



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

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On Behalf of the Mu3e Collaboration

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Outline

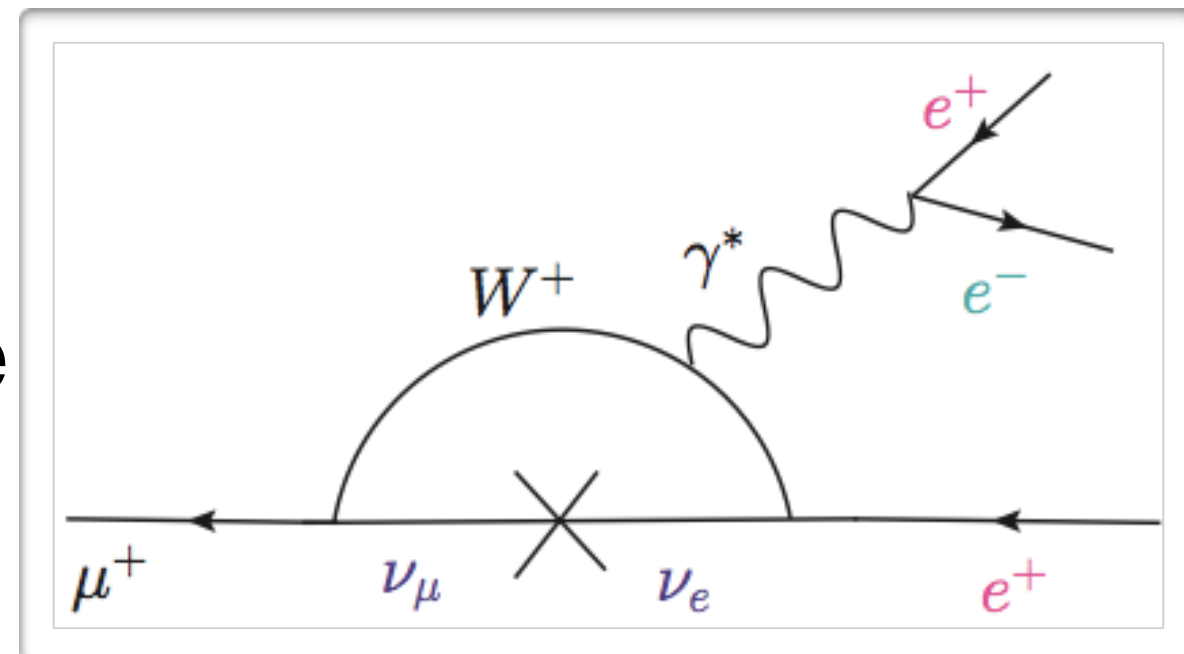
- The decay $\mu \rightarrow eee$
- The Mu3e Experiment
 - The Mu3e Pixel Detector based on HV-MAPS
 - Results from Test Beam at DESY 2013/2014



Motivation

- The Mu3e experiment searches for :
 - Lepton flavor violation in the decay of $\mu^+ \rightarrow e^+ e^+ e^-$ with a sensitivity of $\text{BR} < 10^{-16}$
 - Four orders of magnitude improvement over the most stringent limit to date

- In the SM, the decay is suppressed to unobservable levels ($\text{BR} < 10^{-54}$)

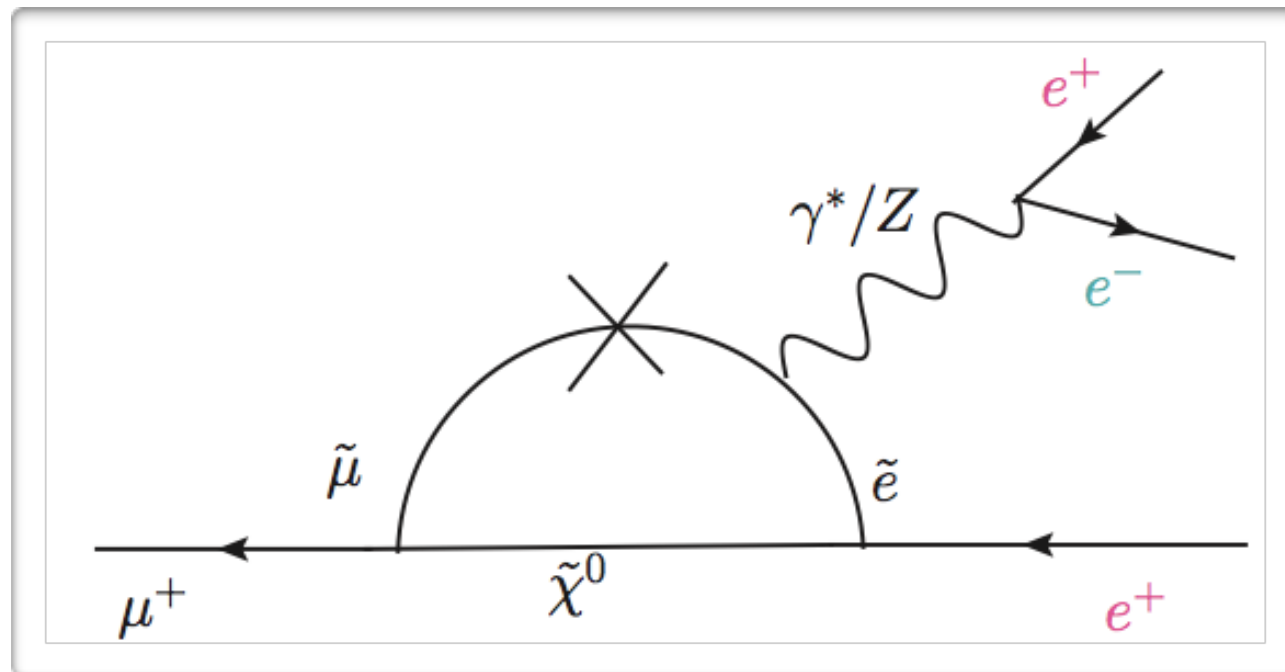


- Any observed signal event is a clear signature of new phenomena beyond the SM

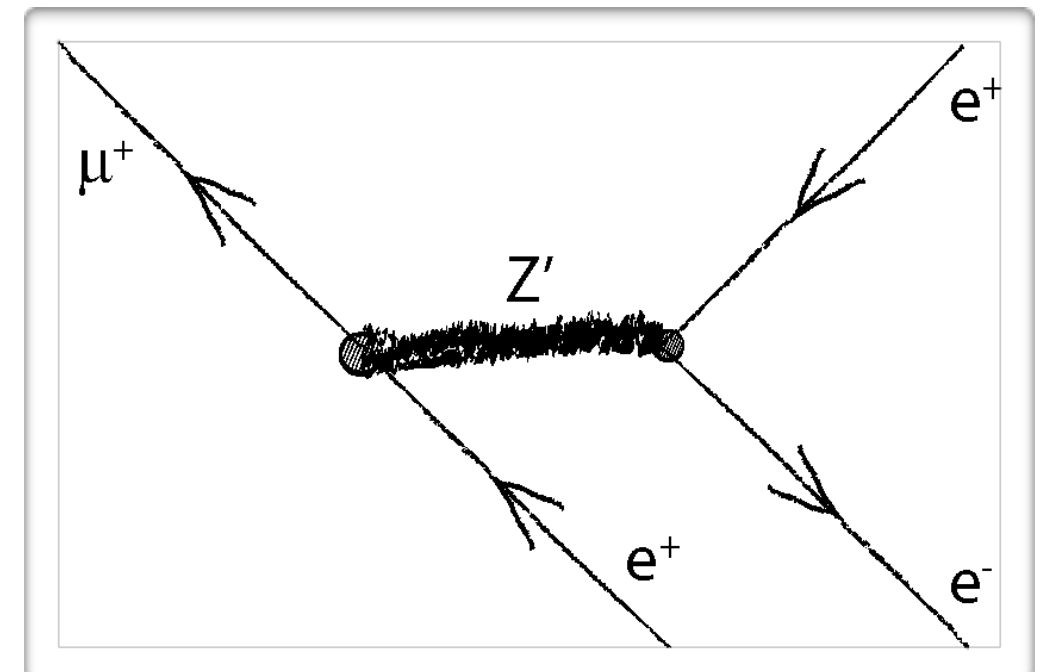


Motivation

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



Supersymmetry



LFV at tree level



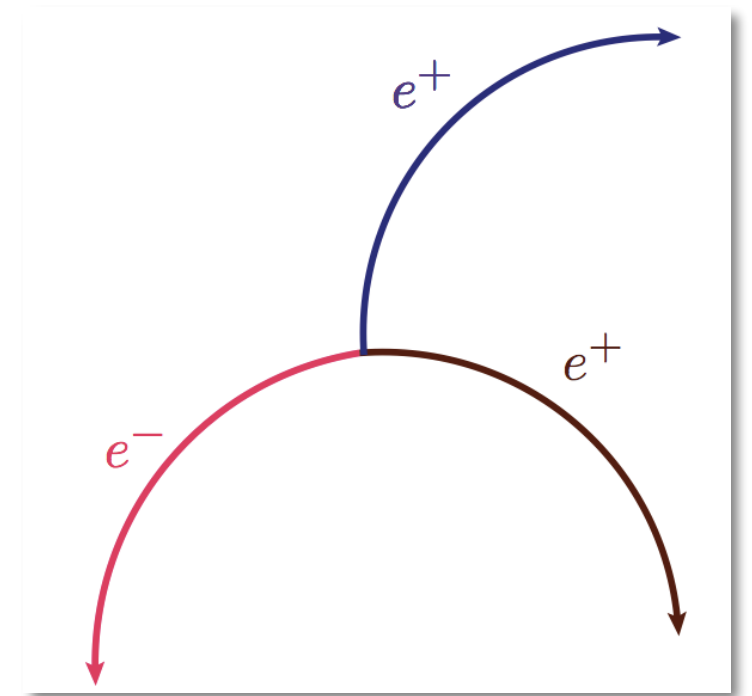
Signal and Backgrounds

- 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: $|\vec{p}_{tot}| = |\Sigma \vec{p}_i| = 0$

