Year 1 HEP Presentation

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A Study of the GPU Reconstruction Algorithm for the Mu3e Experiment

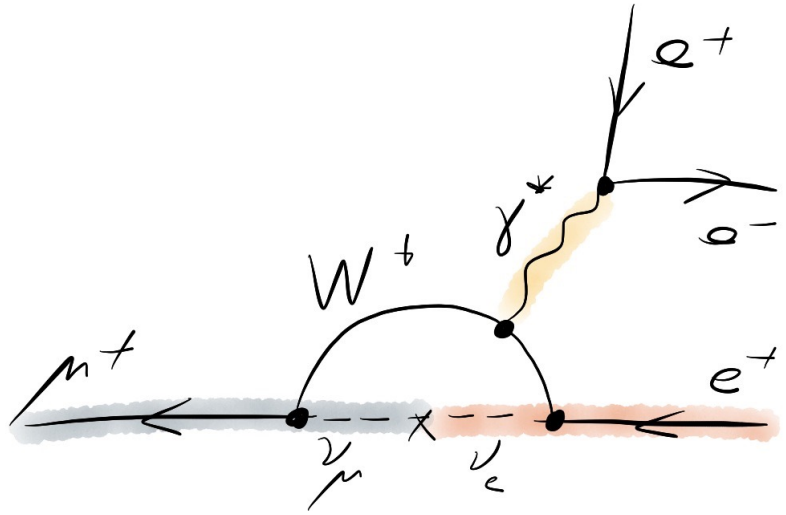
25/06/25

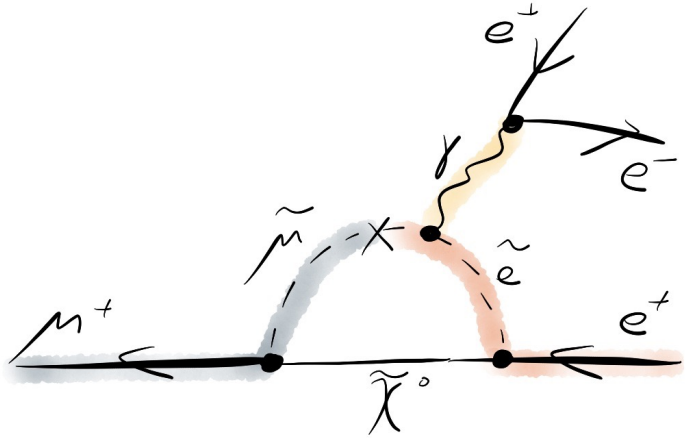
The Mu3e Experiment

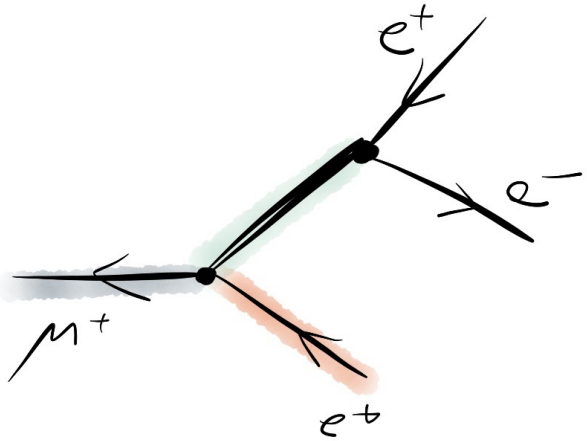
- Dedicated search for the **Charged Lepton Flavour Violating** (CLFV) decay of an anti-muon into two positrons and an electron: $\mu^+ \rightarrow e^+e^+e^-$.
- Decay is heavily suppressed within the Standard Model (SM) to unobservable rates.

$$\mathcal{B}_{\mu\rightarrow eee} \propto \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \Rightarrow \mathcal{B}_{\mu\rightarrow eee} < 10^{-54}$$

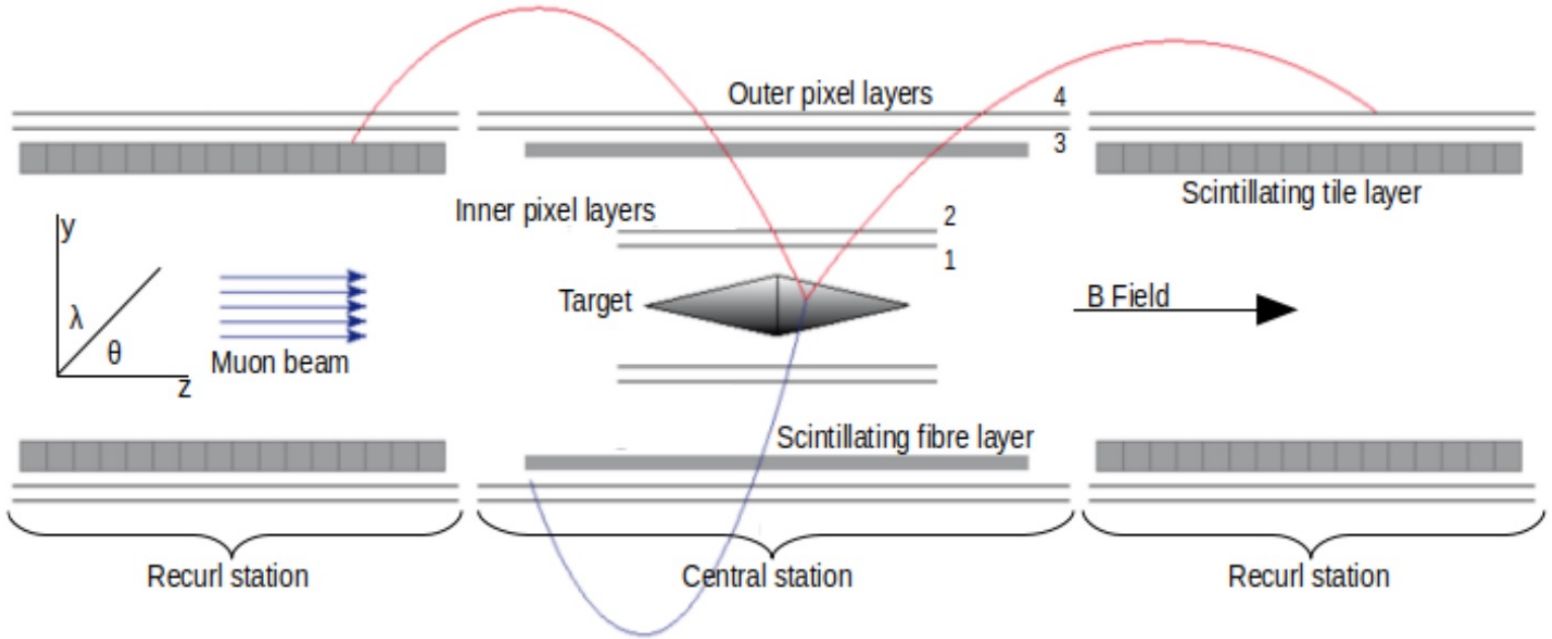
- Observation of the decay is unequivocal evidence for new physics, otherwise exclude a $\mathcal{B}_{\mu\rightarrow eee} > 10^{-16}$ at the 90% Confidence Level (CL).
- Improvement on current best $\mu \rightarrow eee$ sensitivity limits by 4 orders of magnitude!

