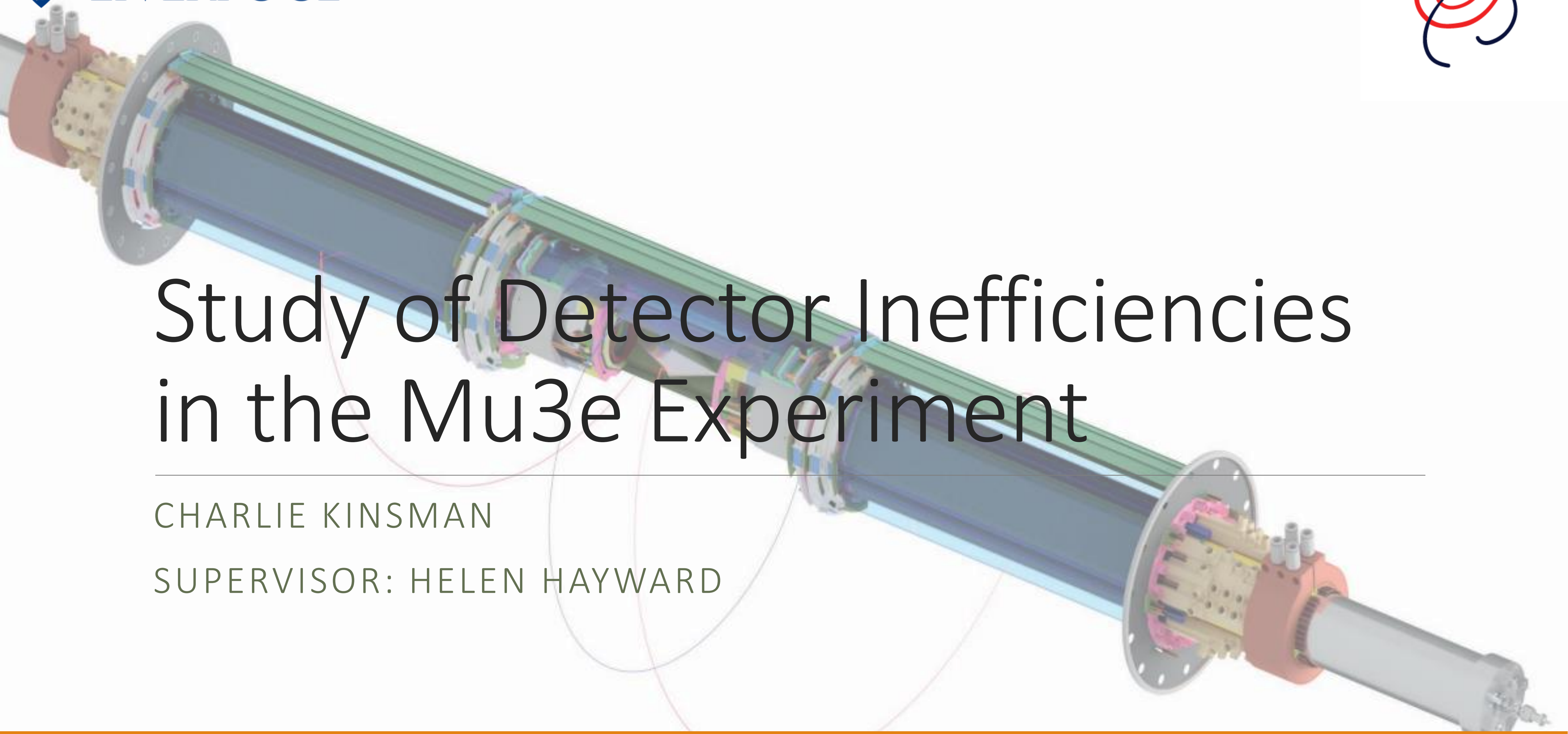


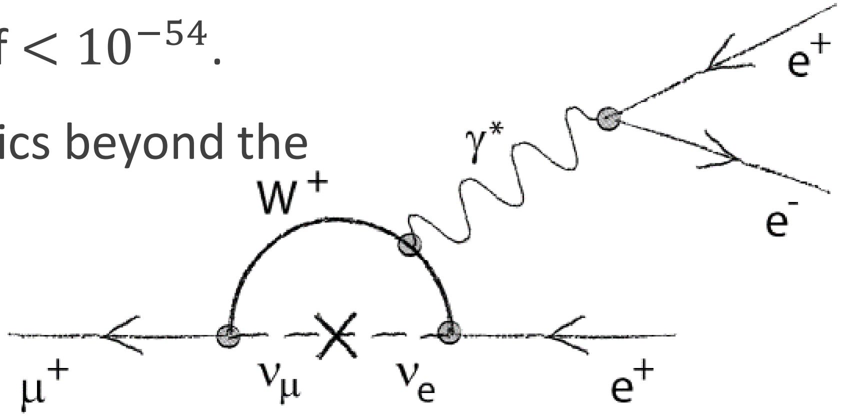
Study of Detector Inefficiencies in the Mu3e Experiment

CHARLIE KINSMAN

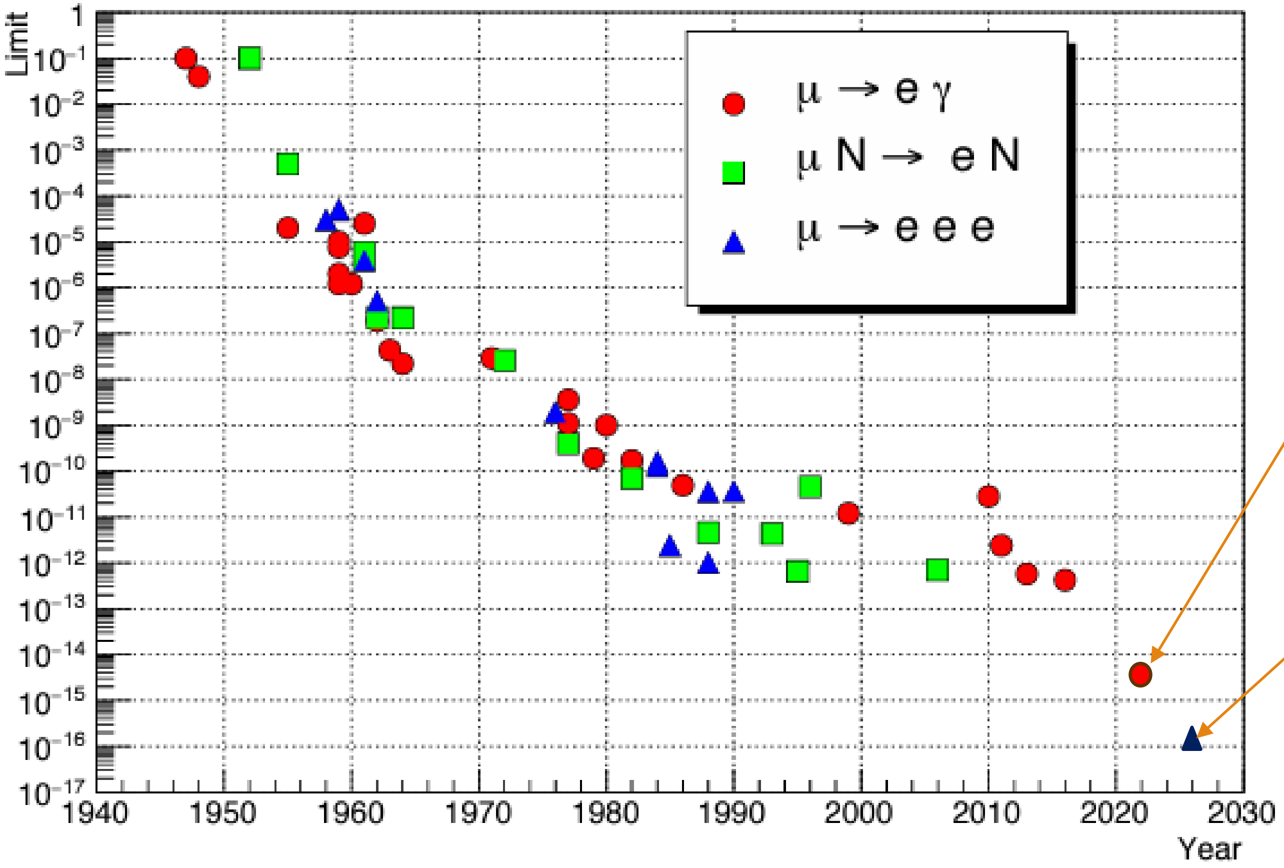
SUPERVISOR: HELEN HAYWARD

Charged Lepton Flavour Violation

- The Standard Model in its most basic form describes lepton flavour as a conserved quantity and the neutrino as massless.
- This has been proven wrong with the evidence of a massive neutrino and lepton flavour violation in the neutral sector (neutrino oscillations).
- Charged Lepton Flavour Violation is forbidden at the tree level and is only accessed through neutrino oscillations at higher order diagram or through slepton mixing in SUSY models.
- These processes are heavily suppressed, with a branching ratio of $< 10^{-54}$.
- Evidence of a branching ratio higher than this is evidence of physics beyond the Standard Model



