Track pileup mitigation for the Mu3e experiment

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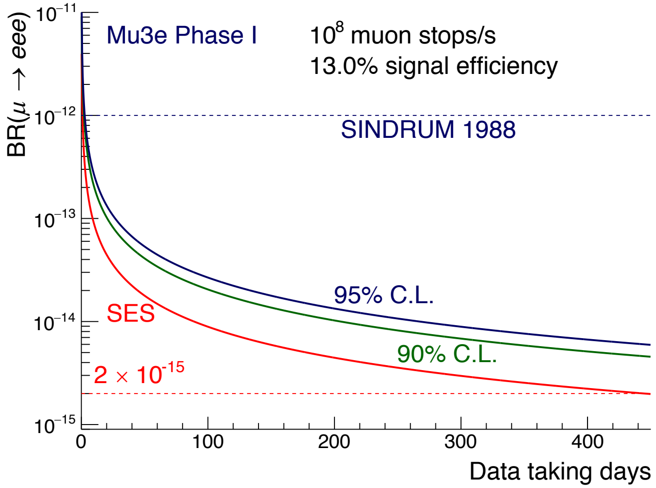
Introduction

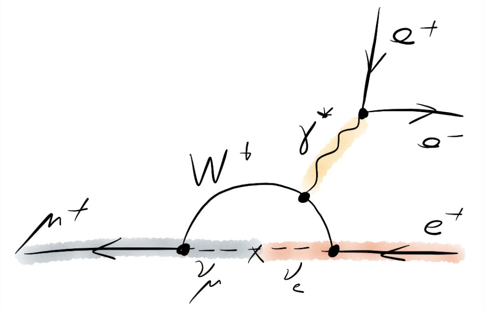
- Searching for charged lepton flavour violation (cLFV)
- The Mu3e experiment
- Track and time reconstruction
- Track pileup mitigation in fibre clusters

Mu3e signal decay

- Search for the rare cLFV $\mu^+ \rightarrow e^+e^+e^-$
  - Single vertex, three tracks coincident in time
- Aim for BR ~ 10^{-15} in phase I
  - 10^3 better than current limit
- Interaction possible via neutrino mixing in SM
  - Suppressed to experimentally unobservable levels, BR~ 10^{-54}
- Any observation would be a sign of new physics
  - Probe mass scales > current reach



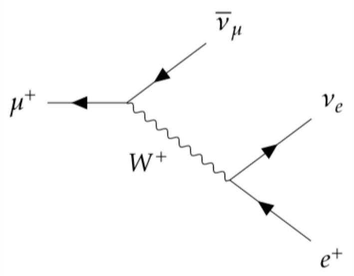
Single event sensitivity anticipated during phase I [1].



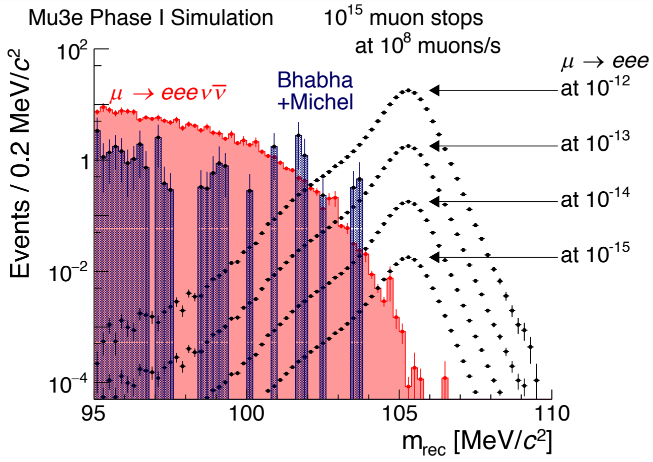
$\mu \rightarrow eee$ via neutrino mixing

Mu3e backgrounds

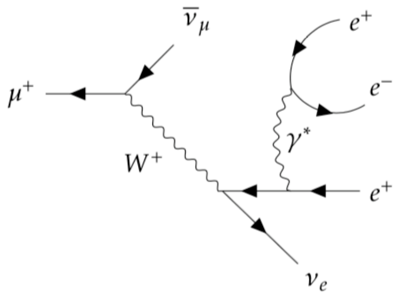
- Largest muon decay mode is Michel decay
- Radiative muon decay with internal conversion (IC) closely mimics signal decay
  - Use missing energy from neutrinos – requires excellent momentum resolution
- Accidental backgrounds involve combinations of these decays and Bhabha scattering
  - Use timing of muon decays to separate decays – requires very good timing resolution



Michel decay, $\mu \to e\bar{\nu}\nu$.



