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Calibration of the Mu2e momentum scale using $\pi^+ \to e^+ \nu_e$ decays

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for the Mu2e Experiment

UC DAVIS
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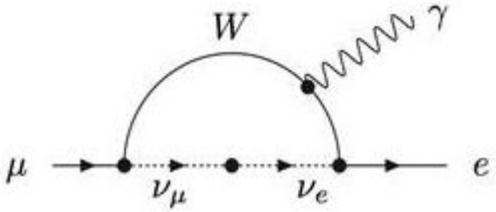
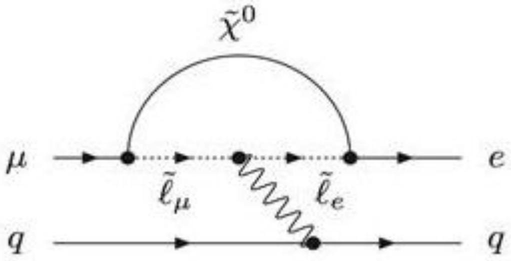
Mu2e experiment for CLFV search

- In the previous presentation Sophie has explained the design and goals of the Mu2e experiment.
- Experimental observation of any Charge Lepton Flavor Violation (CLFV) process would imply the presence of physics beyond the SM.
- The Mu2e experiment, at Fermilab has been designed to observe coherent neutrinoless muon to electron conversion $\mu^- A \rightarrow e^- A$, in the Coulomb field of an Al nucleus

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1))}$$



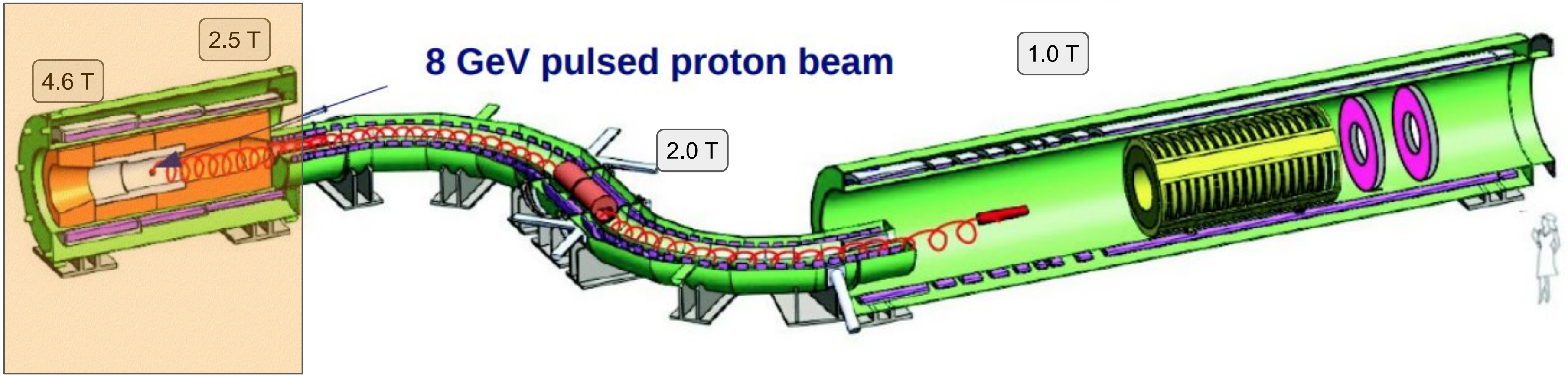


Muon CLFV experiments

Channel	Present Limit	Future Exps, Limit
$\mu^+ \to e^+ \gamma$	4.2×10^{-13} (90% CL) MEG Collaboration	MEG-II, $\sim10^{-14}$
$\mu^+ \to e^+ e^- e^+$	1.0×10^{-12} (90% CL) SINDRUM Collaboration	Mu3e, $\sim10^{-16}$
$\mu^- N \to e^- N$	7.0×10^{-13} (90% CL) SINDRUM II Collaboration	Mu2e, COMET, $\sim10^{-17}$
$\mu^+ e^- \to \mu^- e^+$	8.3×10^{-11} (90% CL) SINDRUM Collaboration	

- As muons are long lived and easier to produce using accelerators, search for muon to electron flavor violations can reach the highest sensitivity levels for many models.
- Mu2e plans to improve the search sensitivity by 10^4 over the present limit set by SINDRUM-II.
- The current Mu2e run plan assumes two data-taking periods, Run I and Run II, separated by an approximately two-year-long shutdown, targeting X 10^3 in Run-1 and X 10^4 in Run-II.

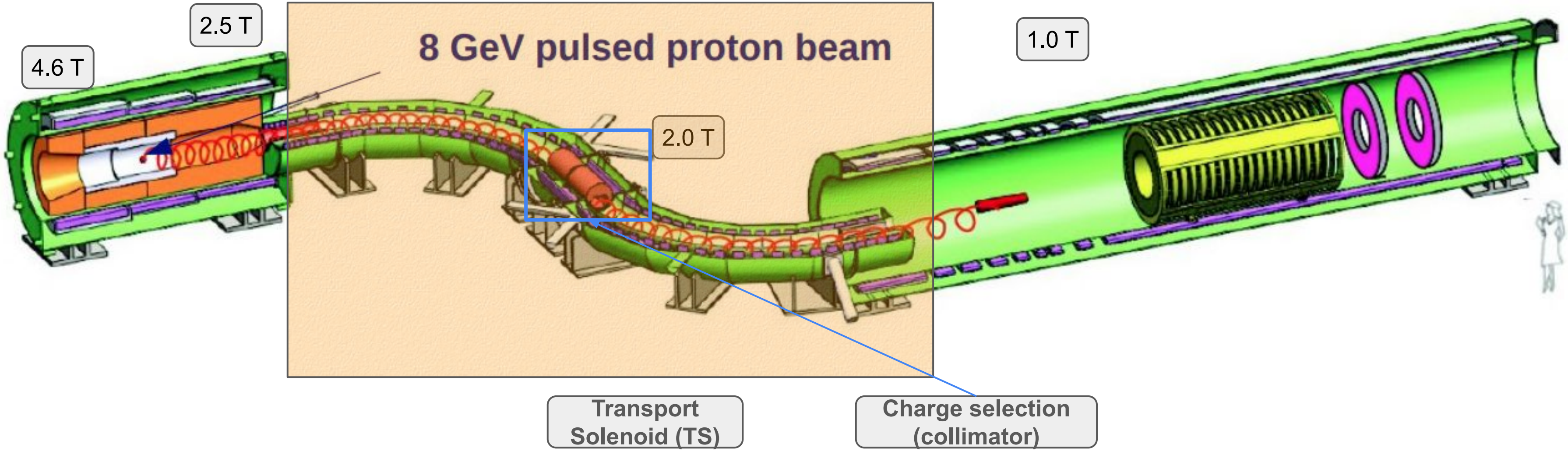
Components of the Mu2e detector



Production Solenoid (PS)

