

Track Based Alignment for the Mu3e Pixel Detector

U. Hartenstein

DPG-Frühjahrstagung 2017

For the Mu3e Collaboration



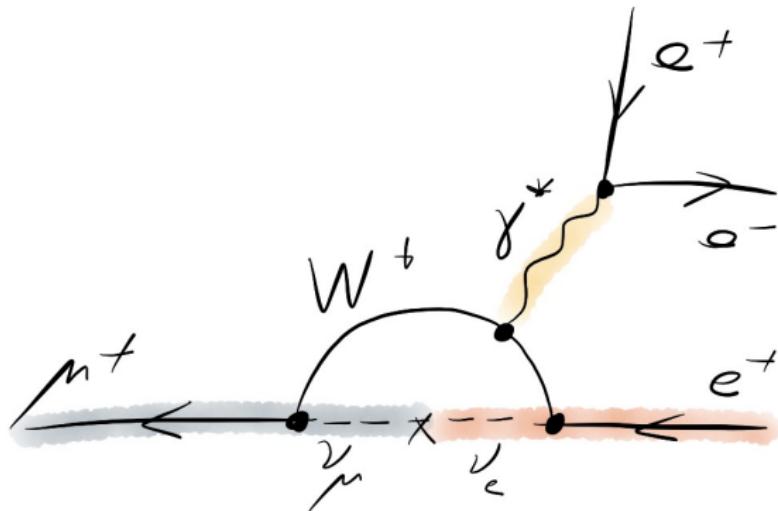
The Mu3e Experiment

Mu3e - In the Standard Model

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

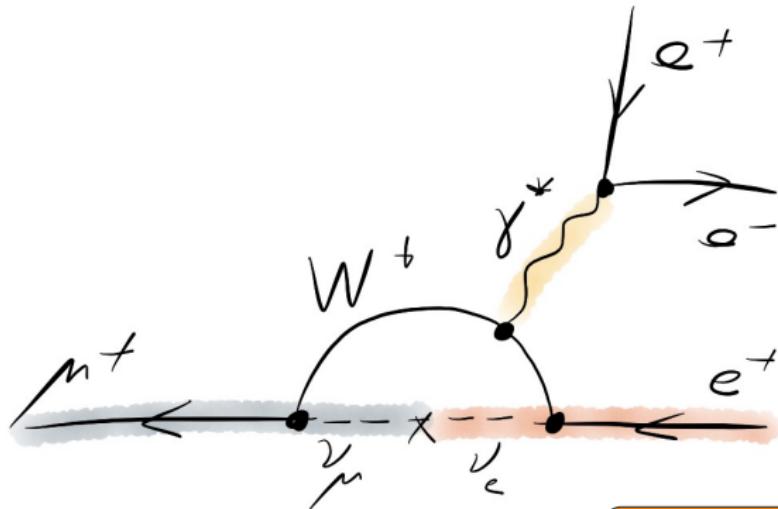
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Mu3e - In the Standard Model

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

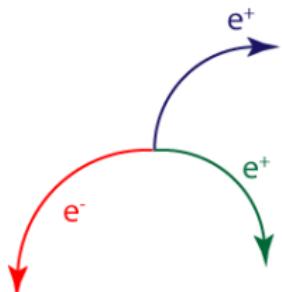


$$\mathcal{BR} < 10^{-54}$$

Beyond the Standard Model?

Motivation

- new physics?!
 - predictions from SUSY, Leptoquarks, ...
- current status (SINDRUM 1988): $\mathcal{BR} < 10^{-12}$

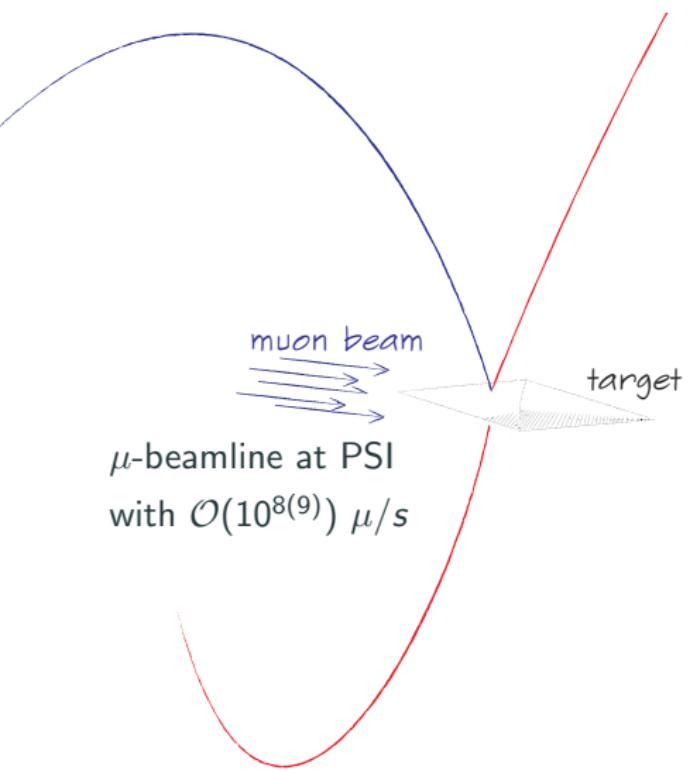


Goal

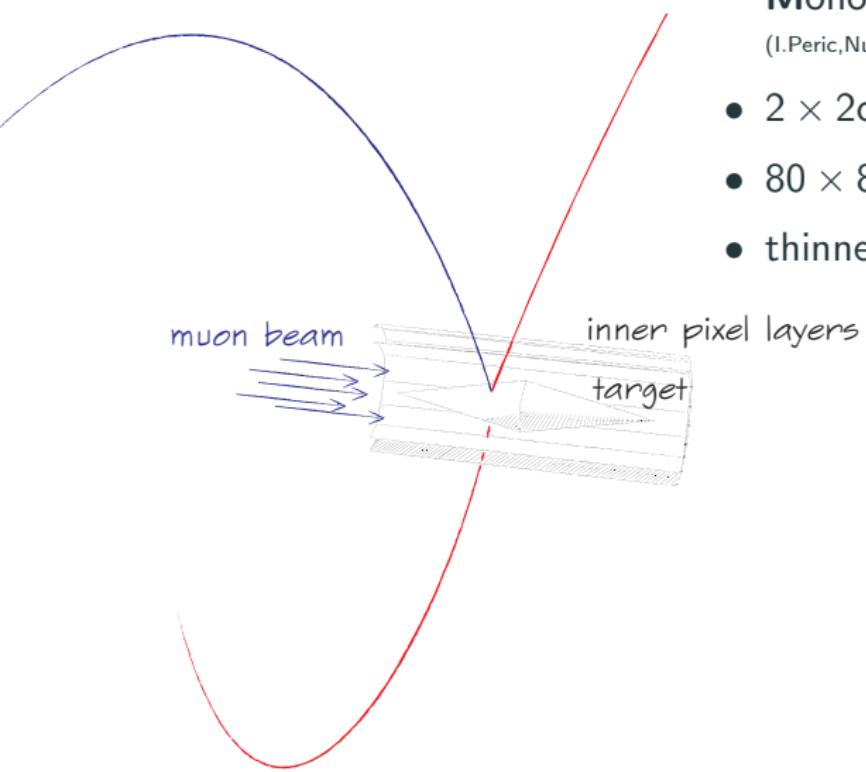
$\mu^+ \rightarrow e^+ e^- e^+$
with a sensitivity of $\mathcal{O}(10^{-16})$

