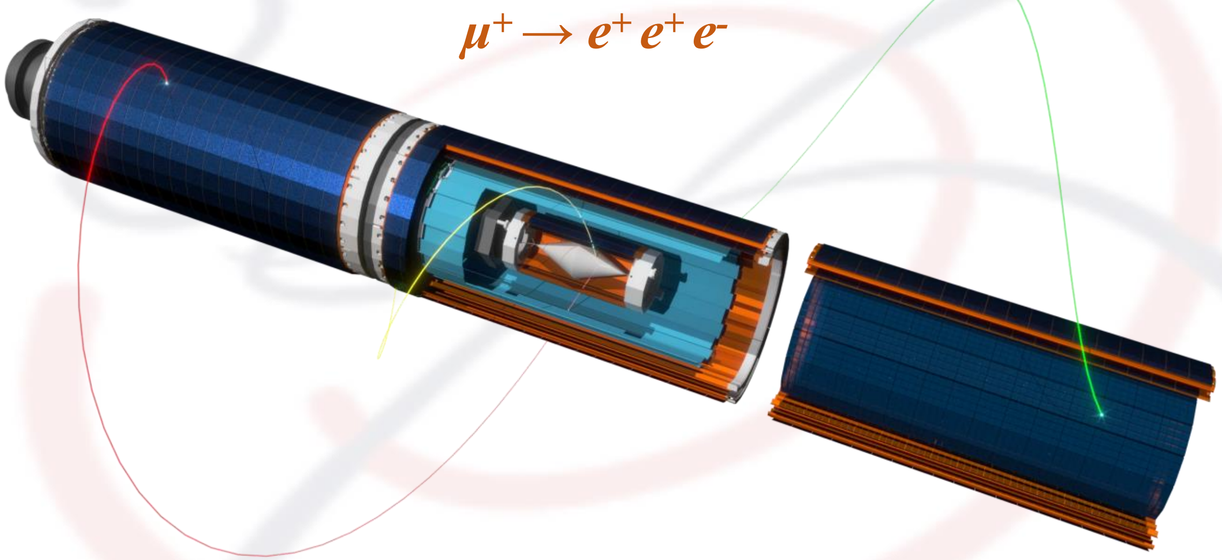
The Mu3e Experiment Searching for the Lepton Flavour Violating Decay

$\mu^+ \rightarrow e^+ e^+ e^-$



Afaf Wasili* on behalf of the Mu3e Collaboration**

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**) Paul Scherrer Institute (PSI), Uni Bristol, Uni Geneva, Uni Heidelberg, KIT Karlsruhe, Uni Liverpool, UCL London, JGU Mainz, Uni Oxford, ETH Zürich, Uni Zürich

Overview:

- Search for signal muon decays, background categories and the detector concepts for the Phase I and II of the Mu3e Experiment

Software:

- Studies of Mu3e tracking performance for different categories of particle tracks when effected by:

✓ Missing hits due to by dead layers dead chip or individual dead pixels
✓ Misaligned detector
✓ Noise in the pixel sensors

Hardware:

- Test-Beam Data Acquisition System for Characterization of High Voltage Monolithic Active Pixel Sensors

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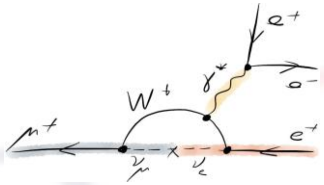
Motivation & Challenges

Search for Lepton Flavour Violation:

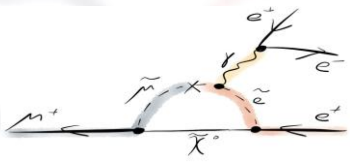
Decay : $\mu^+ \to e^+ e^+ e^-$

- Negligible in Standard Model **($Br < 10^{-54}$)**
- Can be enhanced in New Physics : (SUSY, leptoquarks, etc.), any observed decay will point to NP

- Current status: **$Br < 10^{-12}$ (SINDRUM)** at 90% CL
- **Mu3e Phase I**: Aiming for **$O(10^{-15})$** sensitivity at existing $\pi E5$ beamline**: 10^8 μ/s**
- **Mu3e Phase II**: Aiming for **$O(10^{-16})$** sensitivity at a new high-intensity muon beamline (HiMB)**: >10^9 μ/s**



Muon decay in the SM



Muon decay BSM (SUSY)

Signal:

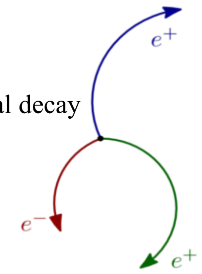
- Three tracks: $\mu^+ \to e^+ e^+ e^-$
- Decay at rest
- $P_e < 53$ MeV/c
- Common vertex
- Coincide in time
- $\Sigma P = 0$, $\Sigma E = m_\mu$

Background:

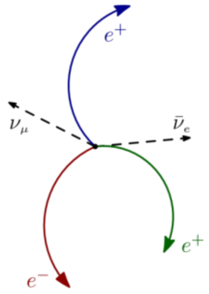
- Internal conversion background (IC BG): $\mu^+ \to e^+ e^+ e^- \nu^+ \bar{\nu}$ (suppressed by good momentum resolution)

- Accidental background (Acc. BG): Michel $\mu^+ \to e^+ \nu^+ \bar{\nu}$ with $e^+ e^-$, etc (suppressed by good time and vertex resolution)

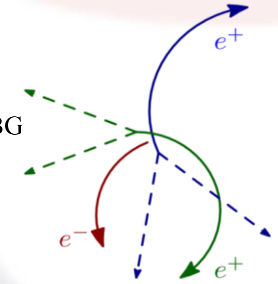
Signal decay



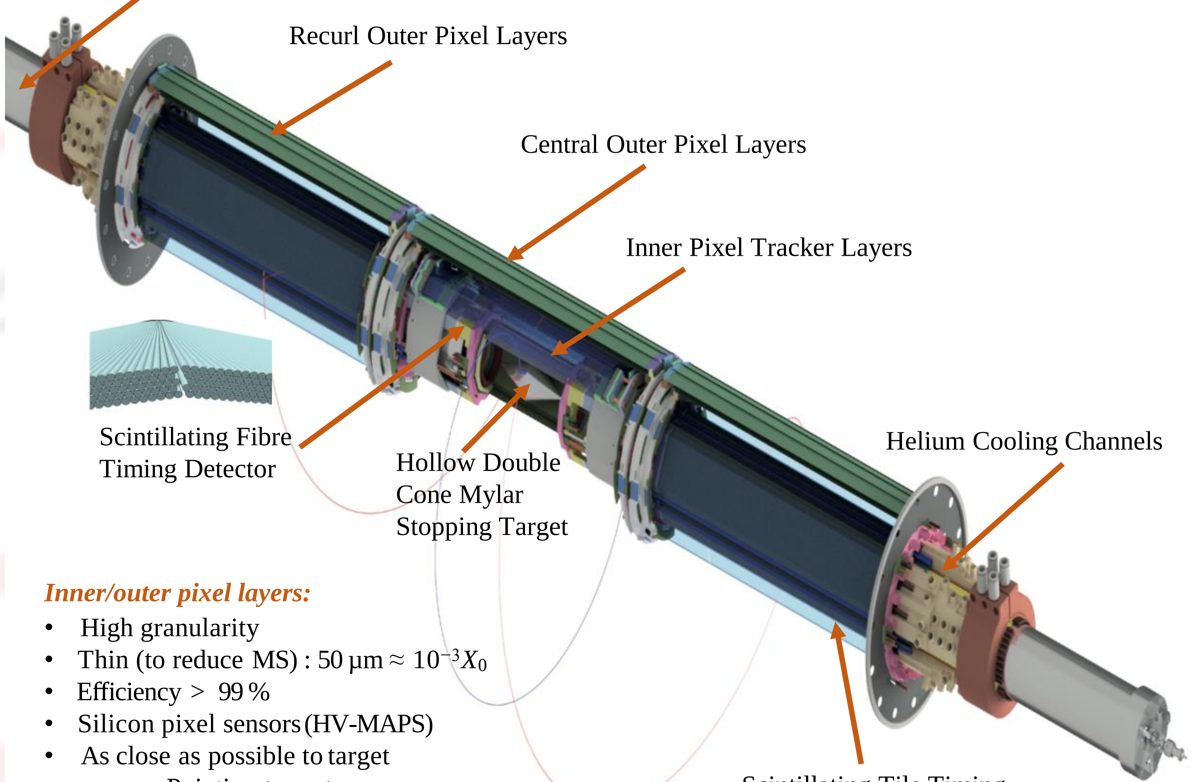
IC BG

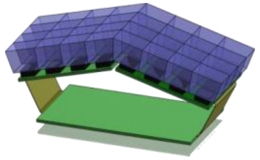


Acc. BG



Mu3e Detector Design





Inner/outer pixel layers:

- High granularity
- Thin (to reduce MS) : 50 μm ≈ $10^{-3} X_0$
- Efficiency > 99 %
- Silicon pixel sensors (HV-MAPS)
- As close as possible to target
  - Pointing to vertex
  - Reduce effect of MS

Target:

- Hollow double cone Mylar stopping target
- vertex separation

Fibre/tile timing detector:

- Precise timing
- Suppress Acc. BG
- Charge ID

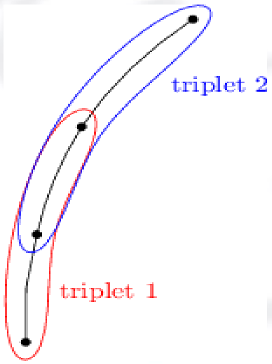
Simulation & Reconstruction

- Full detector Simulation (Geant4) in 50 ns framelength

Track Reconstruction

Triplet:

- Track is a sequence of triplets
- Basic block for track reconstruction
- 3 hits (combination 2 helices)
- Optimization the nonlinear problem multiple scattering



Categories of Nominal Tracks:

Short tracks:

- 4 hits in the silicon layers
- Seeds for long tracks

Long (recurl tracks):

- Combine 1 short track with 2 hits in recurl detector (6 hits)
- Combine 2 short tracks (8hits)

Categories of New Tracks:

➢ Artificially introduce different inefficiencies level into pixel layers in the central station and investigate recovering track efficiency by allowing holes on the track

Short tracks:

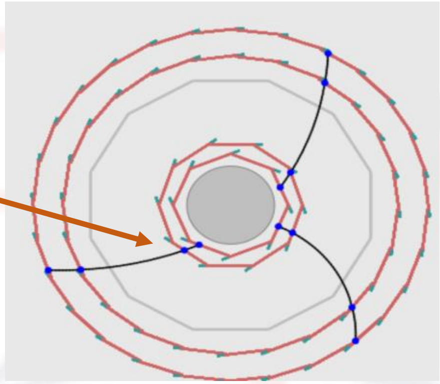
- 3 hits in the silicon layers with a missing pixel hit
- Seeds for long tracks

Long (recurl tracks):

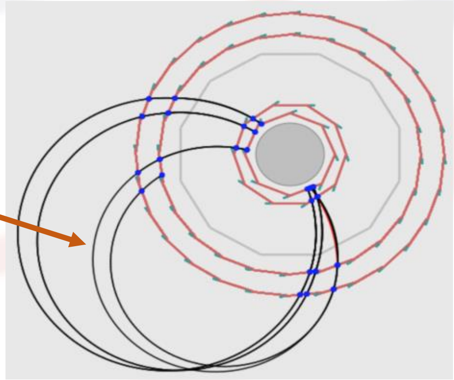
- Combine 1 short track with 2 hits in recurl detector (5 hits)
- Using long track with 5-pixel hits with two more hits in the CS of the detector (7-pixel hits)

Categories of Nominal Tracks

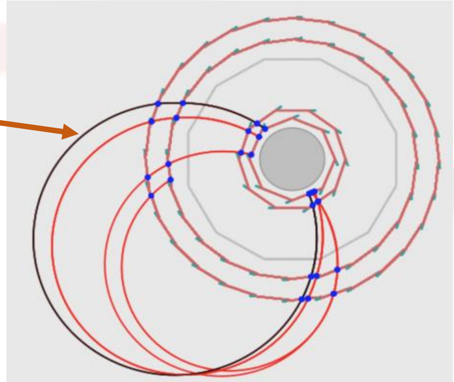
Standard short track with 4-pixel hits only in CS of the detector



Standard long track including 6-pixel hits via using short tracks as seed either in CS or 2-RS of the detector

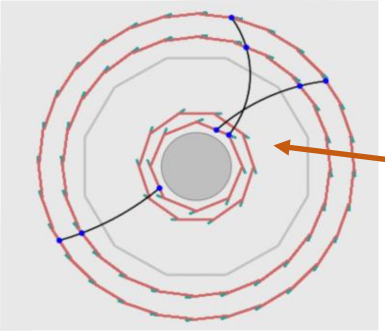


Standard long track including 8-pixel hits via using 2-short tracks as seed only in CS of the detector