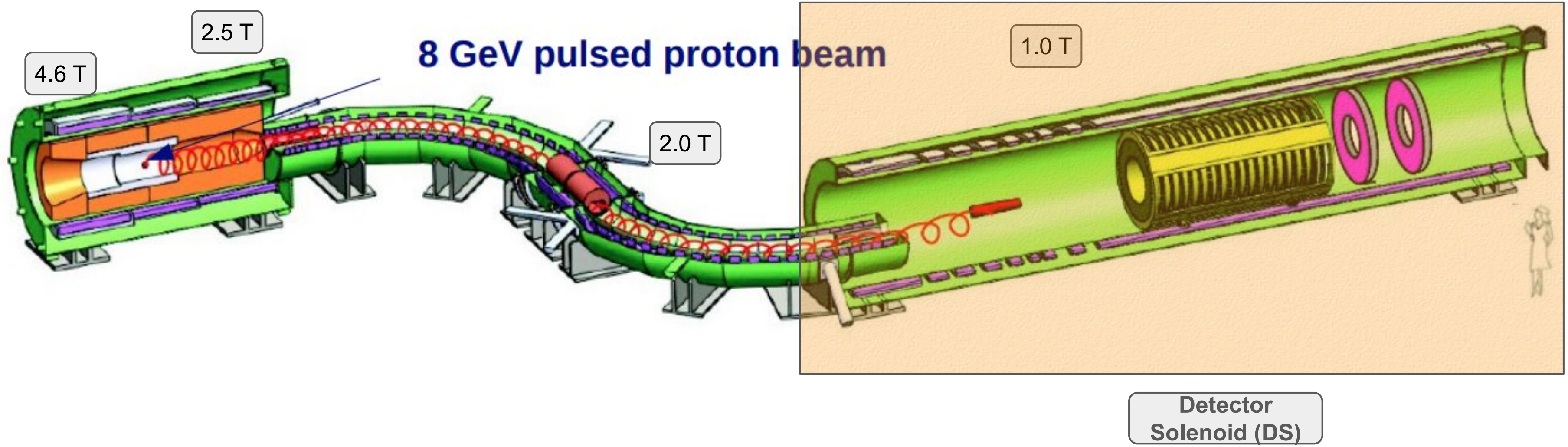
- The graded field in the PS reaches up to 4.6 T, in the TS between 2.5 T to 2.1 T and in the DS, 1 T.
- PS optimized for backward pions and reflected slow forward pions,
- Production Target: radiatively cooled tungsten

Components of the Mu2e detector



- Unique S-shaped TS guides the muons towards stopping target, rejects other particles based on charge and momentum.
- Collimators are placed, such that positive and negative charged particles are deflected in opposite direction, and select either one.
- DS field 1 T, for momentum measurement.

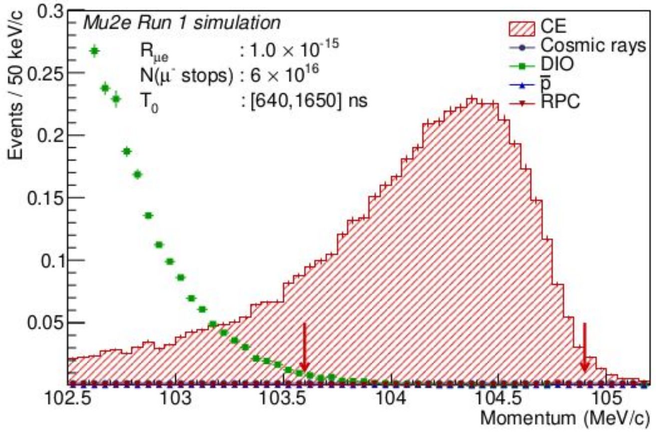
Components of the Mu2e detector



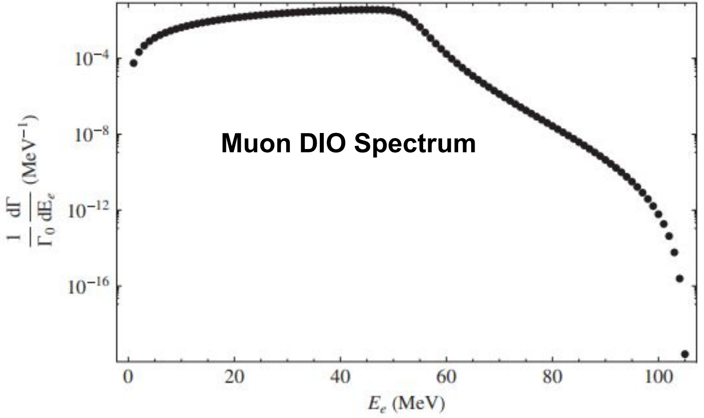
- Al Stopping Target (ST)
- Tracker: 18 stations of discs with straw tubes spanning 3 m, total no. 96x3x4x18 = 20736
- Electromagnetic Calorimeter: CsI crystals with SiPMs, total no. 2x674 = 1348 dim: (3.4*3.4*20 cm^3)
- To suppress cosmic background: Cosmic Ray Veto (CRV), 4 layers of extruded plastics scintillators, readout with SiPMs.

Physics goal

- The Conversion Electrons (CE), ~104.97 MeV (E_{CE}) from stopped μ^{-}s are of primary interest for the collaboration.
- Decays in orbit (DIO) of muons stopped in the stopping target and captured by the Al atoms produce electrons with a momentum spectrum extending up to E_{CE}.
- We need to determine the tracker momentum scale to distinguish the signal from DIO.
- The requirement is momentum resolution ~ 1% FWHM and a momentum scale calibrated to an accuracy of better than 0.1% or 0.1 MeV/c

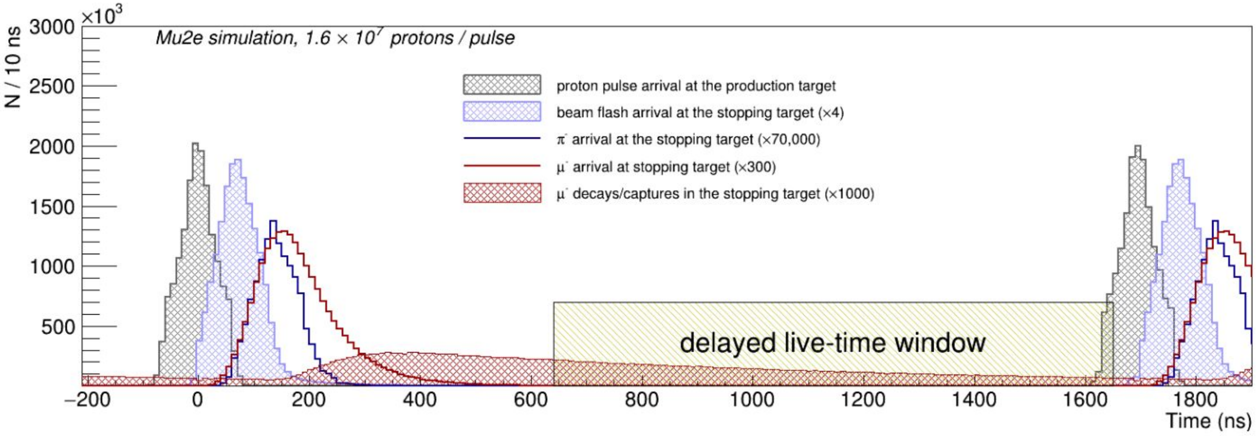


Mu2e Collaboration, *Universe 2023, 9, 54.*



Czarnecki et al, *PHYSICAL REVIEW D 84, 013006 (2011)*

Momentum scale calibration



Options are:

- 69.8 MeV/c e^+ from stopped π^+s in the stopping target. $\pi^+ \rightarrow e^+ \nu_e$ decays.
- measurement of the Michel positron spectrum $\mu^+ \rightarrow e^+ \nu \nu$

Challenges for $\pi^+ \rightarrow e^+ \nu_e$:

- The Mu2e detector is optimized for CE with 105 MeV/c @ 1 T.
- It has been designed to suppress pions to avoid Radiative Pion Capture (RPC) Therefore, π^+ rate is too low: ~ 1e-6/POT
- BR($\pi^+ \rightarrow e^+ \nu_e$) ~ 1.23×10^{-4}
- Large background from μ^+ decay-in-flight (DIF).

$$\frac{\Gamma(\pi \rightarrow e\nu + \pi \rightarrow e\nu\gamma)}{\Gamma(\pi \rightarrow \mu\nu + \pi \rightarrow \mu\nu\gamma)} \propto \left(\frac{m_e}{m_\mu}\right)^2$$