The Detector

Building the Detector

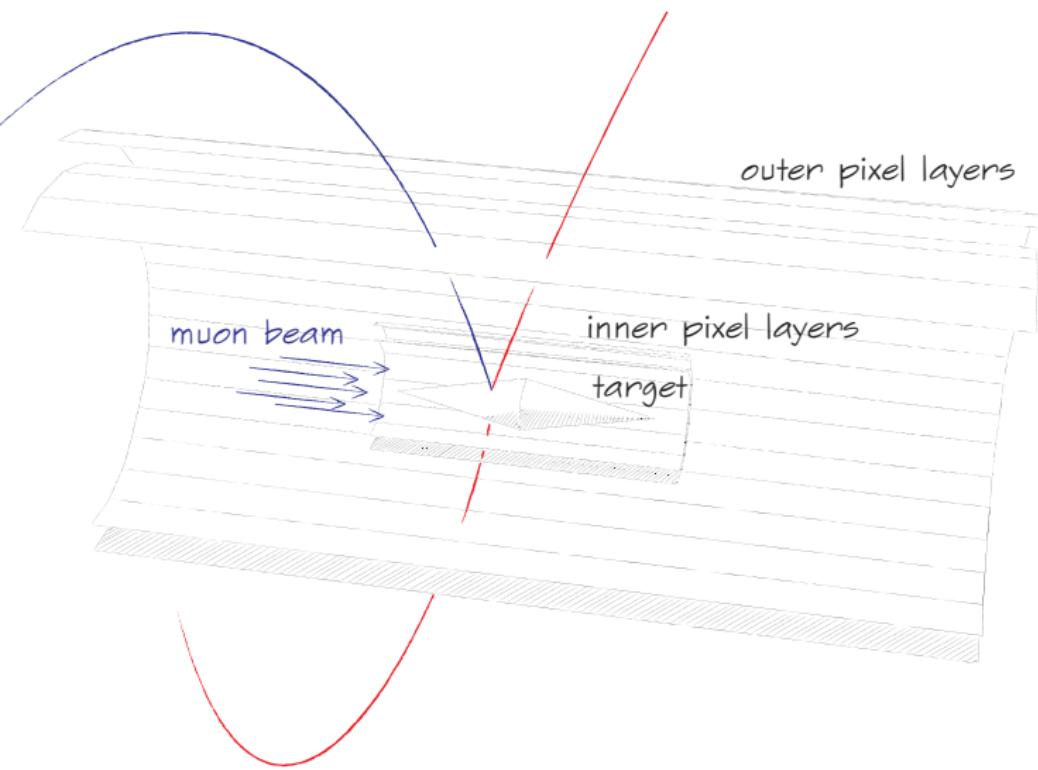


Building the Detector

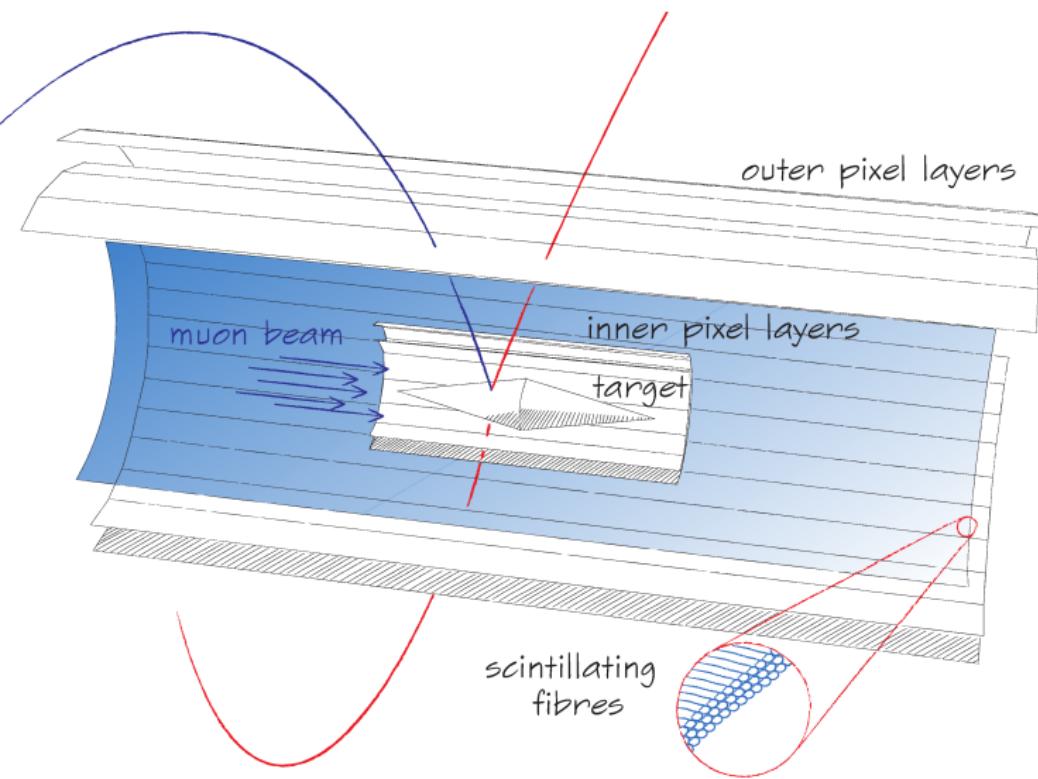


- "MuPix": High Voltage Monolithic Active Pixel Sensors
(I.Peric,Nucl.Instr.Meth.,2007, A582, 876)
- $2 \times 2\text{cm}^2$ sensors
- $80 \times 80\mu\text{m}^2$ pixels
- thinned to $50\mu\text{m}$

Building the Detector



Building the Detector

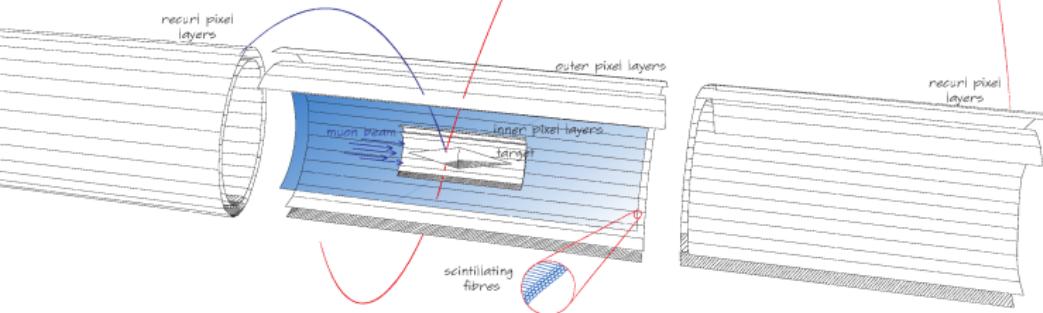


Building the Detector

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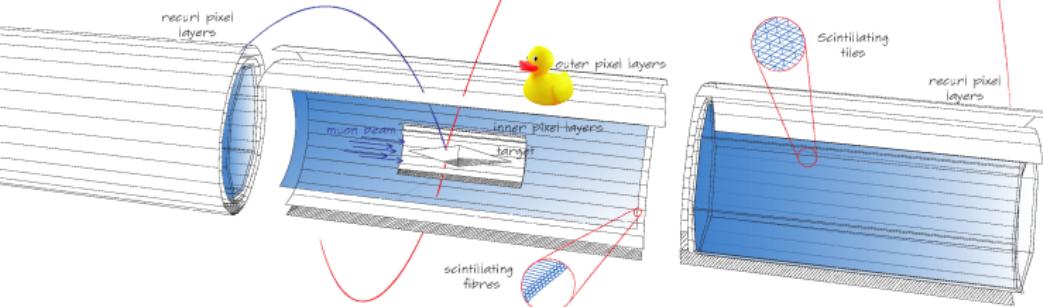
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alignment goal: $\sigma \approx 2\mu\text{m}$

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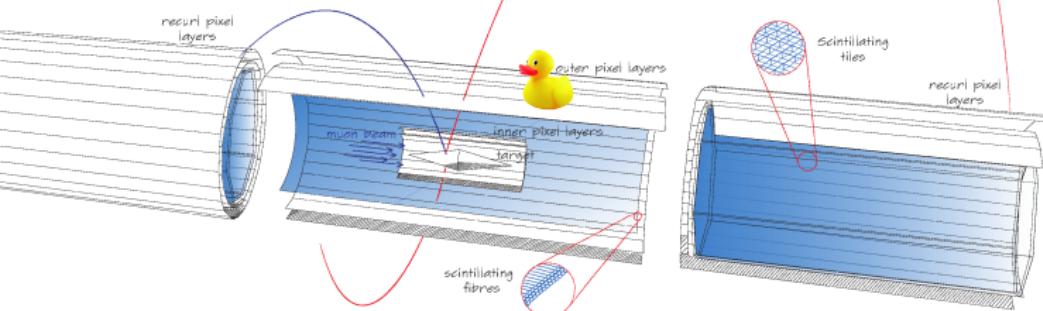
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impossible to have sufficient alignment after construction!

