The Mu3e Experiment

Niklaus Berger
Physics Institute, University of Heidelberg

DESY Joint Instrumentation Seminar
• The Question:
  Can we observe charged lepton flavour violation?

• The Challenge:
  Finding one in $10^{16}$ muon decays

• The Mu3e Detector:
  Minimum Material, Maximum Precision
The hunt for charged lepton flavour violation
The Standard Model of Elementary Particles

All there, works beautifully, but...

- Why three generations?
- Why the mixing patterns between generations?
- Is there more to it? (the dark universe...)

Niklaus Berger – DESY, February 2014 – Slide 4
All there, works beautifully, but...

- Why three generations?
- Why the mixing patterns between generations?
- Is there more to it? (the dark universe...)

The Standard Model of Elementary Particles

Leptons

Higgs

\[ \begin{align*}
\text{u} & \quad \text{c} & \quad \text{t} \\
\text{d} & \quad \text{s} & \quad \text{b} \\
\text{e}^- & \quad \text{\(\mu\)}^- & \quad \text{\(\tau\)}^- \\
\nu_e & \quad \nu_{\mu} & \quad \nu_{\tau} \\
\end{align*} \]
Lepton Bookkeeping

Normal Muon Decay:

\[ \mu^- \rightarrow e^- + \nu_e + \bar{\nu}_e + \nu_\mu \]
Lepton Bookkeeping

Normal Muon Decay:

\[ \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \]

Muon number 1

Electron number 1

Electron number -1

Muon number 1
Normal Muon Decay:

μ⁻

Muon number 1

Before:
Muons 1
Elektrons 0

e⁻

Electron number 1

νμ

Muon number 1

νₑ

Electron number -1

After:
Muons 1
Electrons 0
Cooked books?

$\nu_e$  
Electron number 1

$\nu_\mu$  
Muon number 1
Cooked books?

How about charged leptons (Muons)?

Before:
- Muons: -1
- Electrons: 0

After:
- Muons: 0
- Electrons: -1

Muon number: -1

Electron number: -1

$\mu^+$

$e^-$

$e^+$

$e^-$
This
(charged lepton flavour violation)
has never been seen
and not because we have not looked
History of LFV experiments

LFV Muon Decays: Experimental Situation

- $\mu^+ \rightarrow e^+\gamma$
- $\mu^- N \rightarrow e^- N$
- $\mu^+ \rightarrow e^+e^-e^+$

MEG (PSI)
$B(\mu^+ \rightarrow e^+\gamma) < 5.7 \cdot 10^{-13}$
(2013)

running

SINDRUM II (PSI)
$B(\mu^- Au \rightarrow e^- Au) < 7 \cdot 10^{-13}$
(2006)

SINDRUM (PSI)
$B(\mu^+ \rightarrow e^+e^-e^+) < 1.0 \cdot 10^{-12}$
(1988)
LFV Muon Decays: Standard Model

\[ \mu^+ \rightarrow e^+\gamma \quad \mu^- N \rightarrow e^- N \quad \mu^+ \rightarrow e^+e^-e^+ \]

Branching ratios suppressed by

\[ \propto \left( \frac{(\Delta m^2)_{\nu}}{m_W^4} \right) \approx 10^{-50} \]
LFV Muon Decays: Susy Loops

$\mu^+ \rightarrow e^+ \gamma$  $\mu^- N \rightarrow e^- N$  $\mu^+ \rightarrow e^+ e^- e^+$

Suppressed by extra vertex w.r.t. $\mu \rightarrow e \gamma$
LFV Muon Decays: Susy Loops

SUSY - like many BSM models - naturally induces LFV

Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

Suppressed by extra vertex w.r.t. $\mu \to e\gamma$
SUSY - like many BSM models - naturally induces LFV

LFV in $\mu^+ \rightarrow e^+\gamma$ implies LFV also in $\mu^-N \rightarrow e^-N$ and $\mu^+ \rightarrow e^+e^-e^+$

