# Mu3e Testbeam Measurements at DESY

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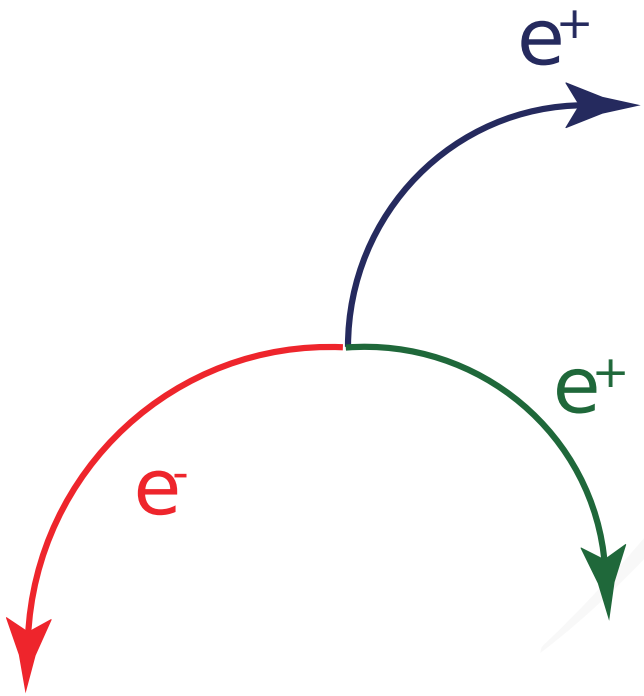
Telescopes and Testbeams, Hamburg, 30. June 2014

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

# The Mu3e Experiment





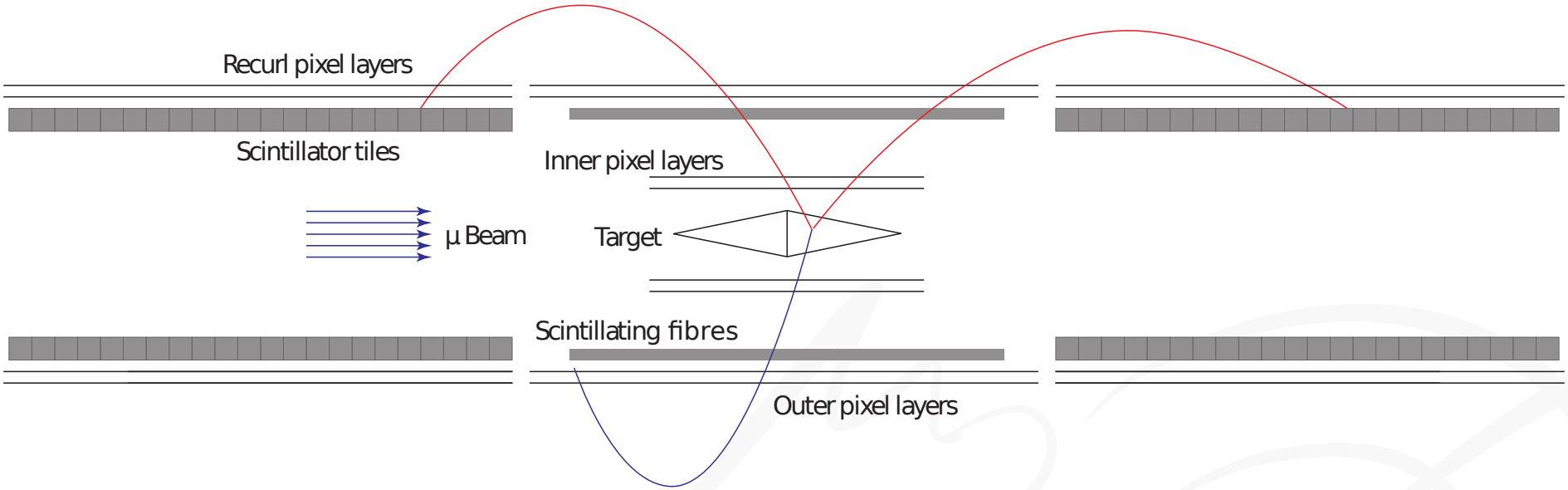

- Precision experiment
- Search for $\mu^+ \rightarrow e^+e^-e^+$
- Sensitivity $< 1$ in $10^{16}$ decays
- Standard Model $\ll 1$ in $10^{50}$

Importance ?

- New physics search
- High sensitivity

# The Mu3e Experiment






## Environment

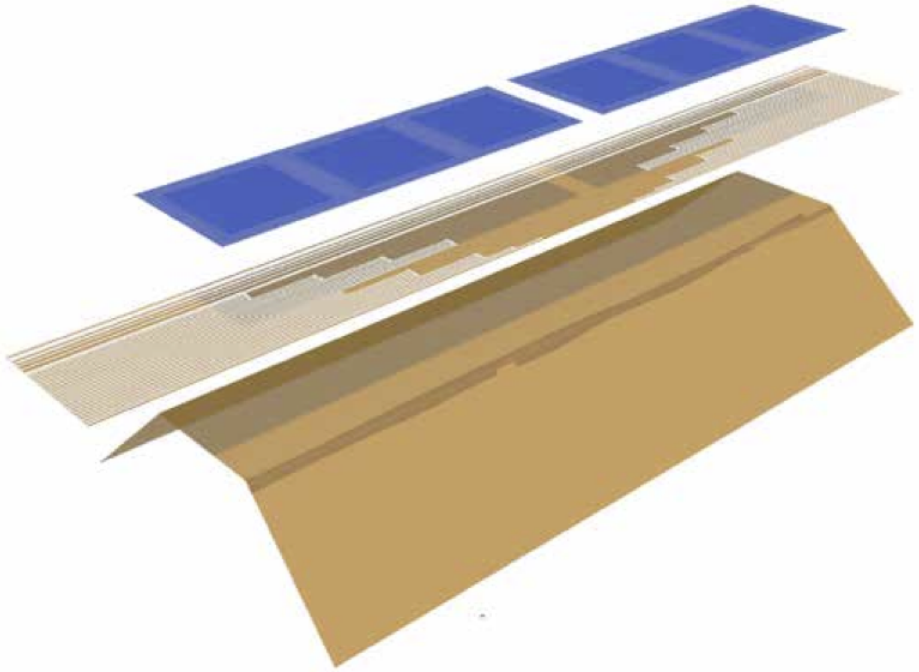
- $> 10^9$ $\mu^+$ Decays/s
- Electrons p $< 53$ MeV
- Dominated by multiple scattering

## Pixel Sensor Requirements

- Fast $< 20$ ns
- Thin $\leq 1$ ‰ $X_0$
- Pixel $80 \times 80$ µm$^2$

# Ultra-Lightweight Mechanics





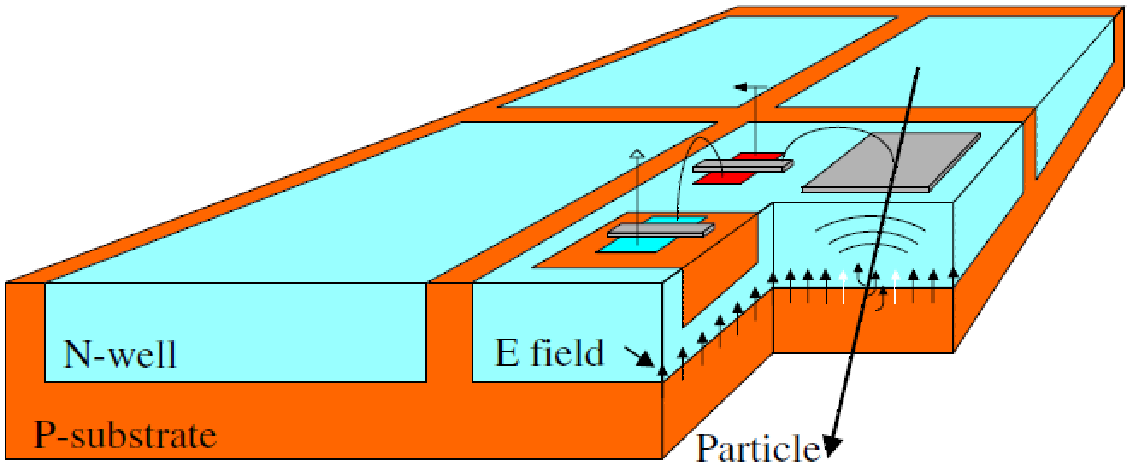
- 50 µm Silicon sensor
- 50 µm Kapton flexprint
- 25 µm Kapton support frame

$\rightarrow \leq 1\,‰$ Radiation length

# Testing Pixel Sensor Prototypes

# Monolithic Active Pixel Sensors

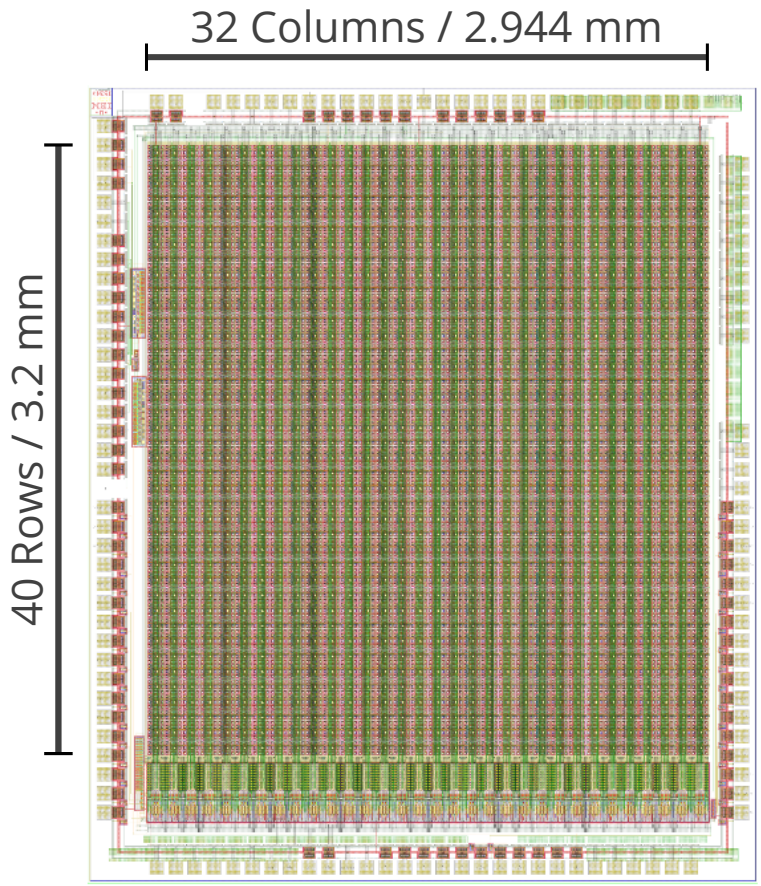





- HV $\sim 70\,\mathrm{V}$ (HV-MAPS)
- Fast charge collection by drift
- Thin active zone $< 20\,\mu\mathrm{m}$
- Cheap, commercial process