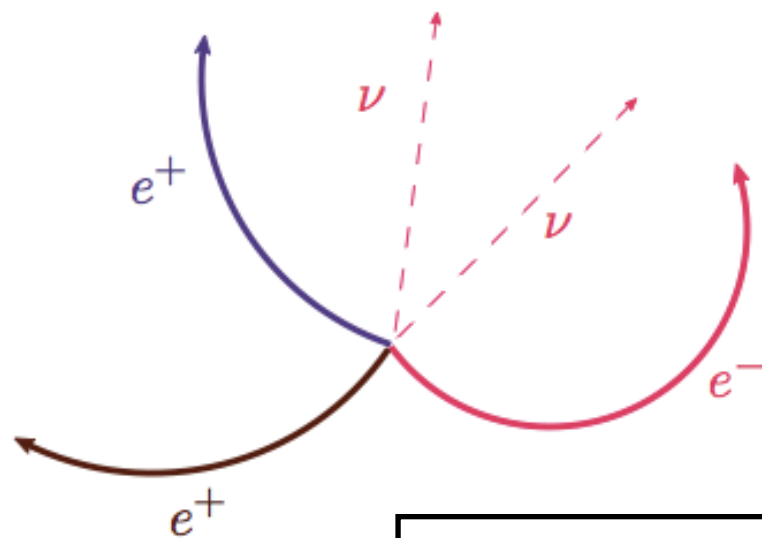
- Energy conservation: $E_{tot} = \Sigma E_i = m_\mu c^2$

- Individual energies are below 53 MeV

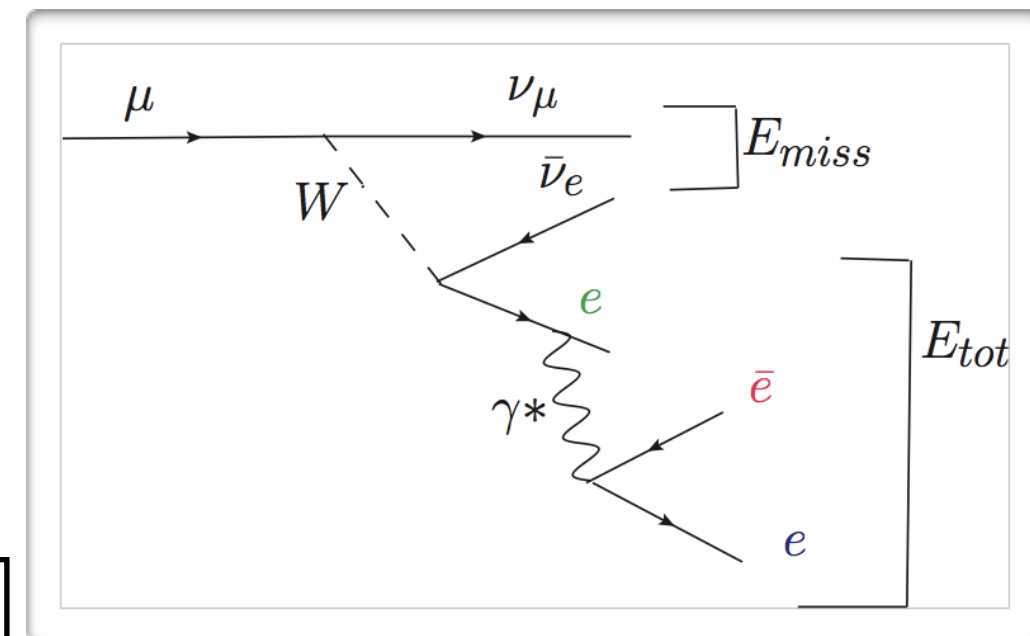


Signal and Backgrounds

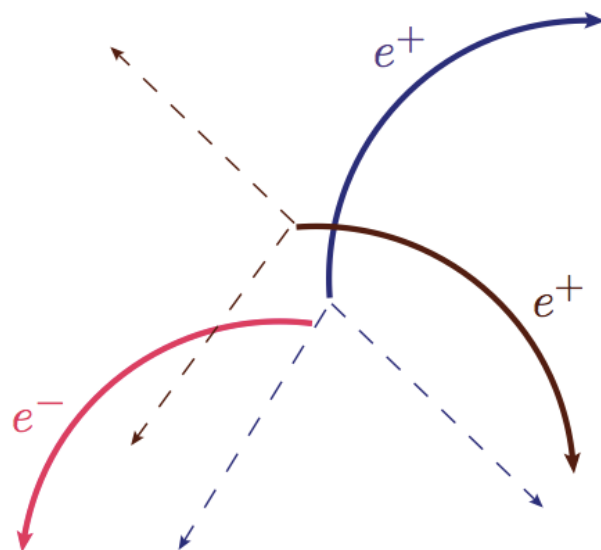
- Internal Conversion (Radiative muon decay)



Good momentum and total energy resolution required



- Combinatorials

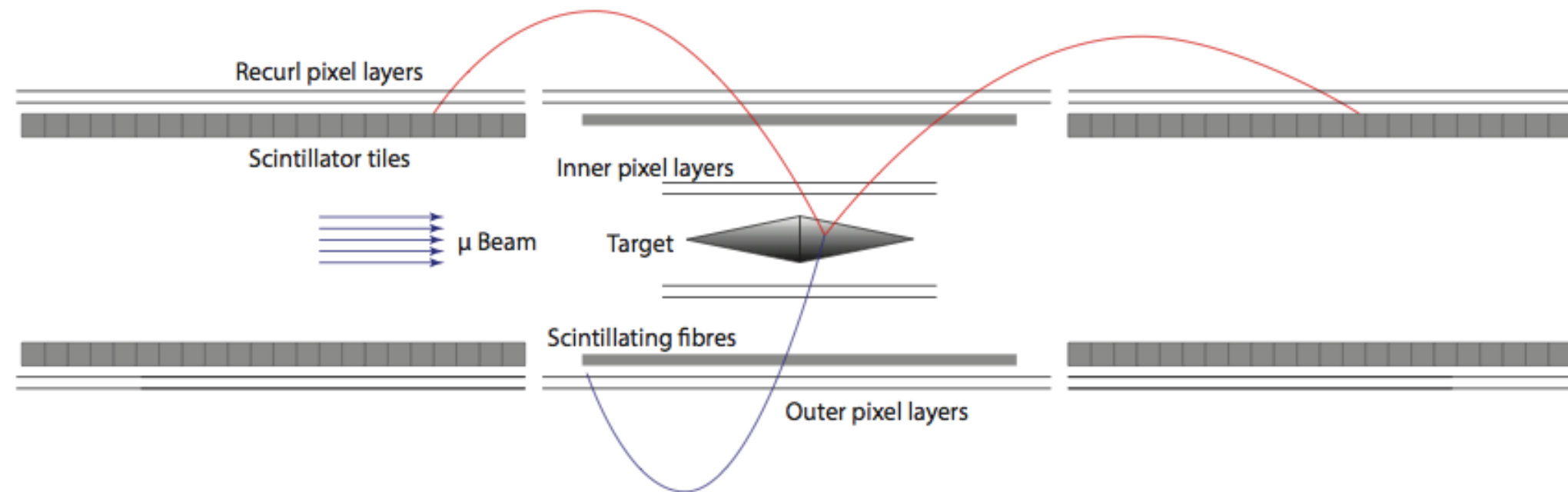


Precise timing, good momentum and vertex resolution required

$$\sigma_p < 0.3 \text{ MeV}, \quad \sigma_t < 100 \text{ ps}$$



Mu3e Experiment

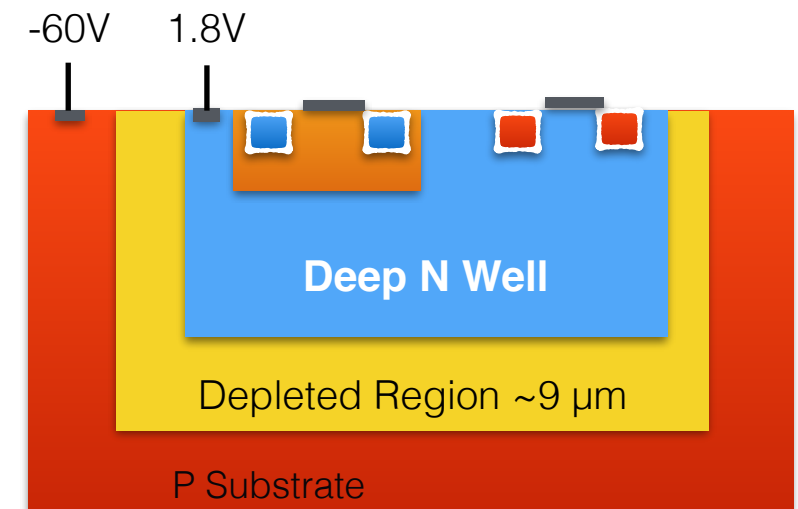


- To achieve sensitivity goal:
 - 10^9 muon decays/s
 - excellent vertex resolution
 - excellent time resolution
- Low $p_T < 53$ MeV/c decay product, track resolution dominated by multiple scattering.
- High granularity Si- based tracking detector made of HV-MAPS