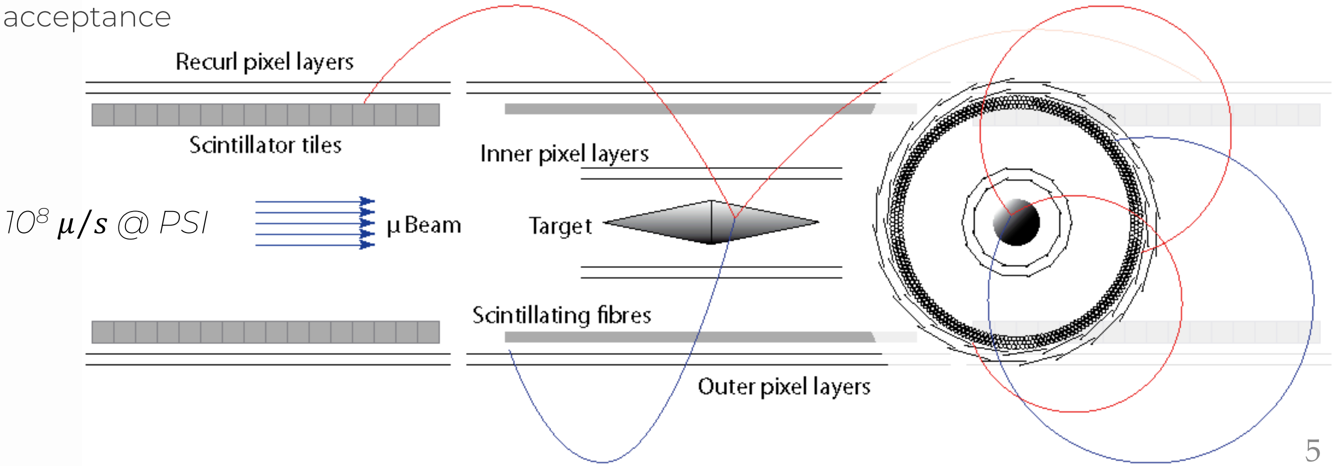
Reconstructed invariant mass for signal events and Bhabha + Michel decays [1].



Radiative muon decay with internal conversion, $\mu \to eee\bar{\nu}\nu$.

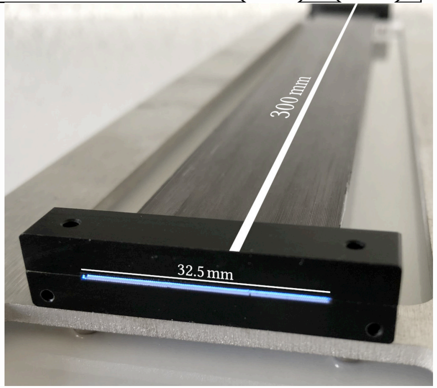
Mu3e phase I detector

- Priority is to minimise material amount to limit multiple scattering (MS)
- Four tracking layers of ultra thin HV-MAPS (MuPIX)
- Thin scintillating fibres in central station and thicker scintillator tiles in recurl stations provide precise timing information
- Situated in 1 T magnetic field, leading to recurling particles
  - Use recurl stations to increase acceptance

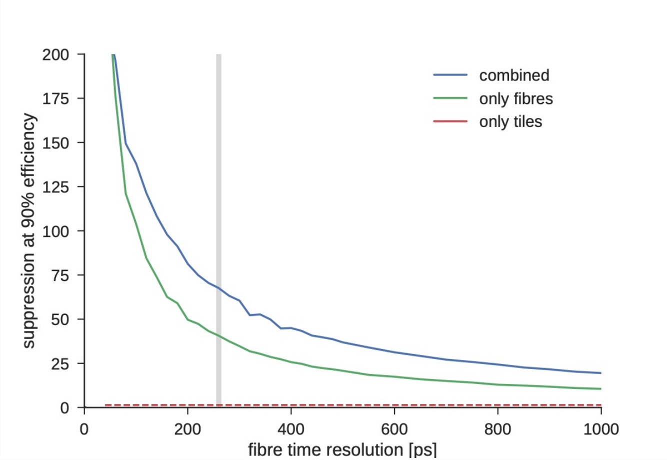


Scintillating fibres

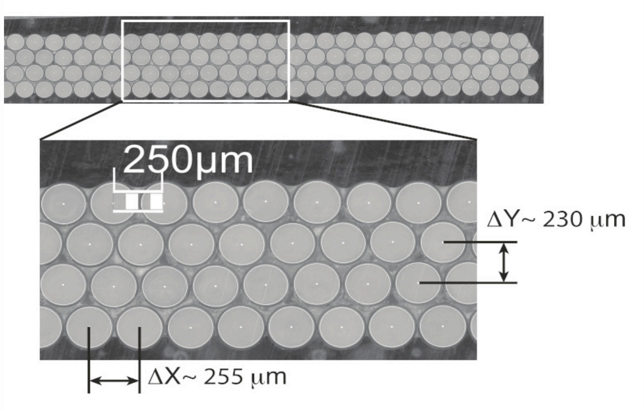
- Charged particles intersecting fibres produce light
- Silicon photomultiplier (SiPM) arrays detect this light at both ends of fibres
- Time resolution ~ 250 ps



View of a fibre ribbon prototype with preliminary holding structure [1].