# MuPix4 HV-MAPS Prototype



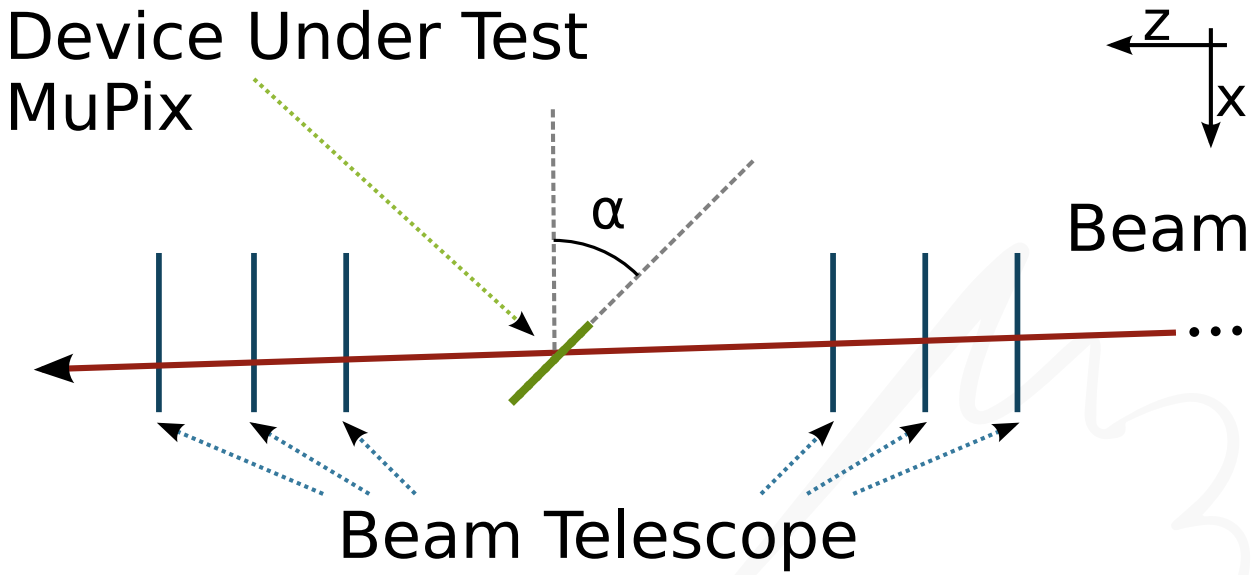



- $92 \times 80\,\mu m^2$ pixel size
- Global threshold
- Zero-suppressed digital readout
- Timestamps
- 93 % active area

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

# Testbeam Setup w/ MuPix4

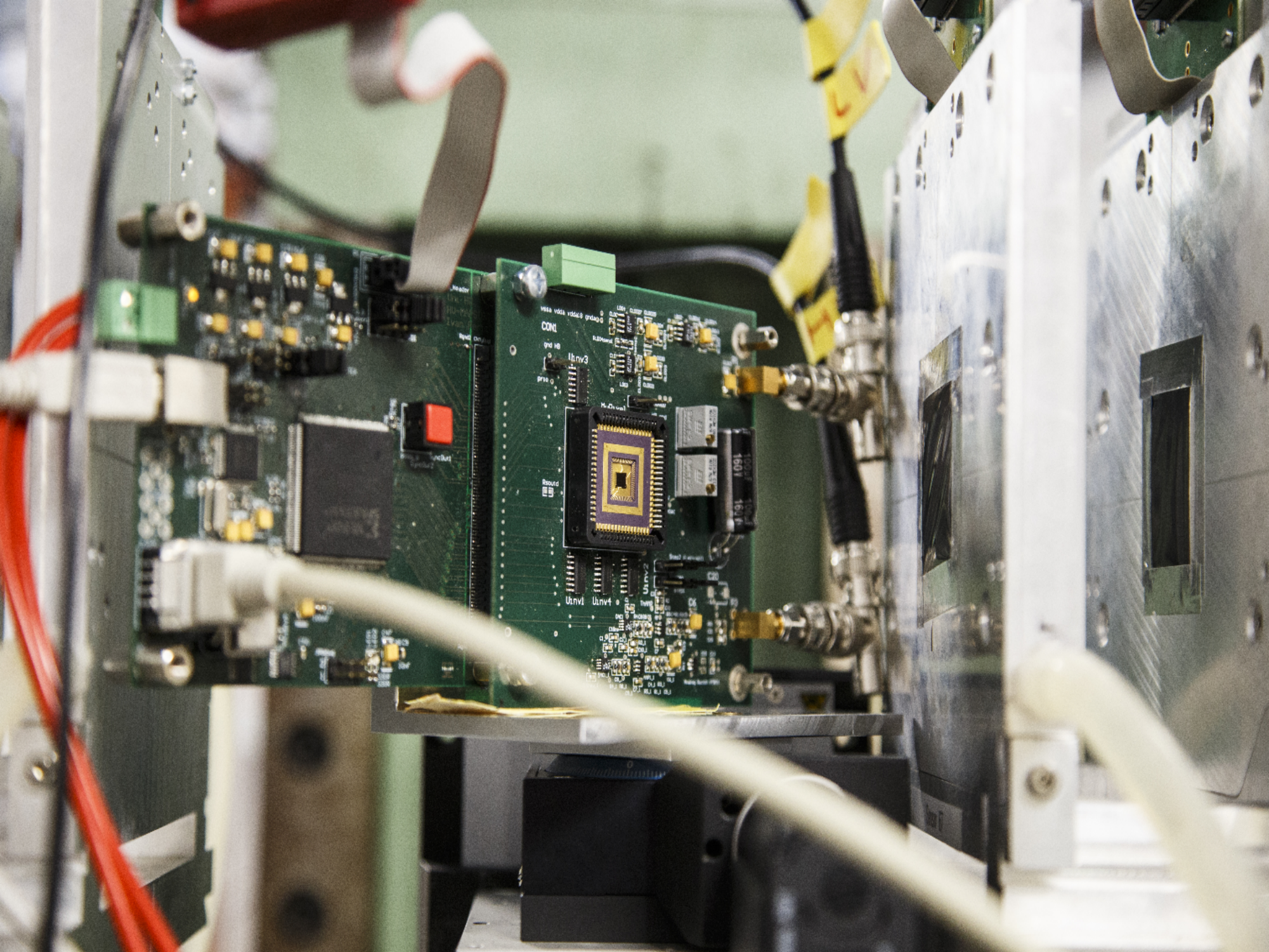





- Full EUDAQ (v1.1) integration
- Reconstruction w/ EUTelescope (v00-09-xx)

Provided by DESY

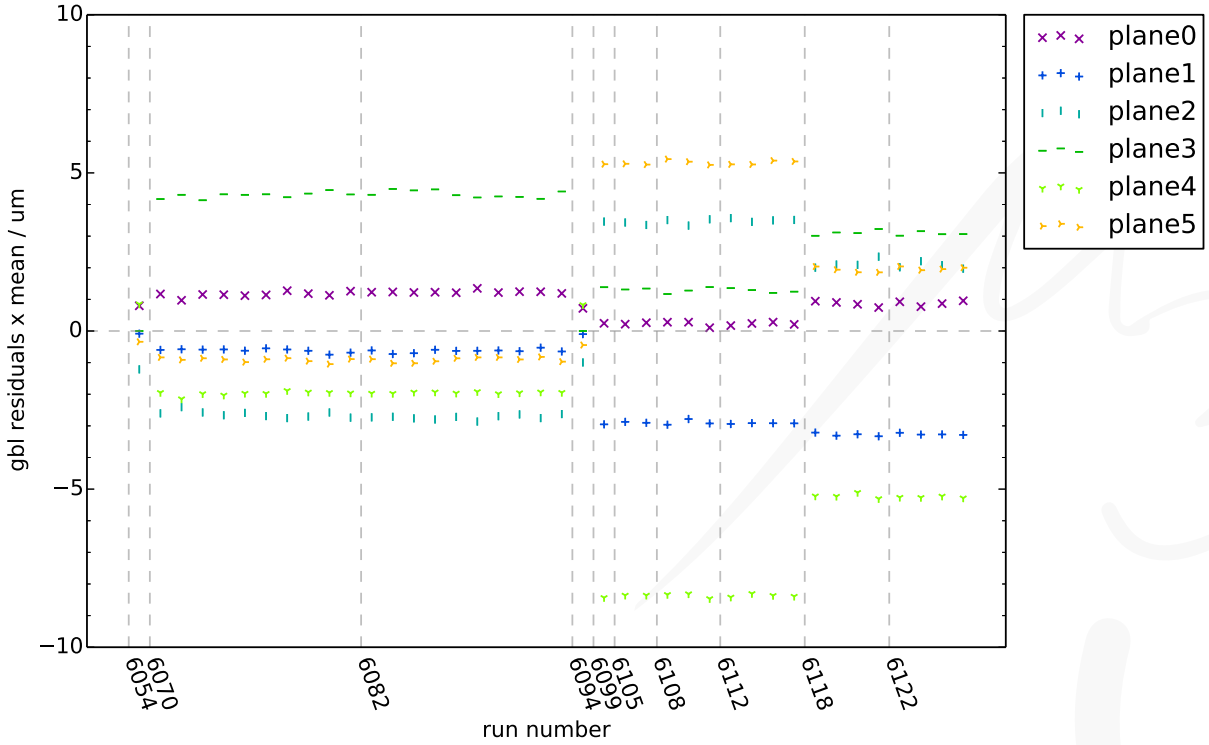
- Beamline T22
- 1 GeV to 6 GeV electrons
- Aconite beam telescope