Charged Lepton Flavour Violation



MEG-II 2023 Result

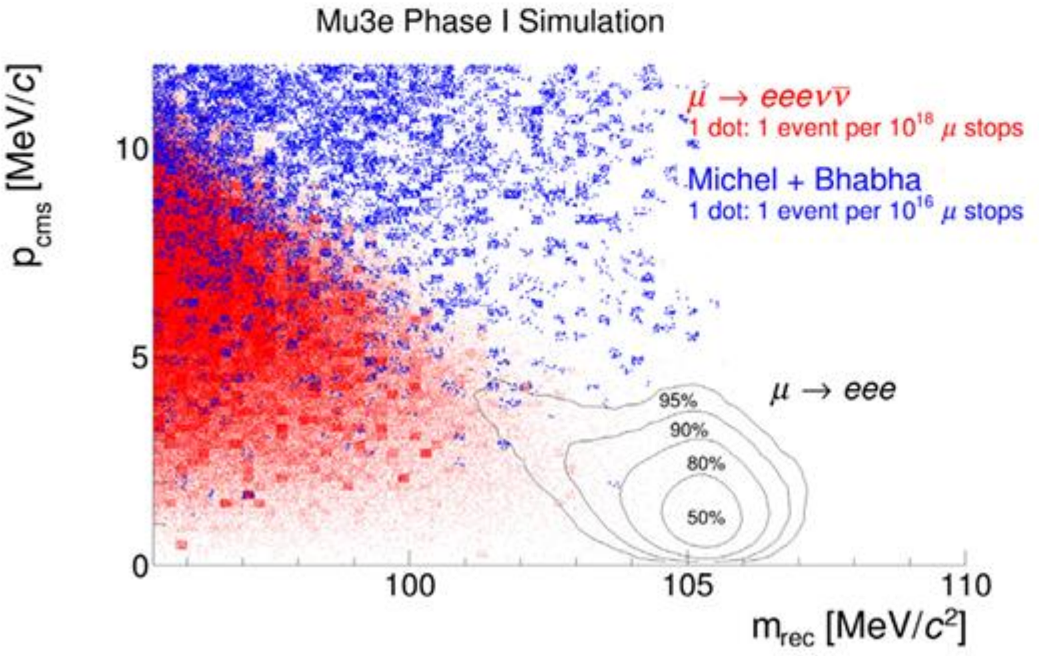
Mu3e Final Sensitivity

Mu3e Physics

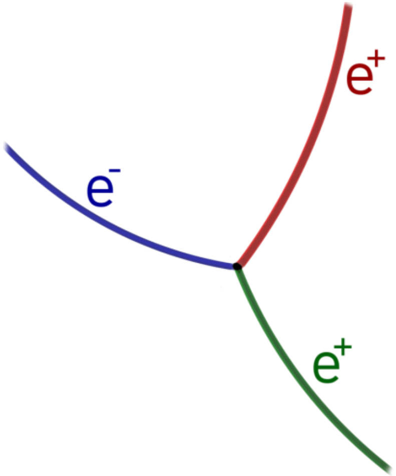
- Mu3e aims to observe the decay: $\mu^+ \rightarrow e^+ e^+ e^-$
- If not exclude a branching ratio of $> 10^{-16}$ (Phase II) at a 90% confidence interval.
- We exploit the kinematic feature below:

$$\sum p = 0 \quad \text{and} \quad \sum E = m_\mu$$

- By reconstructing the tracks and deducing their momenta will be used to identify signal events.
- For this an excellent mass (and therefore momentum) resolution is required to discriminate signal events from background.

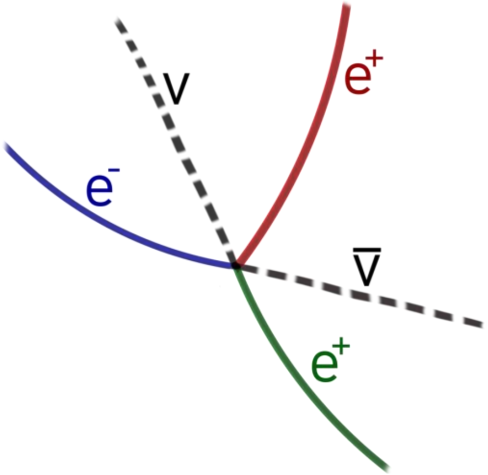


Background



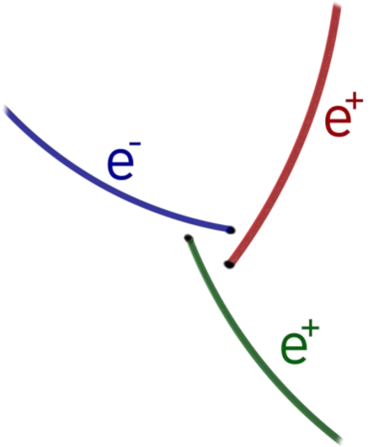
Signal Event:

- Three decay products from a single vertex.
- $\sum p = 0$ and $\sum E = m_\mu$



Internal Conversion:

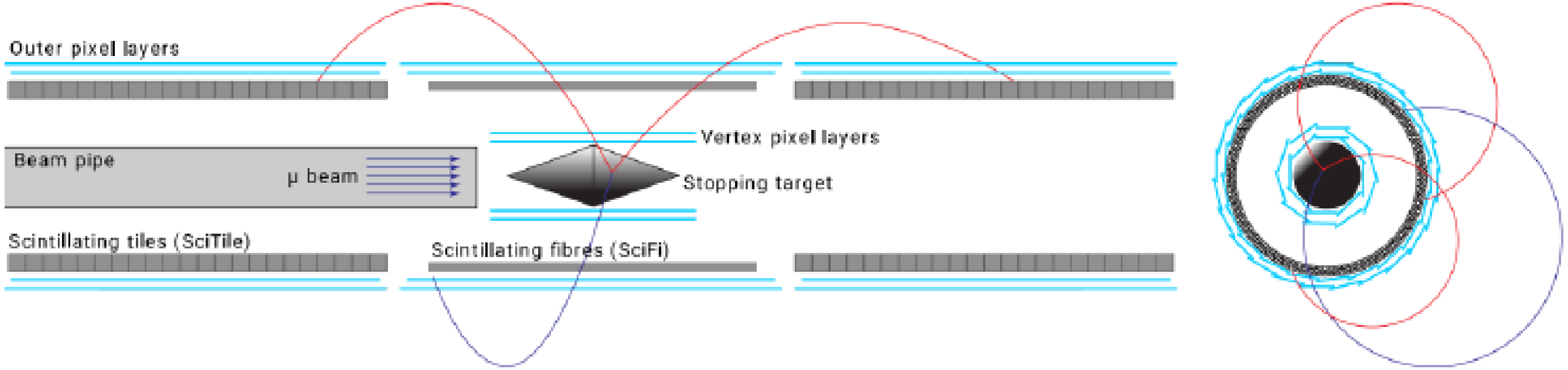
- Physical Background (Standard Model approved decay).
- Three decay products from a single vertex.
- $\sum p \neq 0$ and $\sum E \neq m_\mu$



Combinatorial Background:

- Background from algorithm.
- Michel decays that recurl multiple times and overlap.
- Combined with radiative decays or Bhabha.

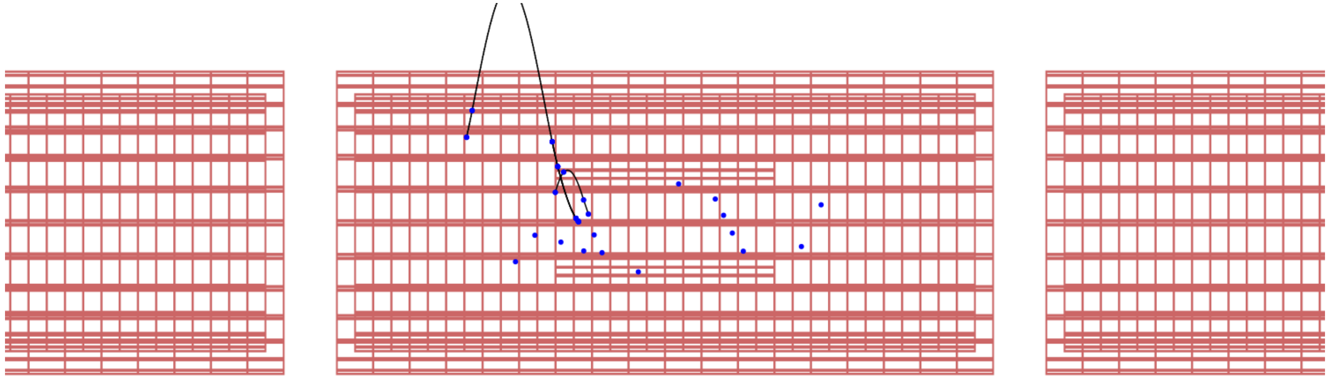
Experimental Design

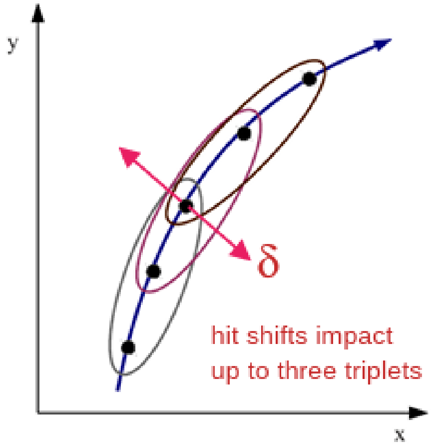


- This shows a basic view of the phase-I Mu3e detector.
- Muons are deposited on the surface of the stopping target.
- After decay, the products are driven into helices by the magnet that sits around the detector.
- A series of layers of pixel detectors take measurements of the position of the decay products in flight.
- A layer of scintillating fibres in the central station and scintillating tiles in the recurl stations provide temporal information on the tracks.
- Precise measurements of the track position and momentum are required; the task is to reduce the material budget and therefore the multiple scattering.