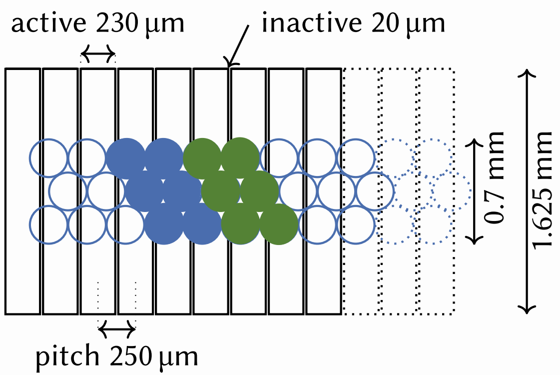
Background suppression of Bhabha + Michel decays versus fibre time resolution[1].



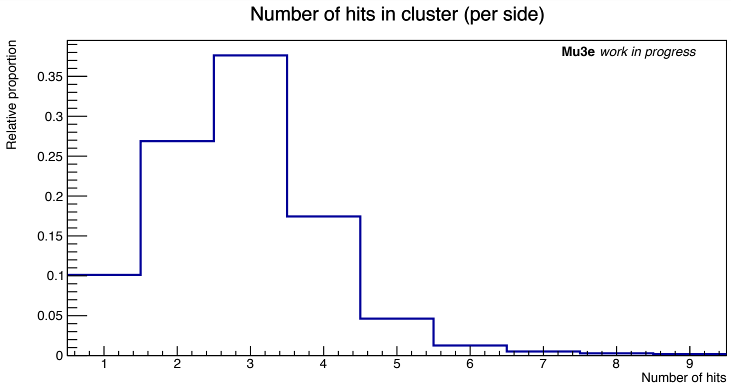
Front view of a fibre ribbon prototype [1].

Scintillating fibres - clustering

- Clusters are built per ribbon (side) with *adjacent* columns
- Time of cluster is the earliest hit time
  - Good handle on recurlers
- Track pileup occurs when there are 'bridging' columns
  - Multiple tracks end up in one cluster together (normally two)
- How to fix clusters with track pileup?

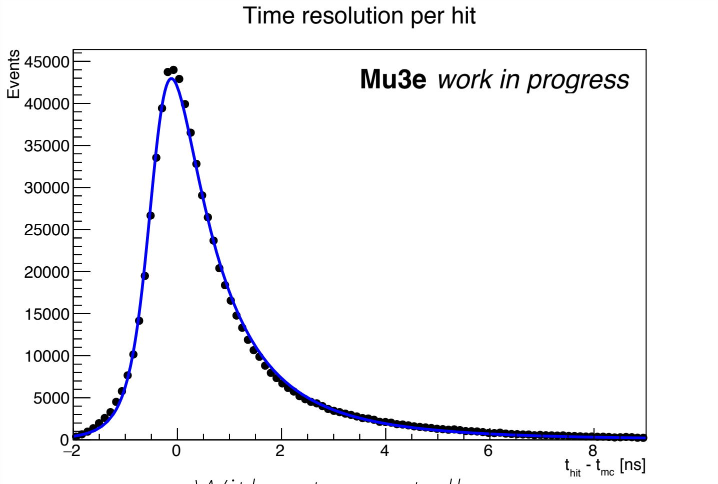


Overlap of ribbon fibres and SiPM array, no direct mapping is possible. (adapted from) [1].

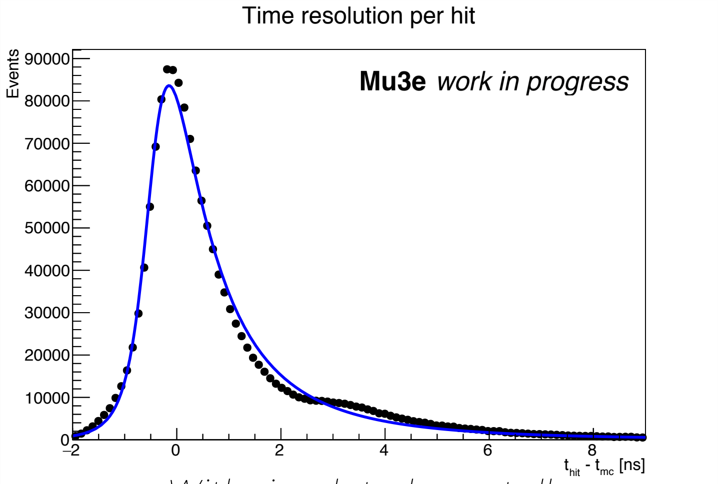


Fitting fibre clusters

- Using MC data, fit the underlying hit time distribution
- With shape set, only location and amplitude of PDF will vary when applied to clusters
- Crosstalk not accounted for yet
  - Effect of crosstalk on timing delay to be studied