Building the Detector

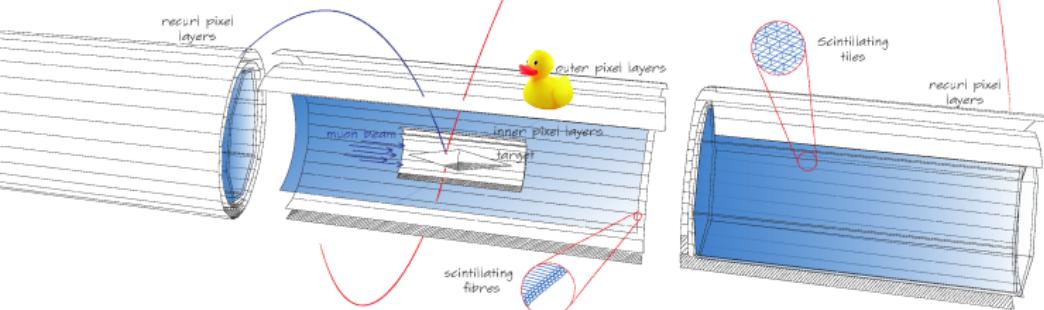
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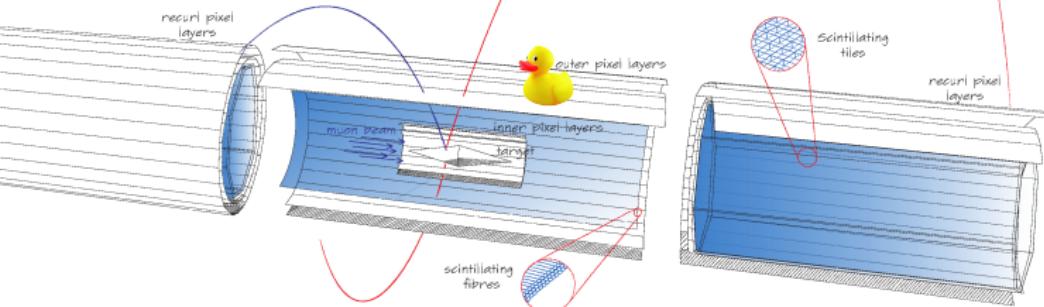
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Track Based Alignment

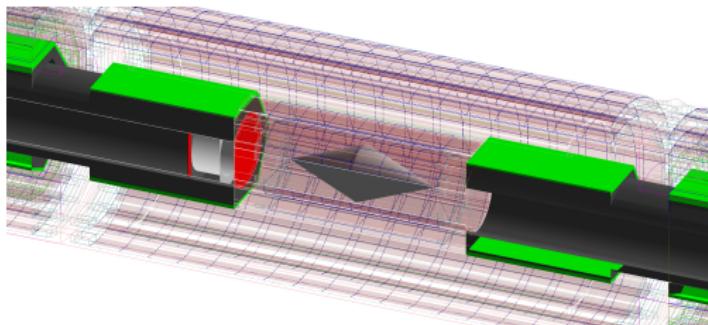
Track Based Alignment and the Software for it

- with cosmics, lower rate, ...
 - $\sigma_{position} \leq 80\mu\text{m}$, $\sigma_{orientation} \leq 0.3^\circ$ (from misalignment studies)
 - track based alignment
 - $\sigma \approx 2\mu\text{m}$

Track Based Alignment and the Software for it

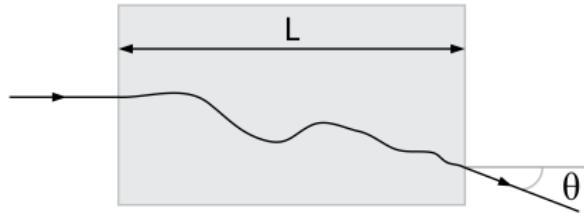
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 - track based alignment
 - $\sigma \approx 2\mu\text{m}$
- Mu3e software package
- General Broken Lines (GBL) (V. Blobel, C. Kleinwort, arXiv:1201.4320v1)
- Millepede-II (MP-II) (V. Blobel, C. Kleinwort, arXiv:1103.3909v1)

Mu3e Track-Reconstruction:
A. Kozlinskiy - Thu,16:45 T 116.1



General Broken Lines Fit

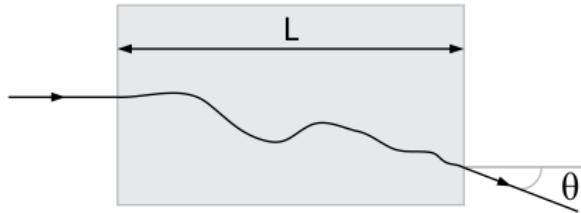
- multiple scattering & energy loss
→ more advanced track models: e.g. GBL



 GBL

General Broken Lines Fit

- multiple scattering & energy loss
→ more advanced track models: e.g. GBL
- track refit to account for **multiple scattering**
- complete covariance matrix of all track parameters at any point
→ track based alignment with **Millepede-II**



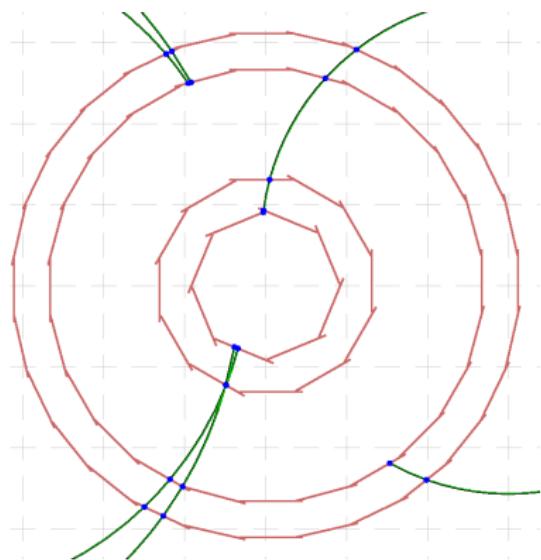
Millepede-II

A least squares fit with a very large number of parameters

each track j has

measurements: $m_{ij} \pm \sigma_{ij}$ and

is modelled by $f_{ij}(\mathbf{q}_j, \mathbf{p})$



Millepede-II

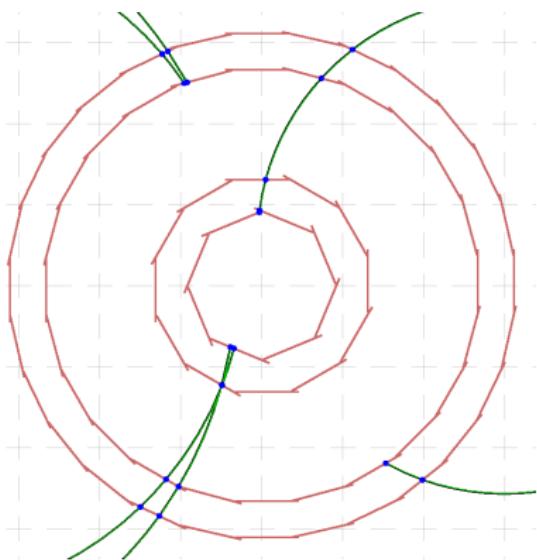
A least squares fit with a very large number of parameters

$$\chi^2 = \sum_j \sum_i^{tracks\ measurements} \left(\frac{m_{ij} - f_{ij}(\mathbf{q}_j, \mathbf{p})}{\sigma_{ij}} \right)^2$$

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- minimise χ^2
 - 1.5 mio track parameters \mathbf{q}_j
 - 45 000 alignment parameters \mathbf{p}



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 - invert a 1545000×1545000 matrix



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 - 1.5 mio track parameters \mathbf{q}_j
 - 45 000 alignment parameters \mathbf{p}
 - invert a 1545000×1545000 matrix
 - MP-II → reduction to 45000×45000



Surface Deformations

Surface Deformations

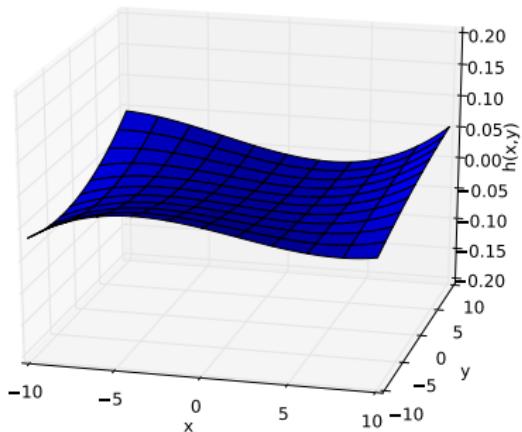
- $50\mu\text{m}$ chips won't be rigid!
- Idea: align not only for rotations and shifts but also for
 - surface deformations
 - temperature effects ($\Delta T \approx 70\text{K}$)



