Track reconstruction for the Mu3e experiment

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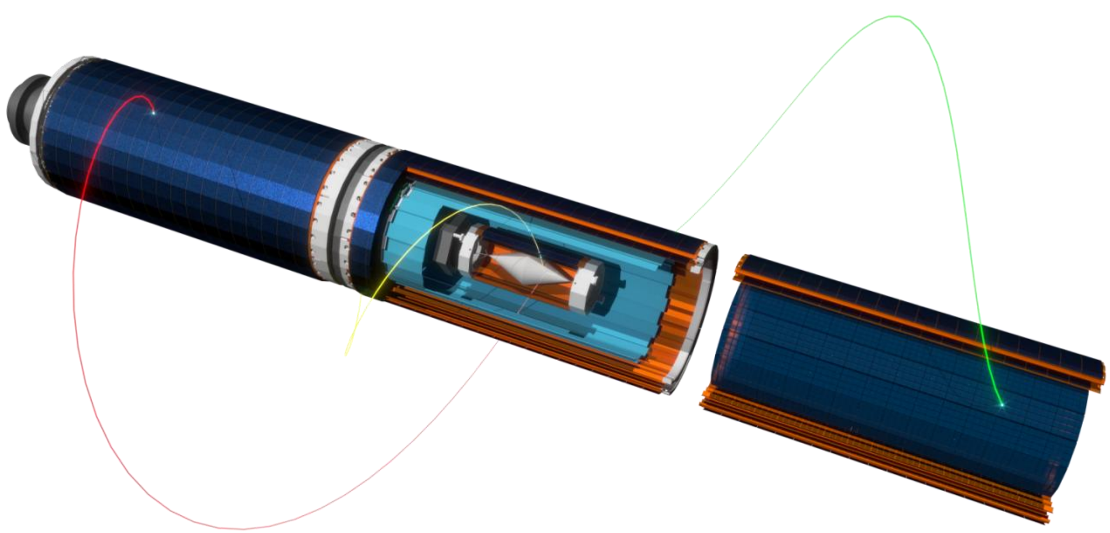
for the Mu3e collaboration

DPG 2018 @ Würzburg (.03.22, T85.1)



Mu3e Experiment

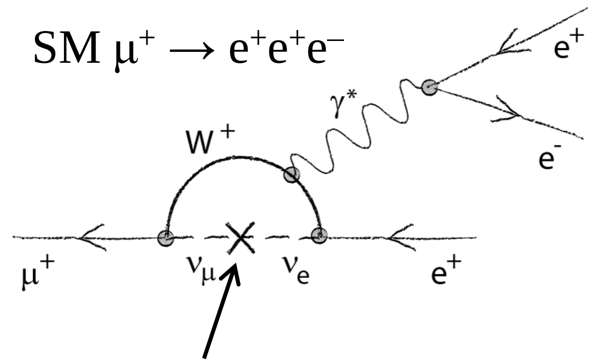
Mu3e Experiment:
- Search for **L**epton **F**lavor **V**iolation (LFV)
  - Decay: $\mu^+ \rightarrow e^+e^+e^-$
  - **S**tandard **M**odel: Br < 10^{-54} (unobservable)
  - Enhanced in **N**ew **P**hysics models:
    - SUSY, leptoquarks, etc.
  - *Any observed decay will point to NP*

- Location: Paul Scherrer Institute (PSI)
  - Commission in 2019, start in 2020

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

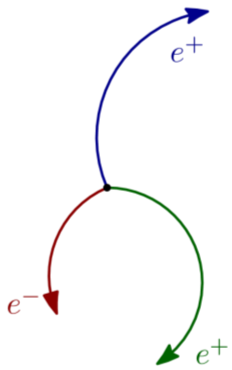
Mu3e aims for sensitivity of one in 10^{15} μ-decays
- Existing beam line: 10^8 μ/s
- With new beam line: one in 10^{16}

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



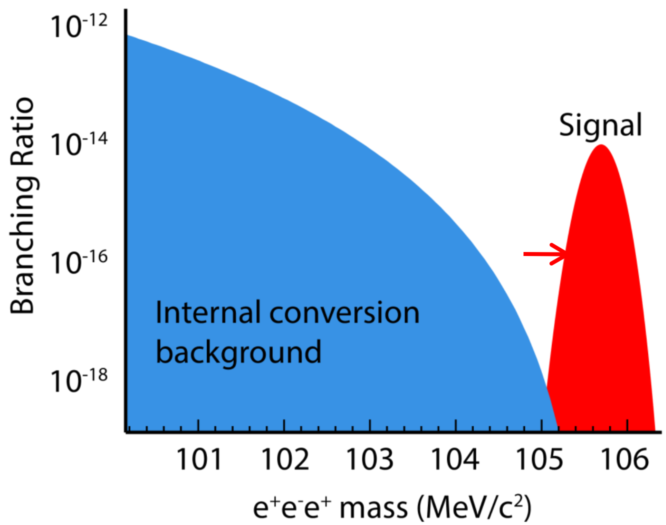
Neutrino mixing

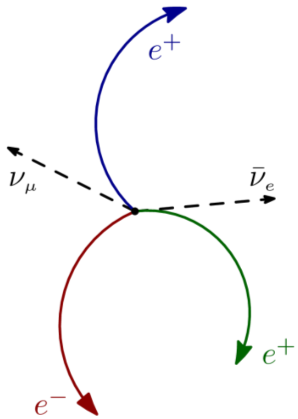
Signal



Signal: $\mu^+ \to e^+e^+e^-$
- Three tracks
- Decay at rest
  - Common vertex
  - Same time
  - $\sum \mathbf{p}_e = 0$
  - $\sum E_e = m_\mu$
  - $e^\pm$ energy < 53 MeV/c

Background:
- Random combinations:
  - $\mu^+ \to e^+ + 2\nu$
  - e^+/e^- scattering
  - Fake tracks
  - Not same vertex, time, etc.
  - Good vertex/time resolution
- Internal conversion:
  - $\mu^+ \to e^+e^+e^- + 2\nu$
  - Missing momentum & energy:
  - Need good momentum resolution

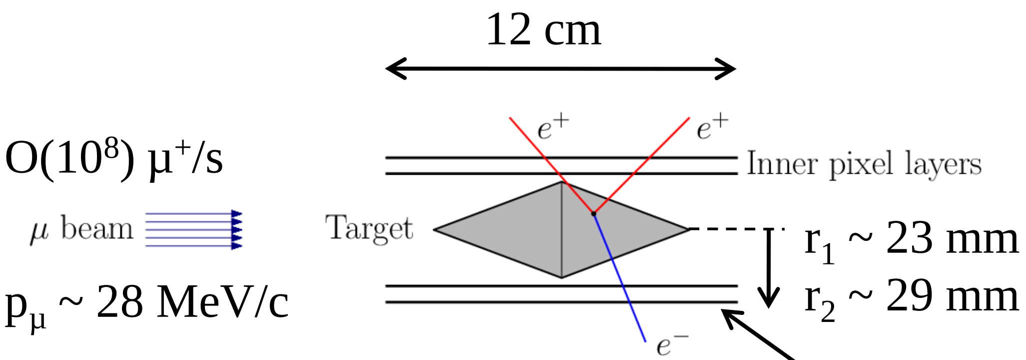


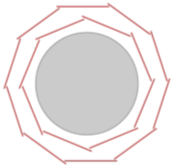


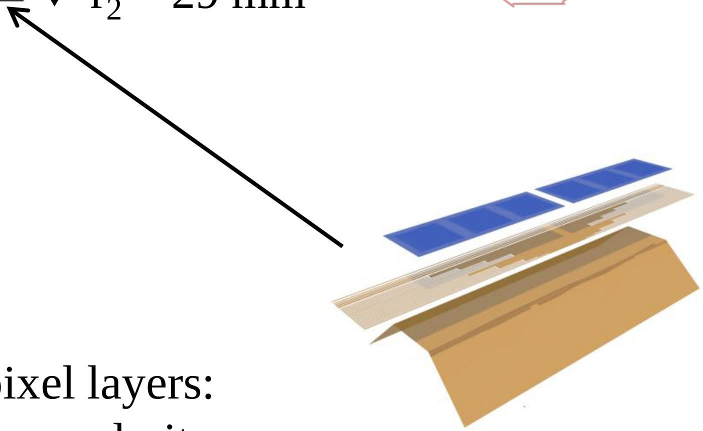
Mu3e Detector

He

B = 1 T







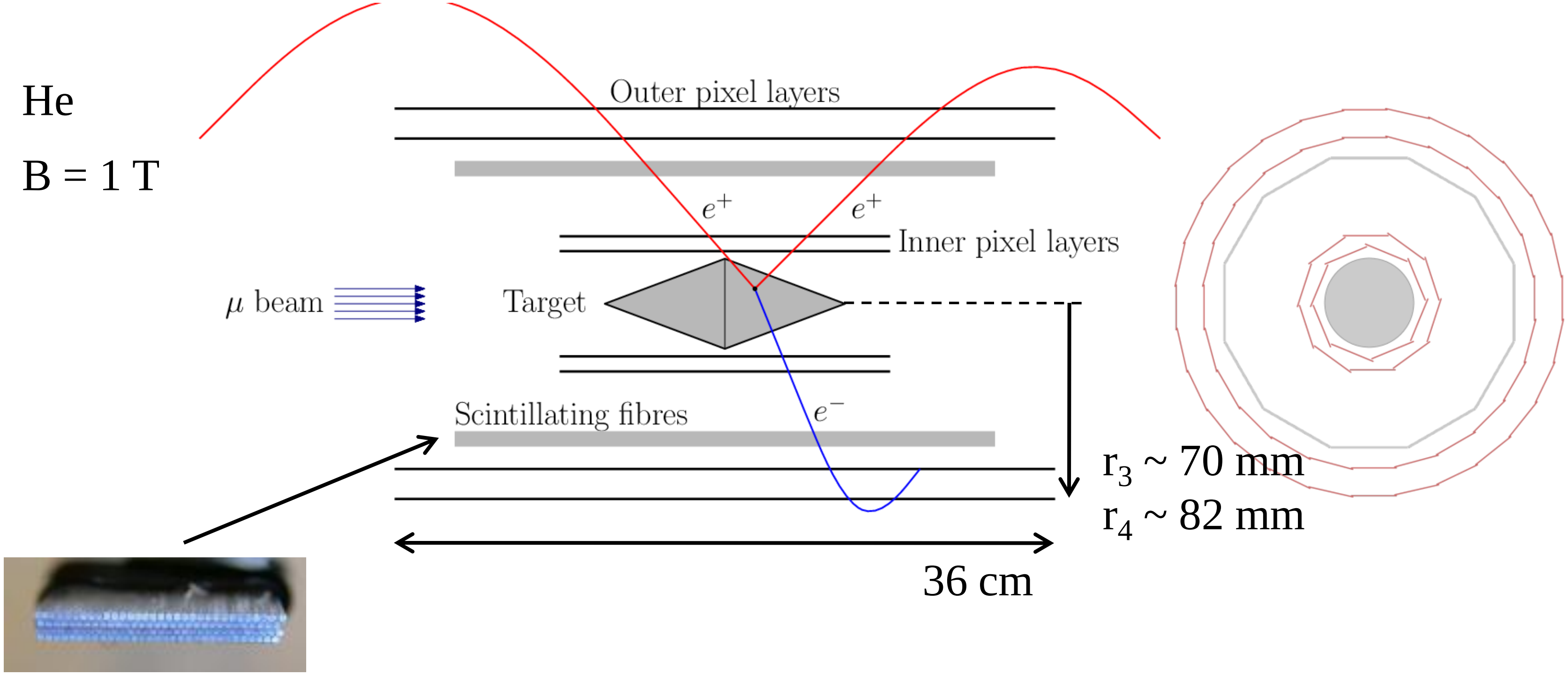
Muons stop and decay on target:

- Double cone hollow target
  - O(100) μm thickness
  - Vertex separation
- Existing beam line at PSI:
  - Continuous muon beam
  - O(10^8) μ^+/s

Inner pixel layers:

- High granularity
- Thin (to reduce MS) & efficient
  - Silicon pixel sensors (HV-MAPS)
- As close as possible to target
  - Pointing to vertex
  - Reduce effect of MS

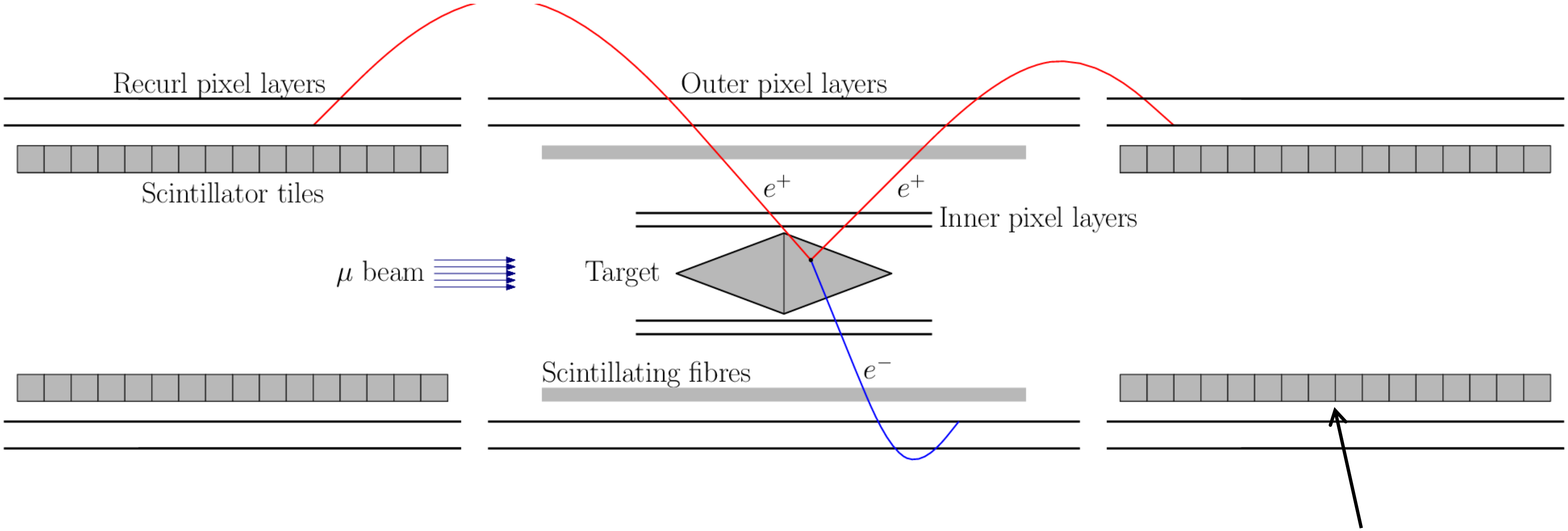
Mu3e Detector



Fibre detector:
- $\sigma_t < 1$ ns
- Suppress accidental BG
- Charge ID

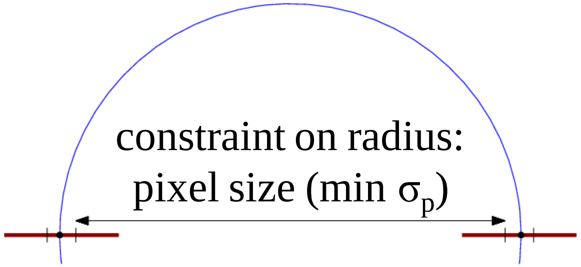
Two outer pixel layers:
- B = 1 Tesla
- Minimum $p_T \sim 12$ MeV/c
  - *Limited by outer layer radius*

Mu3e Detector



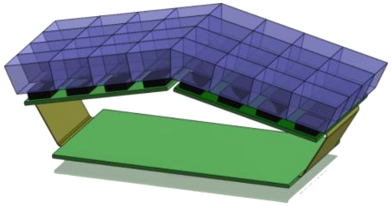
Particles (electrons) bend back in magnetic field:

- Use recurl stations to detect them
- Improve momentum resolution
  - Factor 5-10 improvement



Recurl stations:

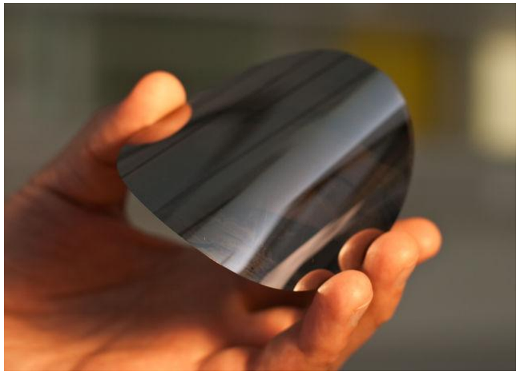
- Two pixel layers (same as central station)
- Tile detector
  - $\sigma_t < 100$ ps
  - Suppress accidentals



HV-MAPS

High Voltage – Monolithic Active Pixel Sensor:

- Commercially available technology
- Large area (2×2 cm^2)
- High granularity (pixel ~ 80×80 μm^2)
- Thin (~ 50 μm)
- Fast – charge collection via drift (HV, σ_t ~ 15ns)
- High efficiency (> 99%)



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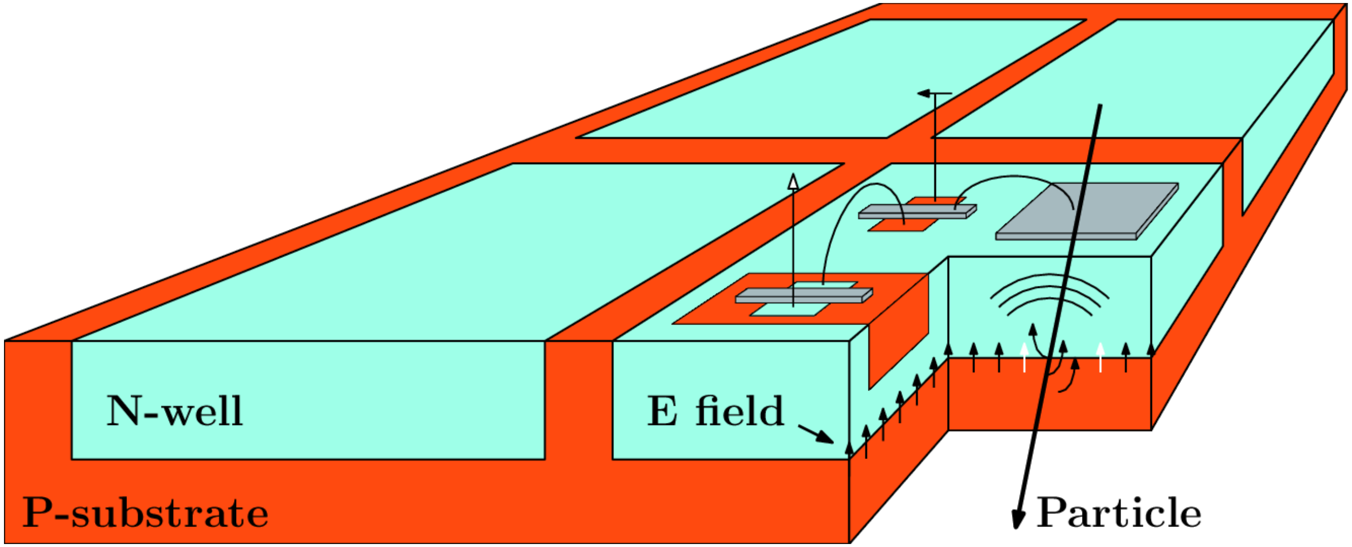
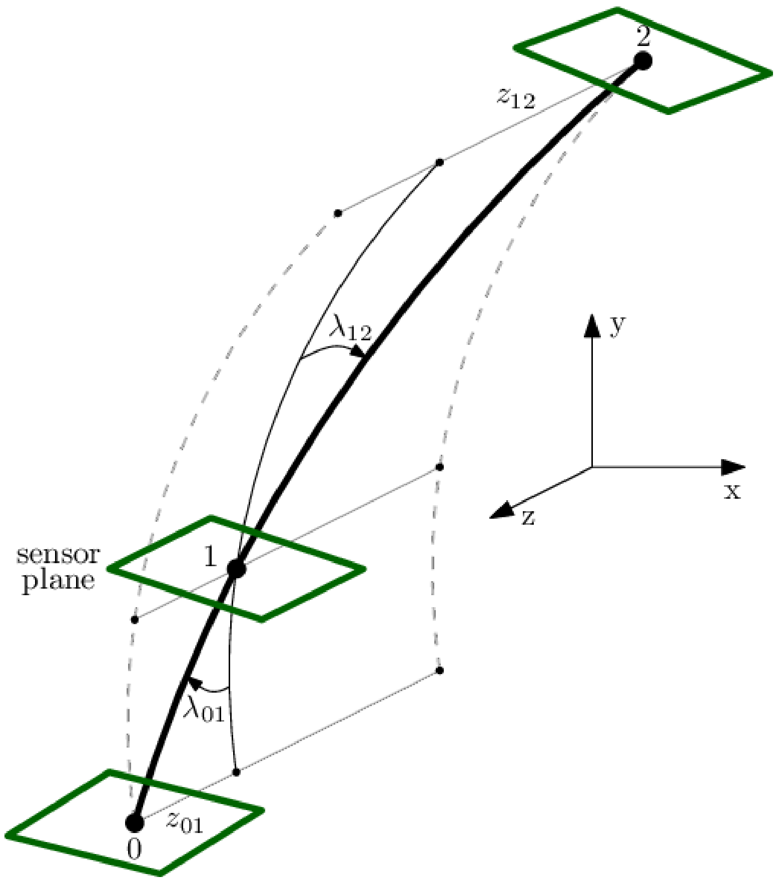


Triplet fit

- Track reconstruction in mag.field
  - Helical trajectory
  - Require minimum 3 hits