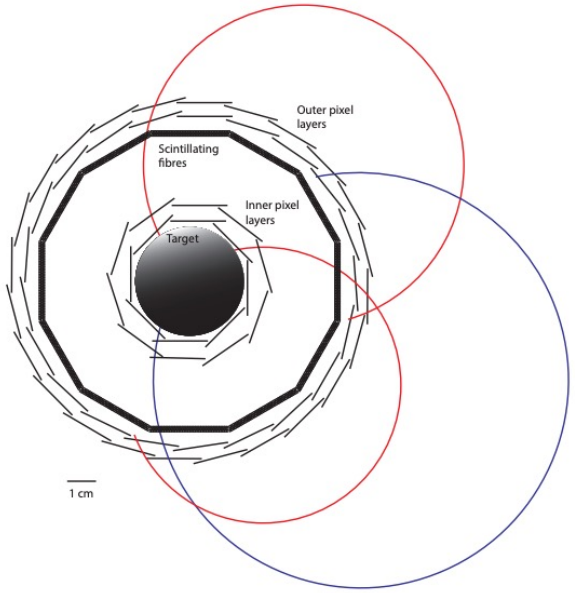






The Mu3e Experiment



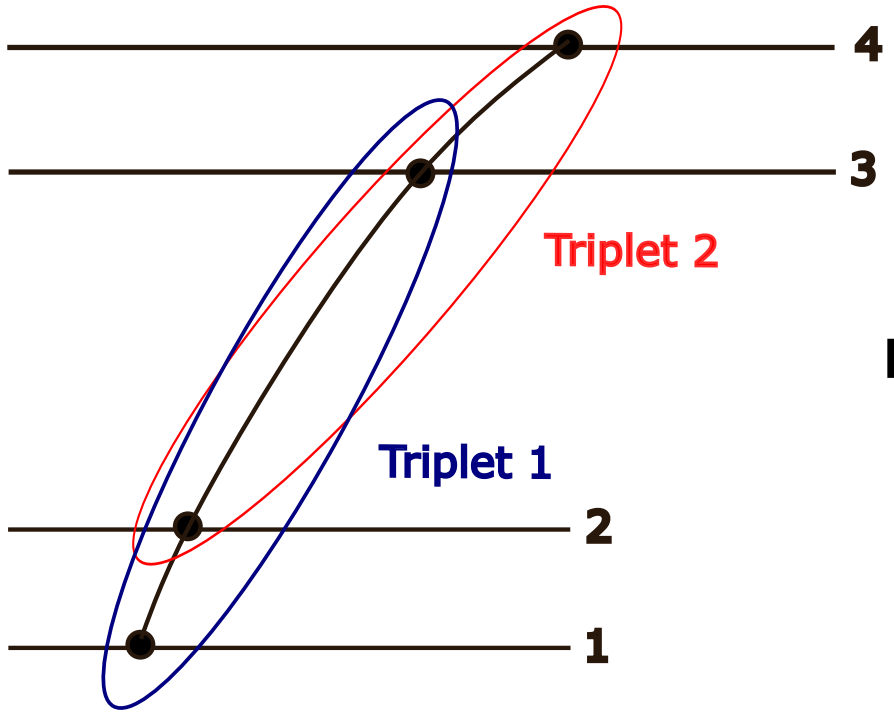


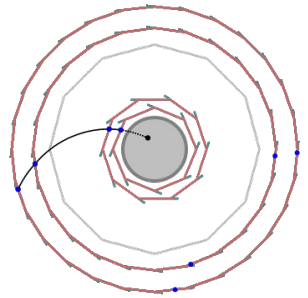
Modified from [1] K. Arndt et al., "Technical Design of the Phase I Mu3e Experiment, Aug. 2021

- In order to separate signal events from background, excellent momentum, vertex, and timing resolution is required.
- Hit information is provided by the inner and outer pixel layers; precise timing information is provided by the Sci-Fi and tile detectors.

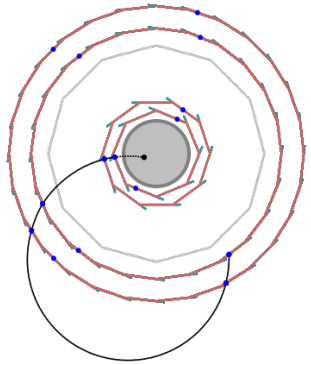
Offline Track Reconstruction

The triplet is the basic building block of the track reconstruction algorithm!



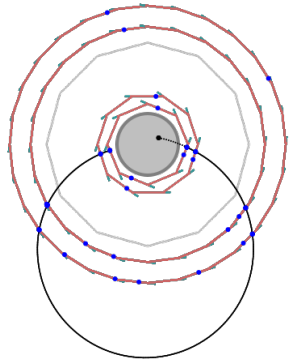


4-hit track (‘short’)



6-hit track

‘Long’



8-hit track

Offline Track Reconstruction

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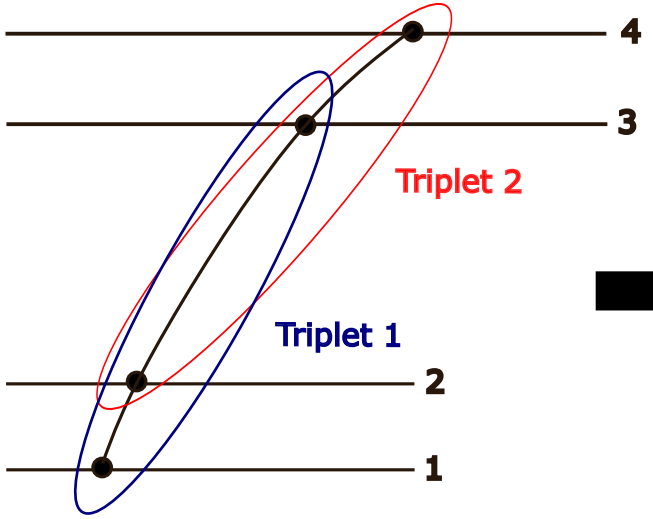
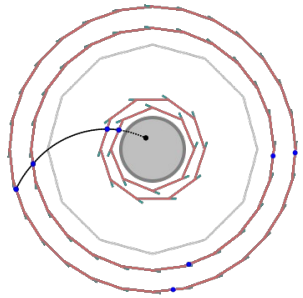
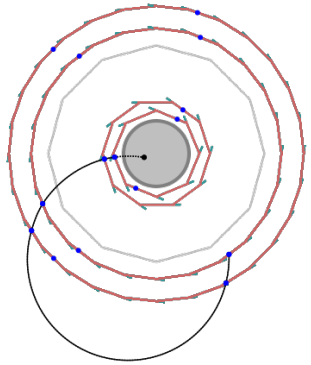