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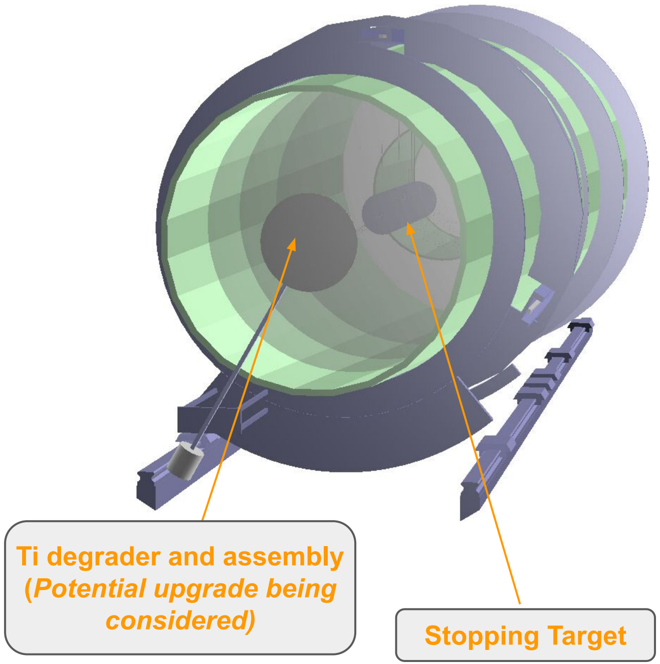
Modifications used in this analysis to track e^+ from $\pi^+ \rightarrow e^+\nu_e$

- A retractable degrader of Ti, upstream of the stopping target is added.
- TS3 collimator rotated to allow positive particles
- A reduced-DS B field (0.7 T) has been used to allow e^+ coming from π^+ to pass through the detectors instead of the un-instrumented part.
- An early timing window (200 ns earlier) has been used.
- Beam intensity reduced to 10% from nominal.



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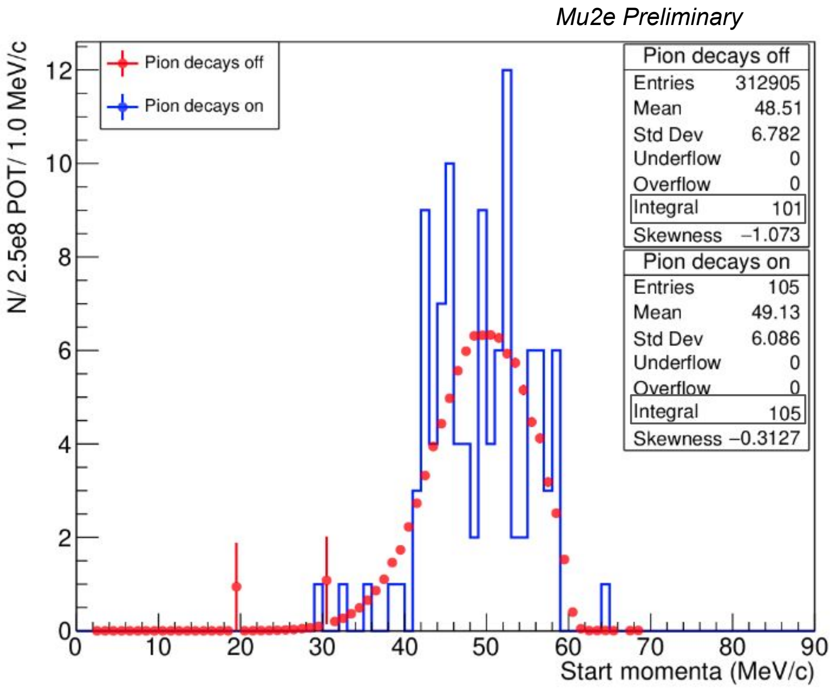
Calibrations: signal and backgrounds

Channel	Description
Stopped $\pi^+ \to e^+$ in ST	**Signal**
Stopped $\pi^+ \to e^+$ in Degrader	Background
Stopped $\pi^+ \to \mu^+ \to e^+$ in both ST and Degrader	Background
In-flight $\pi^+ \to \mu^+ \to e^+$ and $\pi^+ \to e^+$	Background
Stopped $\mu^+ \to e^+$ in both ST and Degrader	Background
Decay In-flight $\mu^+ \to e^+$ (DIF)	**Background**
Beam flash (other than π^+, μ^+)	Background

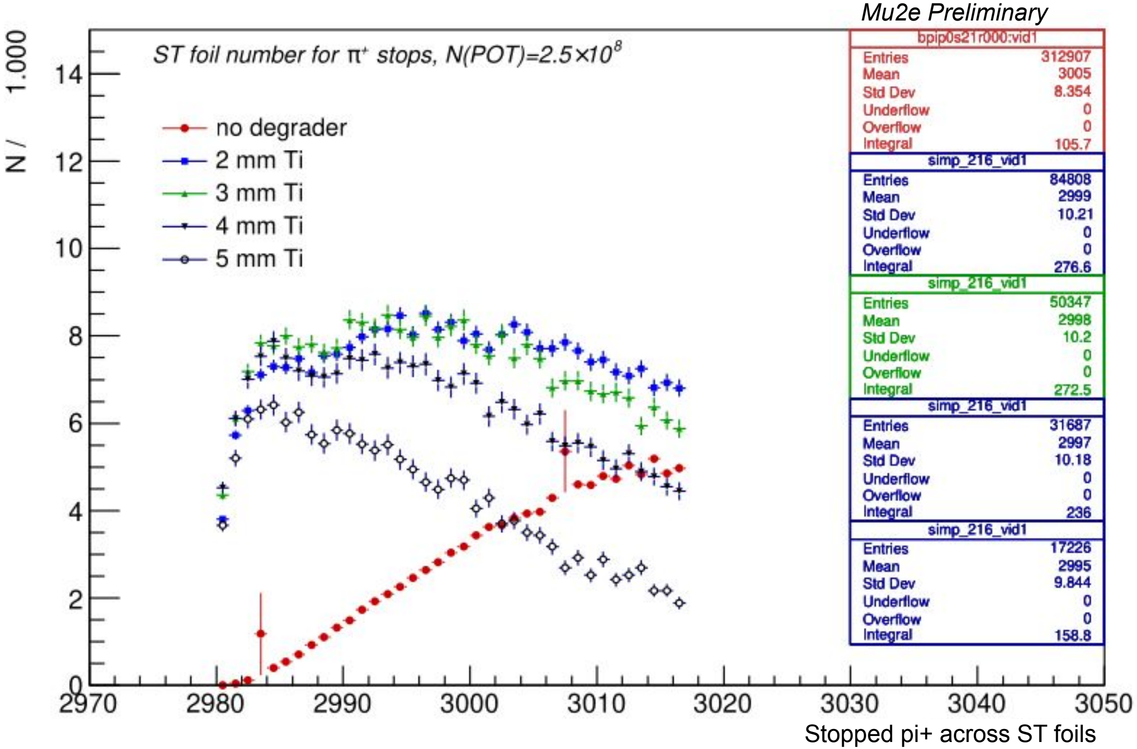
- Other backgrounds are small compared to μ^+ DIF.

Simulation of the signal and background

- Mu2e uses a multi-stage event-processing framework, "art" with Geant4 at its core.
- The pion beam simulation had the charged pion decays turned off. The survival probability of stopped π^{+}'s was stored and used in the analysis as the event weight.
- This strategy has been validated by comparing stopped π^{+}s' momenta in both scenarios (same integrated yield for both samples).
- For μ^{+} DIF, the proper time were restricted so that most of them decay in the tracker region. The scale factor was stored and used in the analysis as event weight.
- This way, Improved statistics and effective computation power is achieved.



