Track Based Alignment for the Mu3e Pixel Detector

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For the Mu3e Collaboration

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

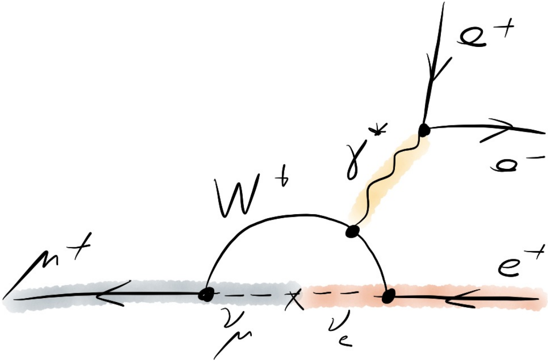
JG|U

The Mu3e Experiment

Mu3e - In the Standard Model

$$\boxed{\mu^+ \rightarrow e^+ e^- e^+}$$

$$\boxed{\mu^+ \to e^+ e^- e^+}$$



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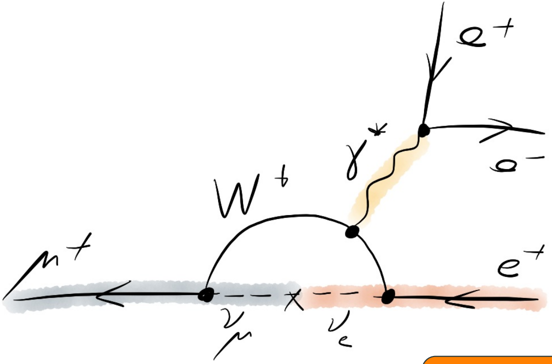
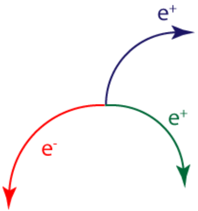


$$\mathcal{BR} < 10^{-54}$$

Beyond the Standard Model?

Motivation

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



Goal

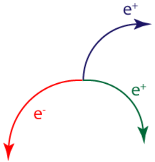
$$\mu^+ \to e^+ e^- e^+$$

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

The Signal

Signal

- $\mu^+ \to e^+ e^- e^+$
- muons stopped and decay at rest $\to$ three tracks
  - same time
  - common vertex
  - $\sum \mathbf{p_e} = 0$
  - $\sum E_e = m_\mu$



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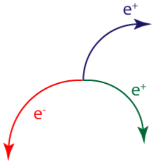
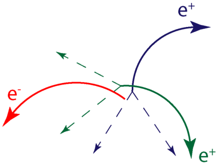




Background

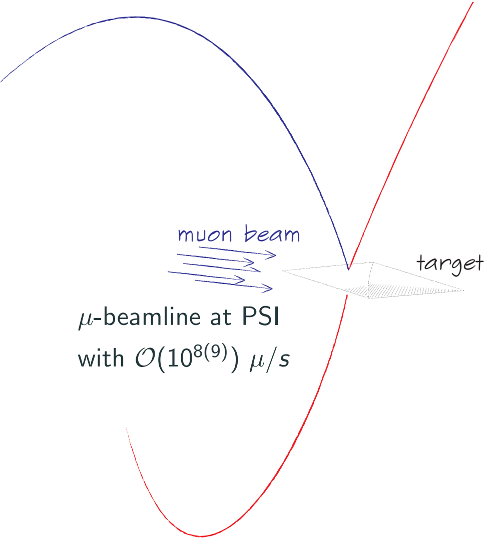
- internal conversion: $\mu^+ \rightarrow e^+ e^- e^+ + 2\nu$
  - missing momentum/energy

  $\rightarrow$ requires good momentum resolution
- random combinations
  - $\mu^+ \rightarrow e^+ + 2\nu$
  - e^+/e^- scattering
  - not the same vertex/time

