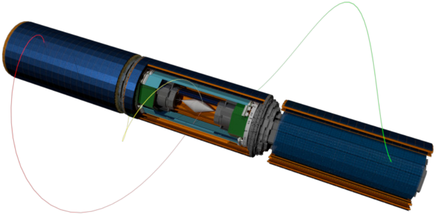
Track reconstruction for the Mu3e experiment

Alexandr Kozlinskiy (Mainz, Institut für Kernphysik)

on behalf of the Mu3e collaboration

DPG 2019 @ Aachen (.03.26, T42.1)

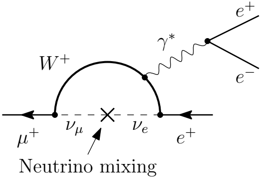


Mu3e Experiment

Mu3e experiment:

- Search for Lepton Flavor Violation (LFV)
  - Decay: $\mu^+ \to e^+e^+e^-$
  - Standard Model: Br $< 10^{-54}$ (not observable)
    - Enhanced in New Physics (NP) models
    - *Any observed decay will point to NP*
- Location: Paul Scherrer Institute (PSI)
  - Commission in 2020-21

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



Current experimental status:

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

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

- With existing beam line at PSI: $10^8 \mu/\mathrm{s}$
- Better sensitivity with new beam line ($10^9 \mu/\mathrm{s}$)

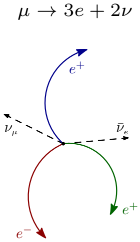
Signal & Background

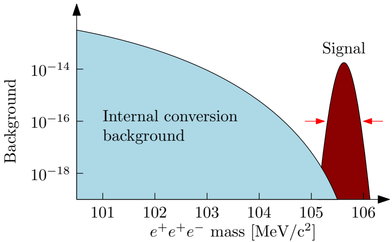
Signal:

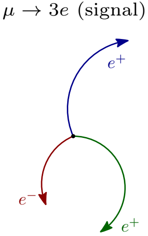
- Three tracks
- Decay at rest
  - $\sum E_e = m_\mu$ $(E_e < 53\,\mathrm{MeV/c})$
  - $\sum \mathbf{p}_e = 0$
  - Common vertex & time

Background:

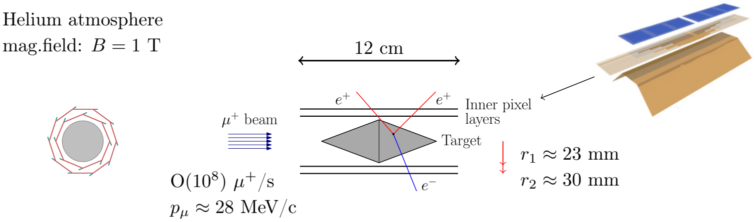
- Random combinations:
  - $\mu^+ \to e^+ + 2\nu$, $e^\pm$ scattering
  - *Fake* tracks
  - Not same vertex, time, etc.
- Internal conversion:
  - $\mu^+ \to e^+e^+e^- + 2\nu$
  - Missing momentum & energy







Mu3e Detector (1)

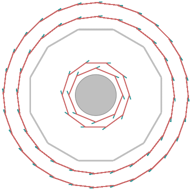


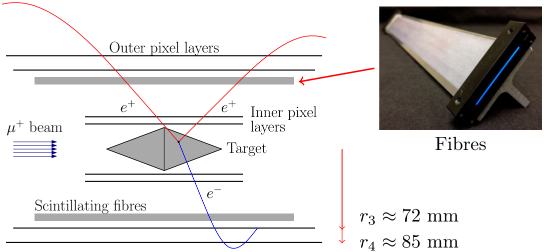
Muons stop and decay on target:

- 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:

- Thin & high granularity
- 99.9% efficiency
- As close as possible to target
  - Reduce effect of Multiple Scattering (MS) and pixel size
  - Improve vertex resolution