- Assuming no pixel uncertainty and no energy loss (Mu3e conditions):
  - One parameter to describe trajectory – curvature *r* (or momentum)
  - Triplet – trajectory with multiplet scattering (MS) in middle hit
  - MS angles are function of curvature – $\varphi_{ms}(r)$, $\lambda_{ms}(r)$

- Fit – minimize χ^2 (scattering angle):
  - $\chi^2 = \varphi^2_{ms}/\sigma^2_{ms,\varphi} + \lambda^2_{ms}/\sigma^2_{ms,\lambda}$
  - No analytical solution
  - Small MS angles → linearization around known solution (circle in xy-plane)



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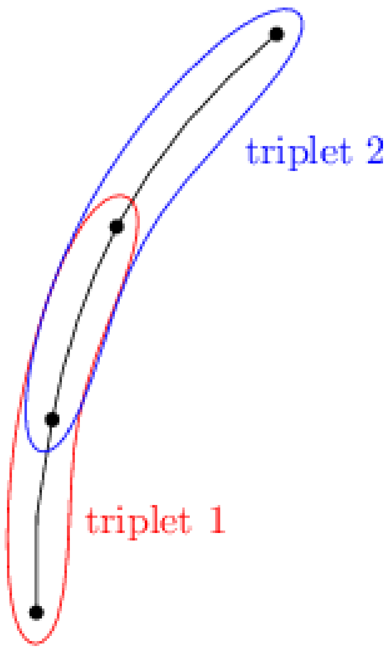
Track fit

Track/Segment:

- Sequence of triplets
- 3D radius:
  - Minimize combined χ^2
  - Simple solution: $r = \frac{\sum r_i/\sigma_i^2}{1/\sigma_i^2}$

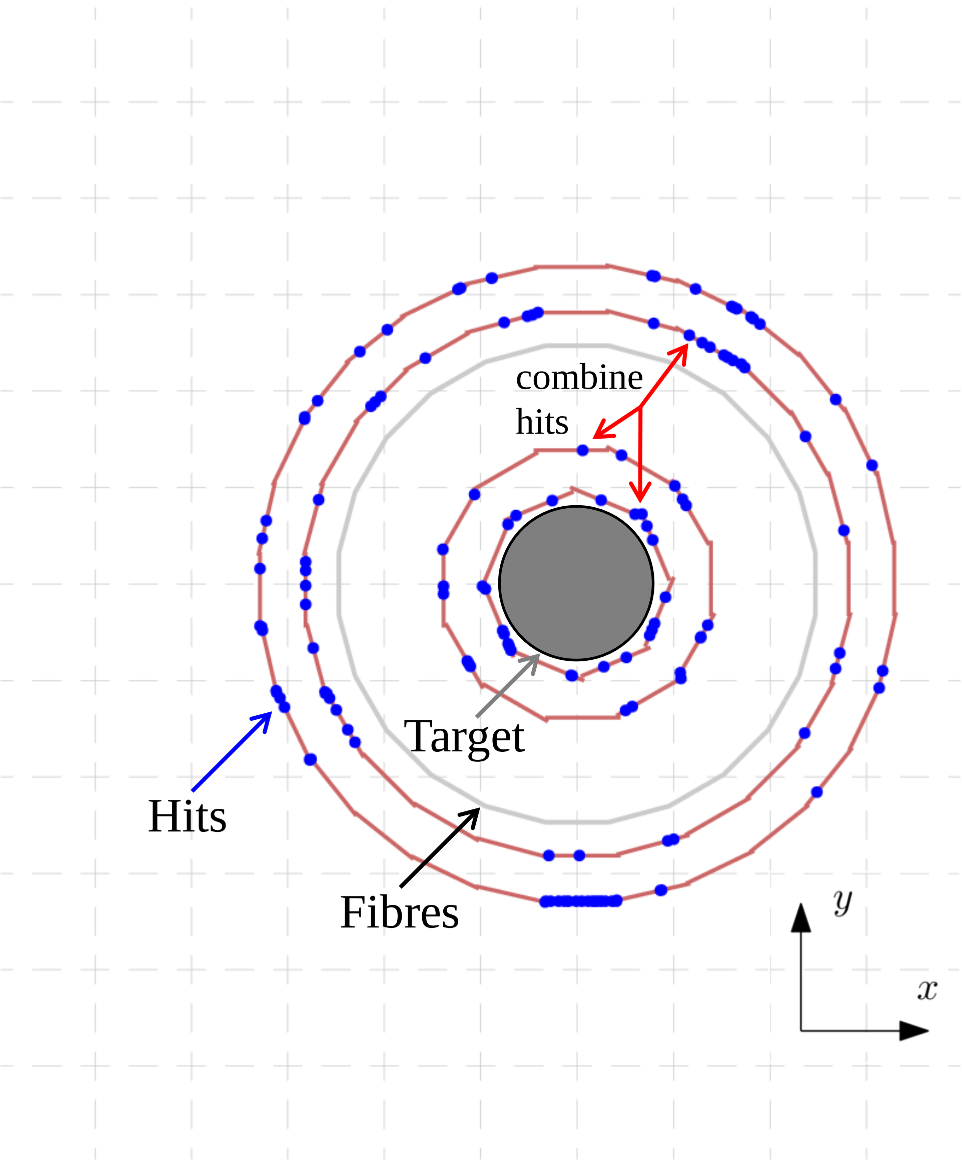
  where r_i – individual triplet solutions
  (*weighted average*)



Note:

- Theoretically individual triplets can be fitted in parallel and then combined.
- In practice start from seed triplet and then add more hits.

Triplets



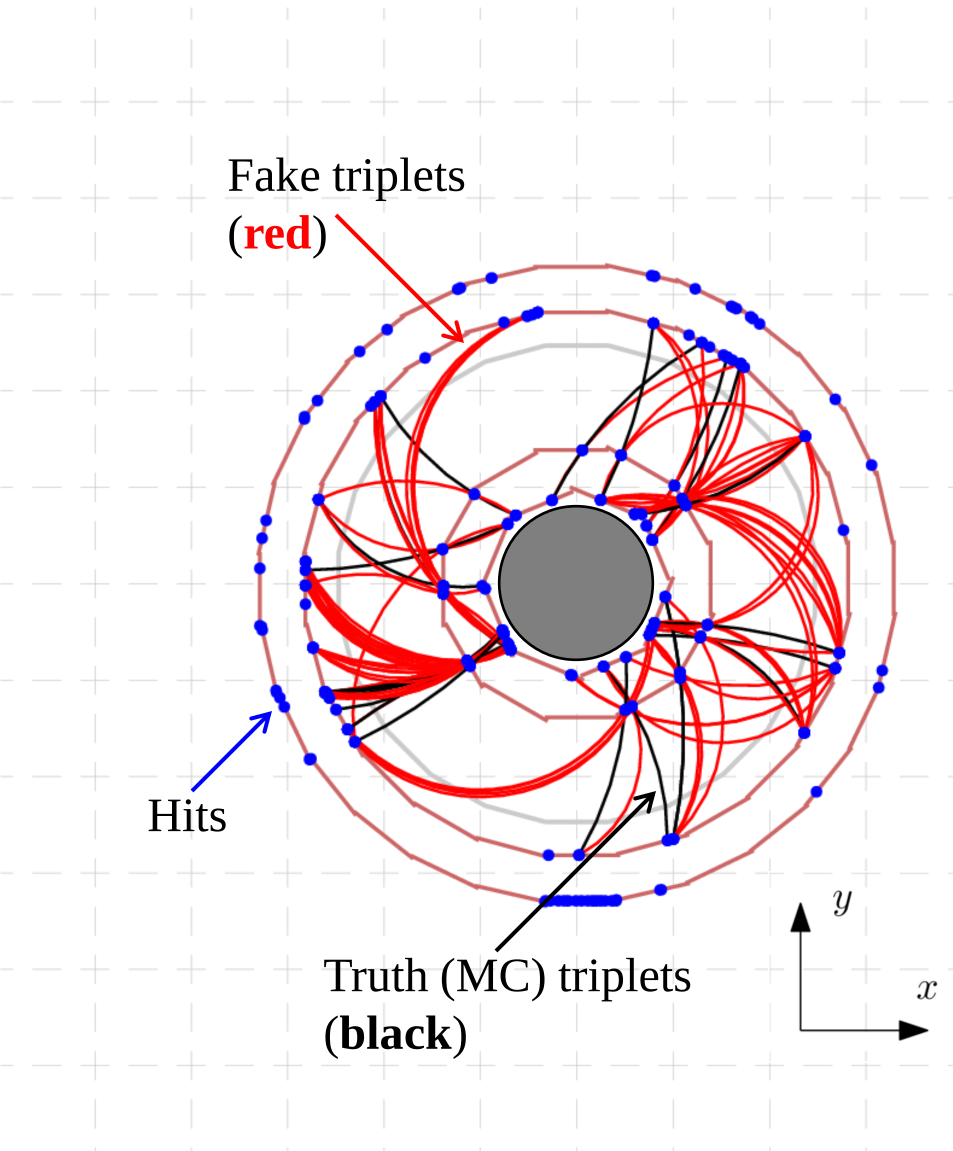
Make triplets:

- Combine hits of first 3 layers

- n – number of hits per layer
  - Difficulty: O(n^3) combinations
- 10 hits per layer in 50 ns
  - O(1K) combinations per frame
  - 10^{11} per second – large