  $\rightarrow$ requires good vertex/time resolution

The Detector

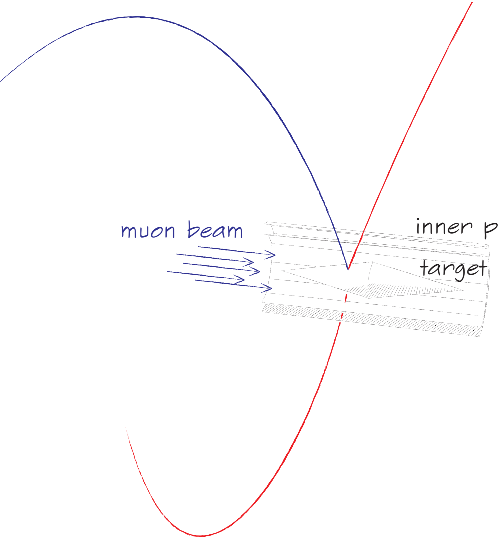
Building the Detector

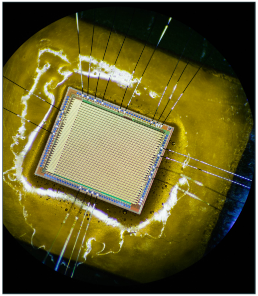


μ-beamline at PSI

with $\mathcal{O}(10^{8(9)})\ \mu/s$

- "MuPix": **H**igh **V**oltage **M**onolithic **A**ctive **P**ixel **S**ensors
  (I.Peric,Nucl.Instr.Meth.,2007, A582, 876)
- $2 \times 2\mathrm{cm}^2$ sensors
- $80 \times 80\,\mu\mathrm{m}^2$ pixels
- thinned to $50\,\mu\mathrm{m}$





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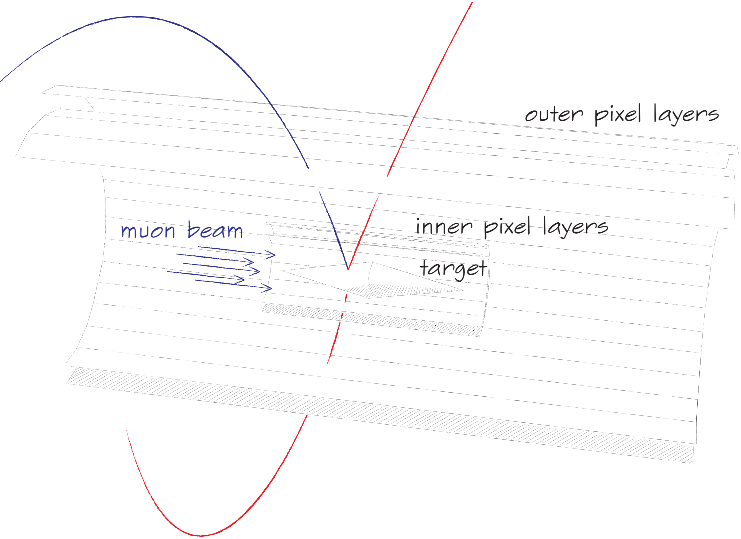

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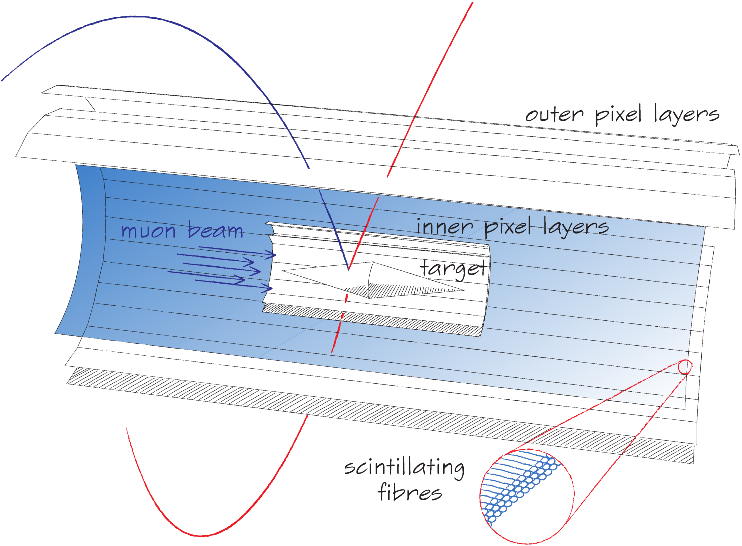

