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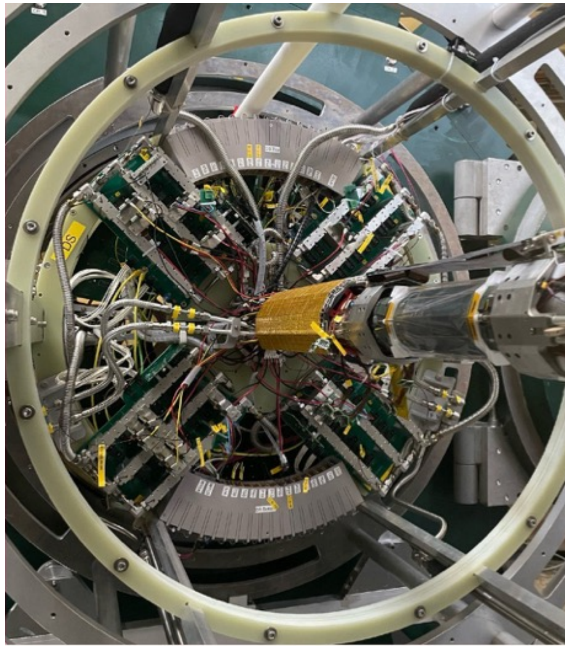


Liverpool Annual HEP Meeting

Jak Woodford (Supervised by: Dr. Nikolaos Rompotis & Prof. Joost Vossebeld)

Data and Simulation-Based Studies for the Mu3e Experiment

21/05/2026

Charged Lepton Flavour Violation

- Lepton flavour is an accidental symmetry of the Standard Model (SM) – many SM extensions predict Charged Lepton Flavour Violation (CLFV) to occur at observable rates

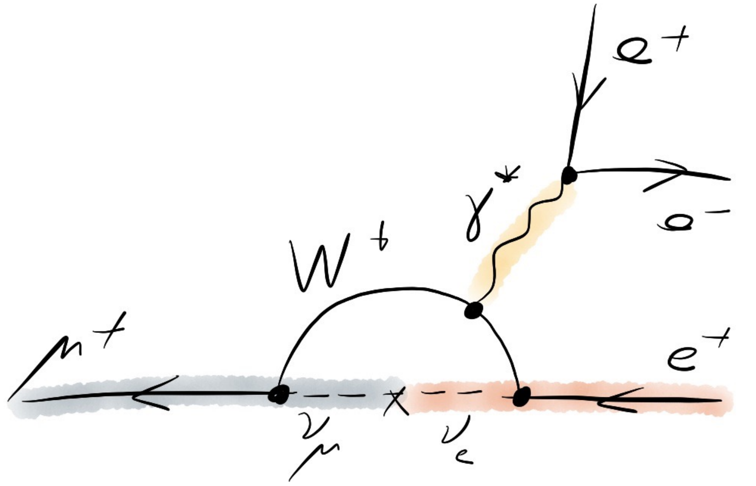
- **The Mu3e experiment** is a dedicated search for the decay $\mu^+ \rightarrow e^+e^+e^-$

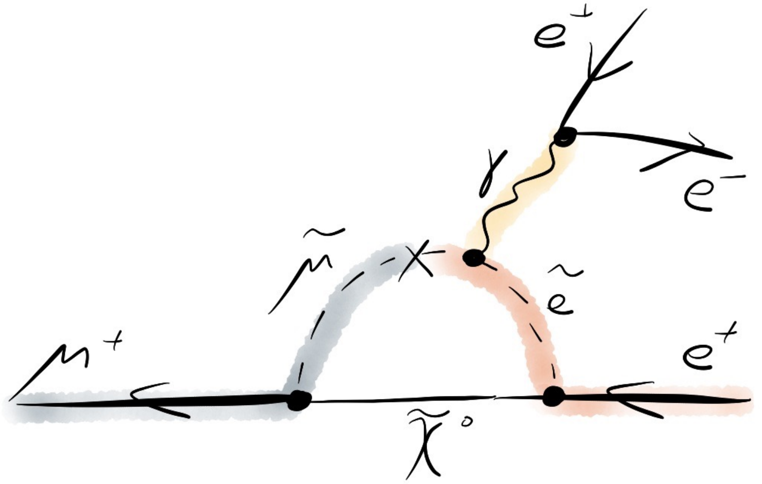
- CLFV is heavily suppressed to unobservable rates within the SM:

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

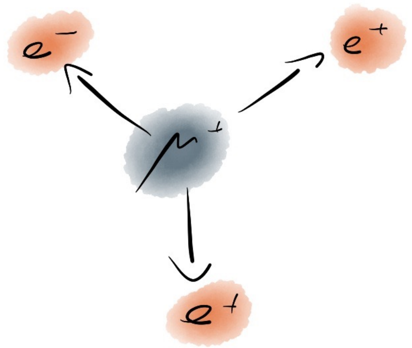
- Any observation of CLFV is unequivocal evidence for **new physics**

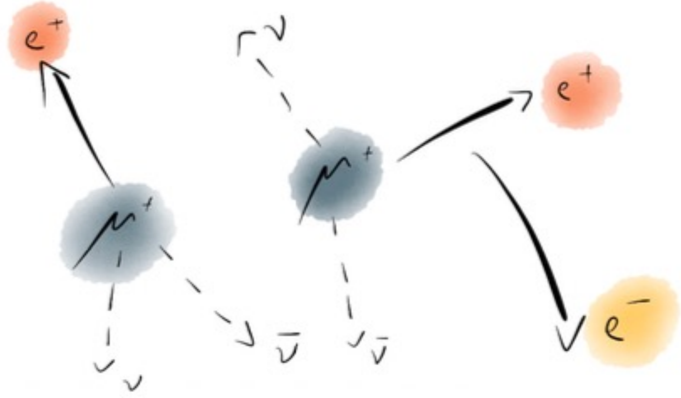
- See **Mark's talk** tomorrow **for more!**





Signal & Background at Mu3e





- Signal $\mu^+ \rightarrow e^+e^+e^-$
- Vertex coincident in space and time
- Muon decay at rest
  - $\Sigma P_e = (m_\mu, \vec{0}, \vec{0}, \vec{0})$
  - Maximum $\vec{p}_e = 53$ MeV
  - $\Sigma \vec{p}_e = \vec{0}$

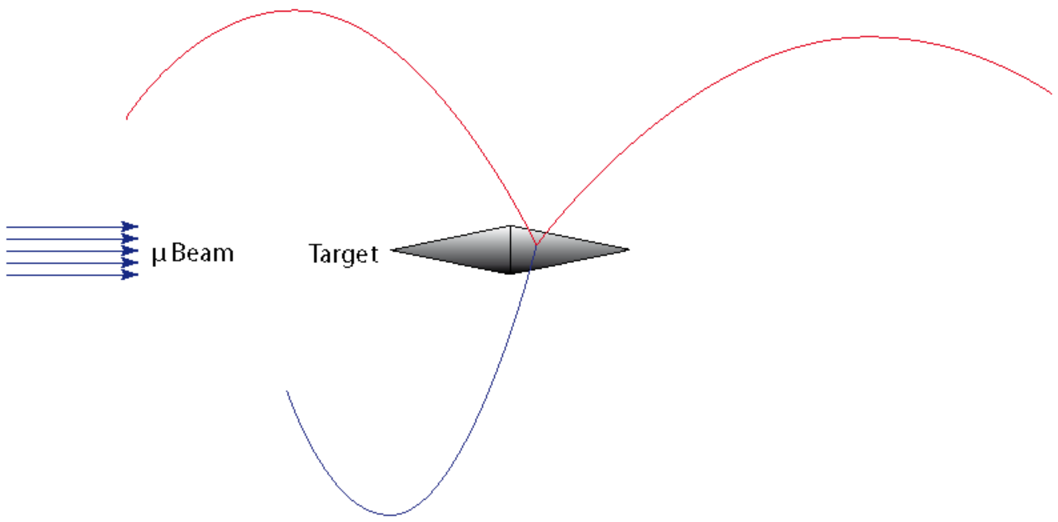
- Background from rare internal conversion (IC) decay $\mu^+ \rightarrow e^+e^+e^-\bar{\nu}_\mu \nu_e$ ($\mathcal{B}_{\mu\rightarrow eee\nu\nu} = 3.4{\times}10^{-5}$)
- Missing momentum from neutrinos
  - Requires excellent momentum resolution

- Combinatorial 2+1 backgrounds
  - Michel ($\mu \rightarrow e\nu\nu$) e^+ plus e^+ that Bhabha scatters with e^- in target material
  - Photon conversion
- Requires excellent vertex and timing resolution

Mu3e Experiment (Phase-I)