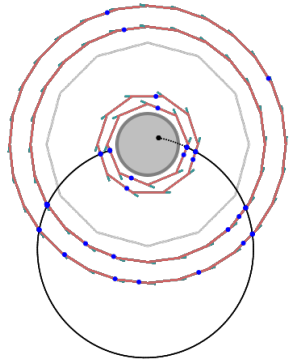


4-hit track (‘short’)



6-hit track

‘Long’



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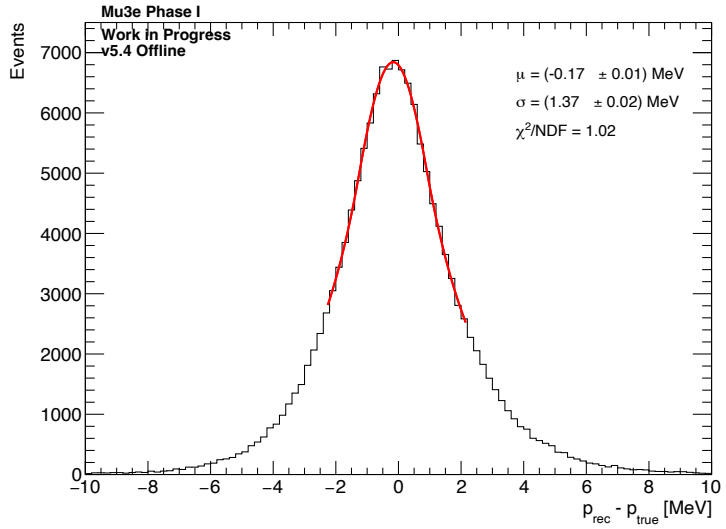
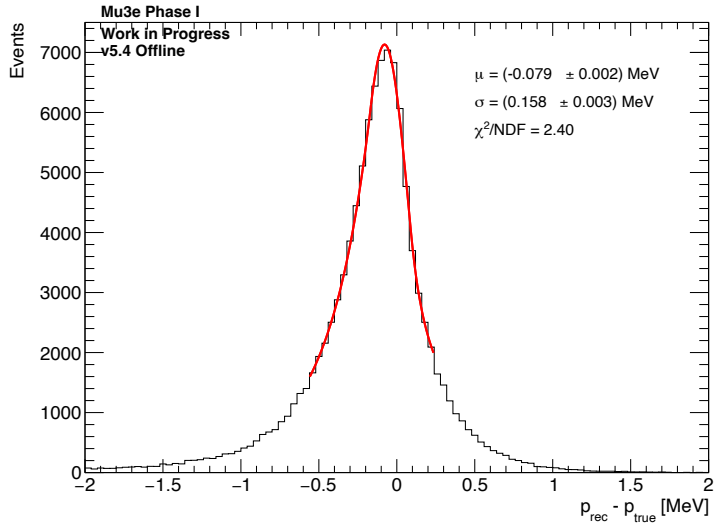




Signal Sample Study

	Frames			Vertices		
	N_{Frames}	ϵ_{step} [%]	ϵ [%]	$N_{Vertices}$	ϵ_{step} [%]	ϵ [%]
All	79921	-	-	26342	-	-
3 tracks from true vertex	23082	28.88	33.93	25945	98.49	38.14
Target region	22804	98.8	33.52	25619	98.74	37.66
Hit sequence number < 3	22496	98.65	33.07	22630	88.33	33.27
Same mother ID	22496	100	33.07	22630	100	33.27
Unique event mother ID	22496	100	33.07	22496	99.41	33.07
Prime track	22253	98.92	32.71	22253	98.92	32.71
Truth $e^+e^+e^-$	22253	100	32.71	22253	100	32.71
Unique track ID	22253	100	32.71	22253	100	32.71
1 recurler	21667	97.37	31.85	21667	97.37	31.85
2 recurlers	19320	89.17	28.4	19320	89.17	28.4
3 recurlers	11316	58.57	16.63	11316	58.57	16.63
$\chi^2 < 15$	10763	95.11	15.82	10763	95.11	15.82
$p_{CMS} < 4$ MeV	10326	95.94	15.18	10326	95.94	15.18
$m_{ee}^{low} < 5$ or $m_{ee}^{low} > 10$ MeV	10122	98.02	14.88	10122	98.02	14.88
$103 < m_{rec} < 110$ MeV	9782	96.64	14.38	9782	96.64	14.38
Timing	8803	90.00	12.94	8803	90.00	12.94

Truth-level cuts

Reconstruction-level cuts

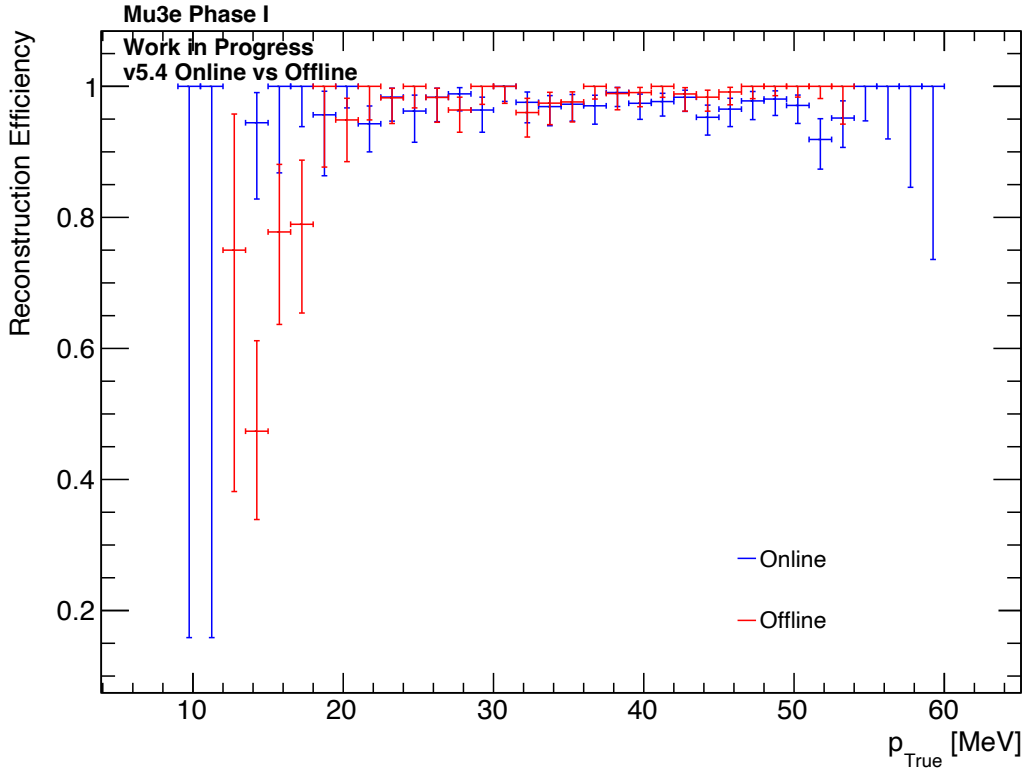
After the application of all cuts, a final signal efficiency of 12.9% is observed – consistent with Mu3e TDR [1] & [2].