$50\mu\text{m}$ silicon

Surface Deformations

- $50\mu\text{m}$ chips won't be rigid!
- Idea: align not only for rotations and shifts but also for
 - surface deformations
 - temperature effects ($\Delta T \approx 70\text{K}$)
- 3rd order polynomials for modelling sensors



a deformed sensor

Outlook

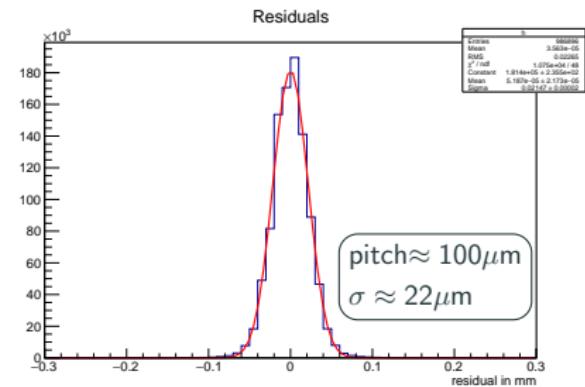
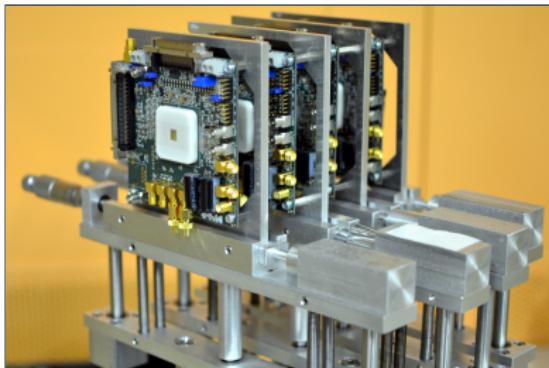
Status & Outlook

- misalignment Studies ✓
- basic software ✓
- MP-II testbed for the “MuPix-Telescope” ✓



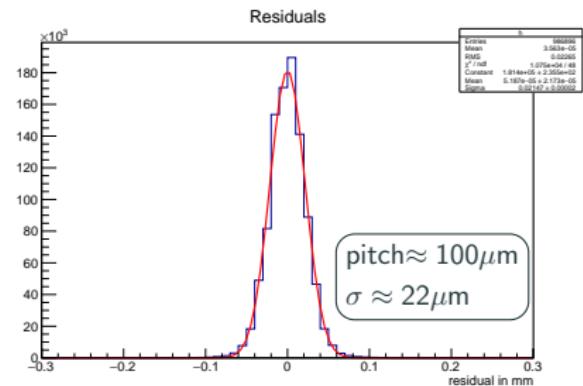
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Status & Outlook

- misalignment Studies ✓
- basic software ✓
- MP-II testbed for the “MuPix-Telescope” ✓
- missing bits and pieces
- blinded tests of alignment software



Backup

Parametrization

- span sensors by two orthonormal vectors u and v
- use right-handed local coordinate system u, v, w
- $w = w(u, v)$ parametrized with Legendre-polynomials and surface coefficients

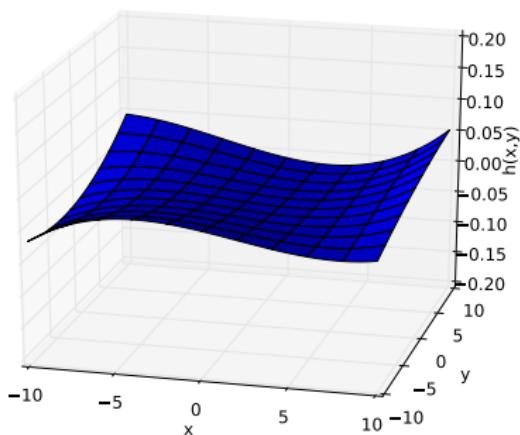


Figure 1: Legendre-Plane: coefficients of $0 - 30\mu m$

Parametrization

- spanned by two orthonormal vectors defining the local u - & v -coordinates
- w -coordinate defined via $u \times v$ with a value of $h(u, v)$

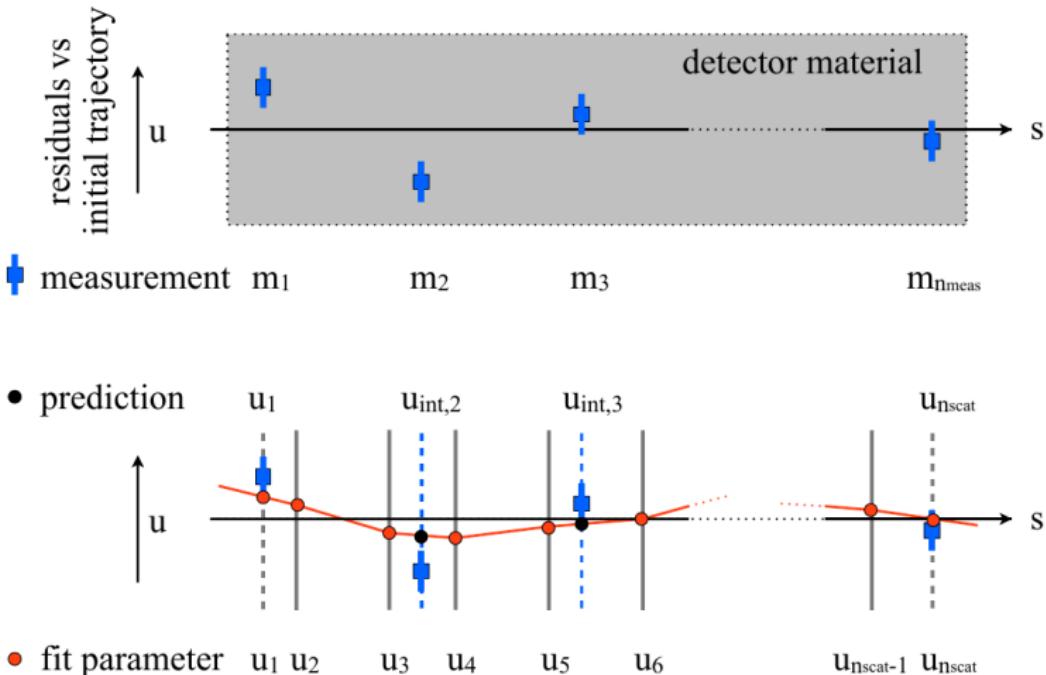
$$h(x, y) = \sum_{i=0}^N \sum_{j=0}^i c_{ij} P_{i-j}(x) P_j(y), \quad (1)$$

with Legendre-polynomials

$$P_n(x) = 2^n \sum_{k=0}^n \binom{n}{k} \binom{\frac{n+k-1}{2}}{n} x^k. \quad (2)$$