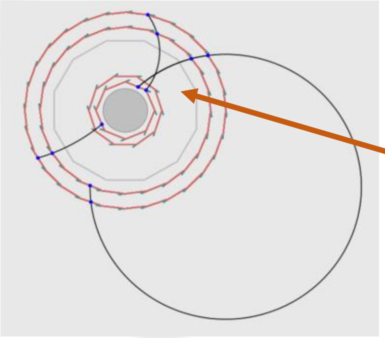


New Categories of Tracks

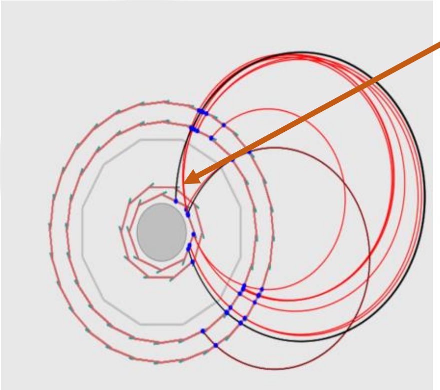
Imperfect short tracks with missing pixel hit in 1-silicon layer



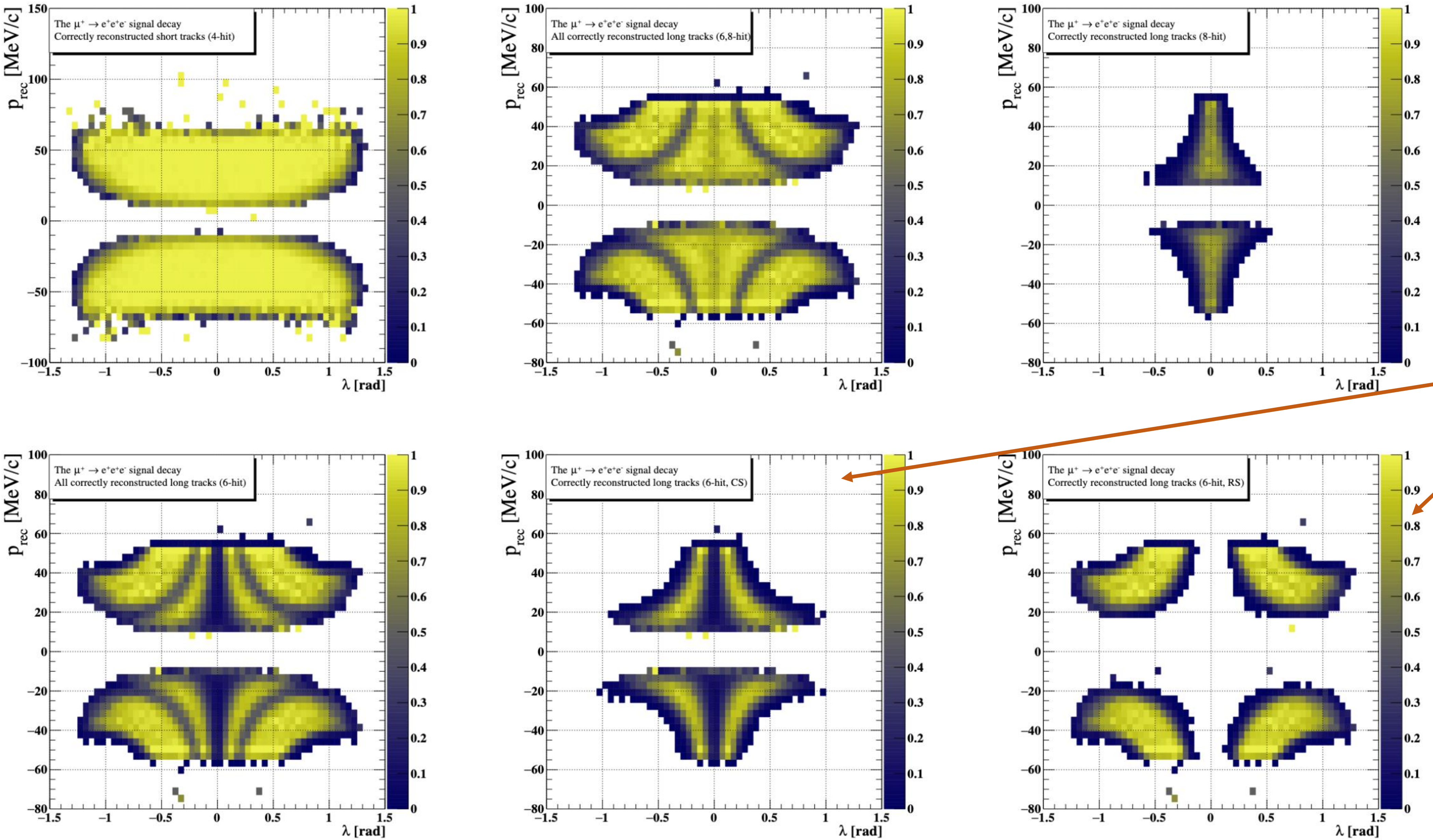
Imperfect long track including 5-hits with a missing pixel hit in 1-silicon layer via using short tracks as seed



Imperfect long track including 7-hits with a missing pixel hit in 1-silicon layer via using long track with 5-hits as seed specifying which hit id (outgoing or ingoing)



Categories of Nominal Tracks in CS or 2-RS of the Detector in 2D



Long Tracks with 6-hits in CS or RS of the Detector

Check the High Purity for the Long Tracks with 6-hits in the 2-RS of the Mu3e Detector

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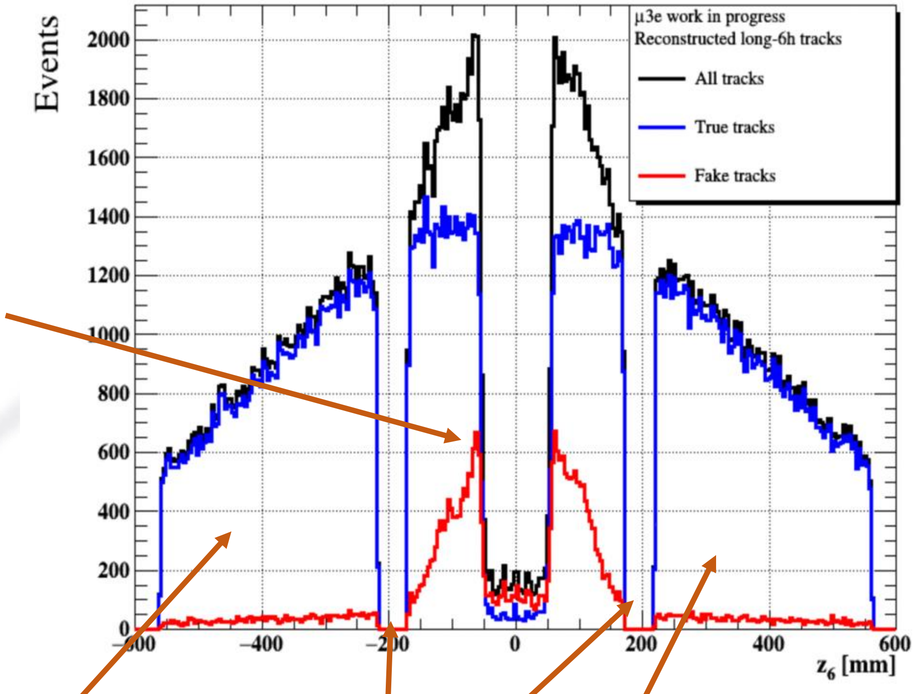
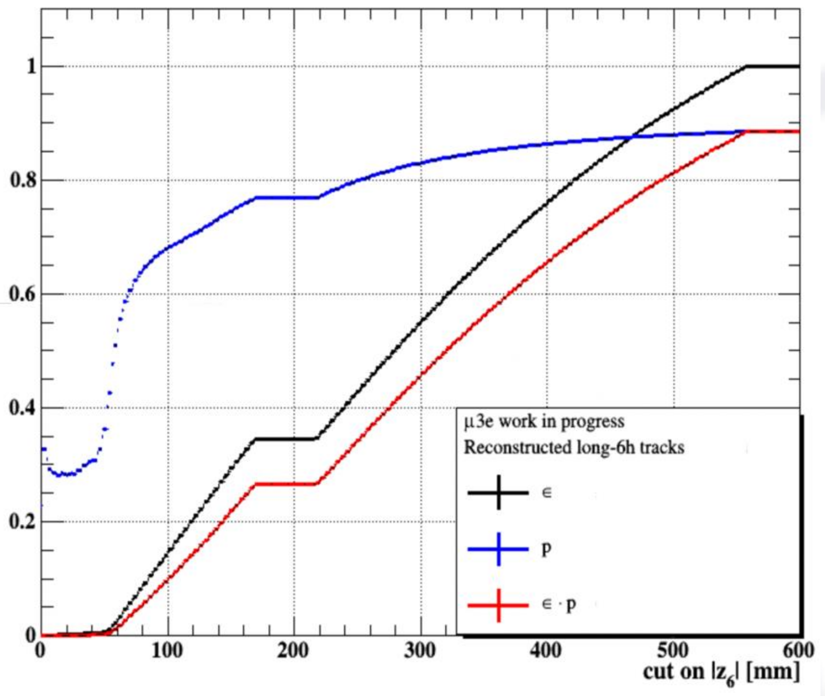


CS of the detector "ingoing tracks"

RS of the detector "outgoing tracks"

Service areas b/w stations

RS of the detector "outgoing tracks"



A Way of Splitting the Long Tracks with 6-hits

- Z6: 6th silicon hit in outer layers either in CS or RS, it is a good cut to to split long tracks with 6 hits recurl back into CS or RS of the detector
- Z6 < 200 mm: tracks can recurl back into CS
- Z6 > 200 mm: tracks can extrapolate into RS "that is because outer silicon detector is started from roughly 200 mm"

Reconstruction		CS (z6 < 200 mm)	RS (z6 > 200 mm)	CS and RS
Full	ϵ			0.837(267)
Full long-6h	ϵ			0.885(360)
Long-6h	ϵ ϵ relative to full long-6h	0.767(514) 0.365(36)		
Long-6h	ϵ ϵ relative to full long-6h		0.962(494) 0.578(266)	
Full long-8h	ϵ	0.549(513)		

TABLE 28: Efficiency ϵ for only correctly reconstructed long tracks with 6, 8, and all hits tracks.

Simulation and Track/Vertex Reconstruction of the Mu3e Detector & Timing Information

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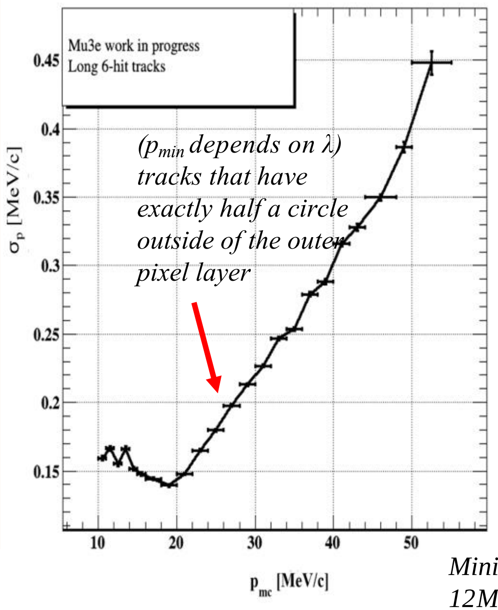
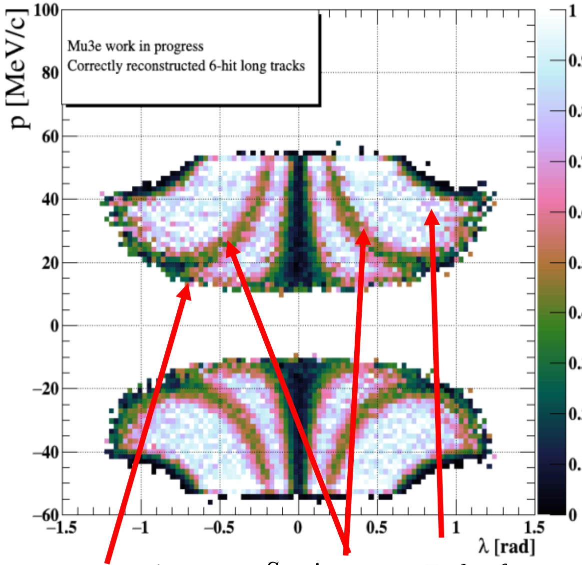
Acceptance and Efficiency



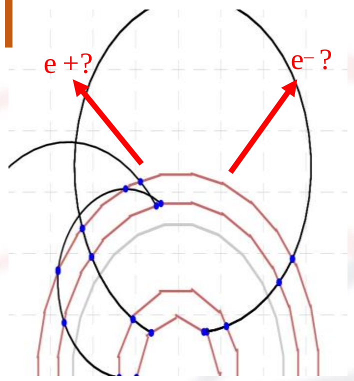


Minimum p_T acceptance ~ 12MeV/c (Limited by outer layerradius)