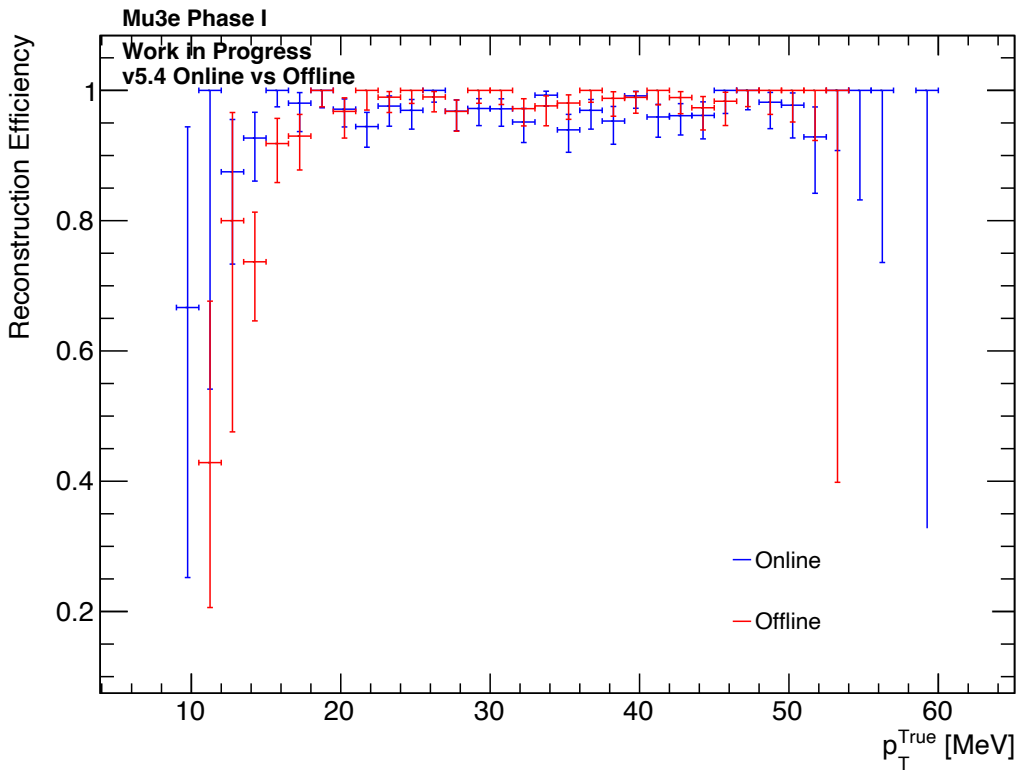
[2] S. Hughes PhD Thesis, “Towards the search for Charged Lepton Flavour Violation with The Mu3e Experiment”, Sep. 2023

Online Track Reconstruction

The reconstruction of short tracks is performed on a GPU filter farm at Mu3e – each of the 12 GPUs on the filter farm reconstruct all tracks and apply a selection in the algorithm, searching for $\mu^+ \rightarrow e^+e^+e^-$ signatures.

Important to observe how the GPU reconstruction performs in comparison to the offline reconstruction.



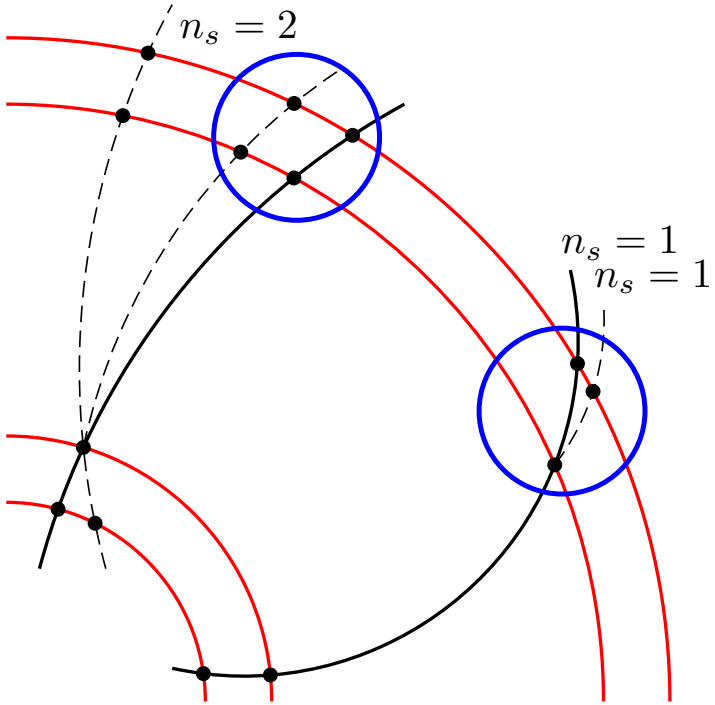


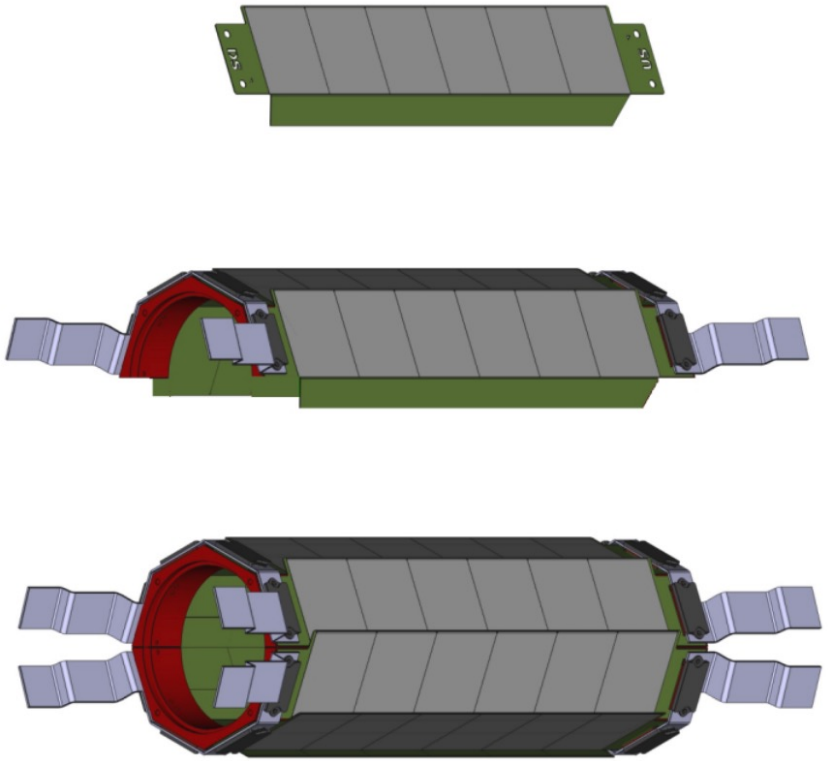
Online Track Reconstruction

Delving a bit further into the comparison, however...