CON1
Uinv3
Uinv1
Uinv4
Uinv2

# Telescope (Mis-)Alignment



## Track Residuals in X / All Planes

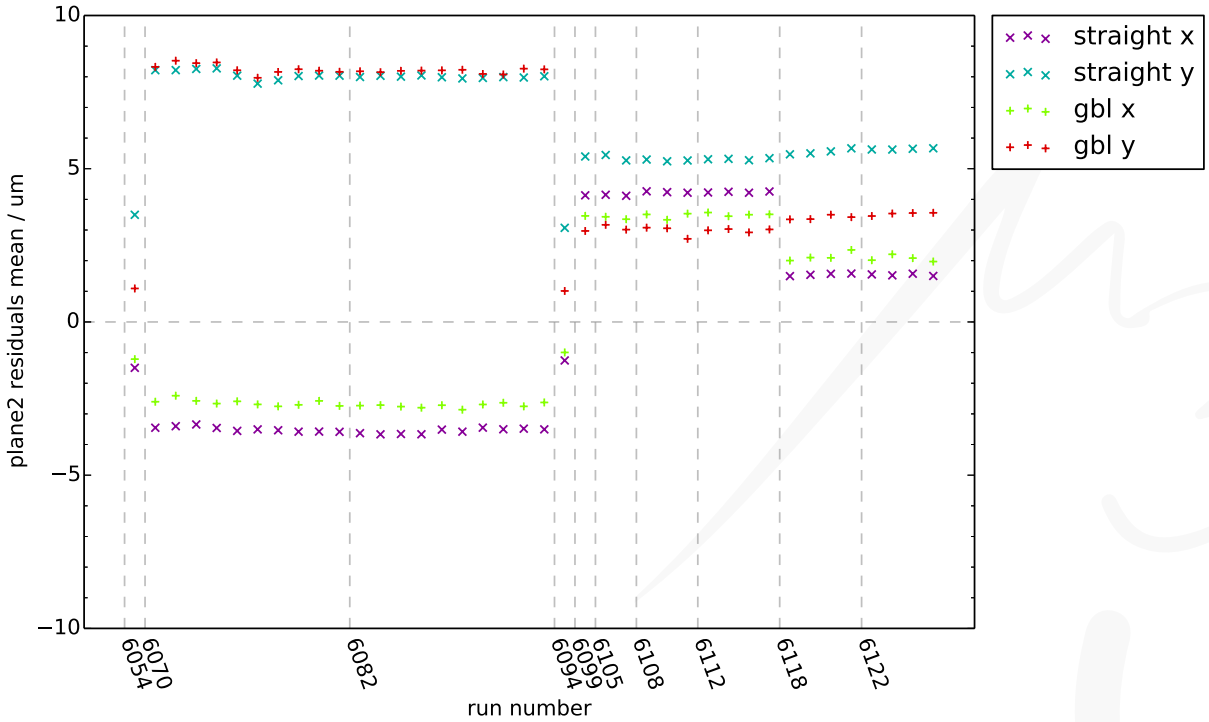



- GBL / Millepede Alignment
- Systematic Shift
- Complimentary before / after DUT
- Not visible in alignment runs

# Telescope (Mis-)Alignment



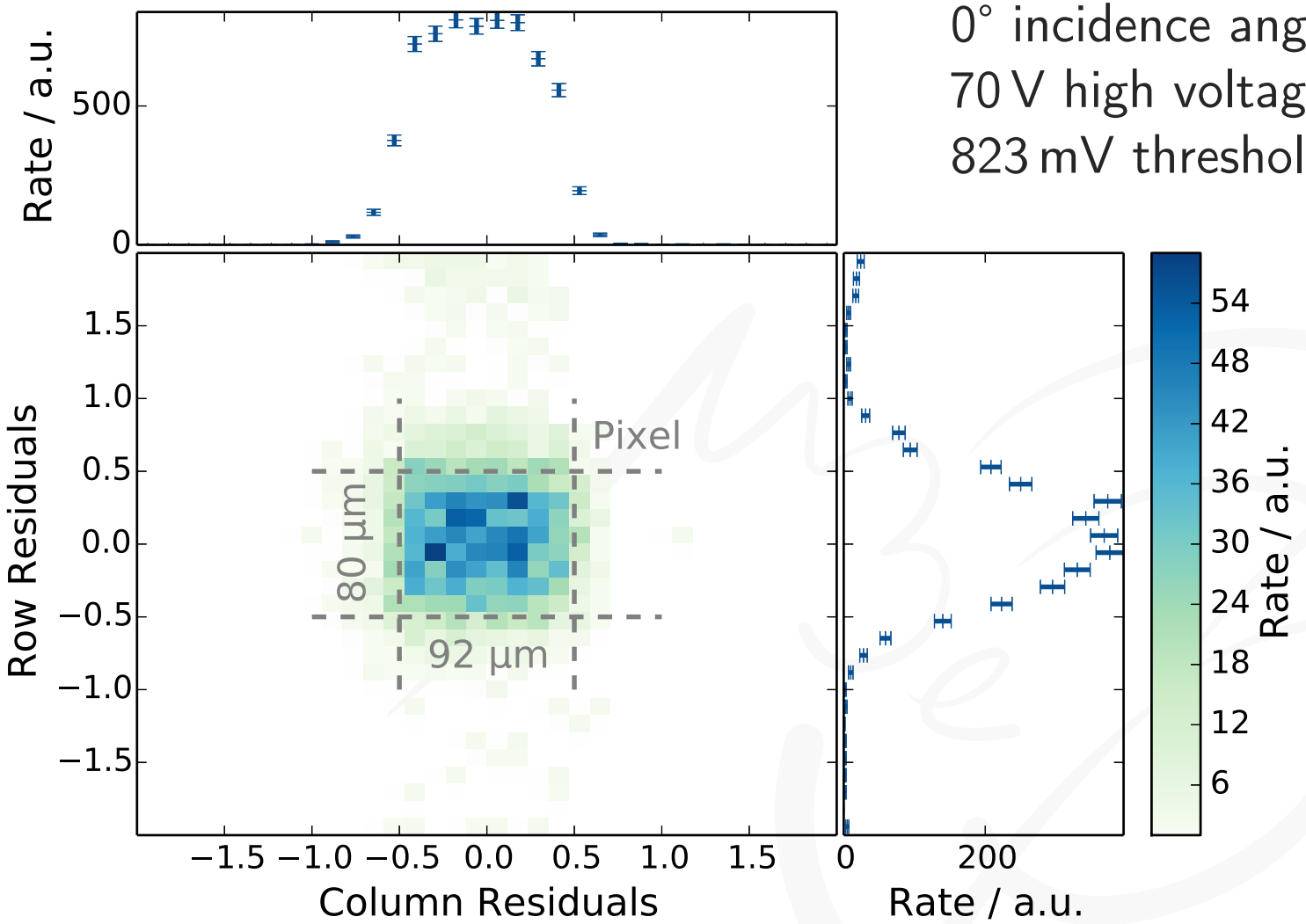
## Track Residuals / Plane 2




- GBL / Millepede Alignment
- Systematic Shift
- Complimentary before / after DUT
- Not visible in alignment runs