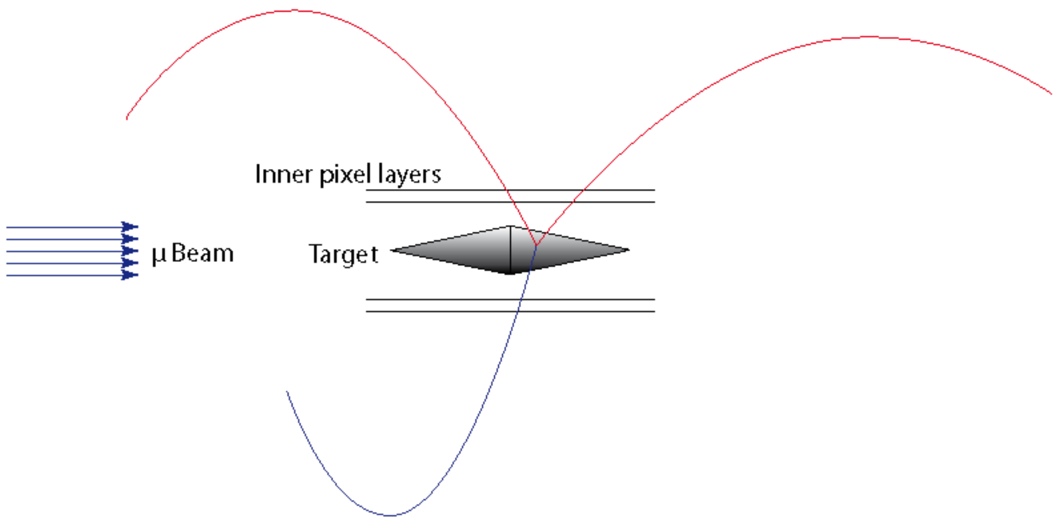
- Continuous beam of muons stop and decay at rest on target

Mu3e Experiment (Phase-I)



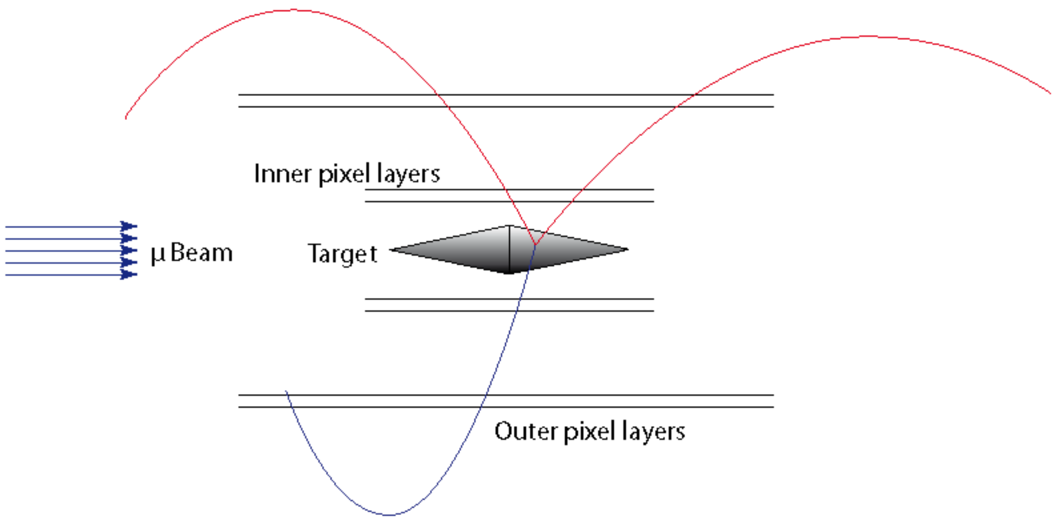
- Continuous beam of muons stop and decay at rest on target
- Track e^+/e^- trajectories in 1 T magnetic field

Mu3e Experiment (Phase-I)



- Continuous beam of muons stop and decay at rest on target
- Track e^+/e^- trajectories in 1 T magnetic field
- 4 layers of ultra-thin silicon pixel sensors

Mu3e Experiment (Phase-I)

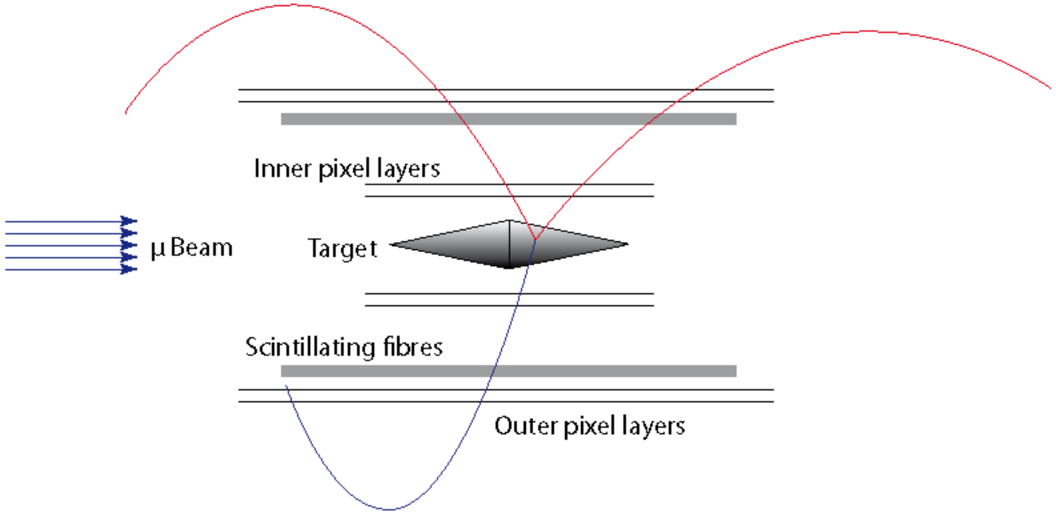


- Continuous beam of muons stop and decay at rest on target

- Track e^+/e^- trajectories in 1 T magnetic field

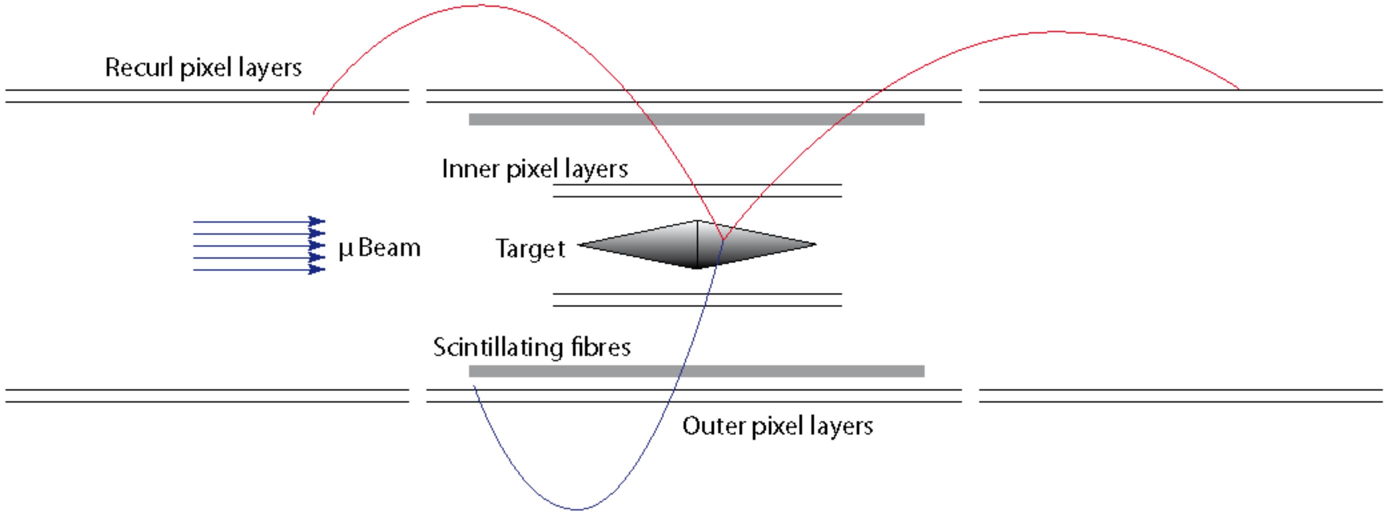
- 4 layers of ultra-thin silicon pixel sensors

Mu3e Experiment (Phase-I)



- Continuous beam of muons stop and decay at rest on target
- Track e^+/e^- trajectories in 1 T magnetic field
- 4 layers of ultra-thin silicon pixel sensors
- Timing information provided by scintillating fibres

Mu3e Experiment (Phase-I)

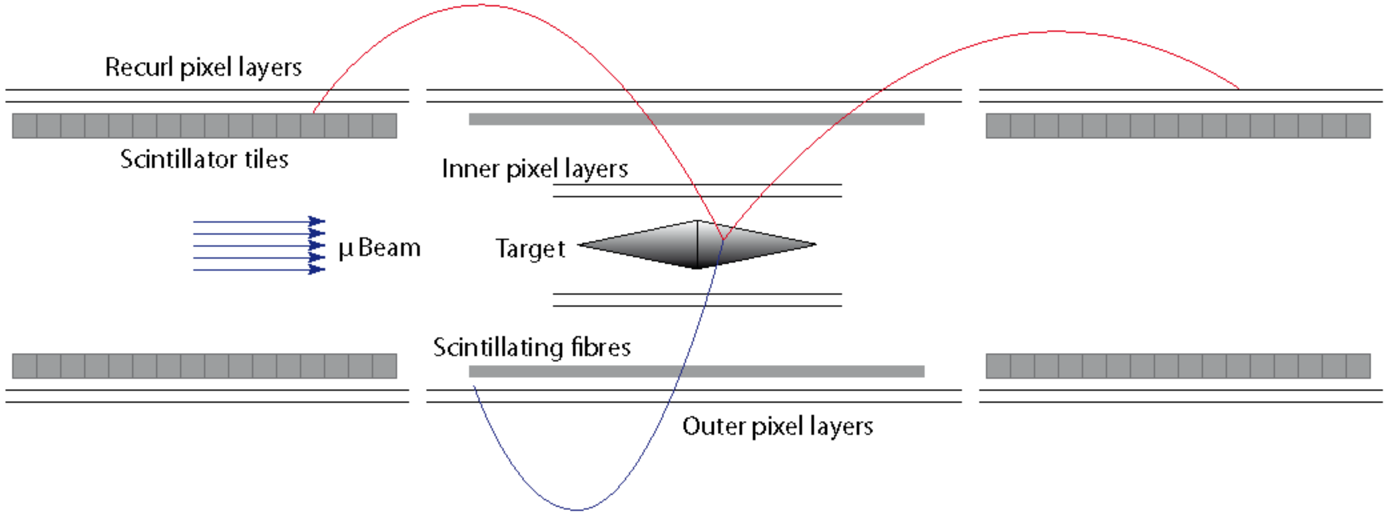


- Continuous beam of muons stop and decay at rest on target
- Track e^+/e^- trajectories in 1 T magnetic field