	Reconstructed Truth-Matched Tracks	MC Tracks	Reconstruction Efficiency
Online	2187	2255	96.98%
Offline	1965	2011	97.71%

There is a discrepancy between the number of MC tracks online and offline – why?

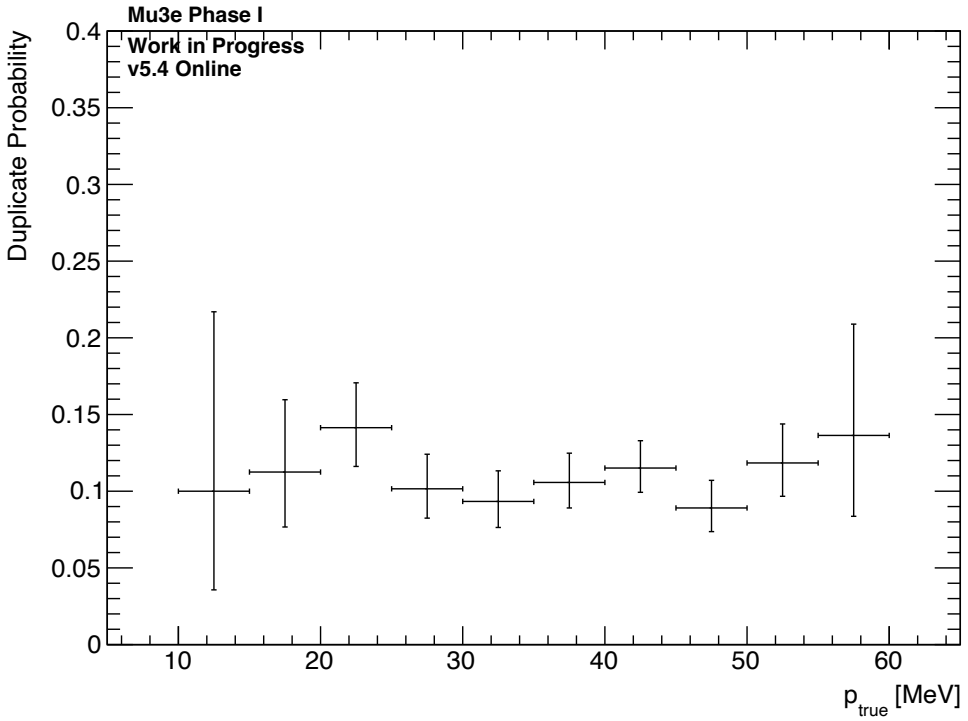


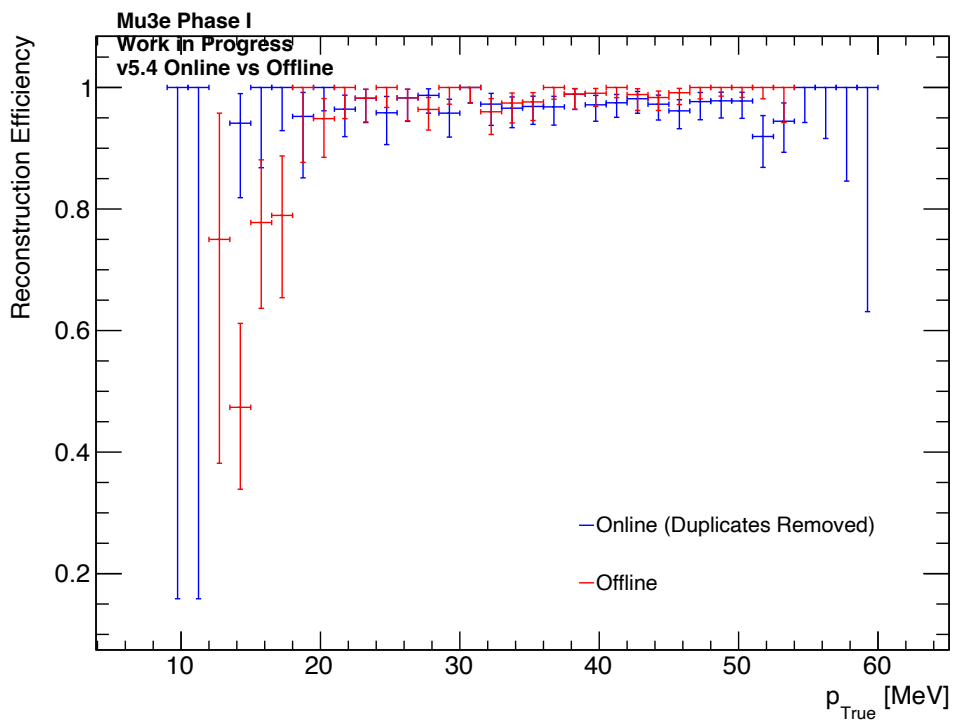


Online Track Reconstruction

After accounting for these “double hits”, a more robust comparison can be made between the reconstruction algorithms.

	Including Double Hits			Excluding Double Hits		
	Reconstructed	MC	Efficiency	Reconstructed	MC	Efficiency
Online	2187	2255	96.98%	1951	2011	97.02%
Offline	1965	2011	97.71%	1965	2011	97.71%