Degrader thickness 2 mm - 5 mm



Degrader Thickness	Yield
No degrader	106
2 mm	277
3 mm	273
4 mm	236
5 mm	159

- To optimize, degrader thickness is varied in the range 2-5 mm with a step of 1 mm.

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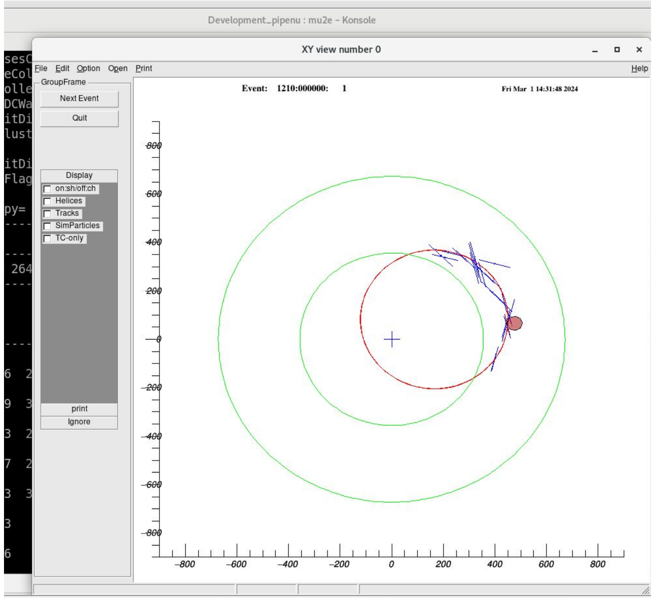
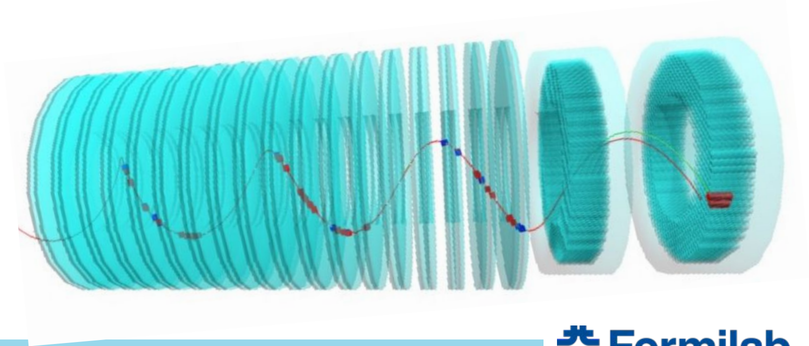
Track Reconstruction

- The Mu2e track reconstruction includes a pattern recognition and Kalman filter-based toolkit which takes into account particle’s mass, propagation direction, and momentum.
- The timing and position information are obtained from the hits on the straw tube.
- Moreover, charged particles propagate in helical paths in the magnetic field. Therefore, a helix finder algorithm is used.
- Different background flagging and noise rejection mechanisms are used.





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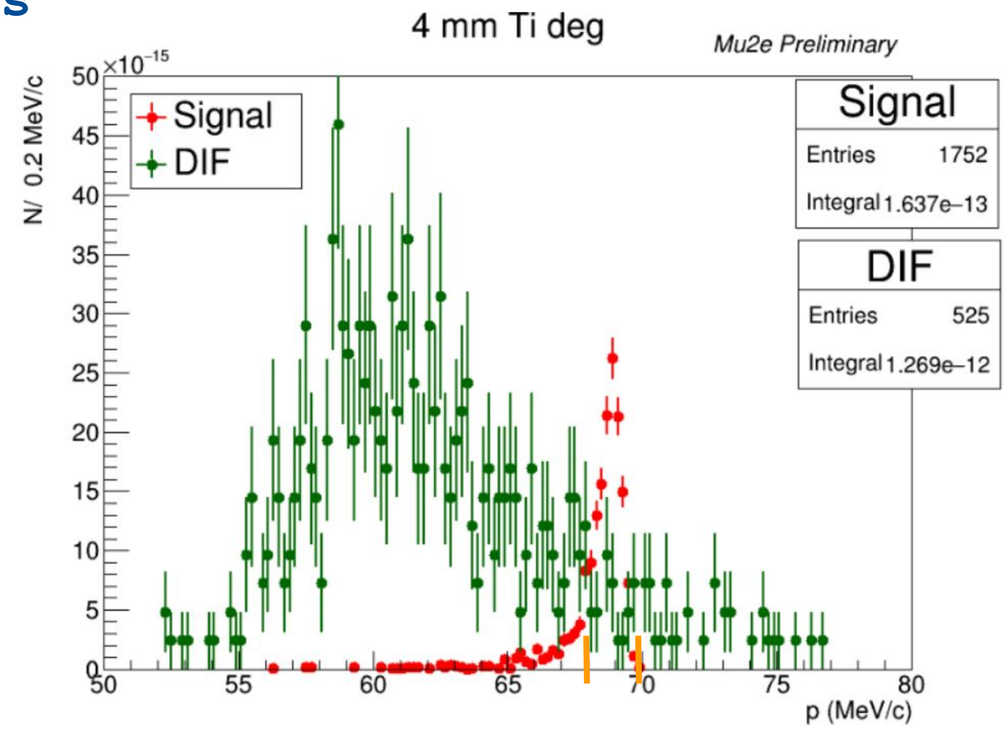
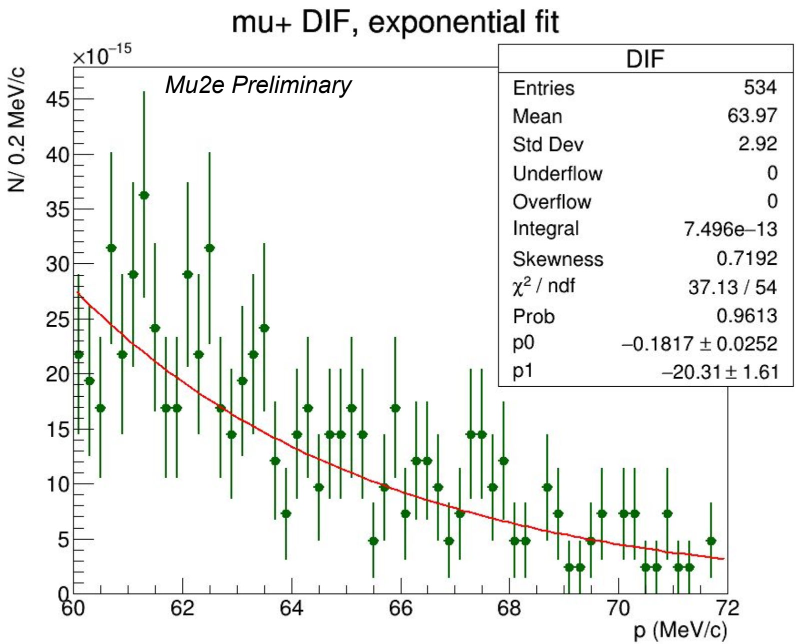
Signal/Background statistics