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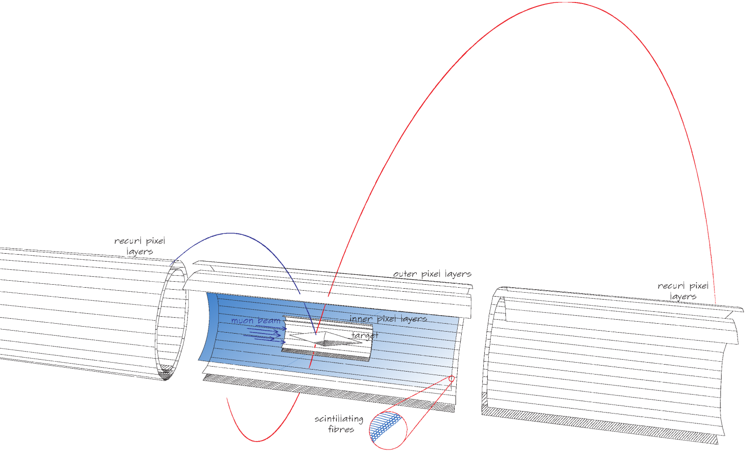
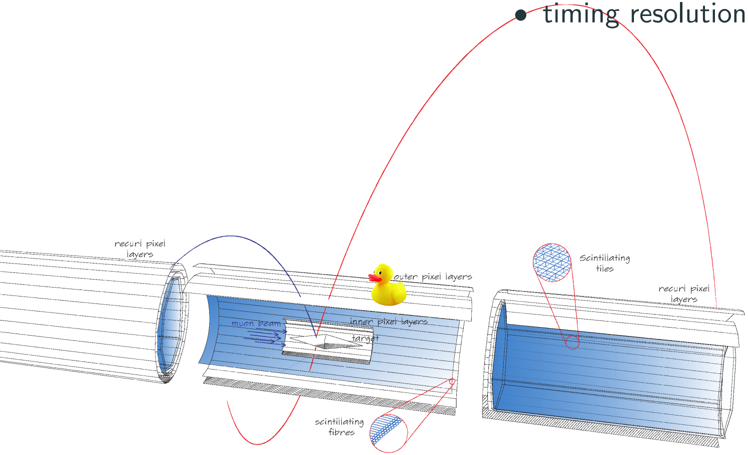


Building the Detector

- momentum resolution < 0.5MeV
- timing resolution < 500ps



Building the Detector

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

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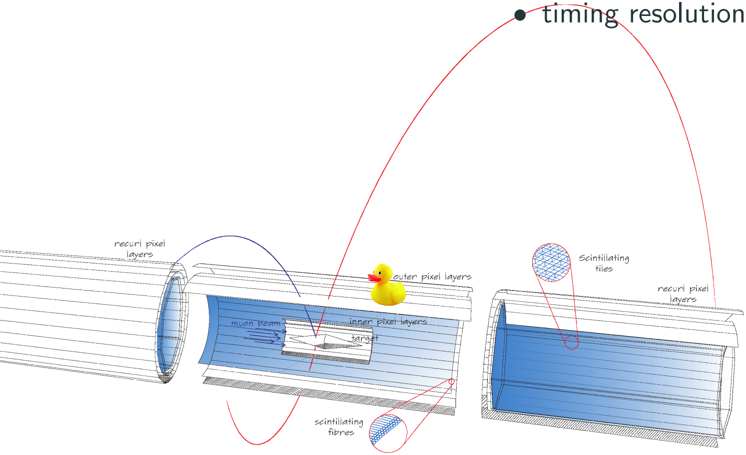

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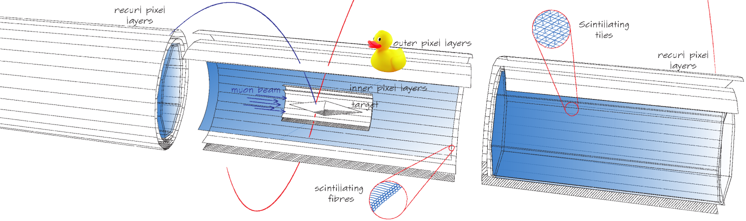
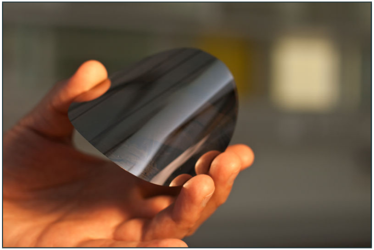


impossible to have sufficient alignment after construction!

