Track reconstruction for the Mu3e experiment

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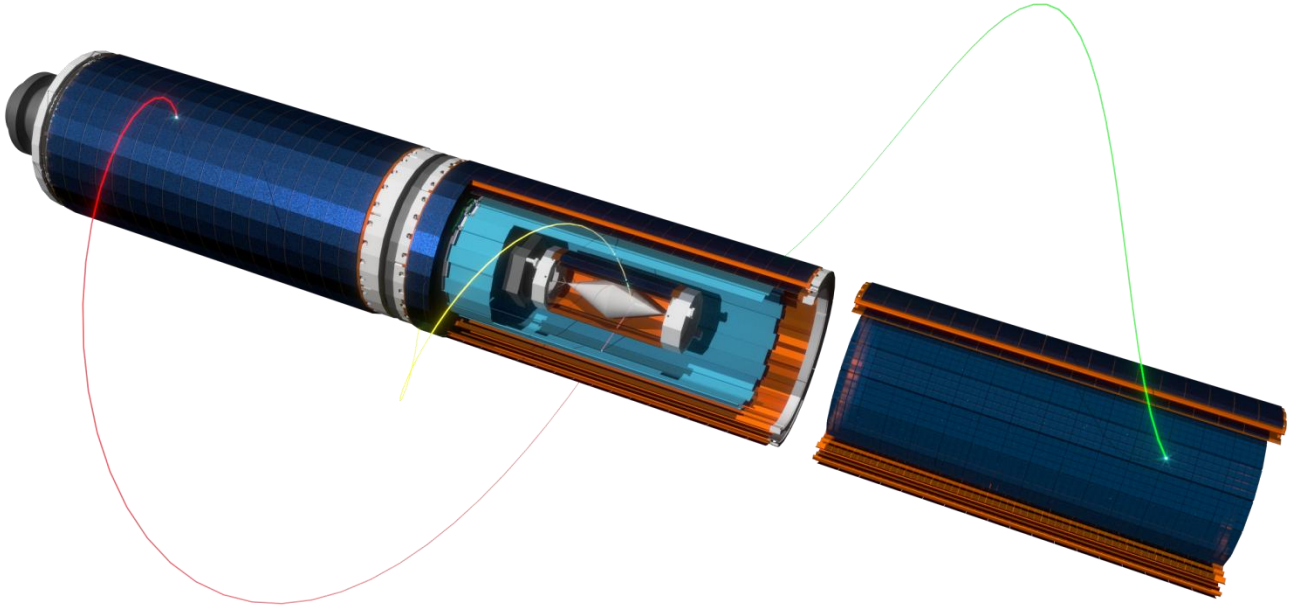
On behalf of the **Mu3e** collaboration



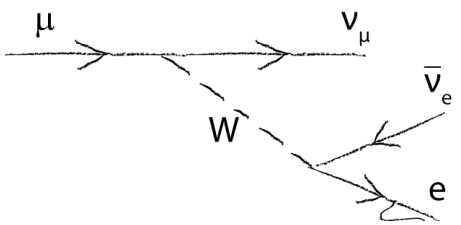
Introduction

Mu3e Experiment:

- Search for **L**epton **F**lavor **V**iolation (LFV)
  - Decay: $\mu^+ \rightarrow e^+e^+e^-$
  - **S**tandard **M**odel: Br < 10^{-54} (unobservable)
  - Enhanced in **N**ew **P**hysics models
  - *Any observed decay will point to NP*
- Location: Paul Scherrer Institute (PSI)
  - Start in 2018

Michel decay

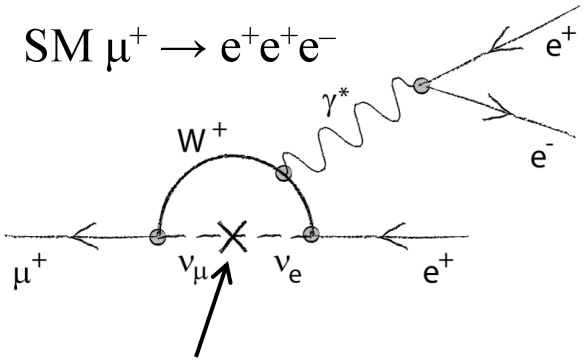
conserved flavor



Current experimental status:

- SINDRUM (1988) *Nucl.Phys.B299(1988)1*
- Br($\mu^+ \rightarrow e^+e^+e^-$) < 10^{-12} at 90% c.l.

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



Neutrino mixing

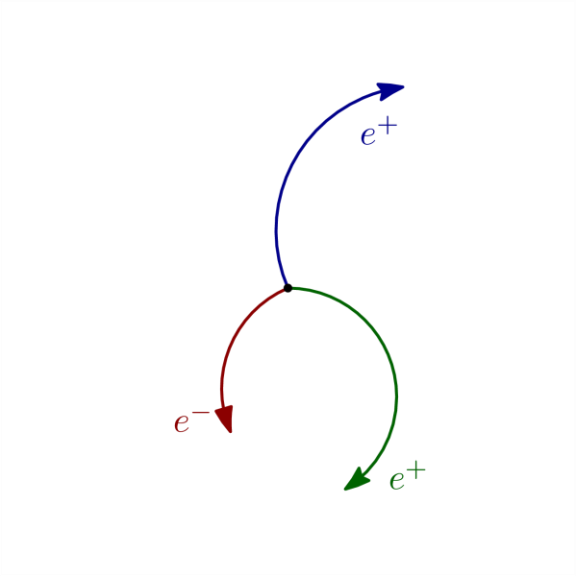
Mu3e aims for sensitivity of one in 10^{15} μ-decays