Coherent conversion in nucleus field for $Q^2(\gamma) \sim 0$

Suppressed by extra vertex w.r.t. $\mu \rightarrow e\gamma$
LFV Muon Decays: Tree diagrams

\[ \mu^+ \rightarrow e^+ \gamma \quad \mu^- N \rightarrow e^- N \quad \mu^+ \rightarrow e^+ e^- e^+ \]

- Not allowed
- e.g. Leptoquarks
- e.g. extra Z', LFV Higgs etc.
LFV Muon Decays: Experimental signatures

- $\mu^+ \to e^+\gamma$
- $\mu^- N \to e^- N$
- $\mu^+ \to e^+e^-e^+$

**Kinematics**

- 2-body decay
- Monoenergetic $e^+, \gamma$
- Back-to-back

- Quasi 2-body decay
- Monoenergetic $e^-$
- Single particle detected

- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$
LFV Muon Decays: Experimental signatures

**Kinematics**
- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

**Background**
- Accidental background

**Kinematics**
- Quasi 2-body decay
- Monoenergetic $e^-$
- Single particle detected

**Background**
- Decay in orbit
- Antiprotons, pions

**Kinematics**
- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

**Background**
- Radiative decay
- Accidental background
LFV Muon Decays: Experimental signatures

**Kinematics**
- 2-body decay
- Monoenergetic $e^+$, $\gamma$
- Back-to-back

**Background**
- Accidental background

**Continuous Beam**

**Kinematics**
- Quasi 2-body decay
- Monoenergetic $e^-$
- Single particle detected

**Background**
- Decay in orbit
- Antiprotons, pions

**Pulsed Beam**

**Kinematics**
- 3-body decay
- Invariant mass constraint
- $\Sigma p_i = 0$

**Background**
- Radiative decay
- Accidental background

**Continuous Beam**
New physics in $\mu^+ \rightarrow e^+e^-e^+$

**Loop diagrams**
- Supersymmetry
- Little Higgs models
- Seesaw models
- GUT models (leptoquarks)
- and much more...

**Tree diagrams**
- Higgs triplet model
- Extra heavy vector bosons ($Z'$)
- Extra dimensions (Kaluza-Klein tower)
Searching for \( \mu^+ \rightarrow e^+e^-e^+ \) at the \( 10^{-16} \) level
The Mu3e experiment at PSI

Search for $\mu^+ \rightarrow e^+e^-e^+$

Aim for sensitivity

- $10^{-15}$ in phase I
- $10^{-16}$ in phase II

Project approved in January 2013 just passed first review
The Mu3e Collaboration

- DPNC, Geneva University
- Physics Institute, Heidelberg University
- KIP, Heidelberg University
- ZITI Mannheim, Heidelberg University
- Paul Scherrer Institute
- Physics Institute, Zürich University
- Institute for Particle Physics, ETH Zürich
The Goal: 10^{-16}

• We want to find or exclude $\mu \rightarrow eee$ at the 10^{-16} level

• 4 orders of magnitude over previous experiment (SINDRUM 1988)

The Challenges

- Observe more than $10^{16}$ muon decays:
  - 2 Billion muons per second
- Suppress backgrounds by more than 16 orders of magnitude
- Be sensitive for the signal

Muons from PSI

DC muon beams at PSI:

- πE5 beamline: $\sim 10^8$ muons/s
  (MEG experiment, Mu3e phase I)
Muons from PSI

DC muon beams at PSI:

- πE5 beamline:  ~ 10^8 muons/s  
  (MEG experiment, Mu3e phase I)

- SINQ (spallation neutron source) target could even provide  
  ~ 5 × 10^{10} muons/s  
  High intensity muon beamline (HIMB) proposal

- The μ → eee experiment (final stage) requires 2 × 10^9 muons/s focused and collimated on a ~2 cm spot

- These are slow muons (29 MeV/c)  
  Stop and wait for decay
The High-Intensity Muon Beamline (HIMB)

- Muon rates in excess of $10^{10}$/s in acceptance
- $2 \times 10^9$/s needed for $\mu \rightarrow eee$ at $10^{-16}$
- Not before 2017
The signal