- 4 layers of ultra-thin silicon pixel sensors
- Timing information provided by scintillating fibres

- Recurl stations with pixel sensors

Mu3e Experiment (Phase-I)

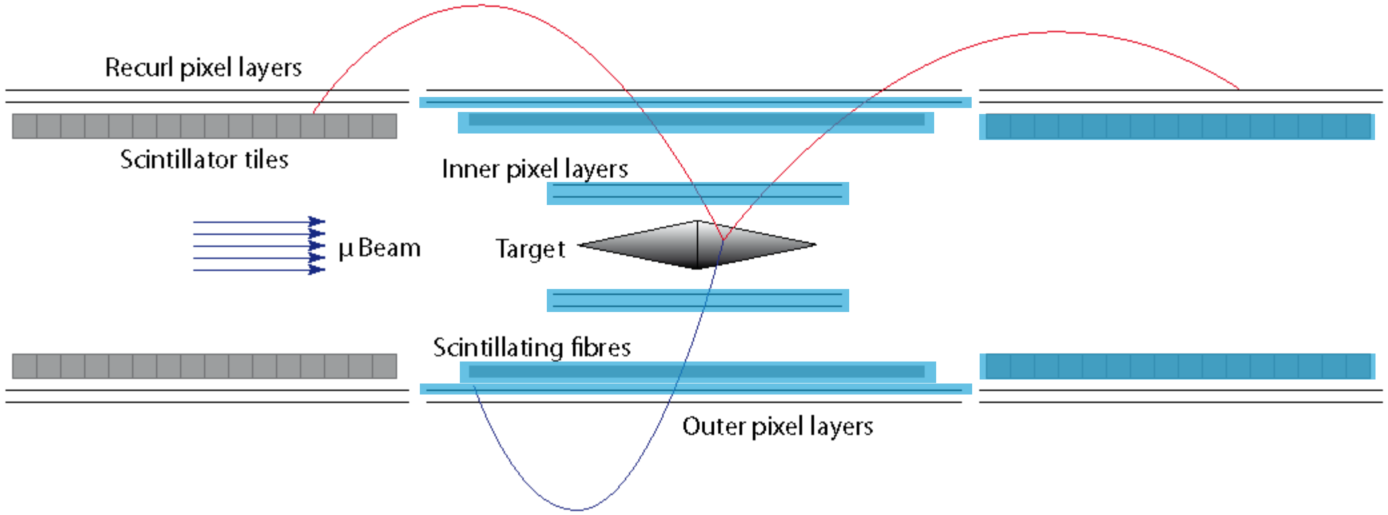


- Continuous beam of muons stop and decay at rest on target
- Track e^+/e^- trajectories in 1 T magnetic field

- 4 layers of ultra-thin silicon pixel sensors
- Timing information provided by scintillating fibres

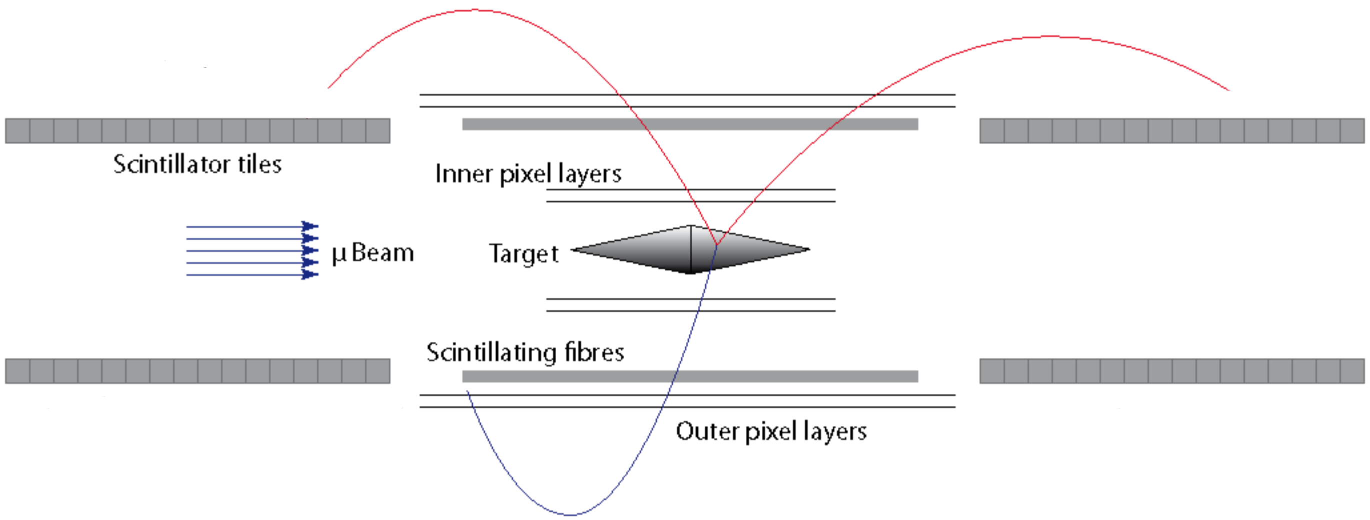
- Recurl stations with pixel sensors and scintillating tiles

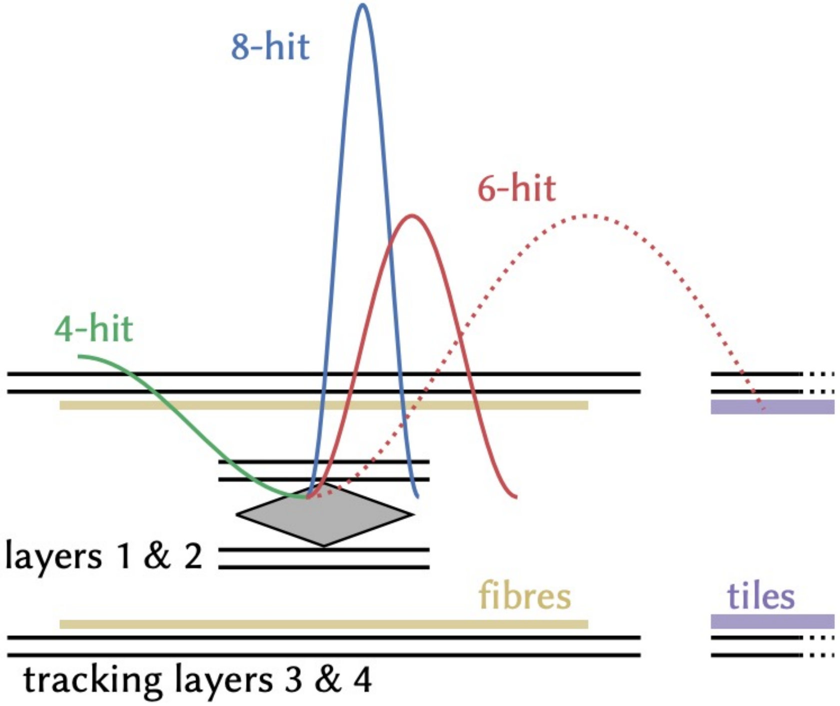
Mu3e Experiment (2026)



- **New** vertex detector (70 μm sensors; 50 μm in 2025)
- 3 pixel layers (1 outer layer)
- Short beam time (~8 weeks)
  - Likely commissioning (detectors, GPU filter farm)
  - Potential for background studies

Mu3e Experiment (Towards 2027)