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

Triplets



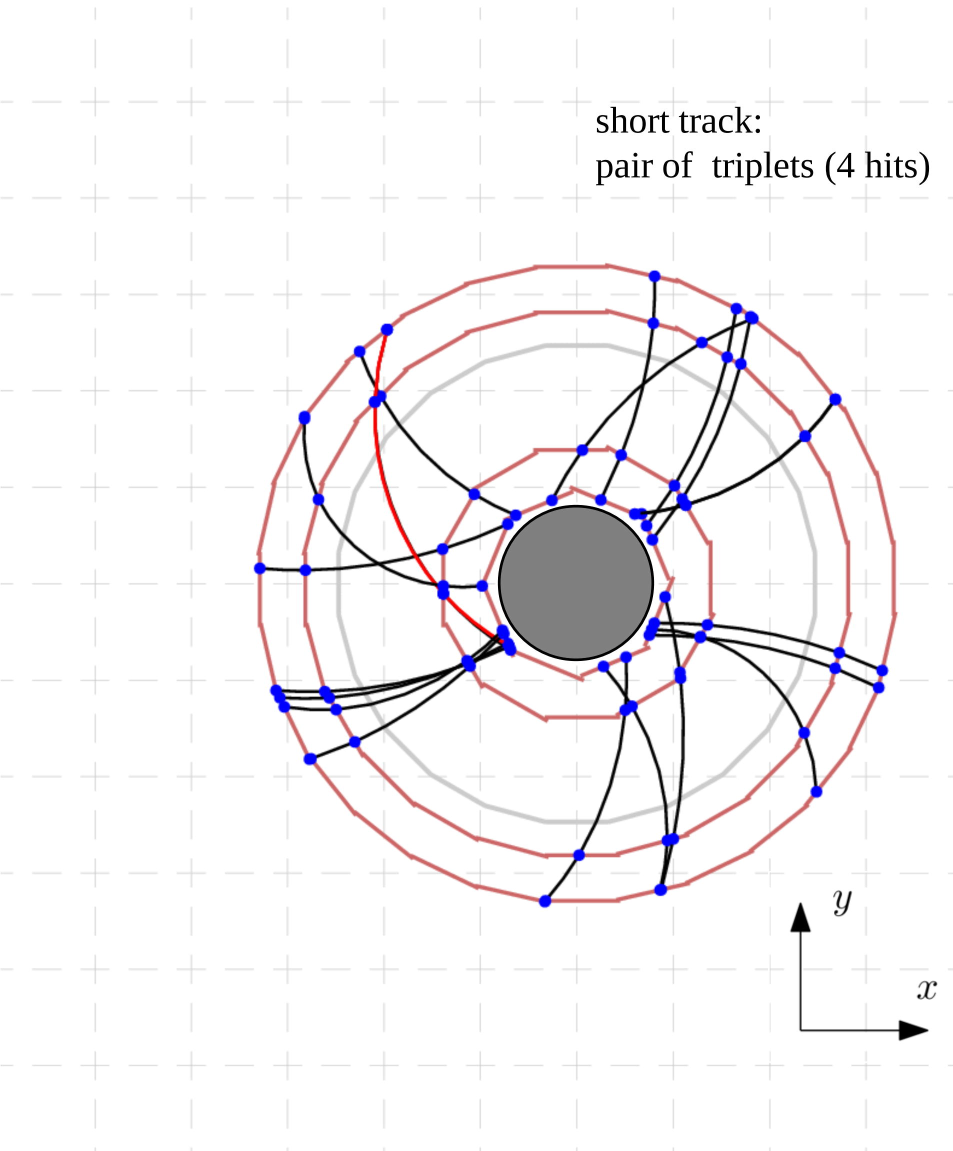
Selections:

- Geometrical
    - Distance between hits, opening angles, etc.
    - Factor 50 reduction in number of fitted combinations

- 10^9 fits per second
    - GPU filter farm
- Reduce background: triplet χ^2
    - Cut on MS angles

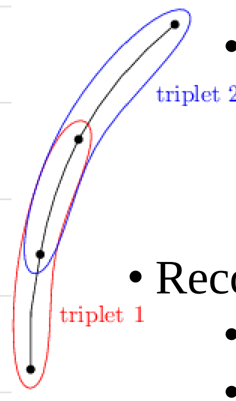
- Fake rate (fake combinations per one truth track) ~ 4
    - 10 truth triplets & 40 fakes

Short tracks



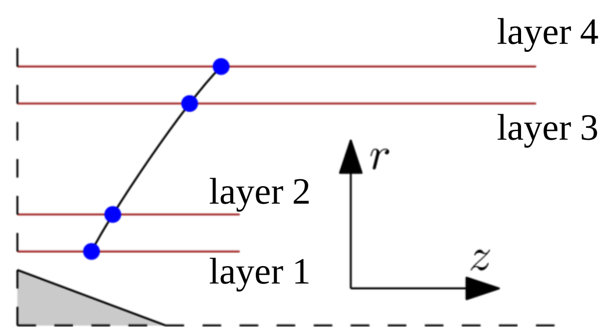
Make short tracks:

- Use triplets as seeds
  - Estimate hit at last layer
  - Lookup in φ/z window

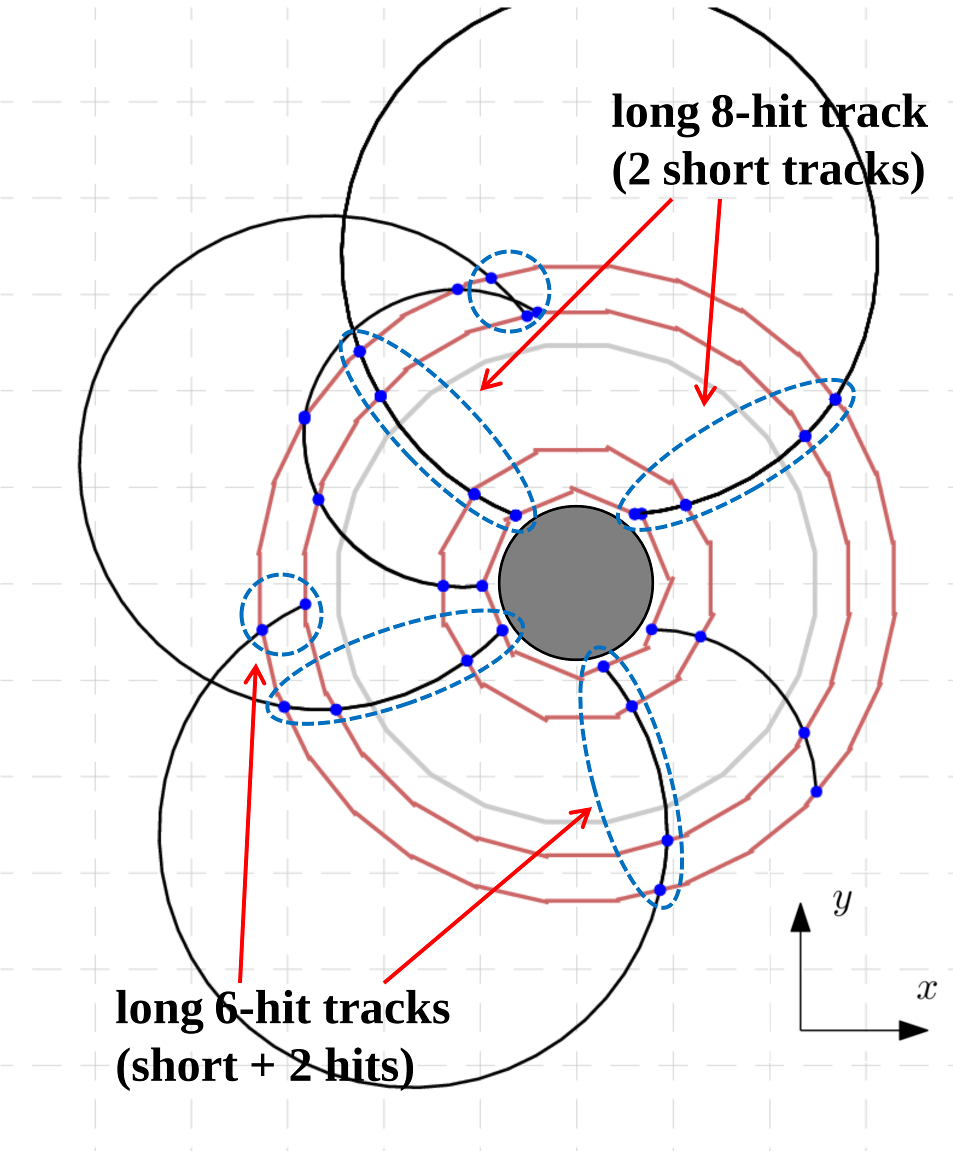


- Combine 4 hits (triplet + hit)
  - 2 triplets (2 shared hits)
  - Fit (weighted average)

- Reconstruction frame (50 ns):
  - O(10) short tracks
  - Fake rate ~ 1.9%

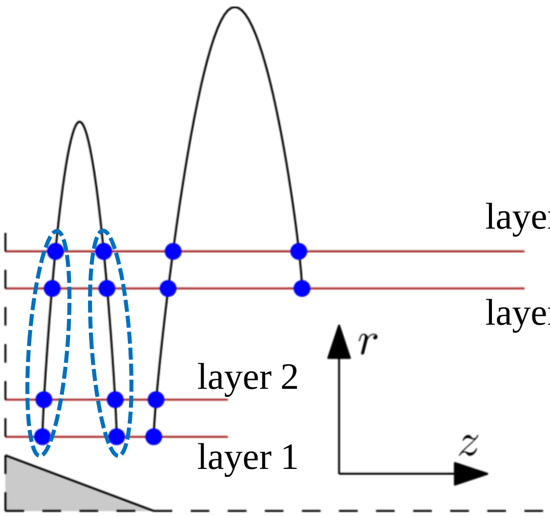


Long 8-hit tracks



Long (6- and 8- hit) tracks:

- Combine short track and pair of hits or two short tracks:
- Fake rate ~ 10-30%
  - 1% **true** random combinations
  - Rest – hits from same tracks, different **turns**
- Fibre hits (one per short segment)
  - Reject wrong combinations
  - Charge ID



Acceptance & Efficiency

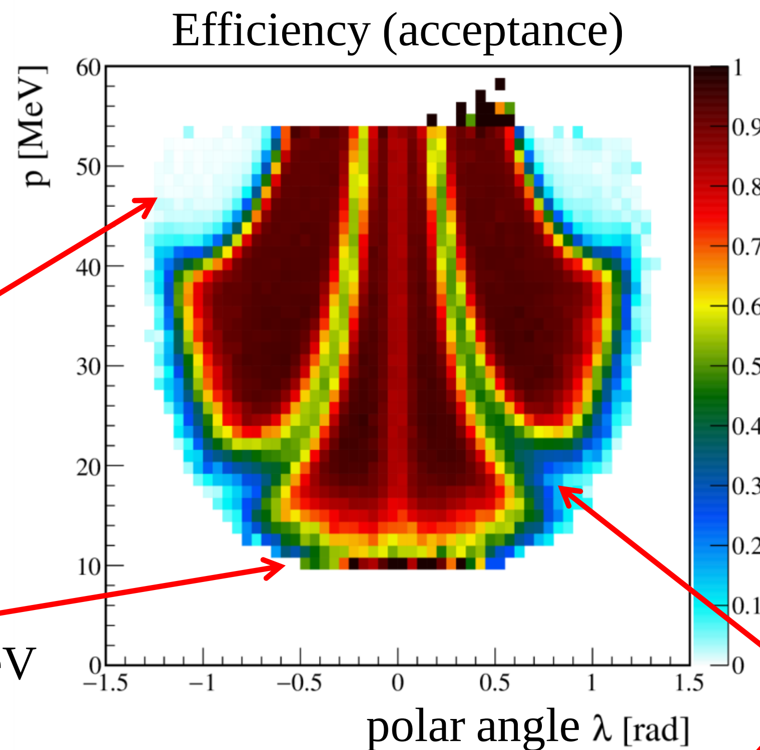
- Full Geant4 simulation of Mu3e detector
  - 50 ns event (frame)
- Decay: $\mu^+ \rightarrow e^+\upsilon\upsilon$, 10^8 stopped muons per second
  - ~ 5 decays within frame

- Acceptance (geometry):
  - Require minimum 4 hits (1 per layer)
  - p_T – inner/outer layer radius
  - polar angle (λ) – length of detector
  - acceptance ~ 80%

Reconstruction efficiency:

- Short tracks ~ 95%
  - Geometrical cuts and χ^2 cuts
- Long tracks
  - Used for signal reconstruction – vertex fit, etc.
  - 80% of short tracks are reconstructed as long

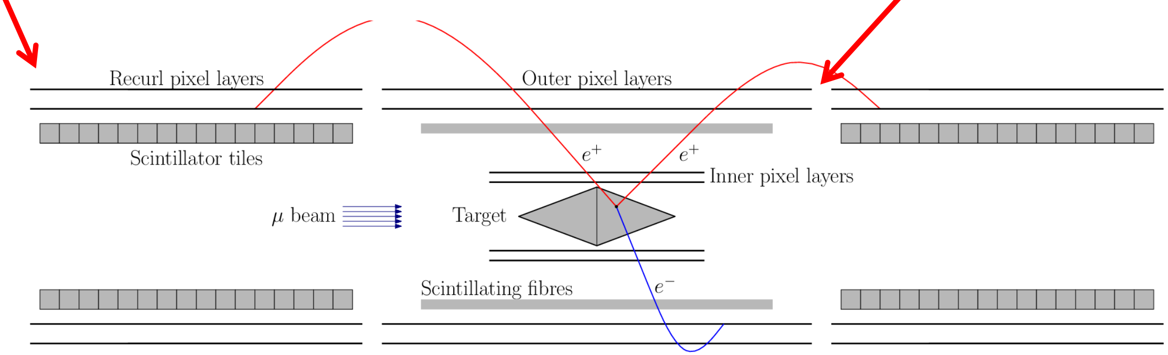
Long tracks reconstruction efficiency



Ends of recurl stations

min p_T ~ 10 MeV

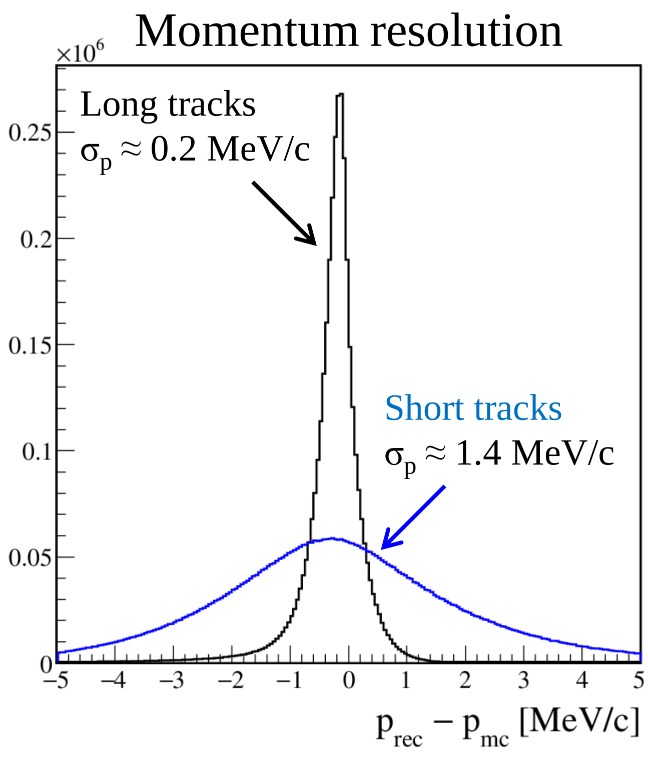
Service areas between stations

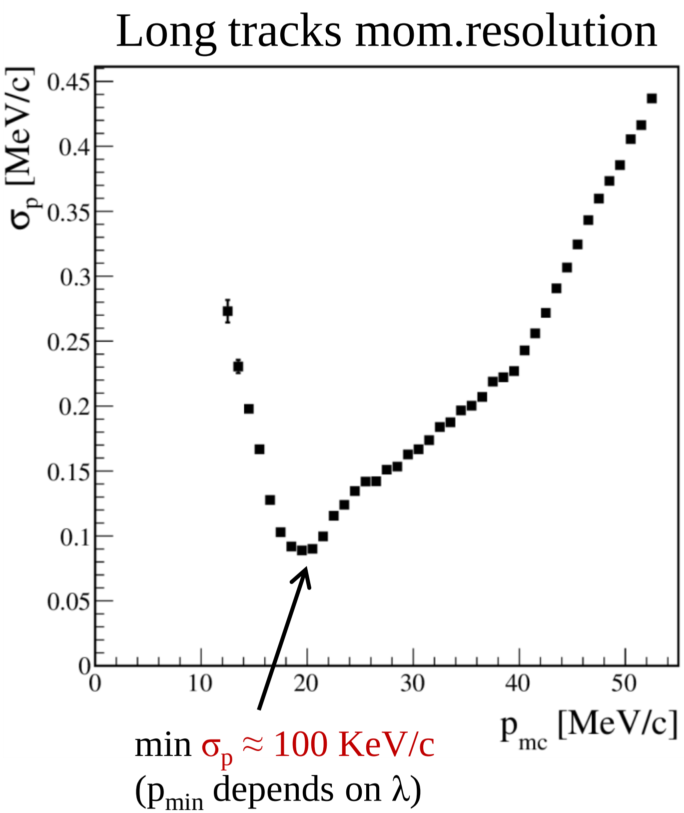


Momentum resolution

Short tracks (4 hits)
- $<\sigma_p> \approx$ 1.4 MeV/c
- Depends linearly on momentum

Long tracks (6 and 8 hits)
- $<\sigma_p> \approx$ **0.2 MeV/c**
- **min** $\sigma_p \approx$ 100 KeV/c

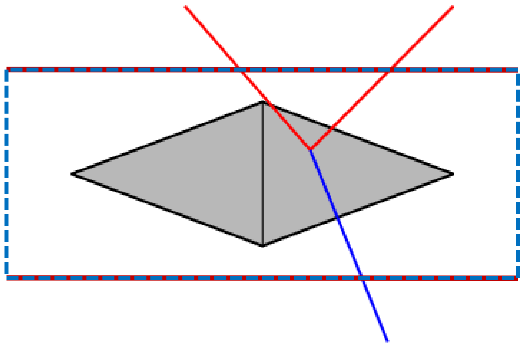


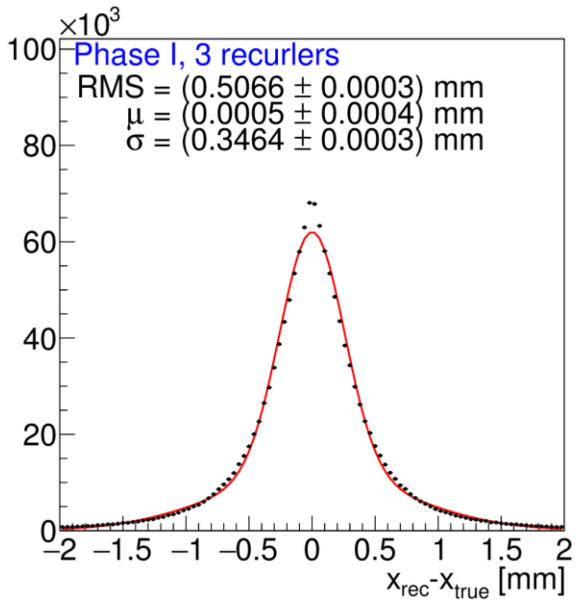


Vertex fit

Signal – 3 tracks ($e^+e^+e^-$):

- Long (recurl) tracks and/or short tracks
- MS in first layer
- Pixel size & energy loss
- Energy loss in target





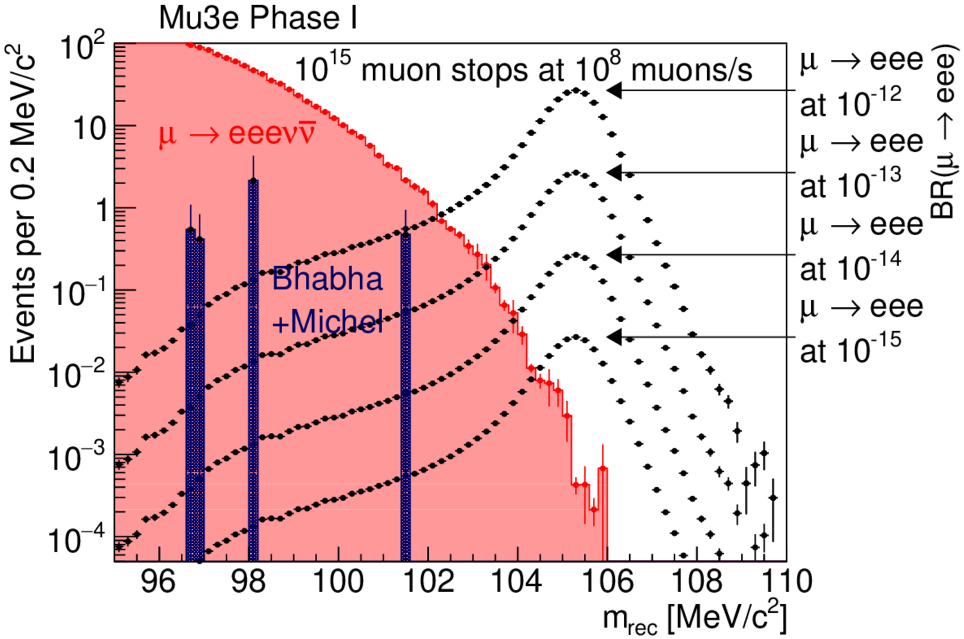
Vertex:

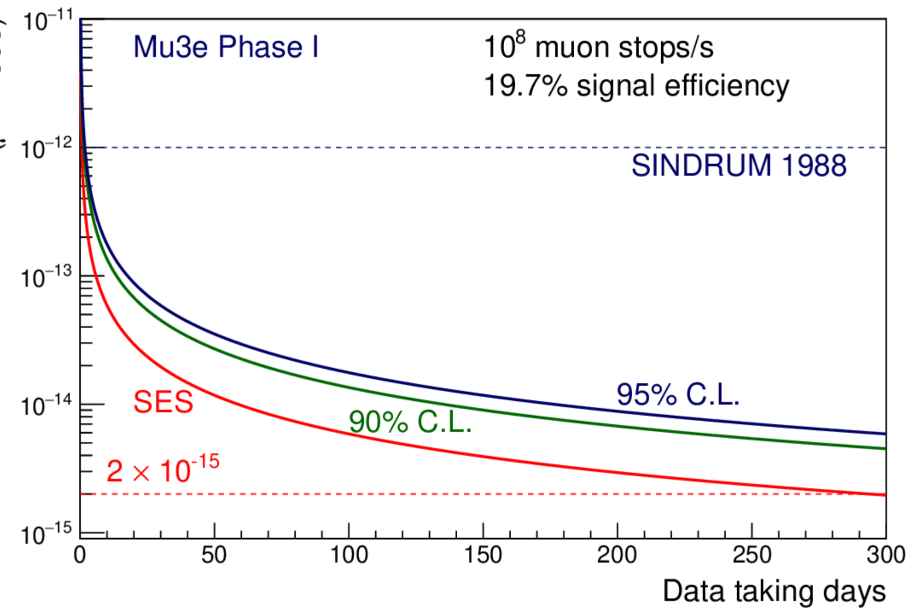
- Constrained to target area
    - Or target surface
- Material (first layer & **target**):
    - Scattering, pixel size, energy loss
- Same time at vertex (fibres and/or tiles)
- Vertex resolution:
    - σ_z = 230 μm (*limited by MS*)
    - $\sigma_{x,y}$ = 350 μm (MS + σ_p)

Signal sensitivity

Phase I detector:

- Main background:
  - Radiative decay (momentum resolution)
  - Bhabha + Michel (vertex resolution)
- Sensitivity:
  - 10^{15} muon stops, one year of data taking
  - Br ~ $5 \cdot 10^{-15}$ at 95 c.l.