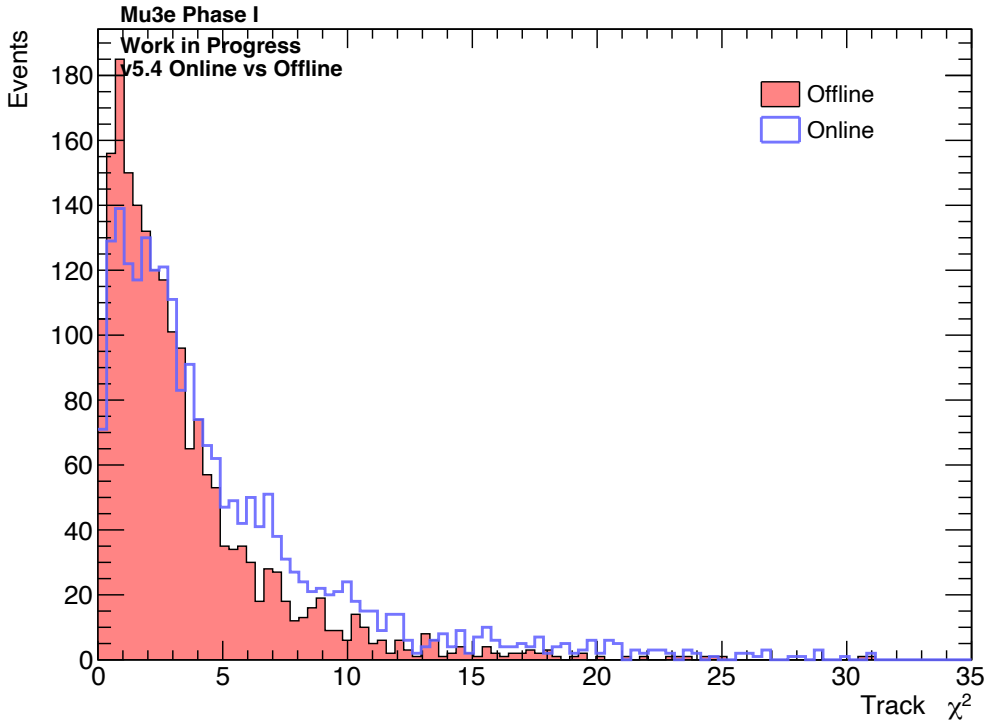


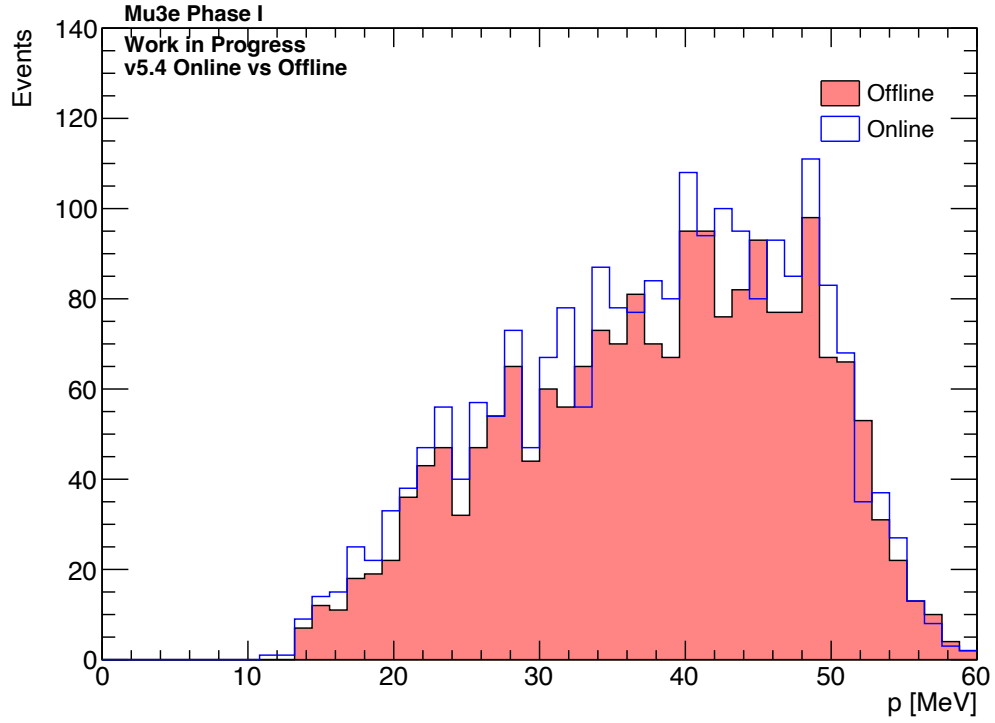


Online Track Reconstruction

Finally, how do some reconstructed properties of the tracks compare between the online and offline algorithms?

Selection	N_{Tracks}	ϵ_{reco} [%]	ϵ_{step} [%]
Initial Reconstructed Tracks	2241	99.38	–
$\chi^2 < 32$	2213	98.14	98.75
$zcpa_z < 55$ or $zpca_{rt} < 22$	2187	96.98	97.59





Conclusions & Future Work

- The Mu3e experiment is a dedicated search for CLFV in the muon sector, aiming to improve on the current best $\mu^+ \rightarrow e^+e^+e^-$ sensitivity limit by 4 orders of magnitude.

- The offline track reconstruction and vertex algorithms have been briefly explained, as well as a dedicated signal sample study yielding an overall signal efficiency of 12.9%.

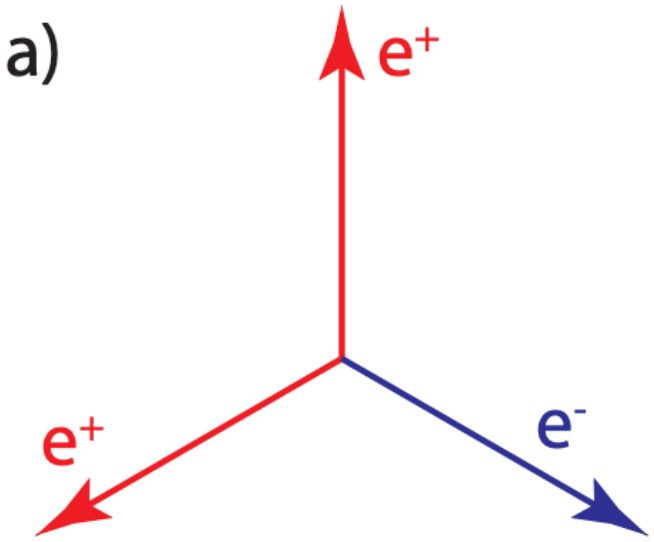
- A fast and efficient online reconstruction algorithm is required to reject backgrounds and reduce the amount of data written to disk. The latter has been highlighted here and compared to the offline reconstruction performance.

- Future work will focus on a mix of hardware and software:

  - Continue to perform quality control tests on chips for the outer pixel detector.
  - Be part of an analysis team to measure the Michel spectrum using the two-layer detector setup.
  - Studies will be performed initially with MC, before analysing the beam data (beam data-taking stopped just last week!)