- $\mu^+ \rightarrow e^+e^-e^+$
- Two positrons, one electron
- From same vertex
- Same time
- Sum of 4-momenta corresponds to muon at rest
- Maximum momentum: $\frac{1}{2} m_\mu = 53$ MeV/c
Accidental Background

- Combination of positrons from ordinary muon decay with electrons from:
  - photon conversion,
  - Bhabha scattering,
  - Mis-reconstruction

- Need very good timing, vertex and momentum resolution
Internal conversion background

- Allowed radiative decay with internal conversion:
  \[ \mu^+ \rightarrow e^+e^-e^+\nu\bar{\nu} \]
- Only distinguishing feature: Missing momentum carried by neutrinos

- Need excellent momentum resolution

Building the Mu3e Experiment
Momentum measurement

- 1 T magnetic field
- Resolution dominated by multiple scattering
- Momentum resolution to first order:

\[ \frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega} \]
- Precision requires large lever arm (large bending angle \( \Omega \)) and low multiple scattering \( \theta_{MS} \)
Fast and thin sensors: HV-MAPS

High voltage monolithic active pixel sensors

- Implement logic directly in N-well in the pixel - smart diode array
- Use a high voltage commercial process (automotive industry)
- Small active region, fast charge collection via drift
- Can be thinned down to < 50 μm

(I.Peric, P. Fischer et al., NIM A 582 (2007) 876)
The MUPIX chips

**MUPIX2**
- 36 x 42 pixels
- 30 x 39 μm pixel size
- 1.8 mm² active area

**MUPIX3 and 4**
- 40 x 32 pixels
- 80 x 92 μm pixel size
- 9.4 mm² active area

**MUPIX6**
- submitted

For Mu3e:
- 256 x 256 pixels
- 80 x 80 μm pixel size
- 4 cm² area, 95% active

**HV-MAPS chips: AMS 180 nm HV-CMOS**

- **MUPIX2:**
  - Characterization during 2012
  - Single pixel Time-Over-Threshold
  - Binary pixel matrix

- **MUPIX3 and 4:**
  - Tested extensively during 2013 and right now here at Testbeam 22
  - Column logic with address generation
  - (#3 had configuration problems, #4 works nicely, address problems in half the columns)
MUPIX4 Results

99% efficient - some room for improvement through individual pixel tuning
Data folded to four by four pixels

- Some loss at edges through charge sharing
- Guard ring at wrong potential (fixed in MUPIX 6)
- Half the pixels without row address (fixed in MUPIX6)
Spatial resolution

- Binary readout:
  Given by pixel size plus telescope contribution

```
rms x = 0.028 mm
rms y = 0.029 mm
```
**Signal-to-Noise**

- Signal calibrated with Strontium source
- Noise from fit to S-curve (width of threshold) with a fixed injection signal
- Signal/Noise above 30

![Graph showing Signal-to-Noise](image)

**Parameters**

- Temperature: 70°C
- HV: -70V
- BL: 0.79V
- SNR: 36.79

**Model**

<table>
<thead>
<tr>
<th>Model</th>
<th>erfSQRT2 (User)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation</td>
<td>y = a * erf((1/(sqrt(2)*b)) * (x - xc) + c)</td>
</tr>
<tr>
<td>Chi-Quadr. Reduziert</td>
<td>6.92489</td>
</tr>
<tr>
<td>Kor. R-Quadra</td>
<td>0.99645</td>
</tr>
</tbody>
</table>

**Fitted Parameters**

- xc: 1.00263 ± 1.81603E-4
- b: 0.06578 ± 2.12187E-4
- a: 49.56733 ± 0.44927
- c: 49.86121 ± 0.43005
Temperature stability

Latency measurement

- LED pulse to pixel discriminator output
- Setup in oven, 20-70°C
- Temperature dependence within resolution of setup

![Graph showing temperature dependence of MuPix4 signal latency](image)
**Time measurement**

- External Gray-counter (100 MHz) registered on hit
- 17 ns time resolution, with significant contribution from setup

