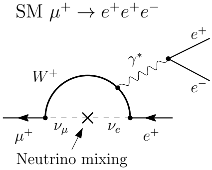
Track reconstruction for the Mu3e experiment

DPG Dresden

T 127.5 2023-03-23 @ WIL/C129 15:50-16:05

Alexandr Kozlinskiy (JGU Mainz, Institut für Kernphysik)

Mu3e Experiment



Search for charged Lepton Flavor Violation

- Through a decay $\mu^+ \to e^+e^+e^-$
- Allowed in the Standard Model but not observable (Br $< 10^{-54}$)
- *Any observation will point to New Physics*

Current experimental status:

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

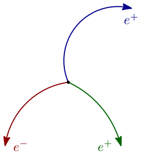
Mu3e aims for sensitivity of $2 \cdot 10^{-15}$ (Phase 1)

- Under construction at Paul Scherrer Institute using existing beam line (πE5, $10^8 \mu/\mathrm{s}$)
- Further improve to 10^{-16} (Phase 2) with new beam line (HIMB)

Signal

Signal ($\mu \to 3e$):

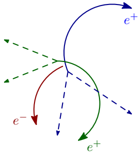
- Decay at rest to two positrons and one electron
  - Common vertex & time
  - Invariant mass: $M_{e^+e^+e^-} = m_\mu$
  - Total (missing) momentum: $\sum \mathbf{p}_e = 0$
- Require good momentum, vertex and time resolution
- Tracks with maximum momentum of 53 MeV/c
  - Large Multiple Scattering (MS) $\to$ minimize material budget



Background sources

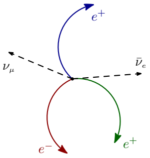
1st - random combinations:

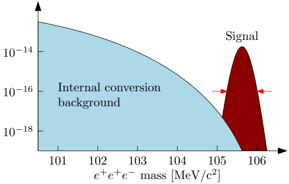
- Overlap of several $\mu^+ \to e^+ + 2\nu$ and/or $e^\pm$ scattering
- Contribution from *fake* tracks
- Signature: not same vertex, time, etc.

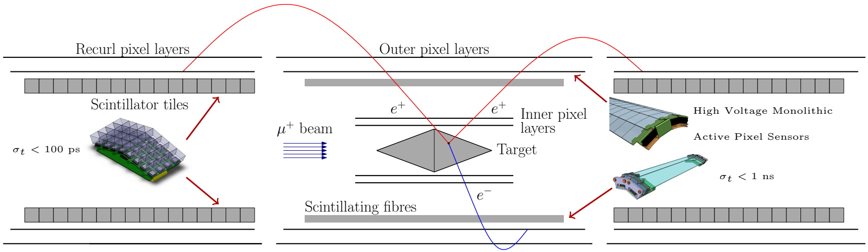


2nd - internal conversion:

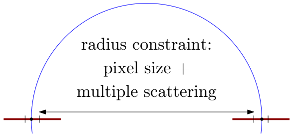
- $\mu^+ \to e^+ e^+ e^- + 2\nu$
- Signature: missing momentum & energy



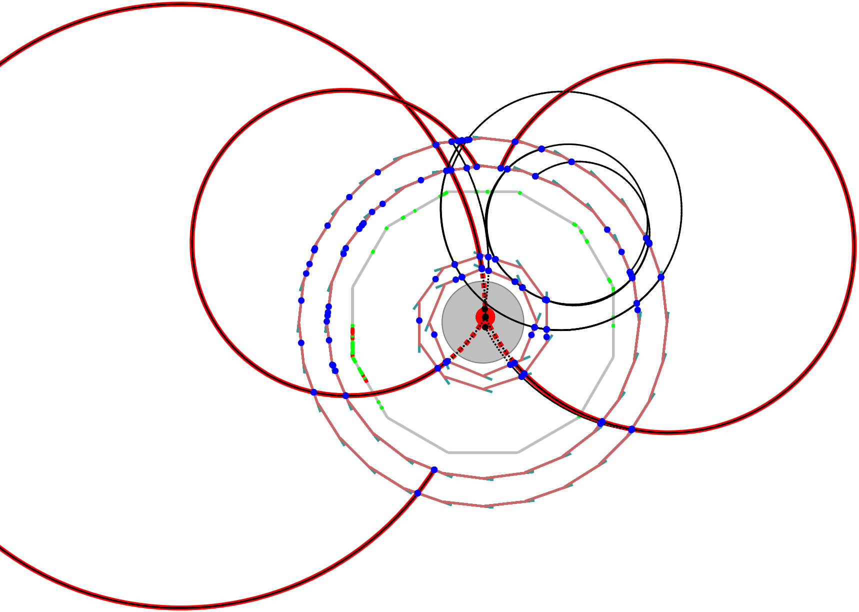




- Muons stop on target and decay at rest
- 4 pixel layers provide hits for track reconstruction
- Particles bend back in magnetic field and measured again, improving momentum resolution