Tracking in the Mu3e Experiment

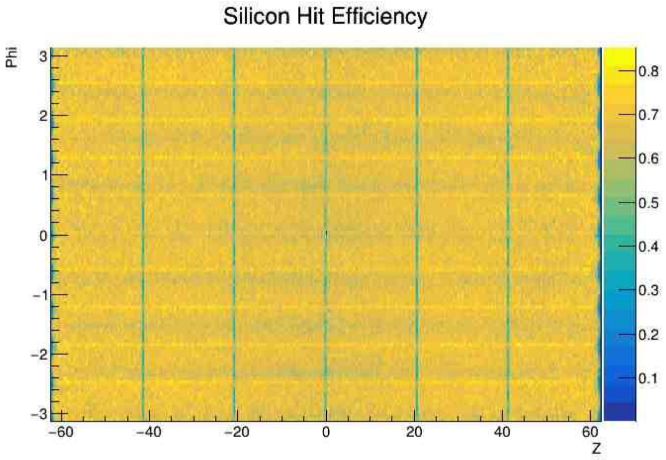
- The Mu3e experiment is sat in a homogenous magnetic field and therefore the decay products trajectory are described by a helix.
- The base unit for the fitting is a triplet of hits. The fitting is factorised into a circle fit in the plane transverse to the magnetic field and a straight line fit in the longitudinal plane. The deflection angles due to multiple scattering and the hit position resolution are treated as the sources of uncertainty in the fitting.
- The task is to find a three-dimensional curvature whereby the below equation is minimised:
  - $\chi^2(p;\vec{\delta}\,) = \sum_{triplet\ j=0}^{nhit\ -3} \sin(\vartheta_j)^2 \frac{\Delta\Phi_{MS,j}(p;\vec{\delta})^2}{\sigma_{MS,j}^2(p)} + \frac{\Delta\Theta_{MS,j}(p;\vec{\delta})^2}{\sigma_{MS,j}^2(p)} + \sum_{hit\ k=0}^{nhit\ -1} \vec{\delta}_k^{\mathrm{T}}\, V_k^{-1} \vec{\delta}_k$



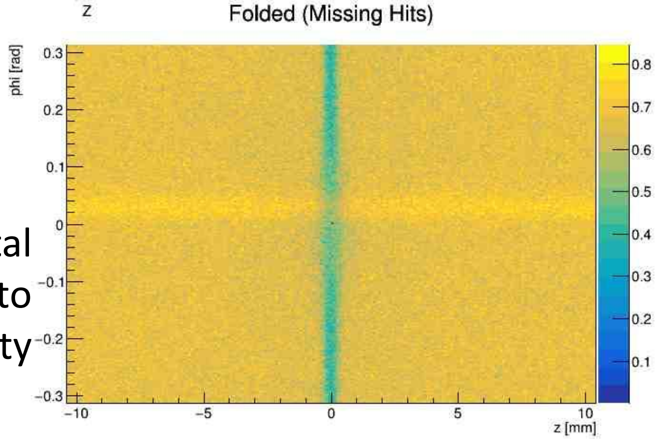


Tracking: Detector Hit Efficiency

- Initially, an algorithm was designed to detect inefficiencies in the silicon tracking layers. This was completed using an adaptation to the Mu3e tracking algorithm.
- A 'dead' layer is introduced by ignoring the hits from a given silicon layer in the detector. Tracks were then reconstructed with n-1 hits.
- The layer was then switched back on and hits were added to the tracks if they fell within the trajectory of the track.
  - Assuming 100% purity of the tracks, if a hit was not readded, it can be assumed the track passed through an inefficient or 'dead' area.
  - By studying the effect purity has on the efficiency calculation, this is used as a systematic uncertainty.
- The ratio of the number of tracks that showed an inefficiency against the number of tracks that had hits readded was used to calculate the hit efficiency of a given layer.



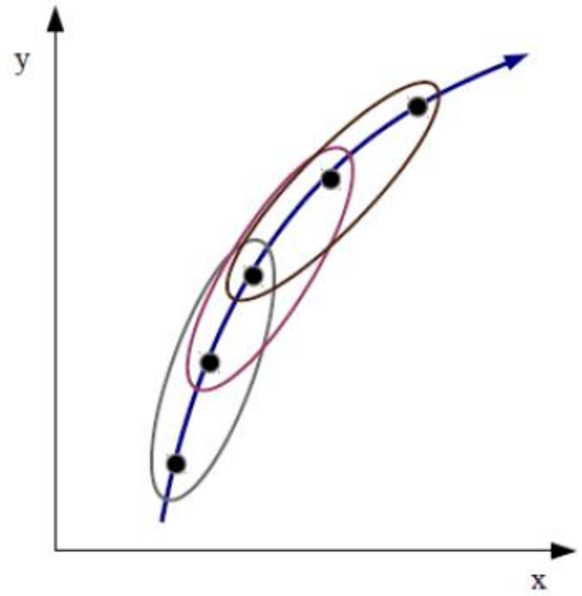
$$Efficiency = \frac{Tracks\text{: } Hit\ Found}{Total\ Tracks}$$



From a 75% efficiency, the total hit efficiency was calculated to be 74.1 +/- 0.84%. (Uncertainty from statistics)

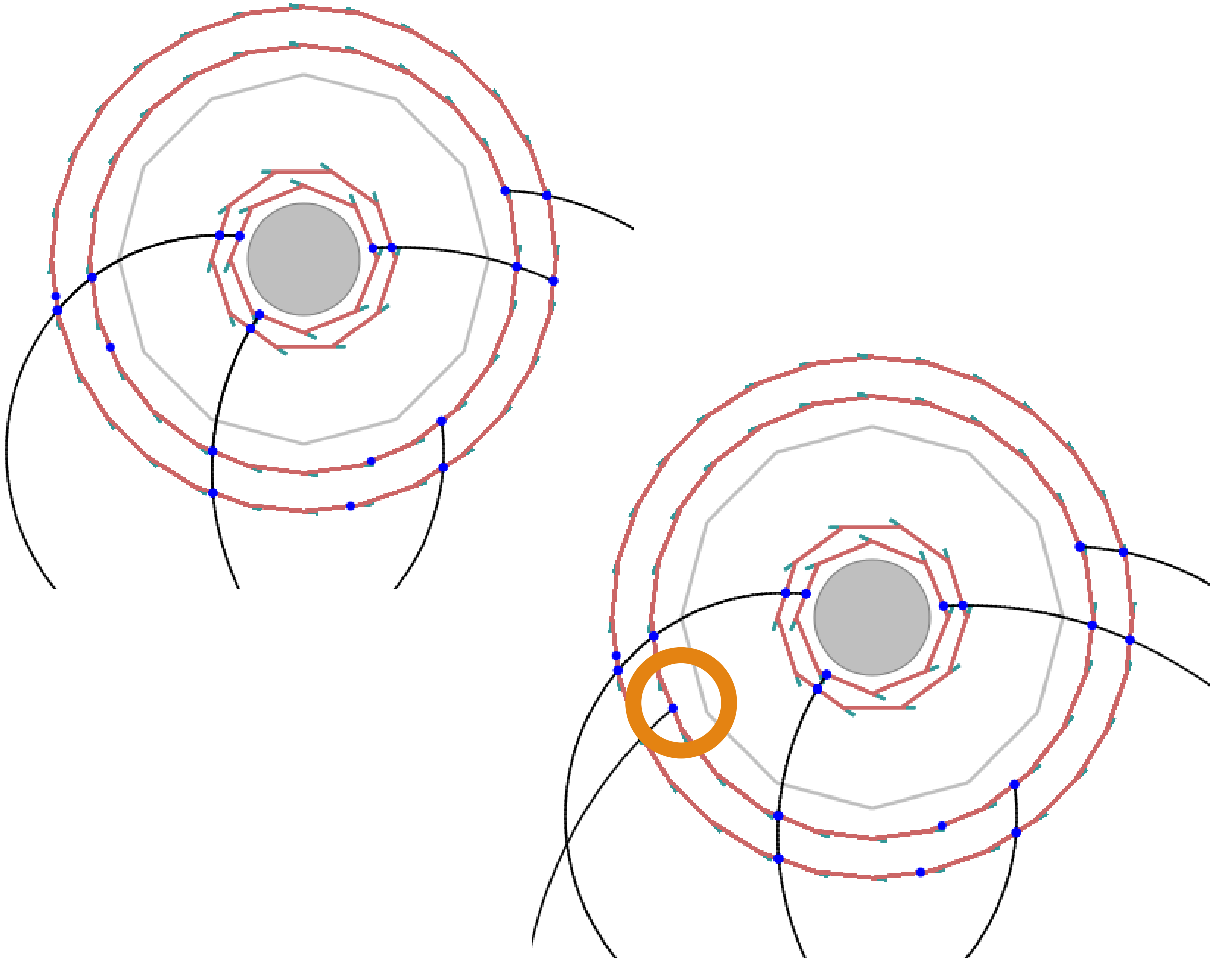
Tracking: Recovering Detector Efficiency

- Following this, an algorithm was written to recover tracks that would otherwise be lost due to inefficiencies in a given layer.
- The Mu3e tracking algorithm is designed to reconstruct 4, 6, or 8 hit tracks, provided that the tracks have hits in every silicon tracking layer consecutively.
  - This presented the issue that if a hit had not been recorded by the detector (due to inefficiency or a broken chip), the track and, therefore, any information on the respective vertex would be lost.
- In the nominal tracking algorithm, hits are combined into triplets from the innermost layer working outwards. A fourth hit is added, which combines two triplets. Longer tracks are extrapolated afterward.



