A New Track Trigger for Characterization of the Antiproton-Induced Background in the Mu2e Experiment

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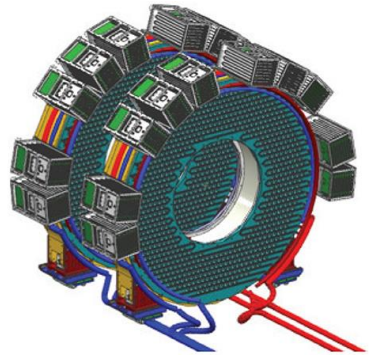
Overview

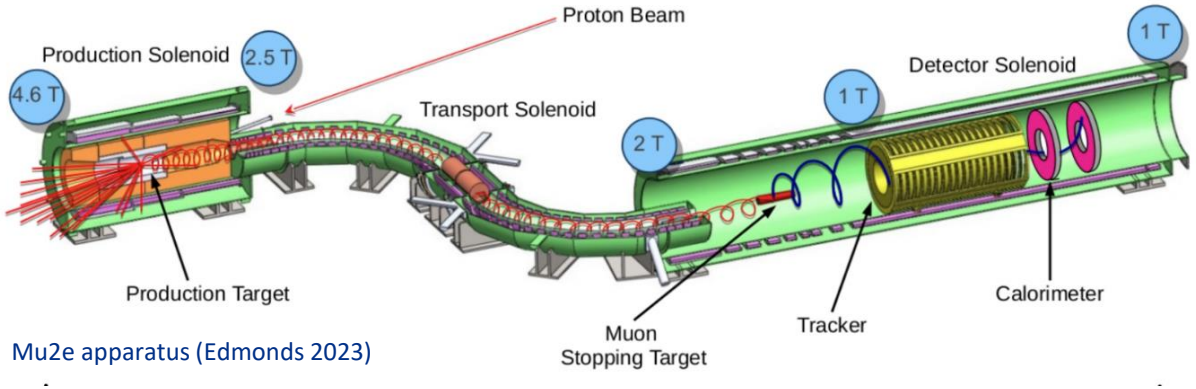
- Introduction
  - The Mu2e Experiment
  - Antiproton Annihilation in Mu2e
- Topology of Antiproton-Induced Events
- Antiproton (Pbar) Trigger
  - Trigger Sequences in Mu2e
  - Definition
  - Performance
- Conclusion and Next Steps

The Mu2e Experiment

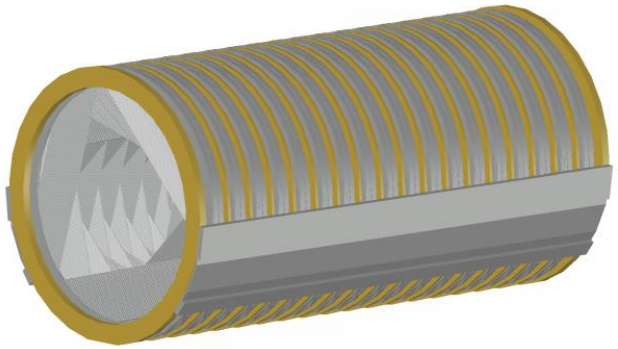
- Search for neutrinoless muon-to-electron conversion in the field of an Al nucleus
- Monochromatic conversion electron signal of ~105 MeV
- Sensitivity goal of 3×10^{-17} (improvement from previous upper limit by 4 orders of magnitude)
- Muon beam supplied from pulsed proton beam incident on Tungsten target (~3×10^{7} protons every 1.7 μs)
- Charged particles travel in helical shape through Detector Solenoid
- Tracker composed of hollowed planes consisting of 23,000 straw tubes
  - Excellent momentum resolution
- Calorimeter comprised of two annular disks containing a total of 674 CsI crystals
  - Excellent timing and energy resolution



Mu2e calorimeter (Bernstein 2019)



Mu2e apparatus (Edmonds 2023)



Mu2e tracker (Bernstein 2019)