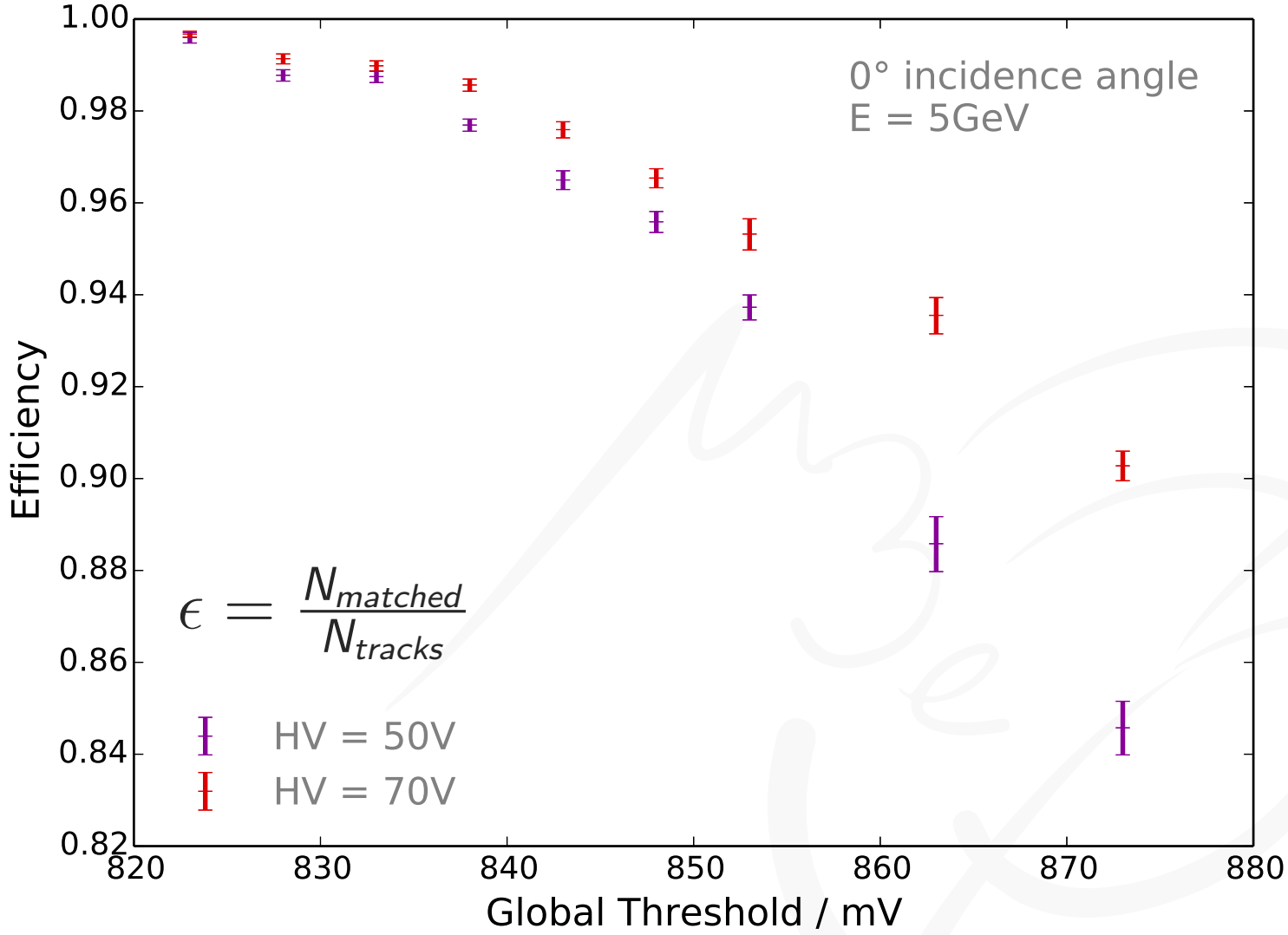
# Single Hit Resolution





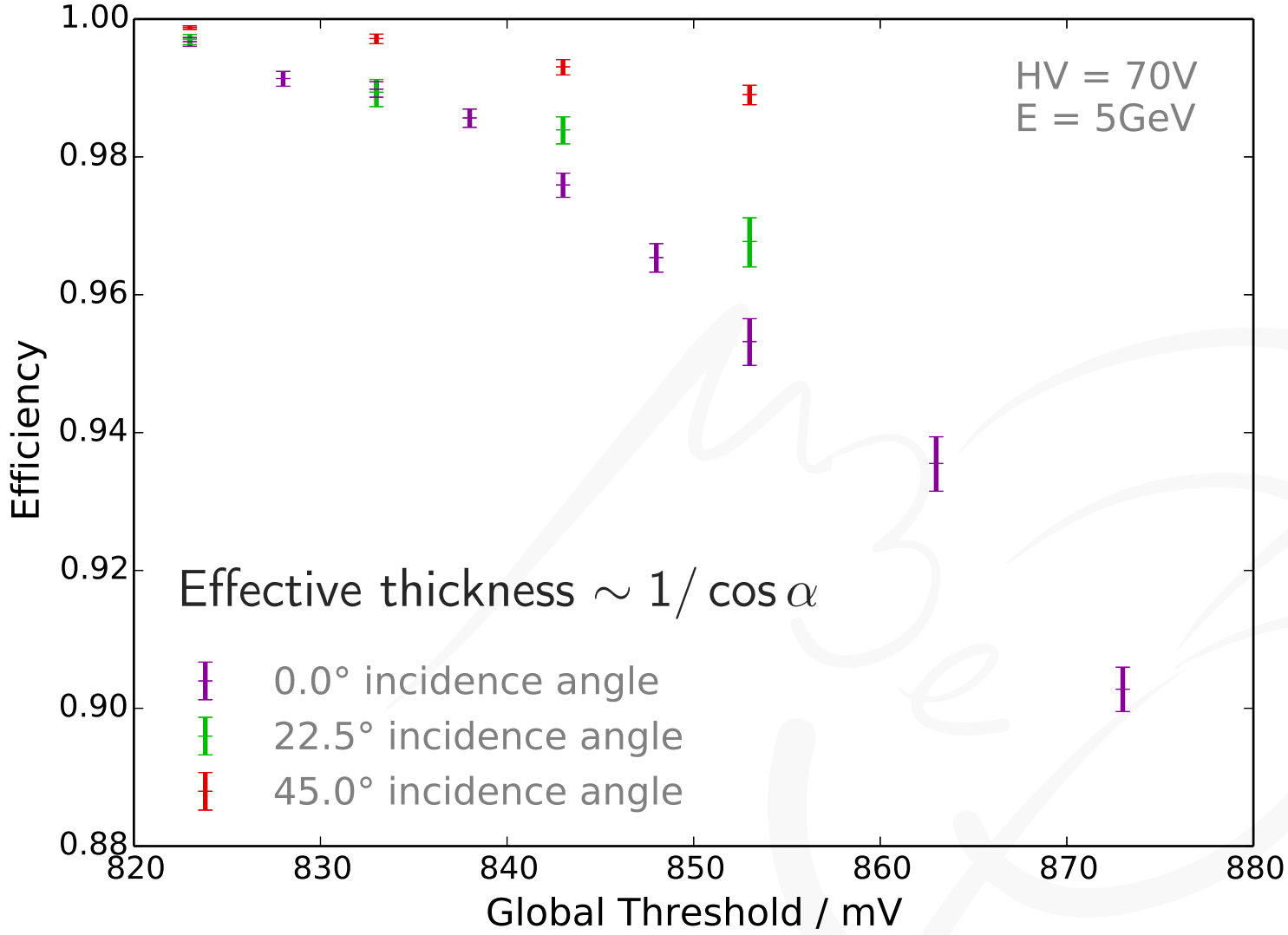
# Global Efficiency / High Voltage





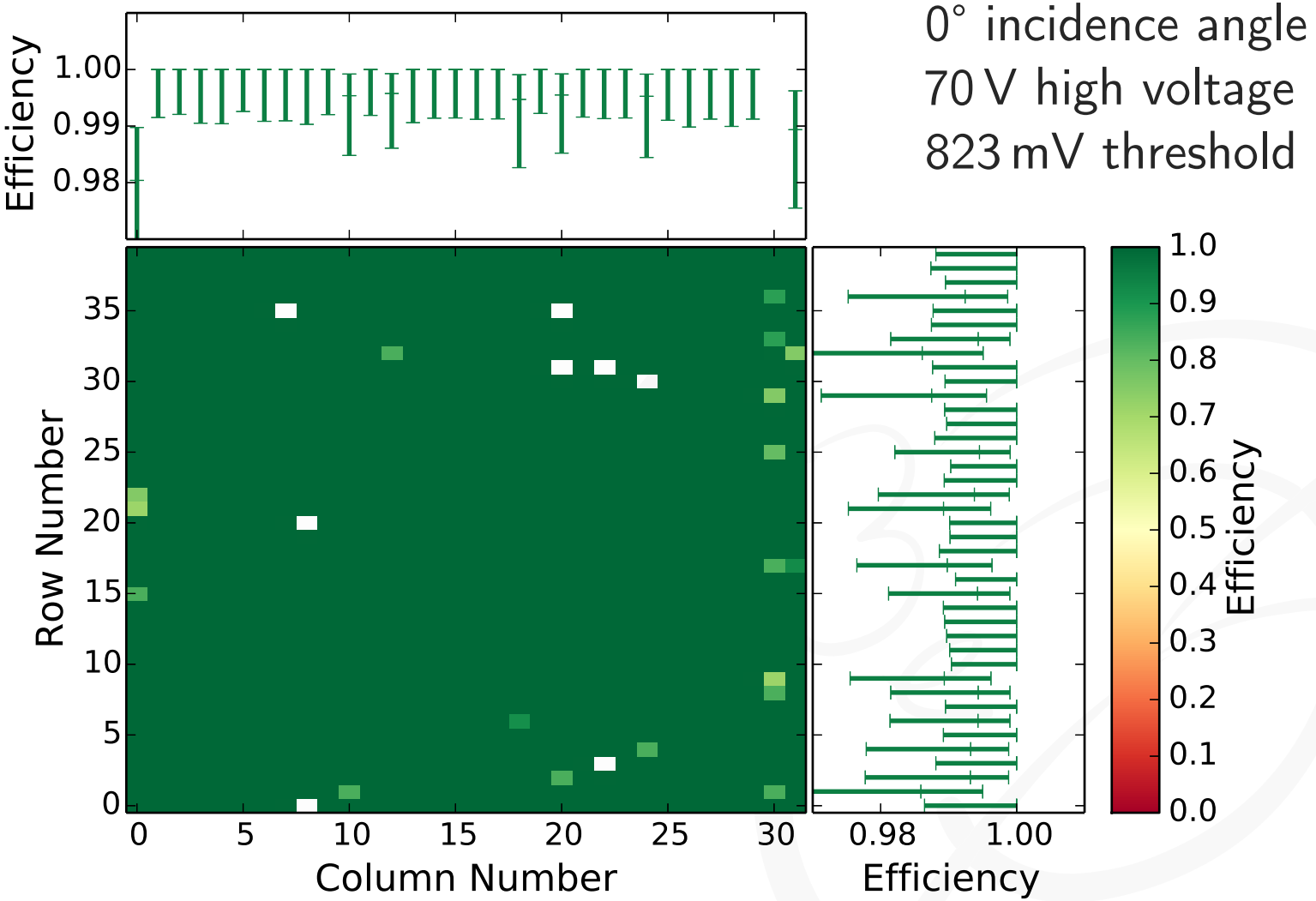
# Global Efficiency / Incidence Angle



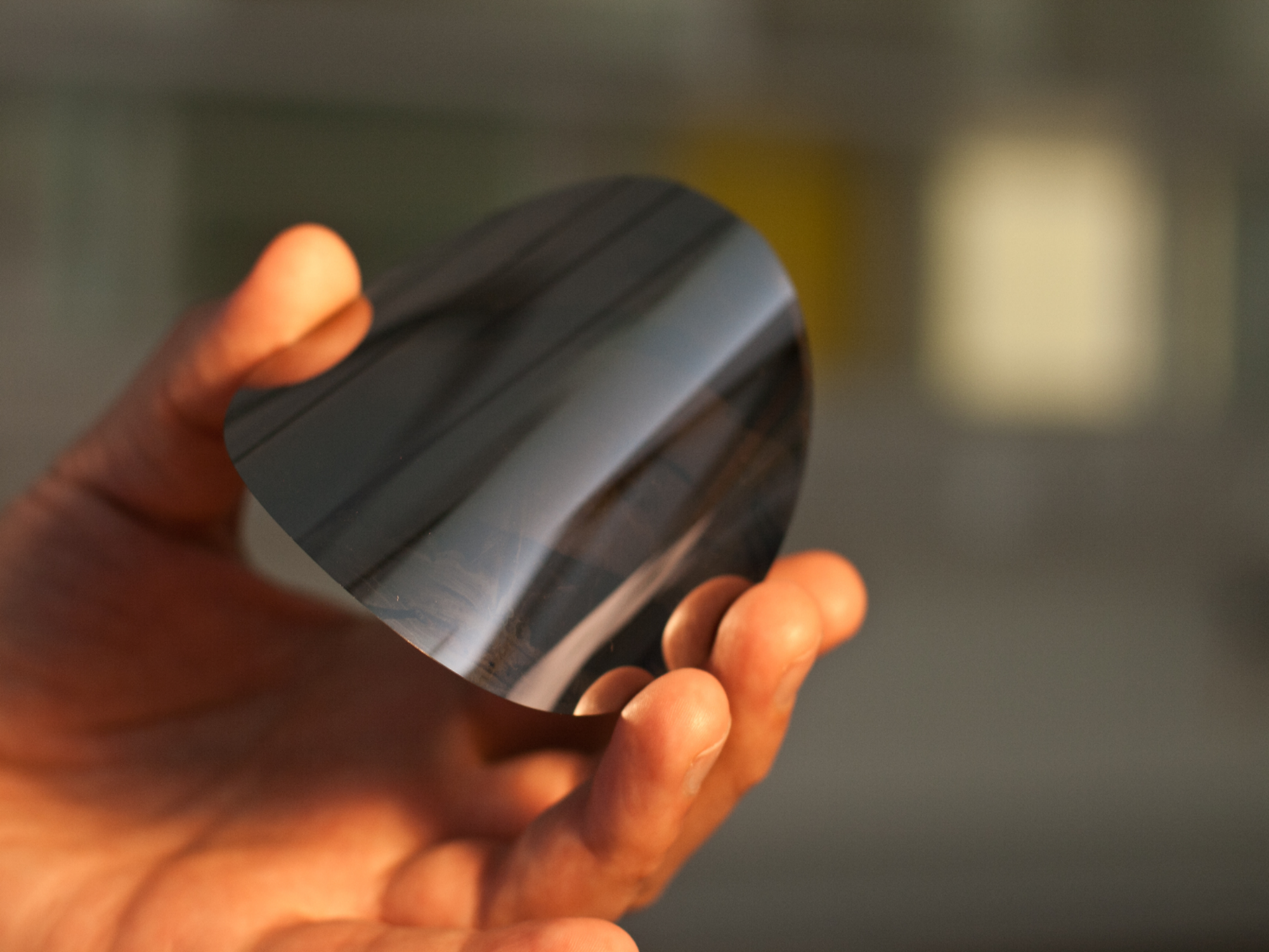


# Pixel Efficiency





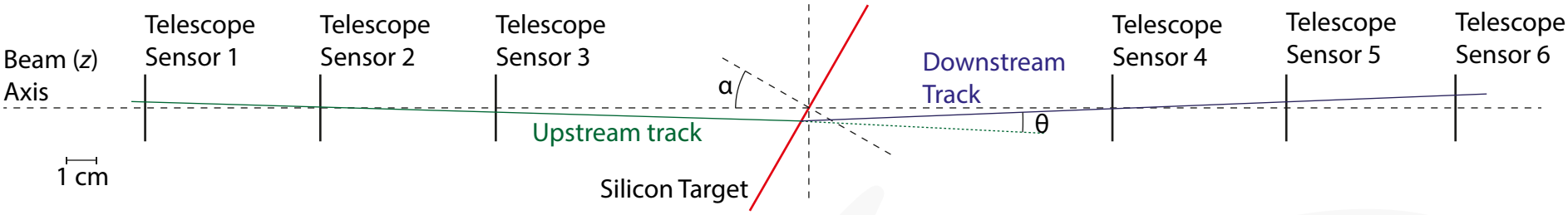
# Multiple Scattering in Thin Silicon



# Testbeam Setup w/ Silicon Wafer



N. Berger, M. Kiehn, et.al. arXiv:1405.2759 (accepted by JINST)




## Measured Scattering Distributions

$$t(\theta) = f_{upstream} \otimes f_{downstream}$$