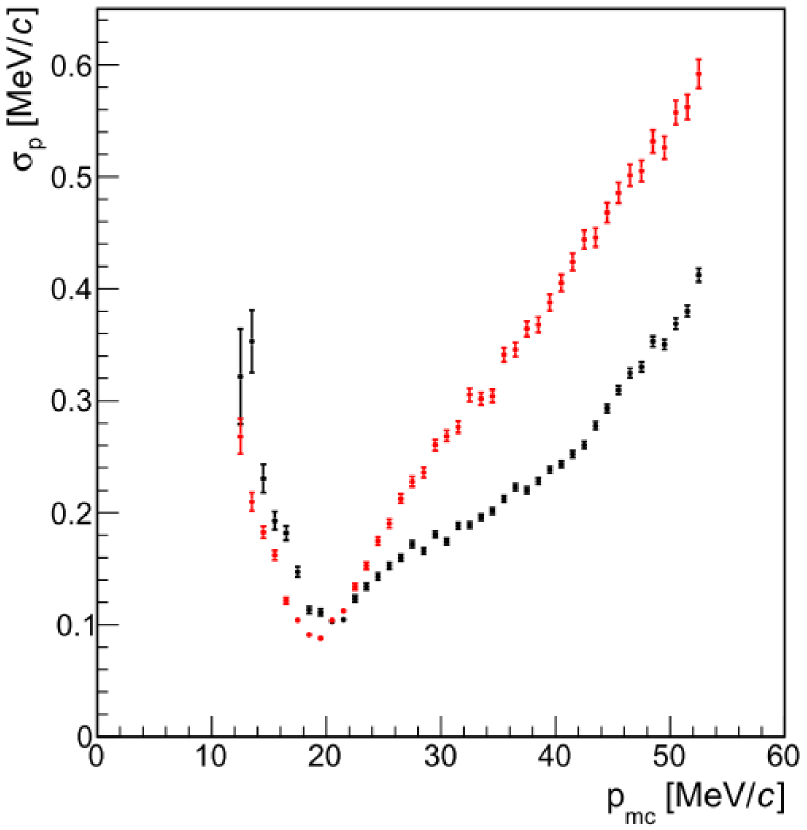
Tracking: Recovering Detector Efficiency

- In this alternative tracking algorithm, triplets are generated from every layer, not just the first. They are also found pointing both inwards and outwards.
- Combinations of triplets are then connected based on common hits to form sequential tracks.
- If an inefficiency is present, unique combinations of triplets will reveal the inefficient layer, and subsequent action can be made to look for additional hits.
- Using this method, track reconstruction efficiency can be recovered in the event of broken or noisy sensors.
- The task became assessing if n-1 hit tracks have an acceptable resolution and the effect that including the new set would have on the momentum and mass resolution.



Tracking: Recovering Detector Efficiency

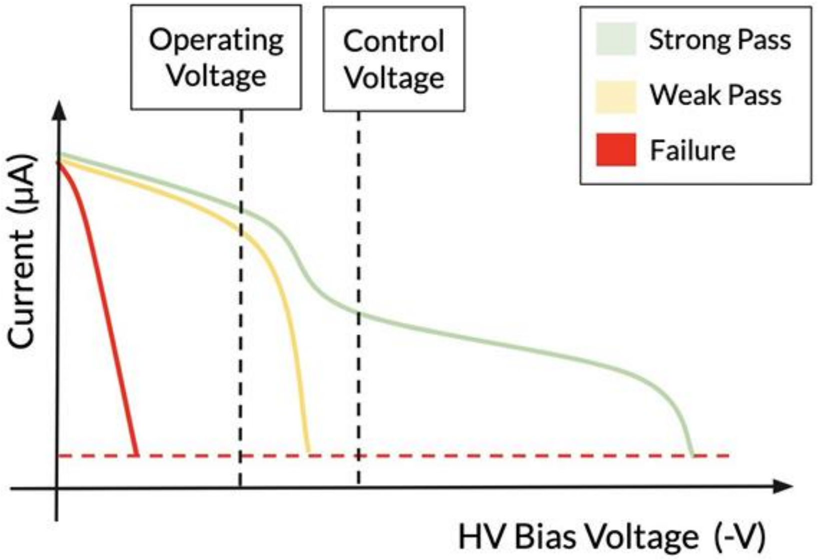
- An excellent mass resolution is required to suppress internal conversion events and combinatorial background.
- To achieve the required mass resolution; an excellent momentum resolution is required ($< 1\ MeV/c$).
- Preliminary results show the 5 hit tracks to have a resolution $\approx 0.5\ MeV/c$.
  - The uncertainties on this calculation are large ($\approx 0.07\ MeV/c$) and are expected to vary depending on the layer presenting inefficiency.
- Whilst there is a reduction in the precision of the momentum measurement and therefore the vertex analysis, there is a significant increase in track reconstruction efficiency in the presence of detector inefficiencies.

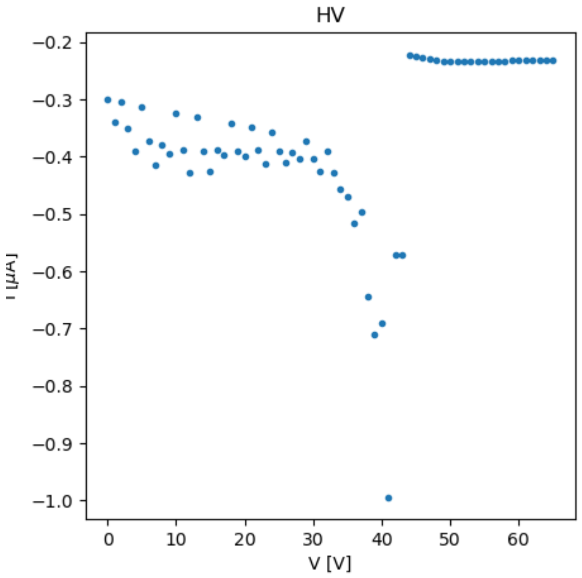


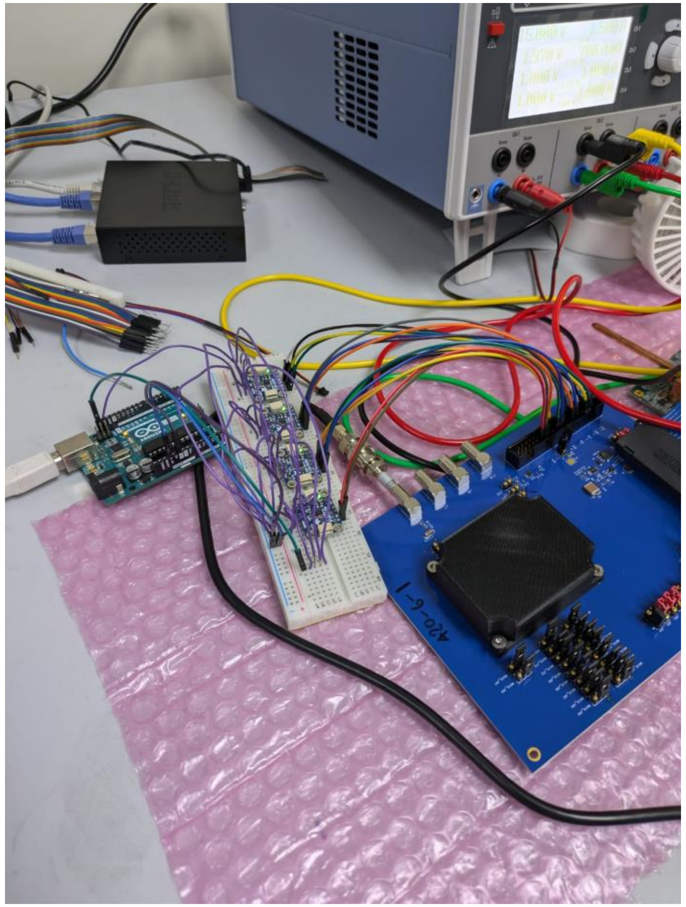
Thank You

Questions?