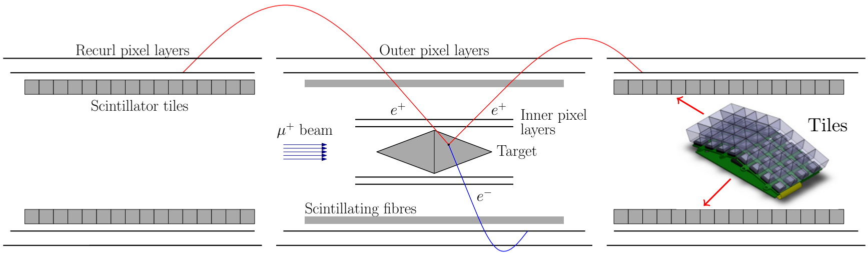


Two outer pixel layers:

- Reconstruct momentum
- 1 Tesla $\rightarrow$ min $p_T \approx 12$ MeV/c (limited by outer layer radius)

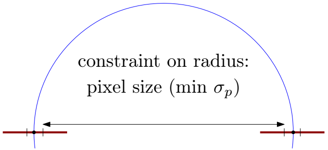
Scintillating fibres:

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



Particles bend back in magnetic field:

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

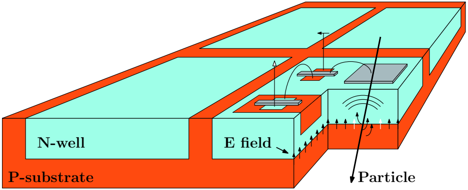


Recurl stations:

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

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 ($> 99\%$)



I.Peric, NIM A582(2007)876

*See **T-27.1** and **T-27.2***

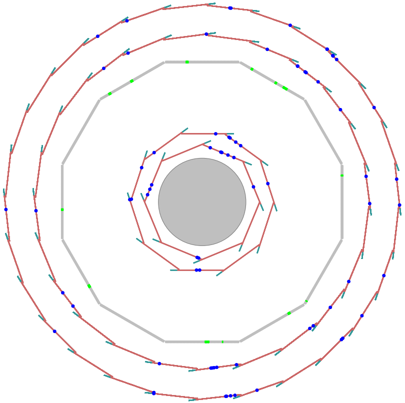
"Motivation"

A lot of data from detector:

- $10^8 \mu/\text{s}$ stop and decay on target
  $\approx$ same number of electrons
- O(10^{10}) pixel hits/s
  + fibre & tile hits

Need reconstruction:

- Fast (online tracking @ filter farm)
- $\rightarrow$ fast fit



Triplet fit

Track in mag.field:

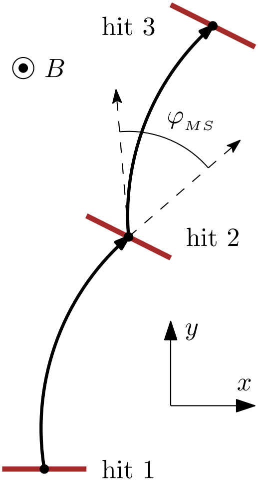
- Helical trajectory
- Require minimum 3 hits

If no pixel uncertainty and no energy loss:

- Triplet - trajectory with Multiple Scattering (MS) in middle point
- One parameter - curvature r (momentum p)
- MS angles - $\varphi_{MS}(r)$, $\lambda_{MS}(r)$

Fit - minimize χ^2 (scattering angle):

- $\chi^2 = \varphi^2_{MS}(r)/\sigma^2_{MS} + \lambda^2_{MS}(r)/\sigma^2_{MS}$
- No analytical solution
- Small MS angles $\rightarrow$ linearization around known solution (circle in xy-plane)



NIM A844(2017)135

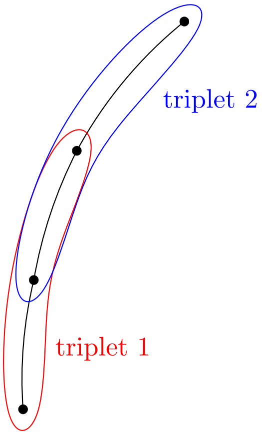
Track fit

Track/Segment:

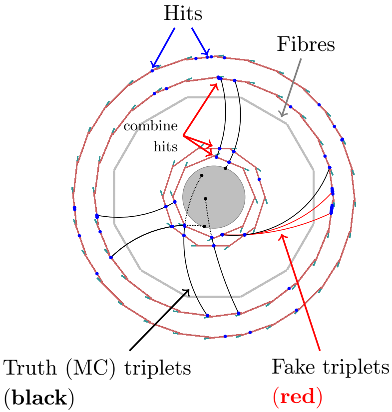
- Sequence of triplets
- 3D radius:
  - Minimize combined χ^2
  - Simple solution $r = \frac{\sum r_i/\sigma_i^2}{1/\sigma_i^2}$
    where r_i - individual triplet solution
    (*weighted average*)

Note:

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



Reconstruction: triplets

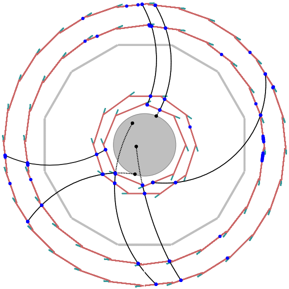


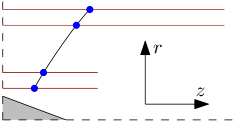
Combine hits of first 3 layers:

- 10 hits per layer per event (50 ns)
- O(1K) triplet combinations
- Factor 50 reduction with geometrical selections
- 10^8 triplet fits each second

Result:

- Collection of triplets (seeds)
- Fake rate ≈ 1 (1 fake per truth track)



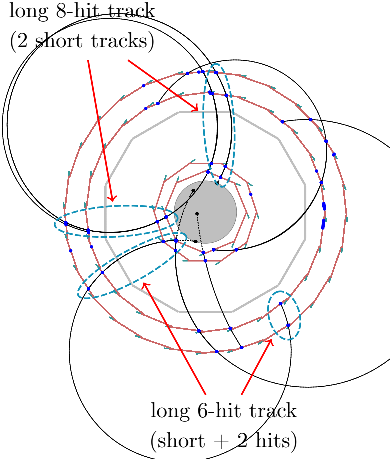


Make short tracks:

- 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)

O(10) short tracks

- Fake rate ≈ 1.0%



Long (6- and 8-hit) tracks:

- Combine short track with pair of hits or another short tracks
- Fake rate ≈ 3.7%
  - ≈ 0.5% **true** random combinations
  - Rest - hits from same tracks, different turns

Acceptance & efficiency

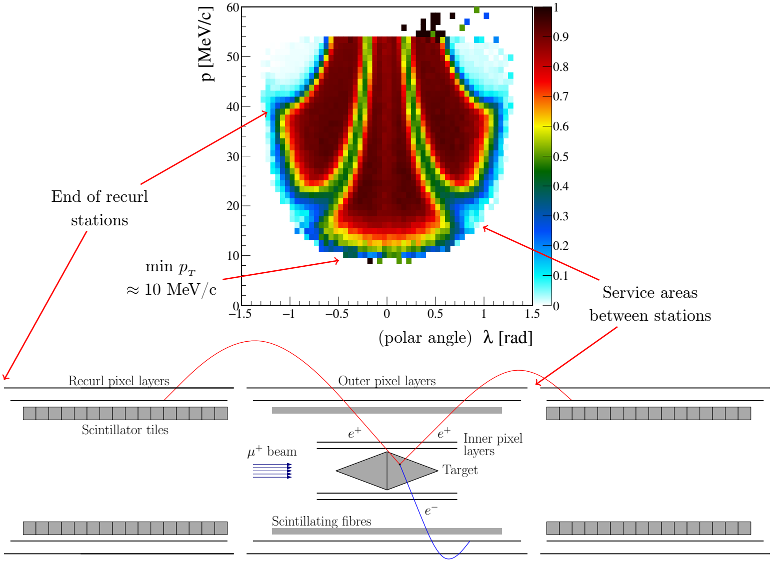
Full Geant4 simulation of Mu3e detector

- Decay: $\mu^+ \to e^+\nu\nu$ (≈ 5 decays within frame)
- 50 ns frame (event size)

Reconstruction efficiency:

- Acceptance: $\epsilon_{acc} \approx 80\%$
  - Require minimum 4 hits (1 per layer)
  - min p_T, etc.
- Short tracks: $\varepsilon_S \approx 95\% \cdot \varepsilon_{acc}$
  - Geometrical and χ^2 cuts
- Long tracks: $\varepsilon_L \approx 80\% \cdot \varepsilon_S$
  - Used for analysis (vertex fit, etc.)