$$s(\theta) = f_{upstream} \otimes f_{Si} \otimes f_{downstream}$$

$$= (f_{upstream} \otimes f_{downstream}) \otimes f_{Si}$$

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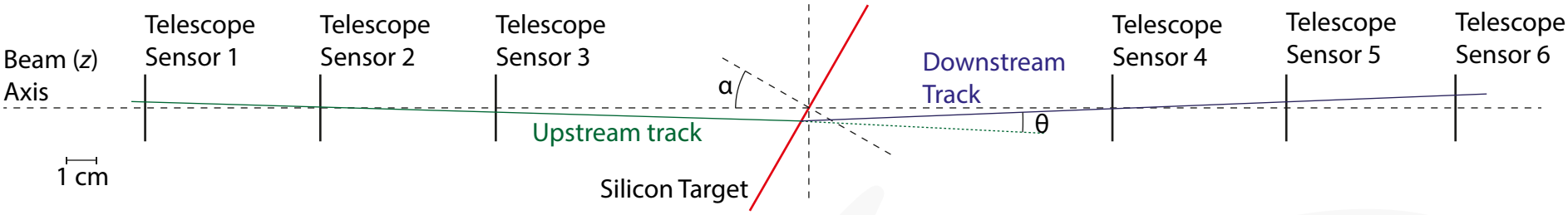



## Fitted Scattering Distributions

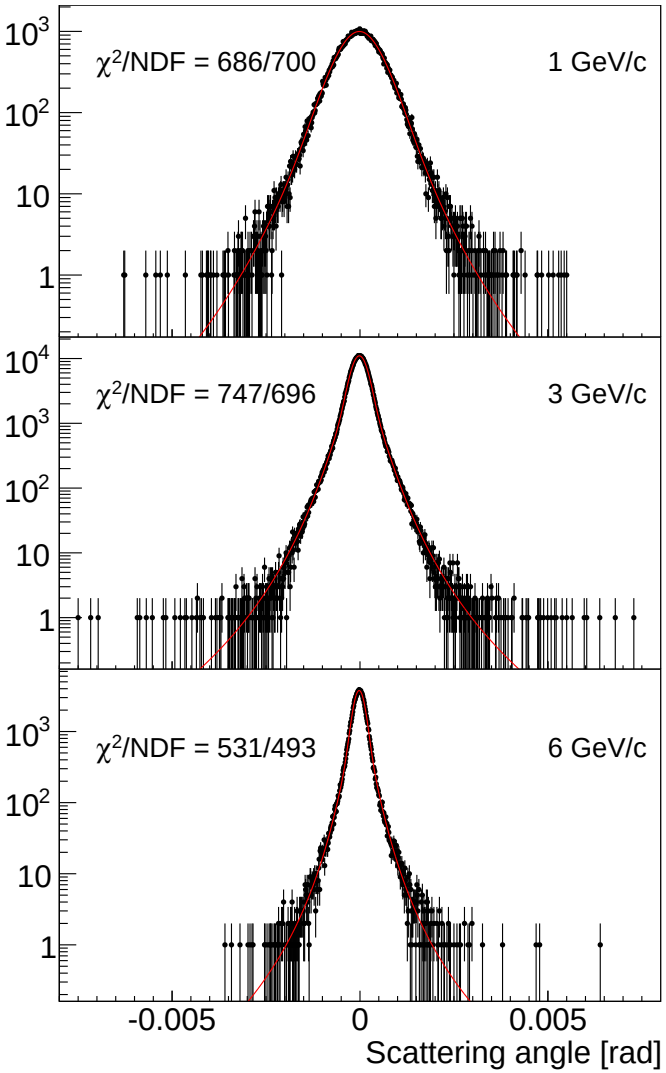
$$t(\theta) \sim \mathit{normal}(\mu, \sigma_1) + \epsilon \cdot \mathit{studentt}(\mu, \sigma_2, \nu_2)$$

$$s(\theta) \sim t_{\mathit{fixed}} \otimes \mathit{studentt}(\mu, \sigma, \nu)$$