Antiproton Annihilation in Mu2e

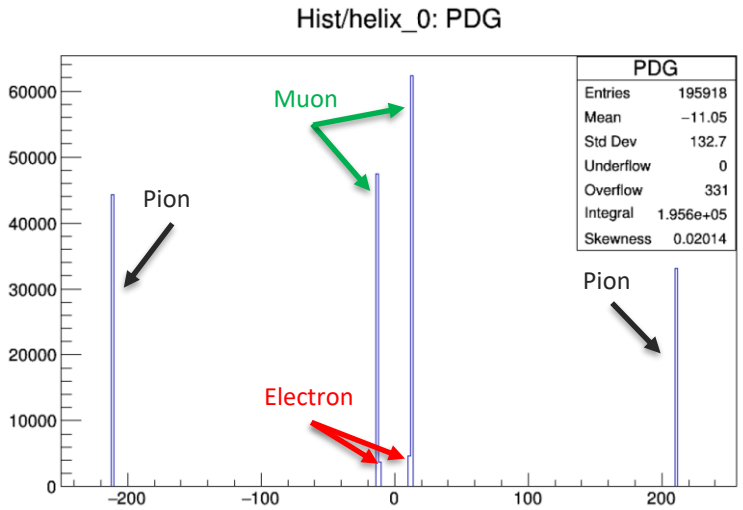
- Antiprotons produced from proton beam's collision with Production Target
- Reach Detector Solenoid and annihilate with protons in Al Stopping Target
  - ~2 GeV available in annihilation
  - Produces pions, muons, and electrons
- Expect electrons that mimic conversion electron signal to be produced at a rate of 0.010 ± 0.010
  - Large systematic uncertainty due to theoretical model of antiproton production cross-section

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})\ ^{+0.025}_{-0.015}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat}) \pm 0.010\ (\text{syst})$
RPC in-time	$0.010 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\text{stat})\ ^{+0.1}_{-0.3}\ (\text{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

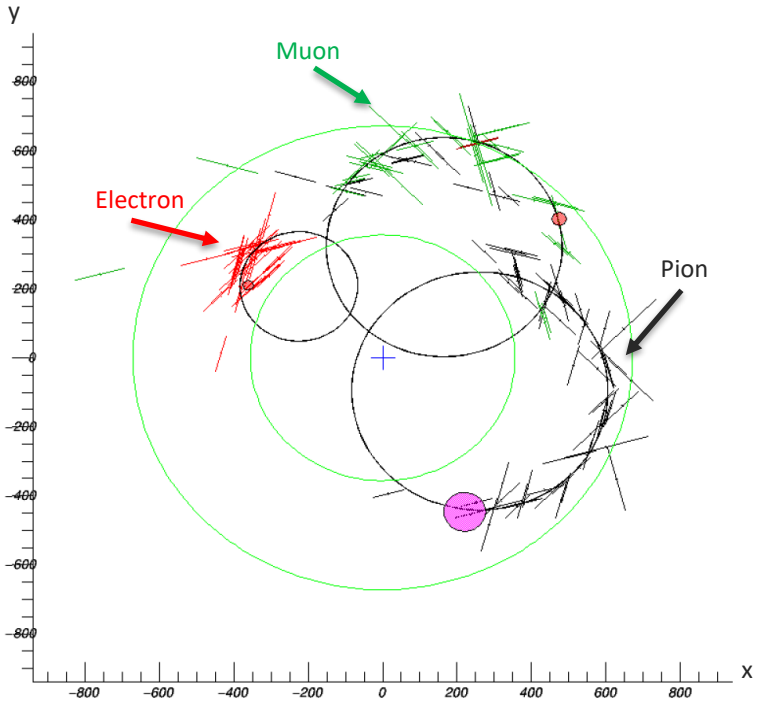
Projected backgrounds for Mu2e Run 1

Antiproton Annihilation in Mu2e

- Challenging for conversion electron reconstruction
  - Non-electron particles
  - Particles overlapping in space and time
- No problem for agnostic reconstruction
  - Excellent reconstruction of multiple particles close in space and time
  - Efficient with non-electron particles
  - No initial assumptions on particle trajectory