Service areas b/w stations

Ends of recurl stations

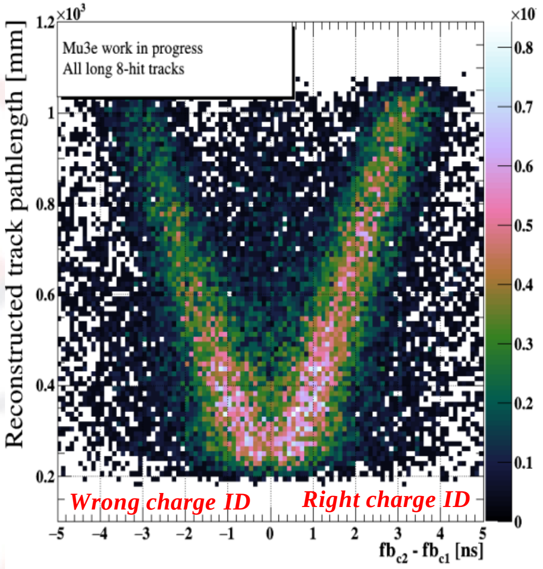
Timing and Charge ID

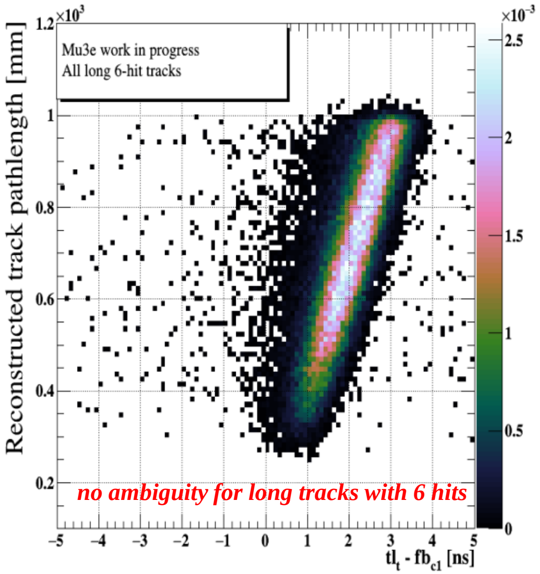


Ambiguity for central 8-hit tracks:

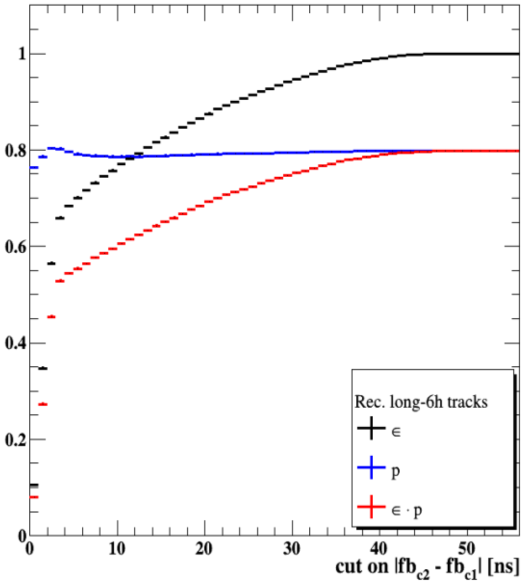
Charge ID for long 8-hit track:

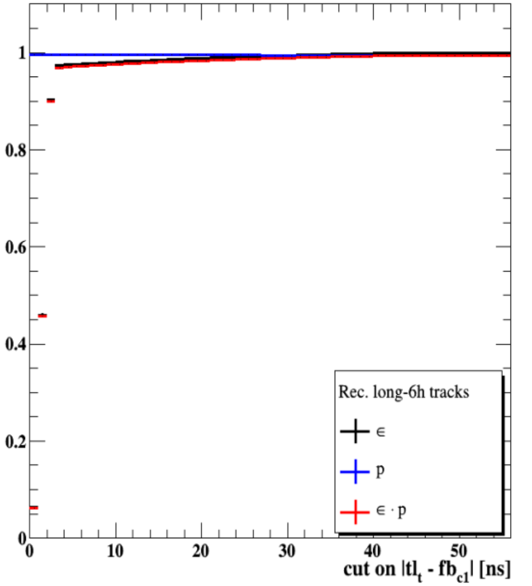
- Unknown direction
- Use fibre time information and pathlength between fibre hits





Rec.		No cuts	Cuts applied
6h(CS)	ϵ	1	0.78
	p	0.79	0.90
	$\epsilon \cdot p$	0.79	0.71
6h(RS)	ϵ	1	0.98
	p	0.99	0.99
	$\epsilon \cdot p$	0.99	0.97
8h(CS)	ϵ	1	0.88
	p	0.56	0.89
	$\epsilon \cdot p$	0.56	0.78





Track/Vertex Efficiency After Track Reconstruction and Vertex Fit Step for Phase Space Distributed Signal Muons Events

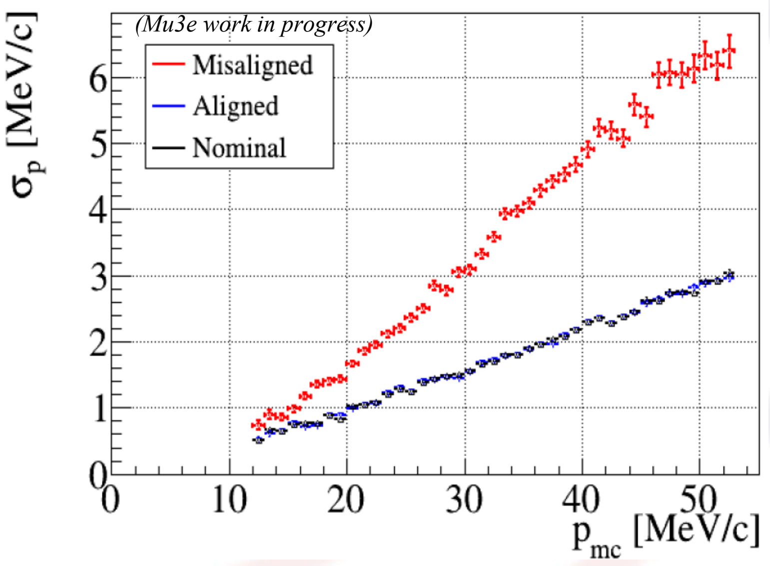
(Mu3e work in progress)

Phase space	$\epsilon_{\text{all tracks (4, 6, 8 hits)}}$	$\epsilon_{\text{3 long tracks (6, 8 hits)}}$
events in acceptance	0.412(1)	0.265(1)
relative to events in acceptance		0.643(3)
events after track reconstruction	0.368(1)	0.185(1)
relative to events in acceptance	0.892(5)	0.698(5)
events with reconstructed vertex	0.374(1)	0.188(1)
relative to events in acceptance	0.907(5)	0.708(5)
relative to events after track reconstruction	0.998(8)	0.998(8)
events with reconstructed vertex after cuts	0.290(1)	0.163(1)
relative to events with reconstructed vertex before cuts	0.776(4)	0.866(7)
relative to events in acceptance	0.704(4)	0.614(4)
relative to events after reconstruction	0.789(4)	0.879(7)

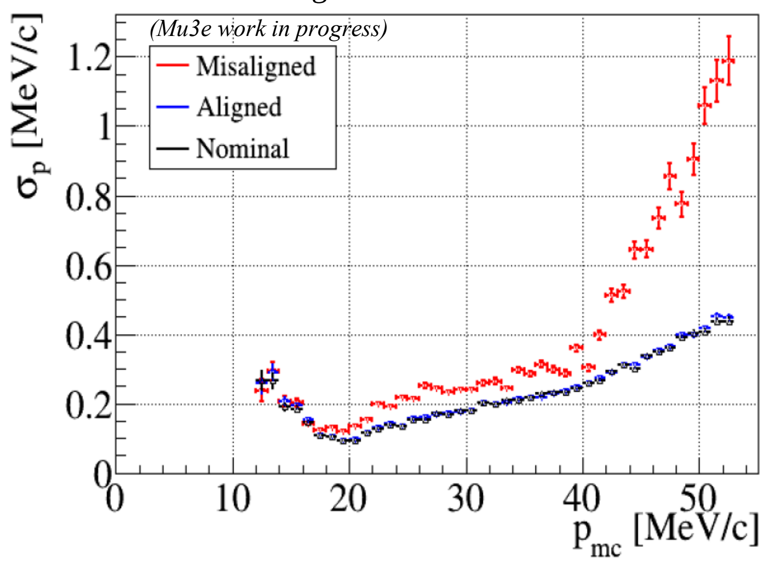
Track Based Alignment of the Mu3e Pixel Detector Studies

- Many misalignment modes can be applied for all individual sensors or composite parts level
- Using Millipede-II alignment algorithm to align detector
- Study the performance of nominal tracks with misaligned and aligned and compare it with nominal detector

Short tracks with 4-hits



Long tracks with 6/8-hits



Results of the vertex reconstruction of signal events with three recurlers required; for a nominal, a misaligned and an aligned detector. The mean stems from a fit of the sum of two Gaussians and the quoted width is the area-weighted mean

parameter	nominal	misaligned	aligned
$x_{rec} - x_{true}$	$\mu = -0.004 \pm 0.002$ $\sigma = 0.212 \pm 0.002$	$\mu = 3.00 \pm 0.00$ $\sigma = 672 \pm 0.009$	$\mu = -0.003 \pm 0.002$ $\sigma = 0.212 \pm 0.002$
$y_{rec} - y_{true}$	$\mu = 0.004 \pm 0.002$ $\sigma = 0.214 \pm 0.002$	$\mu = -0.261 \pm 0.08$ $\sigma = 0.570 \pm 0.03$	$\mu = 0.005 \pm 0.002$ $\sigma = 0.217 \pm 0.002$
$z_{rec} - z_{true}$	$\mu = -0.0 \pm 0.001$ $\sigma = 0.115 \pm 0.001$	$\mu = 0.001 \pm 0.00$ $\sigma = 0.760 \pm 0.00$	$\mu = -0.00 \pm 0.001$ $\sigma = 0.115 \pm 0.001$

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Results: The Performance of Tracks in the Reconstruction Step (Perfect & Imperfect Tracks)

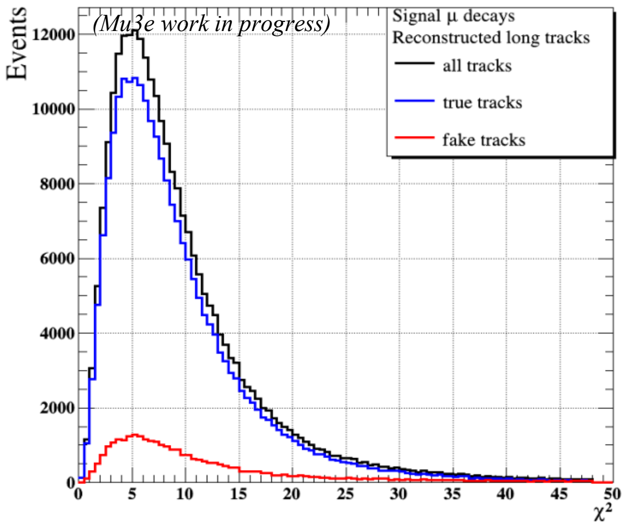
Performance & Goal

- Study tracking performance with imperfect detector for signal muon decays. Artificially introduce 100% inefficiencies into 1/2-pixel layer in the central station of the detector
- Goal was to allow tracking algorithm to access dead sensor in a missing layer
- Study and optimizing the tracks cut requirements with understand the tracking efficiency, purity rates for new categories of tracks

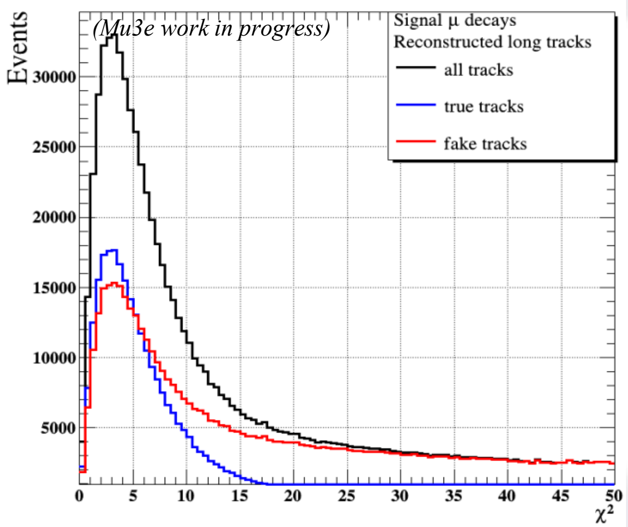
$$\varepsilon(\chi^2_{\max}) = \frac{S_{\text{cut}}(\chi^2_{\max})}{S_{\text{total}}}, \qquad 0 \leq \varepsilon \leq 1.$$

$$P(\chi^2_{\max}) = \frac{S_{\text{cut}}(\chi^2_{\max})}{S_{\text{cut}}(\chi^2_{\max}) + B_{\text{cut}}(\chi^2_{\max})}, \qquad 0 \leq P \leq 1.$$

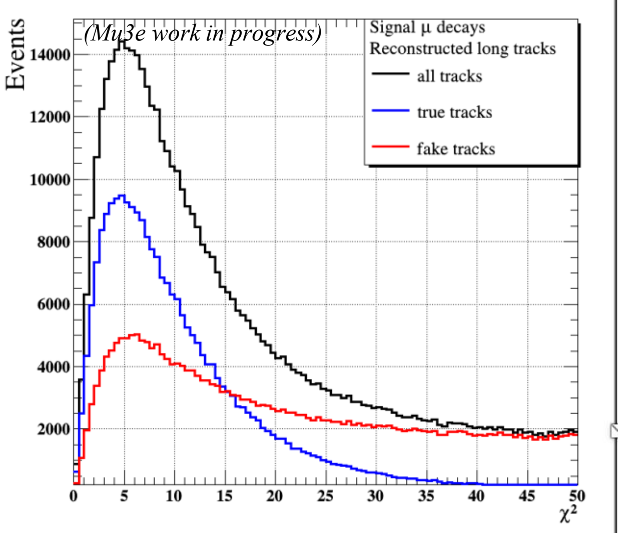
Perfect tracks with 6-pixel hits In the CS or RS of the detector with 0% inefficiency