Pixel and Module QC



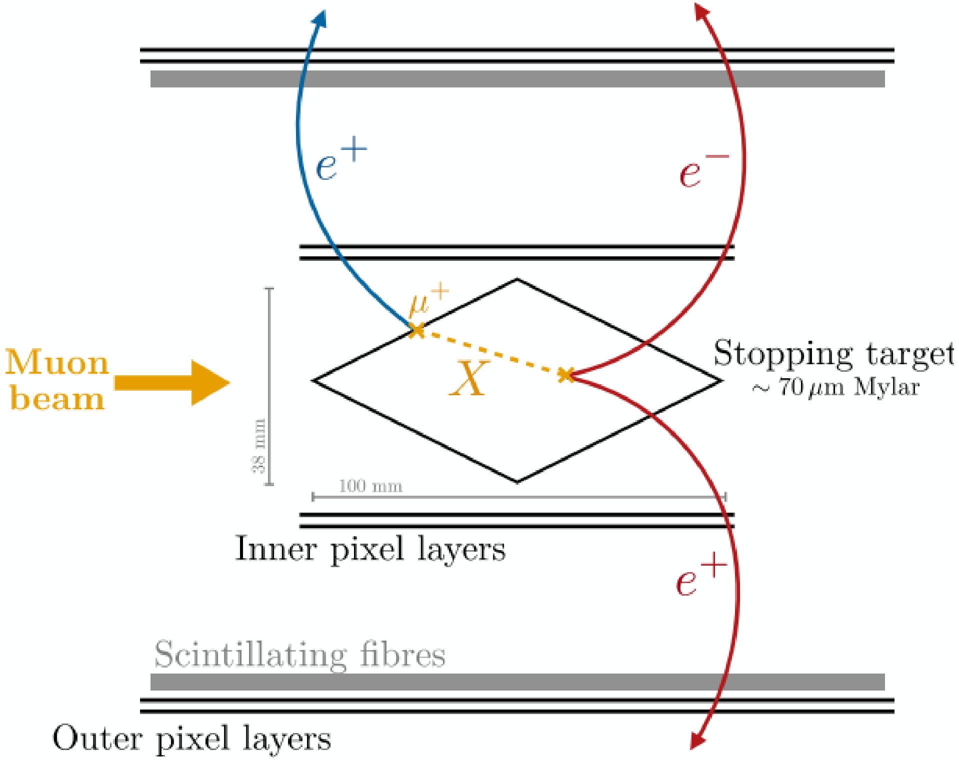




- In the clean room we have a setup that is going to complete pixel and module quality control tests.
- This consists of a probe station looking for mechanical faults and defects.
- We currently have a PC that completes electrical QC tests by taking DAQ variables from our pixel probe card.

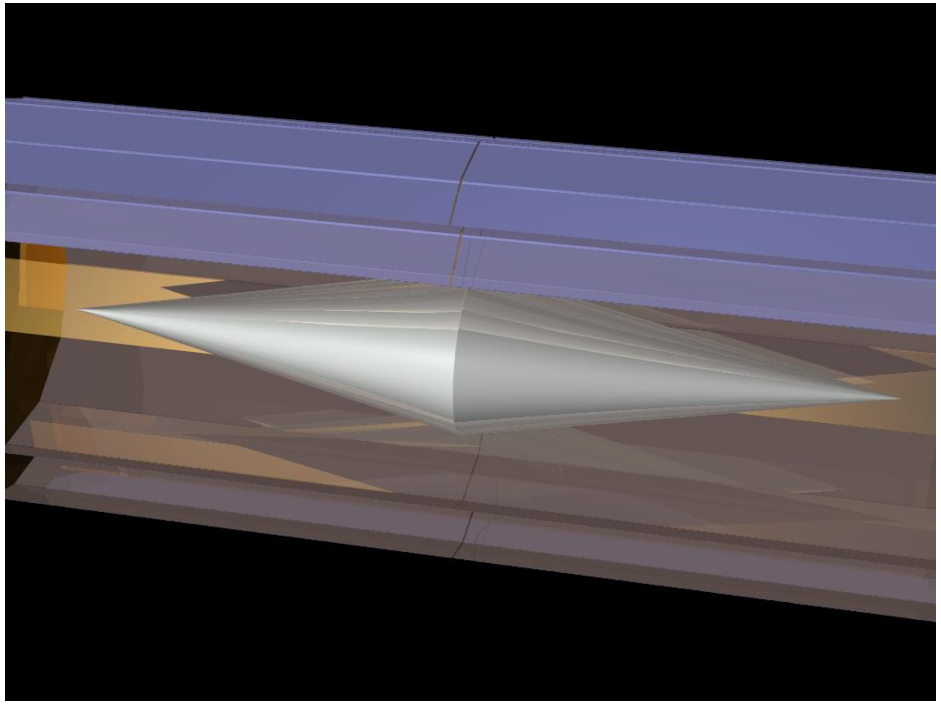
Other BSM Physics

- The Mu3e detector could also be used to detect further beyond the Standard Model decay channels.
- Examples of this are:
  - $\mu \rightarrow eX$ which would present as a peak in the Michel spectrum.
  - Decay of muon to dark photon and electron, with the dark photon further decaying to e^+e^- pair.
  - Muon decay to electron and axion-like particle. This would promptly decay to e^+e^- pair.
  - Muon decay to electron, two neutrinos and axion-like particle. This again would promptly decay to e^+e^- pair.
- This analysis would be looking for a displaced vertex, but in most cases still be able to exploit the kinematic feature of the muons rest mass.



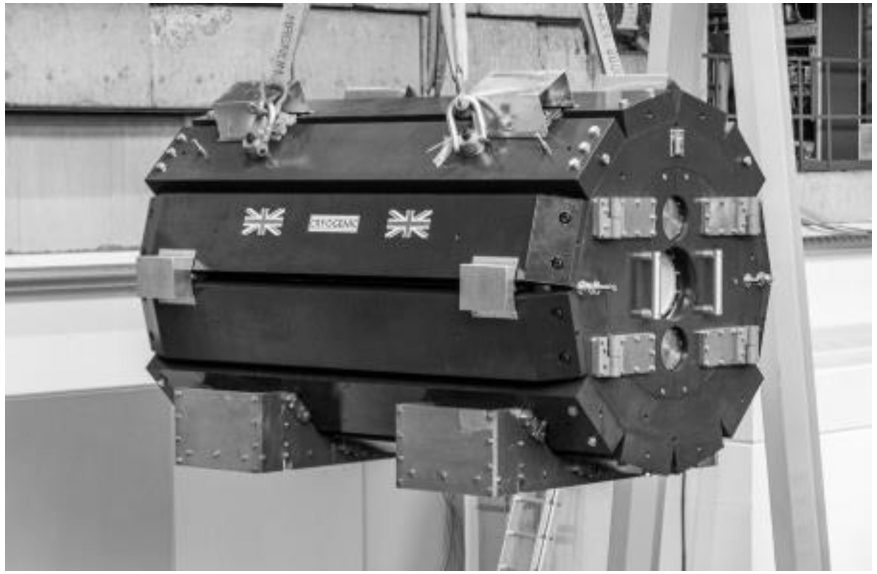
Muon Beam and Stopping Target

- The experiment is based at PSI using the CMBL.
- This will deliver a muon rate $\sim 10^8 \mu^+$/s.
- These are deposited on the stopping target to bring them to rest.
- The target is a double cone with an opening angle of 23.8°. The material is $\approx 90\mu m$ Mylar.
- The aim is to reduce the material budget and therefore the radiation length. A double cone at a low angle increases the stopping power in the beam direction but not in the decay direction. It also spreads out the decay vertices across itself.
- Mylar is a low-Z material, further reducing the multiple scattering.
- Approximately 95.5% of the muons are stopped on the target.



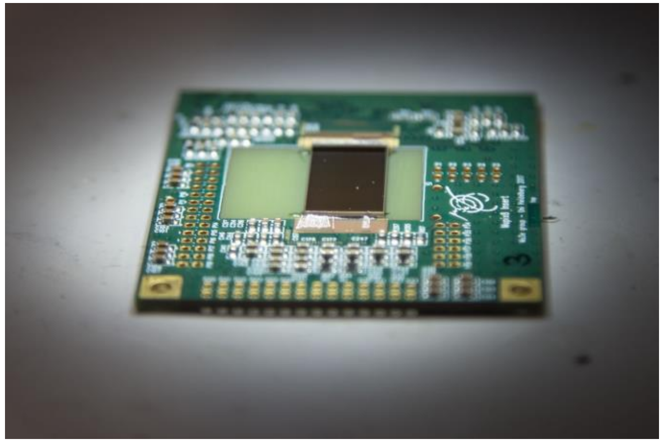
Magnet

- To experiment sits in a homogenous, solenoidal 1T magnet. This forces the decay products into characteristic helices.
- Accurate measurements of the momentum ($\frac{\sigma_p}{p} = 0.01$) of the particles are required to suppress the physical background. A 1T magnet increases the lever arm and drives the decay products into the recurl stations.
- With a 1T magnet, particles with a momentum $< 10MeV$ are rejected.
- The magnet must have a stability ${}^{\Delta B}/_{B} \leq 10^{-4}$ over 100 data-taking days. Inhomogeneities are required to be $\leq 10^{-3}$ in a $60cm$ radius around the magnet centre.