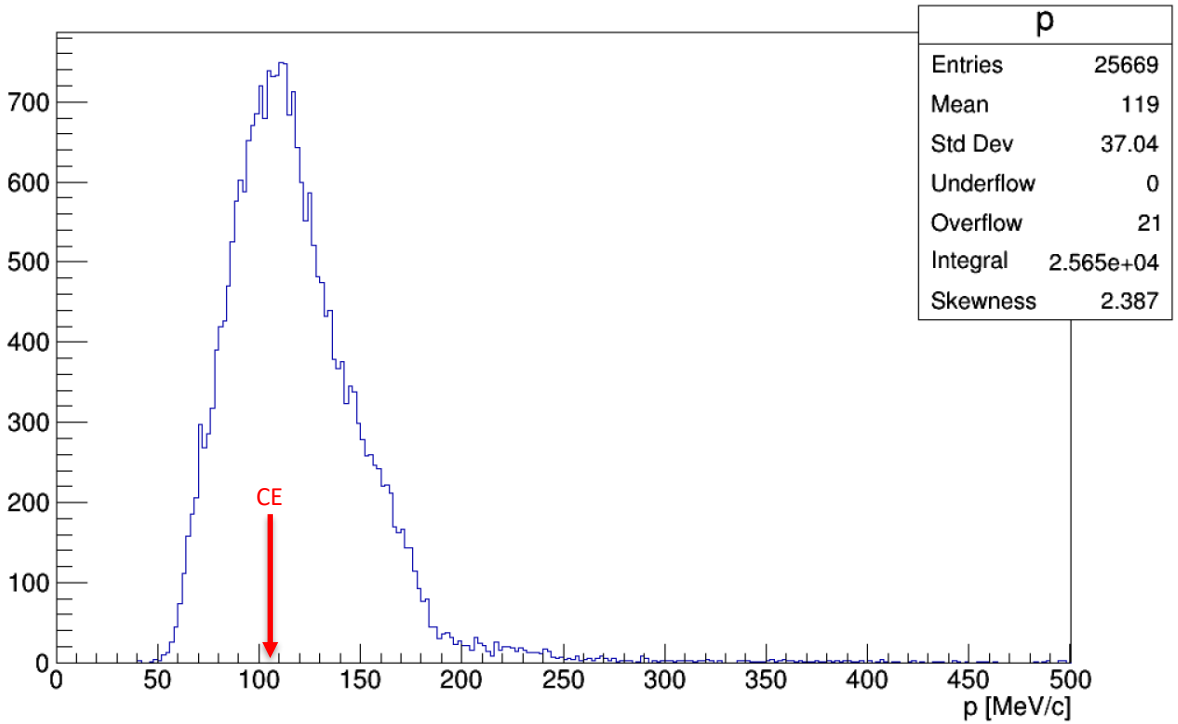


Agnostic reconstructed particle PDG of antiproton-induced events.