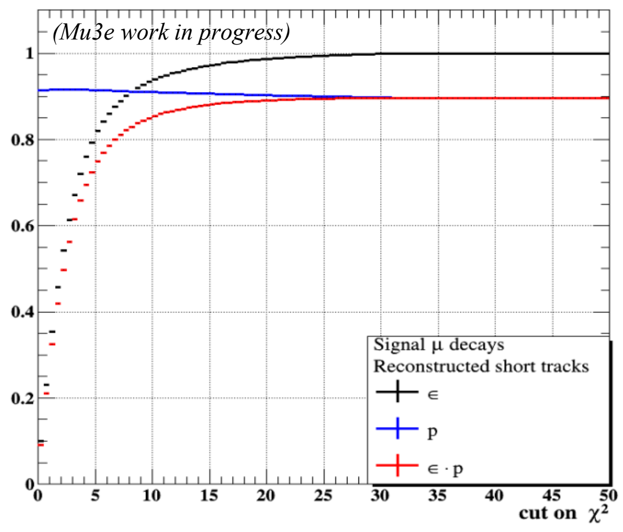


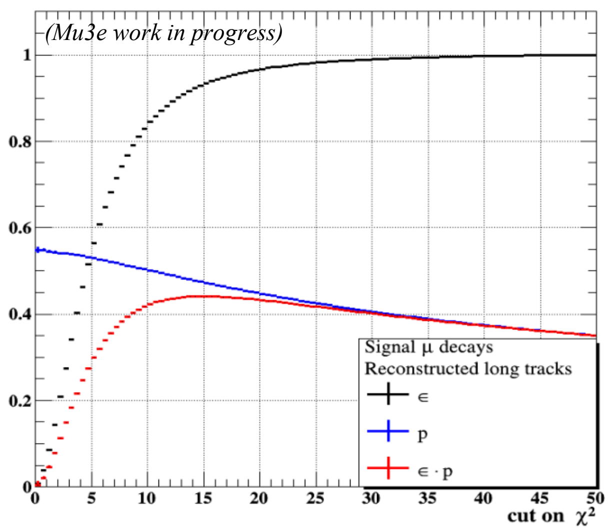
Imperfect tracks with 5-pixel hits In the CS or RS of the detector(100% inefficiency in 1-pixel layer)

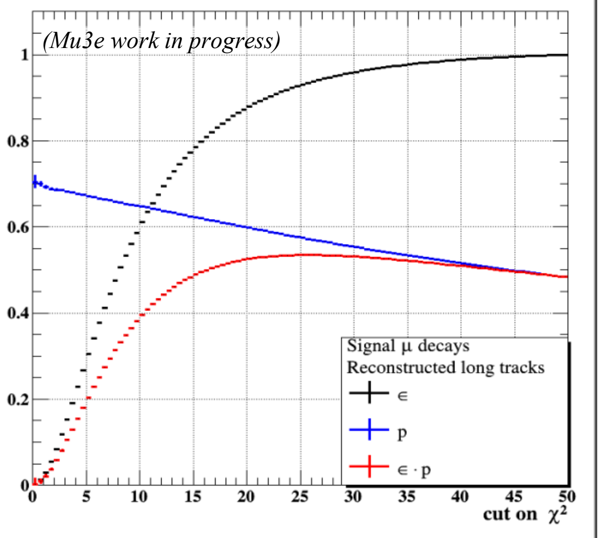


Imperfect tracks with 5-pixel hits In the CS or RS of the detector(100% inefficiency in 2-pixel layer)









Momentum Distribution before and after applying cuts for Different Categories of Tracks

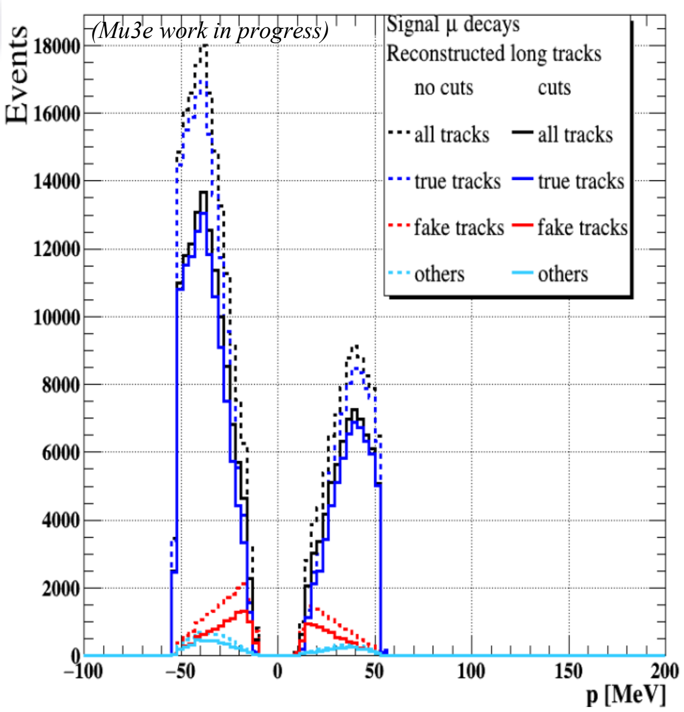
Selection cuts for long tracks with 6-pixel hits in perfect detector:

z0 (mm)	< 50
$\lambda01(rad)$: $6hits$	> 0.1
χ^2 : $6hits$	30

Selection cuts for long tracks with 5-pixel hits in imperfect detector:

z0 (mm)	< 50
$\lambda01(rad)$: $5hits$	> 0.1
χ^2 : $5hits$	20

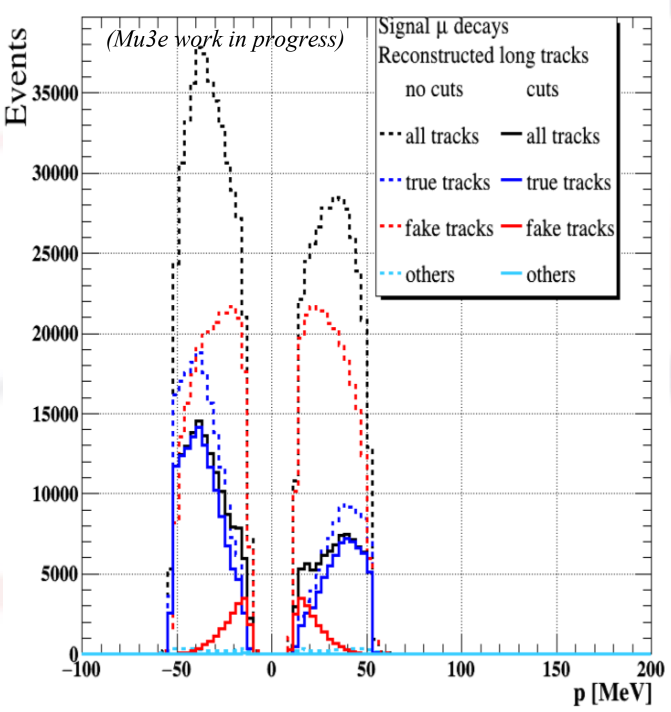
Perfect tracks with 6-pixel hits In the CS or RS of the detector with 0% inefficiency in 1-pixel layer



Reconstruction		No cuts	Cuts applied
Long 6-hit tracks	ϵ	1	0.898
	p	0.885	0.907
	$\epsilon \cdot p$	0.885	0.814

TABLE 14: Efficiency ϵ, purity p and $\epsilon \cdot p$ before and after applying cuts for signal muon decays.

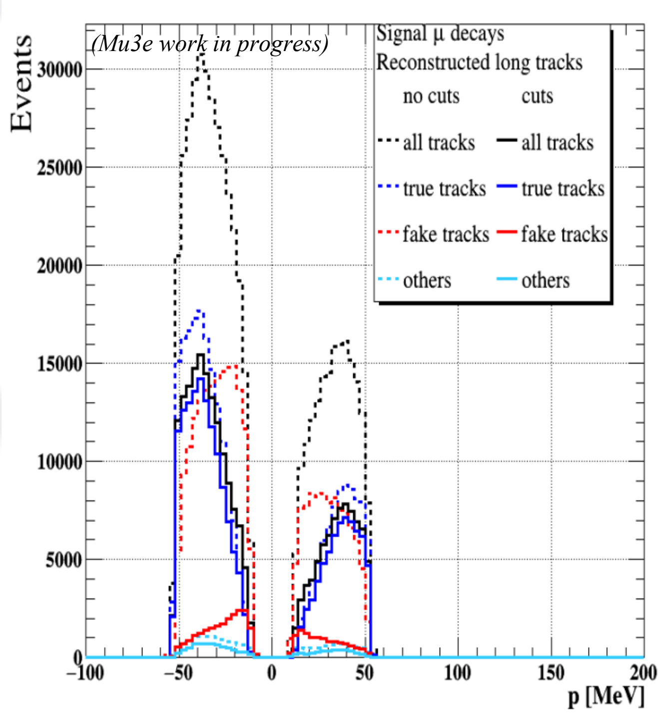
Imperfect tracks with 5-pixel hits In the CS or RS of the detector(100% inefficiency in 1-pixel layer)



Reconstruction		No cuts	Cuts applied
Long 5-hit tracks	ϵ	1	0.743
	p	0.350	0.848
	$\epsilon \cdot p$	0.350	0.631

TABLE 14: Efficiency ϵ, purity p and $\epsilon \cdot p$ before and after applying cuts for signal muon decays.

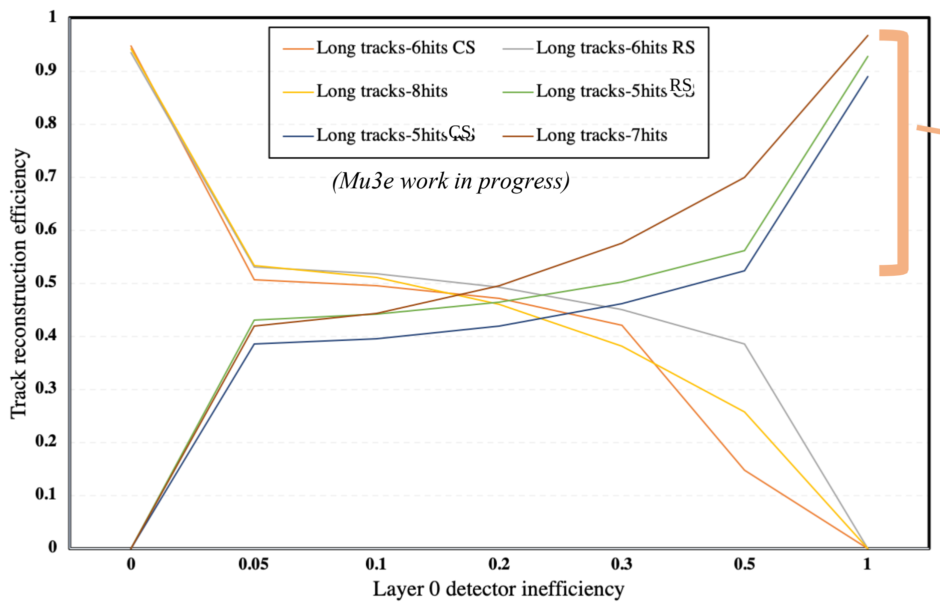
Imperfect tracks with 5-pixel hits In the CS or RS of the detector(100% inefficiency in 2-pixel layer)



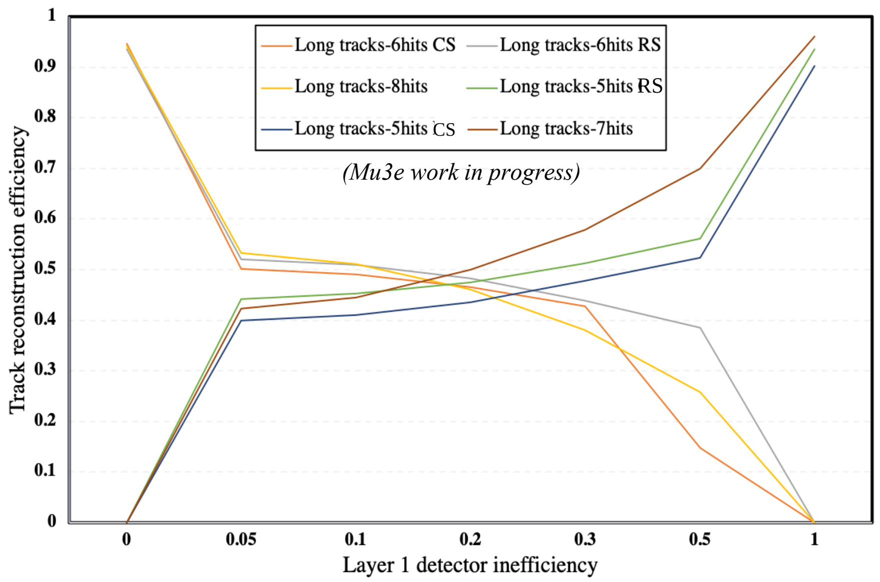
Reconstruction		No cuts	Cuts applied
Long 5-hit tracks	ϵ	1	0.79
	p	0.483	0.856
	$\epsilon \cdot p$	0.483	0.676

TABLE 14: Efficiency ϵ, purity p and $\epsilon \cdot p$ before and after applying cuts for signal muon decays.