Pixel Detector

- The pixel detectors provide positional information on the tracks as they pass through the detector.
- This is achieved using a HV-CMOS sensor comprising of 256×200 pixels of pitch $80 \times 80 \mu m^2$.
- To reduce the material budget, the sensors are back-thinned such that the total depth is $50\mu m$. This results in a radiation length $X/_{X_0} = 0.115\%$ per tracking layer.
- The spatial resolution of these sensors should be $\leq 30\mu m$.
- The hit efficiency of MuPix11 is $\geq 99\%$.



sensor dimensions [mm^2]	$\leq 21 \times 23$
sensor size (active) [mm^2]	$\approx 20 \times 20$
thickness [µm]	≤ 50
spatial resolution µm	≤ 30
time resolution [ns]	≤ 20
hit efficiency [%]	≥ 99
#LVDS links (inner layers)	1 (3)
bandwidth per link [Gbit/s]	≥ 1.25
power density of sensors [mW/cm^2]	≤ 350
operation temperature range [°C]	0 to 70

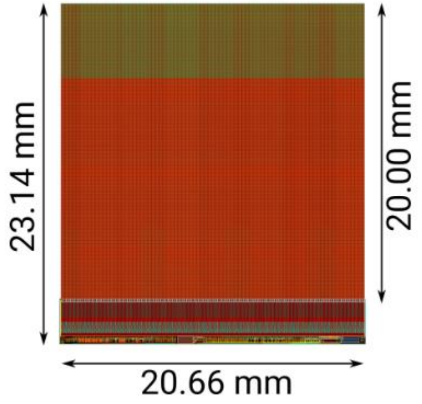
HV-MAPS and MuPix11

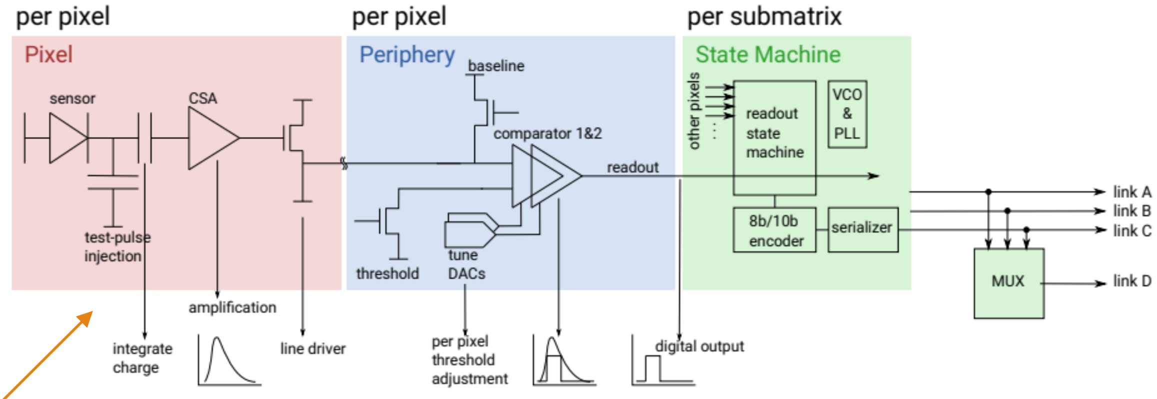
- This technology should collect charge via drift, with a $\sim 5ns$ time resolution.

- The pixel detectors used are constructed with a CMOS complimentary metal-oxide semiconductor) fabrication process. Described as complimentary due to the use of both P and N-channel transistors, also referred to as ‘floating logic’.

- The advantage of using this design allows for an excellent fill-factor, can be very radiation hardened, and a high bias voltage can be applied to increase the size of the depletion zone thus increasing the hit efficiency to $\geq 99\%$.

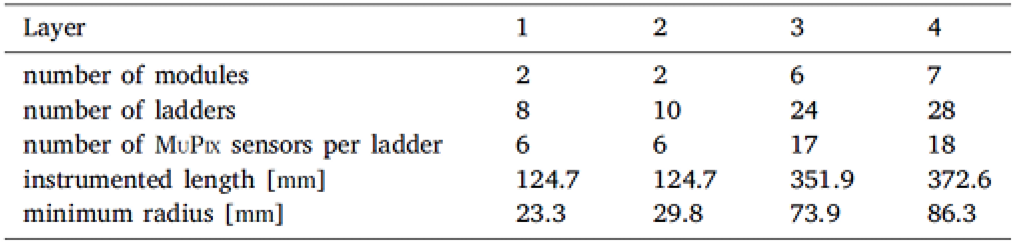
- CMOS devices also allow readout circuitry to be buried in the N-well. The circuitry for MuPix can be seen here.



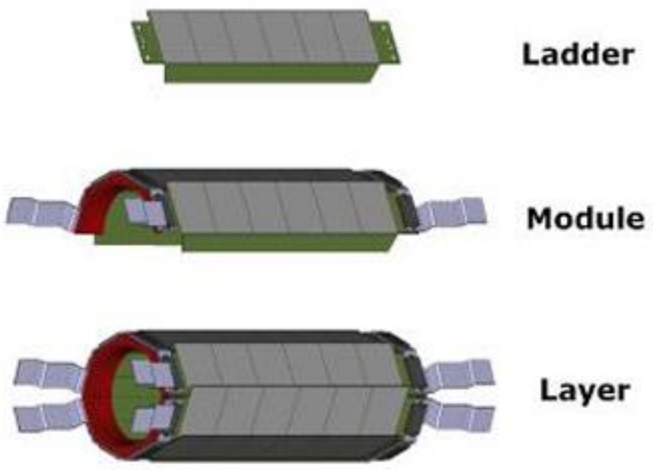


Ladders and Modules

- The individual sensors are placed next to each other as a ‘ladder’.
- These ladders are then placed in parallel next to each other in groups of 4 as a module.
- A layer is series of modules sat parallel to each other as shown to the right.
- Each layer is cooled with a $50 g/s$, $5 kW$ helium cooling system.
- The radiation length of a given layer is $X/X_0 \approx 0.1\%$

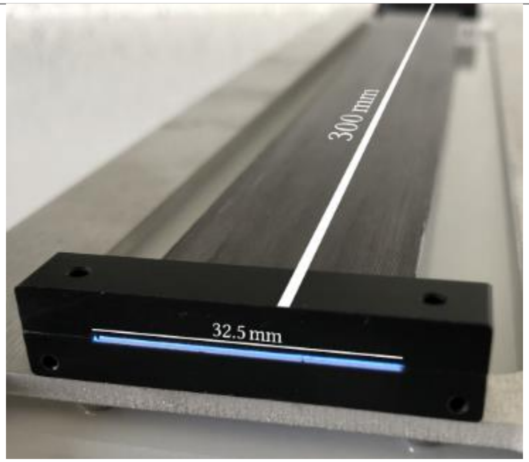


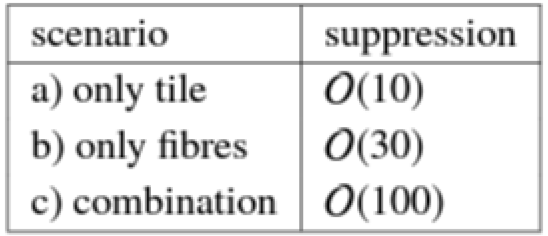
Layer	1	2	3	4
number of modules	2	2	6	7
number of ladders	8	10	24	28
number of MuPix sensors per ladder	6	6	17	18
instrumented length [mm]	124.7	124.7	351.9	372.6
minimum radius [mm]	23.3	29.8	73.9	86.3



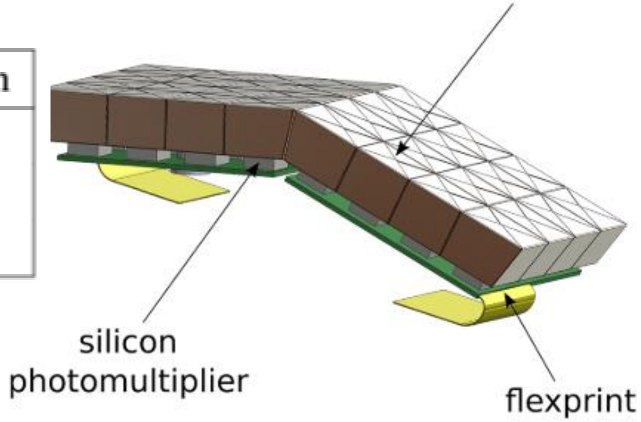
Timing Detectors

- Combinatorial background is the coincidence of multiple decays overlapping in the same frame. Suppression of this is achieved with excellent timing resolution and good vertexing. The additional suppression due to timing with different sub-detectors is shown here.
- This timing is achieved with scintillating fibres in the central station and scintillating tiles in the recurl stations. Both are arranged as a cylindrical layer such as the pixel detectors. The efficiency of these detectors is $95 - 100\%$.
- The fibres produce a time resolution of $< 0.5ns$ and the tiles produce a resolution $\approx 100ps$. 59% of the decay products reach the tile detectors.
- The radiation length of the fibres is $< 0.3\%$.