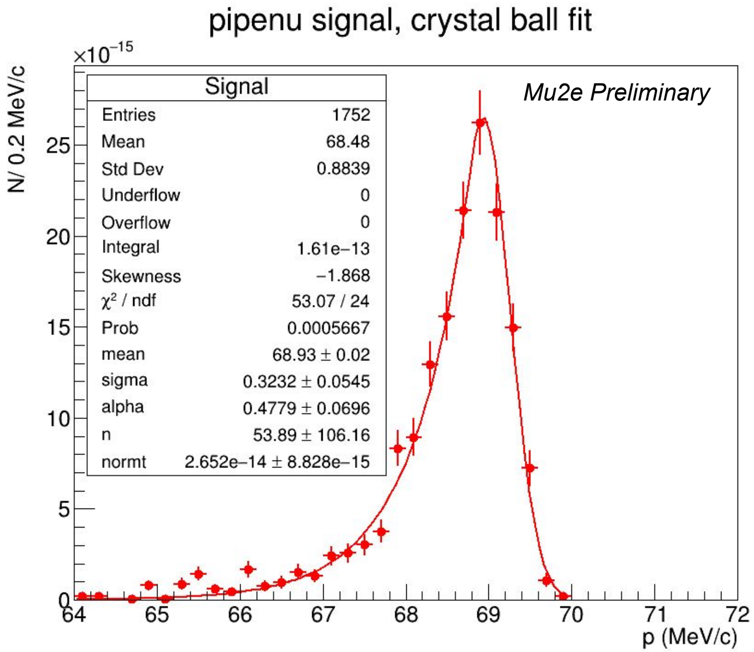
- Selecting a $\pm 2.5\sigma$ around the peak, data with 4 mm Ti degrader has signal to background yield, S/B >3.0.
- While it's necessary to have decent S/B, a slight increase in S/B does not affect the uncertainty in the signal peak over a slowly varying background.
- Assume 10% from nominal intensity, ~50% data taking efficiency, 4 mm Ti deg



In one day: 1.61e-13 * 1.99e17 * 0.1 * 0.5 = ~1600 signal events
In one day: 7.45e-13 * 1.99e17 * 0.1 * 0.5 = ~7500 background events

Signal/Background Fits with 4 mm degrader

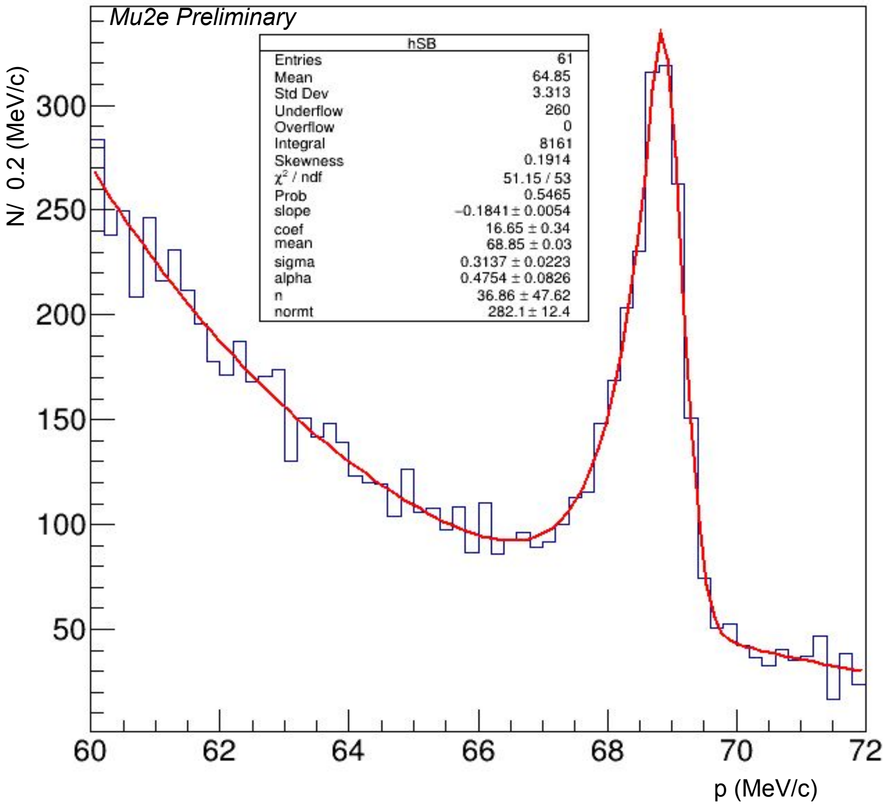




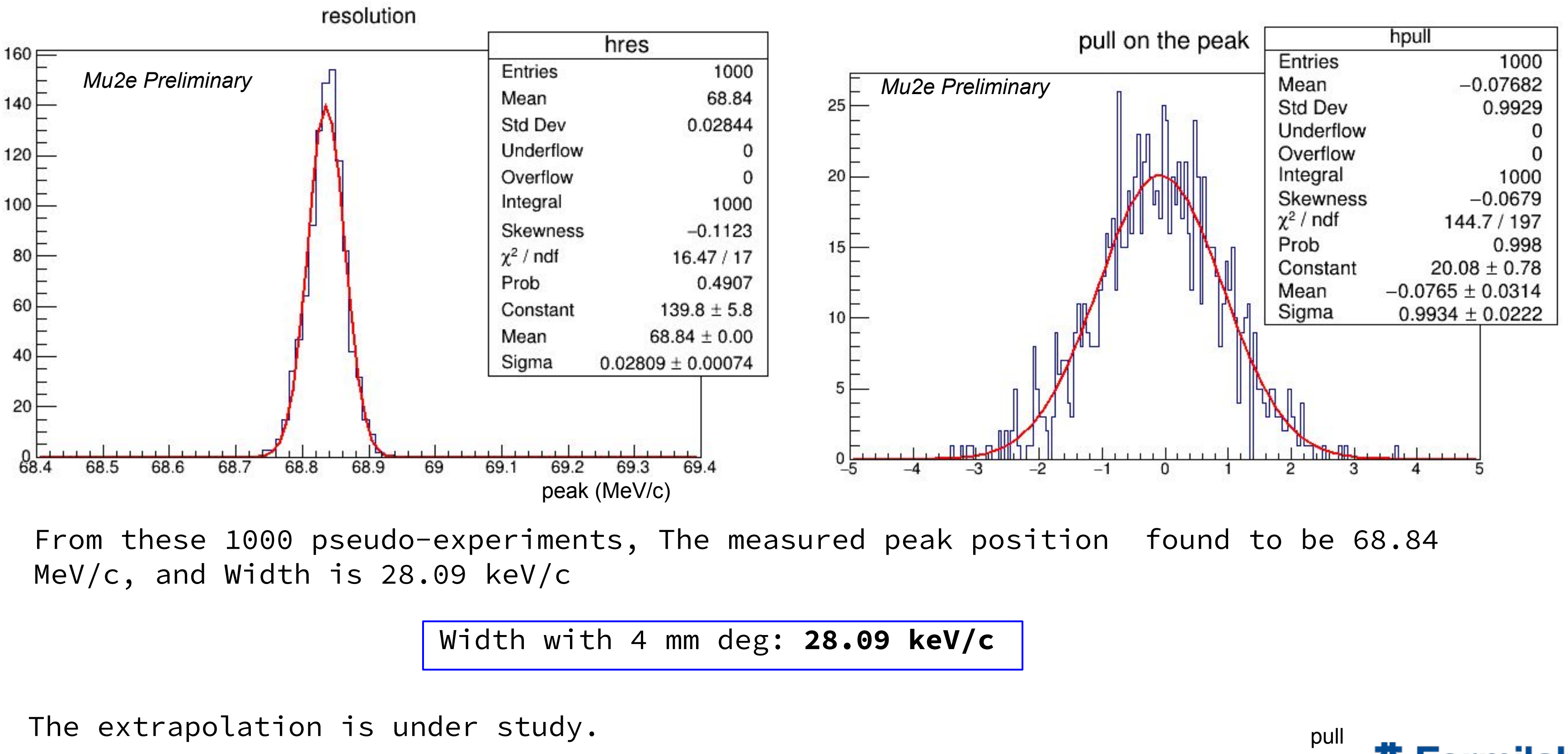
- e^+ signal from π^+ fitted with a Crystal ball function, and background fitted with a single exponential function.