Without crosstalk

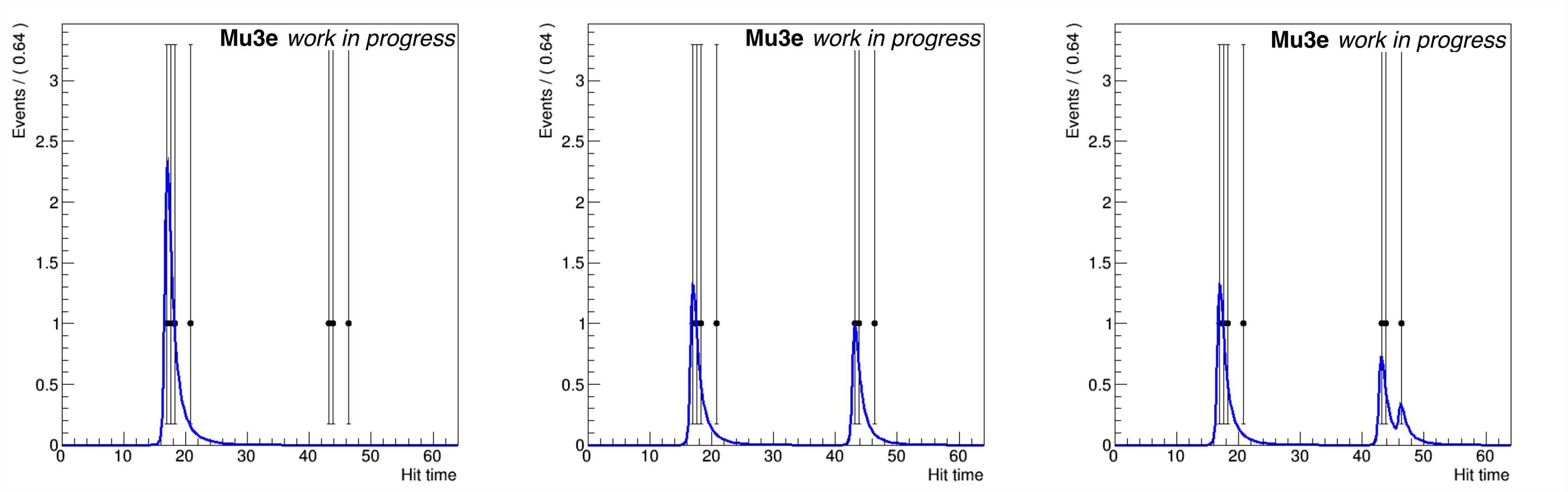


With simulated crosstalk

Applying fit to track pileup

- How many tracks in this cluster and where in time were these intersections?

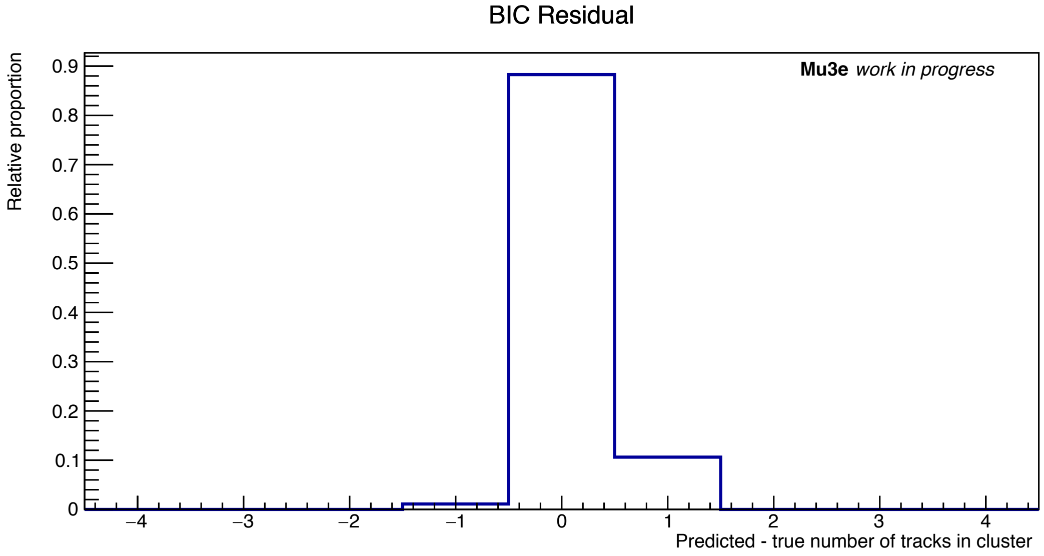
- For example, two true clusters here - how to choose the best model?
  - Cluster assigned to both tracks – correct time for one track, incorrect for the other