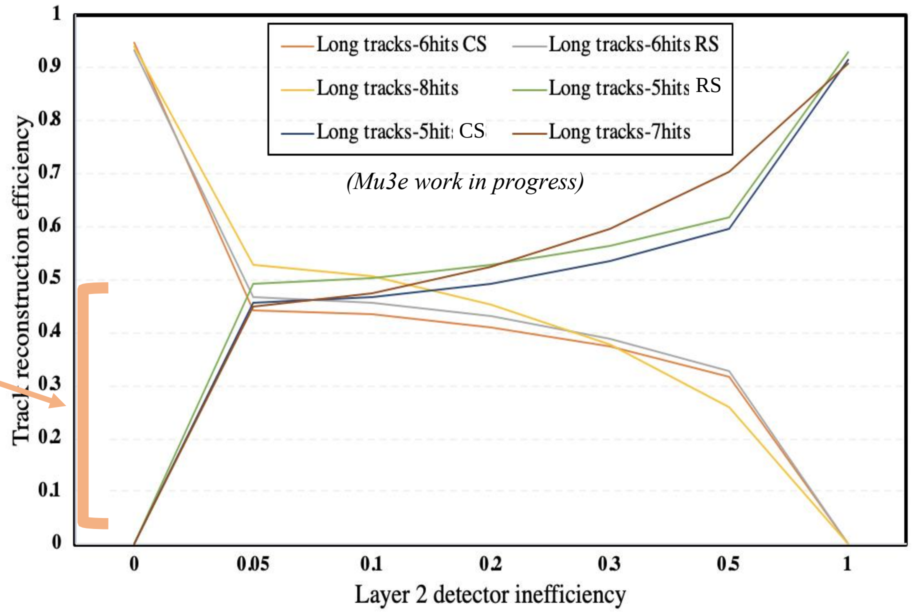
Summary Plot for How Many Imperfect Correctly Reconstructed Tracks Could Recover in the Case of a Missing Layer at a Different Level of Inefficiency



More imperfect correctly reconstructed tracks could recover at highest level of inefficiency in 0, 1 or 2-pixel layer



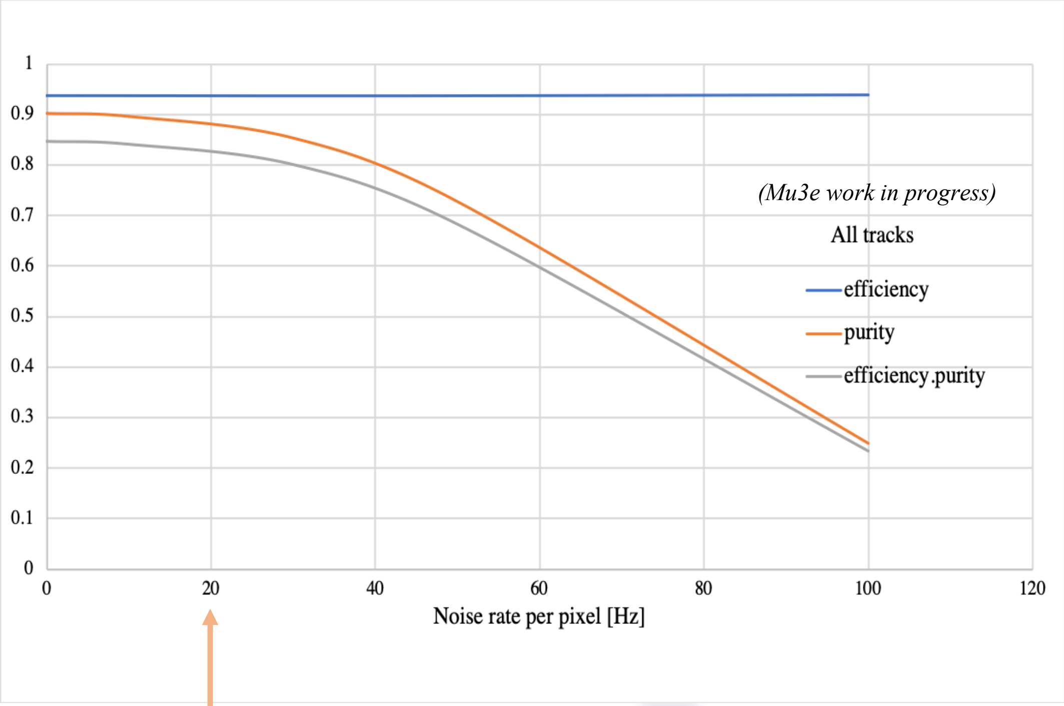
less or 0 imperfect correctly reconstructed tracks could recover at lowest level of inefficiency in 0, 1 or 2-pixel layer



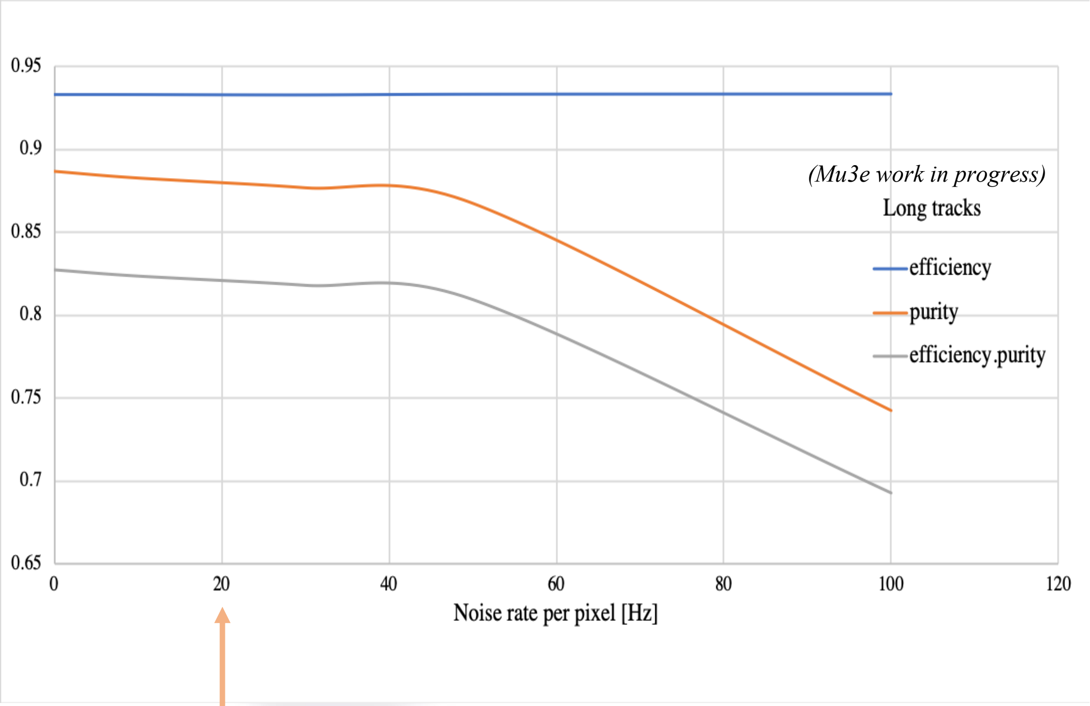
- *What is the effect on efficiency and purity for the performance of the track reconstruction as the noise rate per pixel goes from 0 to highest rates in 20Hz as height noise rate per pixel (MuPix8)?*

Purity is relatively stable until a noise rate of approximately 40Hz, which is much larger that the highest noise rate seen for the MuPix8 prototypes of 20 Hz

Summary plot for different detector noise rates per pixel go from 0 to 20 Hz vs. tracking efficiency and purity of track candidates:



highest noise rate per pixel for MuPix8 prototype



highest noise rate per pixel for MuPix8 prototype

Vertex fit step

Signal efficiency after reconstruction and vertex fit step for phase space distributed events for perfect and noise detector (injecting 20 Hz as highest noise rate per pixel)

Default selection cuts applied to distinguish $\mu^+ \rightarrow e^+ e^+ e^-$ and suppress different background categories

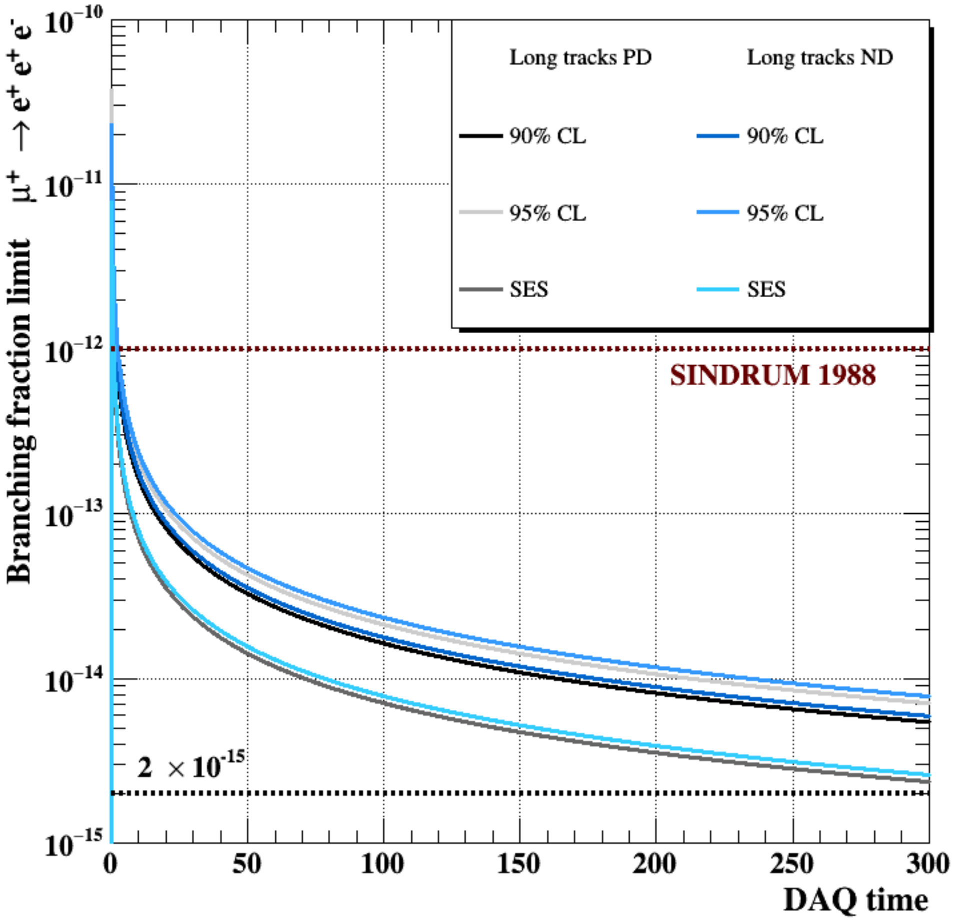
Variable	Value Cut	Comment
χ^2_{vertex}	<30	3 degrees of freedom
$\lvert\vec{p}_{eee}\rvert = \lvert\sum \vec{p}_i\rvert$	<8 Mev/c	
distance: $\vec{v}$ to target	<3 mm	
m_{eee}	103.5 Mev $\leq$ m $\leq$ 115 Mev	
crossed tracking layers	$\geq$ 4	4,6,8 hits tracks
χ^2_{timing}	< 6 ns	

Track/Vertex Efficiency After Track Reconstruction and Vertex Fit Step for Phase Space Distributed Signal Muons Events in perfect or Noise detector (Mu3e work in progress)