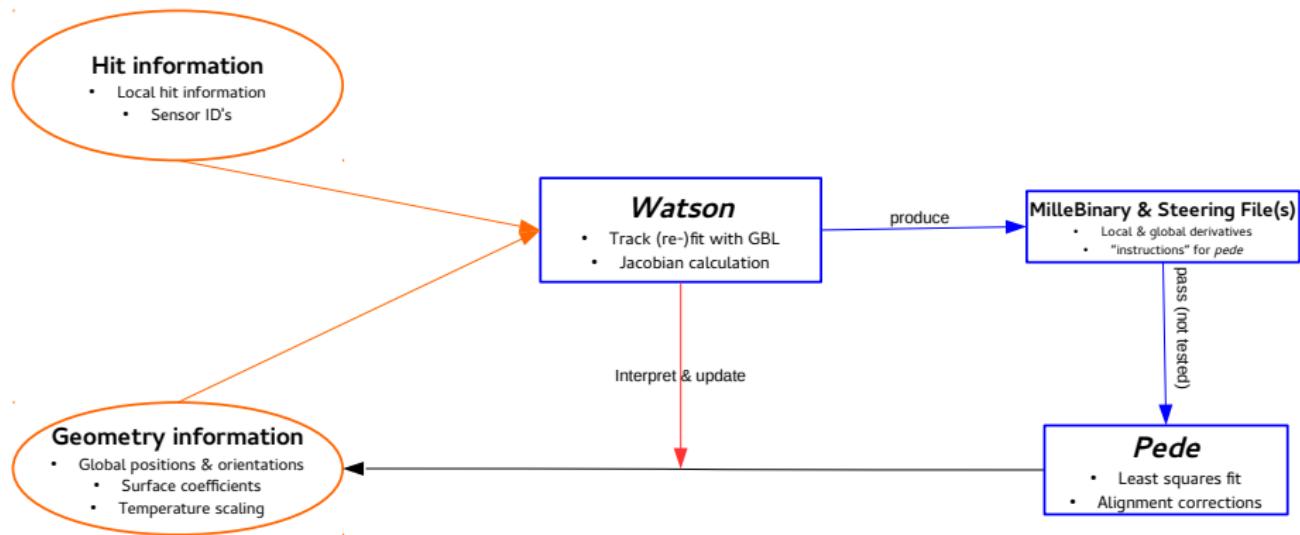
and surface coefficients c_{ij}

General Broken Lines Fit

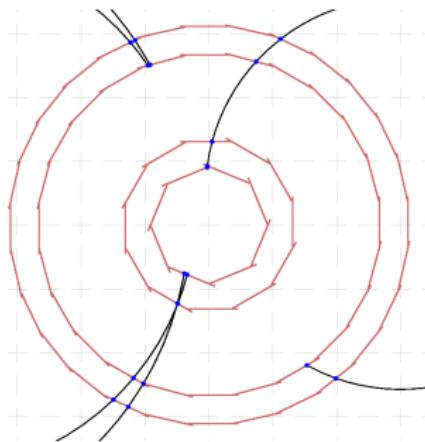


GBL

Alignment Procedure

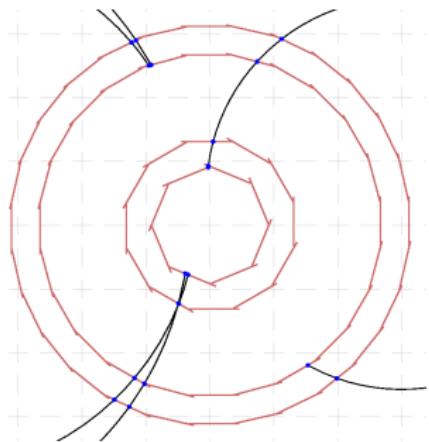


Misalignment

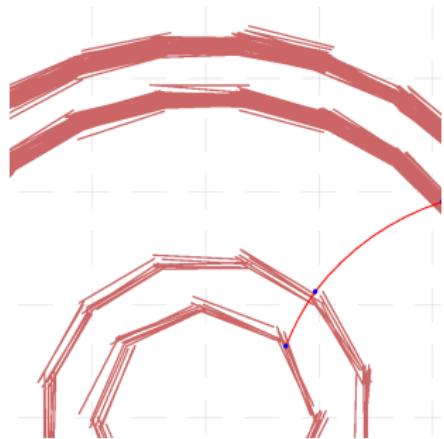


- perfect alignment

Misalignment



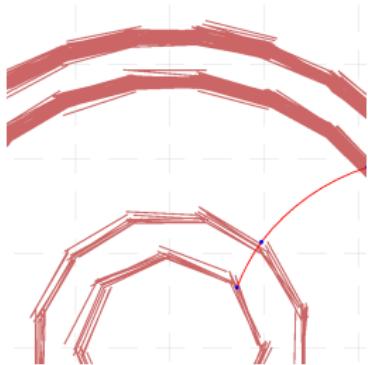
- perfect alignment



- misaligned sensors

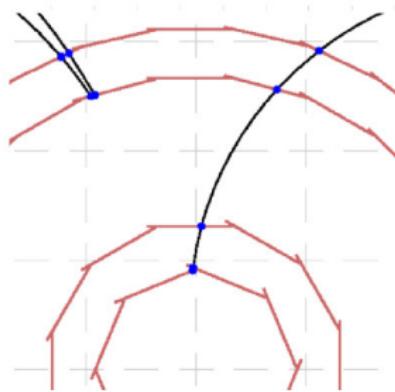
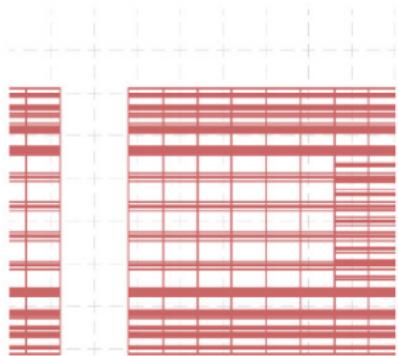
Misalignment Studies

- what does that mean?
 - need for alignment algorithm
- for track based alignment tracks are needed!
- “how well (mechanically) aligned to be able to align (with software)?”

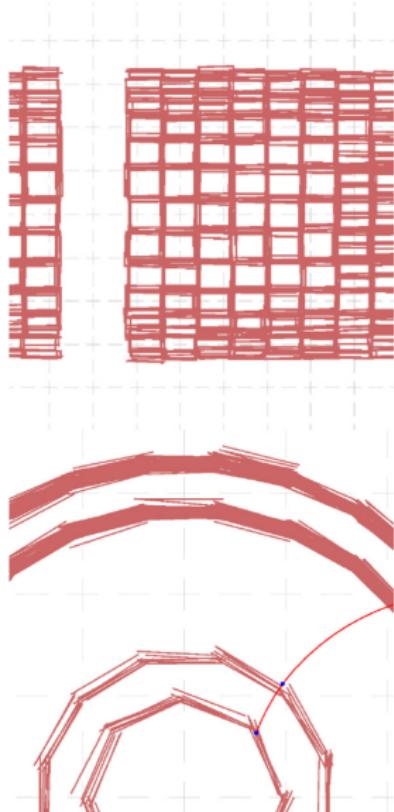
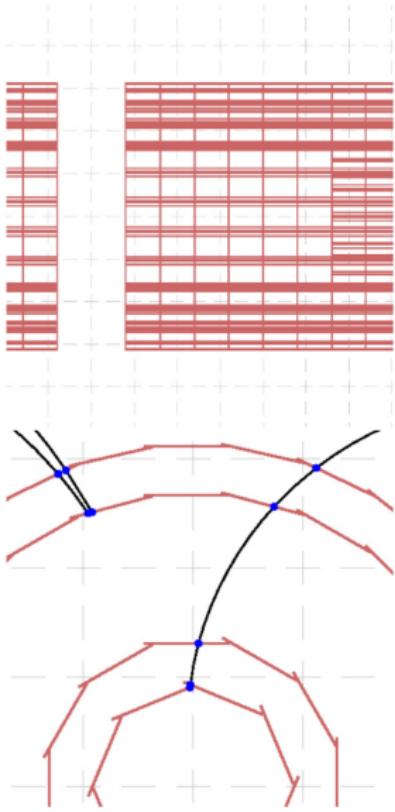