HV-MAPS

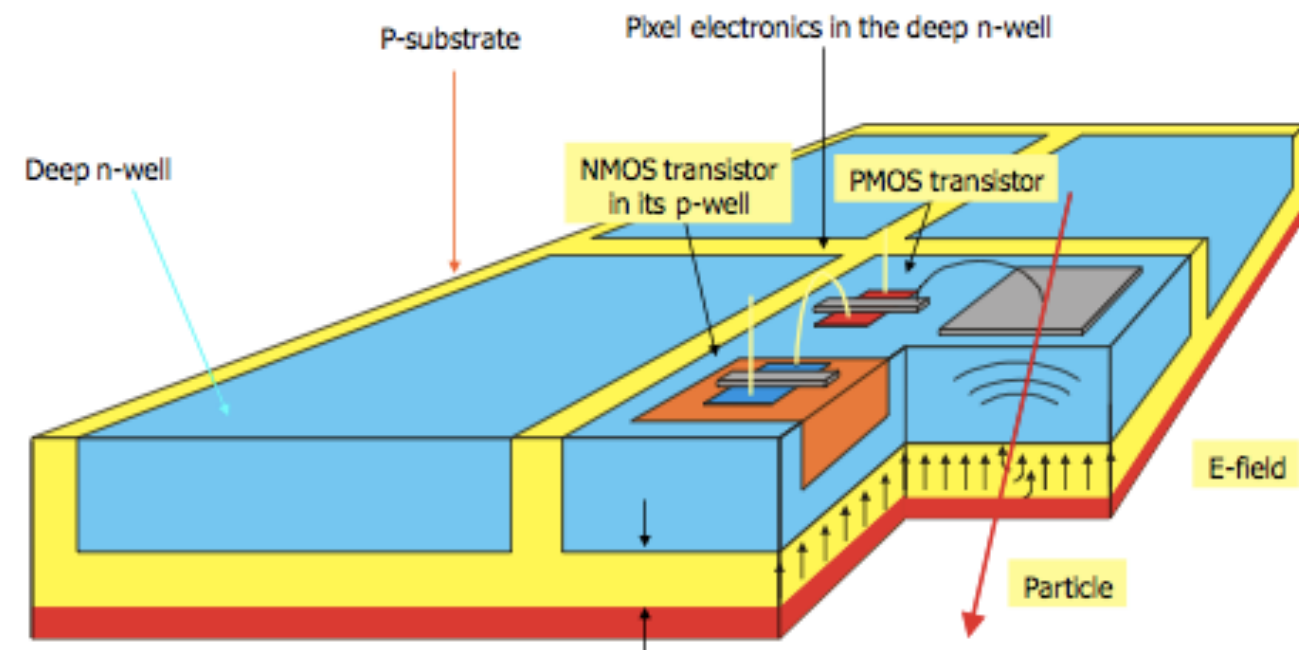
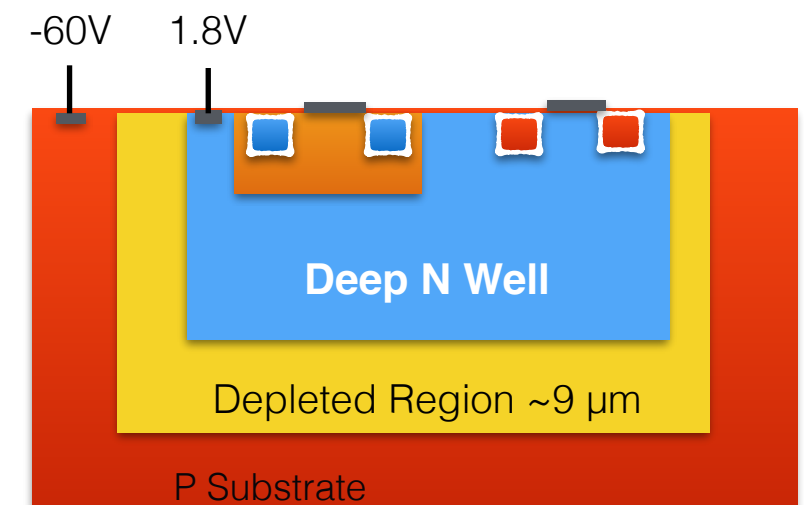
- HV-MAPS as a particle detector
- Based on 180 nm HV-CMOS technology
- Fast charge collection (< 100 ps) via drift, results in high radiation tolerance
- Thinning to < 50 μm
- Power consumption ~ 7.5 $\mu\text{W}/\text{pixel}$
- Relatively cheap due to use of commercial process



HV-MAPS



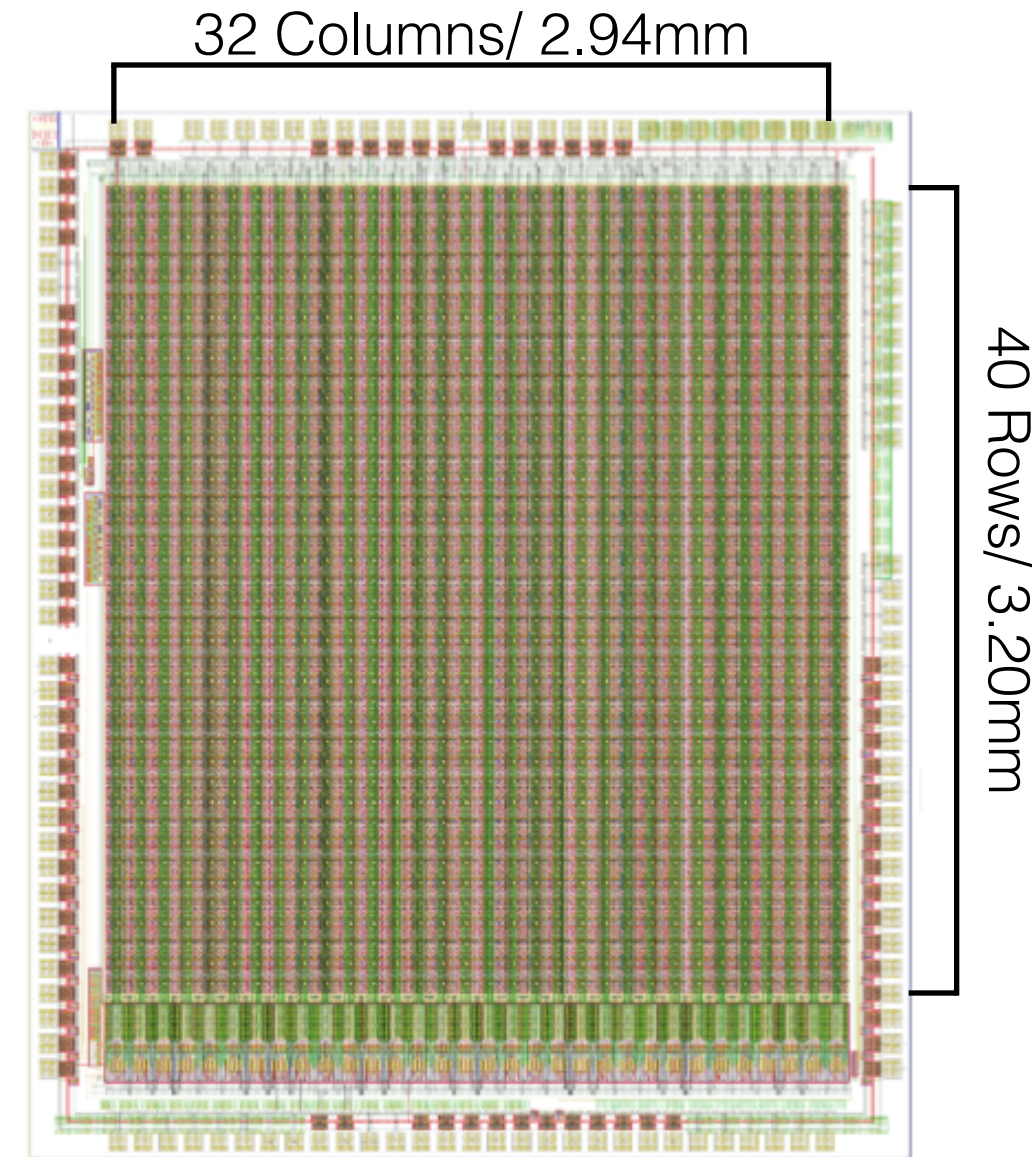
- Low doped deep N- well as signal collecting region
- Depleted p-n junction as a sensor $\sim 9 \mu\text{m}$
- The charge collected by drift $\sim 625 \text{ e}$ in depleted region using Sr^{90} as a source
- Entire pixel electronics CMOS transistors inside the deep N-well
- Integrated readout electronics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





