Track reconstruction for the Mu3e experiment

DPG 2021 @ Dortmund (T40.1)

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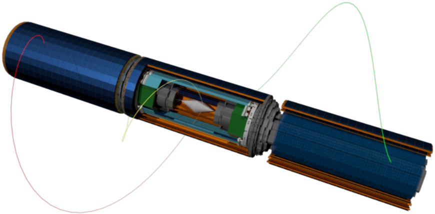
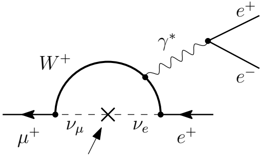
on behalf of the Mu3e Collaboration



Mu3e Experiment

Mu3e experiment:

- Search for Lepton Flavor Violation (LFV)
  - Decay: $\mu^+ \rightarrow e^+e^+e^-$
  - Standard Model: Br $< 10^{-54}$ (not observable)
    - *Any observed decay will point to New Physics*
- Location: Paul Scherrer Institute (PSI)
  - Commission in 2021-2022



Current experimental status:

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

Mu3e aims for Single Event Sensitivity of $2 \cdot 10^{-15}$

- Reachable with existing beam line at PSI: $10^8 \mu$/s
- Better sensitivity with new beam line ($> 10^9 \mu$/s)

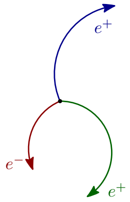
Signal & Background

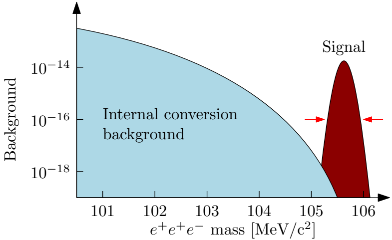
Signal ($\mu \to 3e$):

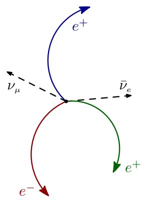
- Three tracks
- Decay at rest
  - $\sum \mathbf{p}_e = 0$
  - Common vertex & time
  - $|\mathbf{p}_e| < 53$ MeV/c,
    large Multiple Scattering (MS)

Background:

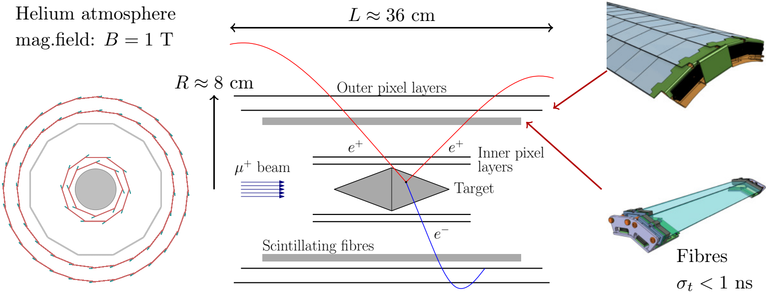
- Random combinations:
  - $\mu^+ \to e^+ + 2\nu$, $e^\pm$ scattering
  - *Fake* tracks
  - Not same vertex, time, etc.
- Internal conversion:
  - $\mu^+ \to e^+ e^+ e^- + 2\nu$
  - Missing momentum & energy







Mu3e Detector (1)



Double cone hollow target:

- Muons stop and decay at rest
- Vertex separation

Four layers of silicon pixel layers:

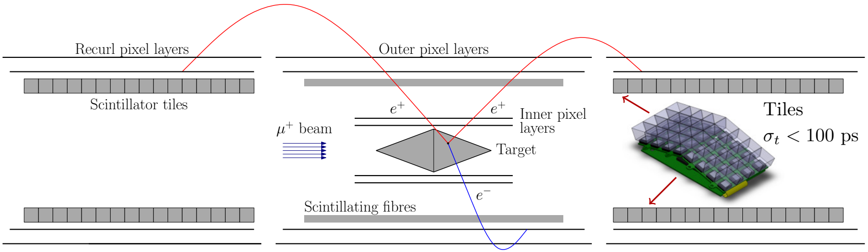
- Track reconstruction
- Minimize material (MS dominates)
- HV-MAPS sensors

High Voltage - Monolithic Active Pixel Sensor (HV-MAPS)

- 2×2 cm^2, pixel size 80×80 µm^2
- Thin (50 µm)
- Fast ($\sigma_t < 15$ ns)
- High efficiency (> 99%)

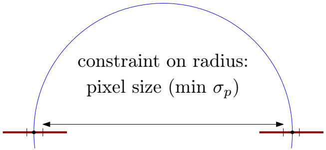
see: T14.1, T14.2 (Monday)