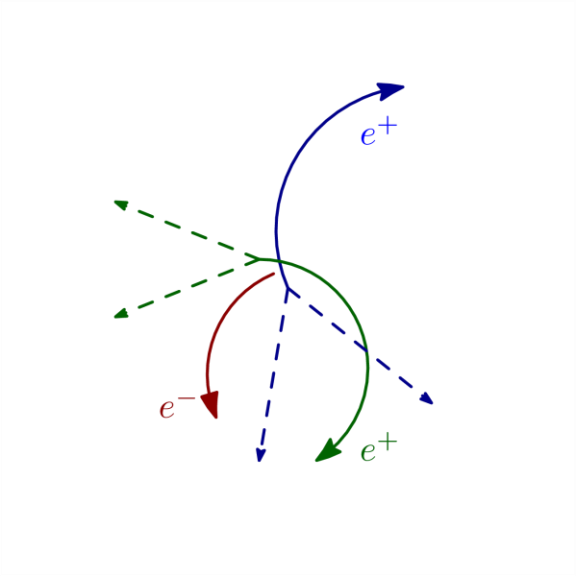
- Existing beam line: 10^8 μ/s
- With new beam line: one in 10^{16}

Mu3e experiment

Signal: $\mu^+ \rightarrow e^+e^+e^-$
- 3 tracks (positron & electron)
- Vertex, same time
- Decay at rest:
  - $\sum p = 0$
  - $e^{\pm}$ energy < 53 MeV/c
- Invariant mass:
  - $\sum e = m_\mu$

Background: random combinations
- Michel decay: $\mu \rightarrow e\nu\nu$
- e^+/e^- scattering
- Fake tracks, etc
- Not same vertex, time, etc.
  - Good vertex/time resolution

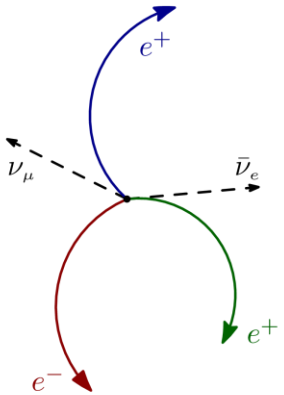


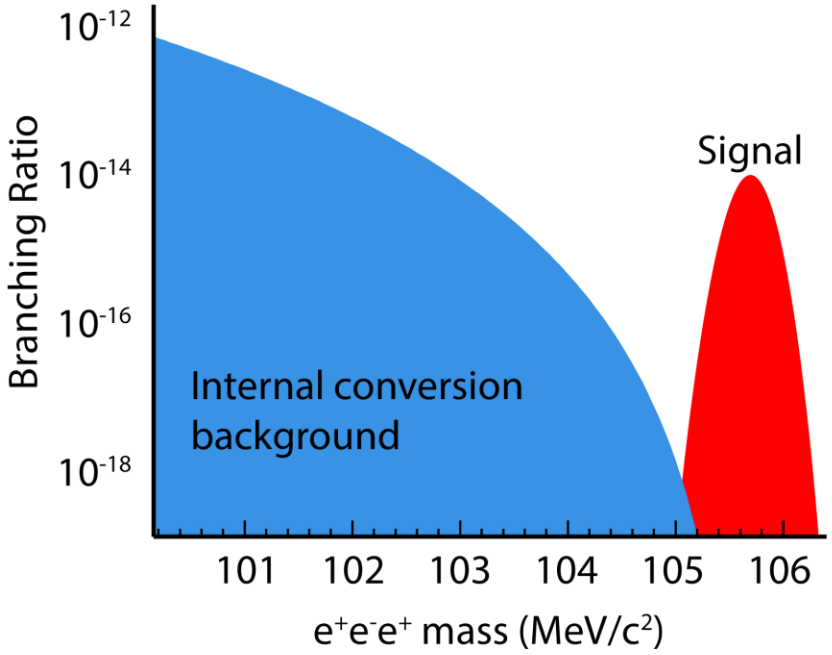


Background: internal conversion

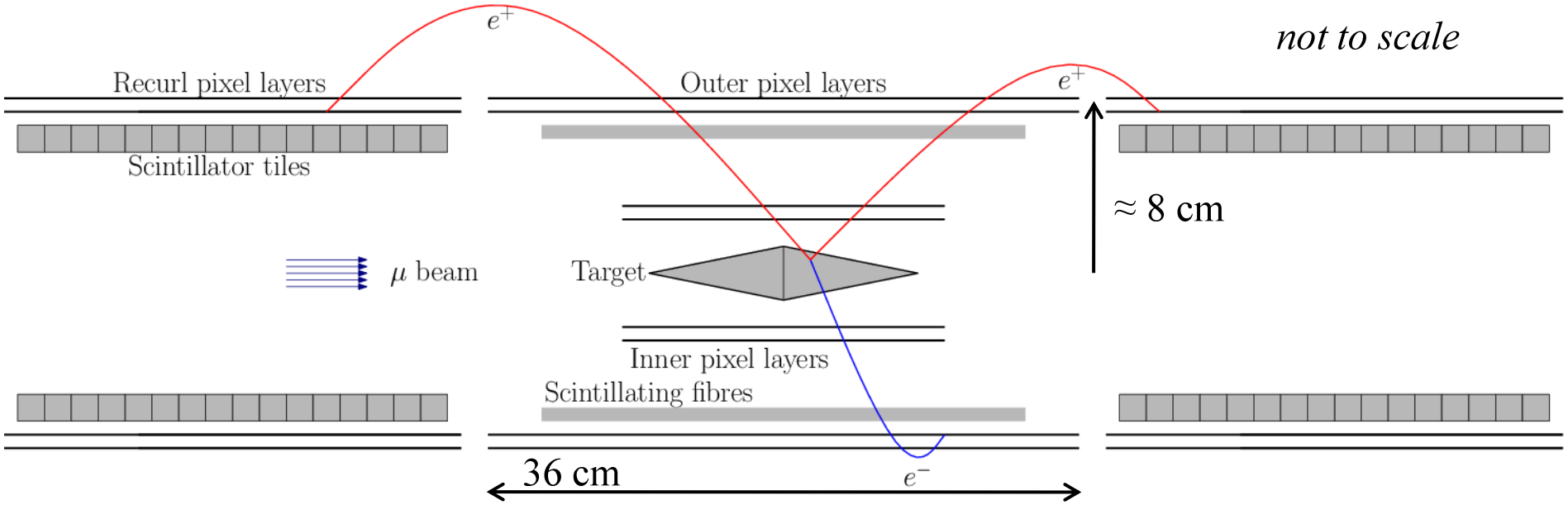
Internal conversion:

- $\mu^+ \rightarrow e^+e^+e^- + 2\nu$
- Missing momentum & energy:
  - $\sum p \neq 0$
  - $\sum e \neq m_\mu$
- Need good momentum resolution





Mu3e Detector



Double cone hollow target:
- Muons stop and decay at rest
- Spread decay vertices in space

Four layers of pixel sensors:
- High granularity
- Thin (minimum multiple scattering)

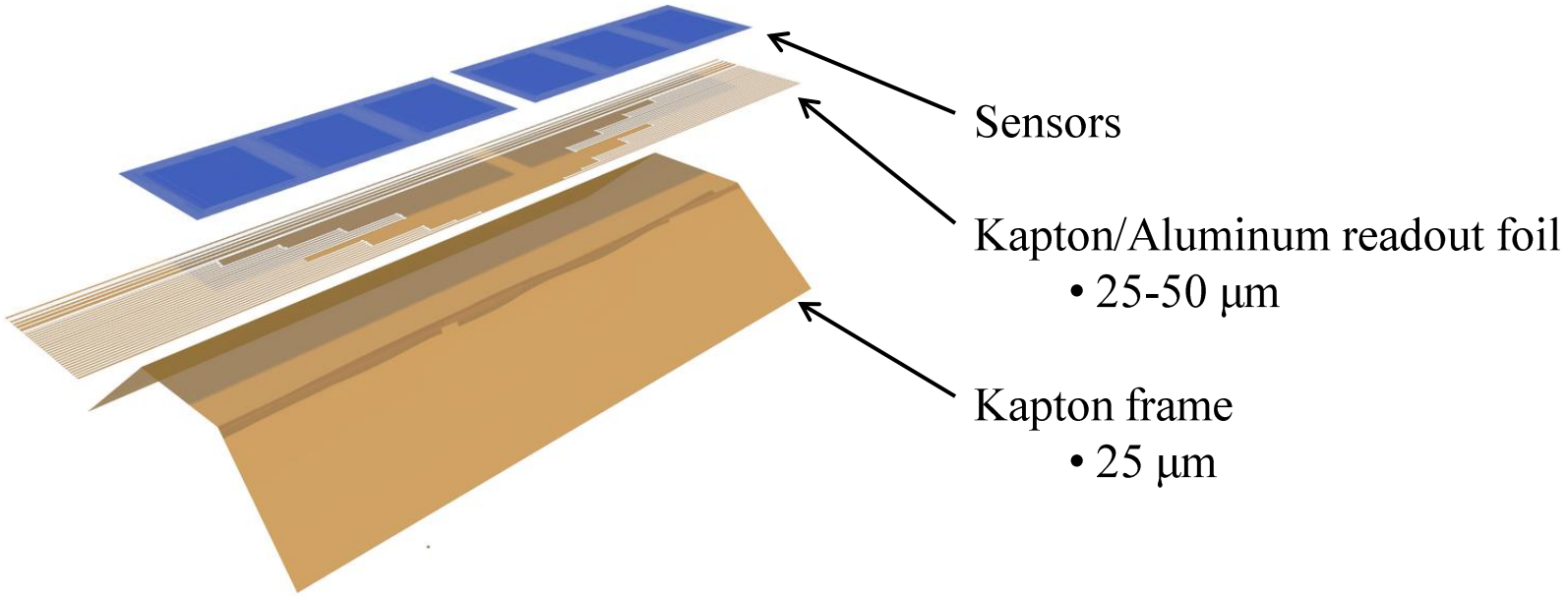
Recurl pixel layers:
- Improve momentum resolution

Timing detectors:
- Fibres (~1 ns resolution)
- Tiles (~100 ps resolution)