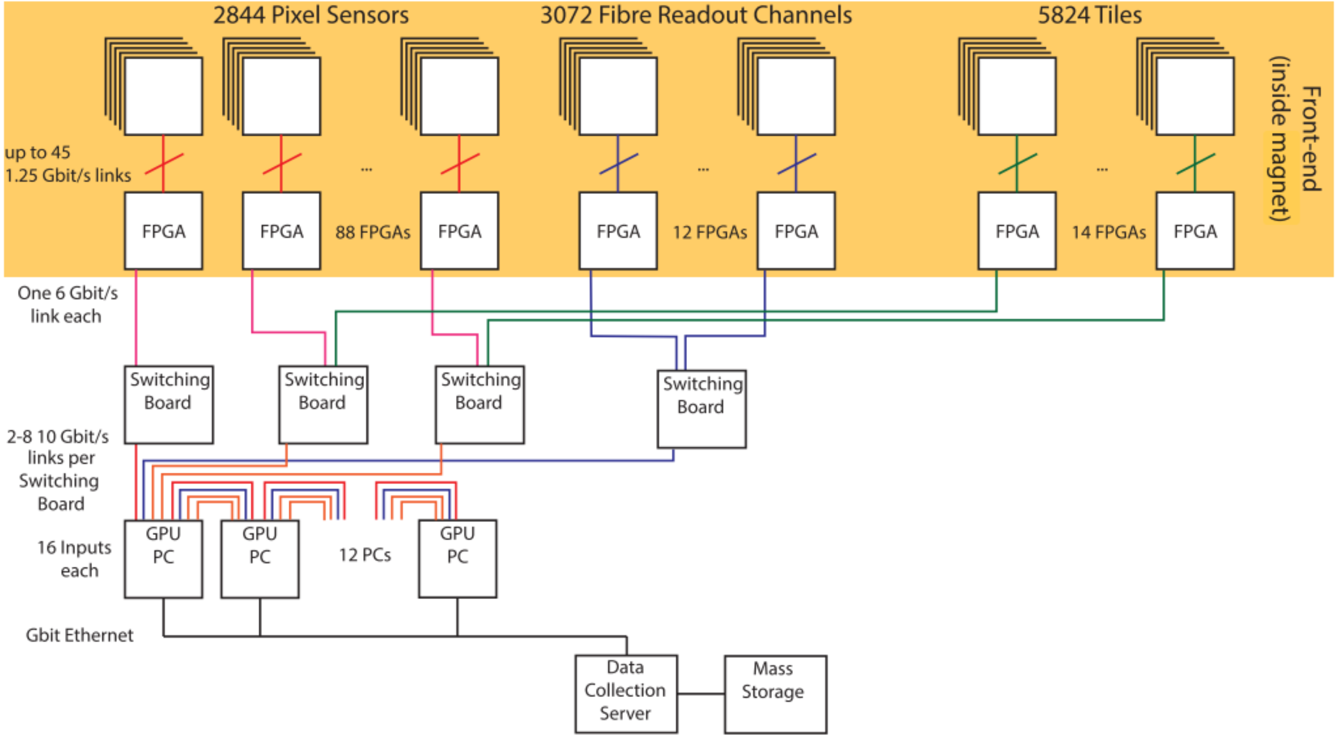


scenario	suppression
a) only tile	$\mathcal{O}(10)$
b) only fibres	$\mathcal{O}(30)$
c) combination	$\mathcal{O}(100)$



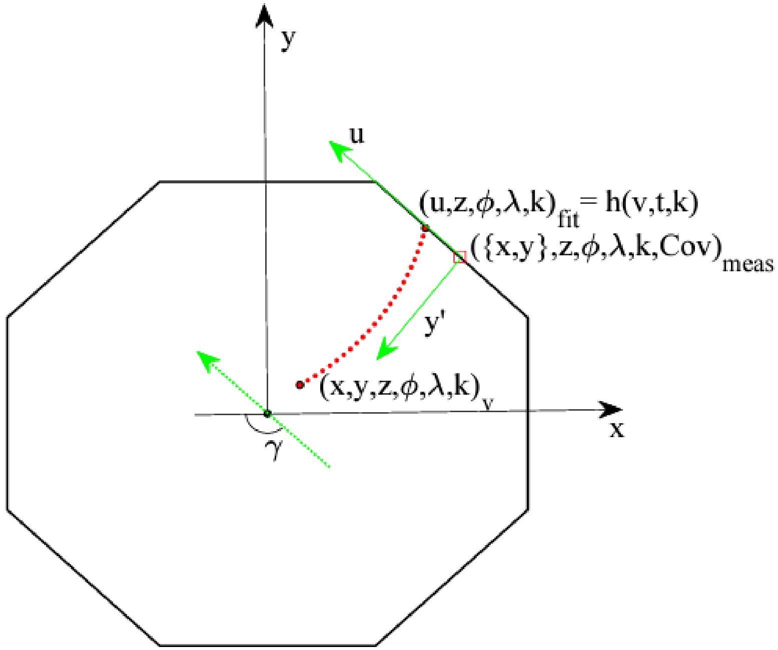
Data Acquisition

- The detector has no hardware trigger and therefore sends zero-suppressed hit information continuously.
- Frontend FPGA’s take data from the MuPix and MuTrig sensors and package it.
- This is passed through to the switching boards which acts as a switch between the FPGAs and filter farm, allowing the latter to see the full detector.
- The switching PCs are equipped with a combination of FPGA’s and GPUs to complete online selection.



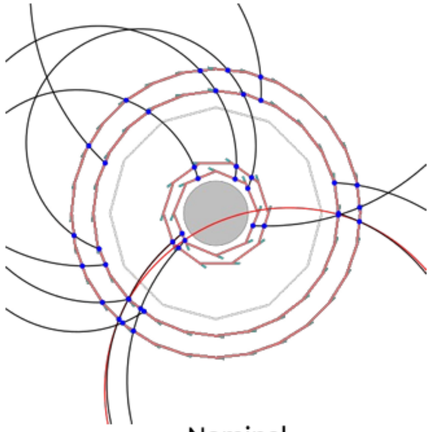
Vertexing in Mu3e

- The purpose of the algorithm is both to find and fit a given vertex.
- Every ++- combination in a 64ns frame is considered.
- The vertex finding is achieved by taking the trajectories of the three tracks and propagating back from a reference surface (the first pixel layer) back to the stopping target.
- The average of these three propagations is the first guess.
- By using the errors associated with the tracking (hit resolution, multiple scattering and energy loss), a least squares fitting algorithm can be applied to fit a vertex and further minimise the χ^2 value.

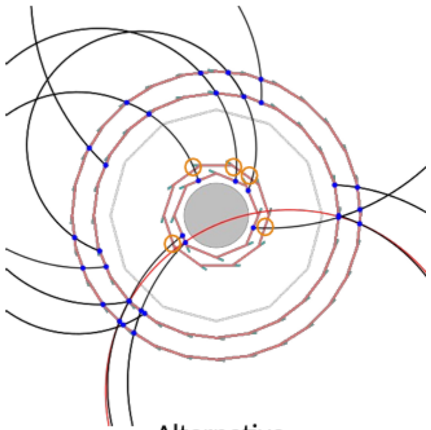


Liverpool Activities

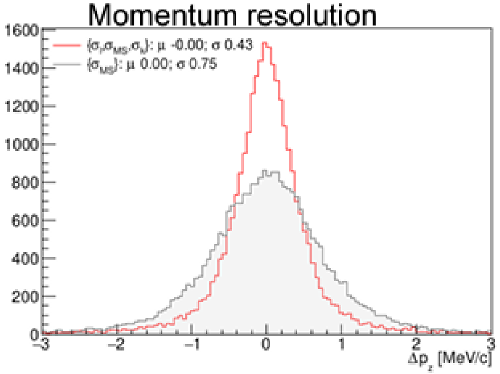
- Staff Members:
  - Joost Vossebeld
  - Helen Hayward
  - Nikos Rompotis
  - Paolo Beltrame
  - Mark Wong
  - Matthew Brown
  - Andrea Loreti
- PhD Students:
  - Jak Woodford
  - Charlie Kinsman
  - Sean Hughes
- Undergraduate Students:
  - Ting Chan
  - Kameron Vickers
  - Dan King