Mu3e Detector (2)



Particles bend back in magnetic field:

- Dedicated 'recurl' stations
- Improve momentum resolution (factor 5-10 improvement)



Recurl stations:

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

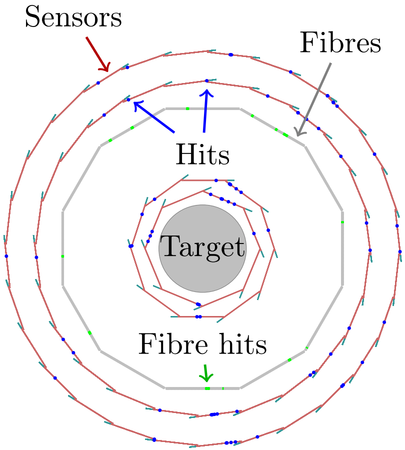
Data

A lot of data from detector:

- $10^8 \mu/s$ stop and decay on target
  $\approx$ same number of electrons
- $\rightarrow$ O(10^9) pixel hits/s
  + fibre & tile hits
- Need to reduce rate by factor 100

Fast reconstruction:

- Online (GPU filter farm) and offline
- Track reconstruction and vertex fit
- Need fast fit in MS dominated environment



Track in magnetic field:

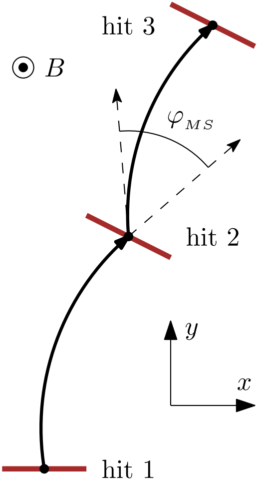
- Described by helical trajectory
- Require minimum 3 hits to reconstruct track

Triplet = trajectory with Multiple Scattering (MS) in middle point

- o pixel uncertainty and no energy loss
- Only one parameter - curvature r (momentum p)
- MS angles are functions of r
  $\varphi_{MS}(r)$, $\lambda_{MS}(r)$

Triplet fit:

- Define $\chi^2 = \varphi^2_{MS}(r)/\sigma^2_{MS} + \lambda^2_{MS}(r)/\sigma^2_{MS}$
- Minimize χ^2, equivalent to minimization of scattering angle



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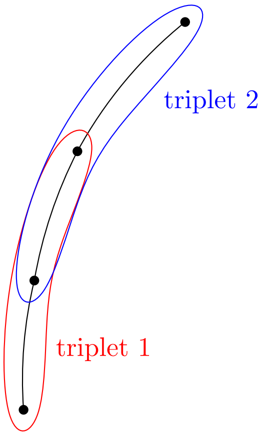
Track fit

Triplet fit:

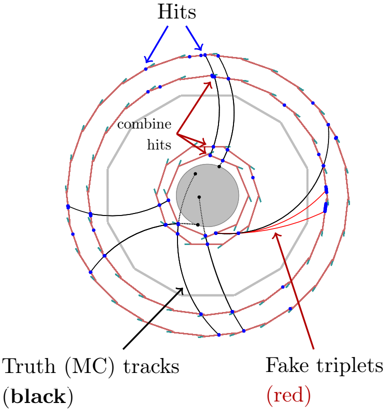
- No analytical solution
- Small MS angles → linearization around known solution (circle in xy-plane)

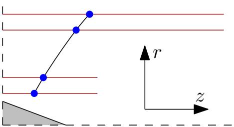
Track:

- Sequence of triplets (2 consecutive triplets share pair of hits)
- Minimize combined χ^2
  - r = weighted average of individual triplet solutions



Reconstruction: from triplets to short tracks





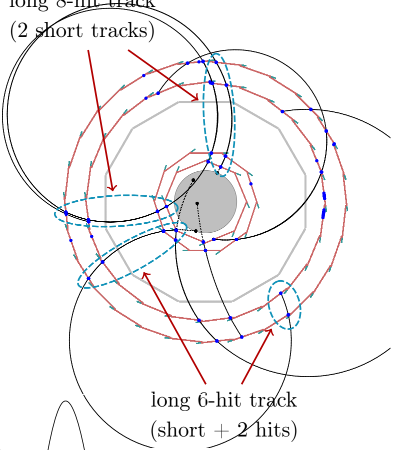
Triplets:

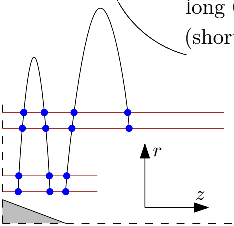
- Combine hits from first 3 layers
- 10 hits per layer, O(1K) combinations
- Total 10^8 triplet fits each second
- Fake rate ≈ 1 (1 per truth track)