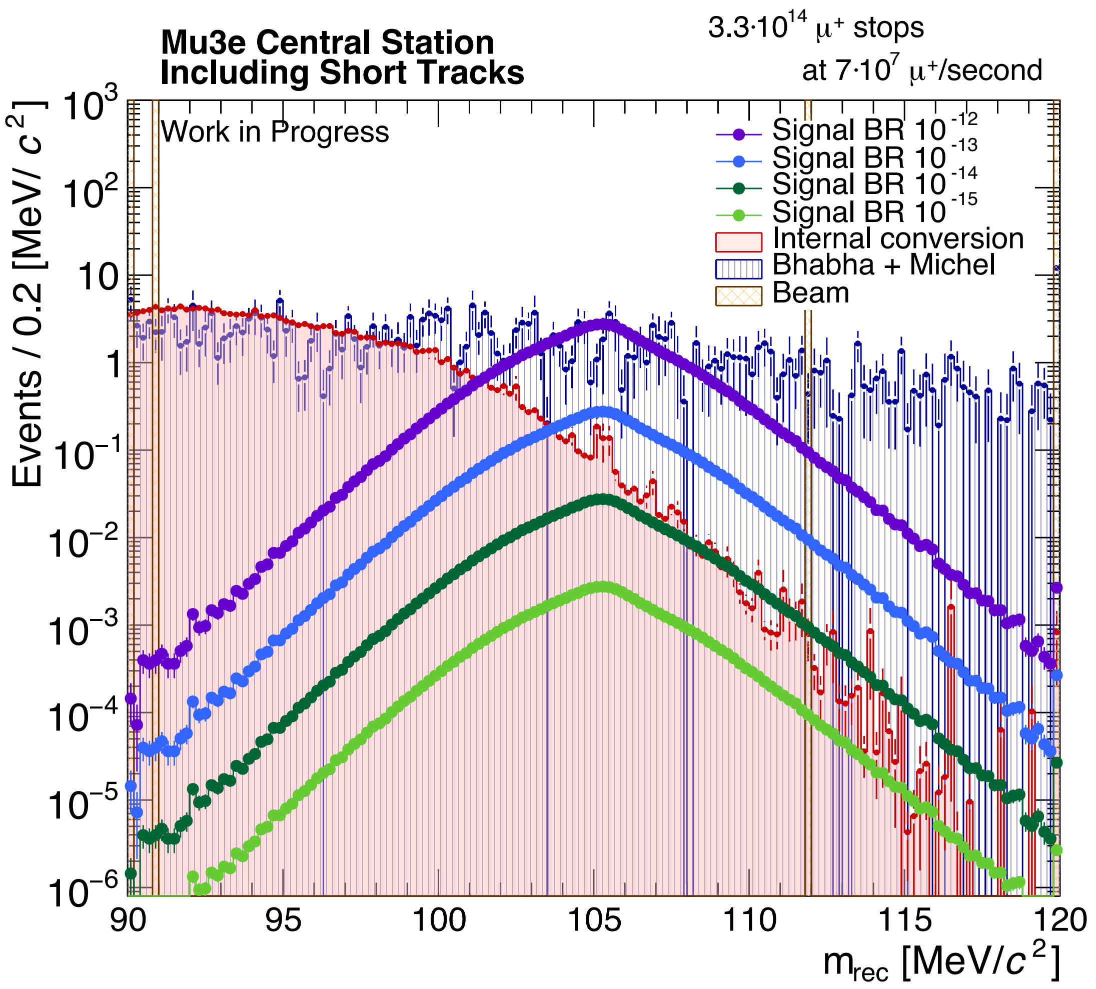


- Towards a first physics run in 2027, the above 4-layer setup is the expected detector configuration
  - All following simulation analyses consider this detector configuration
  - Simulation analyses include sensitivity studies and dedicated 2+1 background studies

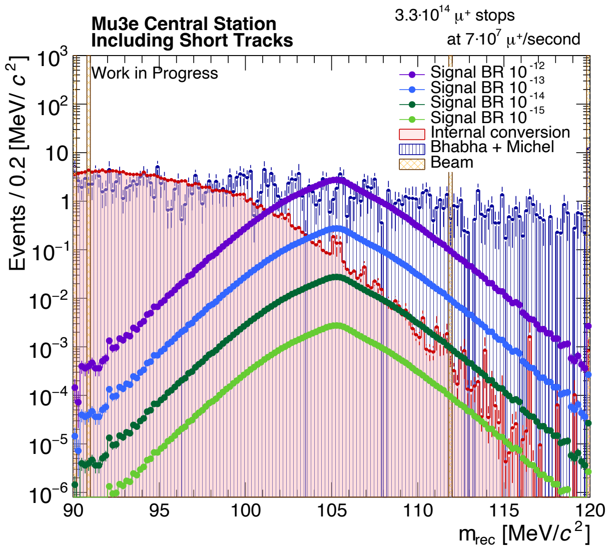
Sensitivity (All Track Types)

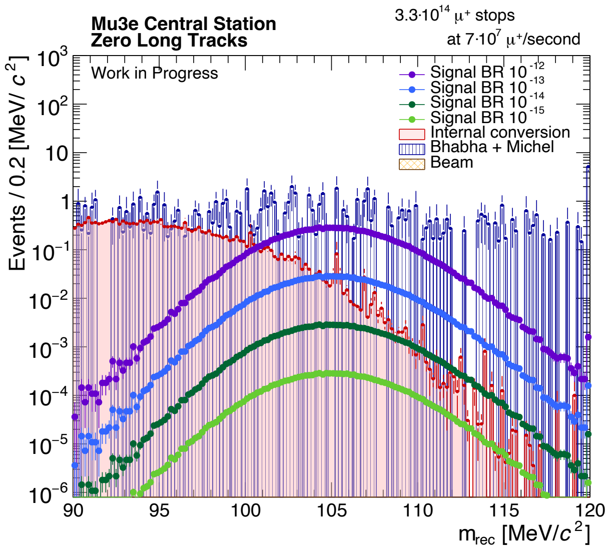
- First sensitivity study of this detector configuration
  - Prove we can do physics and beat best limit (10^{-12})
- All combinations of $e^+e^+e^-$ are fitted to a common vertex
  - Weight IC and Bhabha events with corresponding matrix element value
  - Apply various selection criteria
- Study is performed to determine if short tracks can be used in analyses in 2027
- **Work in progress** to suppress Bhabha + Michel background with **dedicated timing study** and cut optimisation