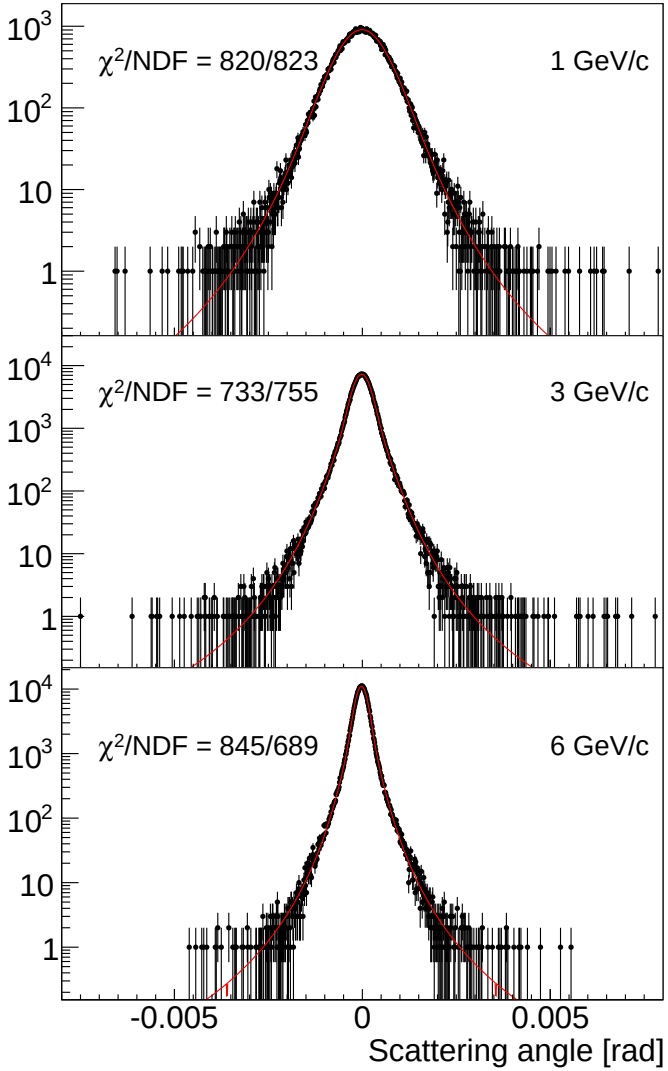
# Measured Scattering Distributions



## No Silicon



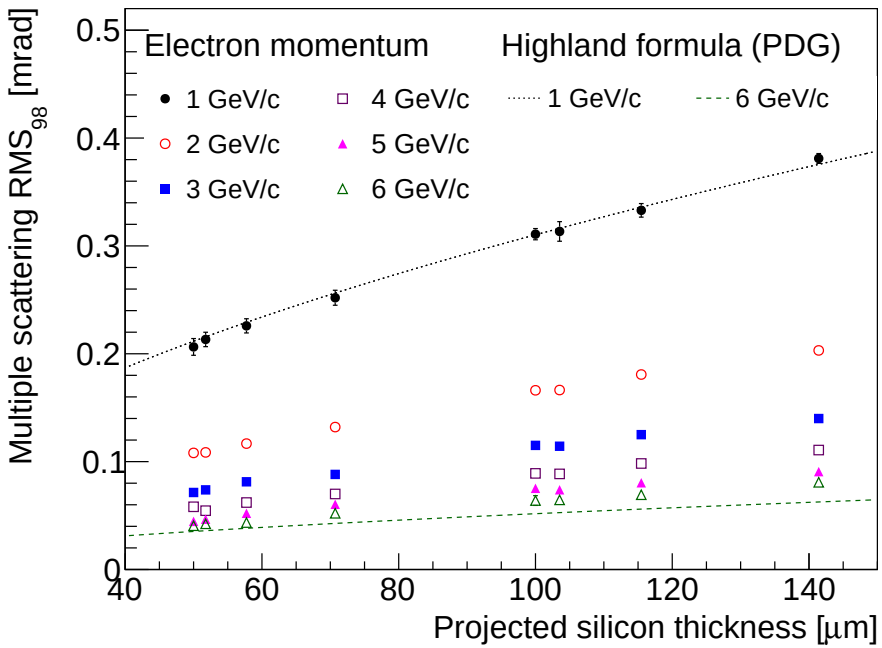

## 50 µm Si, $\alpha = 15°$



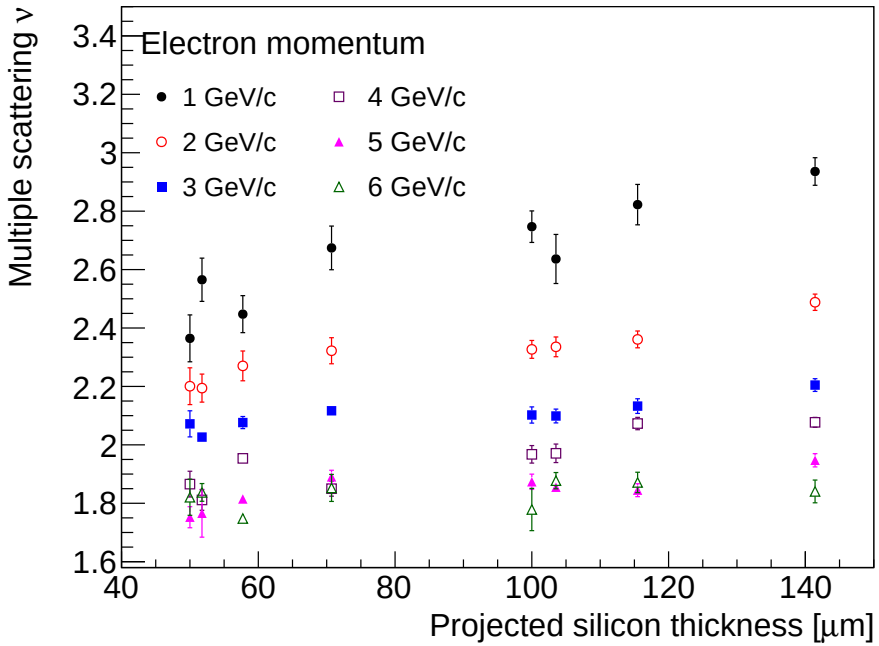
# Distribution Parameters



## $RMS_{98}$ vs Thickness




## Tail Parameter $\nu$ vs Thickness

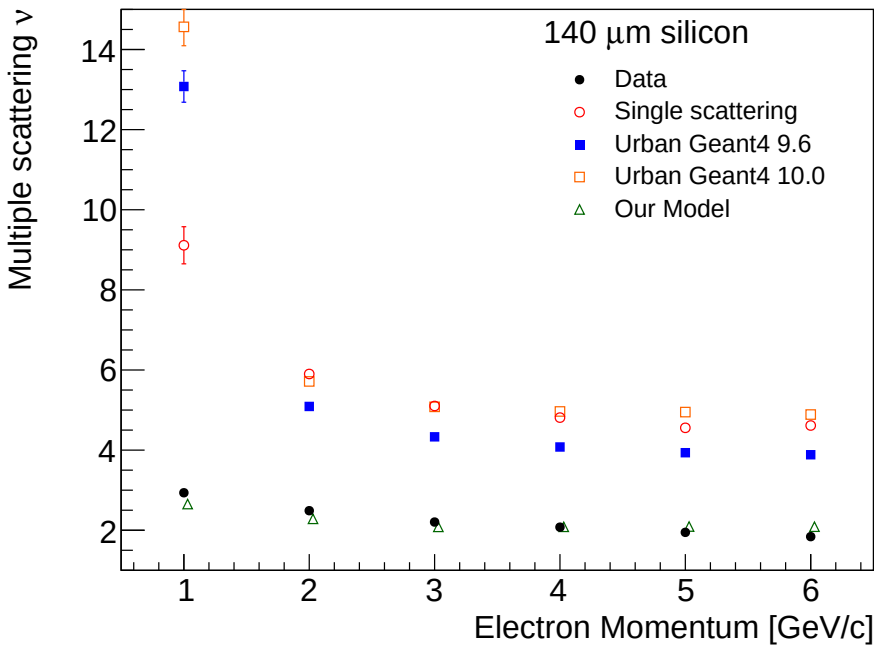



- $RMS_{98}$ is consistent w/ PDG $\sim 1/p\sqrt{t}(1 + 0.038 \ln t)$
- Tail fraction $\sim 1/\nu$

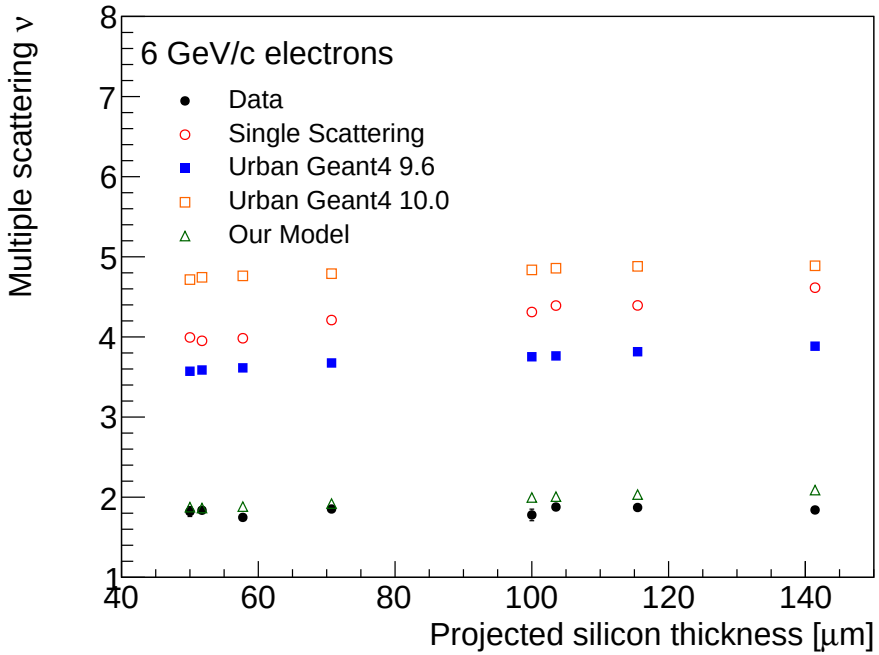
# GEANT4 Validation



## Tails vs Momentum




## Tails vs Thickness




- GEANT4 simulation of Telescope Setup
- $RMS_{98}$ is well described (not shown)
- Default models underestimate tails
- Shape is not described

# Summary & Outlook



## Mu3e

- Search for $\mu^+ \to e^+e^-e^+$
- R&D in progress

## Testbeams at DESY

- MuPix HV-MAPS prototype
- Scattering in thin silicon
- Scintillating tiles / fibres
- ...

## Outlook

- MuPix6 prototype
- Next Testbeam in Oct./Nov. ?

Impossible w/o DESY Testbeam Group. Thank You.

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# Backup

# t-Distribution Scattering Model

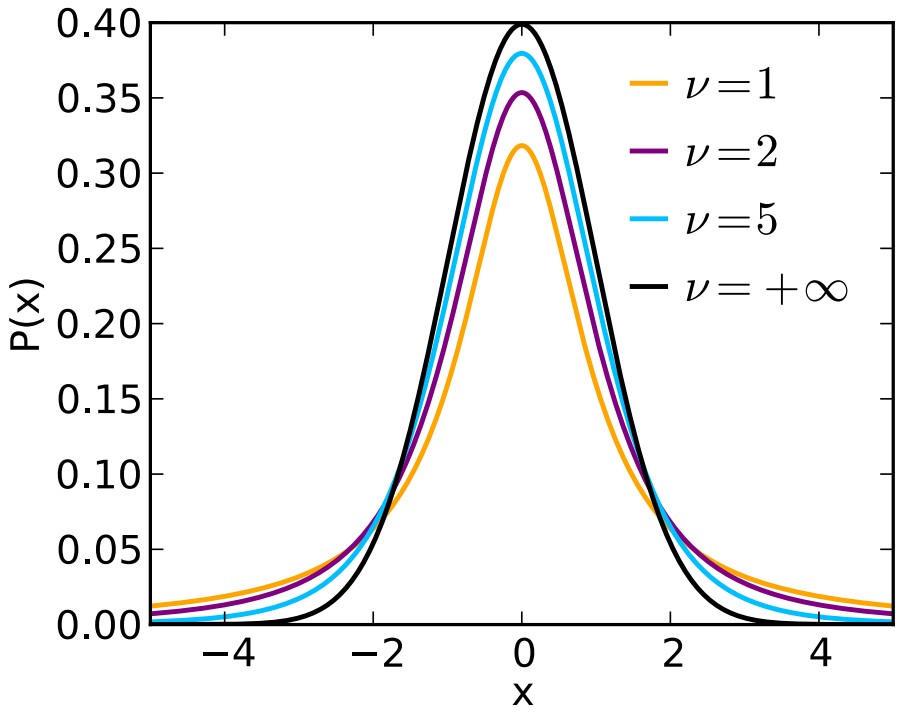


N. Berger, M. Kiehn, et.al. arXiv:1405.2759

## Idea

- Based on Urban model
- Angles from t-distribution
- $\nu$ from fit to data

$$\nu(p,t) = A + B\frac{1}{p-D} + Cd$$




https://en.wikipedia.org/wiki/Student-t

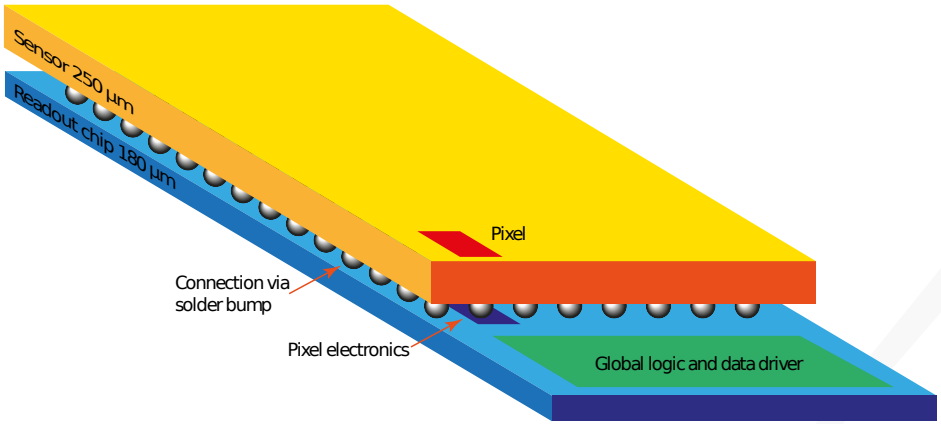
## Caveats

- Purely empirical
- Valid only for
  1 GeV to 6 GeV electrons
  50 µm to 141 µm Si

# Silicon Pixel Sensors

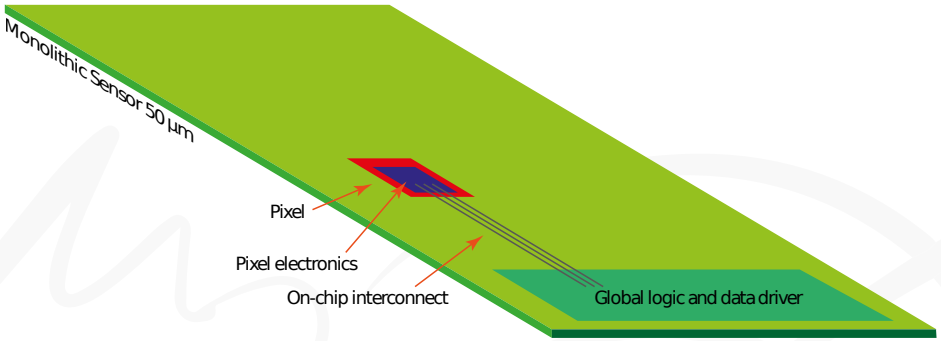


## Hybrid




- HV $\sim$ 700 V
- Sensor thickness $\sim$ 250 µm
- Extra material
- Complex and expensive