Predicting number of tracks

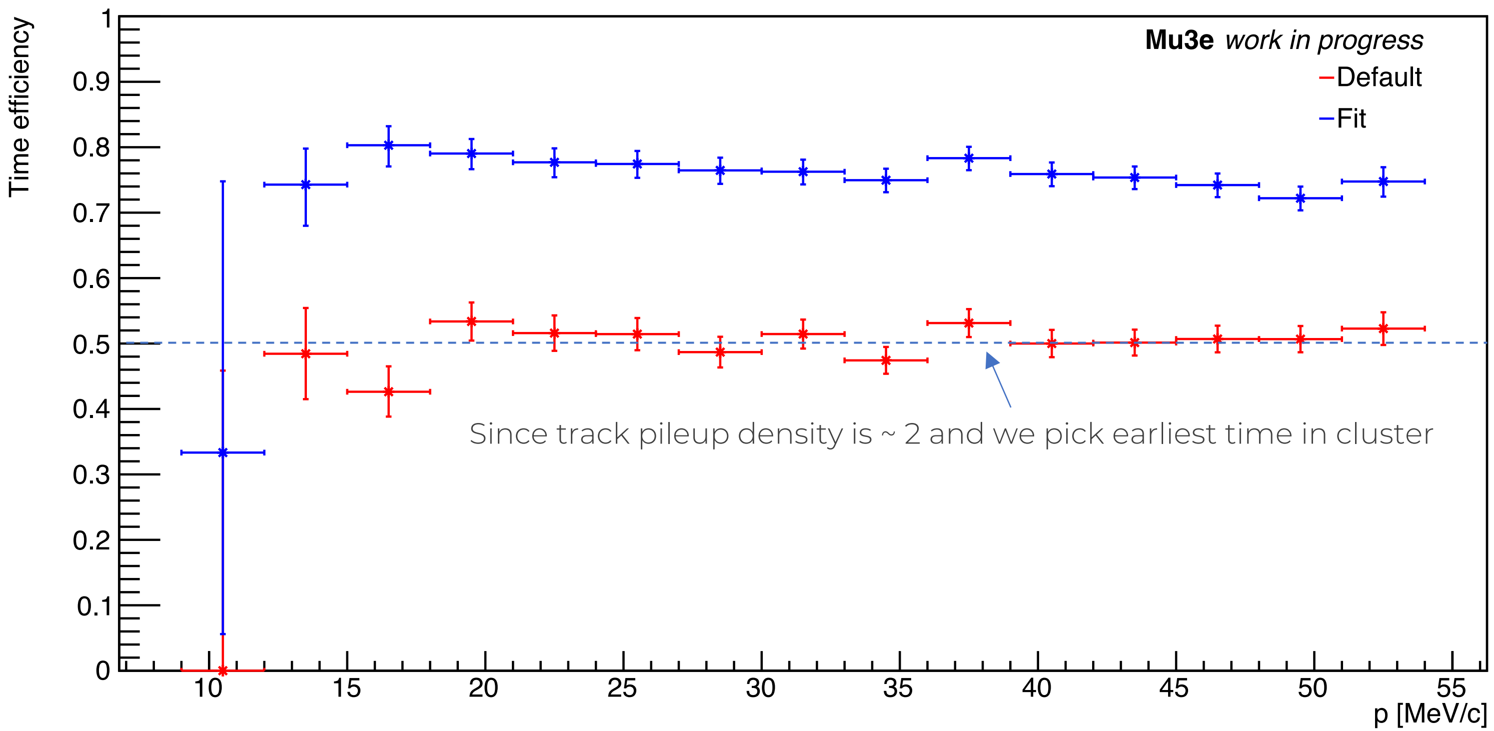
- Use Bayesian Information Criterion (BIC):
  - $BIC = k\ln(n) - 2\ln(\hat{L})$
  - Where k is number of params, n is number of data points, $\hat{L}$ is maximised value of likelihood function.

- Pick model with minimum BIC:
  - Split the cluster according to number of PDFs in this model



Efficiency of affected clusters

- Look at efficiency for cluster to be correctly assigned to track
  - For clusters containing track pileup



Conclusions

- Study aimed to identify and reduce the impact of track pileup in the fibre detectors
- Underlying MC hit time distribution was used to develop a PDF
- Clusters were split up by evaluating models with varying numbers of these PDFs using the Bayesian information criterion
- Method allows for a flexible approach in detecting and mitigating track pileup (as well as other pileup types)

Questions?