MUPIX4

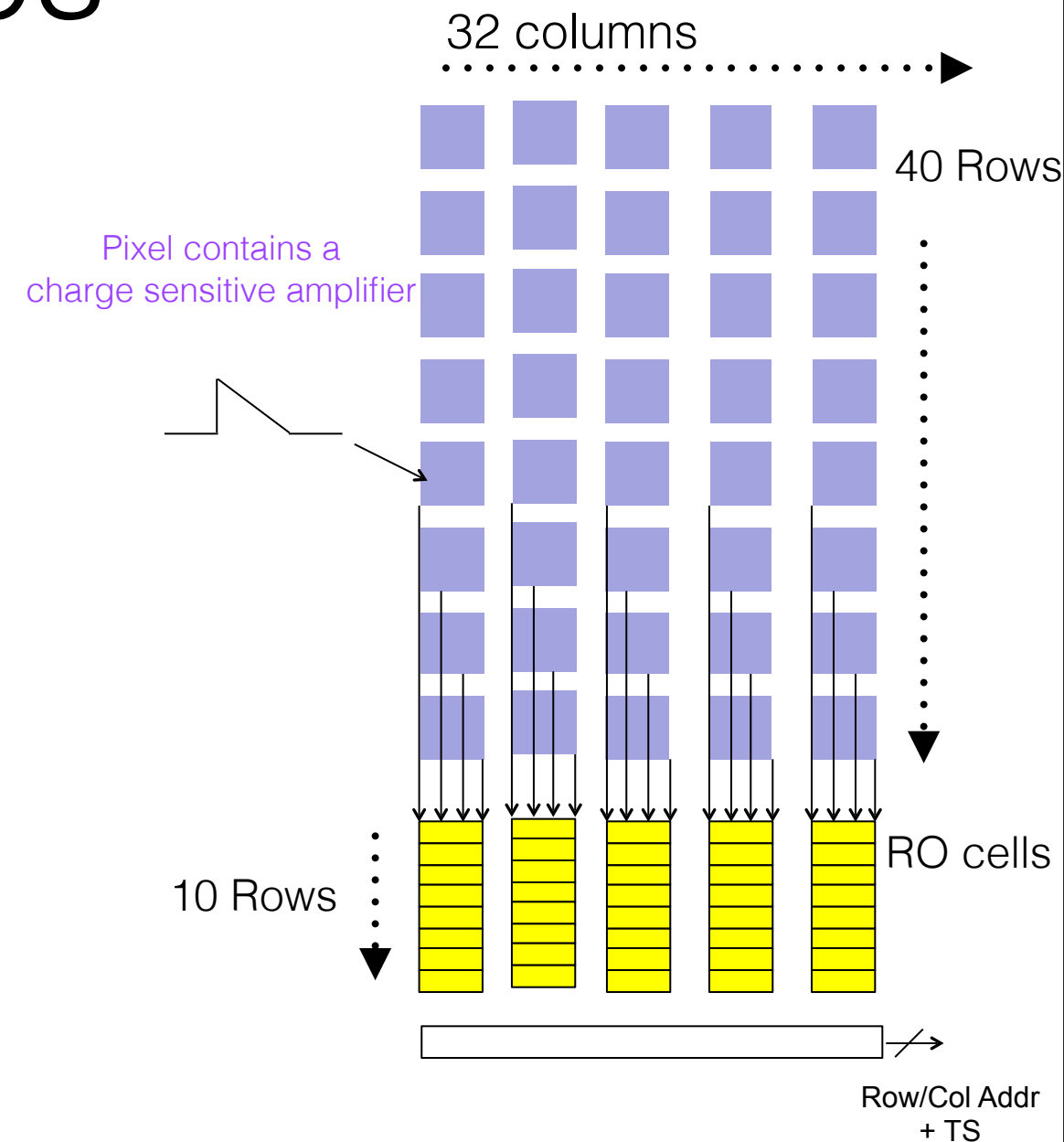
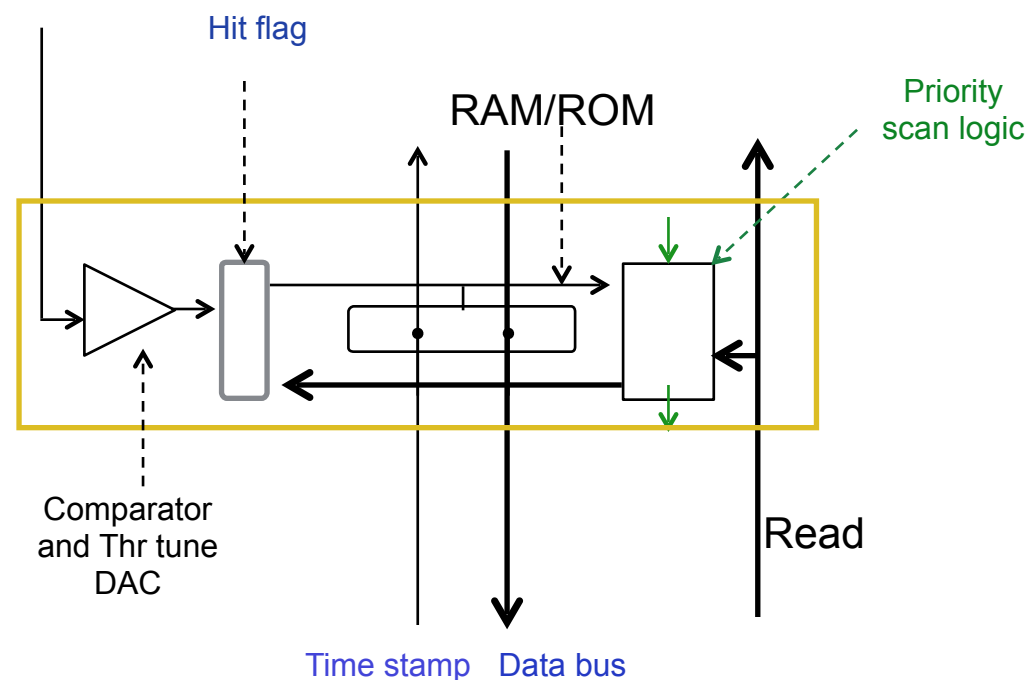
- Features : AMS 180nm process
- Pixel Matrix: 40x32 pixels, 80x92 μm^2 (pixel size) Active area : 9.4 mm²
- Moderate substrate resistivity $\sim 10 \Omega \text{ cm}$
- Designed by Ivan Peric (U. Heidelberg Institute for Computer Science (ZITI))
- Analog part: Small pixel capacitance
Temperature tolerance
- Digital part: Zero suppression
Mostly Ready
Feature: pixel address problem in half column
Fixed in MUIPX6 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