Combined fit and Resolution

- With the signal and background 1000 pseudo-experiments are performed to estimate the peak and it's width.
- Fit parameters used to generate a combined fit function.
- Normalized to 1 day equivalent statistics.
- Binwise variation with a Gaussian uncertainty.
- Fit 1000 times, and estimate the fit resolution.
- Figure in right shows 1 of the pseudo experiments



Combined fit and Resolution



- From these 1000 pseudo-experiments, The measured peak position found to be 68.84 MeV/c, and Width is 28.09 keV/c

Width with 4 mm deg: **28.09 keV/c**

- The extrapolation is under study.

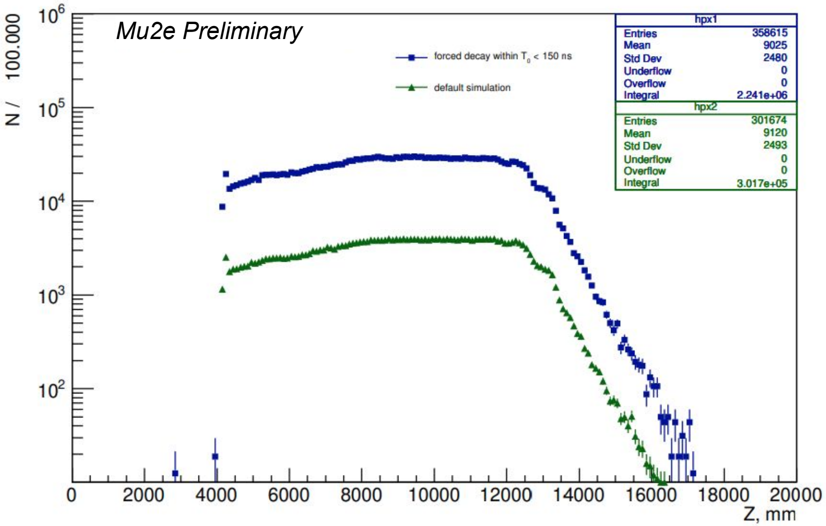
Summary

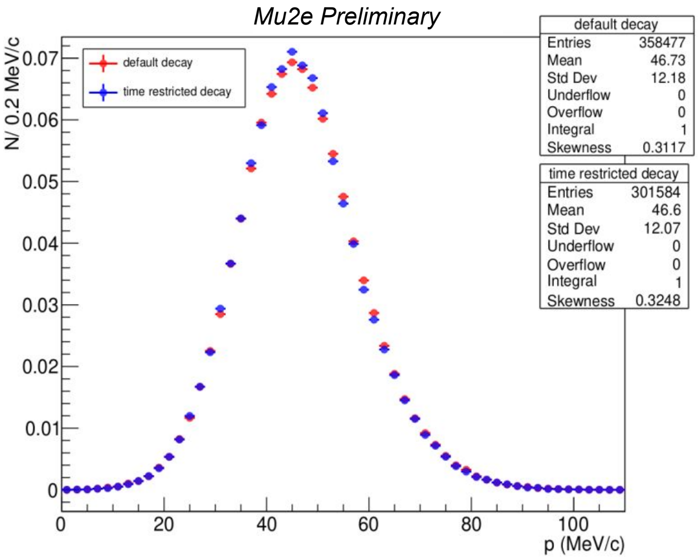
- Accurate calibration of Mu2e momentum scale is crucial to resolve CE from DIO. required accuracy @100 MeV/c: $\sigma P/P$ < 100 keV/c (at 100 MeV/c).
- Several modifications such as rotated collimator, reduced beam intensity, early time window are necessary.
- Further, a pion momentum degrader upstream of the stopping target is studied, which is currently not the part of the Mu2e experiment.
- We expect around 1600 signal events in 1-day of data taking, or ~1e16 protons on target with a 4 mm degrader.
- expected contribution of $\pi^+ \rightarrow e^+ \nu_e$ calibration at 100 MeV/c is under study.

Thank You !

Back up

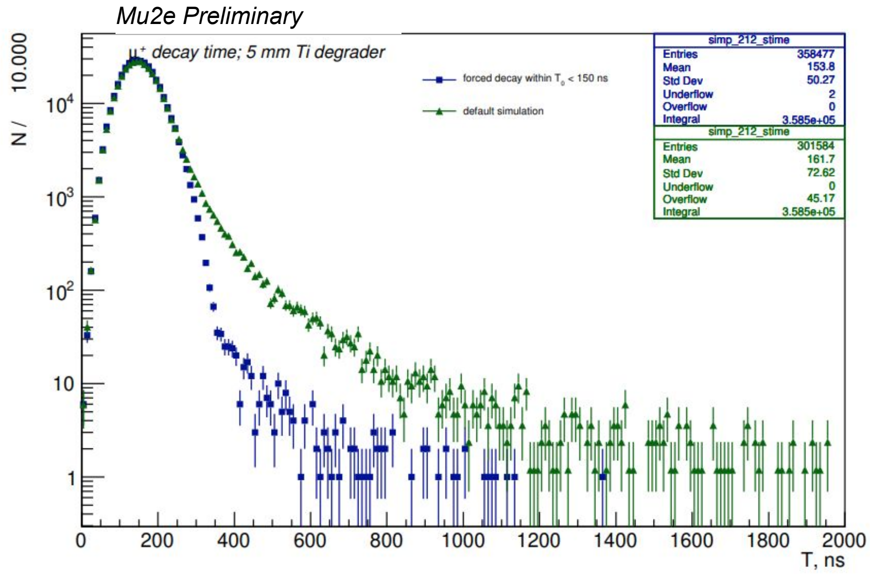
Simulation of the background: $\mu+$ Decay In Flight

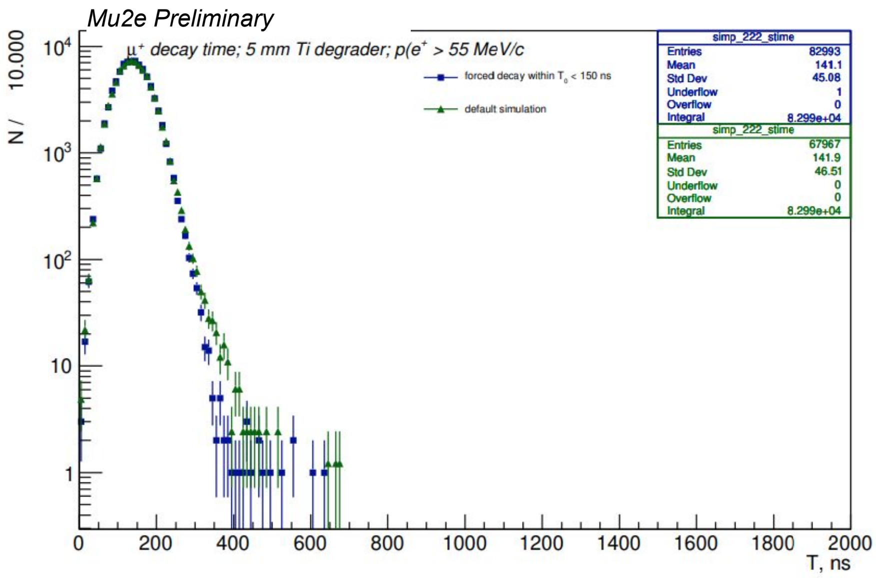




- For DIF, $\mu+$ proper decay times were constrained ($Tmax$ = 150ns)
- Distribution of z-distributions in the $\mu+$ decay vertices with and without the constraint.
- Assigning this time restriction does not change the momentum distribution.