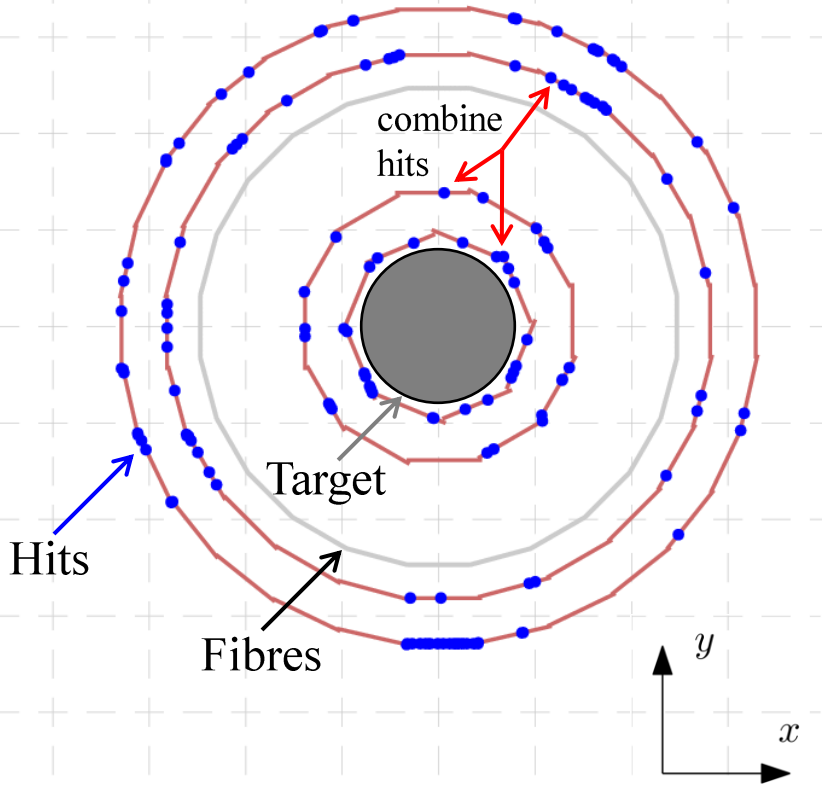
Pixel sensors

High Voltage Monolithic Active Pixel Sensor (HVMAPS)

- 3000 sensors, 2x2 cm^2 area with 80x80 μm^2 pixel size
- 50 μm thick ~ $0.5 \cdot 10^{-3}$ X_0
  - Total thickness (with frame) ~ $1 \div 2 \cdot 10^{-3}$ X_0
  - Typical MS angles ~ 5÷10 mrad
- Efficiency > 99%



Track reconstruction



Make triplets:

- Combine hits of first 3 layers
- n^3 combinations (n – number of hits in a layer)
- 10 hits per layer in 50 ns
    - O(1K) combinations

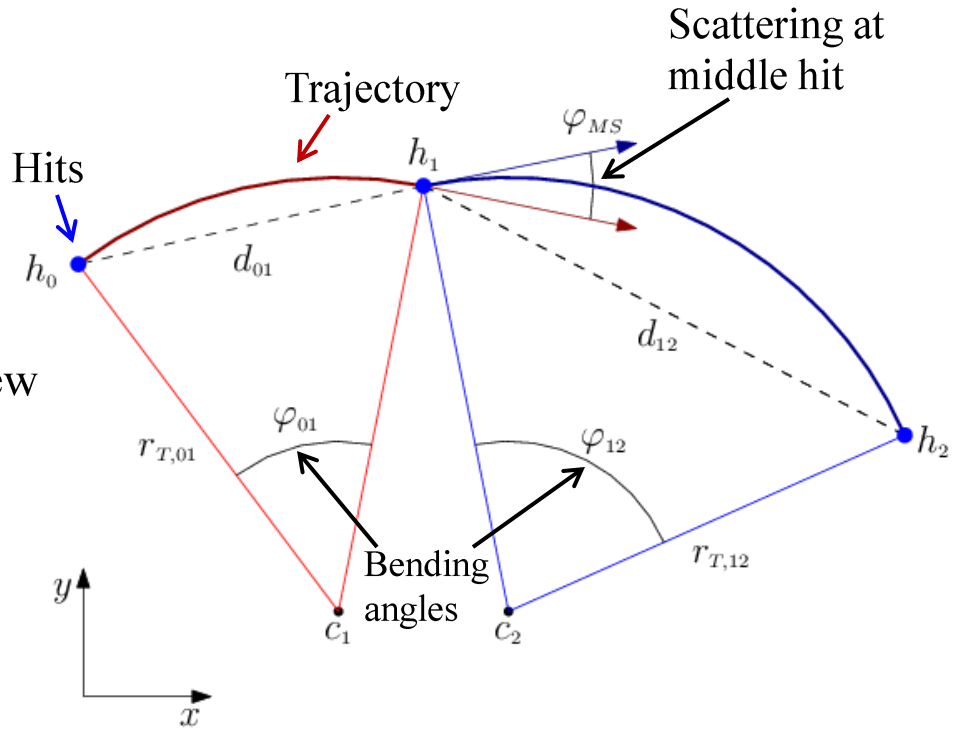
- Reduce number of fits
    - Geometrical selections (opening angles, etc)