Surface Deformations

Surface Deformations

- 50 μm chips won't be rigid!
- Idea: align not only for rotations and shifts but also for
  - surface deformations
  - temperature effects ($\Delta T \approx 70$K)
    $\rightarrow \Delta x \approx 5\,\mu$m for outer pixels



50 μm silicon

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- Idea: align not only for rotations and shifts but also for
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  - temperature effects ($\Delta T \approx 70$K)
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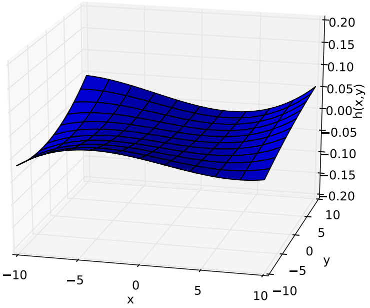
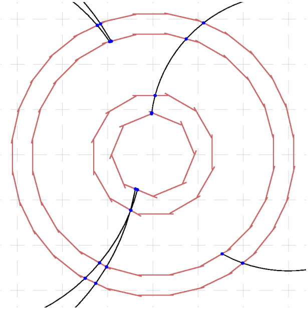
- 3rd order polynomials to model sensors



a deformed sensor

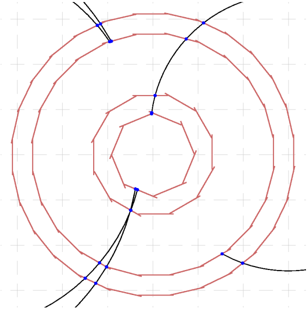
Misalignment

Misalignment



- perfect alignment

Misalignment



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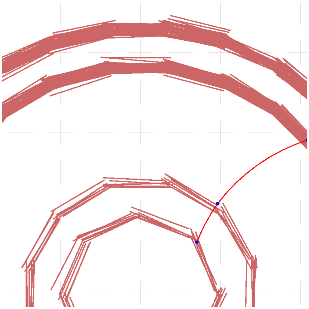
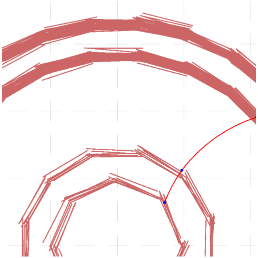


- misaligned sensors

Misalignment Studies

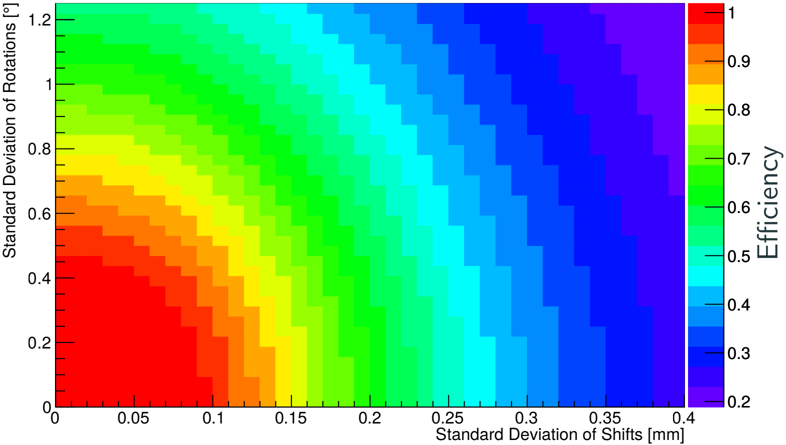
- alignment after construction is not sufficient

  → need for alignment algorithm
- for track based alignment tracks are needed!
- "how well (mechanically) aligned to be able to align (with software)?"



Momentum Reconstruction Efficiency

Randomly Misaligned Sensors



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

Track Based Alignment

Track Based Alignment and the Software for it

- from misalignment studies derived goals:

  $\sigma_{position} \leq 80\,\mu m$, $\sigma_{orientation} \leq 0.3^\circ$
- with cameras, cosmics, lower rate, etc. this goal is possible

  $\rightarrow$ track based alignment $\rightarrow \sigma \approx 2\,\mu m$

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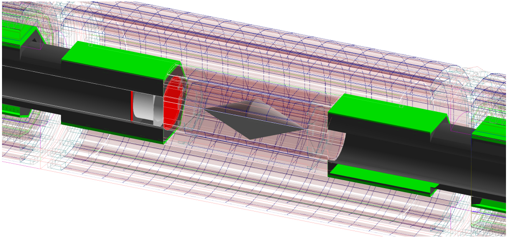
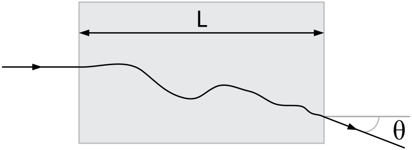
  $\rightarrow$ track based alignment $\rightarrow \sigma \approx 2\,\mu m$
- Mu3e software package
- General Broken Lines (GBL) (V. Blobel, C. Kleinwort, arXiv:1201.4320v1)
- Millepede-II (MP-II) (V. Blobel, C. Kleinwort, arXiv:1103.3909v1)