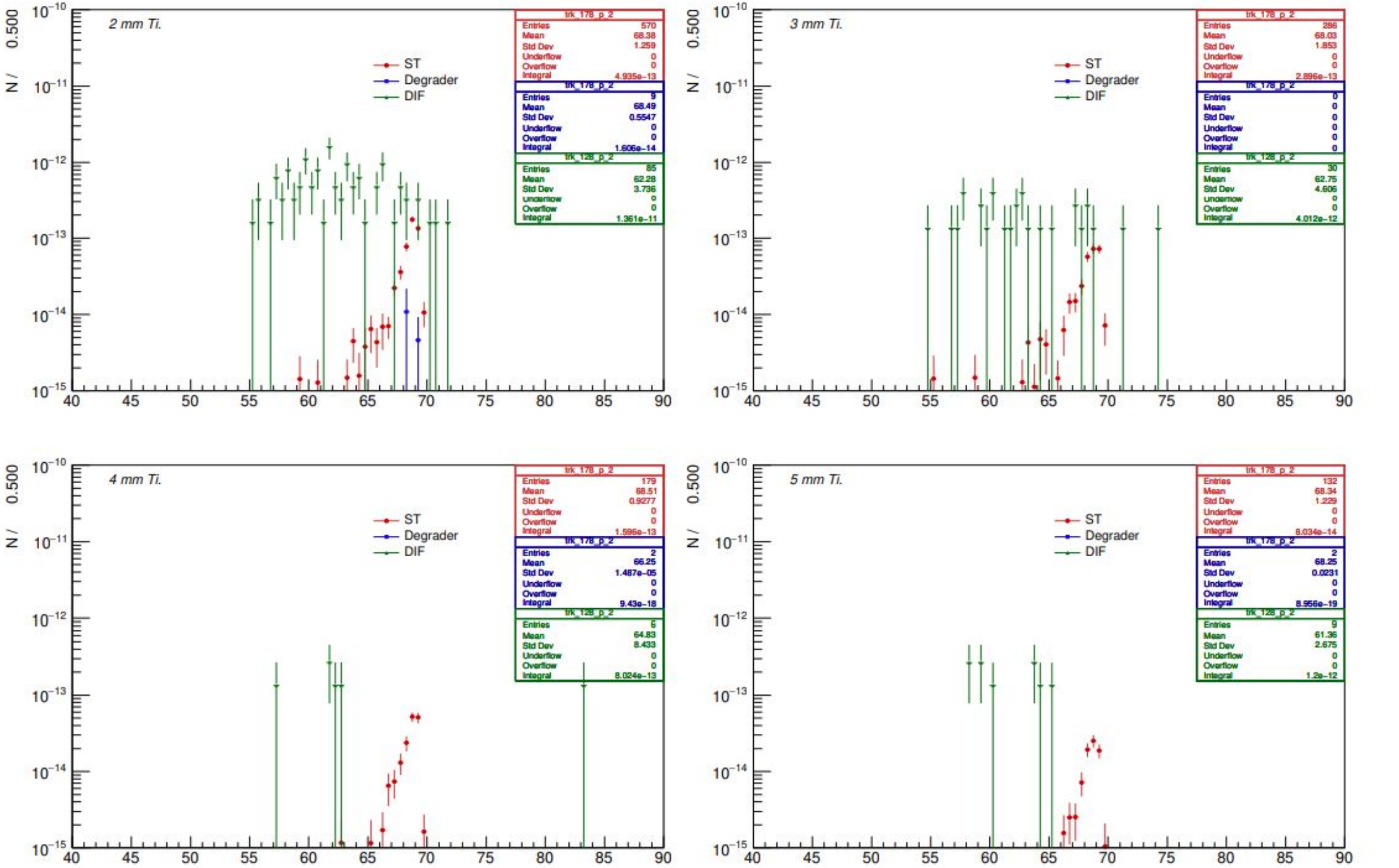
Simulation of the background: μ+ Decay In Flight

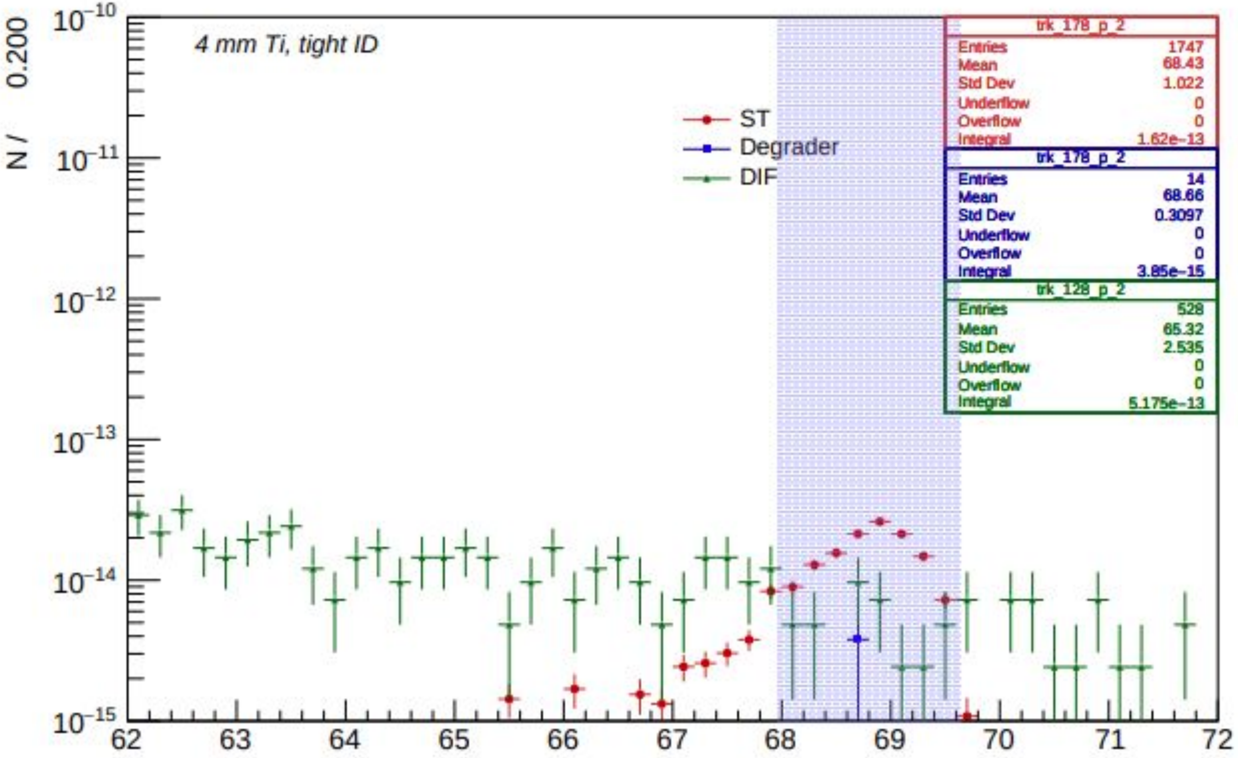




$SF = 1/(1 - exp^{-T_{max}/\tau}) = 15.15 \quad T_{max} = 150$ ns and $\tau = 2197$ ns,

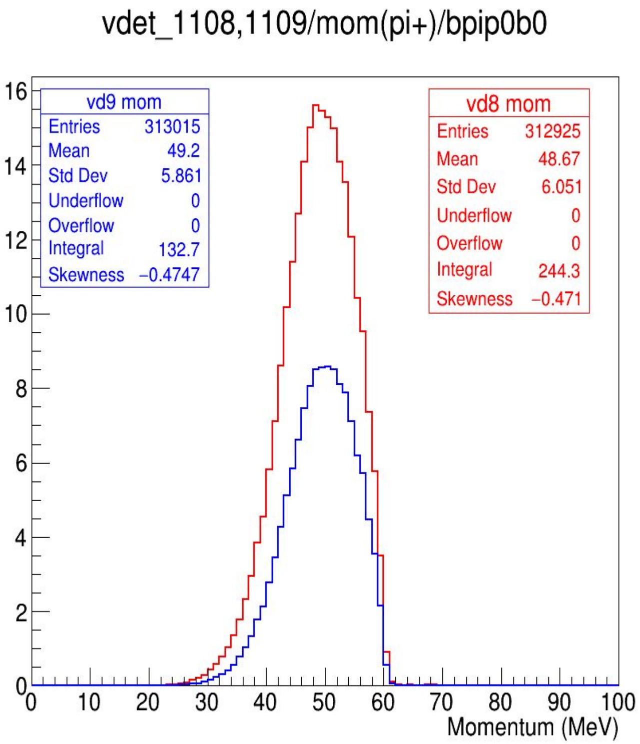
- Late arriving/ low momentum muons are restricted.