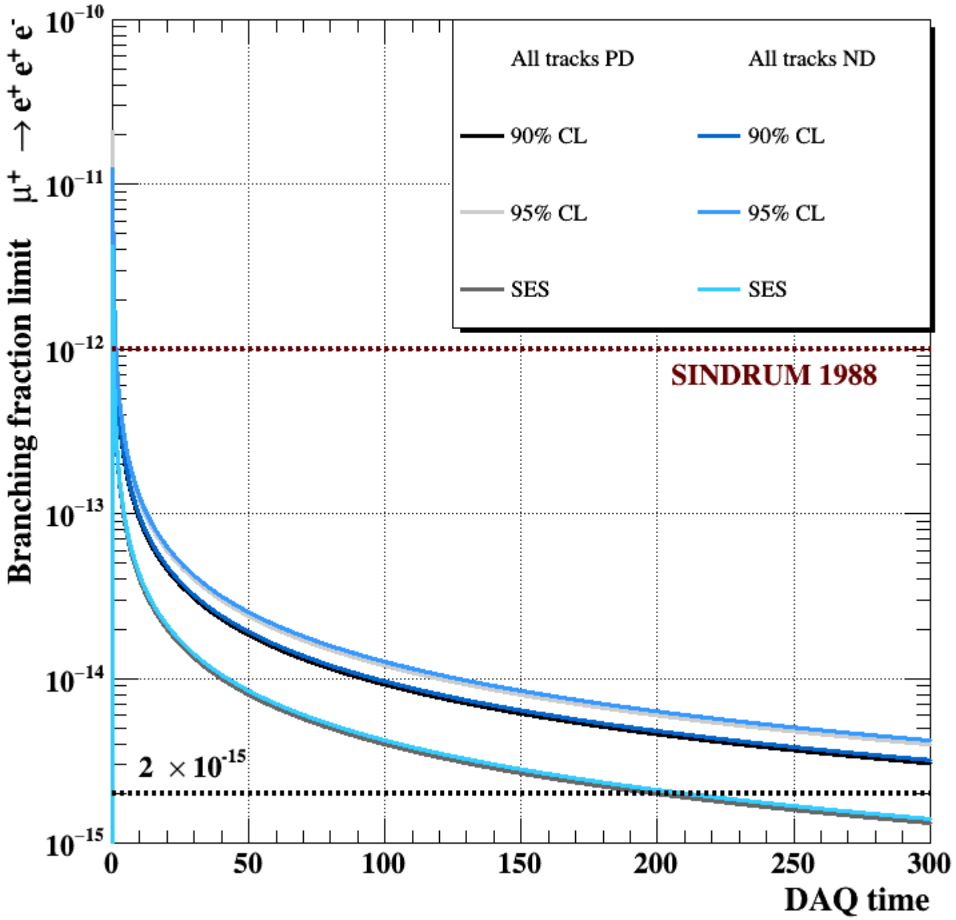
Phase space	$\epsilon_{\text{all tracks}}$ (4, 6, 8 hits)	ϵ_{3} long tracks (6, 8 hits)
events in acceptance	0.412(1)	0.265(1)
relative to events in acceptance		0.643(3)
Perfect detector with 0 Hz noise rate per pixel		
events after track reconstruction	0.368(1)	0.185(1)
relative to events in acceptance	0.892(5)	0.698(5)
events with reconstructed vertex	0.374(1)	0.188(1)
relative to events in acceptance	0.907(5)	0.708(5)
relative to events after track reconstruction	0.998(8)	0.998(8)
events with reconstructed vertex after cuts	0.290(1)	0.163(1)
relative to events with reconstructed vertex before cuts	0.776(4)	0.866(7)
relative to events in acceptance	0.704(4)	0.614(4)
relative to events after reconstruction	0.789(4)	0.879(7)
Noise detector with 20 Hz noise rate per pixel		
events after track reconstruction	0.367(7)	0.179(4)
relative to events in acceptance	0.910(2)	0.684(2)
events with reconstructed vertex	0.354(6)	0.173(4)
relative to events in acceptance	0.878(2)	0.658(2)
relative to events after track reconstruction	0.964(2)	0.962(3)
events with reconstructed vertex after cuts	0.274(5)	0.148(4)
relative to events with reconstructed vertex before cuts	0.735(1)	0.812(2)
relative to events in acceptance	0.680(1)	0.563(1)
relative to events after track reconstruction	0.747(1)	0.823(2)

Single event sensitivity (SES) and the corresponding 90% and 95% C.L. upper limits versus data taking days for the phase I Mu3e detector

Long tracks in perfect (PD) and noise detector (ND) after applying vertex cuts



All tracks in perfect (PD) and noise detector (ND) after applying vertex cuts



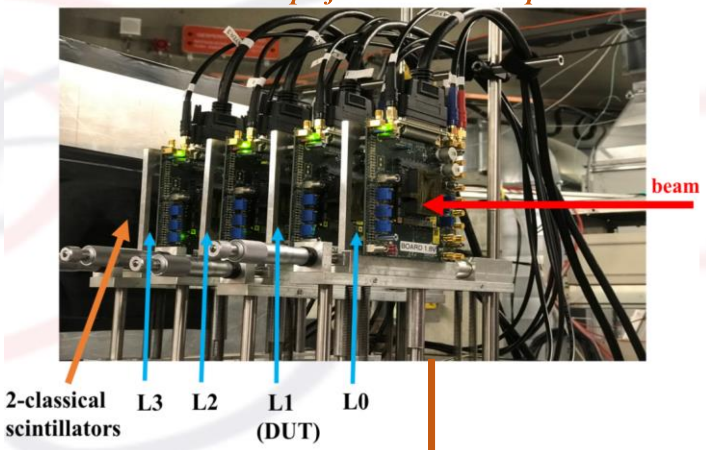
Test-beam Data Acquisition System and Characterisation of HV-MAPS

IOP Institute of Physics
High Energy Particle Physics Group

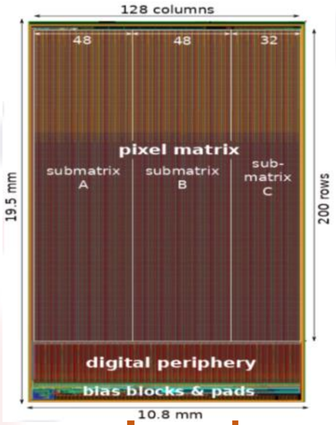
Test-beam @ PSI

The beam with momentum 270 MeV (pion, electrons, and muons), and electrical current is 1860.10μA at πM1 beam area in PSI

Setup of MuPix Telescope



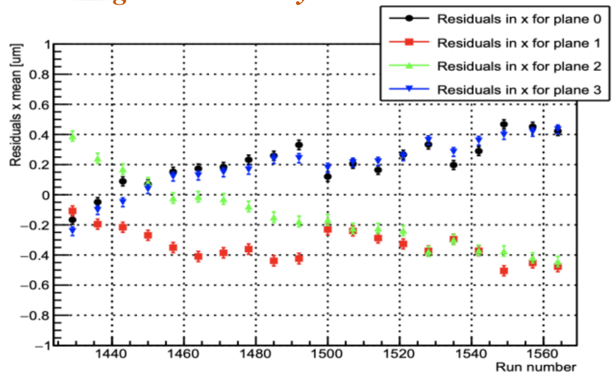
- 3-layers of MuPix8 sensors with DUT layer
- Layer 1 is DUT layer
- 2-classical trigger scintillators
- All PCBs were connected to a HV power supply, and set to - 60 V for all MuPix8 measurements

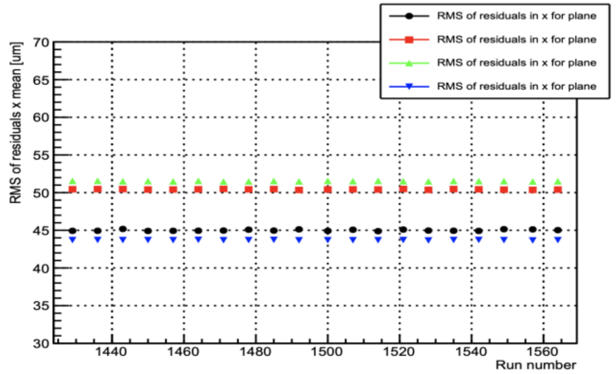


MuPix8 sensor?

- First large prototype in MuPix group
- Pixels have a size of $81 \times 80 \mu m^2$
- Pixels are arrayed in 128×200pixel matrix
- Fast charge collection (O(1ns))
- Integrated readout electronics
- Thickness: 100 μm

Alignment Stability



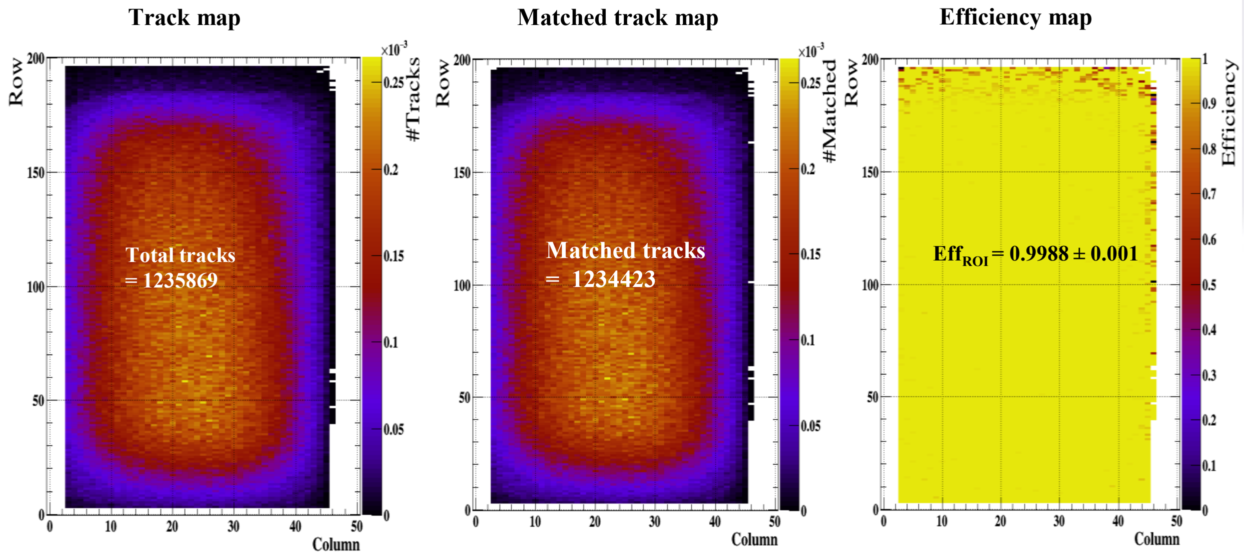


Efficiency Analysis

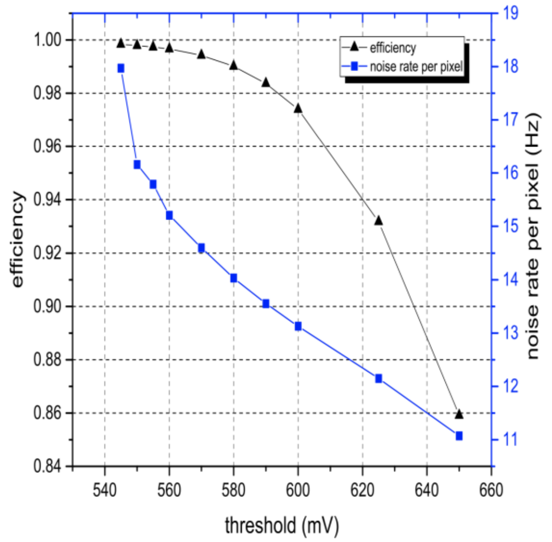
- Efficiency of run 1429 with threshold 545 mV

$$Eff_{ROI} = \frac{\#matched\ tracks}{\#total\ tracks}$$

$$\text{Noise rate per pixel} = \frac{\#hits - \#matched\ tracks}{runtime\ .\ \#pixels}$$



Efficiency and Noise Rate per Pixel for Different DAQ Runs



Summary:

- Acceptance and efficiency of the detector have studied with checking sources of fake tracks by looking at timing information
- The performance of imperfect tracks due to by noise or missing hits have studied with optimising selection cuts
- Test-Beam data acquisition system for characterization of High Voltage Monolithic Active Pixel Sensors has analyzed

Thank you for listening!

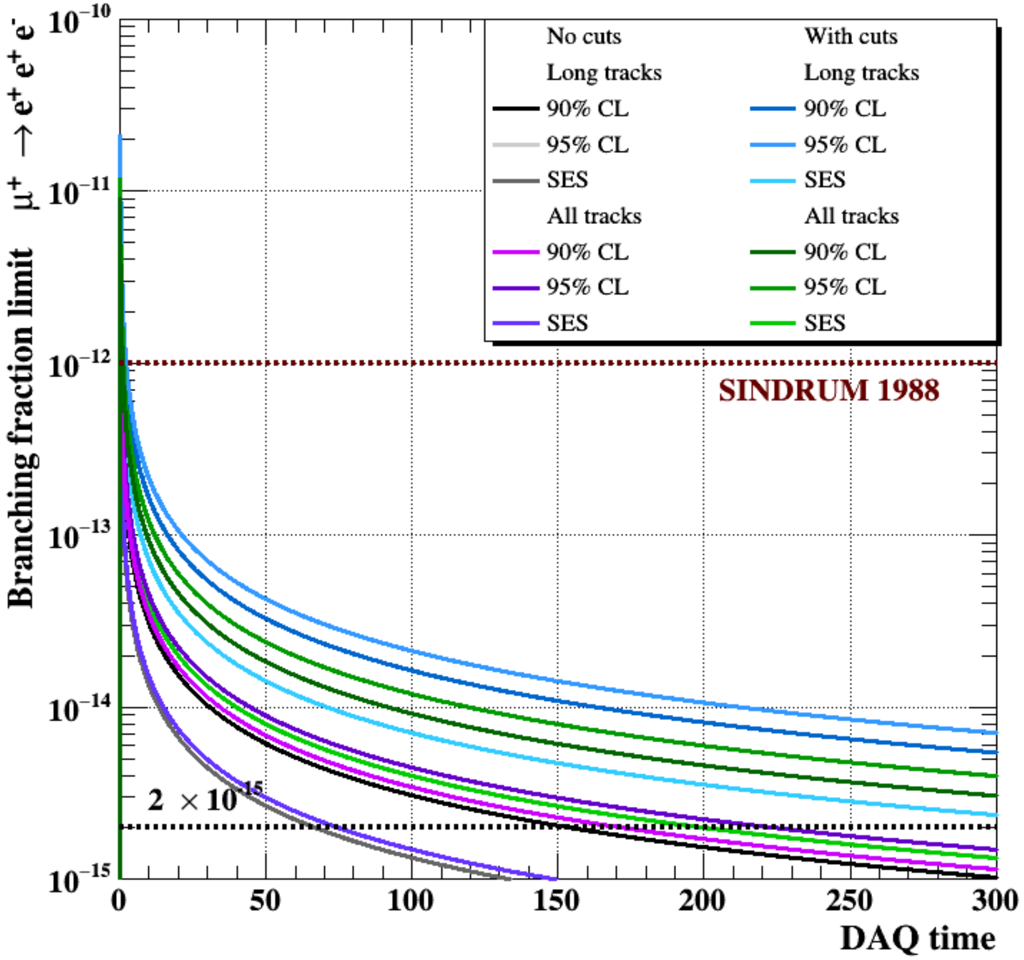
Backup……

What is the Single-Event Sensitivity (SES) with Nosy Detector in Vertex Fit Step and How is Vary from