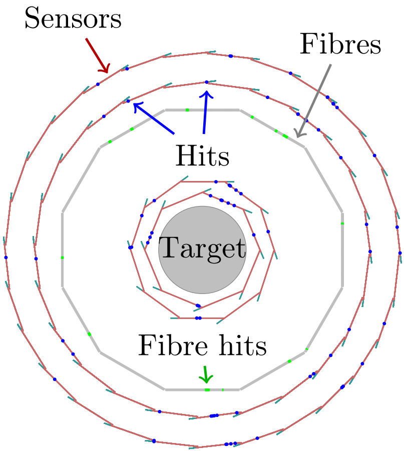


- Two recurl stations to improve acceptance for such particles



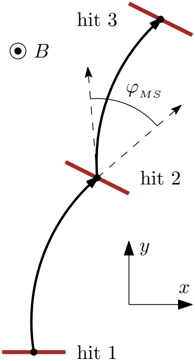
$10^8 \mu$/s stop and decay on target

- Hit rate of 10^9 per second + fibre and & tile hits
- Continuous readout: use time slices of 64 ns as events
- 10-20 hits per layer per event
  $\rightarrow O(10^3)$ track fits per event
  $\rightarrow 10^{10}$ track fits each second
- Need fast and efficient track reconstruction



Transverse view (xy-plane)

Triplet fit



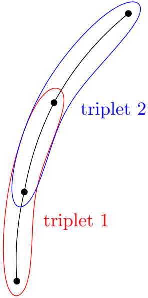
NIM A844(2017)135

Track in magnetic field:

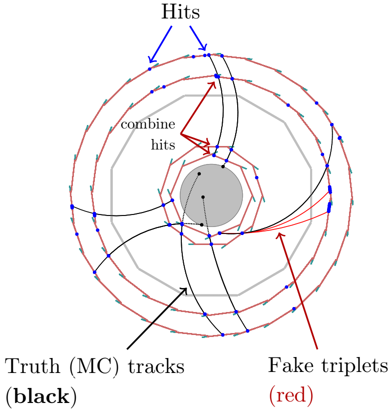
- Described by helical trajectory
- Minimum 3 hits to reconstruct track (triplet)
- Multiple Scattering (MS) in middle point
- One parameter: 3D curvature
  $\rightarrow$ fit: minimize MS

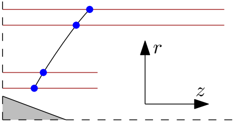
Track ($n_{hit} \geq 4$):

- Sequence of triplets
- Minimize combined χ^2
  $\rightarrow$ weighted average of individual triplets



Reconstruction: from triplets to short tracks





Longitudinal view

Triplet (3 hits) seeds:

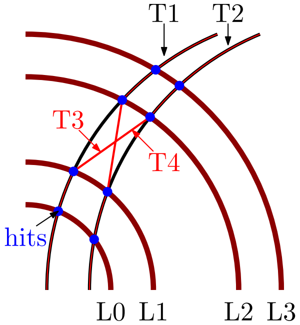
- Combine hits from first 3 layers
- Fake rate $\approx O(1)$ (1 per truth track)

Short (4 hits) tracks:

- Combination of triplet and hit in outer layer
- Fake rate $\approx O(0.1)$

Reconstruction: resolve algorithm

- Some particles can recurl several times (10 and more) in central station
- These particles produce a large number of closely packed hits that result in a large number of reconstructed short tracks (**true** and **fake** combinations)
- Need a way to disentangle (resolve) these groups of tracks, otherwise these events/tracks would be unusable



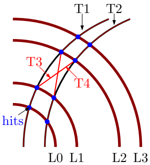
T1 - first recurl of particle

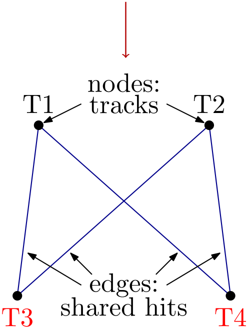
T2 - second recurl of same particle

T3/**T4** - are fake tracks

Reconstruction: resolve algorithm

- The idea is to create graph of connected tracks,
- where each node is a track and edges connect tracks that share hits (intersecting tracks),
- and find largest subset of disconnected nodes (tracks) → standard graph theory exercise