Misalignment Studies

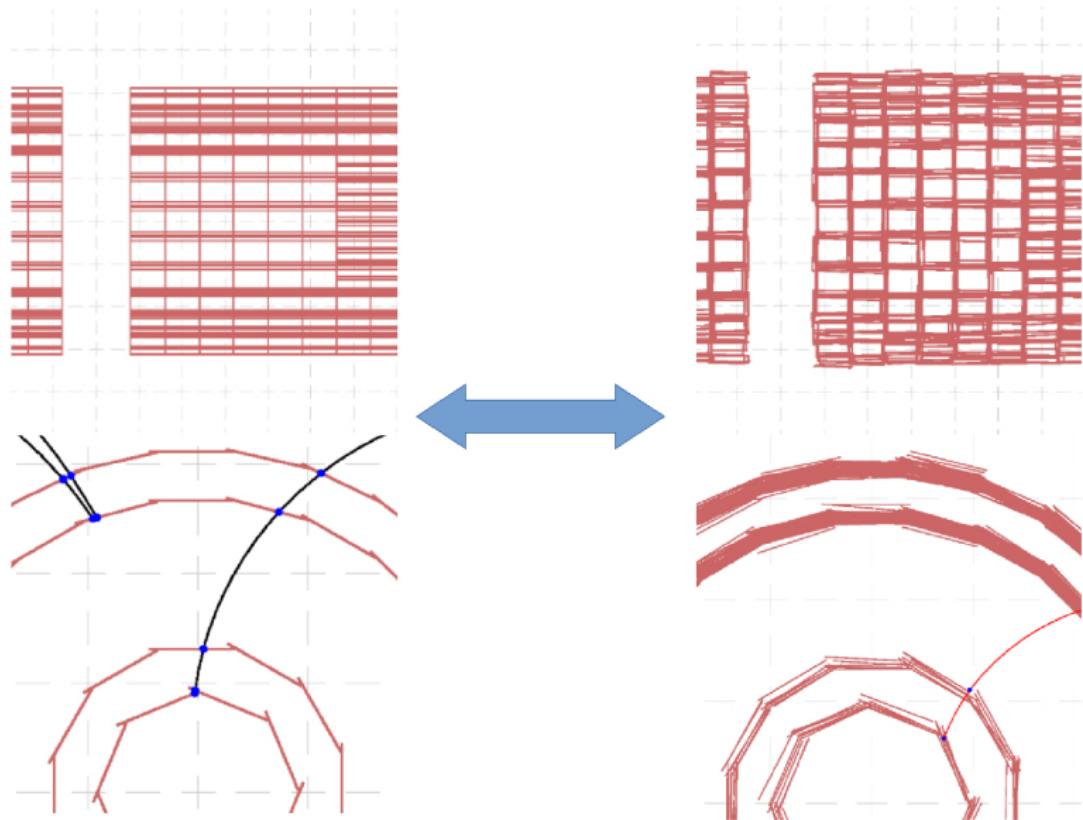
Misalignment Studies



Misalignment Studies

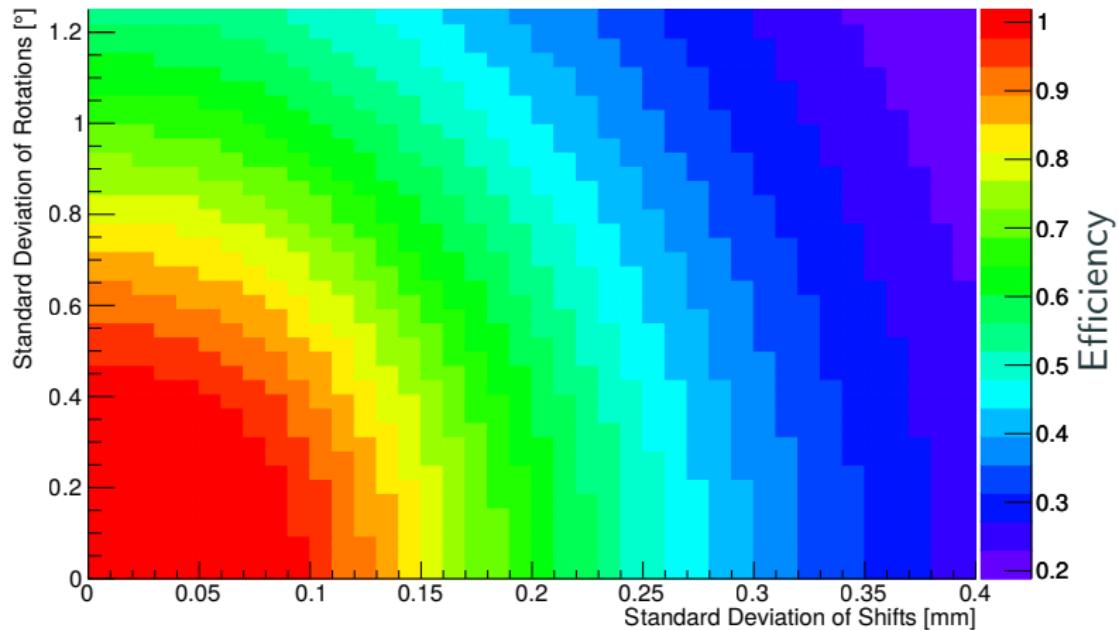


Misalignment Studies



Momentum Reconstruction Efficiency

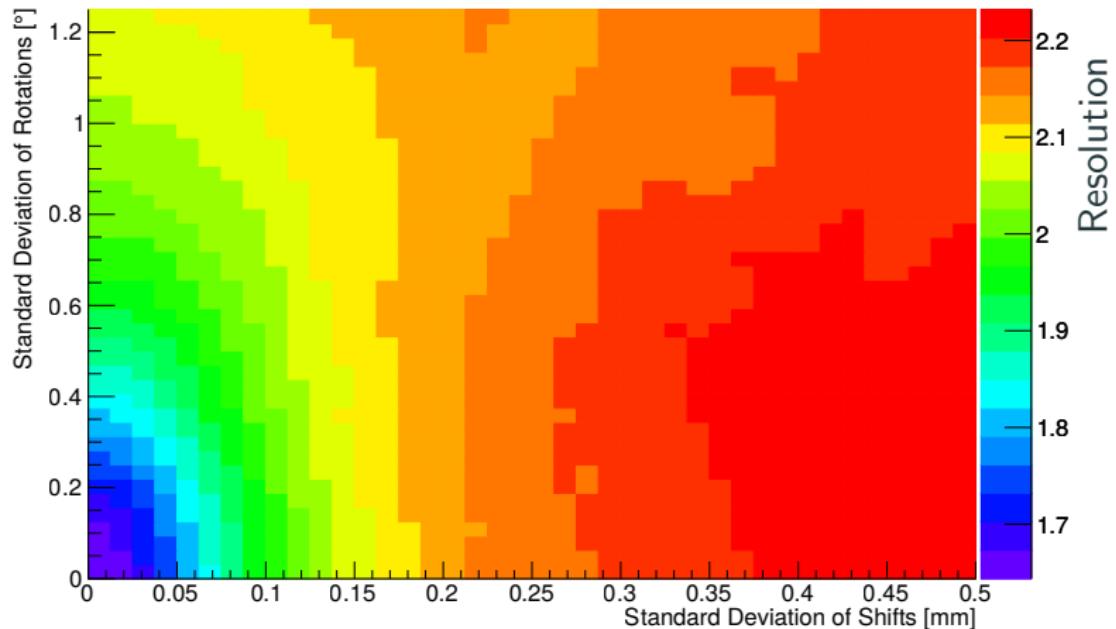
Randomly Misaligned Sensors



- normalised to the efficiency of a perfectly aligned detector
- efficiency plateau

Momentum Reconstruction Resolution

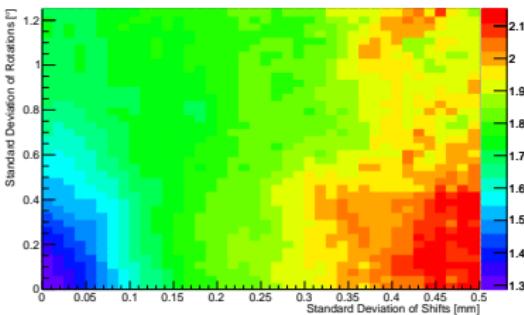
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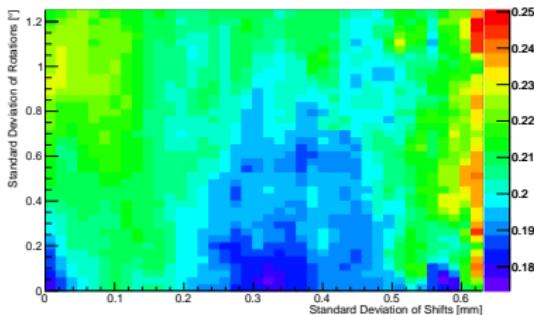
- momentum resolution from RMS of $p_{rec} - p_{MC}$
- for random sensor shifts & rotations in MeV/c

Misalignment Studies - Momentum Resolution Sigma

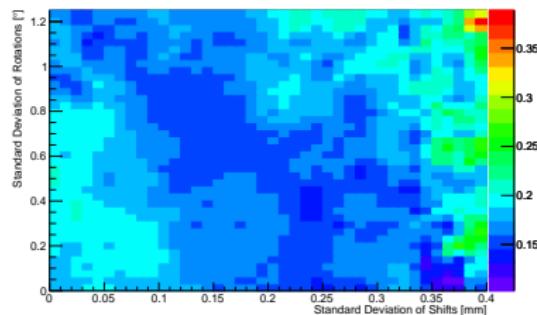
4-hit-segments



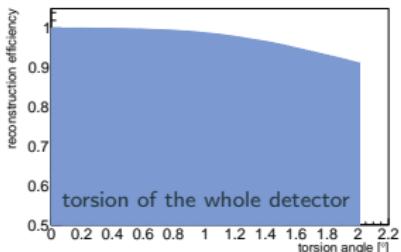
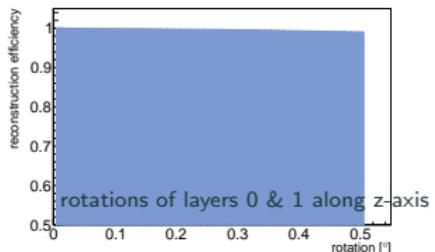
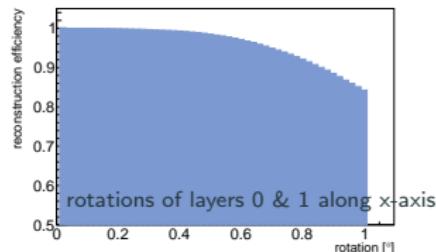
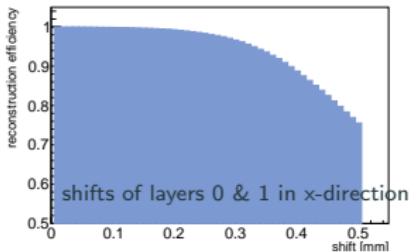
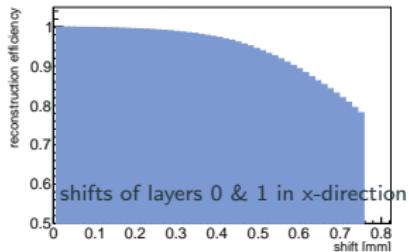
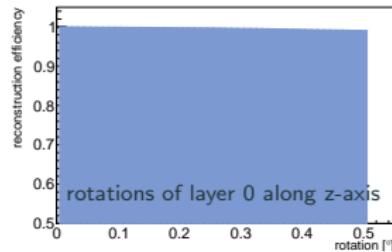
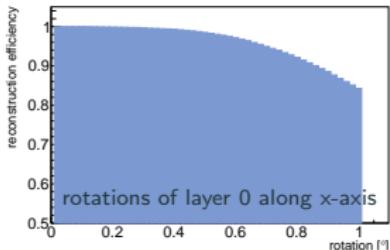
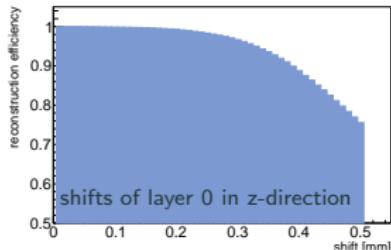
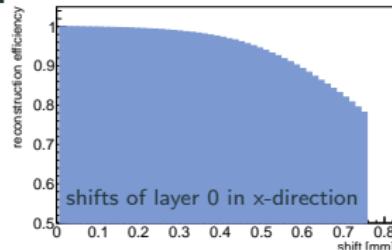
6-hit-segments