Summary

Mu3e experiment:
- Search for LFV $\mu^+ \rightarrow e^+e^+e^-$, Br < $10^{-15(16)}$

Reconstruction:
- Use triplet fit for track reconstruction
  - Fast, will be used offline and online (GPU filter farm)
  - Good performance

- Require good momentum, space and time resolution & efficiency
  - Short tracks: $\langle\sigma_p\rangle \approx 1.4$ MeV/c
  - Long tracks: $\langle\sigma_p\rangle \approx 0.2$ MeV/c
  - Fibre and tile time information
- Already meet/exceed Phase I requirements.

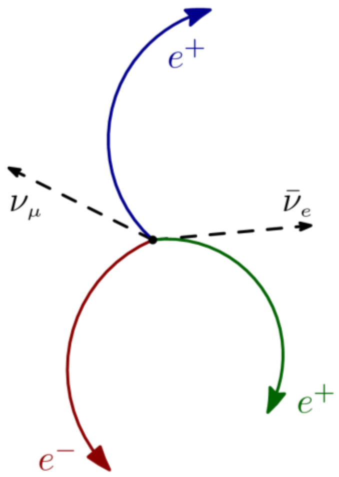
Backup

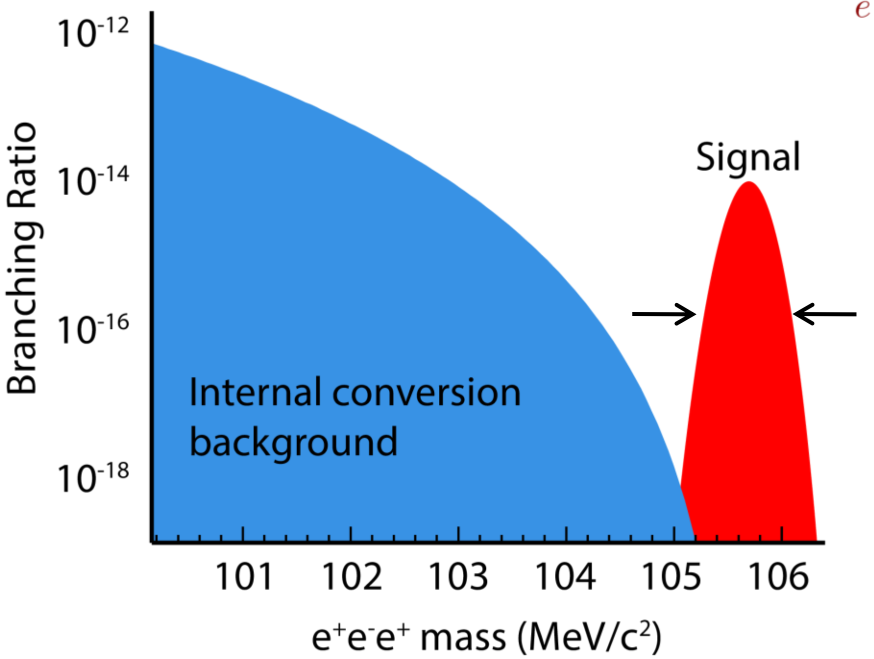
Backgrounds

Internal conversion:

- $\mu^+ \rightarrow e^+e^+e^- + 2\nu$

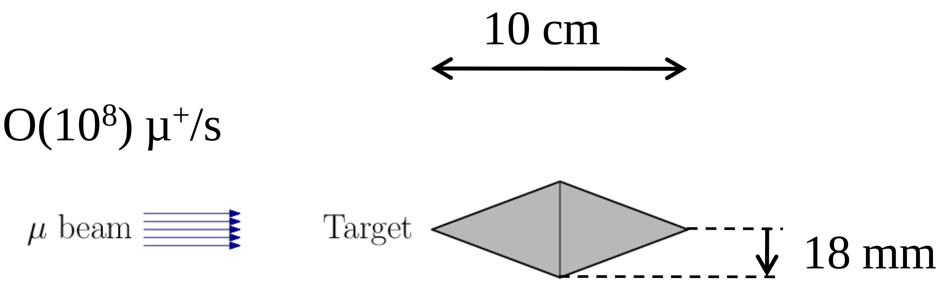
- Missing momentum & energy:
    - $\sum \mathbf{p}_e \neq 0$
    - $\sum E_e \neq m_\mu$
    - Need good momentum resolution





Mu3e Detector

O(10^8) μ^+/s



p_μ ~ 28 MeV/c

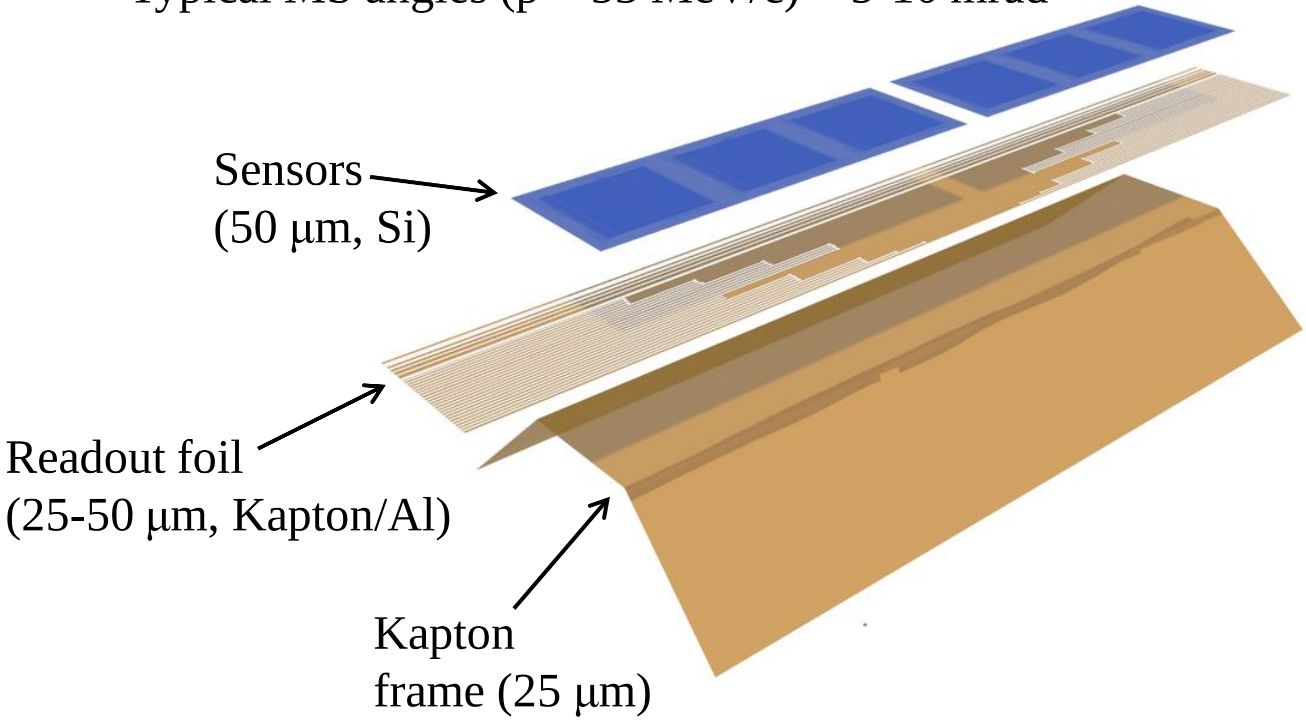
Muons stop and decay at rest on target:

- Existing beam line at PSI:
  - Continuous muon beam
  - O(10^8) μ^+/s

- Double cone hollow target
  - Vertex separation in space
  - 36 mm diameter (to cover beam x-section)
  - O(100) μm thickness

Pixel layers

- Mu3e pixel layers:
  - 2844 sensors (area ~ 1 m^2)
  - sensor size 2x2 cm^2
  - pixel size 80x80 μm^2
- 50 μm thick ~ $0.5 \cdot 10^{-3}\ X_0$
  - Total thickness (with support) ~ $1.1 \cdot 10^{-3}\ X_0$
  - Typical MS angles (p < 53 MeV/c) ~ 5-10 mrad

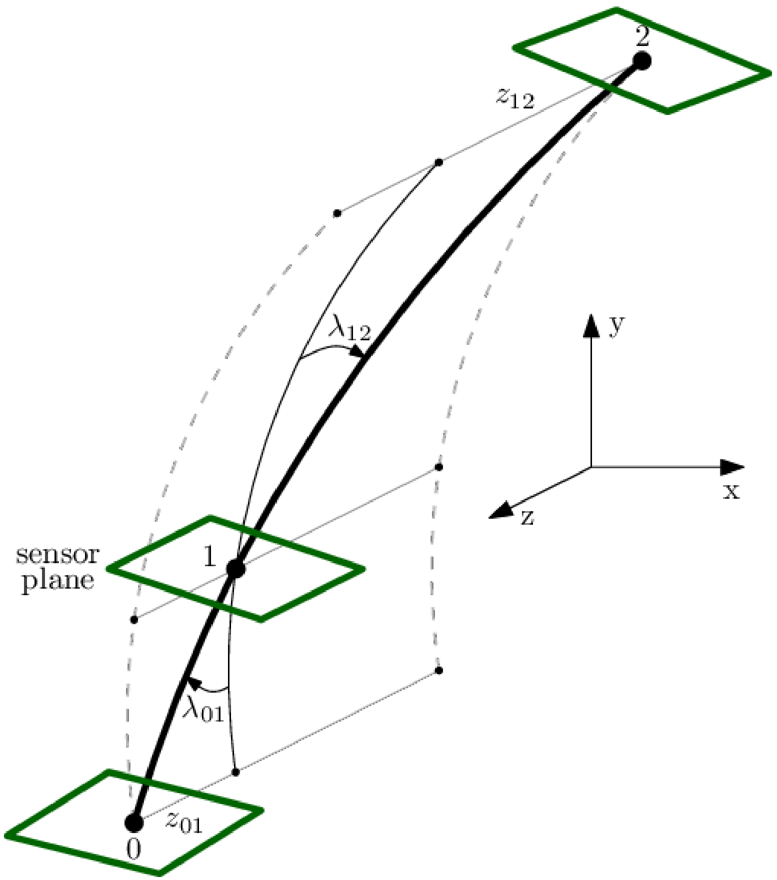


Triplet fit

- "Minimum" track in mag.field
  - **Three** measurements or hits (i.e. in 3 sensor layers)
  - Or **two** helices
- Helix trajectory defined by:
  - Pair of hits (at the end of this helix)
  - And curvature *r* (or momentum)