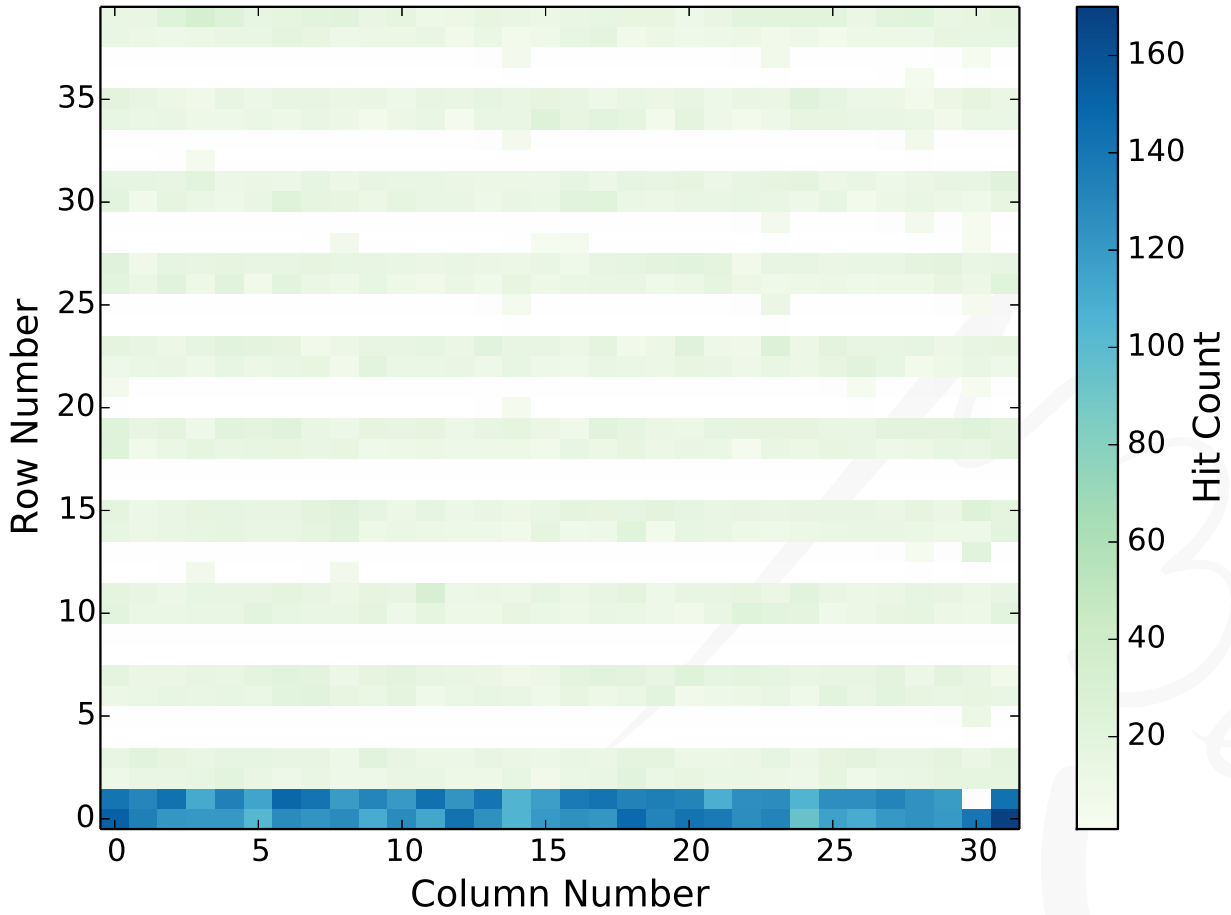
## Monolithic Active Pixel Sensor




- HV $\sim$ 70 V (HV-MAPS)
- Thin active zone $<$ 20 µm
- Cheap, commercial process