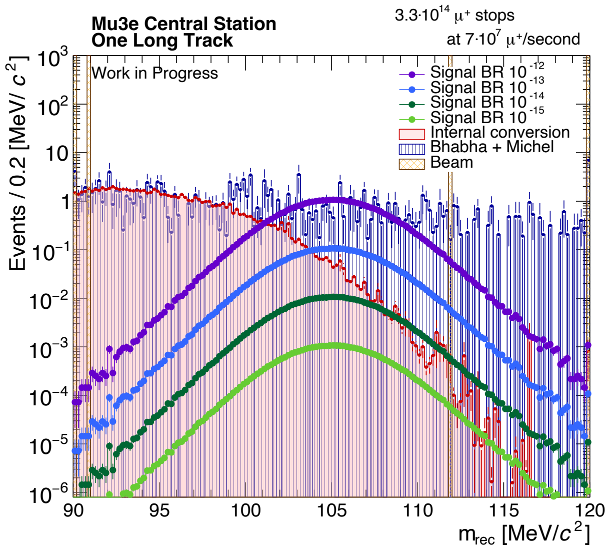
Reconstruction-level cuts



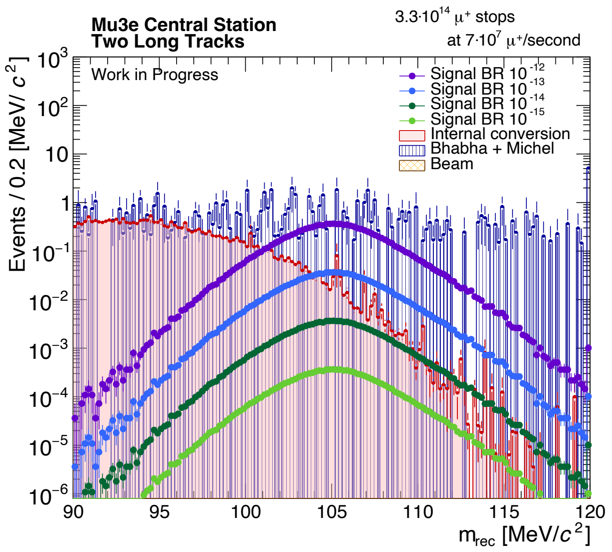
Sensitivity Comparison

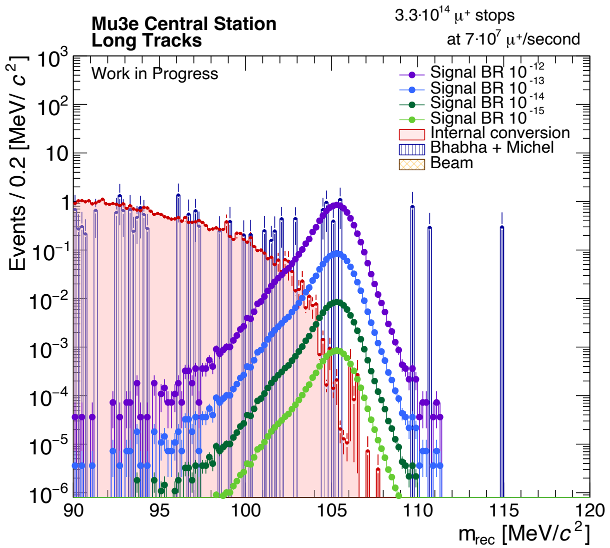




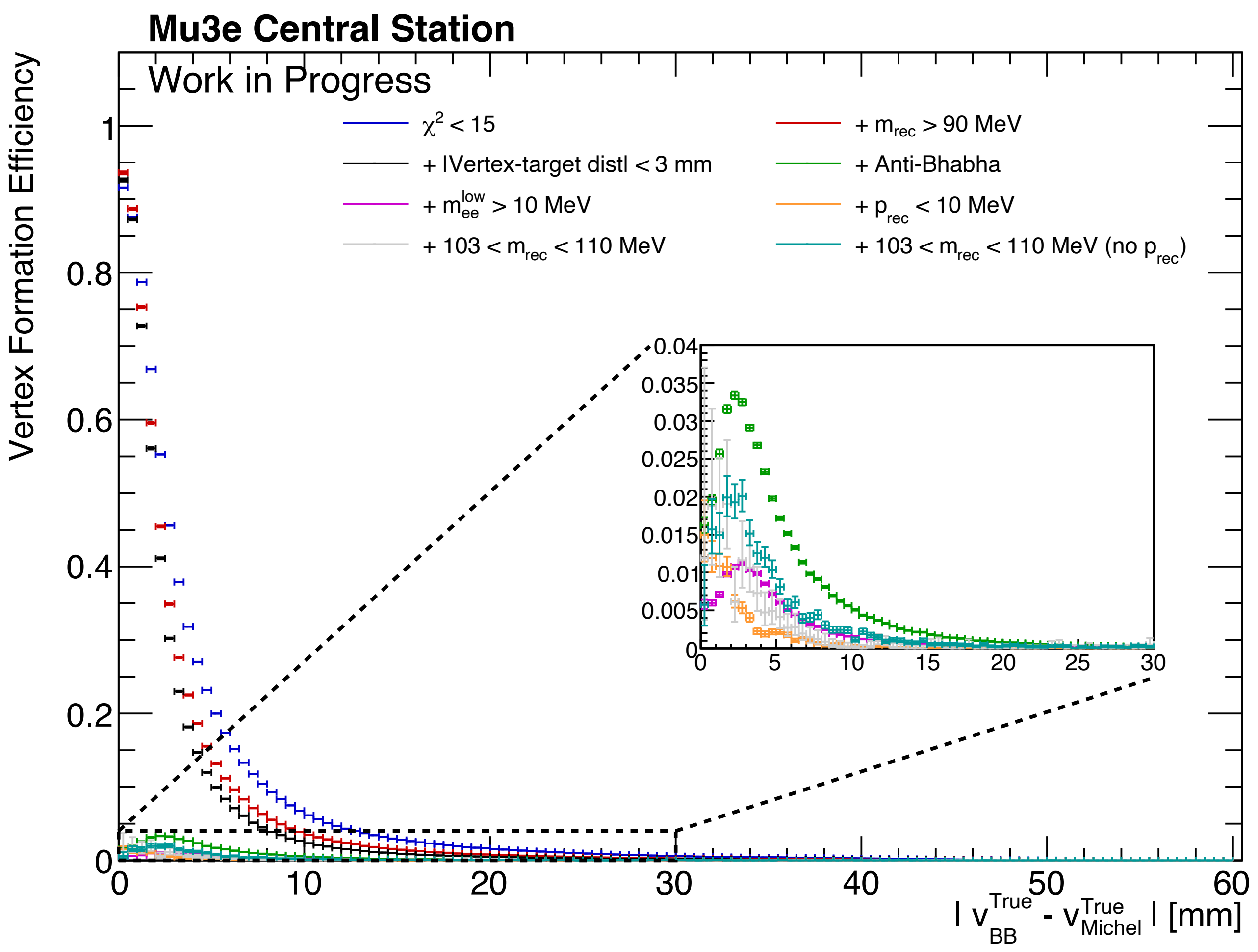


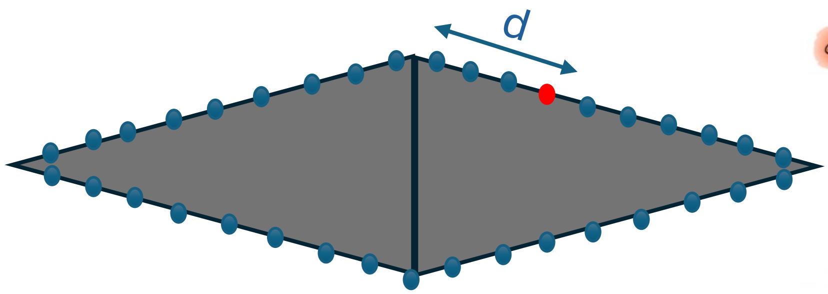
- Reconstruction-level cuts only
- Dominated by Bhabha + Michel background even in the case of 3 long tracks
  - Statistically-limited 2+1 sample
- Short track dominates in broadening our mass resolution

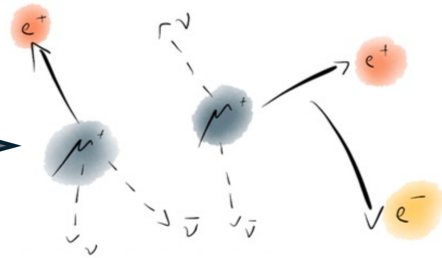




Bhabha + Michel Background Study







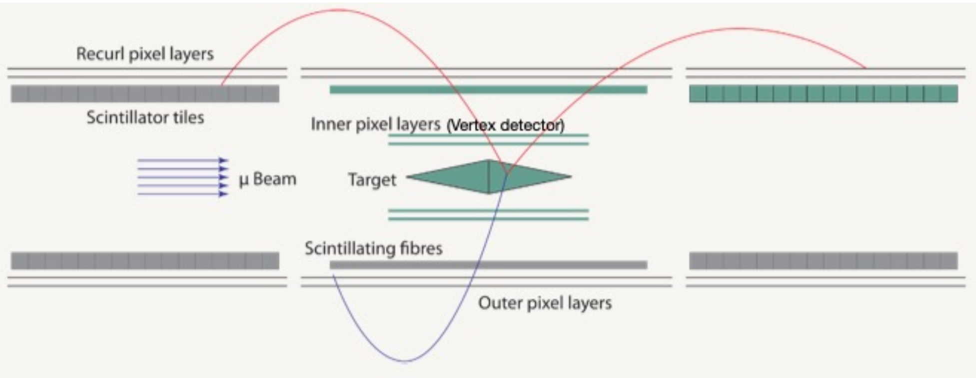
- Michel positron Bhabha scattering with electron in target material
- Michel positrons from muon beam

How efficient are we at forming a 2 + 1 vertex depending on the distance between the Bhabha scattering event and the Michel positron?

$$\text{Efficiency} = \frac{\text{Number of fitted } 2+1 \text{ vertices}}{\text{Number of } 2+1 \text{ vertex candidates}}$$

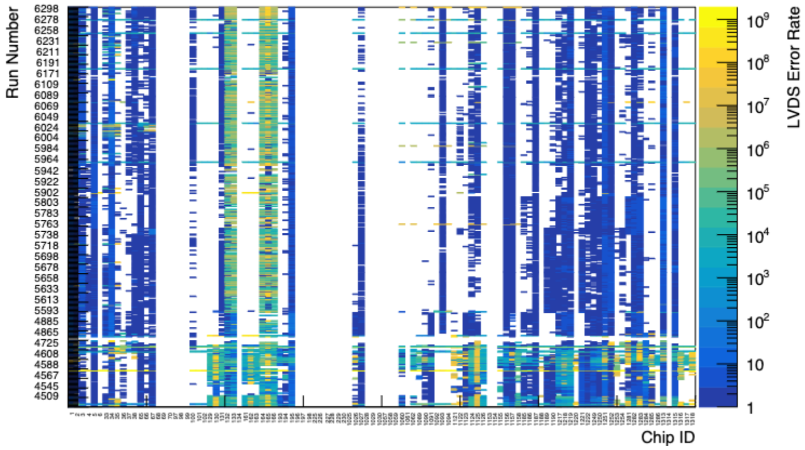
Mu3e 2025 Commissioning Run

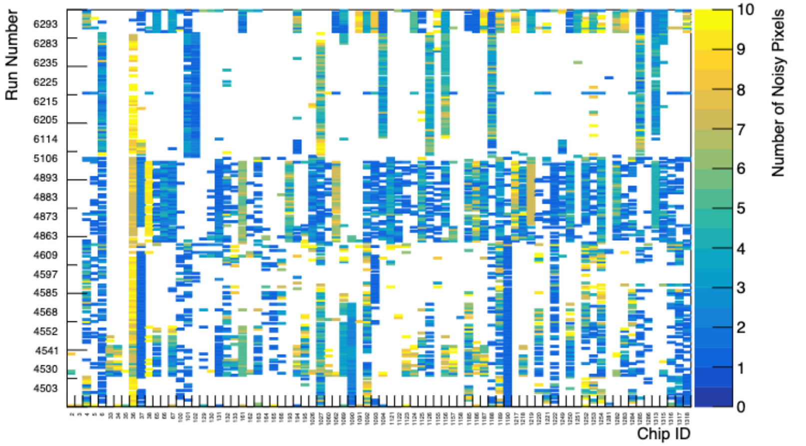
2025 detector configuration



Pixel DQM

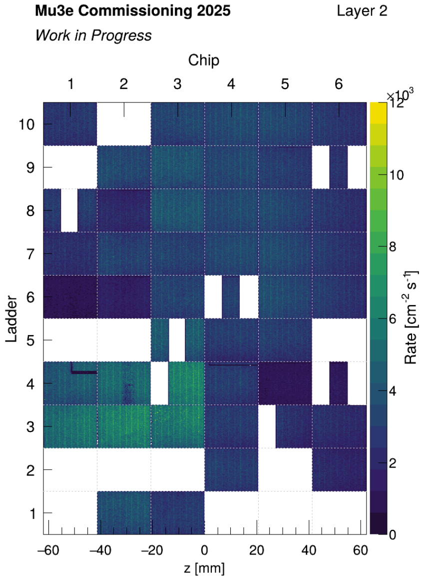
Role in 2025 commissioning run: perform data quality checks with the pixel detector → create pixel "good run" list