Triplet fit

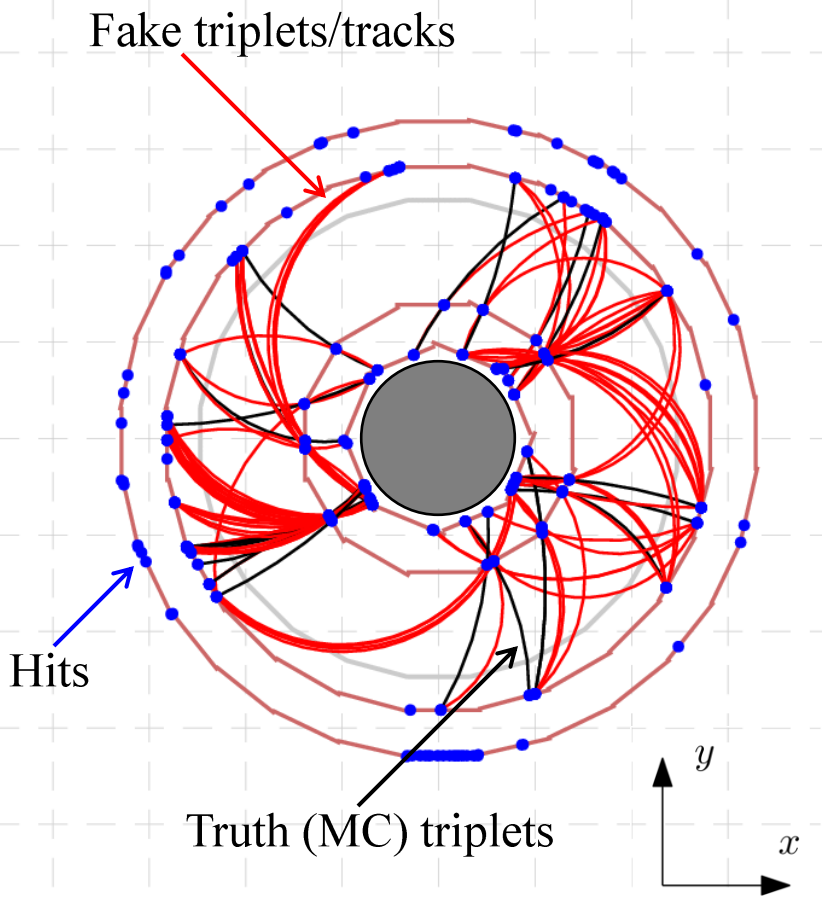
Triplet:
- 3 hits (3D points) form triplet
- Combination of 2 helixes
  - MS at middle hit
  - No energy loss
  - No hit position uncertainty
- Basic block for track reconstruction

Triplet fit solution:
- Minimize scattering angle
- Use linear approximation around circle solution (small MS angles)
- Fast & simple

Transverse view of the triplet



Reconstruction: triplets

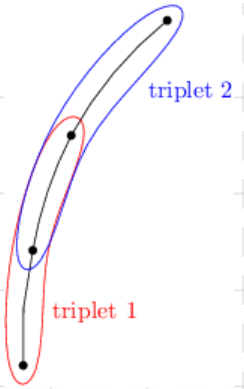


Selections:

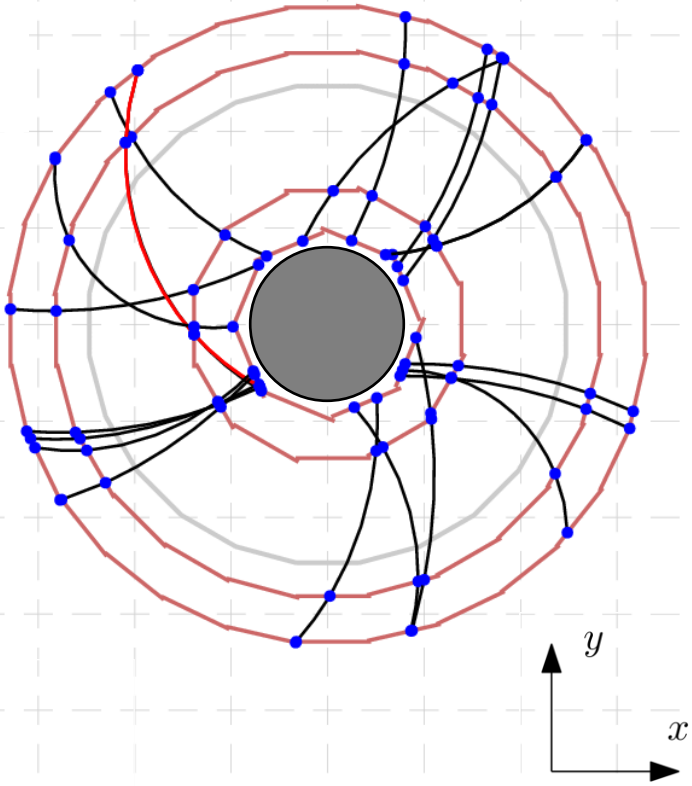
- Geometrical
  - Distance between hits, etc.
  - Factor 50 reduction in number of fitted combinations
- Triplet χ^2
  - Cut on MS angles

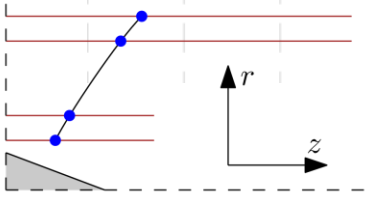
- Fake rate (fake combinations per one truth track) ~ 4
  - 10 truth triplets & 40 fakes