Triplet:

- No hit uncertainty & MS at middle hit
- No energy loss ($r = r_1 = r_2$)
  - MS angles: $\varphi_{ms}(r)$, $\lambda_{ms}(r)$
- Fit – minimize χ^2 (scattering angle):
  - $\chi^2 = \varphi^2_{ms}/\sigma^2_{ms,\varphi} + \lambda^2_{ms}/\sigma^2_{ms,\lambda}$
  - There is no analytical solution
  - Assume small MS angles
  - Start from "circular" solution in xy-plane and linearize



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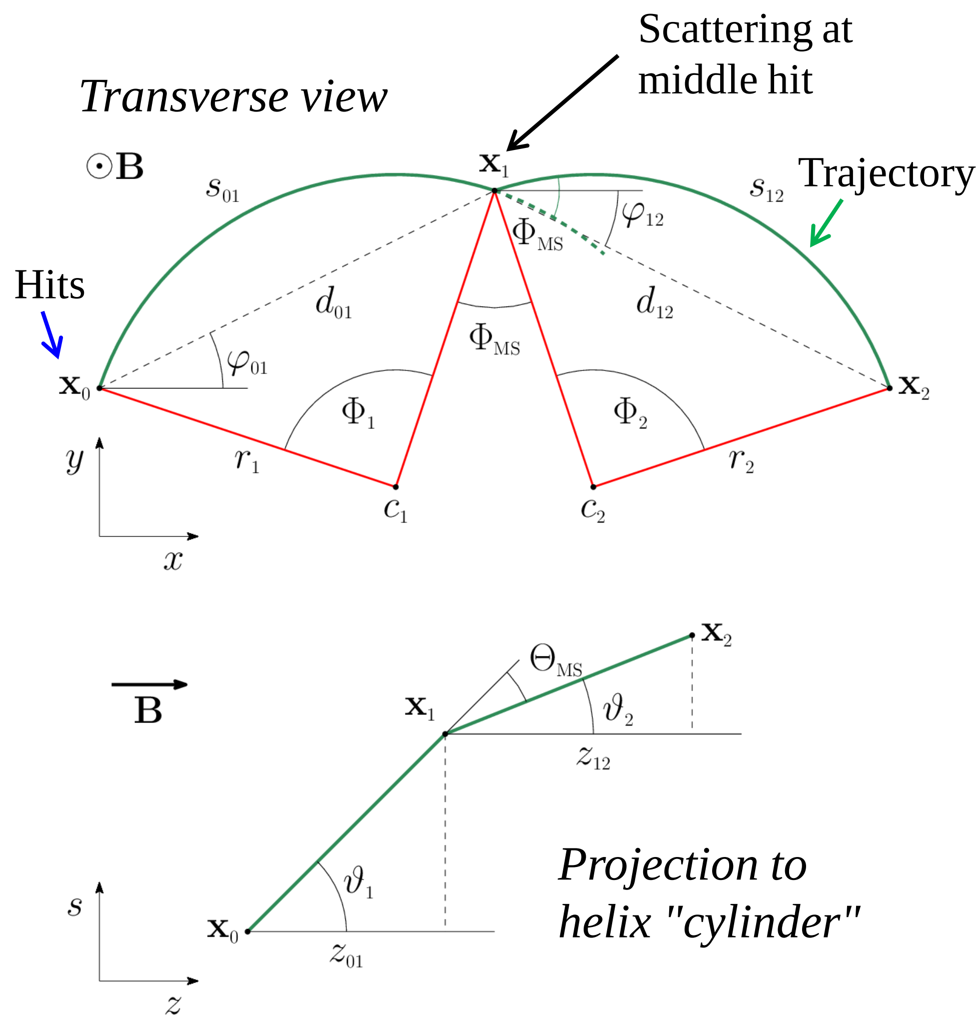
Triplet fit

- No energy loss ($r = r_1 = r_2$)
- No hit position uncertainty
- Consider only MS at middle hit

Triplet:

- 3 hits (3D points) form triplet
  - Combination of 2 helices
- Fully defined by radius r
  - MS angles: $\varphi_{ms}(r)$, $\lambda_{ms}(r)$

- Minimize χ^2 (scattering angle):
  - $\chi^2 = \varphi^2_{ms}/\sigma^2_{ms,\varphi} + \lambda^2_{ms}/\sigma^2_{ms,\lambda}$
  - There is no analytical solution
  - Assume small MS angles
  - Start from known "circular" trajectory in xy-plane
  - Linearization



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Triplet vs Karimäki vs GBL

- Fit performance depends on tracker geometry.
- Mu3e case:
    - Triplet fit has similar performance as **G**eneral **B**roken **L**ines fit
    - Fast, suitable for filter farm (trigger)

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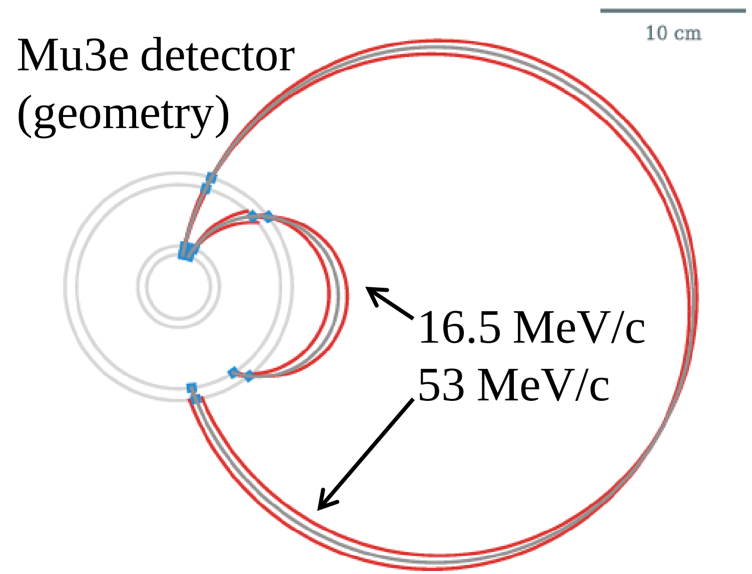
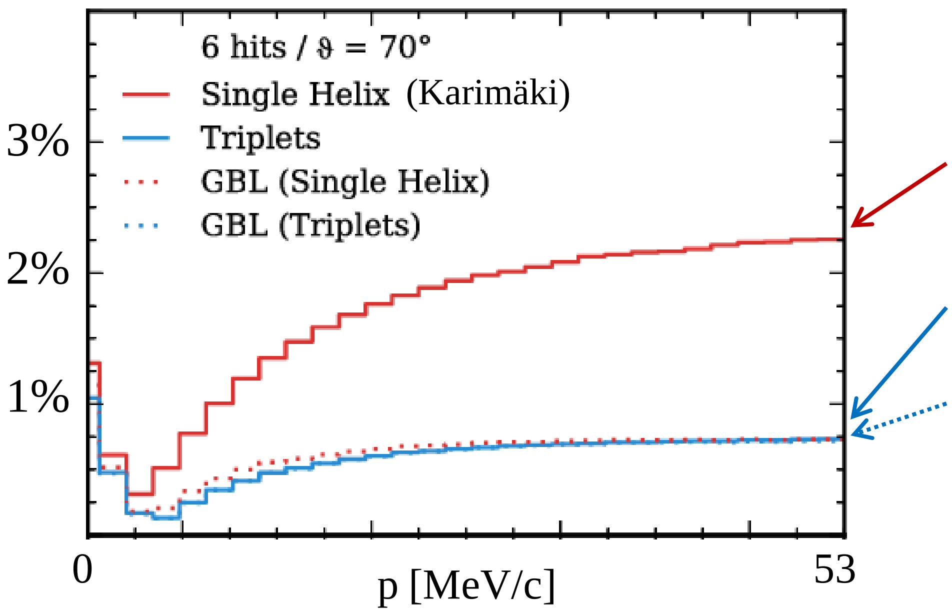


Relative momentum resolution



Single Helix (Karimäki)
- Neglect MS

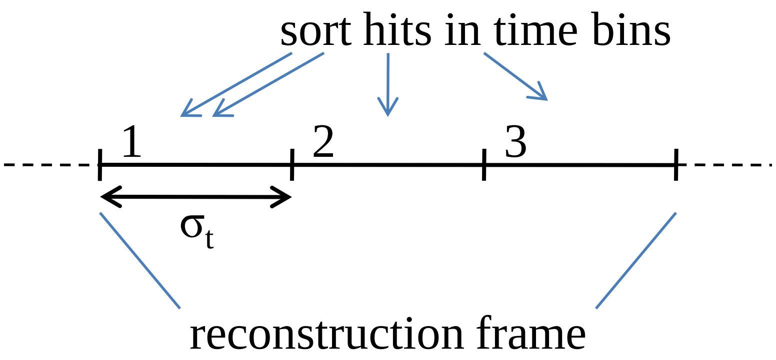
Triplets
- MS fit

GBL (**G**eneral **B**roken **L**ines)
- Fast global track **refit** with full covariance matrix
- Equivalent to Kalman filter