References

- [1] K. Arndt *et al.*, "Technical design of the phase I Mu3e experiment," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 1014, p. 165679, 2021/10/21/ 2021, doi: https://doi.org/10.1016/j.nima.2021.165679.

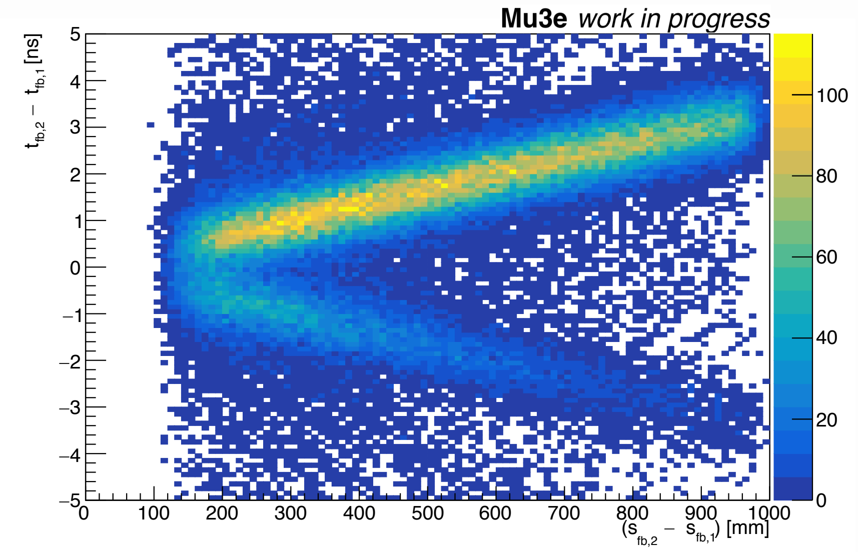
- [2] Simon Corrodi. “A Timing Detector based on Scintillating Fibres for the Mu3e Experiment”. PhD thesis. ETH Zurich, 2018. doi: 10.3929/ethz-b-000299260.

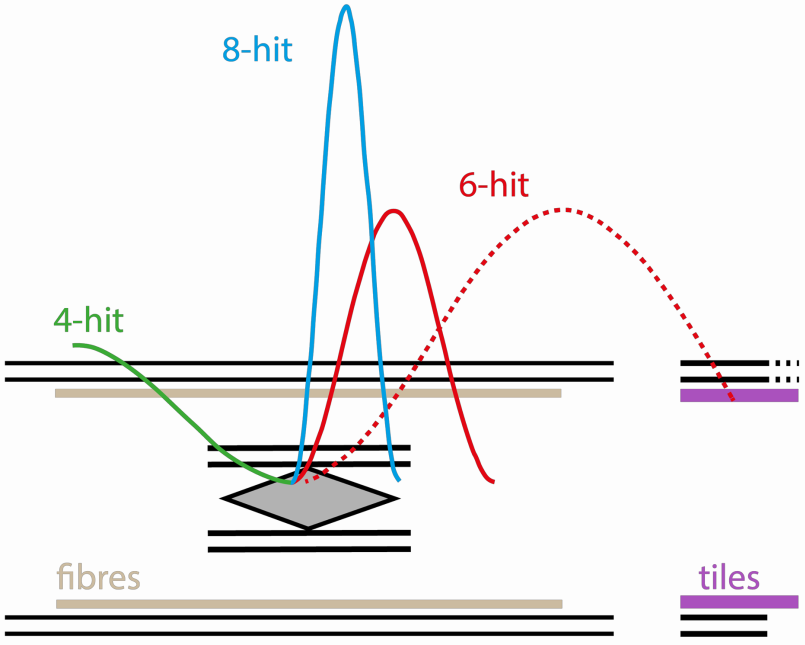
Backup

Track reconstruction

- Two categories of tracks:
  - Short 4-hit tracks (S4)
  - Long recurling 6-hit and 8-hit tracks (L6/L8)