Backup

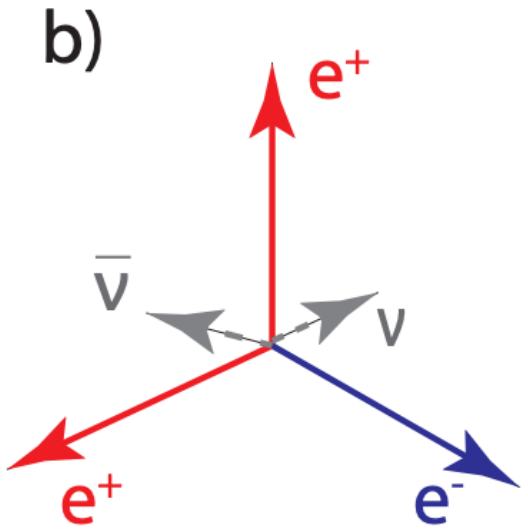
Signal & Backgrounds



a) Signal topology

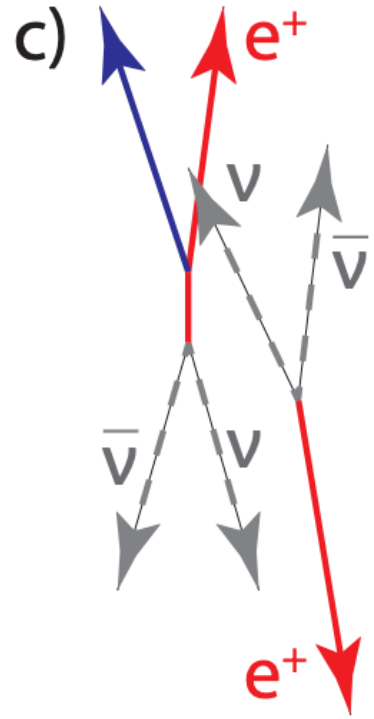
$$m_{inv} = P_{eee} = \sum_i E_i = m_\mu$$

$$|\vec{p}_{tot}| = \left|\sum_i \vec{p}_i\right| = 0$$



b) **Irreducible** internal conversion backgrounds

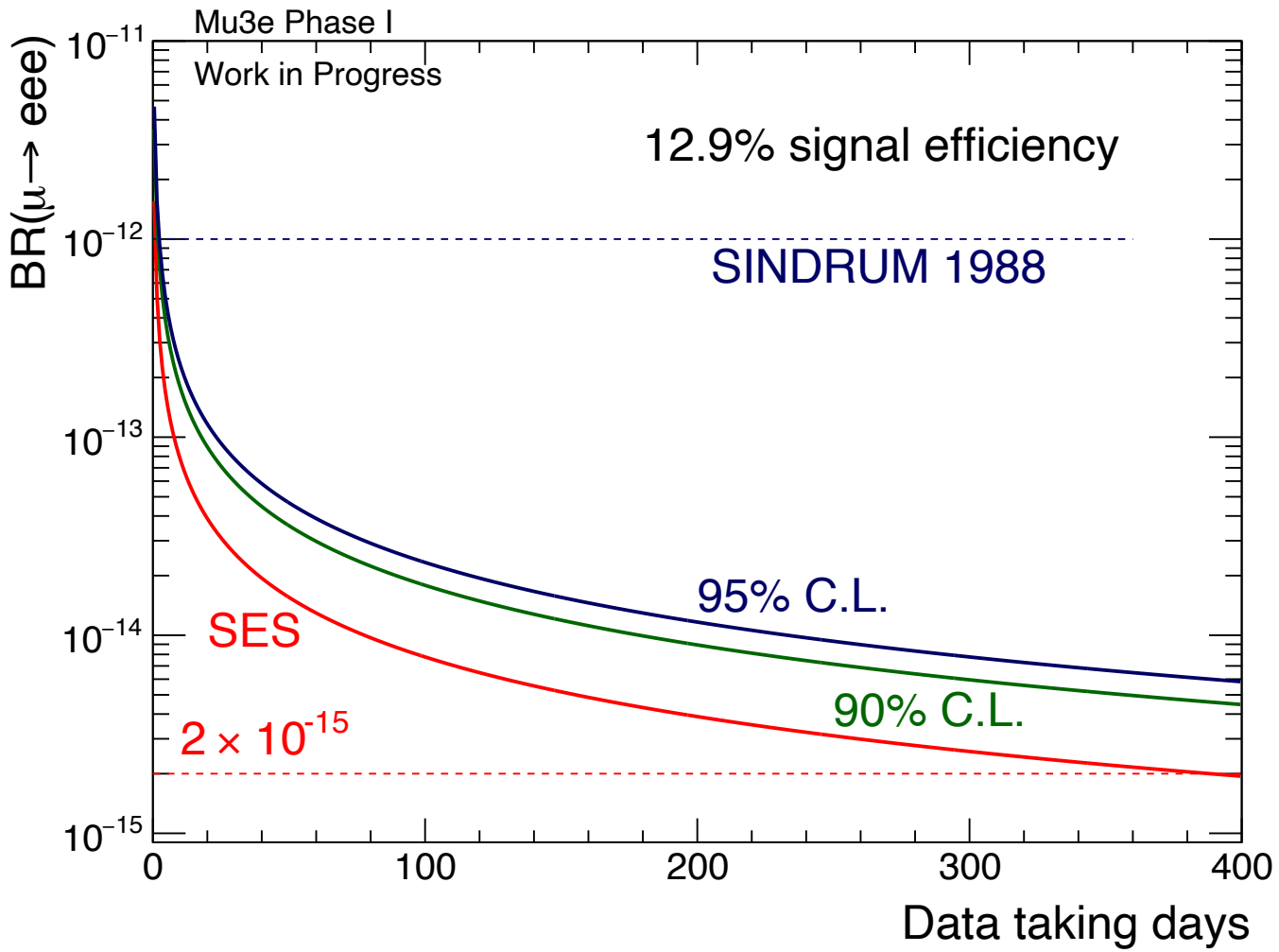
- Energy carried away by neutrinos here!
- Excellent momentum resolution required.



c) Combinatorial backgrounds

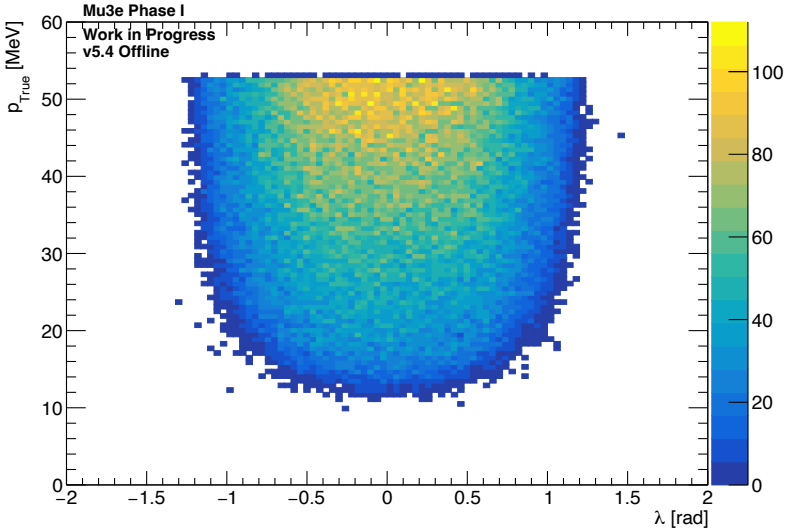
- Pileup of Michel decays and electrons from Bhabha scattering.