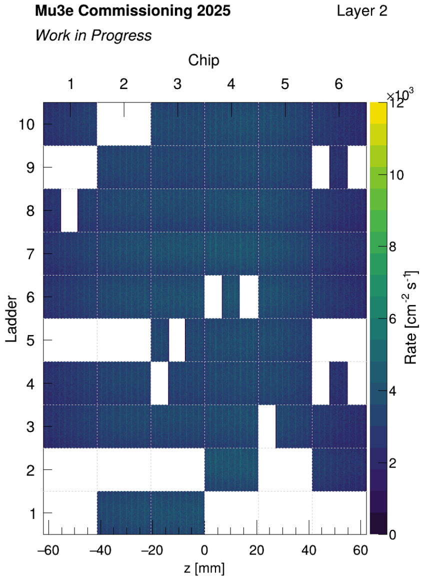


Use "good run", implement in simulation

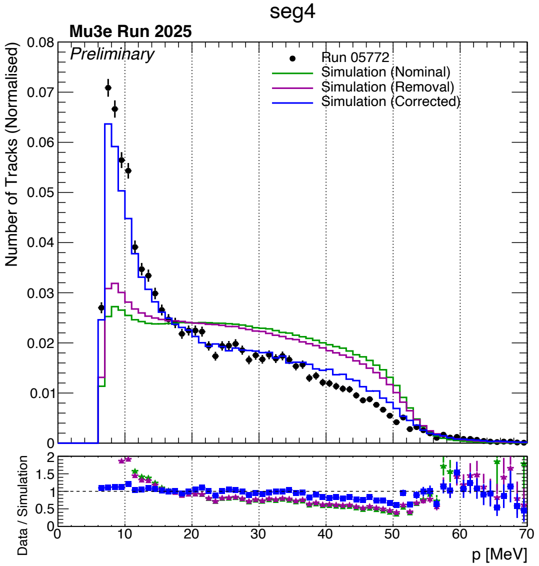
Data



Simulation



Analysis



Summary

2025 work from Mu3e commissioning run (thesis chapter):

- Role: pixel detector DQM; create “good run” list from the pixel detector for the entire beam campaign; perform data-MC analysis on “good runs”
  - Developed algorithm for determining good data readout links/sensors in a run based off LVDS error rates and pixel sensor noise
  - Created “good run” list from above algorithm
  - Use “good run” list to perform data-MC comparisons

Present and future work:

- Sensitivity studies ahead of first physics run in 2027 (thesis chapter)
  - Study to determine if short tracks can be used in analysis
  - Dedicated study of Michel + Bhabha background (WIP)
  - Dedicated timing study for background suppression (WIP)
- DAQ DQM (towards 2026; WIP)
  - Develop framework for frame-based DQM; currently only event-based (multiples of frames)

Backup

Cut Selection (All Track Types)

Selection criteria (reconstruction-level only) used for all 4-layer sensitivity plots using all track types. NOTE: before the “no cuts stage”, the minimum χ^2 vertex is chosen in each frame

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
0	No Cuts	204.51	1.82e+04	5.81e+08	4.29e+13	100.0	100.0	100.0	100.0	100.00	100.00	100.0	100.0	4.8e-12	0.0
1	At least 3 short tracks	204.51	1.82e+04	5.81e+08	4.29e+13	100.0	100.0	100.0	100.0	100.00	100.00	100.0	100.0	4.8e-12	0.0
2	Truth Bhabha check	204.51	1.82e+04	3.22e+08	4.29e+13	100.0	100.0	100.0	100.0	55.39	55.39	100.0	100.0	4.8e-12	0.0
3	$m_{rec} > 90$ MeV	156.63	1.14e+04	2.40e+07	1.03e+13	76.6	76.6	62.7	62.7	4.14	7.47	23.9	23.9	1.5e-11	0.0
4	Vertex $\chi^2 < 15$	105.76	8.28e+03	2.49e+06	1.62e+12	51.7	67.5	45.5	72.5	0.43	10.35	3.8	15.7	6.5e-11	0.0
5	In target region	103.75	8.06e+03	2.25e+06	1.34e+12	50.7	98.1	44.3	97.4	0.39	90.56	3.1	82.6	7.8e-11	0.0
6	$\lvert$Vertex-target distance$\rvert < 3$ mm	99.18	7.32e+03	1.44e+06	6.65e+11	48.5	95.6	40.2	90.8	0.25	63.98	1.5	49.8	1.5e-10	0.0
7	$m_{ee}^{low} < 5$ or > 10 MeV (anti-Bhabha)	97.45	6.24e+03	9.49e+05	6.61e+11	47.6	98.3	34.3	85.3	0.16	65.81	1.5	99.4	1.5e-10	0.0
8	$m_{ee}^{low} > 10$ MeV	97.01	3.83e+03	8.93e+05	6.45e+11	47.4	99.5	21.1	61.4	0.15	94.17	1.5	97.5	1.5e-10	0.0
9	$p_{rec} < 4$ MeV	69.26	1.60e+02	3.01e+02	4.03e+07	33.9	71.4	0.9	4.2	0.00	0.03	0.0	0.0	1.7e-06	0.0
10	$\Delta R_{min} > 0.2$	69.11	1.60e+02	3.00e+02	2.69e+07	33.8	99.8	0.9	99.9	0.00	99.83	0.0	66.7	2.6e-06	0.0
11	$103 < m_{rec} < 110$ MeV	53.73	2.43e+00	6.38e+01	0.00e+00	26.3	77.7	0.0	1.5	0.00	21.23	0.0	0.0	8.1e-01	6.6
12	[10] + $103 < m_{rec} < 110$ MeV	65.51	1.41e+02	1.41e+05	1.10e+11	32.0	121.9	0.8	5812.2	0.02	221484.51	0.3	100.0	5.9e-10	0.0

What are the statistical uncertainties associated with the number of events in the signal region (SR)?

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
11	$103 < m_{rec} < 110$ MeV	53.73 ± 0.04	2.43e+00 ± 1.48e-01	6.38e+01 ± 6.57e+00	0.00e+00 ± 0.00e+00	26.3	77.7	0.0	1.5	0.00	21.23	0.0	0.0	8.1e-01	6.6

Statistical uncertainty, $\sigma_i = N_i \cdot \sqrt{\Sigma w_i^2}$,

where N_i = normalisation factor, Σw_i^2 = sum of the weights squared, i = Signal, IC, BB, Beam

Cut Selection (Short + Long Tracks)

Selection criteria (truth + reco-level) used for all 4-layer sensitivity plots using short + long tracks. NOTE: before the "no cuts stage", the minimum χ^2 vertex is chosen in each frame

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
0	No Cuts	204.51	1.82e+04	5.81e+08	4.29e+13	100.0	100.0	100.0	100.0	100.00	100.00	100.0	100.0	4.8e-12	0.0
13	At least 3 short tracks + truth cuts	93.96	9.96e+03	1.64e+08	9.52e+12	45.9	45.9	54.7	54.7	28.15	28.15	22.2	22.2	9.9e-12	0.0
14	Truth Bhabha check	93.96	9.96e+03	1.64e+08	9.52e+12	45.9	100.0	54.7	100.0	28.15	100.00	22.2	100.0	9.9e-12	0.0
15	$m_{rec} > 90$ MeV	93.60	7.16e+03	4.69e+06	2.61e+12	45.8	99.6	39.4	72.0	0.81	2.87	6.1	27.5	3.6e-11	0.0
16	Vertex $\chi^2 < 15$	88.12	6.78e+03	6.80e+05	7.13e+10	43.1	94.1	37.3	94.7	0.12	14.50	0.2	2.7	1.2e-09	0.0
17	In target region	88.12	6.78e+03	6.50e+05	6.55e+10	43.1	100.0	37.3	100.0	0.11	95.57	0.2	91.9	1.3e-09	0.0
18	$\|$Vertex-target distance$\| < 3$ mm	85.63	6.24e+03	5.13e+05	3.97e+10	41.9	97.2	34.3	92.1	0.09	78.97	0.1	60.5	2.2e-09	0.0
19	$m_{ee}^{low} < 5$ or > 10 MeV (anti-Bhabha)	84.09	5.21e+03	7.06e+04	3.90e+10	41.1	98.2	28.6	83.5	0.01	13.76	0.1	98.4	2.2e-09	0.0
20	$m_{ee}^{low} > 10$ MeV	83.71	2.88e+03	2.30e+04	3.89e+10	40.9	99.5	15.8	55.3	0.00	32.53	0.1	99.8	2.1e-09	0.0
21	$p_{rec} < 4$ MeV/c	64.82	1.31e+02	2.34e+01	2.01e+07	31.7	77.4	0.7	4.5	0.00	0.10	0.0	0.1	3.2e-06	0.0
22	$\Delta R_{min} > 0.2$	64.69	1.31e+02	2.34e+01	2.01e+07	31.6	99.8	0.7	99.9	0.00	100.00	0.0	100.0	3.2e-06	0.0
23	$103 < m_{rec} < 110$ MeV	50.38	1.38e+00	2.42e+00	0.00e+00	24.6	77.9	0.0	1.1	0.00	10.35	0.0	0.0	1.3e+01	25.8
24	[22] + $103 < m_{rec} < 110$ MeV	60.30	1.24e+01	9.13e+02	6.76e+09	29.5	119.7	0.1	892.2	0.00	37697.53	0.0	100.0	8.9e-09	0.0

What are the statistical uncertainties associated with the number of events in the signal region (SR)?