**Timestamp difference to trigger**

<table>
<thead>
<tr>
<th>tdiff</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>$\chi^2$/ndf</th>
<th>p0</th>
<th>p1</th>
<th>p2</th>
<th>p3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>94666</td>
<td>2.729</td>
<td>24.79</td>
<td>1332/99</td>
<td>2328 ± 36.5</td>
<td>-4.702 ± 0.024</td>
<td>1.662 ± 0.023</td>
<td>299.9 ± 1.8</td>
</tr>
</tbody>
</table>

**Time resolution, bins of 10 ns**
Thinned sensors

Single dies thinned to < 90 μm

- Tested in lab and PSI test beam (193 MeV π⁺)
- No significant difference in pulse shape
• 50 μm silicon

• 25 μm Kapton™ flexprint with aluminium traces

• 25 μm Kapton™ frame as support

• Less than 1‰ of a radiation length per layer
Cooling

- Add no material:
  Cool with gaseous Helium
- \( \sim 150 \text{ mW/cm}^2 \) - total 2 kW
- Helium has 16 times mobility of air
- Simulations: Need \( \sim 1 \text{ m/s} \) flow
Cooling simulation

Configuration:
Main helium flux: \( v = 0.5 \text{ m/s} \)
Flux in Nozzle: \( v = 5 \text{ m/s} \)
31.42 mL/s per nozzle
6.786 L/s for 3. Layer

Results:
\( T_{\text{max}} \approx 42^\circ\text{C} \)
\( T_{\text{max}} \) close to end of tube
T raises at last third of tube
Introduction

• X
Cooling test results

- Ohmic heating, 150 mW/cm$^2$
  560 W for two layers
- $\Delta T < 60^\circ$ C for sufficient air flow
- No problems with foil vibrations

Next: Tests with Helium
Momentum measurement

- 1 T magnetic field

- Resolution dominated by multiple scattering

- Momentum resolution to first order:
  \[
  \frac{\sigma_p}{p} \sim \frac{\theta_{MS}}{\Omega}
  \]

- Precision requires large lever arm (large bending angle \(\Omega\)) and low multiple scattering \(\theta_{MS}\)
Precision vs. Acceptance

50 MeV/c  25 MeV/c  12 MeV/c

33 cm
Precision vs. Acceptance

- $B \rightarrow \bar{B}$

- 50 MeV/c
- 25 MeV/c
- 12 MeV/c
Precision vs. Acceptance

50 MeV/c

25 MeV/c

12 MeV/c
Precision vs. Acceptance

- $\Box B$

- 50 MeV/c
- 25 MeV/c
- 12 MeV/c
Precision vs. Acceptance

\[ \mathcal{B} \rightarrow \pi \sim \theta_{\text{MS}} \]

50 MeV/c
25 MeV/c
12 MeV/c

\[ \Omega \sim \pi \]

Niklaus Berger – DESY, February 2014 – Slide 64
Detector Design
Detector Design

Inner pixel layers

μ Beam  Target
Detector Design

Diagram showing the layout of the detector design with layers:
- Outer pixel layers
- Inner pixel layers
- μ Beam
- Target
Detector Design

- Inner pixel layers
- Target
- Scintillating fibres
- Outer pixel layers
- µ Beam
Detector Design

- Inner pixel layers
- Scintillating fibers
- Outer pixel layers
- Ccrl pixel layers
- Beam
- Target
Detector Design

- Inner pixel layers
- Recurl pixel layers
- Outer pixel layers
- Scintillator tiles
- Scintillating fibres
- Beam
- Target
Timing Detector: Scintillating Fibres

- 3 layers of round 250 μm scintillating fibres or 2 layers of square 250 μm fibres
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC from KIP Heidelberg)
- Timing resolution < 1 ns
Timing Detector: Scintillating Fibres
Timing Detector: Scintillating Fibres

- Single fibre readout
  (Geneva, Zürich, ETHZ)
Timing Detector: Scintillating Fibres

Graph showing the relative efficiency in the second detector as a function of the source position. The data is represented with markers and error bars. The x-axis shows the number of photoelectrons in the opposite detector (Si-PM2), ranging from 2 to 12. The y-axis represents the efficiency in percentage. A threshold is indicated at ≥2 photoelectrons.
Timing Detector: Scintillating Fibres

\[ \Delta t = T_{\text{Si-PM1}} - T_{\text{Si-PM2}} \]