Reconstruction: short tracks



short track:
pair of triplets (4 hits)
2 hits shared between triplets

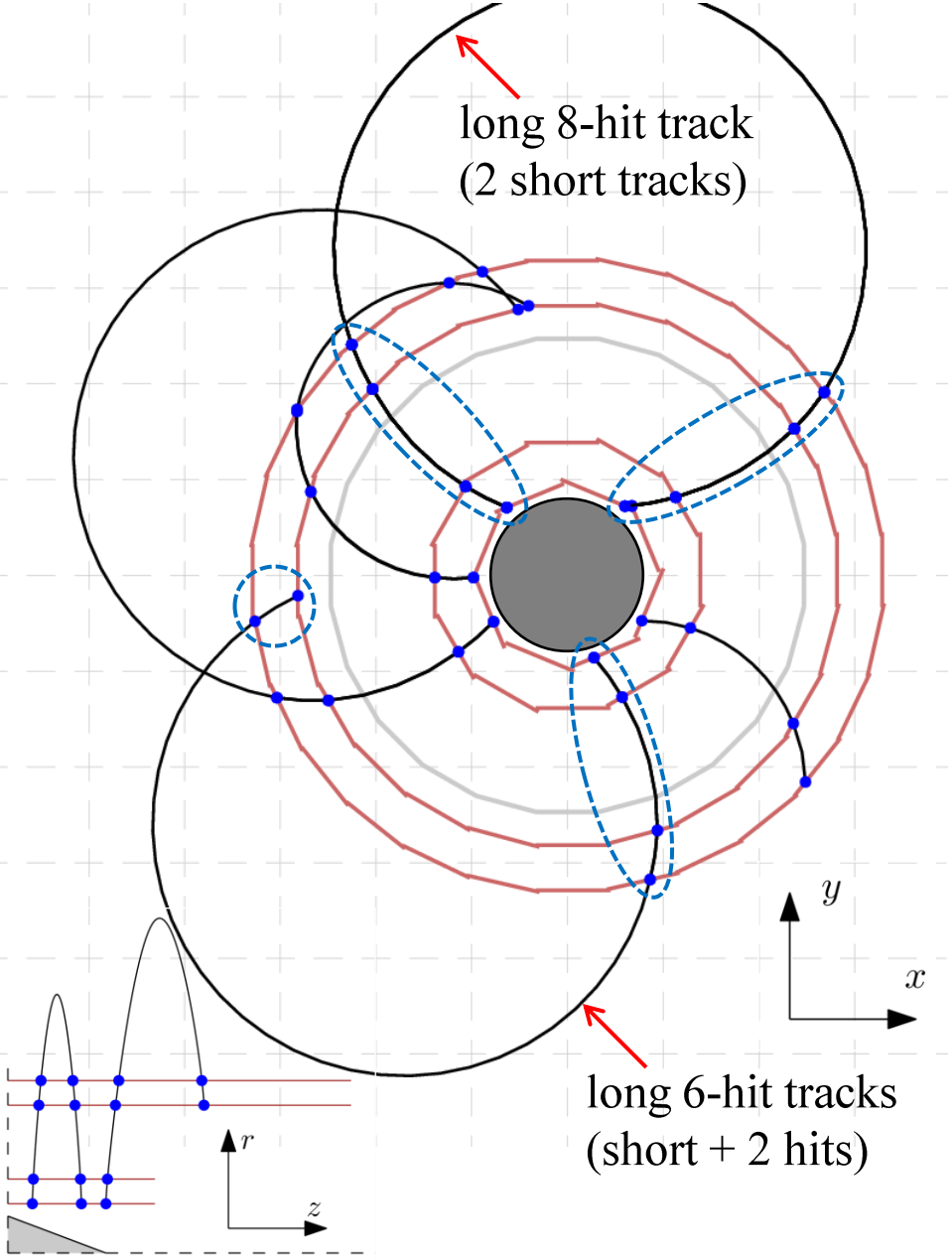




Make short tracks:

- Use triplets as seeds
  - Estimate hit at last layer
  - Lookup in φ/z window
- Combine 4 hits → short tracks
  - 2 triplets (2 shared hits)
  - Fit ≈ weighted average
- O(10) short tracks in 50 ns
- Fake rate ~ 2.5%

Reconstruction: long tracks



Long tracks:
- Bend back (recurl) in the field
- Better constraint on momentum
- Use short tracks as seeds

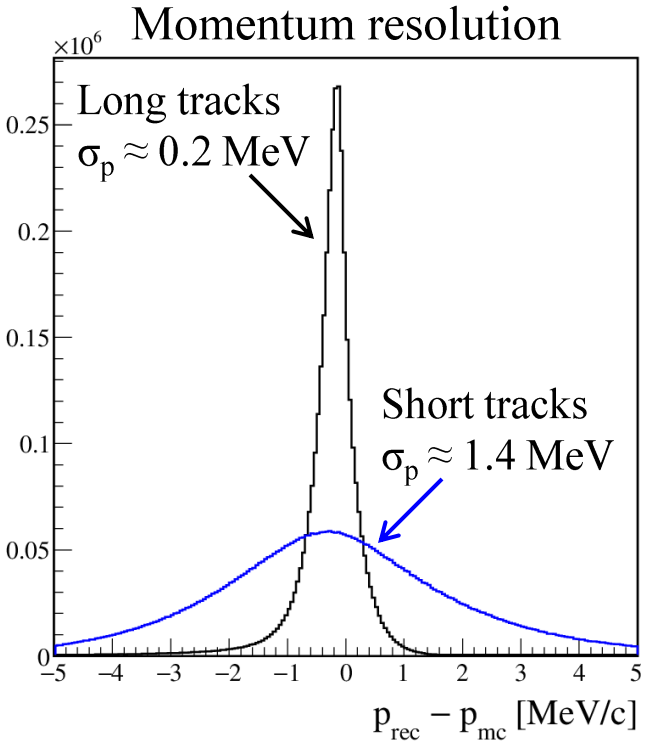
- 6-hit tracks
  - Short track + 2 hits
  - Fibre and/or tile hits
  - Fake rate ~ 2%

- 8-hit tracks
  - 2 short tracks
  - 2 fibre hits
  - Fake rate ~ 1

Performance

Short tracks (4 hits)
- Acceptance: 80%
- Reconstruction efficiency: 95%
  - Geometrical and χ^2 cuts
- $\sigma_p \approx 1.4$ MeV/c