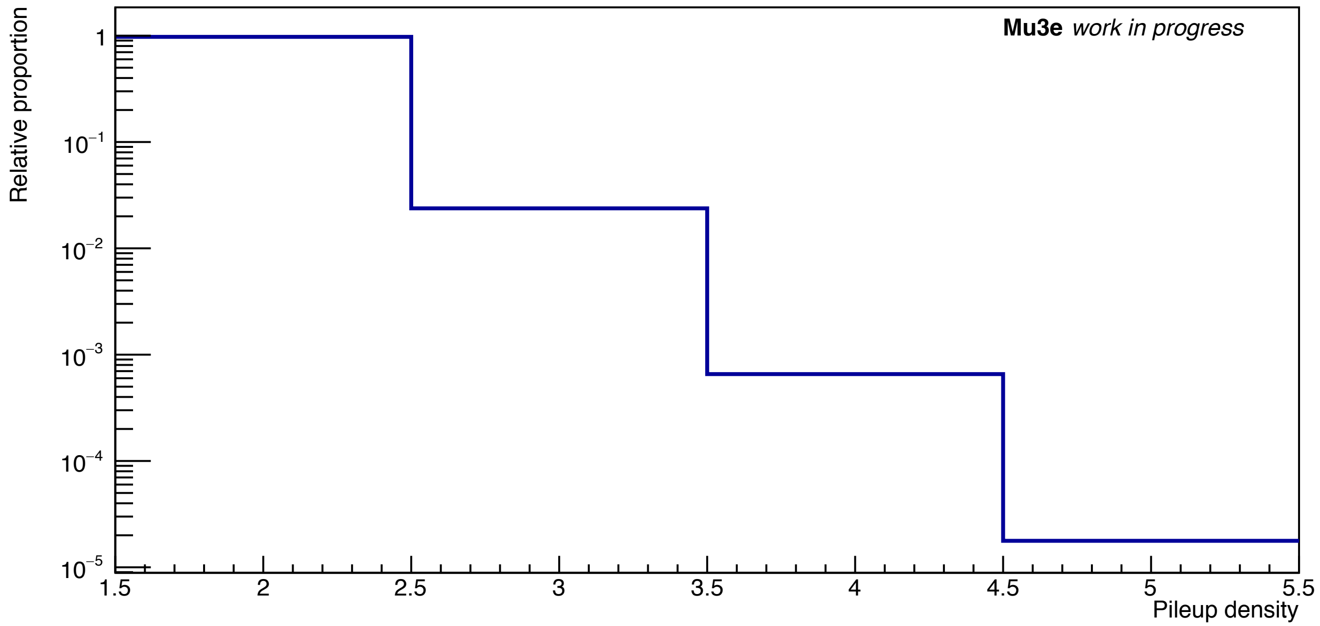
- Long tracks intersect timing detectors twice
  - Use timing for charge identification ($T_2 > T_1$)





Track topologies in Mu3e reconstruction, taken from [2].

Track pileup density in fibre clusters



PDF fit

- Johnson's S_U distribution:

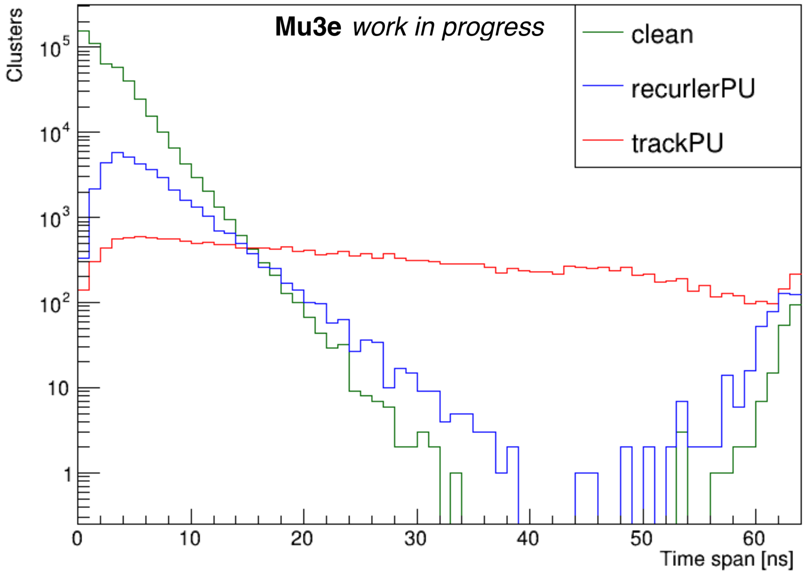
$$p(Y) = \frac{1}{\sqrt{2\pi}} \frac{b}{scale \cdot \sqrt{Y^2 + 1}} e^{-\frac{1}{2}(a + b \cdot \log(Y + \sqrt{Y^2+1}))}$$

$$Y = \frac{X \ - loc}{scale}$$

- a,b,scale are all shape params, while loc is a shifting/location parameter

Proxy for track pileup – cluster time span

- Time span is the latest – earliest hit time in a cluster
- Recurler pileup occurs when recurls overlap in a cluster
- Input for fit method are clusters with high time spans



Fibre timing

- Time is built up from several distributions (per photon per column)
- Choose the earliest time of these photons per column

Gauss(μ, 0.085 ns)