- Far, Time diff. \( \sigma \)
- Near, Time diff. \( \sigma \)
- Mid, Time diff. \( \sigma \)

Least Number of photons detected at both ends

\[ \sigma_{\Delta t} \] [ns]
Timing Detector: Scintillating Fibres

Alternative: Square fibres
(Paul Scherrer Institut)

Example of charge spectrum on one of the two SiPMs

Example of charge spectrum on one SiPM vs the other one

Preliminary

Single Fiber Double Read-Out

time resolution $t_0$

Efficiency

note: Nphe threshold: Channel1&Channel2 > Nphe thr

Niklaus Berger – DESY, February 2014 – Slide 77
Introduction

Y
• X
Timing Detector: Scintillating tiles

- 7.5 x 8.5 x 5.0 mm$^3$ scintillating tiles
- 2304 tiles per station
- Read-out by silicon photomultipliers (SiPMs) and custom ASIC (STiC, KIP Heidleberg)
- Timing resolution $\alpha(100 \text{ ps})$
Tiles in the testbeam
Tile results

• 70 ps time resolution
• Dominated by tile geometry: 40 ps possible with smaller tiles matched to SiPMs
• Efficiency > 99.5%
Data Acquisition

- 280 Million pixels (+ fibres and tiles)
- No trigger
- \(~ 1 \text{Tbit/s}\)
- FPGA-based switching network
- Place-sorted to time-sorted
- \(O(50)\) PCs with GPUs
Online software filter farm

- Continuous front-end readout (no trigger)
- \( \sim 1\, \text{Tbit/s} \)
- PCs with FPGAs and Graphics Processing Units (GPUs)
- Online track and event reconstruction
- \( 10^9 \, 3D \text{ track fits/s achieved} \)
- Data reduction by factor \( \sim 1000 \)
- Data to tape < 100 Mbyte/s
• Bit error rate < $10^{-16}$ at 6.4 Gbit/s  
  (Mezzanine card)
• Tests at 8 Gbit/s ongoing  
  (Mezzanine card)
• Bit error rate < $10^{-16}$ at 4 x 11.3 Gbit/s  
  (On-board QSFP transceiver)
• More than sufficient for phase Ia and Ib  
  (Mezzanine cards)
• More than sufficient for phase 2  
  (QSFP)
• Also: 3.2 Gbyte/s DMA from FPGA to PC
3D multiple scattering track fit

Simulation results:
- 280 keV single track momentum
- 520 keV total mass resolution

Simulated Performance
- Hits fitted per track
- Reconstructed Momentum [MeV/c]
- RMS: 0.28 MeV/c
- RMS: 0.52 MeV/c
- $\sigma_1$: 0.31 MeV/c
- $\sigma_2$: 0.71 MeV/c
- $\sigma_{av}$: 0.37 MeV/c

Reconstructed Mass [MeV/c]
Simulated Performance

$\nu \nu e e e \rightarrow \mu \nu \nu$ generated

$\mu \rightarrow e e e \nu \nu$ simulated

Events per muon decay and 0.1 MeV

Reconstructed Mass [MeV/$c^2$]
Sensitivity

Phase IA: Starting 2015

SINDRUM (90 % CL)

Mu3e (90% CL)
Mu3e continued
Sensitivity Mu3e

running days

Inner pixel layers
μ Beam
Target
Outer pixel layers

Phase IA: Starting 2015
Sensitivity

Phase IB: 2016+

Inner pixel layers
Scintillating fibres

Outer pixel layers

Phase IB: 2016+

Phase I

Phase II

SINDRUM (90 % CL)

Mu3e (90% CL)
Mu3e continued
Sensitivity Mu3e

BR

running days

0 100 200 300 400

$10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$ $10^{-16}$ $10^{-17}$
Sensitivity

Phase II: 2017+
New Beam Line

Phase IA
SINDRUM (90 % CL)
Phase IB
Phase II

Mu3e (90% CL)
Mu3e continued
Sensitivity Mu3e
• Mu3e aims for $\mu \rightarrow eee$ at the $10^{-16}$ level