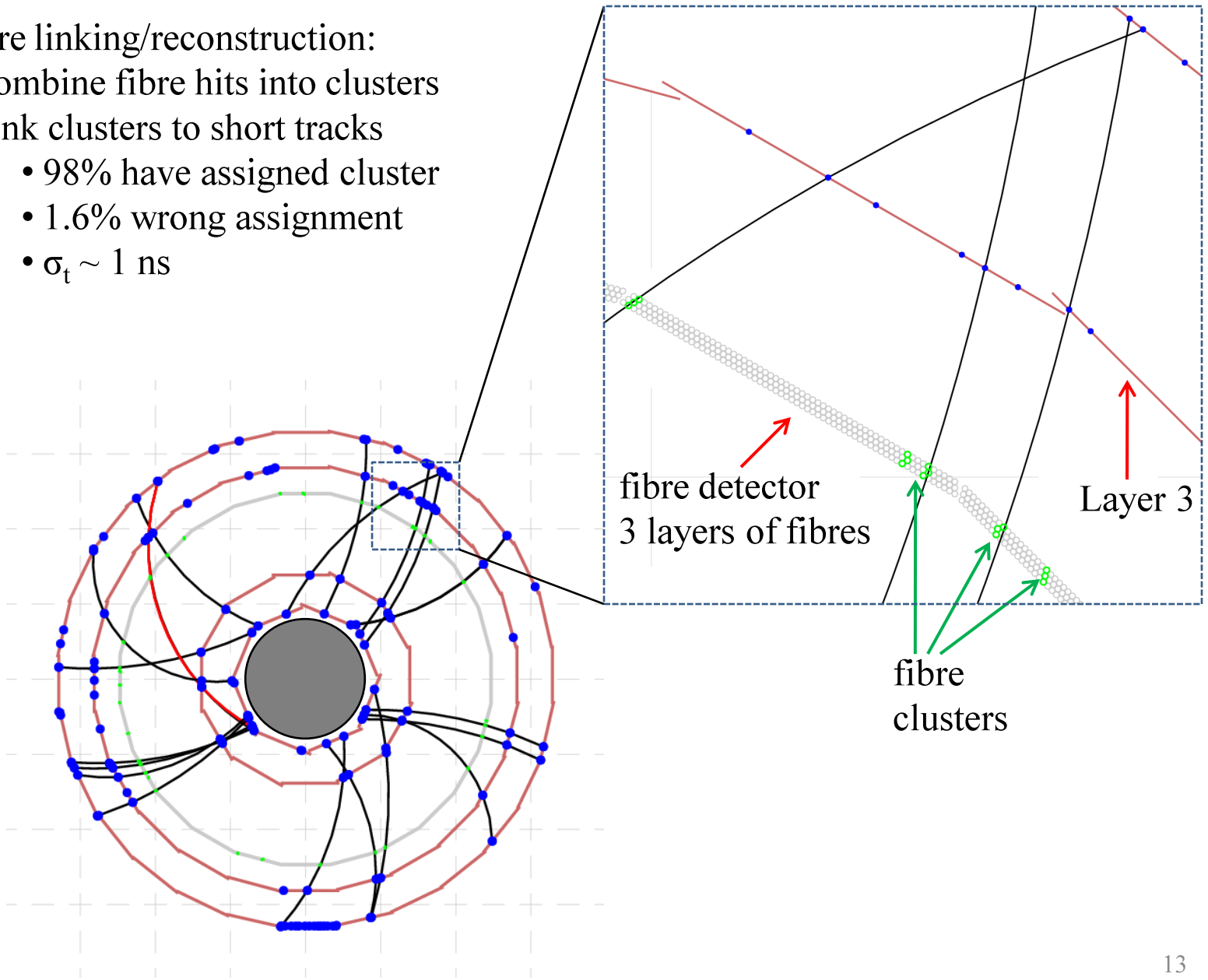
Long tracks (6 and 8 hits)
- 80% of short reconstructed as long
  - Gaps between stations, χ^2 cuts
- $\sigma_p \approx$ **0.2 MeV/c**



Fibre linking

Fibre linking/reconstruction:

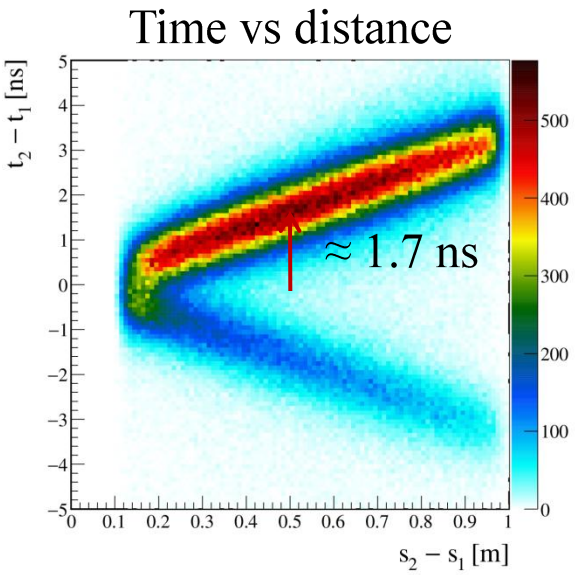
- Combine fibre hits into clusters
- Link clusters to short tracks
  - 98% have assigned cluster
  - 1.6% wrong assignment
  - $\sigma_t \sim 1$ ns