General Broken Lines Fit

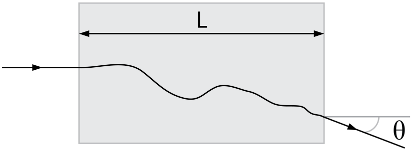
- multiple scattering & energy loss
  $\rightarrow$ advanced track models: e.g. GBL



V. Blobel,
C. Kleinwort,
arXiv:1201.4320v1

General Broken Lines Fit

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



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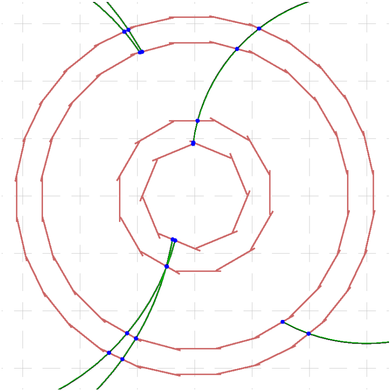
Millepede-II

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 $f_{ij}(\mathbf{q_j}, \mathbf{p})$



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

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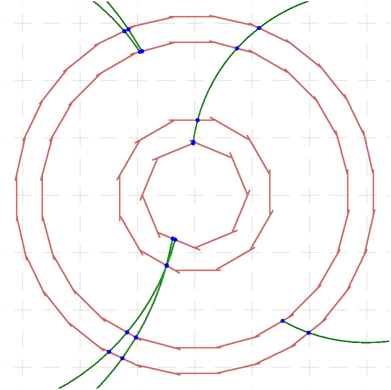
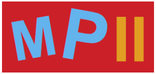
- $\mathbf{q_j}$: track parameters
- $\mathbf{p}$: alignment parameters





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- minimise χ^2
  an example: using 1mio tracks to align 3000 sensors leads to
  - 20 mio track parameters
  - 45 000 alignment parameters

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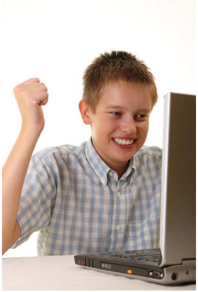
  - 20 mio track parameters
  - 45 000 alignment parameters
    $\rightarrow$ invert a 20045000×20045000 matrix
  - MP-II $\rightarrow$ reduction to 45000×45000
    (not solving for track parameters)



MPII

V. Blobel,
C. Kleinwort,
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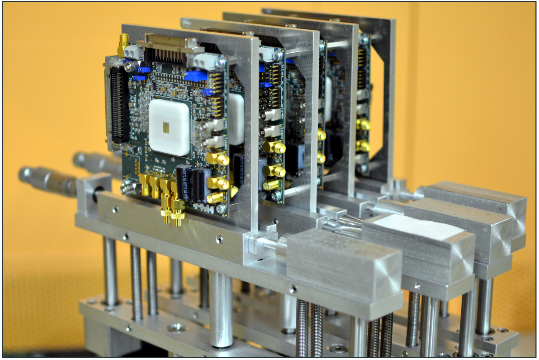
First Tests

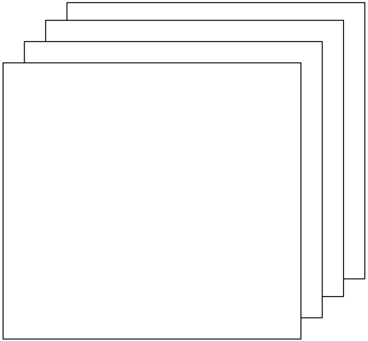
Testing the Alignment Software on a Telescope

- the "MuPix-Telescope" is frequently in use at MAMI
- alignment is already done with Millepede-II and GBL (python implementation)
- use MP-II within our software framework



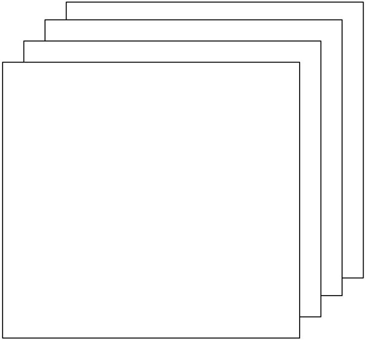
Testing the Alignment Software on a Telescope