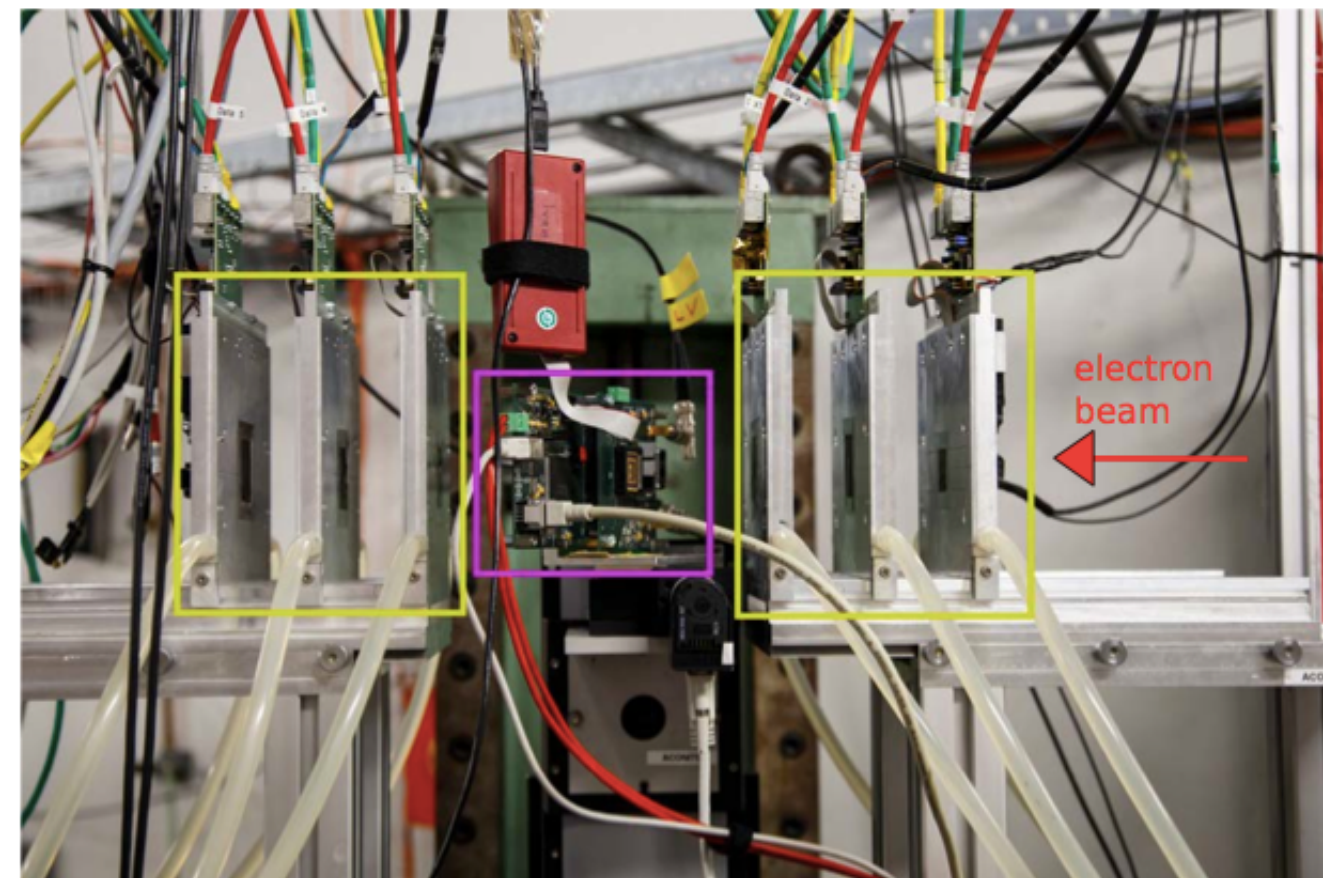
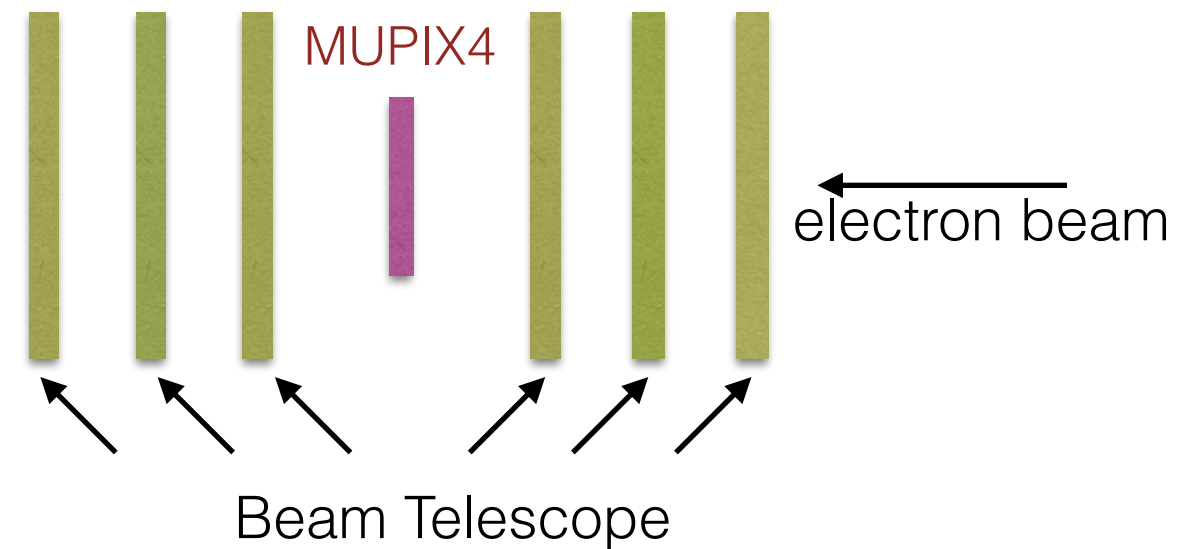
Binary Suppressed read out

RO cell size is $7\mu\text{m} \times 40\mu\text{m}$ 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
 - MUIPX4 prototype



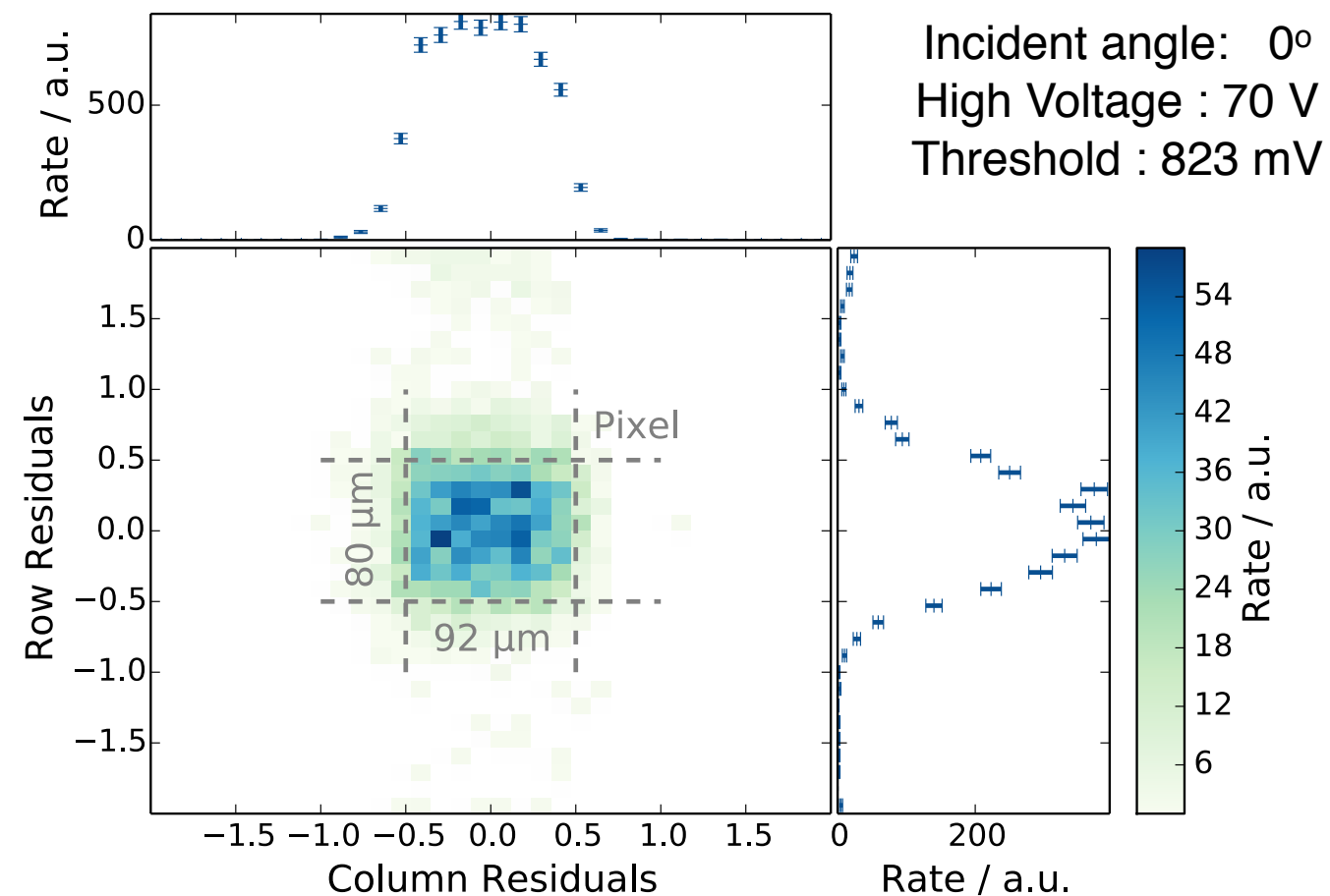
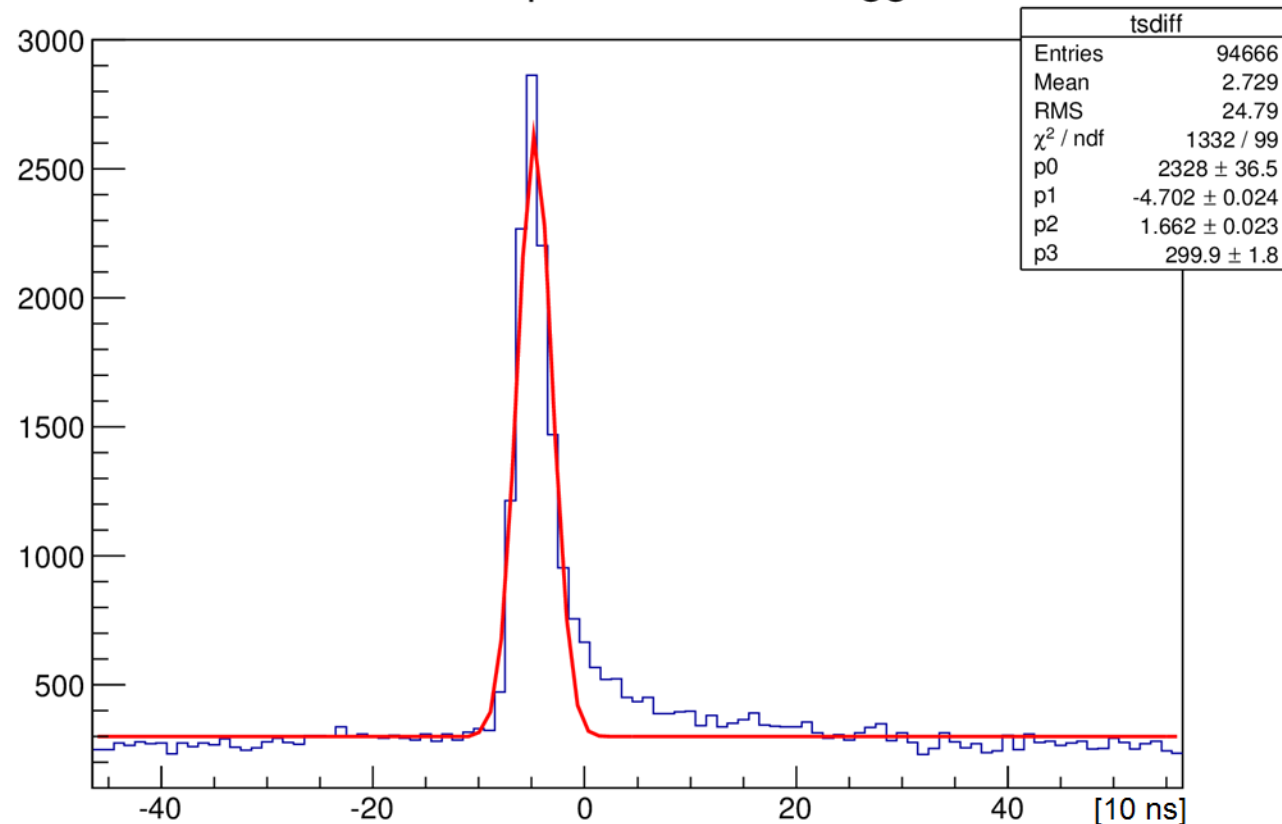