Mu3e Sensitivity

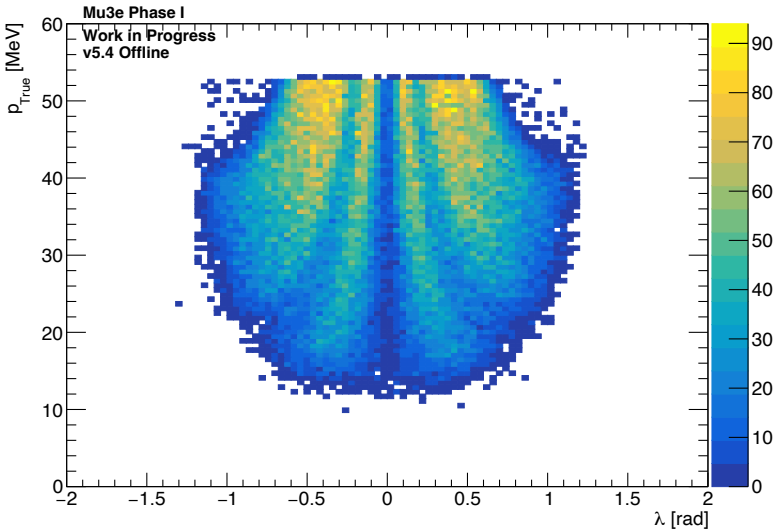


Track Distributions

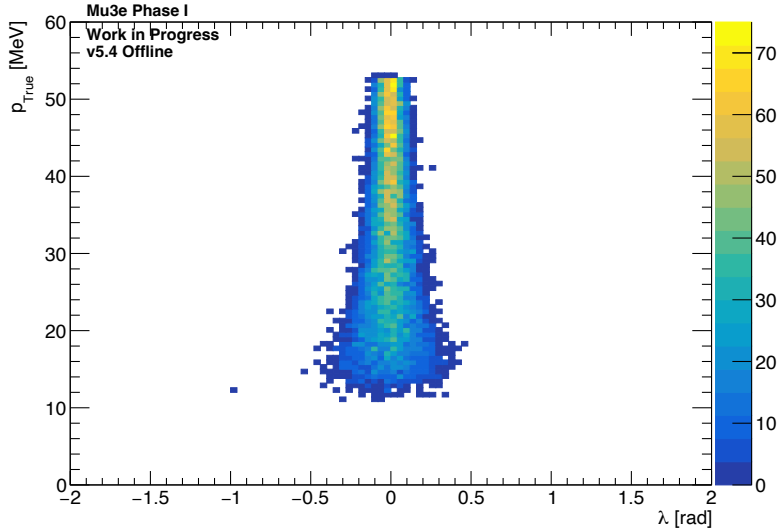
4-hit



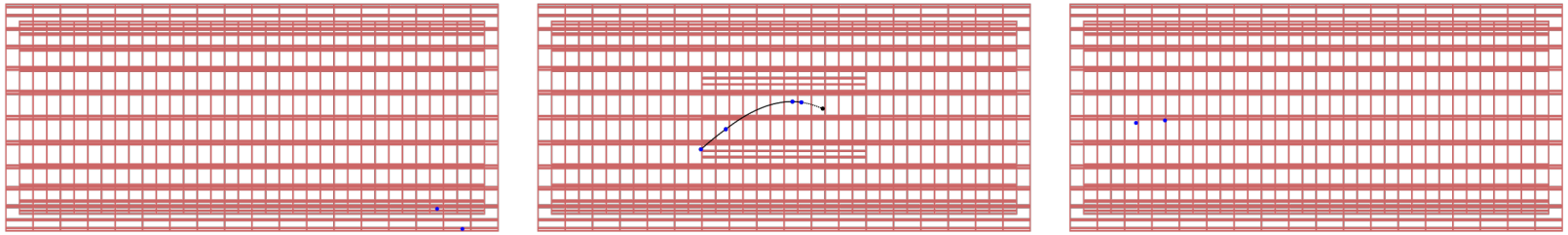
6-hit



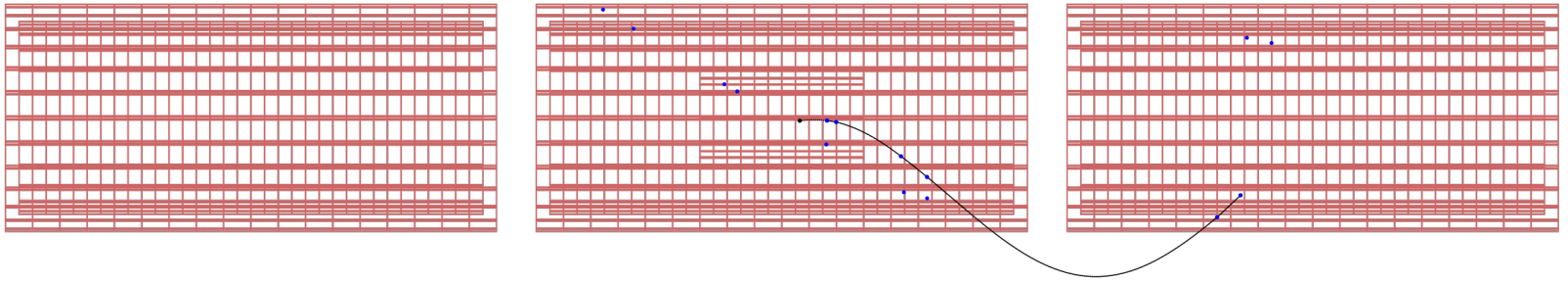
8-hit



Longitudinal Event Displays



4-hit



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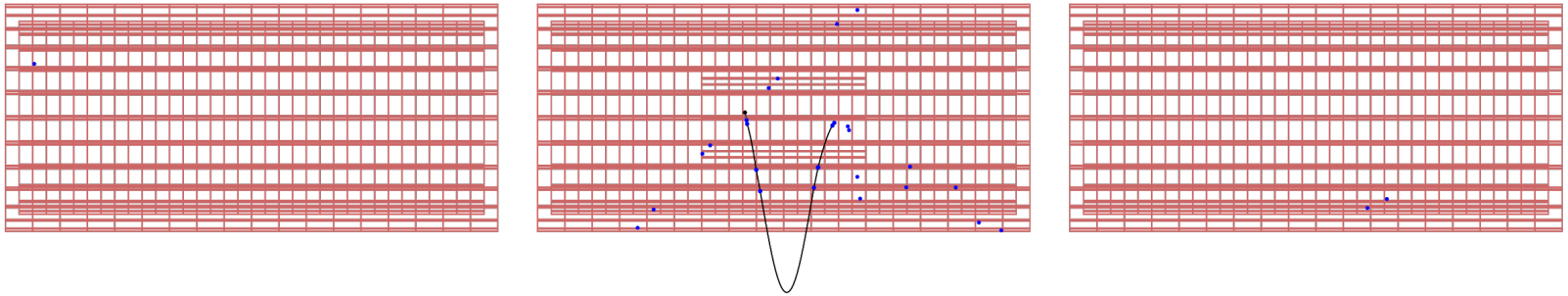

8-hit

Cutflow Efficiencies