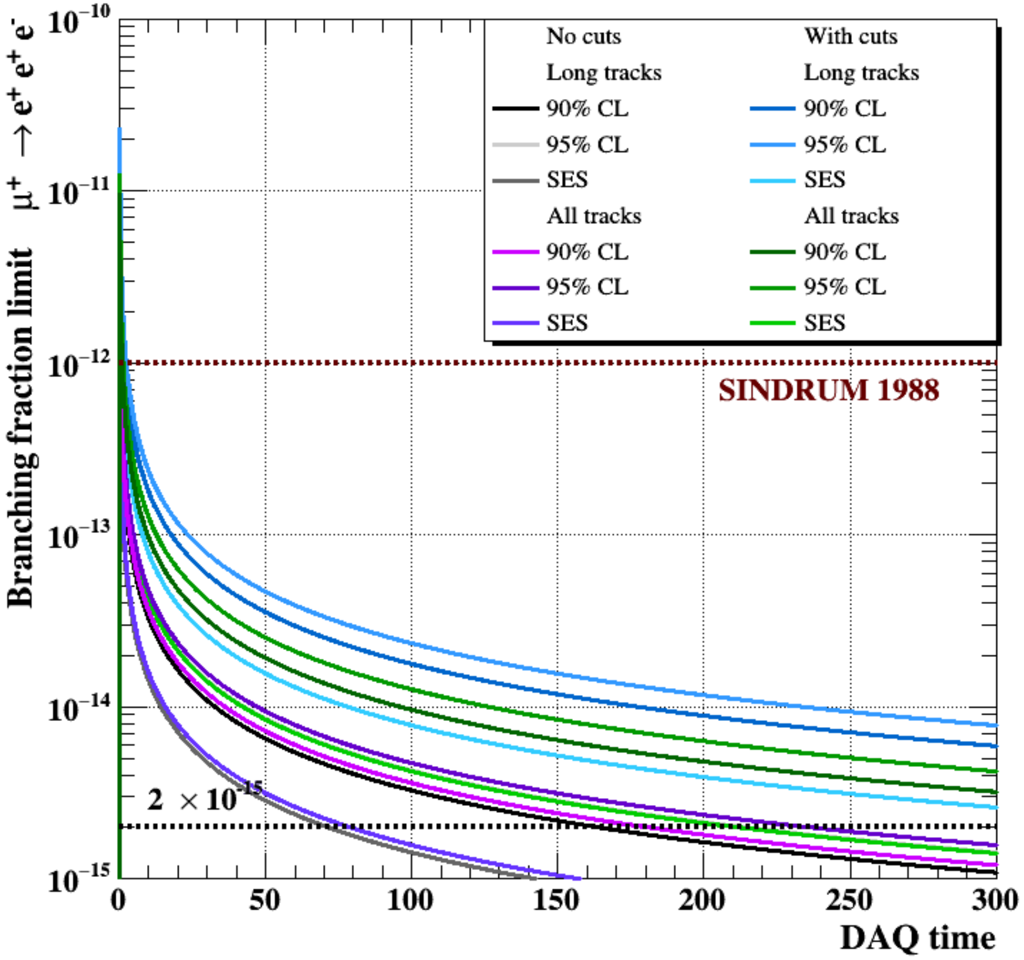
Institute of Physics
High Energy Particle Physics Group

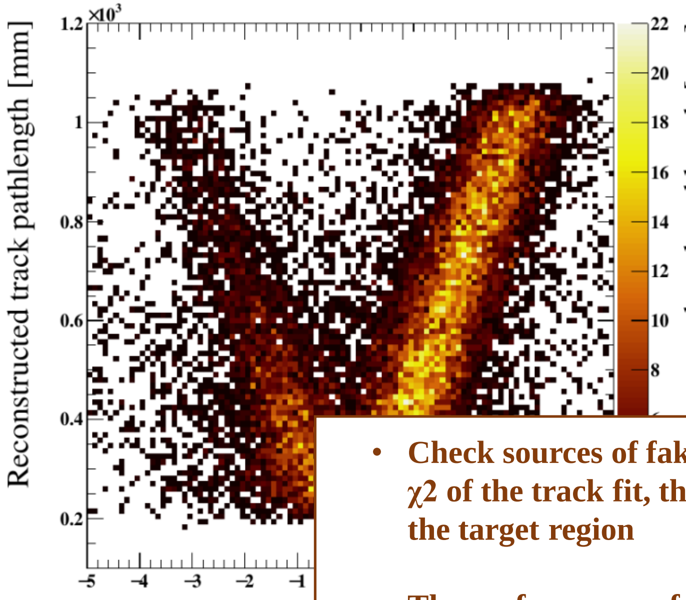
Single event sensitivity (SES) and the corresponding 90% and 95% C.L. upper limits versus data taking days for the phase I Mu3e detector

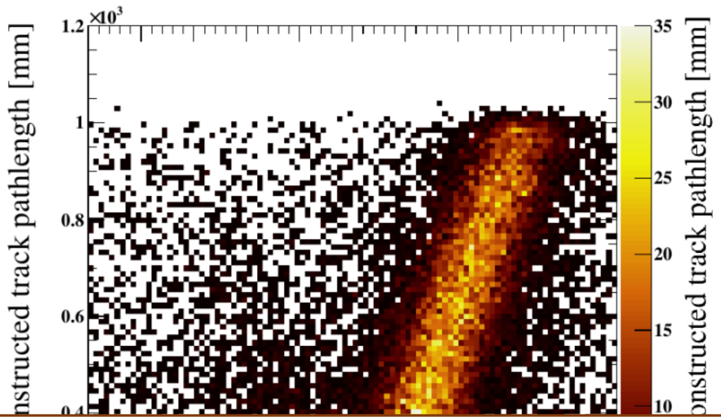
Perfect Detector

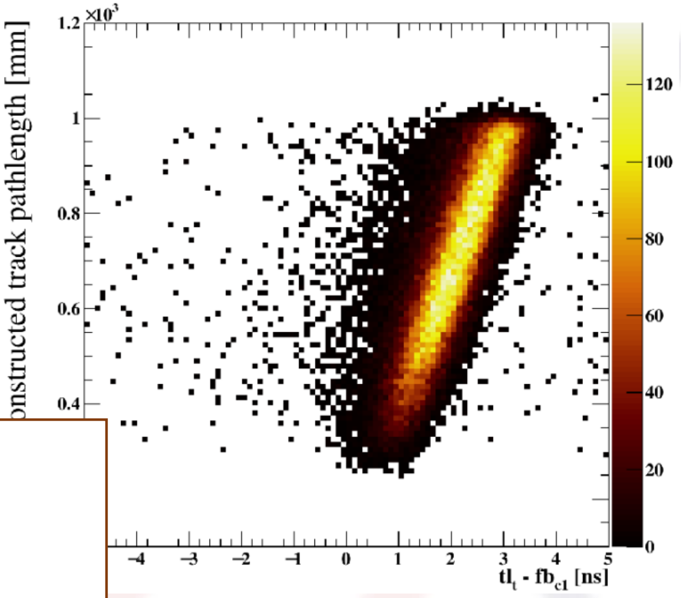


Nosy Detector

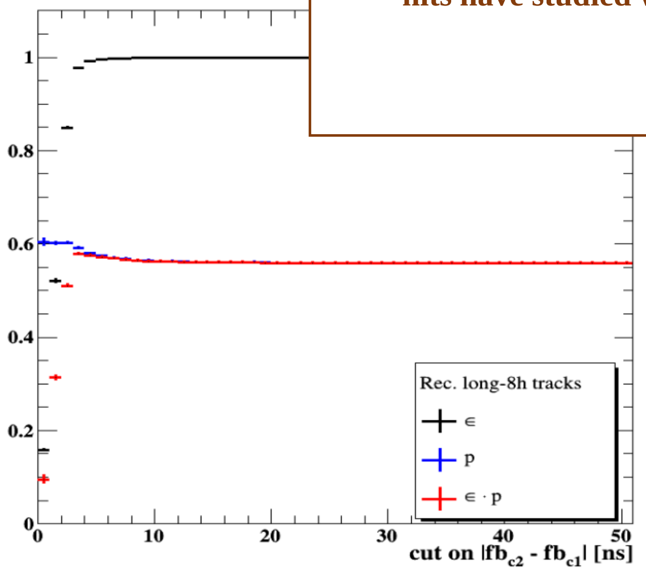


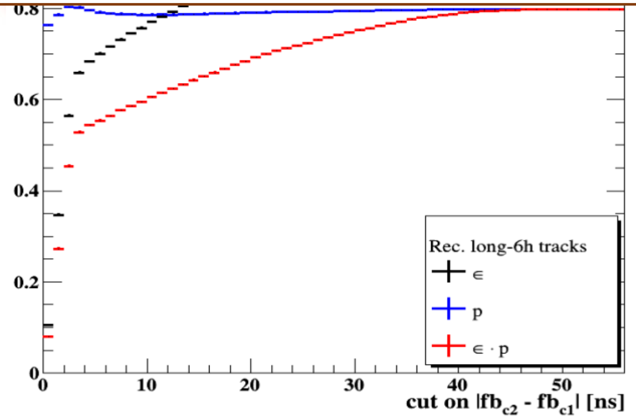


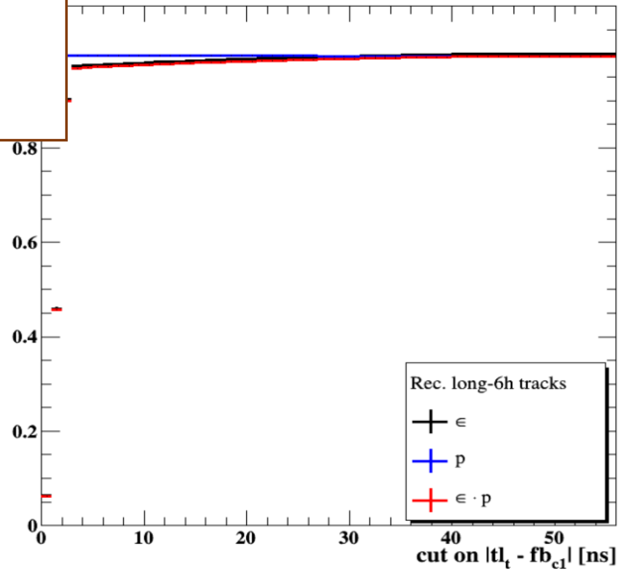




- **Check sources of fake tracks by looking at timing information, χ2 of the track fit, the dip angle λ01 and the intersection z0 with the target region**
- **The performance of imperfect tracks due to by nosy or missing hits have studied with optimising pre-selection and selection cuts**





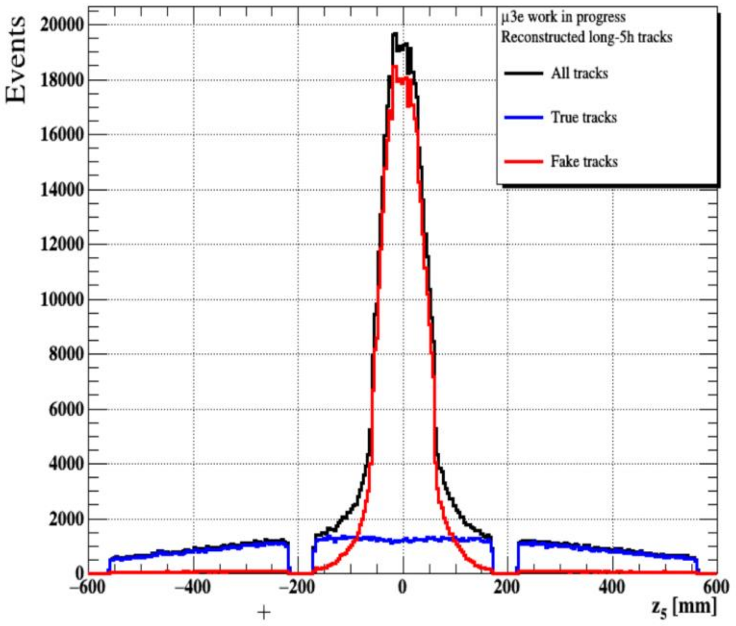


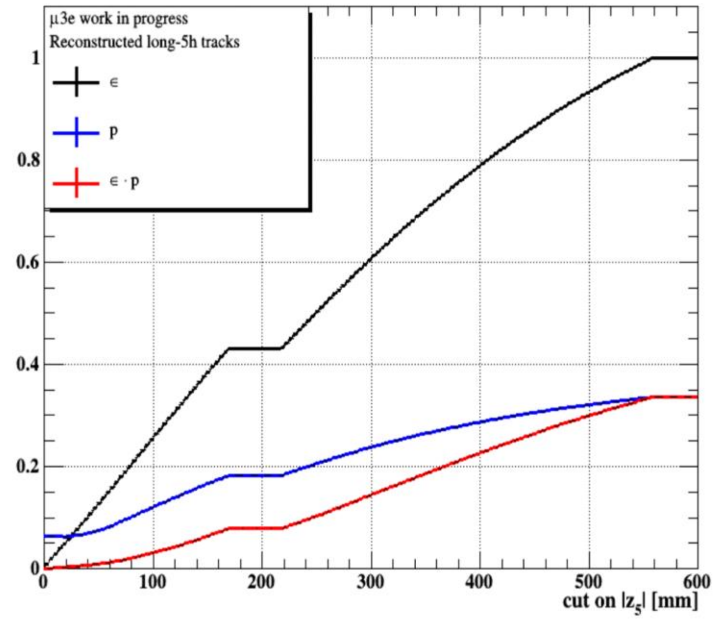
There is a couple of variables that can be used to check the performance of tracks:

- The χ2 of the track fit, the dip angle λ01 (particles perform many loops in the central detector), the intersection z0 of the track with the target region (vertices), and reconstructed curvature (a track of an electron that is mistaken for a positron).