Test Beam Results

Time and Single Hit Resolution



Timestamp difference to trigger



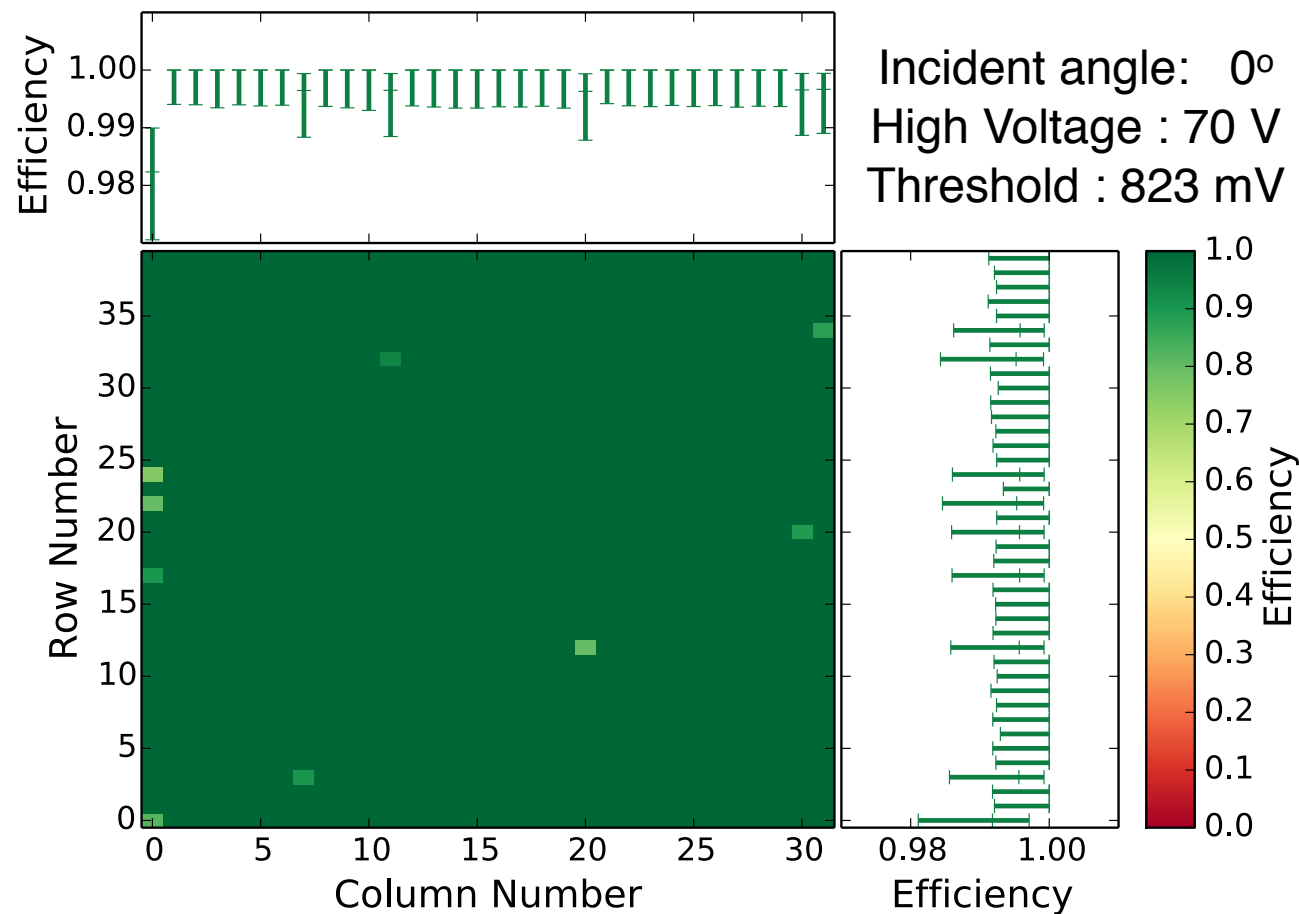
Result: Time Resolution : 17 ns
 (Sensor and DAQ)
 External Gray counter at 100 MHz

Result: Resolution given by pixel size
 Measured track residuals:
 RMS x = $28 \mu\text{m}$, RMS y = $29 \mu\text{m}$