- do the following steps 1000 times:
  (1) simulate a 4-plane telescope



Testing the Alignment Software on a Telescope

- do the following steps 1000 times:
  1. (1) simulate a 4-plane telescope
  2. (2) simulate 10000 tracks



Testing the Alignment Software on a Telescope

- do the following steps 1000 times:
  (1) simulate a 4-plane telescope
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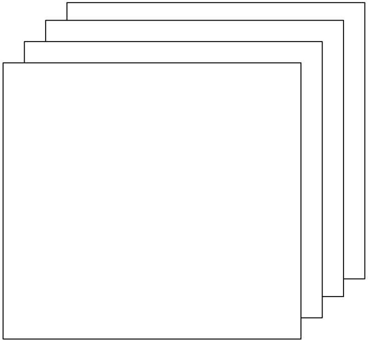
  (3) misalign inner telescope planes randomly
  ($\sigma_{x,y} = 100\,\mu\text{m}$, $\sigma_{rot} = 10\,\text{mrad}$)



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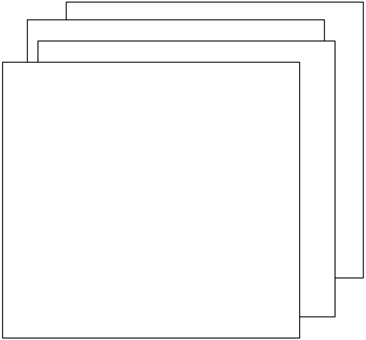

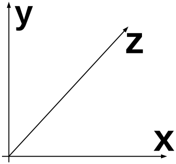

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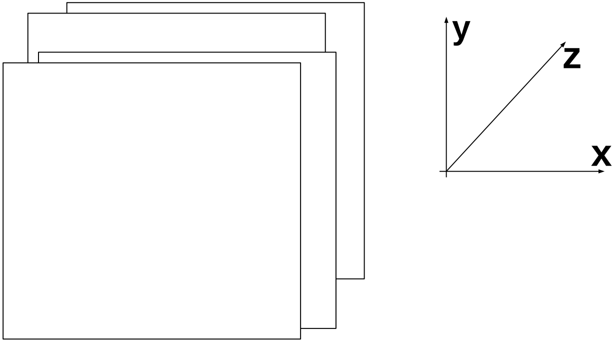

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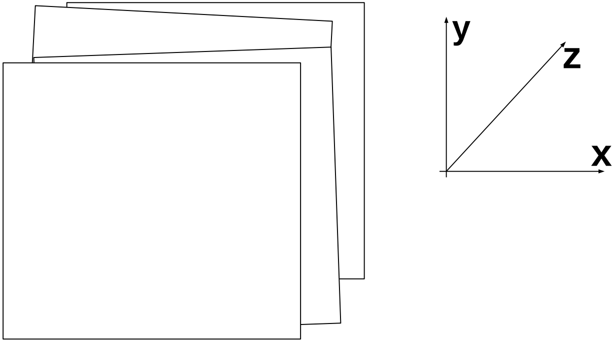

Testing the Alignment Software on a Telescope

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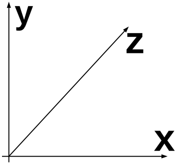
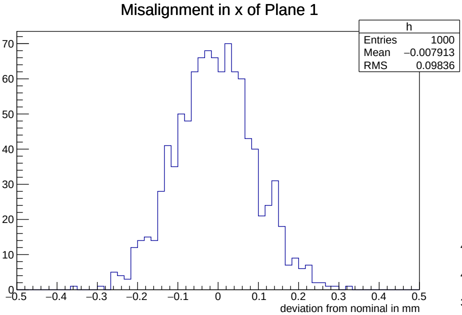
  1. (1) simulate a 4-plane telescope
  2. (2) simulate 10000 tracks
  3. (3) misalign inner telescope planes randomly ($\sigma_{x,y} = 100\,\mu m$, $\sigma_{rot} = 10\,mrad$)
  4. (4) fit tracks (GBL)
  5. (5) use Millepede-II implementation to align
  6. (6) compare to initial misalignment