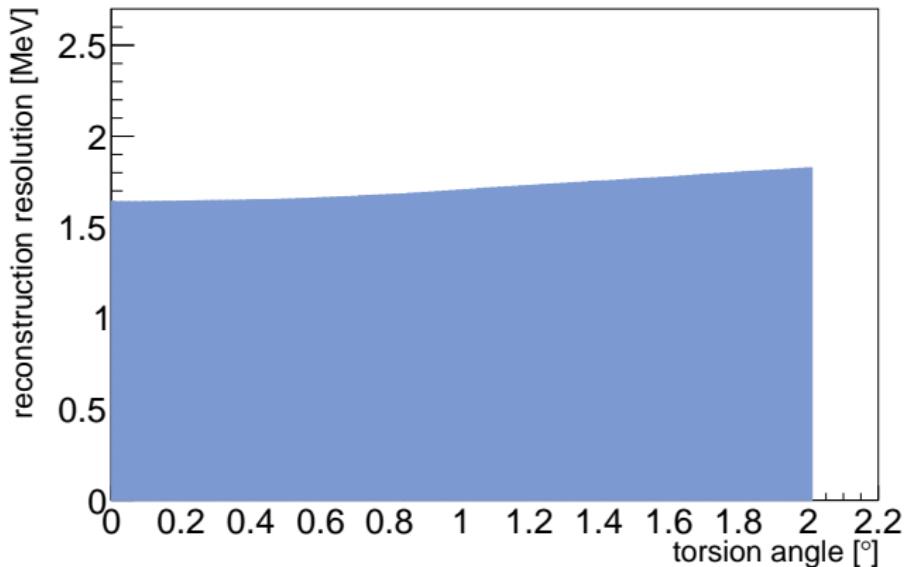
8-hit-segments



Misalignment Studies - Momentum Reconstruction Efficiency (4-hit segments)

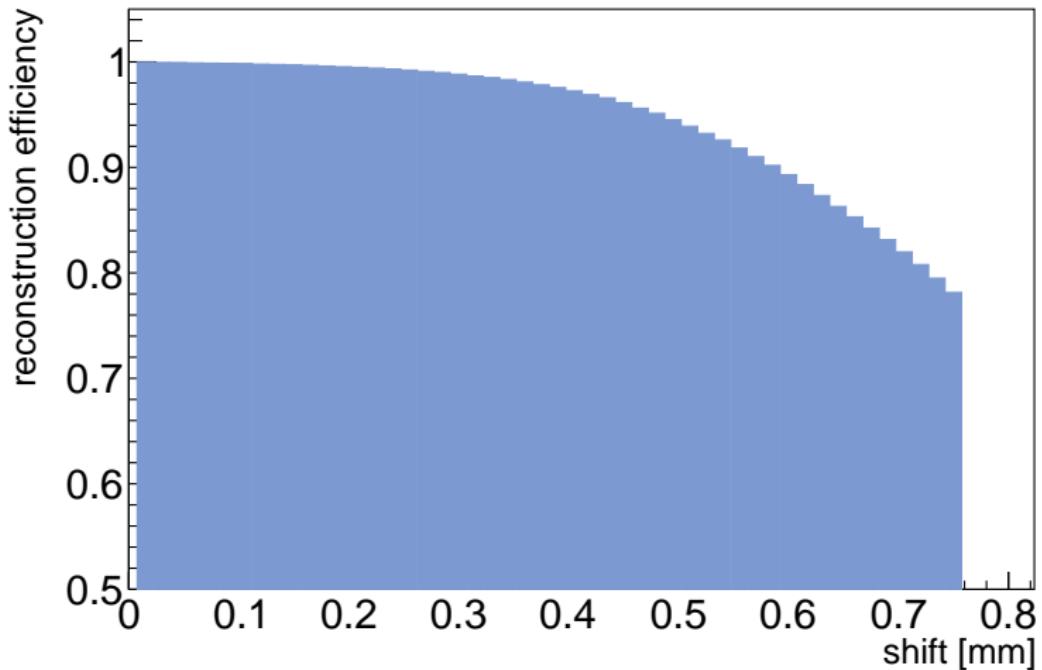


Momentum Reconstruction Resolution



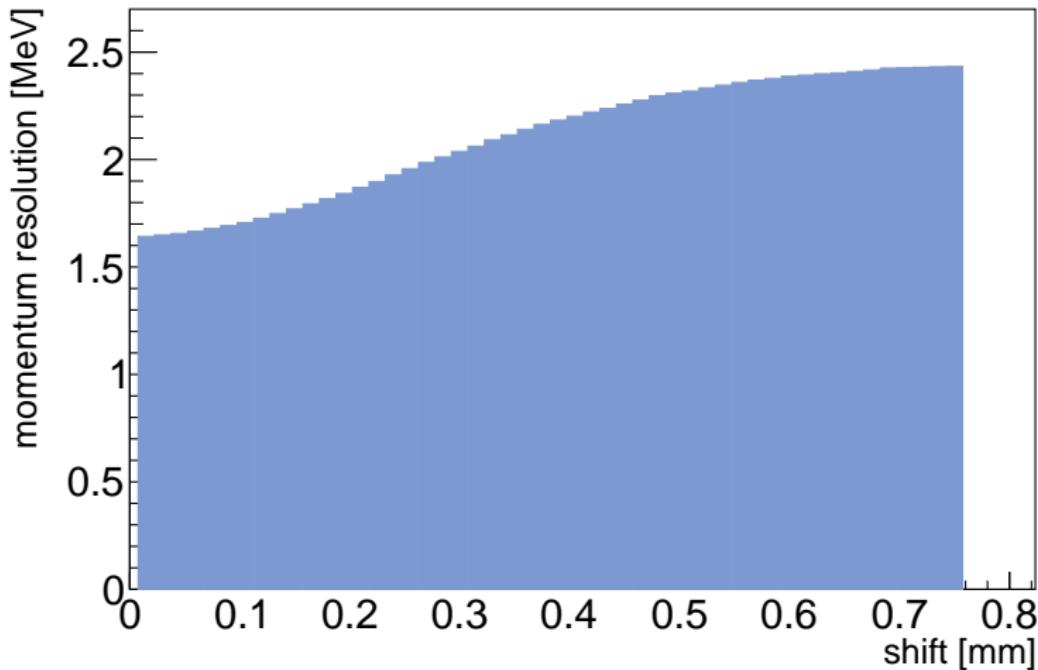
- torsion of the whole detector
- maximum rotation angle of each detector end (total: 4°)
- fairly insensitive to torsion