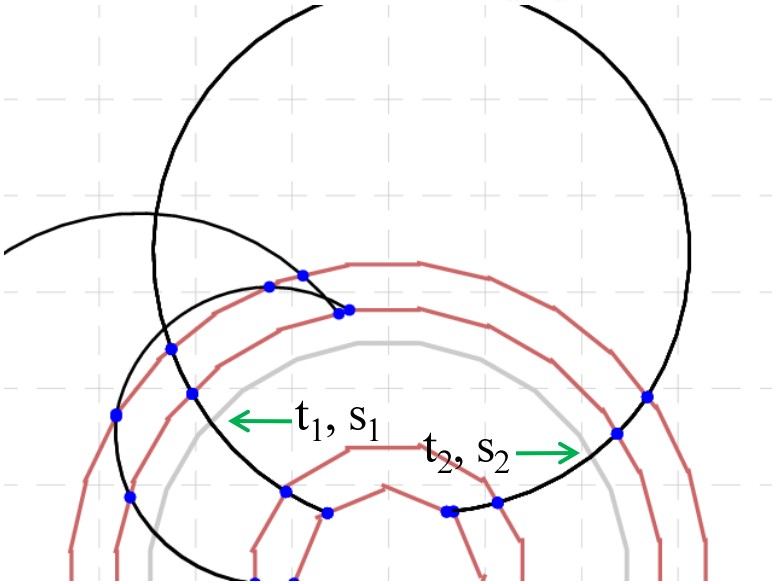


Timing

Time information from fibres/tiles:
- Suppress fakes
- "*Charge ID*": positron (+) or electron (–)
- Additional vertex constraint

Charge ID for long 8-hit track:
- Unknown direction
- Use fibre time information ($t_2 - t_1$) and path length between fibre hits ($s_2 - s_1$)
  - Should match particle traveling with speed of light

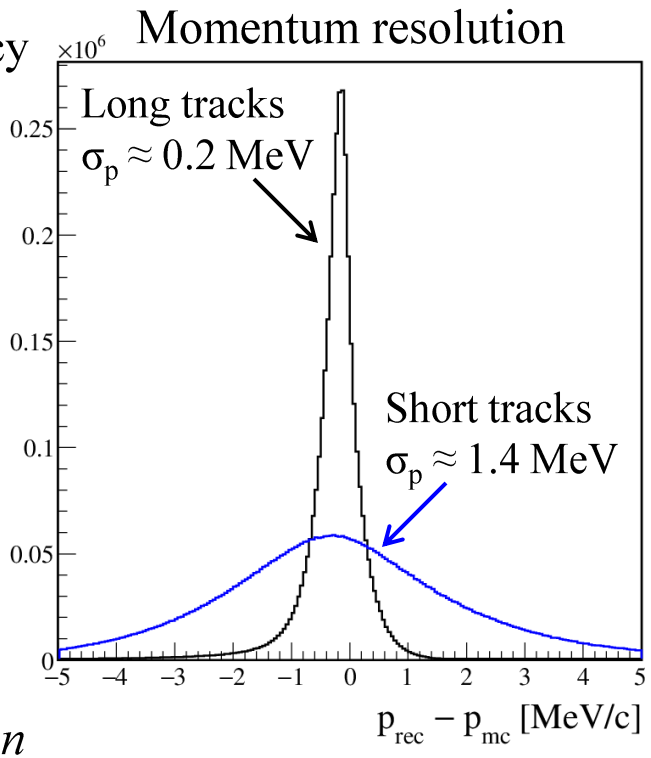




Summary

Mu3e experiment:
- Search for LFV $\mu^+ \rightarrow e^+e^+e^-$, Br < $10^{-15(16)}$
- Require good resolution (space, time) & efficiency
- Large data rates (fast online reconstruction)

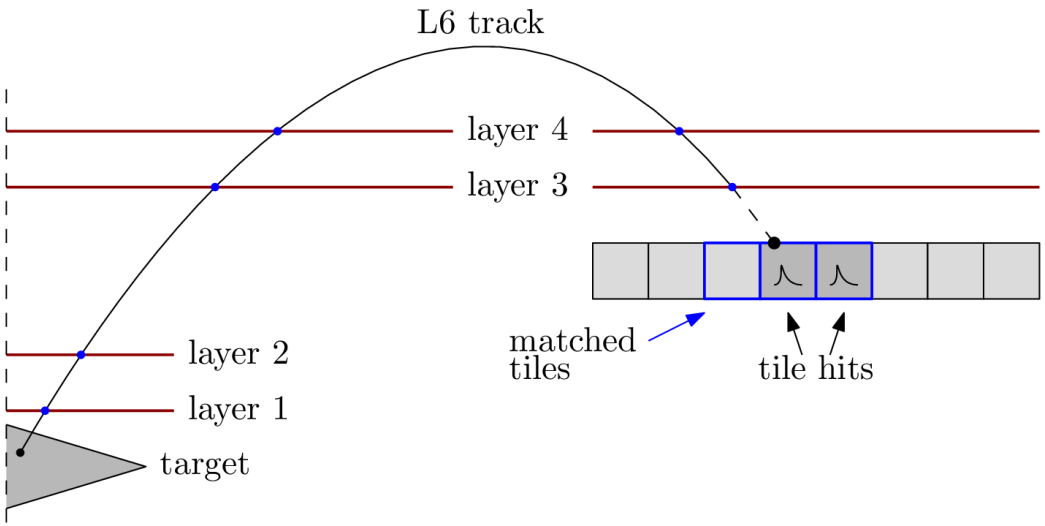
Reconstruction:
- Use triplet fit for track reconstruction
  - Fast, GPU filter farm
- Good performance:
  - Short tracks: $\sigma_p \approx 1.4$ MeV/c
  - Long tracks: $\sigma_p \approx 0.2$ MeV/c
  - Fibre and tile time information



See other talks:
- **T42.5** Dorothea vom Bruch – *GPU reconstruction*
- **T98.5** Uli Hartenstein – *Alignment*

Backup

Timing: tiles



Tile linking:

- Extrapolate track to tiles
- Lookup tile hits in 3×3 matrix
- Link L6 to tile hits:
  - 98.5% have assigned tile hit
  - 1.3% wrong assignment
  - $\sigma_t \approx 80$ ps

Time resolution