Short tracks:

- Start from triplets (seeds)
  - Estimate hit at last layer
  - Lookup in φ/z window
- Combine triplet + hit (4 hits)
  - 2 triplets (2 shared hits)
  - Fit (weighted average)
- Fake rate $\approx 1.0\%$

Reconstruction: long tracks





Long 8-hit tracks:

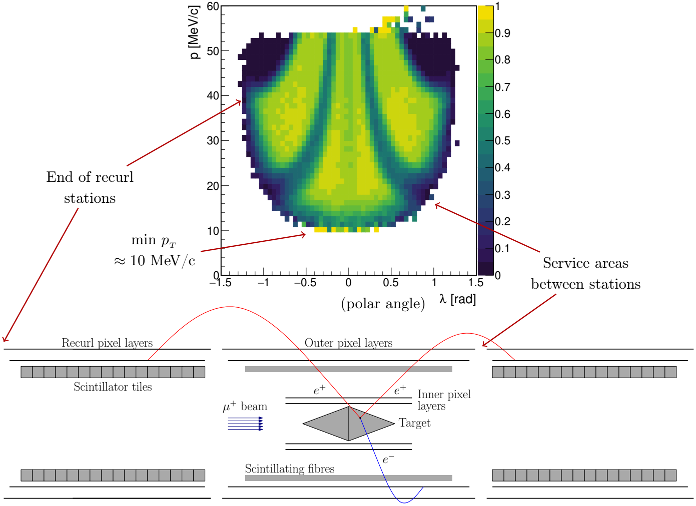
- Combine 2 short tracks with opposite curvature

Long 6-hit tracks:

- Combine short track with pair of hits in outer layers

- Fake rate ≈ 3.7%
  - ≈ 0.5% **true** random combinations
  - Rest - hits from same tracks, different turns

Acceptance and efficiency



- Acceptance: $\epsilon_{acc} \approx 80\%$ (1 hit per layer, min p_T, etc.)
- Short tracks: $\varepsilon_{short} \approx 95\% \cdot \varepsilon_{acc}$ (χ^2 cut)
- Long tracks: $\varepsilon_{long} \approx 80\% \cdot \varepsilon_{short}$ (gaps, etc.) $\rightarrow$ analysis

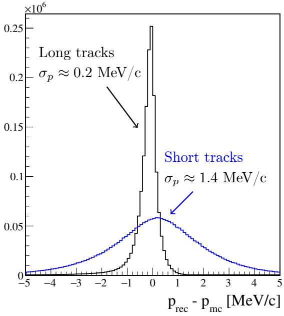
Momentum resolution

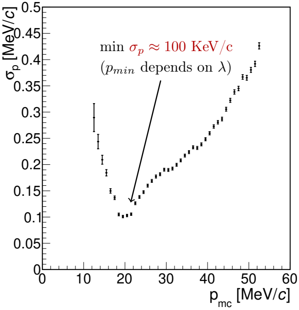
Short tracks (4 hits)

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

Long tracks (6 and 8 hits)

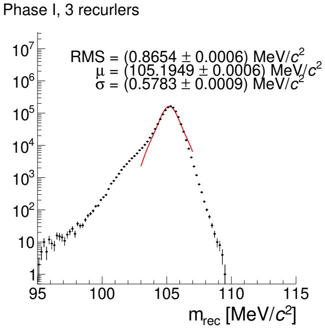
- $\langle\sigma_p\rangle \approx$ **0.2** MeV/c
  - ($\times$10 better than short tracks)
- **min** $\sigma_p \approx 100$ KeV/c





Summary

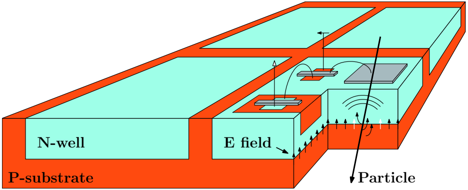
- Track reconstruction based on fast MS (triplet) fit
  - Offline reconstruction: analysis using long and/or short tracks
  - Online (filter farm) reconstruction on GPU (short tracks and vertex) at full rate
- Long tracks momentum resolution of 100-300 keV/c
  - Reconstruct 3-track vertex with mass resolution of 0.6 MeV/c^2 (only long tracks)
  - Reach single event sensitivity of $\approx 2 \cdot 10^{-15}$ (one year of data taking)
- More information in upcoming TDR



Backup

High Voltage - Monolithic Active Pixel Sensor

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



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Sensitivity