Momentum Reconstruction Efficiency



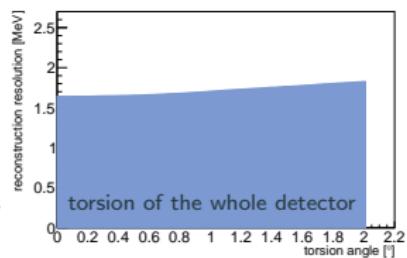
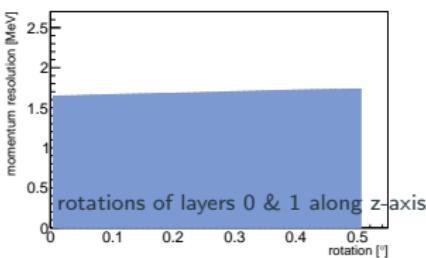
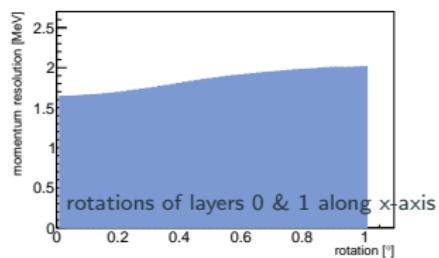
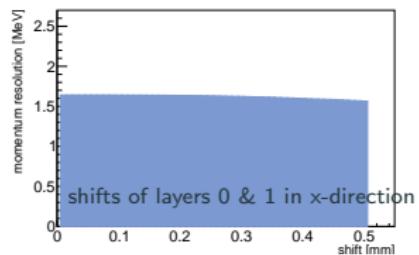
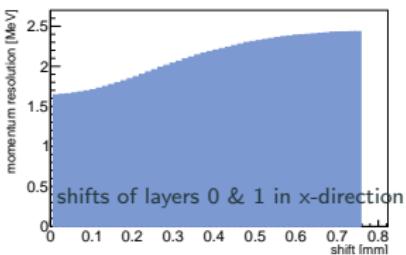
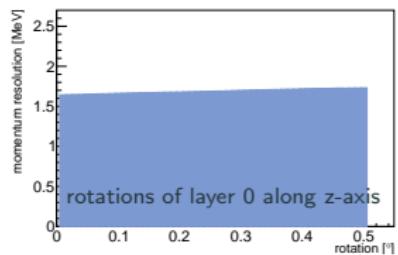
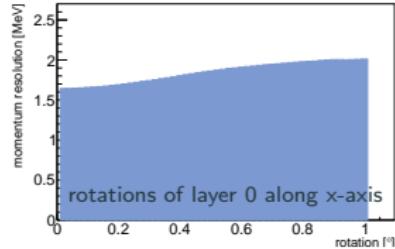
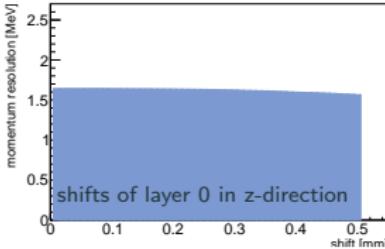
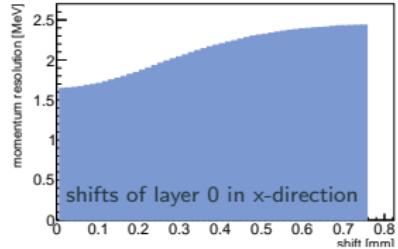
- shifts of the innermost layer in x-direction

Momentum Reconstruction Resolution



- shifts of the innermost layer in x-direction

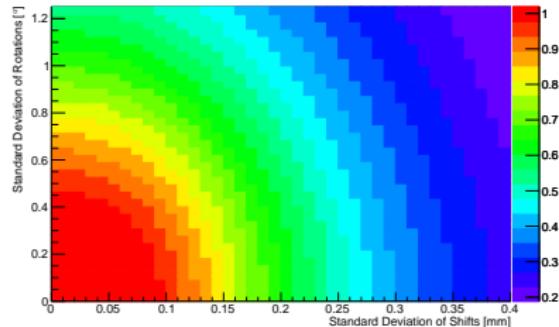
Misalignment Studies - Momentum Resolution RMS (4-hit segments)



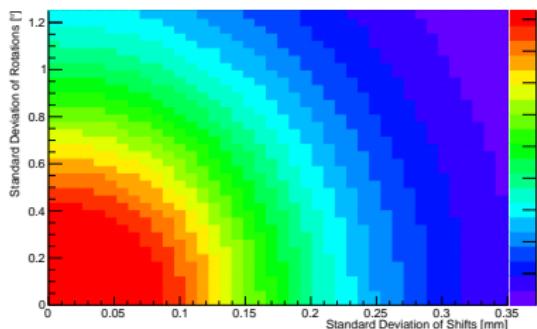
Momentum Reconstruction Efficiency

For Individual Sensors

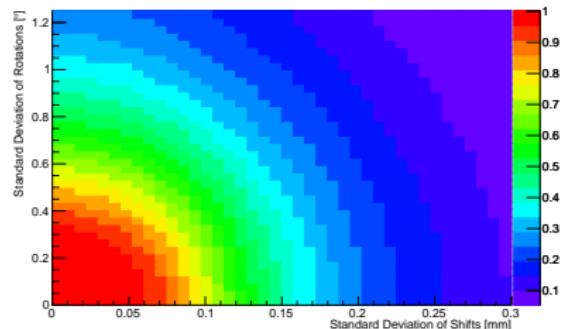
4-hit-segments



6-hit-segments



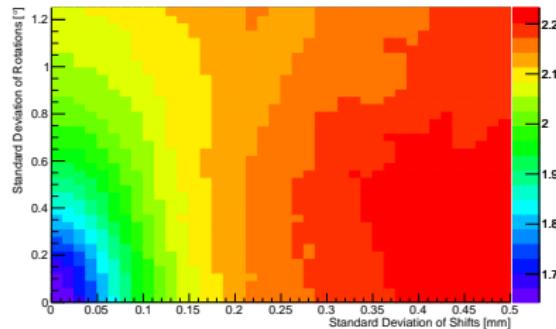
8-hit-segments



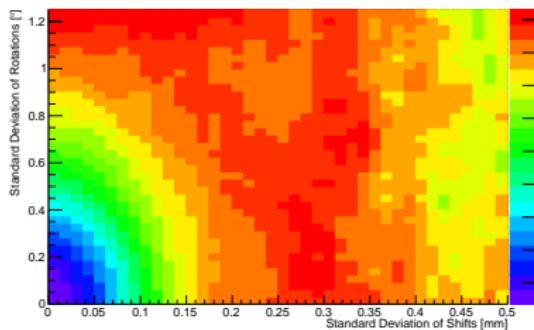
Momentum Resolution

For Individual Sensors

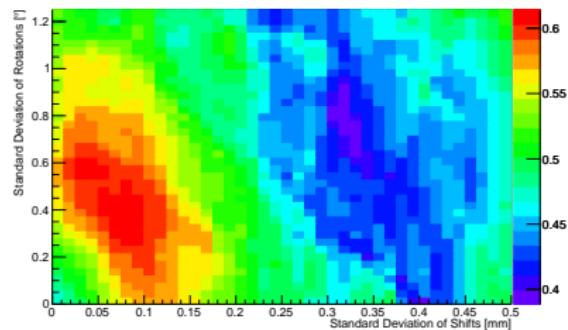
4-hit-segments



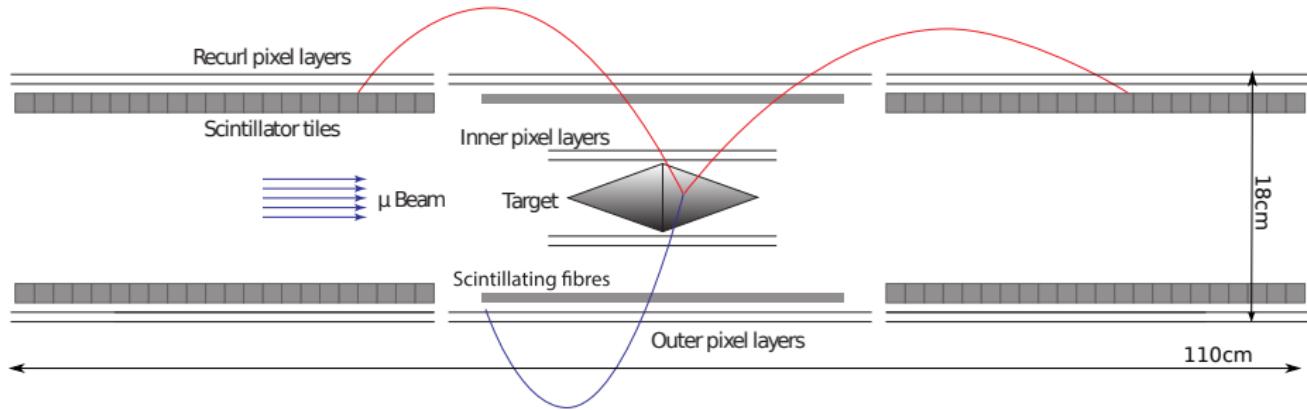
6-hit-segments



8-hit-segments



The Detector



- barrel detector
 - two double layers of silicon sensors
 - scintillating fibre tracker & scintillating tiles (timing)
- hollow double cone target
- use re-curlers
 - allow precise momentum measurements

The Phases of the Mu3e Detector