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
23	$103 < m_{rec} < 110$ MeV	50.38 ± 0.04	1.38e+00 ± 1.82e-02	2.42e+00 ± 1.25e+00	0.00e+00 ± 0.00e+00	24.6	77.9	0.0	1.1	0.00	10.35	0.0	0.0	1.3e+01	25.8

Statistical uncertainty, $\sigma_i = N_i \cdot \sqrt{\Sigma w_i^2}$,

where N_i = normalisation factor, Σw_i^2 = sum of the weights squared, i = Signal, IC, BB, Beam

Cut Selection (3 Long Tracks)

Selection criteria (reconstruction-level only) used for all 4-layer sensitivity plots using **only** long tracks. NOTE: before the "no cuts stage", the minimum χ^2 vertex is chosen in each frame

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
0	No Cuts	204.51	1.82e+04	5.81e+08	4.29e+13	100.0	100.0	100.0	100.0	100.00	100.00	100.0	100.0	4.8e-12	0.0
1	$\geq$ 1 recurling track	161.78	1.51e+04	5.37e+08	4.05e+13	79.1	79.1	83.2	83.2	92.34	92.34	94.4	94.4	4.0e-12	0.0
2	$\geq$ 2 recurling tracks	71.14	9.02e+03	3.87e+08	3.13e+13	34.8	44.0	49.6	59.6	66.55	72.07	72.9	77.2	2.3e-12	0.0
3	3 recurling tracks	21.57	3.28e+03	1.13e+08	9.60e+12	10.5	30.3	18.0	36.3	19.47	29.26	22.4	30.7	2.2e-12	0.0
4	Truth Bhabha check	21.57	3.28e+03	5.73e+07	9.60e+12	10.5	100.0	18.0	100.0	9.86	50.66	22.4	100.0	2.2e-12	0.0
5	$m_{rec} > 90$ MeV	13.70	2.07e+03	1.97e+06	1.60e+12	6.7	63.5	11.4	63.1	0.34	3.44	3.7	16.7	8.5e-12	0.0
6	Vertex $\chi^2 < 15$	10.86	1.77e+03	2.69e+05	2.61e+11	5.3	79.3	9.7	85.6	0.05	13.64	0.6	16.3	4.2e-11	0.0
7	In target region	10.60	1.72e+03	2.34e+05	1.99e+11	5.2	97.6	9.5	97.2	0.04	87.00	0.5	76.3	5.3e-11	0.0
8	|Vertex-target distance| < 3 mm	10.15	1.58e+03	1.35e+05	9.92e+10	5.0	95.7	8.7	91.7	0.02	57.74	0.2	49.8	1.0e-10	0.0
9	$m_{ee}^{low} < 5$ or > 10 MeV (anti-Bhabha)	9.78	1.29e+03	9.69e+04	9.78e+10	4.8	96.4	7.1	81.7	0.02	71.72	0.2	98.6	1.0e-10	0.0
10	$m_{ee}^{low} > 10$ MeV	9.68	6.02e+02	9.24e+04	9.30e+10	4.7	99.0	3.3	46.7	0.02	95.38	0.2	95.1	1.0e-10	0.0
11	$p_{rec} < 4$ MeV	8.90	3.09e+01	2.15e+01	1.34e+07	4.3	91.9	0.2	5.1	0.00	0.02	0.0	0.0	6.6e-07	0.0
12	$\Delta R_{min} > 0.2$	8.86	3.08e+01	2.13e+01	0.00e+00	4.3	99.6	0.2	99.9	0.00	98.92	0.0	0.0	1.7e-01	1.2
13	$103 < m_{rec} < 110$ MeV	8.49	7.52e-02	4.75e+00	0.00e+00	4.2	95.9	0.0	0.2	0.00	22.29	0.0	100.0	1.8e+00	3.9
14	[12] + $103 < m_{rec} < 110$ MeV	8.61	5.56e+00	1.25e+04	1.44e+10	4.2	101.4	0.0	7395.1	0.00	264422.63	0.0	100.0	6.0e-10	0.0

What are the statistical uncertainties associated with the number of events in the signal region (SR)?

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
13	$103 < m_{rec} < 110$ MeV	8.49 ± 0.02	7.52e-02 ± 1.85e-02	4.75e+00 ± 1.82e+00	0.00e+00 ± 0.00e+00	4.2	95.9	0.0	0.2	0.00	22.29	0.0	100.0	1.8e+00	3.9

Statistical uncertainty, $\sigma_i = N_i \cdot \sqrt{\Sigma w_i^2}$,

where N_i = normalisation factor, Σw_i^2 = sum of the weights squared, i = Signal, IC, BB, Beam

Cut Selection (3 Long Tracks)

Selection criteria (truth + reco-level) used for all 4-layer sensitivity plots using **only** long tracks. NOTE: before the “no cuts stage”, the minimum χ^2 vertex is chosen in each frame

Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
0	No Cuts	204.51	1.82e+04	5.81e+08	4.29e+13	100.0	100.0	100.0	100.0	100.00	100.00	100.0	100.0	4.8e-12	0.0
15	Three recurling tracks + truth cuts	9.84	2.09e+03	2.52e+07	9.15e+11	4.8	4.8	11.5	11.5	4.34	4.34	2.1	2.1	1.1e-11	0.0
16	Truth Bhabha check	9.84	2.09e+03	2.52e+07	9.15e+11	4.8	100.0	11.5	100.0	4.34	100.00	2.1	100.0	1.1e-11	0.0
17	$m_{rec} > 90$ MeV	9.78	1.63e+03	4.17e+05	1.60e+11	4.8	99.4	8.9	77.9	0.07	1.66	0.4	17.5	6.1e-11	0.0
18	Vertex $\chi^2 < 15$	9.18	1.54e+03	4.92e+04	3.96e+09	4.5	93.8	8.5	94.5	0.01	11.80	0.0	2.5	2.3e-09	0.0
19	In target region	9.18	1.54e+03	4.70e+04	3.50e+09	4.5	100.0	8.5	100.0	0.01	95.58	0.0	88.5	2.6e-09	0.0
20	|Vertex-target distance| < 3 mm	8.91	1.42e+03	3.72e+04	1.94e+09	4.4	97.1	7.8	92.2	0.01	78.96	0.0	55.4	4.6e-09	0.0
21	$m_{ee}^{low} < 5$ or > 10 MeV (anti-Bhabha)	8.58	1.15e+03	4.53e+03	1.89e+09	4.2	96.3	6.3	80.8	0.00	12.20	0.0	97.6	4.5e-09	0.0
22	$m_{ee}^{low} > 10$ MeV	8.50	4.97e+02	9.87e+02	1.89e+09	4.2	99.0	2.7	43.3	0.00	21.78	0.0	100.0	4.5e-09	0.0
23	$p_{rec} < 4$ MeV/c	8.14	2.54e+01	3.97e+00	0.00e+00	4.0	95.7	0.1	5.1	0.00	0.40	0.0	0.0	2.8e-01	1.5
24	$\Delta R_{min} > 0.2$	8.10	2.54e+01	3.97e+00	0.00e+00	4.0	99.6	0.1	99.9	0.00	100.00	0.0	100.0	2.8e-01	1.5
25	$103 < m_{rec} < 110$ MeV	7.82	1.78e-02	2.54e-01	0.00e+00	3.8	96.4	0.0	0.1	0.00	6.39	0.0	100.0	2.9e+01	15.0
26	[24] + $103 < m_{rec} < 110$ MeV	7.88	2.11e-02	9.47e+00	2.08e+08	3.9	100.8	0.0	118.4	0.00	3734.46	0.0	100.0	3.8e-08	0.0

What are the statistical uncertainties associated with the number of events in the signal region (SR)?