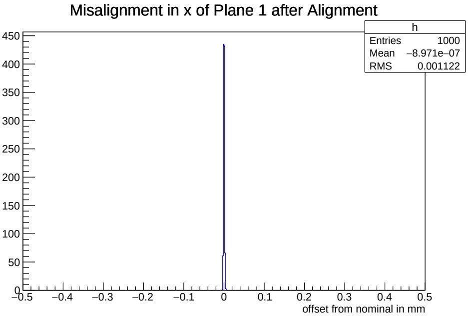


Misalignment: Deviation from Nominal Alignment



before Alignment

RMS : 100 µm → 1 µm



after Alignment

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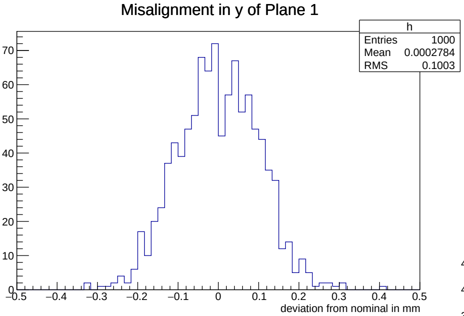

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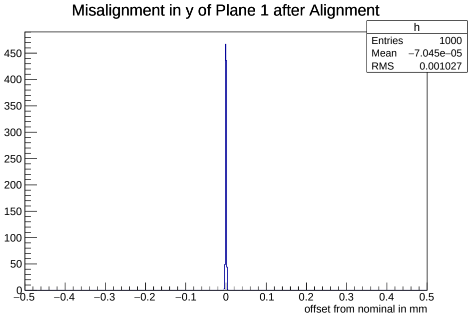

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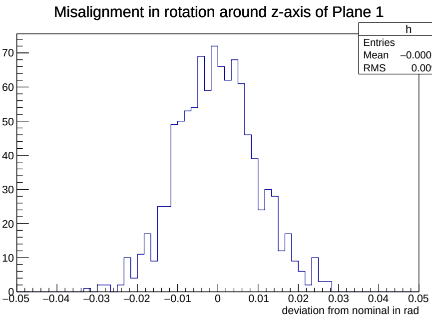
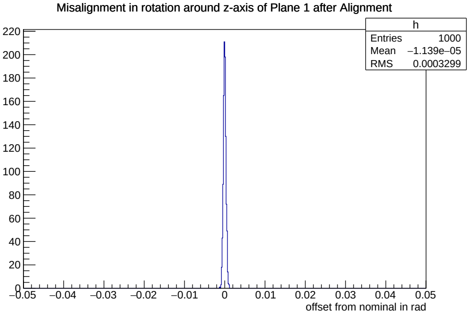


before Alignment

RMS : 10 mrad → 0.3 mrad

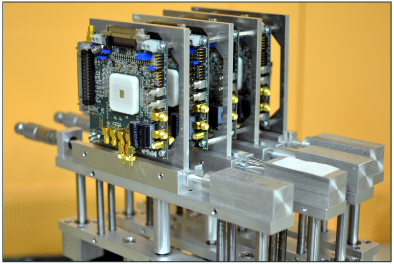


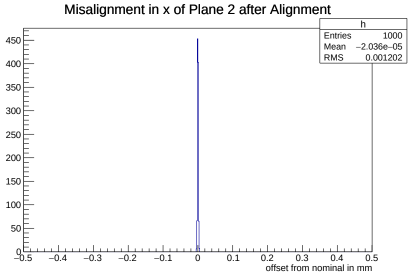
after Alignment

Outlook

Status & Outlook

- misalignment Studies ✓
- basic software ✓
- testing for a (simulated) telescope ✓
- testing for the complete detector (✓)
- alignment for surface deformations (the fundamentals are there)