Mu3e track reconstruction

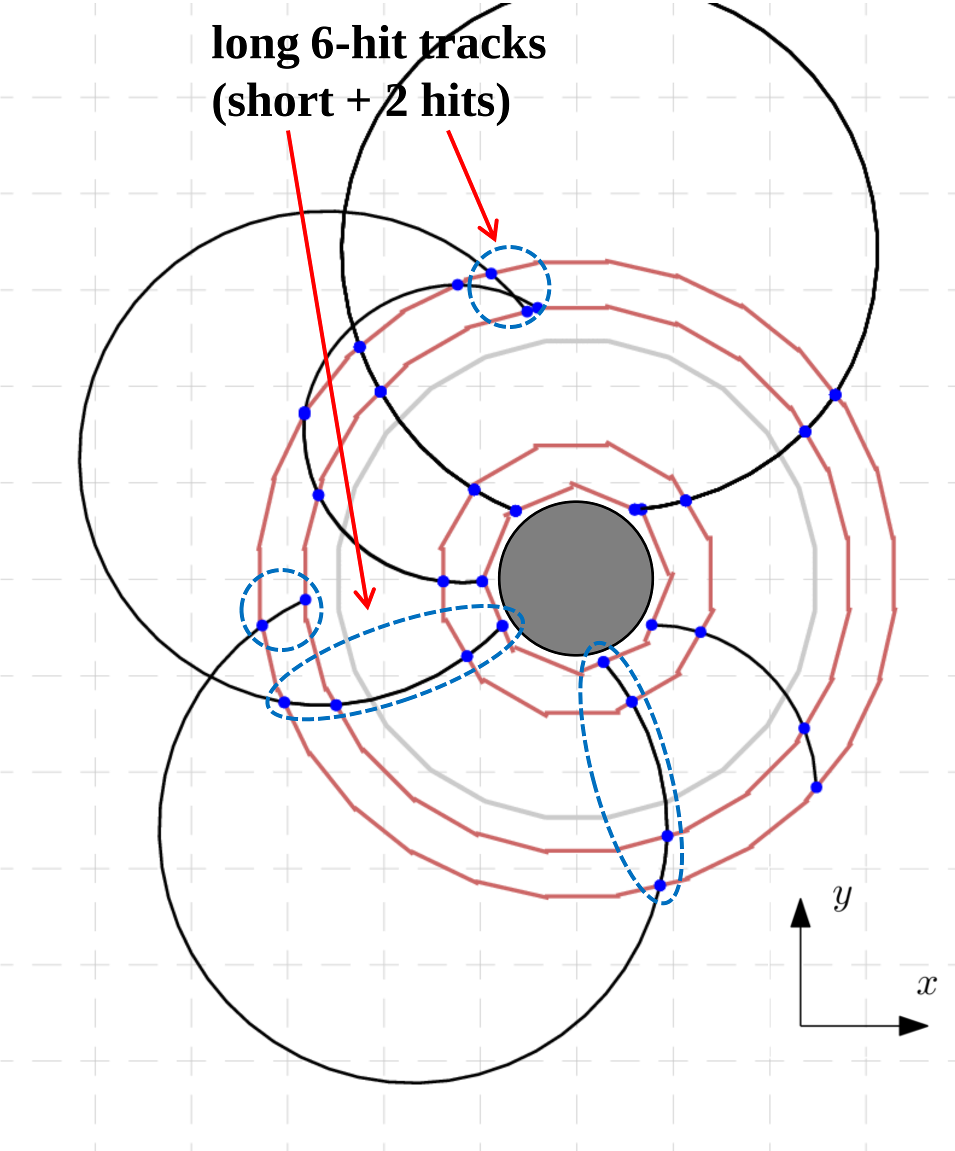
- Track reconstruction is based on triplets
  - Fast and similar performance to GBL (Mu3e environment)
  - The same algorithm will be used offline and online
  - Offline implementation also takes into account pixel size and energy loss (minor fitter change)

- Mu3e readout is essentially continuous:
  - Frame data by combining hits with same (close) timestamps from different system (pixels, fibres, tiles)
  - Reconstruction "frame" of $3 \cdot \sigma_t$



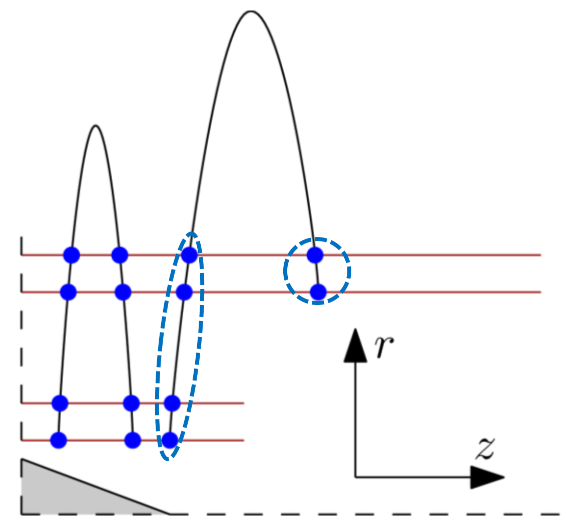
Tracking performance:
- Geant4 simulation of Mu3e detector
- 50 ns reconstruction frame
- 10^8 muon stops, Michel decay

Long 6-hit tracks



Long 6-hit tracks:

- Short track + 2 hits
- Fake rate ~ 9%
    - 1% – random combinations
- Fibre and/or tile hits
    - Reject wrong combinations

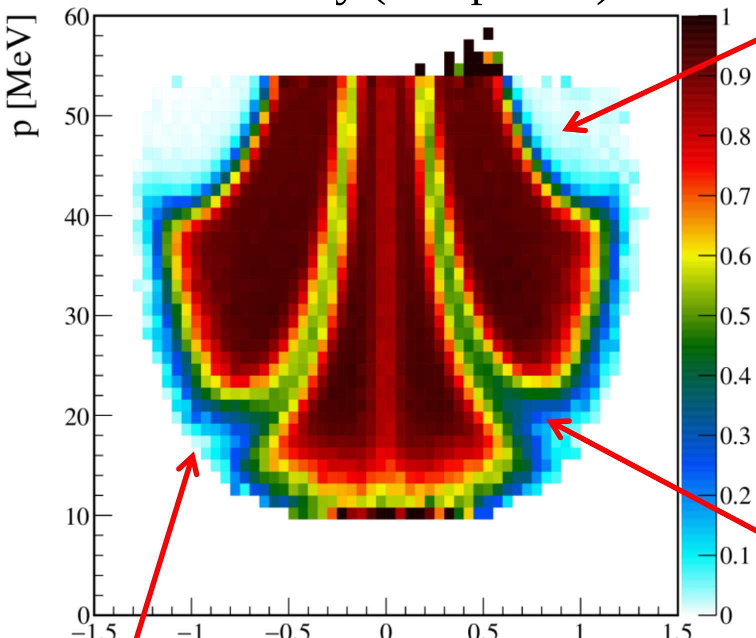


Acceptance & Efficiency

Short tracks (4 hits)
- Geometrical acceptance: 80%
- Reconstruction efficiency: 95%
  - Geometrical cuts and χ^2 cuts

Long tracks (6 and 8 hits)
- 80% of short reconstructed as long
  - Geometry (service areas, etc.)
  - χ^2 cuts

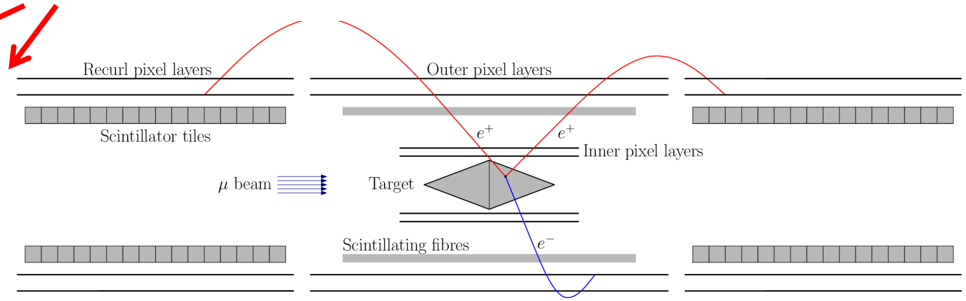
Efficiency (acceptance)



polar angle λ [rad]

p_T acceptance (outer layer radius)

Ends of recurl stations

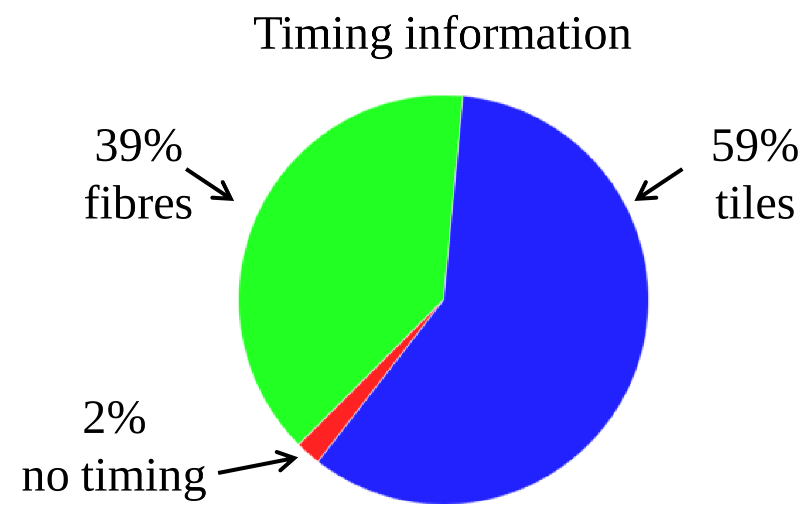


Service areas between stations

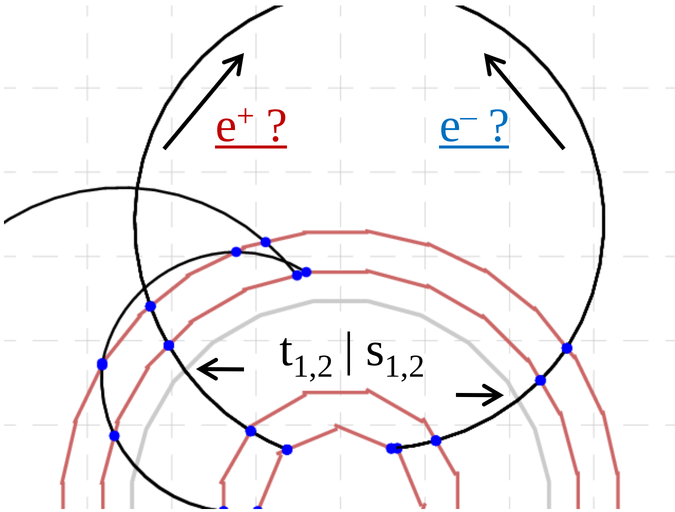
Timing

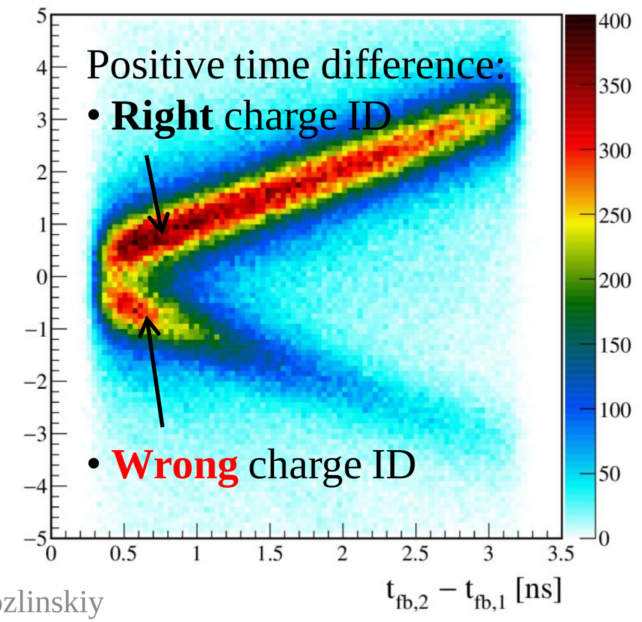
Time information from fibres/tiles:
- Suppress fakes
- Additional vertex constraint
  - Same time at vertex for all tracks

- Charge ID: e^+ or e^-
  - Mainly for long 8-hit tracks
  - Fibre time difference vs path length



Ambiguity for central 8-hit tracks





Charge ID

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