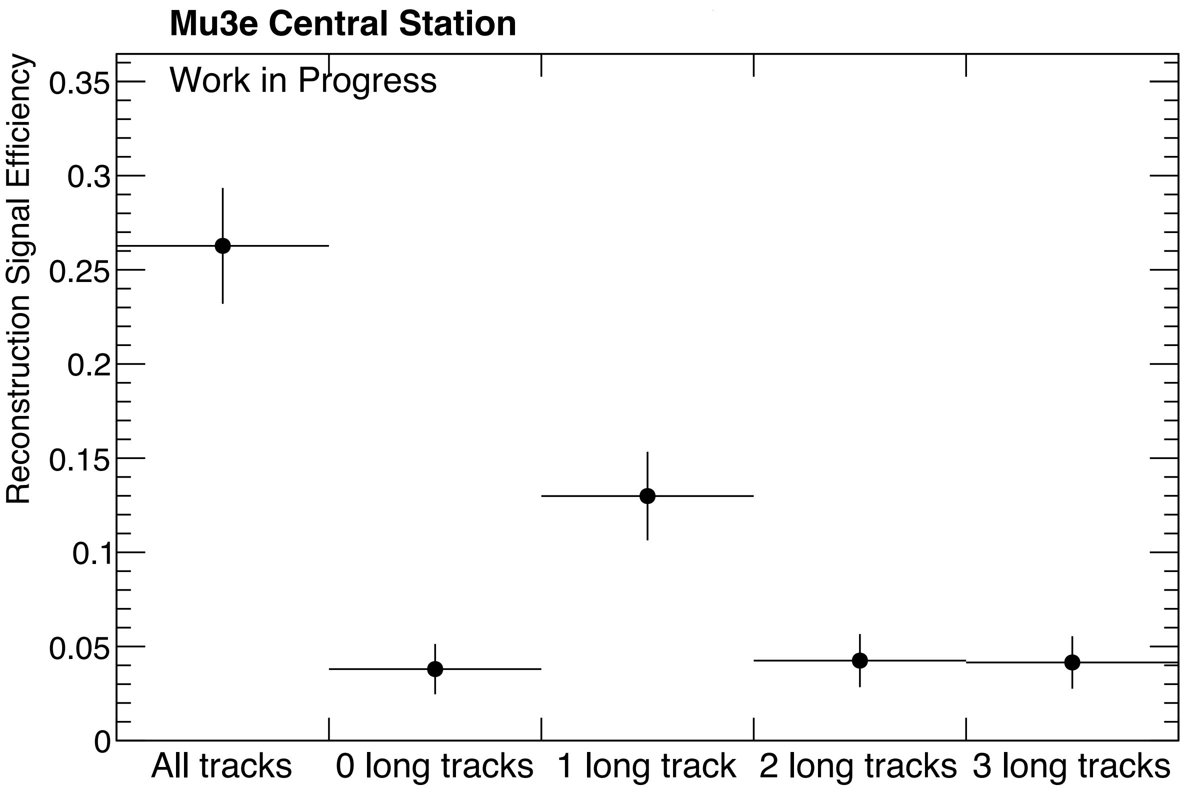
Cut	Selection	Signal	IC	BB	Beam	ϵ_{Signal} [%]	ϵ_{Step} [%]	ϵ_{IC} [%]	ϵ_{Step} [%]	ϵ_{BB} [%]	ϵ_{Step} [%]	ϵ_{Beam} [%]	ϵ_{Step} [%]	S/B	$S/\sqrt{B}$
25	$103 < m_{rec} < 110$ MeV	7.82 ± 0.02	1.78e-02 ± 8.95e-04	2.54e-01 ± 2.54e-01	0.00e+00 ± 0.00e+00	3.8	96.4	0.0	0.1	0.00	6.39	0.0	100.0	2.9e+01	15.0

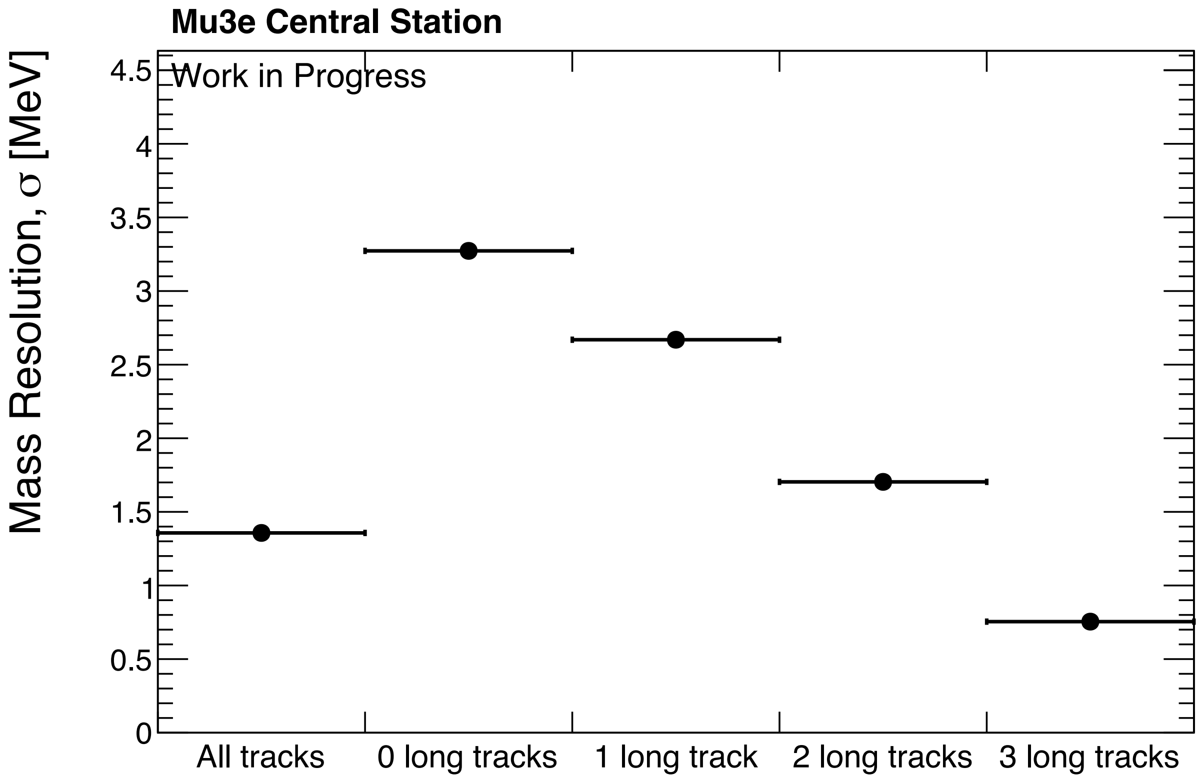
Statistical uncertainty, $\sigma_i = N_i \cdot \sqrt{\Sigma w_i^2}$,

where N_i = normalisation factor, Σw_i^2 = sum of the weights squared, i = Signal, IC, BB, Beam

Sensitivity

- Must consider the trade-off between the signal efficiency and the associated mass resolution of the track types used in the analyses
- Factor of ~3 improvement in signal efficiency with recurl stations present for 3 long tracks





‘Good Frame’ Definitions

- Good frames: number of frames with at least one track from the correct process and vertex originates from within target region cylinder. Can double count frames here. We drop frames that don’t originate from the correct process and don’t originate from a predefined target region cylinder

- Good frames with new decay: same as above but now with the requirement that the truth track ID is unique to the frame (i.e., track wasn’t present in previous frame) as tracks can exist beyond the frame length. This now avoids double counting frames, and the muon decay can be qualified as good for all frames at this stage. The number of frames at this stage is what is used in all normalisations

- Good ID frames (3 signal tracks): same as above but now all frames with 3 signal tracks and not just at least one

This is all done using generator-level information

Normalisation

Signal:

$$Norm_{Sig} = N_{\mu} \cdot \frac{BR_{Sig}}{N_{frames_{good}}}$$

where:

N_{μ} is the total number of muon stops $= 7 \times 10^{7} \cdot 56$ days (assume 8 weeks data-taking as a first approximation; same as 3-layer plots); 7×10^{7} is the muon stopping rate

BR_{Sig} = the signal BR (10^{-12}, 10^{-13}, 10^{-14}, 10^{-15})

$N_{frames_{good}}$ = number of frames with 'good' muon stops (c.f. bullet 2 in slide 2)

Normalisation

Beam:

$$Norm_{Beam} = \frac{N_{\mu}}{\Sigma w_{beam}}$$

where:

N_{μ} is the total number of muon stops $= 7{\times}10^7 \cdot 56$ days (assume 8 weeks data-taking as a first approximation; same as 3-layer plots); $7{\times}10^7$ is the muon stopping rate

Σw_{beam} = sum of weights for all frames where weight!=1 (although weight always = 1 for beam samples)

Normalisation

IC:

$$Norm_{IC} = N_\mu \cdot \frac{BR_{IC} \cdot \epsilon_{gen}}{\Sigma w_{IC}}$$

where:

N_μ is the total number of muon stops $= 7\times10^7 \cdot 56$ days (assume 8 weeks data-taking as a first approximation; same as 3-layer plots); 7×10^7 is the muon stopping rate

BR_{IC} = IC BR = 3.4×10^{-5}

ϵ_{gen} = generator efficiency for IC

Σw_{IC} = sum of weights for all frames where weight!=1

Normalisation

BB:

$$Norm_{BB} = N_\mu \cdot \frac{f_{BB}}{\Sigma w_{BB} \cdot R^2 \cdot t}$$

where:

N_μ is the total number of muon stops $= 7{\times}10^7 \cdot 56$ days (assume 8 weeks data-taking as a first approximation; same as 3-layer plots); $7{\times}10^7$ is the muon stopping rate

f_{BB}= fraction of visible e^+e^- produced in the target region, relative to N_μ = $7.7{\times}10^{-5}$

Electron source	Produced in inner detector	Produced in target region
Bhabha scattering	$5.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-4}$
e^+e^- visible	$4.3 \cdot 10^{-4}$	$7.7 \cdot 10^{-5}$
Photon conversion	$2.3 \cdot 10^{-5}$	$2.1 \cdot 10^{-6}$
e^+e^- visible	$5.7 \cdot 10^{-6}$	$4.6 \cdot 10^{-7}$
Compton scattering	$3.6 \cdot 10^{-5}$	$4.3 \cdot 10^{-6}$
Internal conversion	$3.1 \cdot 10^{-5}$	$2.9 \cdot 10^{-5}$
e^+e^- visible	$1.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$
Total	$6.4 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$

R = stopping-rate ratio $= \frac{\text{beam rate} \cdot f_{target}}{\text{target stop rate}} = \frac{6.17{\times}10^7 \cdot 0.231}{7{\times}10^7}$

f_{target} $=$ target stopping fraction (number of muons that decay in target out of total number of generated muons from simulation)

Σw_{BB} = sum of weights for all frames where weight!=1

t $=$ timing suppression = $70 \cdot 256/50$ (scaled to current frame length)