Mu3e Testbeam Measurements at DESY

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Telescopes and Testbeams, Hamburg, 30. June 2014
The Mu3e Experiment

- Precision experiment
- Search for $\mu^+ \to e^+e^-e^+$
- 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

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

Provided by DESY
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

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
\( E = 5 \text{GeV} \)

HVs: 50V, 70V

\[ 0.82 \quad 0.84 \quad 0.86 \quad 0.88 \quad 0.90 \quad 0.92 \quad 0.94 \quad 0.96 \quad 0.98 \quad 1.00 \]

Global Threshold / mV

Efficiency

\[ 820 \quad 830 \quad 840 \quad 850 \quad 860 \quad 870 \quad 880 \]
Global Efficiency / Incidence Angle

Effective thickness $\sim \frac{1}{\cos \alpha}$

- 0.0° incidence angle
- 22.5° incidence angle
- 45.0° incidence angle
Pixel Efficiency

0° incidence angle
70 V high voltage
823 mV threshold
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

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

Scattering angle [rad]

50 µm Si, $\alpha = 15^\circ$

Scattering angle [rad]
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**

- 140 μm silicon
  - Data
  - Single scattering
  - Urban Geant4 9.6
  - Urban Geant4 10.0
  - Our Model

**Tails vs Thickness**

- 6 GeV/c electrons
  - Data
  - Single Scattering
  - Urban Geant4 9.6
  - Urban Geant4 10.0
  - Our Model

- 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 $\mu^+ \rightarrow e^+e^-e^+$
- 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. ?

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

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

Caveats

- Purely empirical
- Valid only for
  - 1 GeV to 6 GeV electrons
  - 50 \( \upmu \text{m} \) to 141 \( \upmu \text{m} \) Si

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

Hybrid

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

Monolithic Active Pixel Sensor

- HV $\sim 70 \text{ V (HV-MAPS)}$
- Thin active zone $< 20 \mu\text{m}$
- 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
Clustering / Charge Sharing

Cluster Size

2-Pixel Cluster

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

1-pixel cluster dominate
Timing

**Difference Timestamp Hit - Trigger**

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

<table>
<thead>
<tr>
<th>tsdiff</th>
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<tbody>
<tr>
<td>Entries 94666</td>
</tr>
<tr>
<td>Mean 2.729</td>
</tr>
<tr>
<td>RMS 24.79</td>
</tr>
<tr>
<td>$c^2 / \text{ndf}$ 1332 / 99</td>
</tr>
<tr>
<td>$p_0$ 2328 ± 36.5</td>
</tr>
<tr>
<td>$p_1$ -4.702 ± 0.024</td>
</tr>
<tr>
<td>$p_2$ 1.662 ± 0.023</td>
</tr>
<tr>
<td>$p_3$ 299.9 ± 1.8</td>
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</table>
Multiple Scattering

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

Example

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