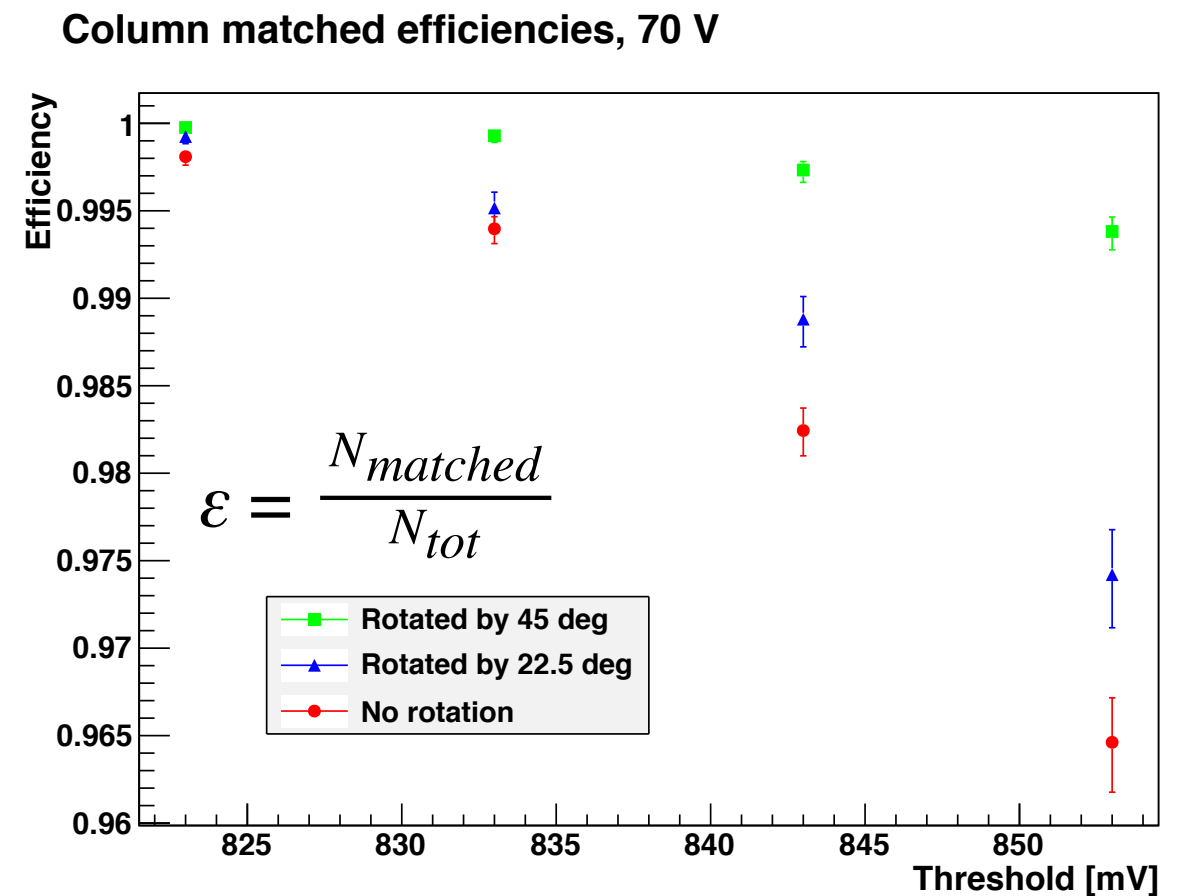
Pixel Efficiency

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 $\text{BR} < 10^{-16}$
- 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

