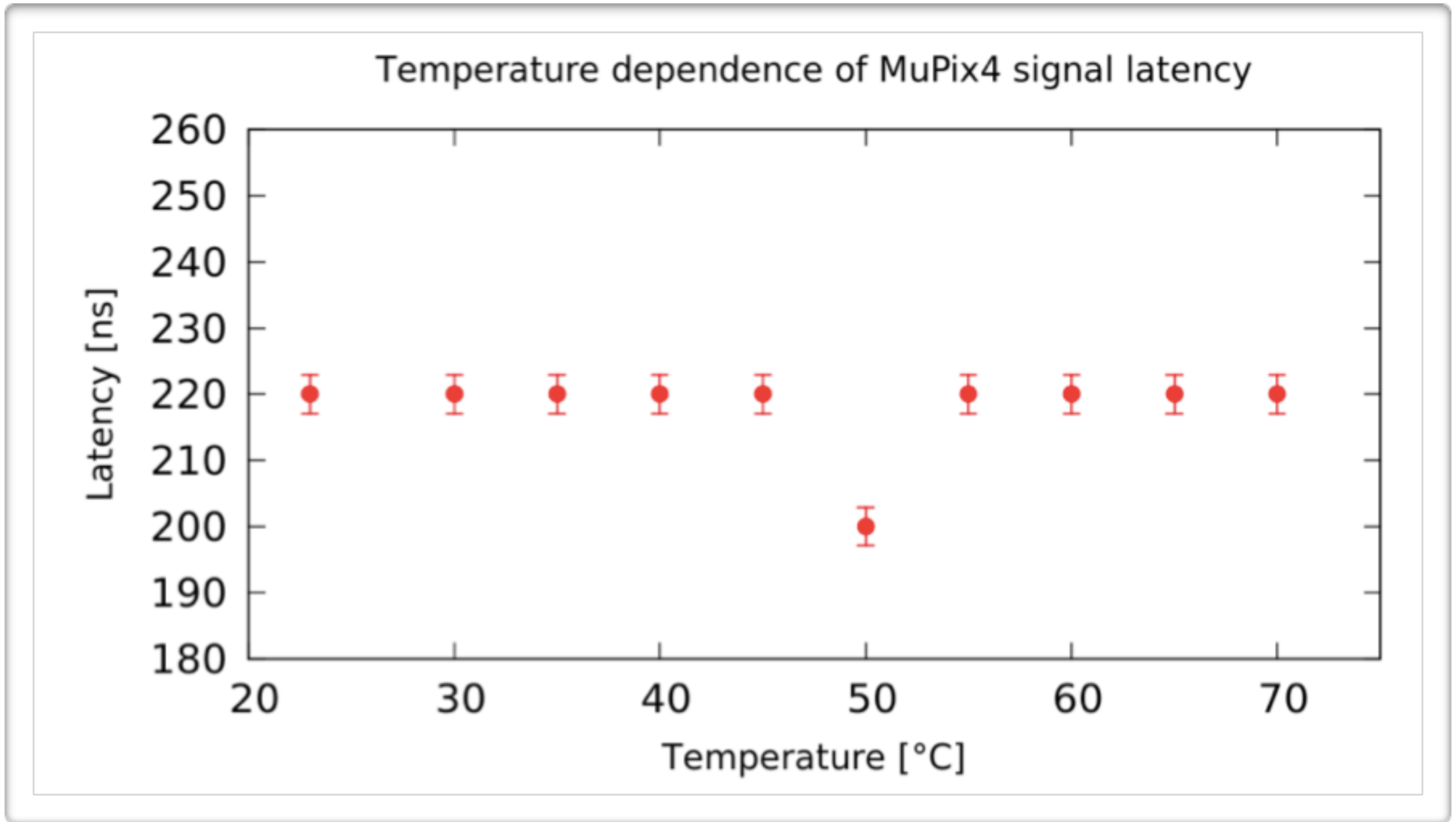


PSI test beam

Result: No significant difference in pulse shape

Temperature stability

- Latency measurement
  - LED pulse to a pixel discriminator output

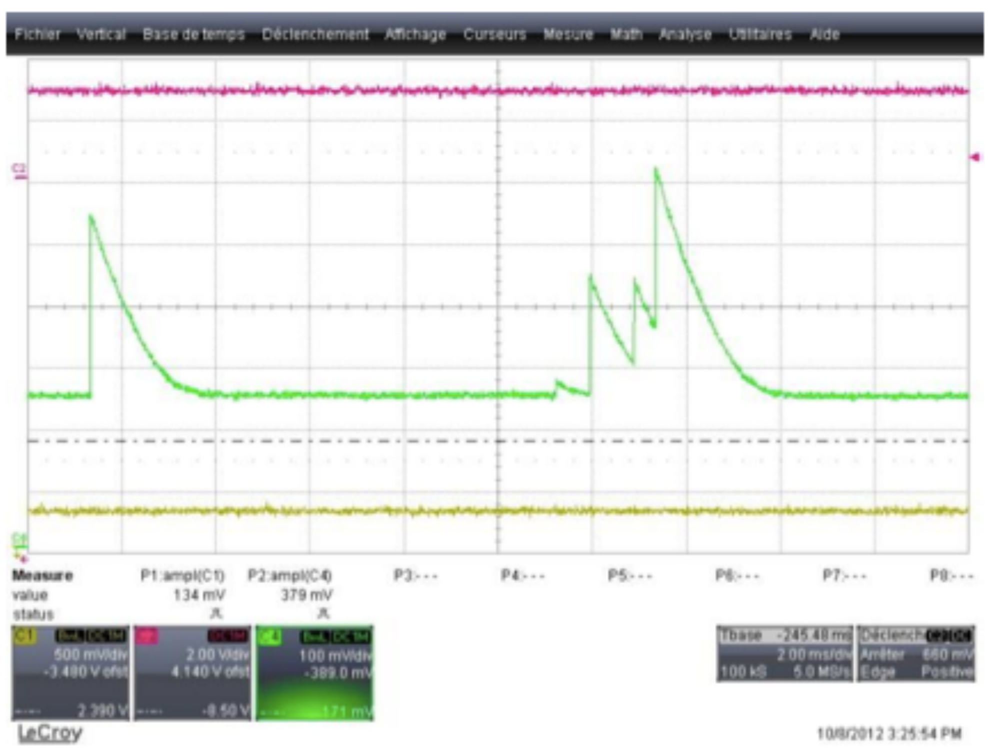


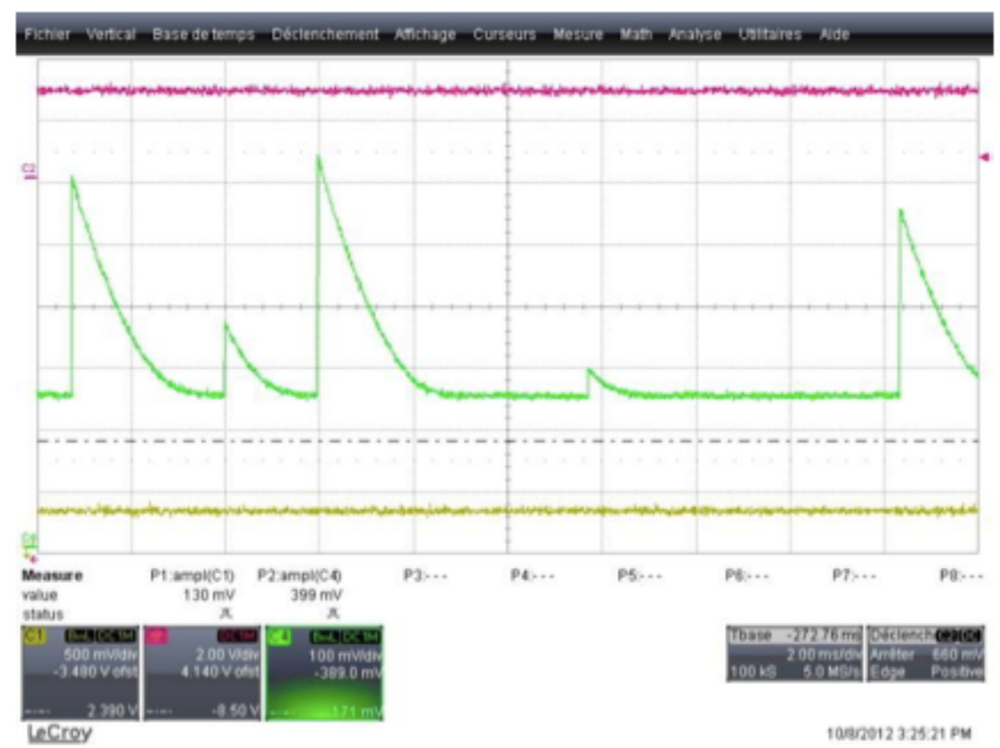
Result: Temperature dependence within the resolution setup

Result after 380MRad radiation and ~ $8x10^{15}n_{eq}$ cm^{-2}

- Perform: Irradiation at PS (CERN) for 180 nm HV CMOS
-

Courtesy: RESMDD 2012, Ivan Peric





Result: The chip works, particles are measured when the chip is in the beam