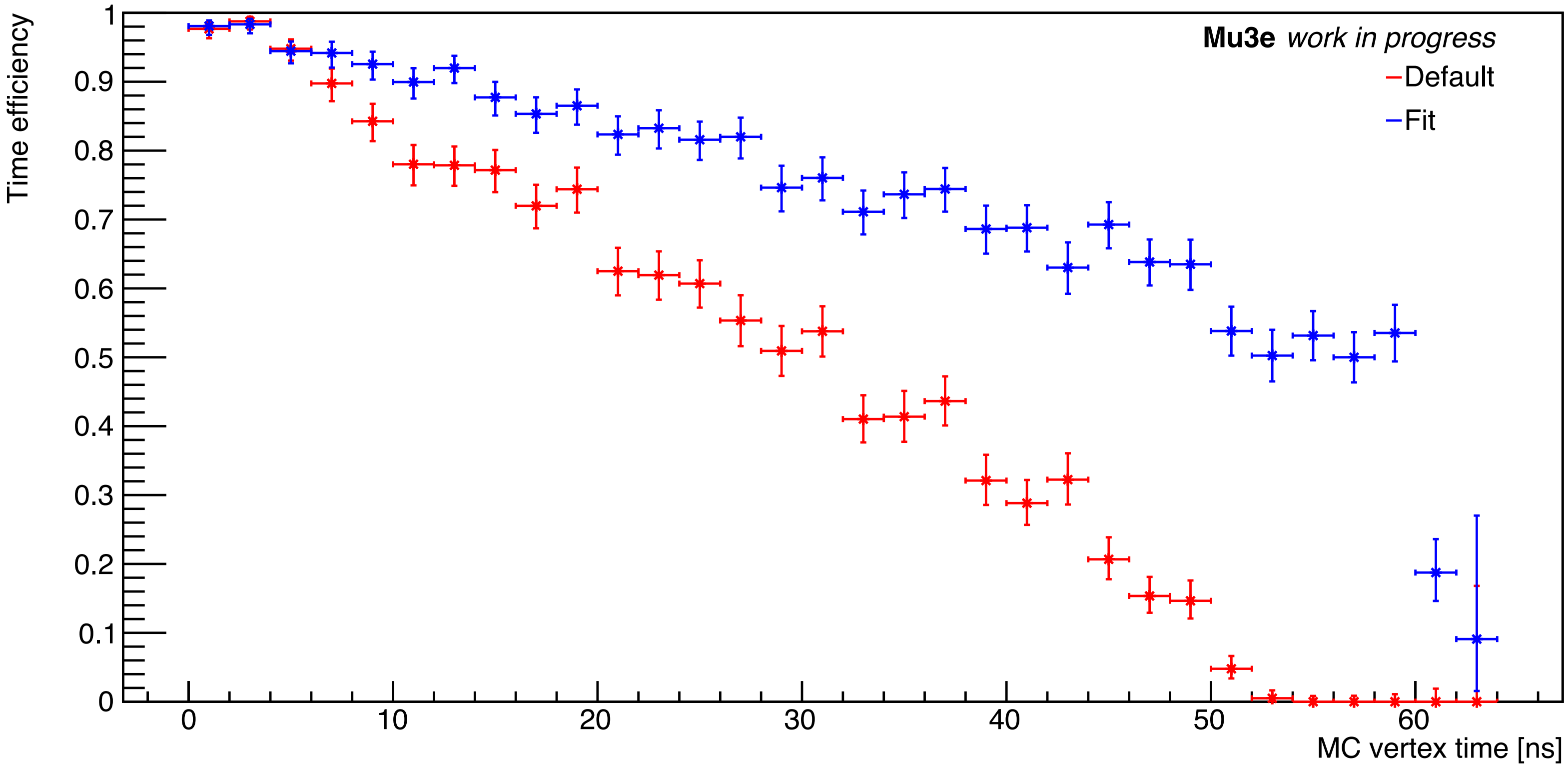
Gauss(1.0 ns, 0.3 ns)

$$t_{det} = t_{MC} + \left(t_{photon\ decay} + t_{photon\ propagation}\right) \pm \sigma_{SPTR} + t_{DAQ\ delay}$$

Exp(2.8 ns)

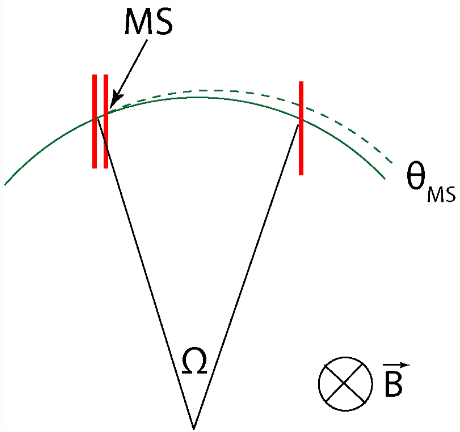
Pathlength distribution - right-angled trapezoid distribution [2]

Efficiency versus MC origin time



Purpose of measuring recurling tracks

- Track deflection, Ω
- MS angle, Θ_{MS}
- After half a turn, effect on MS on momentum uncertainty cancelled to 1st order!



$$\frac{\sigma_p}{p} \propto \frac{\Theta_{MS}}{\Omega}$$