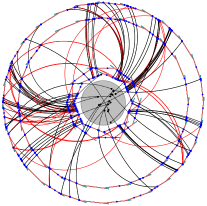
Reconstruction: resolve algorithm

- Exponentially hard algorithm, partially due to unknown number true tracks
- High granularity and efficiency, low noise → estimate number of tracks as $N_{hit}/4$

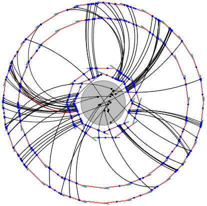
Short track performance:

- Factor 5 reduction in fake rate (from 0.16 to 0.03)
- No efficiency loss (select several sets within distance to minimum χ^2)

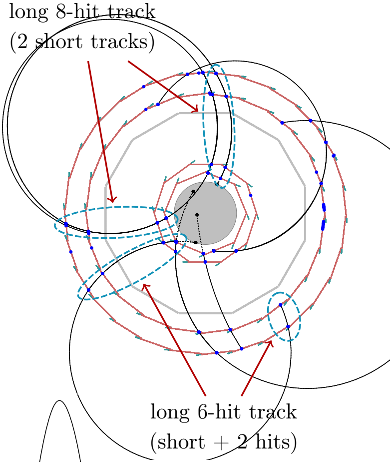
before

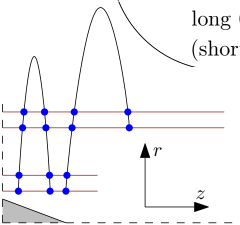


after



Reconstruction: long tracks





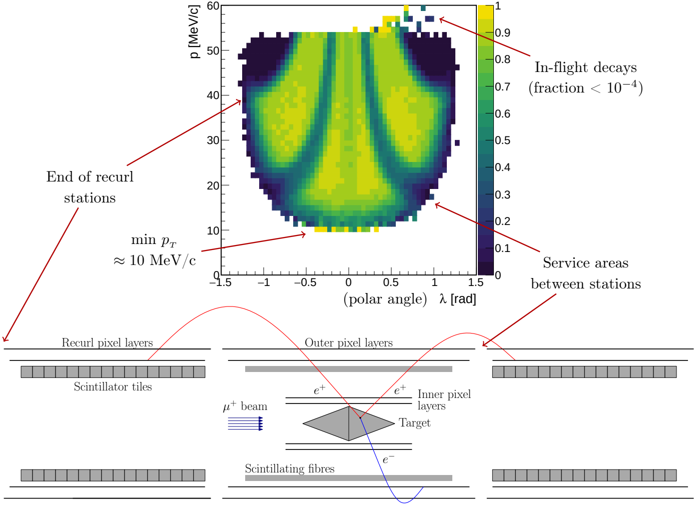
Long 6-hit tracks:

- Combine short track with pair of hits in outer layers

Long 8-hit tracks:

- Combine 2 short tracks with opposite curvature
- Fake rate $\approx O(0.1) - O(1)$ - combination of short tracks from wrong turns
- Direction (charge) ambiguity $\rightarrow$ reconstruct recurl chain

Acceptance and efficiency



- Acceptance: $\epsilon_{acc} \approx 70\%$ (1 hit per layer, min p_T, etc.)
- Short tracks: $\varepsilon_{short} \approx 90\% \cdot \varepsilon_{acc}$ (χ^2 cut)
- Long tracks: $\varepsilon_{long} \approx 70\% \cdot \varepsilon_{short}$ (gaps, etc.) $\rightarrow$ analysis

Summary

- Efficient and fast tracks reconstruction is necessary to reach design sensitivity of $2 \cdot 10^{-15}$
- Track reconstruction handles high occupancy and large MS by utilizing knowledge of high efficiency and low noise of the detector, allowing to reconstruct above 90% of particles within detector acceptance with about 2.5% of the fake tracks (at Phase 1)
- For more information see TDR NIMA **1014** (2021), 165679

Backup

Momentum resolution

Short tracks (4 hits)

- $\langle \sigma_p \rangle \approx 1.4$ MeV/c
- Depends linearly on momentum

Long tracks (6 and 8 hits)

- $\langle \sigma_p \rangle \approx$ **0.2** MeV/c (**min** 100 KeV/c)
  - ($\times 10$ better than short tracks)
- Allows to separate signal from internal conversion decays