• First large scale use of HV-MAPS

• Build detector layers thinner than a hair

• Timing at the 100 ps level

• Reconstruct 2 billion tracks/s in 1 Tbit/s on ~50 GPUs

• Start data taking in 2016

• 2 billion muons/s from HIMB after 2017
The Mupix Telescope
Idea: Use Mu3e components to build a beam telescope

- Scintillating tiles for trigger and timing reference
- Thinned MuPix 4 (or 6) chips on thinned PCBs
- Fast readout, online tracking

- $O\ (200\ \mu m)$ pointing resolution for 50 MeV/c electrons
- Few MHz track rates
- Ideal for PSI beam tests
- First tests this week very promising
Backup Material
Radiation Hardness

- Requirements not as strict as at LHC

- Irradiation at PS
- After 380 MRad \( (8 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2) \)
- Chip still working

(Courtesy Ivan Perić, RESMDD 2012)
MUPIX electronics

**Pixel**
- Sensor
- Injection
- CSA
- Source follower
- VN
- VNFB
- VNLoad
- VNFoll

**Periphery**
- BL
- BLRes
- VPComp
- VPDAC
- Tune DAC
- ThRes
- Comparator
- AC coupling via CR filter
- Set individual threshold
- Digital output (ToT)

Integrate charge
- Amplification of signal line
- Drive high C of signal line

Niklaus Berger – DESY, February 2014 – Slide 99
A general effective Lagrangian

\[ L_{\mu \rightarrow eee} = 2 G_F (m_\mu A_{R} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + m_\mu A_{L} \bar{\mu}_L \sigma^{\mu\nu} e_R F_{\mu\nu} + g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R) + g_3 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_R \gamma^\mu e_R) + g_4 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_L \gamma^\mu e_L) + g_5 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_L \gamma^\mu e_L) + g_6 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_R \gamma^\mu e_R) + H. C. ) \]

Tensor terms (dipole) e.g. supersymmetry

Four-fermion terms e.g. \( Z' \)

\[ + g_1 (\bar{\mu}_R e_L) (\bar{e}_R e_L) + g_2 (\bar{\mu}_L e_R) (\bar{e}_L e_R) \] scalar

\[ + g_3 (\bar{\mu}_R \gamma^\mu e_R) (\bar{e}_R \gamma^\mu e_R) + g_4 (\bar{\mu}_L \gamma^\mu e_L) (\bar{e}_L \gamma^\mu e_L) \] vector

\( \) (Y. Kuno, Y. Okada, Rev.Mod.Phys. 73 (2001) 151)
Comparison with $\mu^+ \to e^+\gamma$

$$L_{LFV} = \frac{m_\mu}{(K+1)\Lambda^2} A_R \mu_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{K}{(K+1)\Lambda^2} (\overline{\mu}_L \gamma^\mu e_L)(\overline{e}_L \gamma^\mu e_L)$$

- One loop term and one contact term
- Ratio $\kappa$ between them
- Common mass scale $\Lambda$
- Allows for sensitivity comparisons between $\mu \to eee$ and $\mu \to e\gamma$
- In case of dominating dipole couplings ($\kappa = 0$):
  $$\frac{B(\mu \to eee)}{B(\mu \to e\gamma)} = 0.006 \quad \text{(essentially $\alpha_{em}$)}$$
MUPIX 2 Results

- Measurements with $^{55}$Fe source
- Good energy measurement
- Very good signal to noise

Details in theses:
available from [www.psi.ch/mu3e](http://www.psi.ch/mu3e)
MUPIX 2 Results

- Measurements with LED pulses
- High-Voltage important for fast signal
- Amplification above ~70 V

Details in theses:
available from [www.psi.ch/mu3e](http://www.psi.ch/mu3e)
MUPIX 2 results

- Test beam at CERN SPS (170 GeV/c pions)
- Timepix telescope
- 2 hours data taking
- Mostly single pixel clusters
- Resolution as expected (pixel size/\sqrt{12})
- More test beam data under study

Resolution for 30 × 40 μm pixels