Mu3e Testbeam Measurements at DESY

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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 $80 \times 80 \mu m^2$
Ultra-Lightweight Mechanics

- 50 µm Silicon sensor
- 50 µm Kapton flexprint
- 25 µm Kapton support frame
→ $\leq 1\%$ Radiation length
Testing Pixel Sensor Prototypes
Monolithic Active Pixel Sensors

- HV $\sim 70\,\text{V}$ (HV-MAPS)
- Fast charge collection by drift
- Thin active zone $< 20\,\mu\text{m}$
- Cheap, commercial process
MuPix4 HV-MAPS Prototype

- 32 Columns / 2.944 mm
- 40 Rows / 3.2 mm

- 92 × 80 µm² 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

Device Under Test
MuPix

Beam Telescope

Provided by DESY

- Full EUDAQ (v1.1) integration
- Reconstruction w/ EUTelescope (v00-09-xx)
- Beamline T22
- 1 GeV to 6 GeV electrons
- Aconite beam telescope
Telescope (Mis-)Alignment

Track Residuals in X / All Planes

- GBL / Millepede Alignment
- Systematic Shift
- Complimentary before / after DUT
- Not visible in alignment runs
Track Residuals / Plane 2

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

0° incidence angle
70 V high voltage
823 mV threshold
Global Efficiency / High Voltage

\[ \epsilon = \frac{N_{\text{matched}}}{N_{\text{tracks}}} \]

0° incidence angle

\[ E = 5\text{GeV} \]

HV = 50V

HV = 70V
Global Efficiency / Incidence Angle

Effective thickness \( \sim \frac{1}{\cos \alpha} \)

- 0.0° incidence angle
- 22.5° incidence angle
- 45.0° incidence angle

HV = 70V
E = 5GeV
Pixel Efficiency

0° incidence angle
70 V high voltage
823 mV threshold
Multiple Scattering in Thin Silicon
Measured Scattering Distributions

\[ t(\theta) = f_{upstream} \otimes f_{downstream} \]
\[ s(\theta) = f_{upstream} \otimes f_{Si} \otimes f_{downstream} \]
\[ = (f_{upstream} \otimes f_{downstream}) \otimes f_{Si} \]
Fitted Scattering Distributions

\[ t(\theta) \sim normal(\mu, \sigma_1) + \epsilon \cdot studentt(\mu, \sigma_2, \nu_2) \]
\[ s(\theta) \sim t_{\text{fixed}} \otimes studentt(\mu, \sigma, \nu) \]
Measured Scattering Distributions

No Silicon

$50 \mu m \text{ Si, } \alpha = 15^\circ$
**RMS\textsubscript{98} vs Thickness**

- RMS\textsubscript{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**

![Graph showing data and models for electron momentum vs multiple scattering for 140 µm silicon.]

**Tails vs Thickness**

![Graph showing data and models for electron thickness vs multiple scattering for 6 GeV/c electrons.]

- GEANT4 simulation of Telescope Setup
- RMS₉₉₈ is well described (not shown)
- Default models underestimate tails
- Shape is not described
Summary & Outlook

Mu3e
- Search for $\mu^+ \rightarrow e^+e^-e^+$
- 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.?
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Impossible w/o DESY Testbeam Group. Thank You.
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Backup
t-Distribution Scattering Model


Idea

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

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

Caveats

- Purely empirical
- Valid only for
  1 GeV to 6 GeV electrons
  50 $\mu$m to 141 $\mu$m Si

See: https://en.wikipedia.org/wiki/Student-t
Silicon Pixel Sensors

Hybrid

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

Monolithic Active Pixel Sensor

- HV $\sim$ 70 V (HV-MAPS)
- Thin active zone $< 20$ $\mu$m
- 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

0° incidence angle
70 V high voltage
823 mV threshold
Pixel Tuning

Before Tuning

After Tuning

45° incidence angle
Cluster Size

2-Pixel Cluster

$\alpha = 0.0^\circ$
$U_{HV} = 70\, V$
$U_{LV} = 823\, \text{mV}$
$E_{beam} = 5\, \text{GeV}$

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

1-pixel cluster dominate
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

\[ \theta_{MS} = \frac{13.6 \text{MeV}}{p} \sqrt{\frac{x}{X_0}} \]

Example

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