# Hitmap a.k.a Hybrid Strixel Sensor

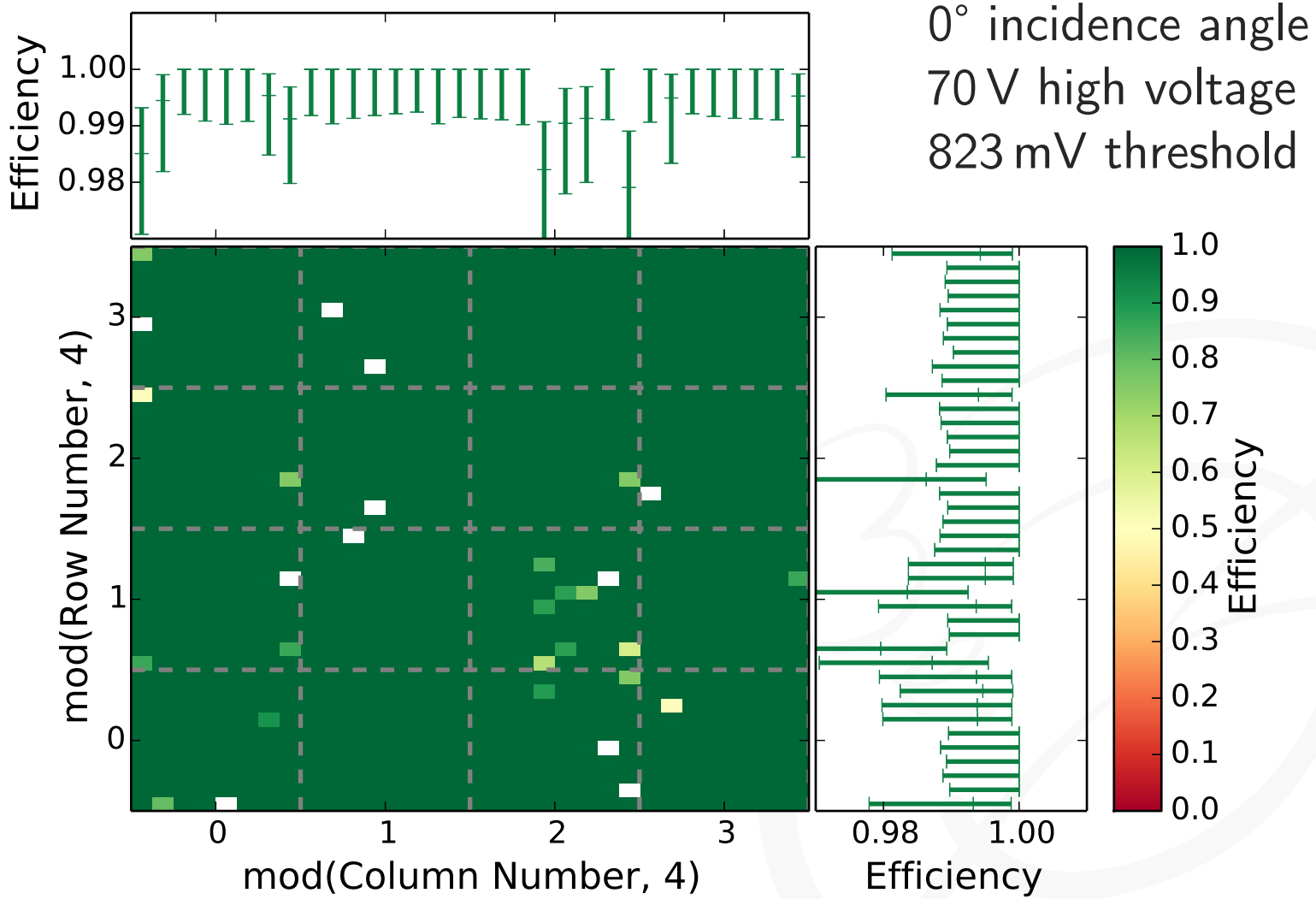





0° incidence angle
70 V high voltage
838 mV threshold
5 GeV beam energy

# Subpixel Efficiency / 4x4 Submatrix

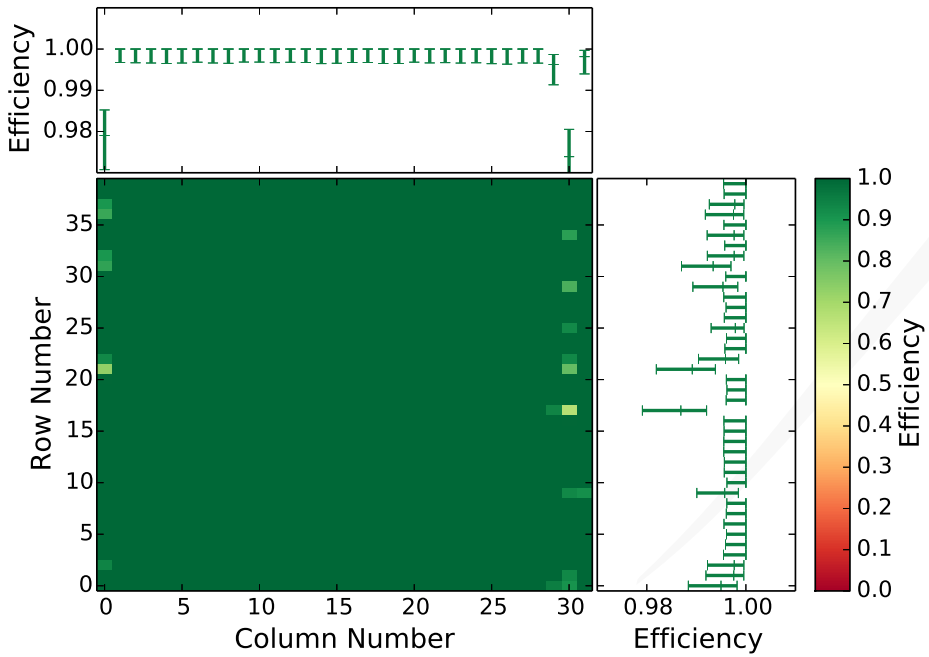




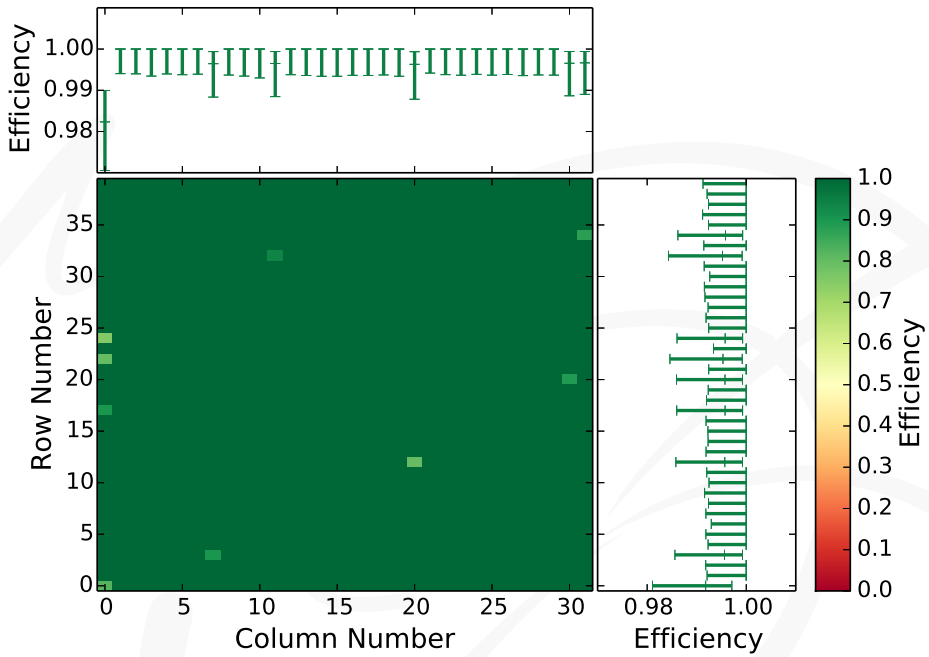
# Pixel Tuning



## Before Tuning




## After Tuning

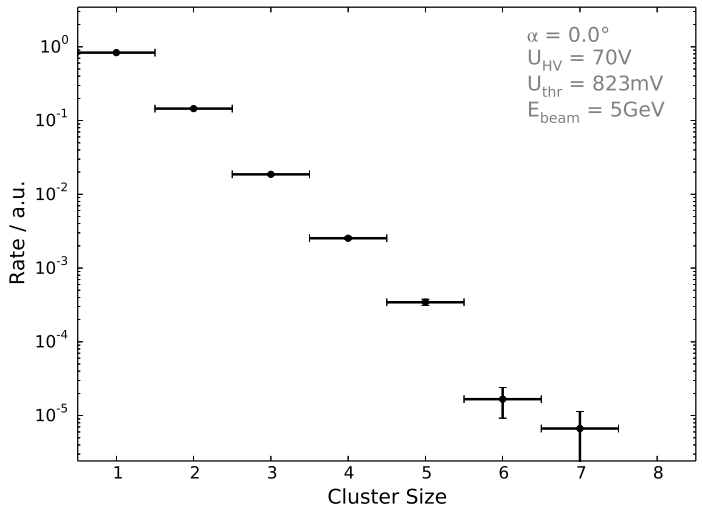



45° incidence angle

# Clustering / Charge Sharing



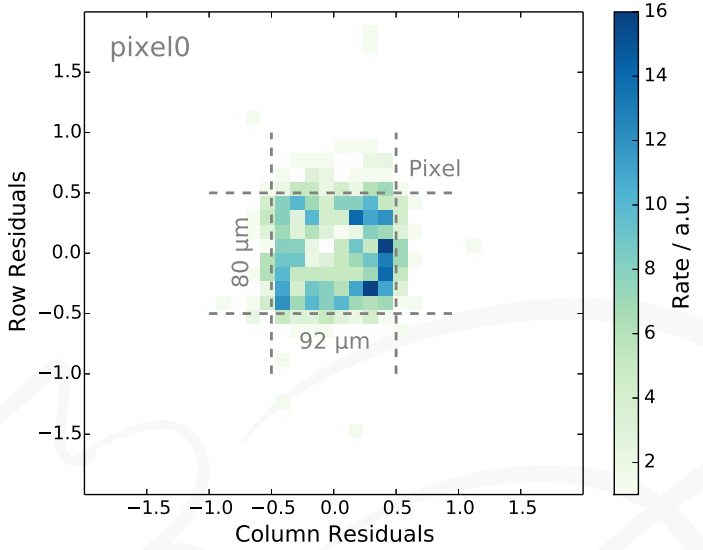
## Cluster Size

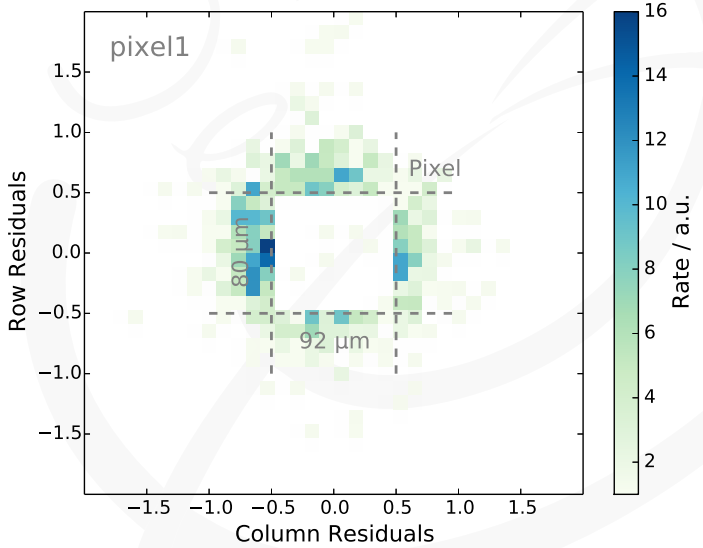



0° incidence angle
70 V high voltage
823 mV threshold
5 GeV beam energy

1-pixel cluster dominate

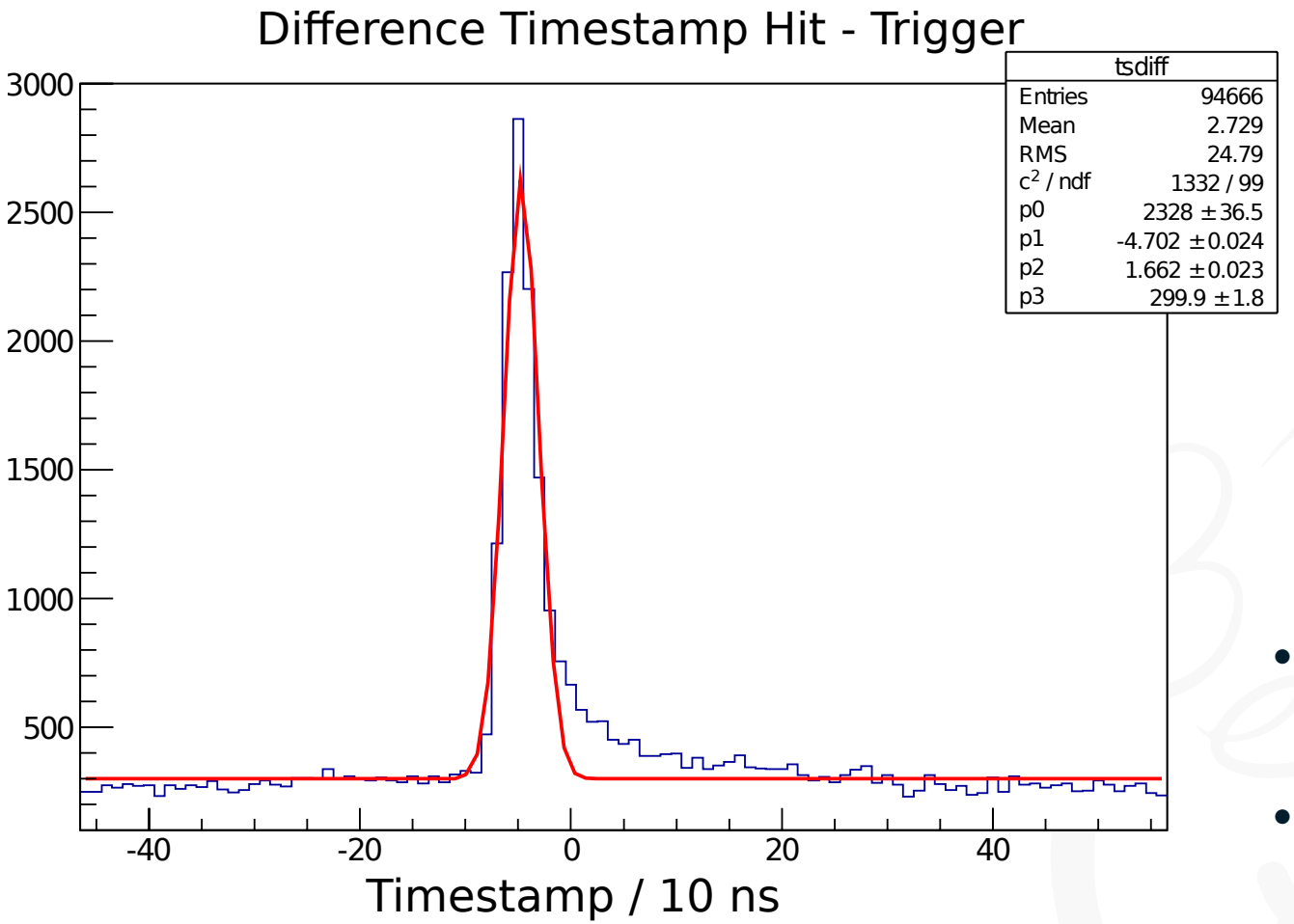
## 2-Pixel Cluster



# Timing






- External timestamp 100 MHz
- Time resolution 17 ns (Sensor + DAQ)

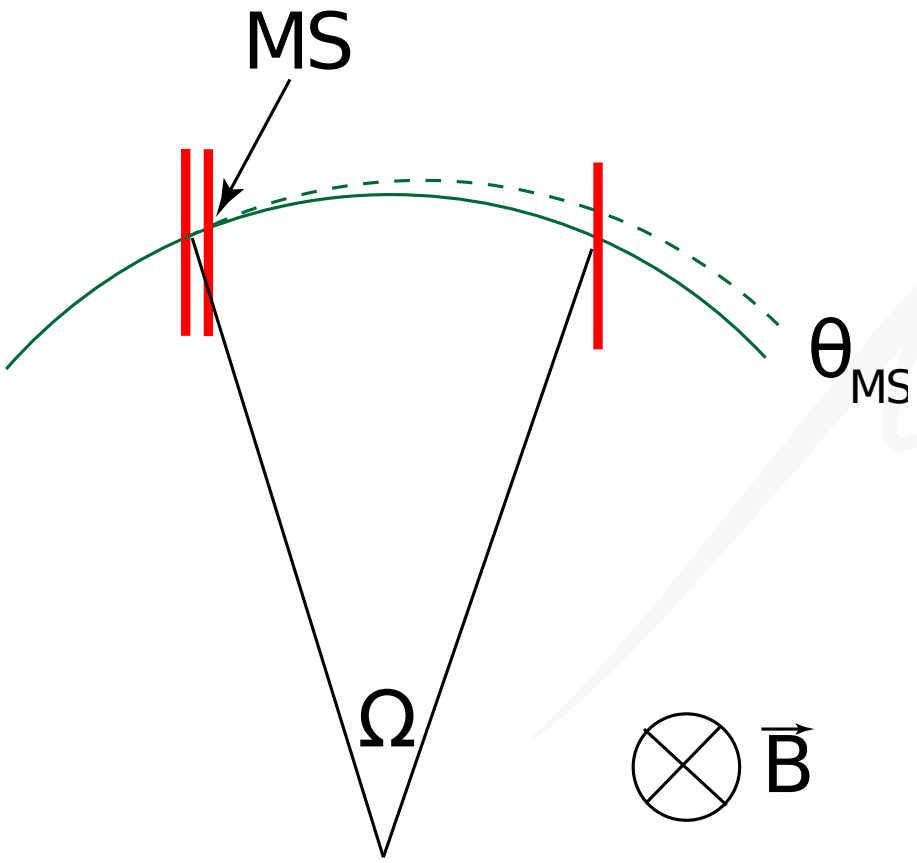
# Mu3e Collaboration



- Paul-Scherrer Institute, Switzerland
- ETH Zürich
- University Zürich
- University Geneva
- Heidelberg University
- ZITI Mannheim

# Multiple Scattering






$$\theta_{MS} = \frac{13.6\,\text{MeV}}{p}\sqrt{x/X_0}$$

Example

- $p = 35\,\text{MeV}$
- $200\,\mu\text{m}$ Si
- $\Omega R = 5\,\text{cm}$
- $\Delta y \approx 1\,\text{mm}$