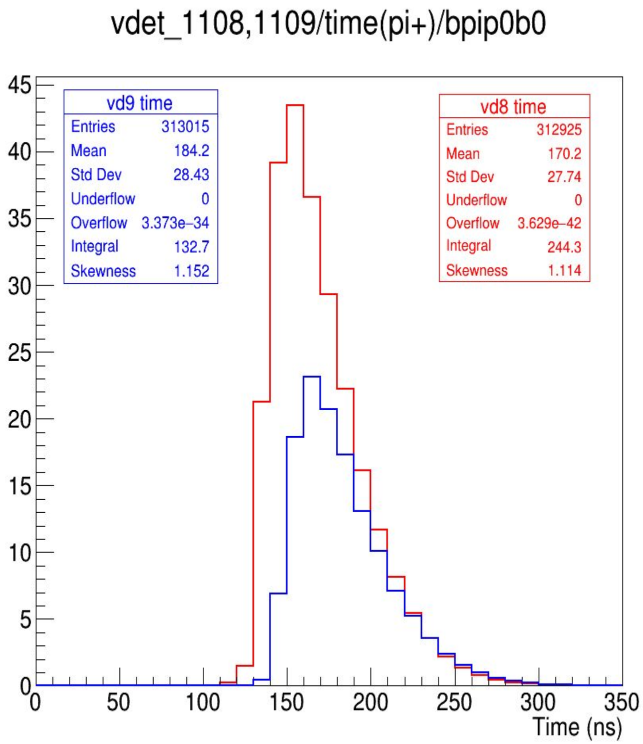

N / 0.500
2 mm Ti.
ST
Degrader
DIF
trk_178_p_2
Entries 570
Mean 68.38
Std Dev 1.259
Underflow 0
Overflow 0
Integral 4.935e−13
trk_178_p_2
Entries 9
Mean 68.49
Std Dev 0.5547
Underflow 0
Overflow 0
Integral 1.606e−14
trk_128_p_2
Entries 85
Mean 62.28
Std Dev 3.736
Underflow 0
Overflow 0
Integral 1.361e−11
3 mm Ti.
trk_178_p_2
Entries 286
Mean 68.03
Std Dev 1.853
Underflow 0
Overflow 0
Integral 2.896e−13
trk_178_p_2
Entries 0
Mean 0
Std Dev 0
Underflow 0
Overflow 0
Integral 0
trk_128_p_2
Entries 30
Mean 62.75
Std Dev 4.606
Underflow 0
Overflow 0
Integral 4.012e−12
4 mm Ti.
trk_178_p_2
Entries 179
Mean 68.51
Std Dev 0.9277
Underflow 0
Overflow 0
Integral 1.596e−13
trk_178_p_2
Entries 2
Mean 66.25
Std Dev 1.487e−05
Underflow 0
Overflow 0
Integral 9.43e−18
trk_128_p_2
Entries 6
Mean 64.83
Std Dev 8.433
Underflow 0
Overflow 0
Integral 8.024e−13
5 mm Ti.
trk_178_p_2
Entries 132
Mean 68.34
Std Dev 1.229
Underflow 0
Overflow 0
Integral 8.034e−14
trk_178_p_2
Entries 2
Mean 68.25
Std Dev 0.0231
Underflow 0
Overflow 0
Integral 8.956e−19
trk_128_p_2
Entries 9
Mean 61.36
Std Dev 2.675
Underflow 0
Overflow 0
Integral 1.2e−12



4 mm Ti, tight ID
N / 0.200
ST
Degrader
DIF
trk_178_p_2
Entries 1747
Mean 68.43
Std Dev 1.022
Underflow 0
Overflow 0
Integral 1.62e-13
trk_178_p_2
Entries 14
Mean 68.66
Std Dev 0.3097
Underflow 0
Overflow 0
Integral 3.85e-15
trk_128_p_2
Entries 528
Mean 65.32
Std Dev 2.535
Underflow 0
Overflow 0
Integral 5.175e-13

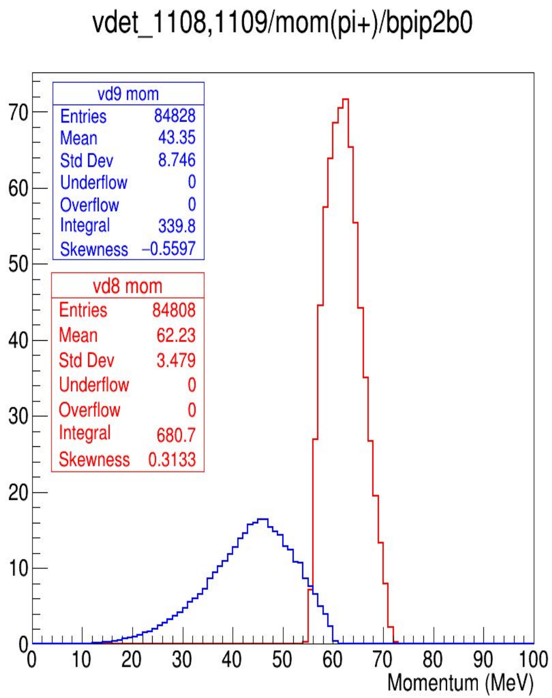
Changing Degrader Thickness

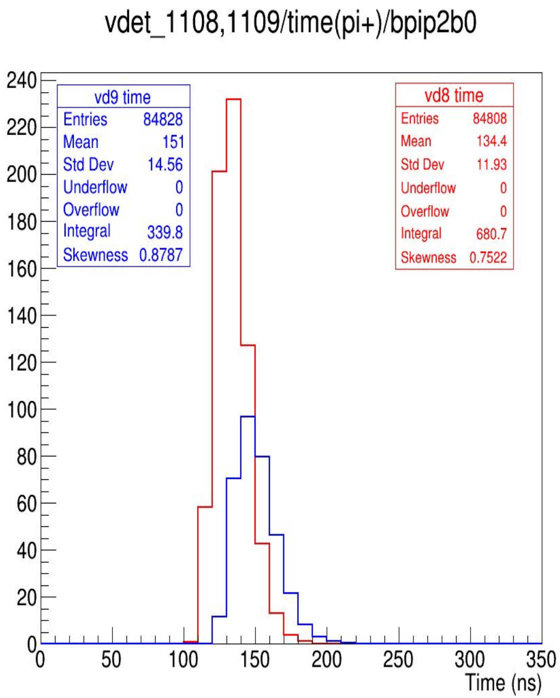




Weighed Momenta and timing distribution of π^+s going to be stopped in ST at VD8 (upstream of the degrader) and VD9 (upstream of the ST).

Changing Degrader Thickness





Weighed Momenta and timing distribution of π^+s going to be stopped in ST at VD8 (upstream of the degrader) and VD9 (upstream of the ST).