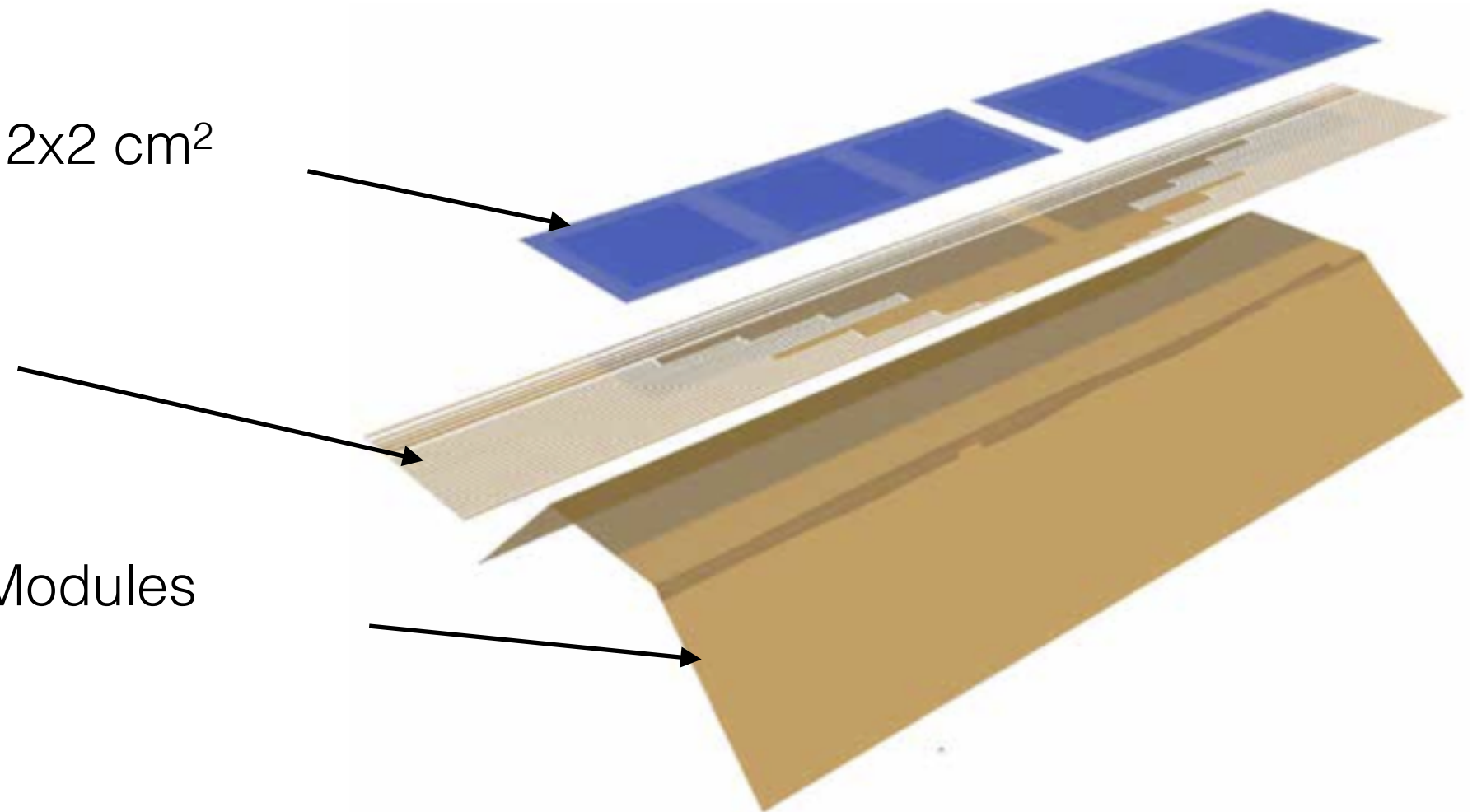
25 μm Kapton™

12.5 μm Al traces

Kapton™ Frame Modules

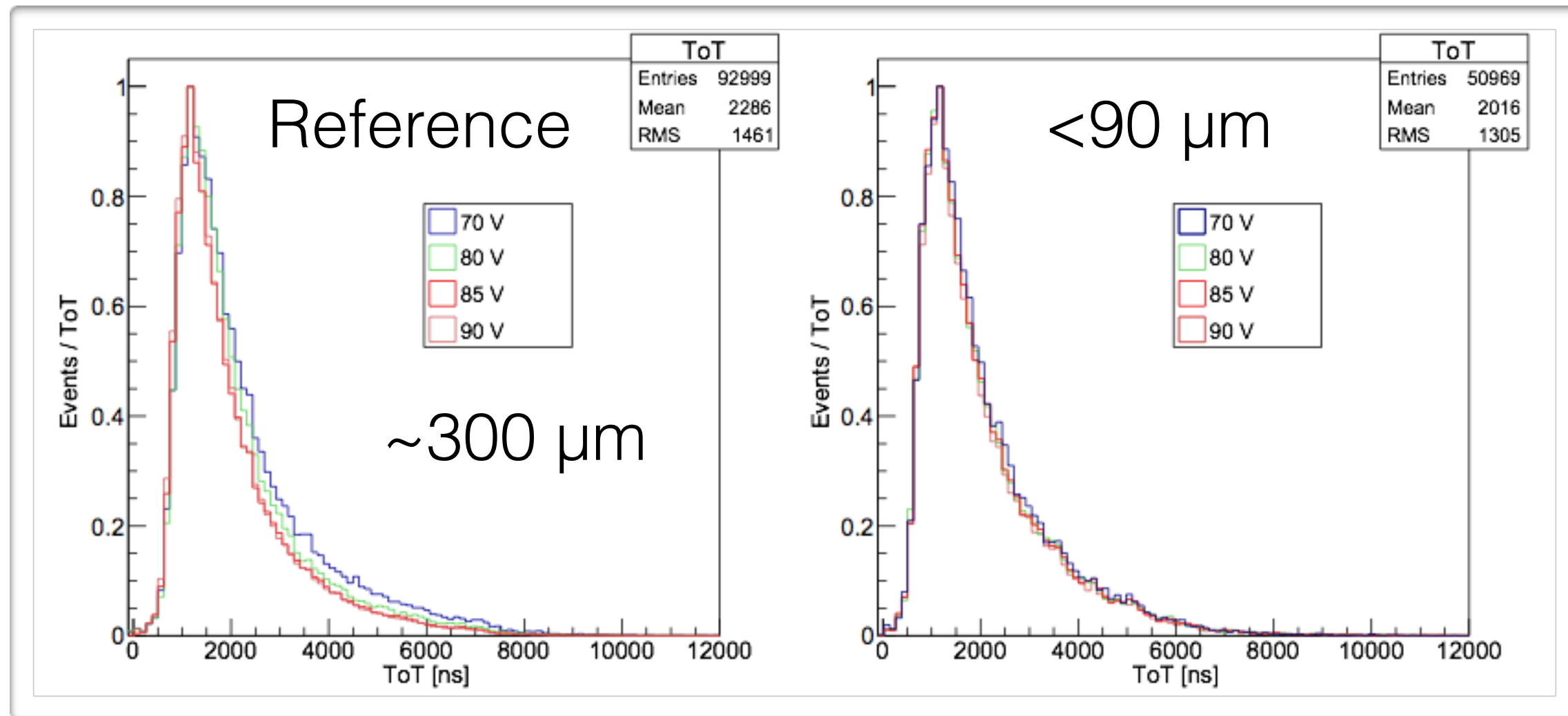
25 μm foil

self support



$<0.1\%$ X_0 per layer

Thinned sensor



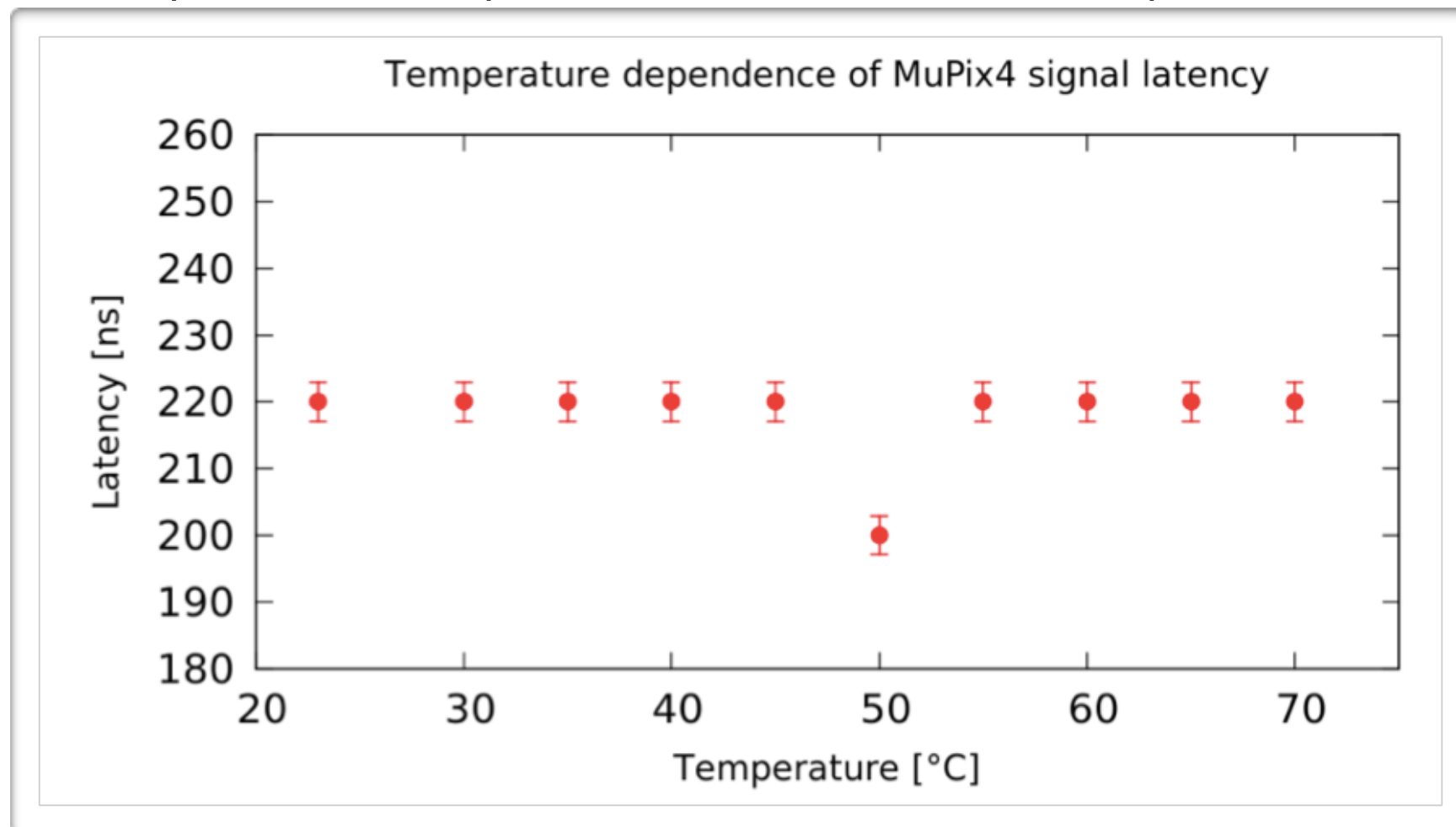
PSI test beam

Result: No significant difference in pulse shape



Temperature stability

- Latency measurement
 - LED pulse to a pixel discriminator output



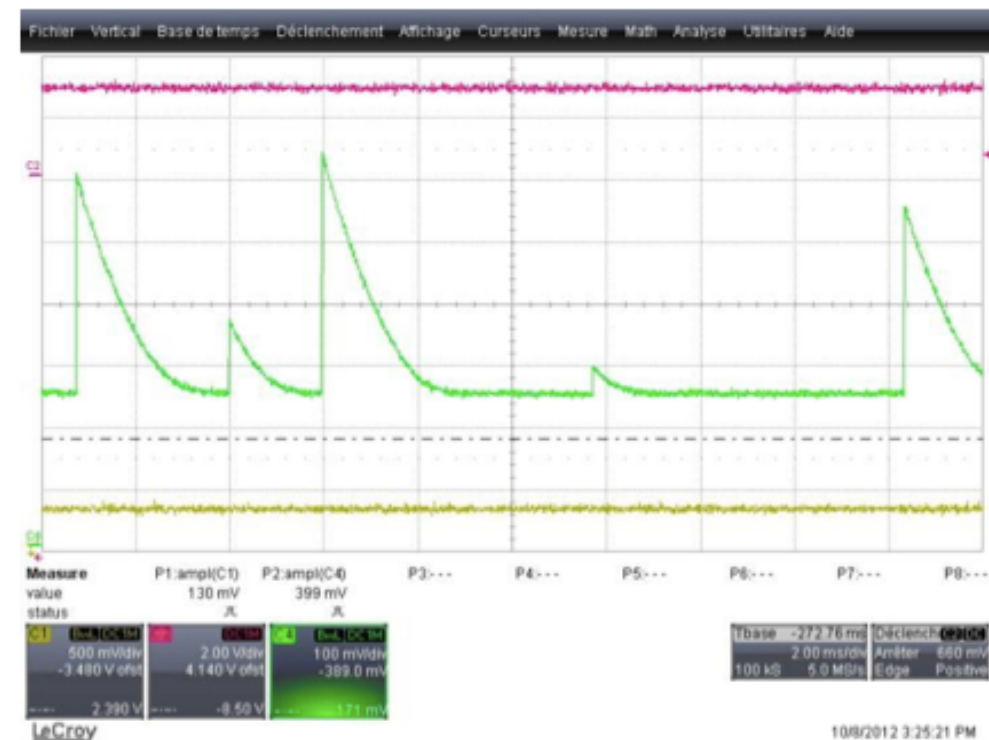
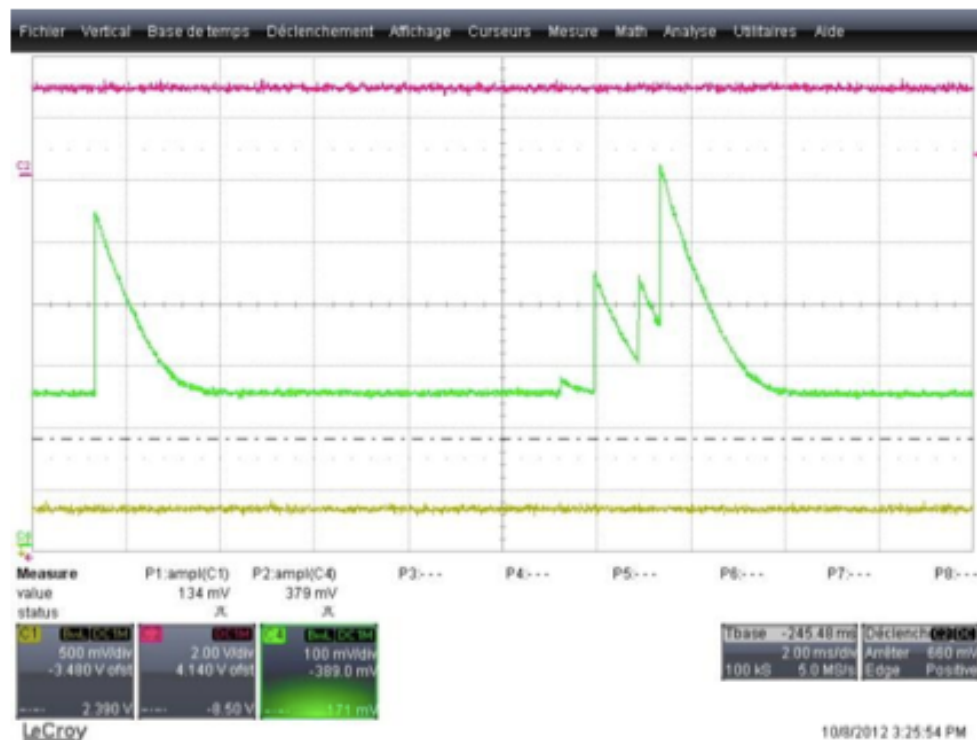
Result: Temperature dependence within
the resolution setup

Result after 380MRad radiation

and $\sim 8 \times 10^{15} n_{eq} \text{ cm}^{-2}$

- 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