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

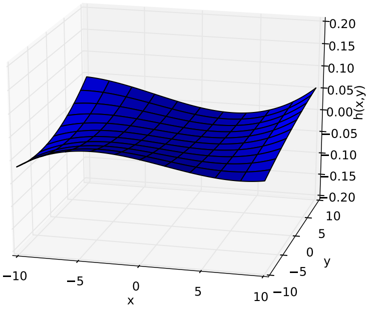


Figure 1: Legendre-Plane: coefficients of $0 - 30\mu m$

Parametrization

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

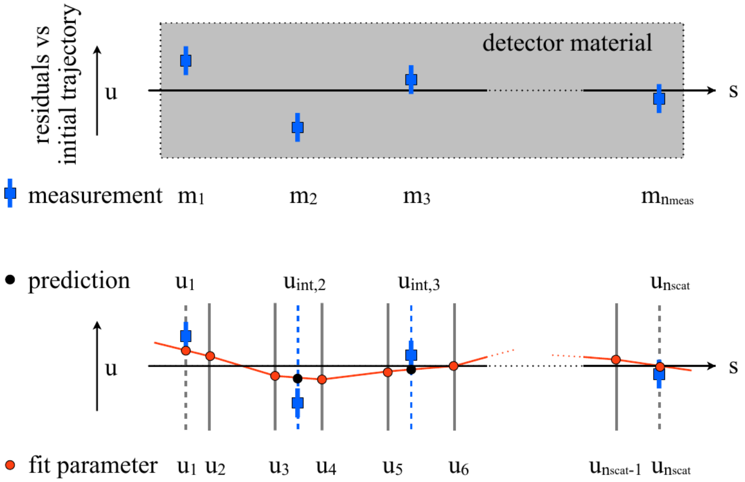
$$h(x, y) = \sum_{i=0}^{N} \sum_{j=0}^{i} c_{ij} \, P_{i-j}(x) \, P_j(y), \tag{1}$$

with Legendre-ploynomials

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

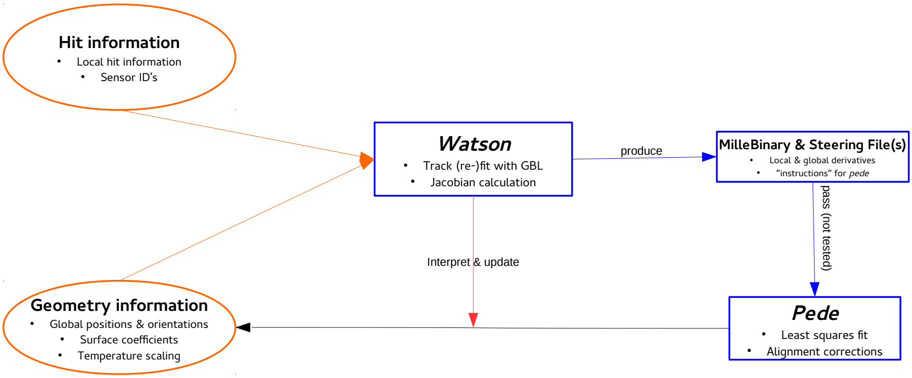
and surface coefficients c_{ij}

General Broken Lines Fit



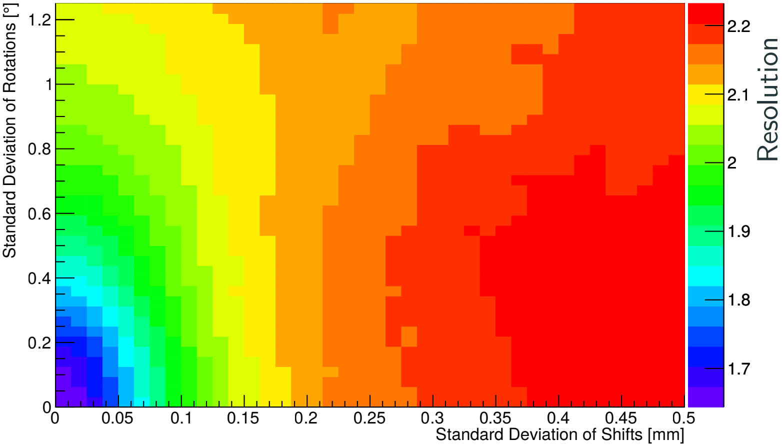
V. Blobel,
C. Kleinwort,
arXiv:1201.4320v1

Alignment Procedure



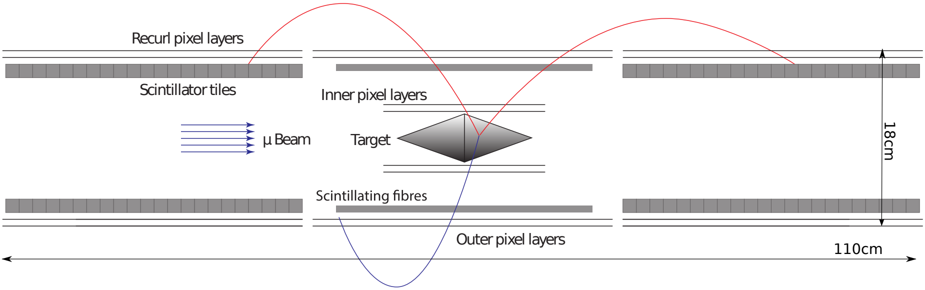
Momentum Reconstruction Resolution

Randomly Misaligned Sensors



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

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