Reconstruction efficiency: long tracks



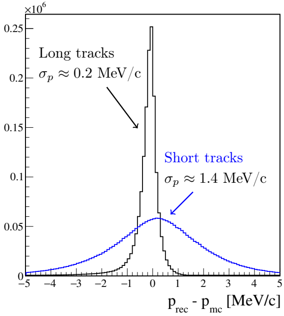
Momentum resolution

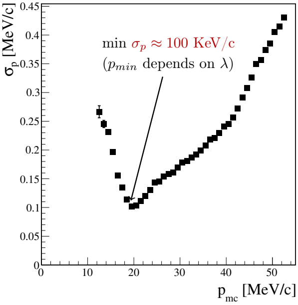
Short tracks (4 hits)

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

Long tracks (6 and 8 hits)

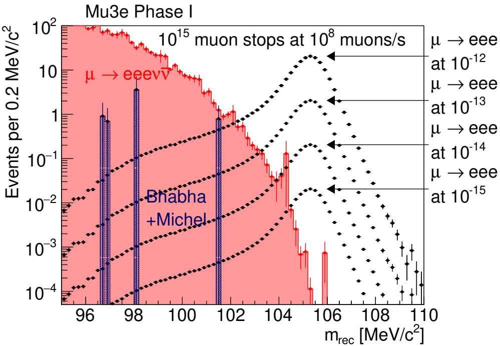
- $\langle \sigma_p \rangle \approx \mathbf{0.2}$ MeV/c
- **min** $\sigma_p \approx 100$ KeV/c

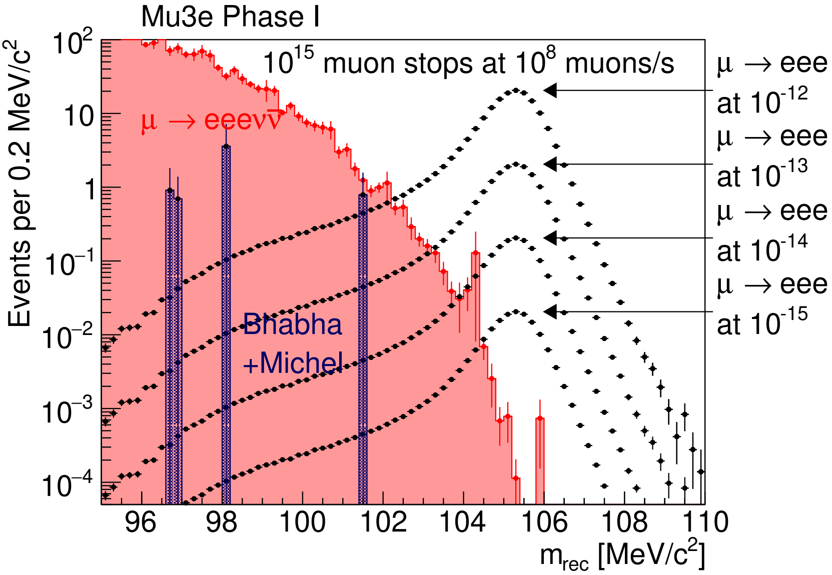




Sensitivity

- Vertex fit (3 long tracks and/or short track)
- Fit invariant mass
- Better tracking → narrow mass distribution
- With current design and $10^{15}\mu$/s: SES $\approx 2 \cdot 10^{-15}$




Mu3e Phase I
Events per 0.2 MeV/c²
10¹⁵ muon stops at 10⁸ muons/s
μ → eeeνν̄
Bhabha
+Michel
μ → eee at 10⁻¹²
μ → eee at 10⁻¹³
μ → eee at 10⁻¹⁴
μ → eee at 10⁻¹⁵
m_rec [MeV/c²]
96
98
100
102
104
106
108
110
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