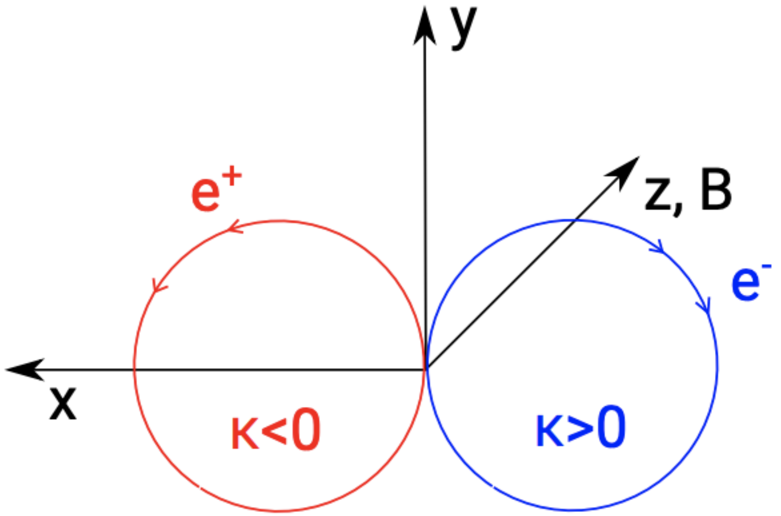
Rec.		No cuts	Cuts applied
6h(CS)	ϵ	1	0.78
	p	0.79	0.90
	$\epsilon \cdot p$	0.79	0.71
6h(RS)	ϵ	1	0.98
	p	0.99	0.99
	$\epsilon \cdot p$	0.99	0.97
8h(CS)	ϵ	1	0.88
	p	0.56	0.89
	$\epsilon \cdot p$	0.56	0.78

A way of splitting the long tracks with 5 hits in CS or RS of the detector





- Z5: 5th silicon hit in outer layers either in CS or RS, it is a good cut to to split long tracks with 6 hits recurl back into CS or RS
- Z5 < 200 mm: tracks can recurl back into CS
- Z5 > 200 mm: tracks can extrapolate into RS “that is because outer silicon detector is started from roughly 200 mm”
- This is an example if there is a missing layer (layer2)



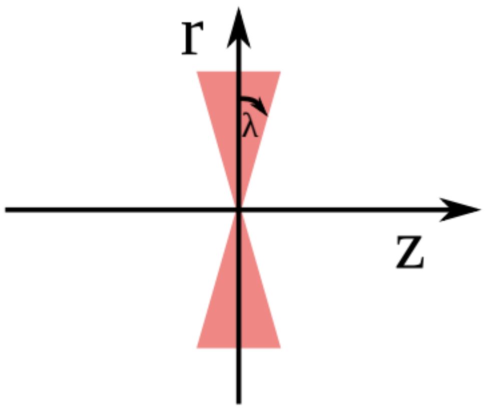


Illustration of the curvature of electrons and positrons in a magnetic field in the right-handed coordinate system of Mu3e. κ indicates the curvature of a track.

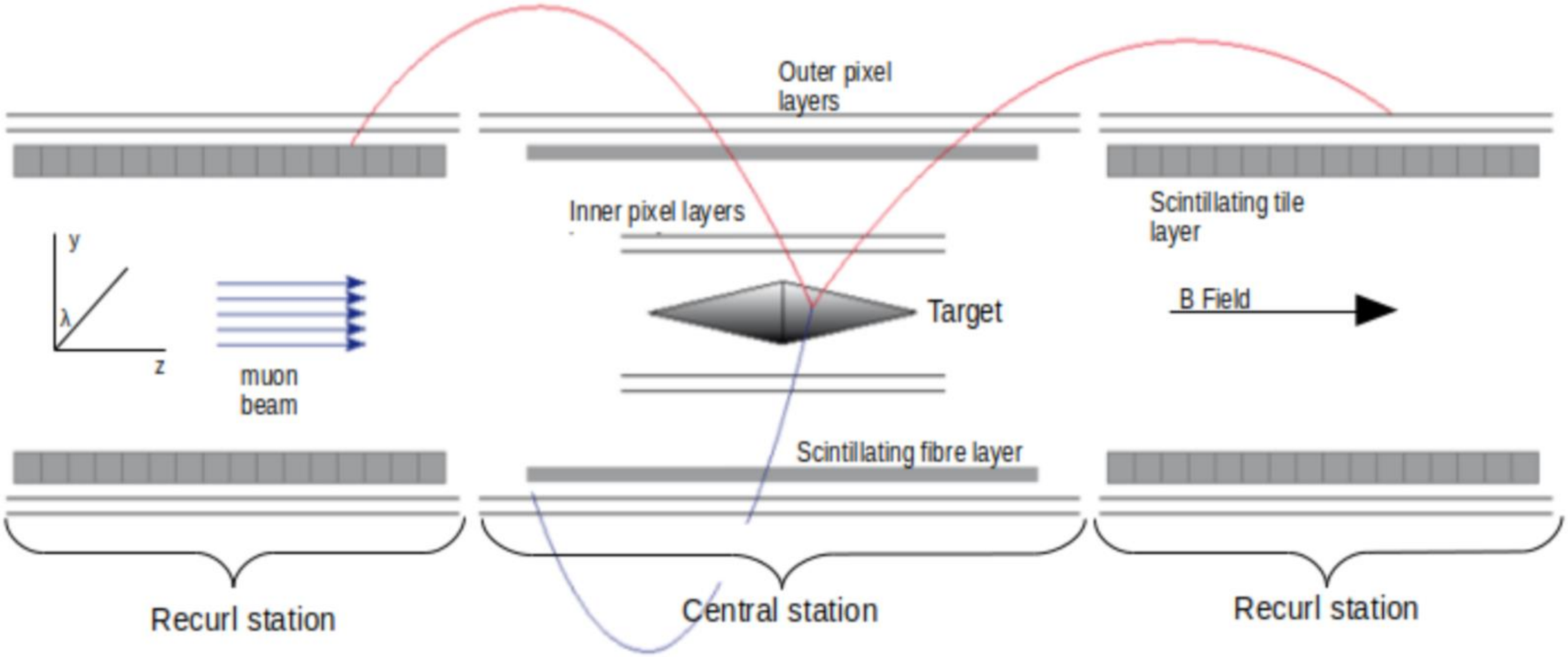
Signal Event Sensitivity:

The sensitivity is estimated by the means of simulation, the selection efficiency is used to estimate the sensitivity of the Mu3e experiment. After applying selection cuts, it is assumed that all types of background will be suppressed. The signal-event sensitivity (SES) is defined as:

$$SES(\mu \to eee) \leq \frac{1}{\epsilon N_\mu}$$

where e is the signal selection efficiency, this efficiency is calculated as defined previously in the equation. Also, Nμ is the number of muon decays on the target region in which for 300 days of data taking or the number of muon decays on the target region with the nominal Phase-I luminosity, this number is taken as Nμ=1×10^15. In the absence of signal which means zero events and because the number of signal decays follows a Poisson distribution, then an upper limit on theμ→eee branching fraction of a rare decay can be derived:
here 1−βis the required confidence level.

$$B_{(1-\beta)CL} = -\ln \beta \times SES = \frac{-\ln \beta}{\epsilon N_\mu}$$



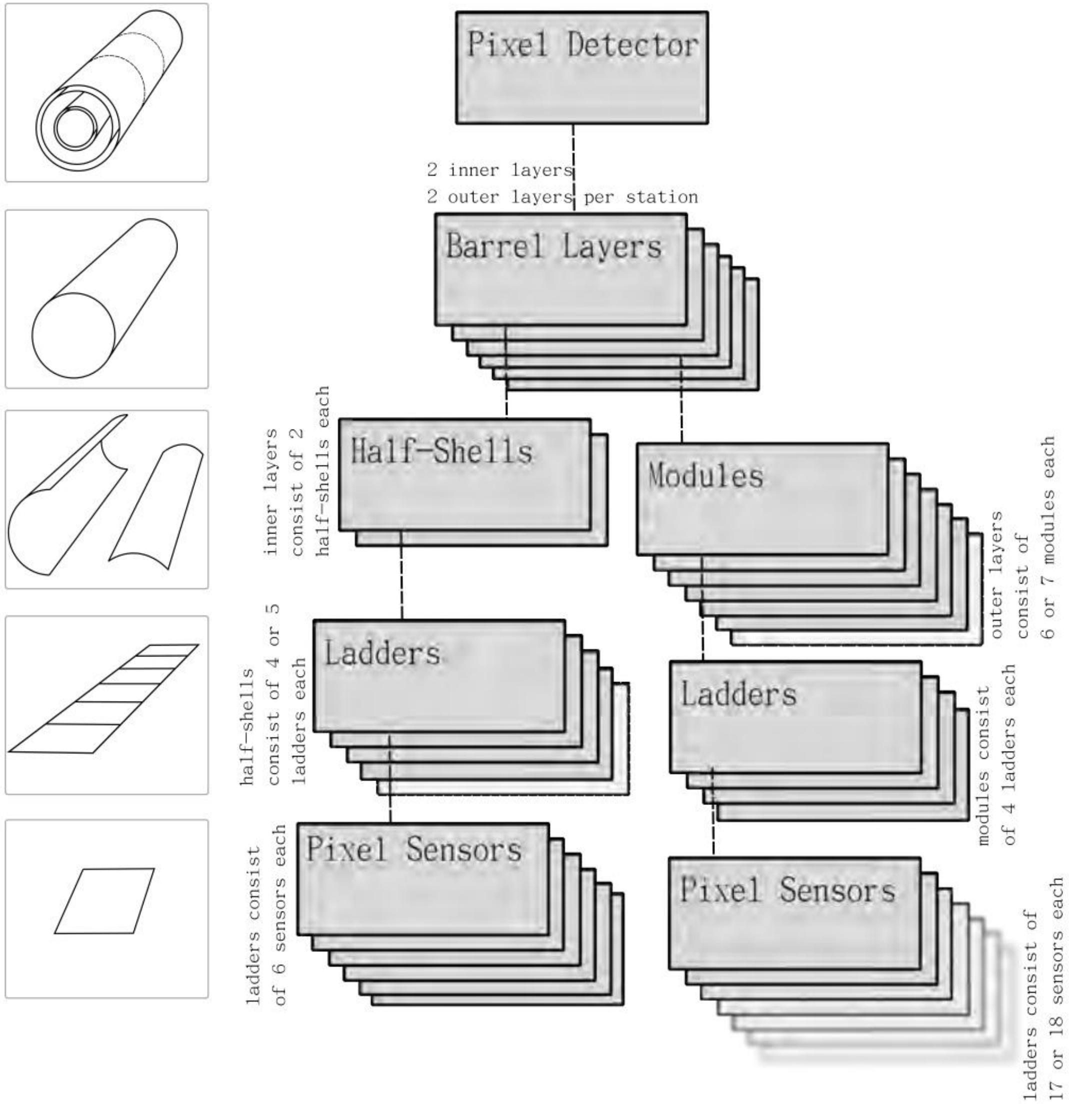
Outer pixel layers
Inner pixel layers
Scintillating tile layer
y
λ
z
muon beam
Target
B Field
Scintillating fibre layer
Recurl station
Central station
Recurl station

What the Misalignment and Alignment Tool do:

- The misalignment tool **MU3EMISAL** has been created, there are many misalignment modes for the pixel detector

Relative misalignment	$\sigma_{off,x,y}$ in µm	$\sigma_{rot,x,y}$ in mrad	$\sigma_{off,z}$ in µm	$\sigma_{rot,z}$ in mrad
sensors vs. ladders	50(100)	5(10)	5(100)	5(10)
ladders vs. modules	150(300)	1(2)	150(300)	1(2)
modules vs. layers	150(300)	1(2)	150(300)	1(2)
layers vs. layer pairs	25(50)	0.2(0.2)	50(50)	0.2(0.2)
layer pairs globally	150(300)	1(2)	250(300)	1(2)

Such a scenario is obtained by estimating the expected error on each entity and modifying the nominal (simulated) geometry by random Gaussian distributed values which reflect these error estimates. In parentheses, the worse case is given.



Pixel Detector
2 inner layers
2 outer layers per station
Barrel Layers
inner layers consist of 2 half-shells each
Half-Shells
Modules
outer layers consist of 6 or 7 modules each
half-shells consist of 4 or 5 ladders each
Ladders
Ladders
modules consist of 4 ladders each
ladders consist of 6 sensors each
Pixel Sensors
Pixel Sensors
ladders consist of 17 or 18 sensors each