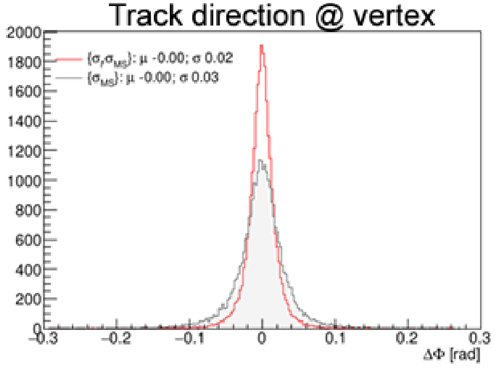


Nominal

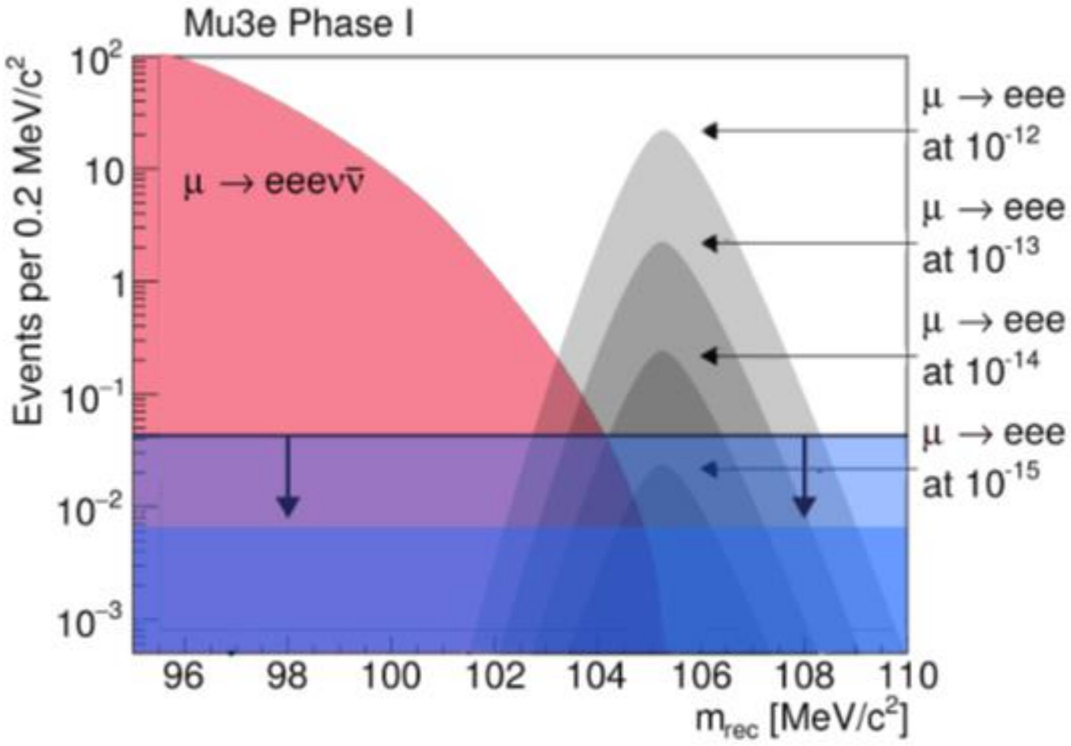


Alternative

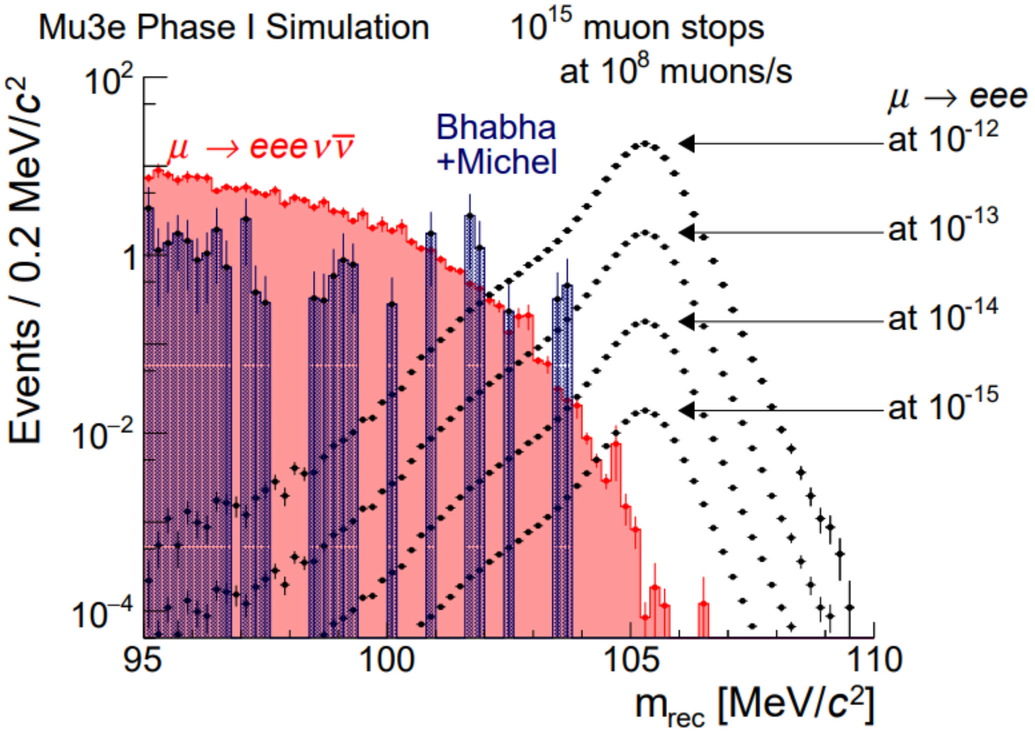


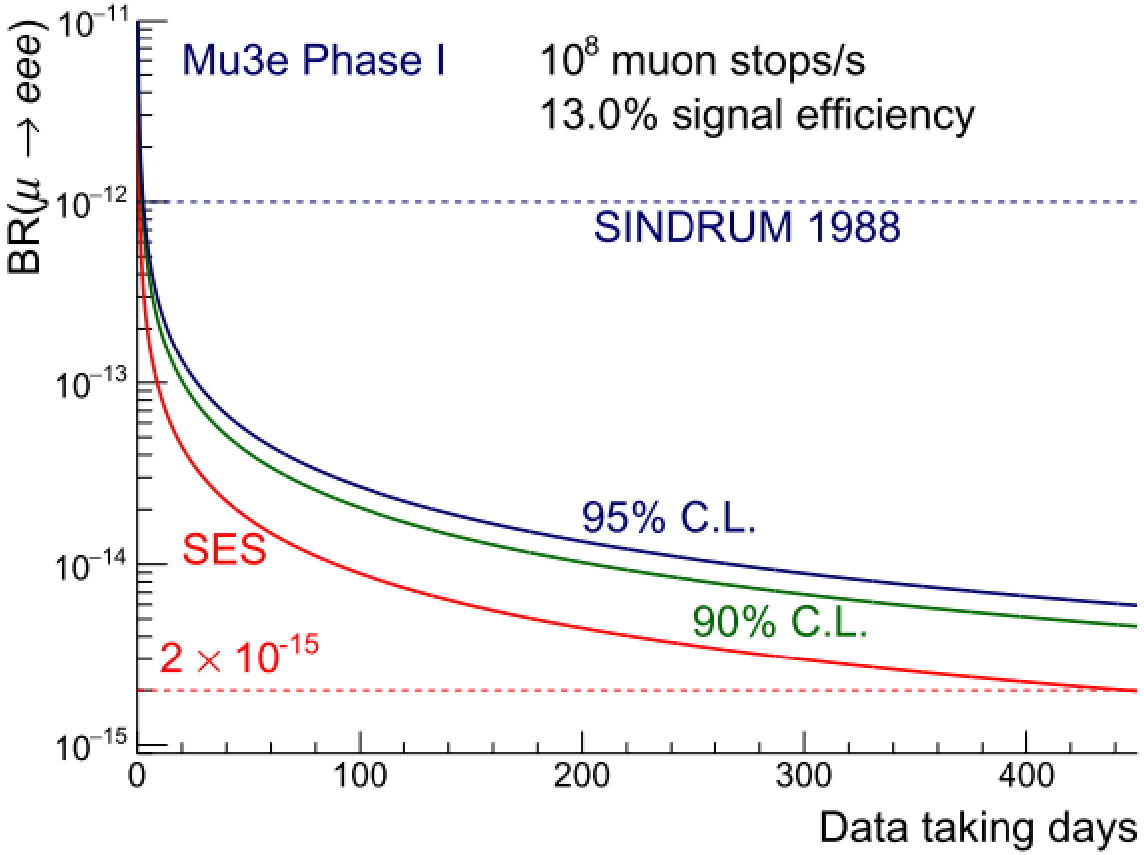


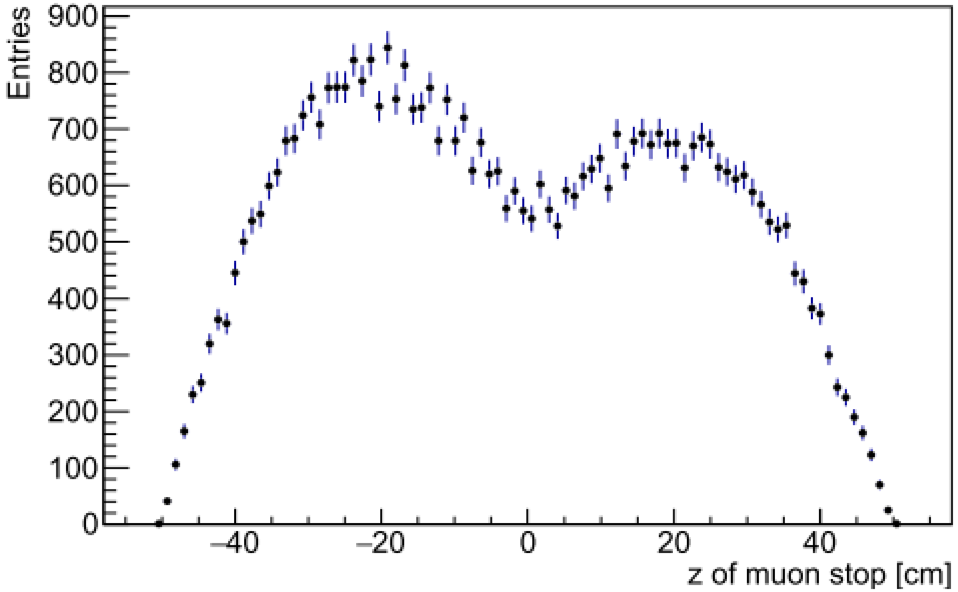
Background


Mu3e Phase I
Events per 0.2 MeV/c^2
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
$\mu \to eee\nu\bar{\nu}$
$\mu \to eee$ at 10^{-12}
$\mu \to eee$ at 10^{-13}
$\mu \to eee$ at 10^{-14}
$\mu \to eee$ at 10^{-15}
96
98
100
102
104
106
108
110
m_{rec} [MeV/c^2]

Background


Mu3e Phase I Simulation
10^{15} muon stops
at 10^8 muons/s
$\mu \to eee\nu\bar{\nu}$
Bhabha
+Michel
$\mu \to eee$
at 10^{-12}
at 10^{-13}
at 10^{-14}
at 10^{-15}
Events / 0.2 MeV/c^2
10^2
1
10^{-2}
10^{-4}
95
100
105
110
m_{rec} [MeV/c^2]


Mu3e Phase I
10^8 muon stops/s
13.0% signal efficiency
SINDRUM 1988
95% C.L.
90% C.L.
SES
2×10^{-15}
$\mathrm{BR}(\mu \to eee)$
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0
100
200
300
400
Data taking days


Entries
900
800
700
600
500
400
300
200
100
0
−40
−20
0
20
40
z of muon stop [cm]