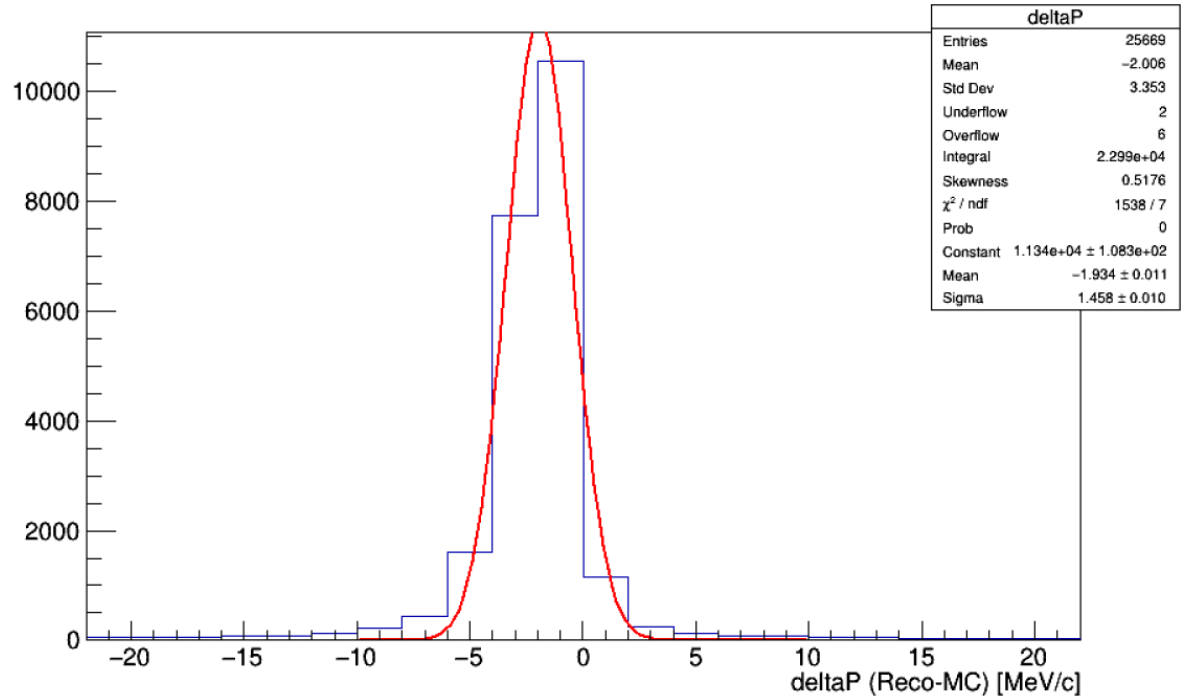


Event display in the transverse plane of the tracker showing agnostic reconstructed antiproton-induced particle trajectories.

Topology of Antiproton-Induced Events: Momentum



Reconstructed momentum of antiproton-induced events.

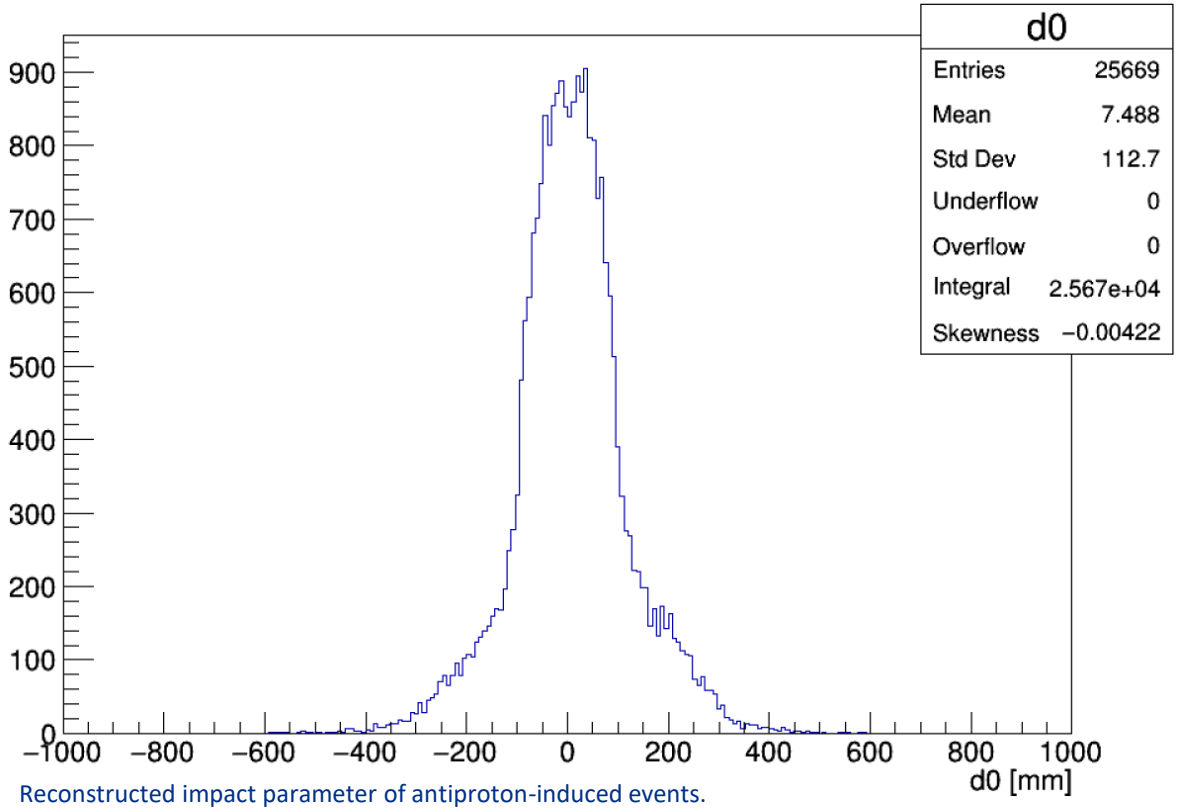


Residual momentum (reconstructed – MC) of antiproton-induced events (blue) with Gaussian fit (red).

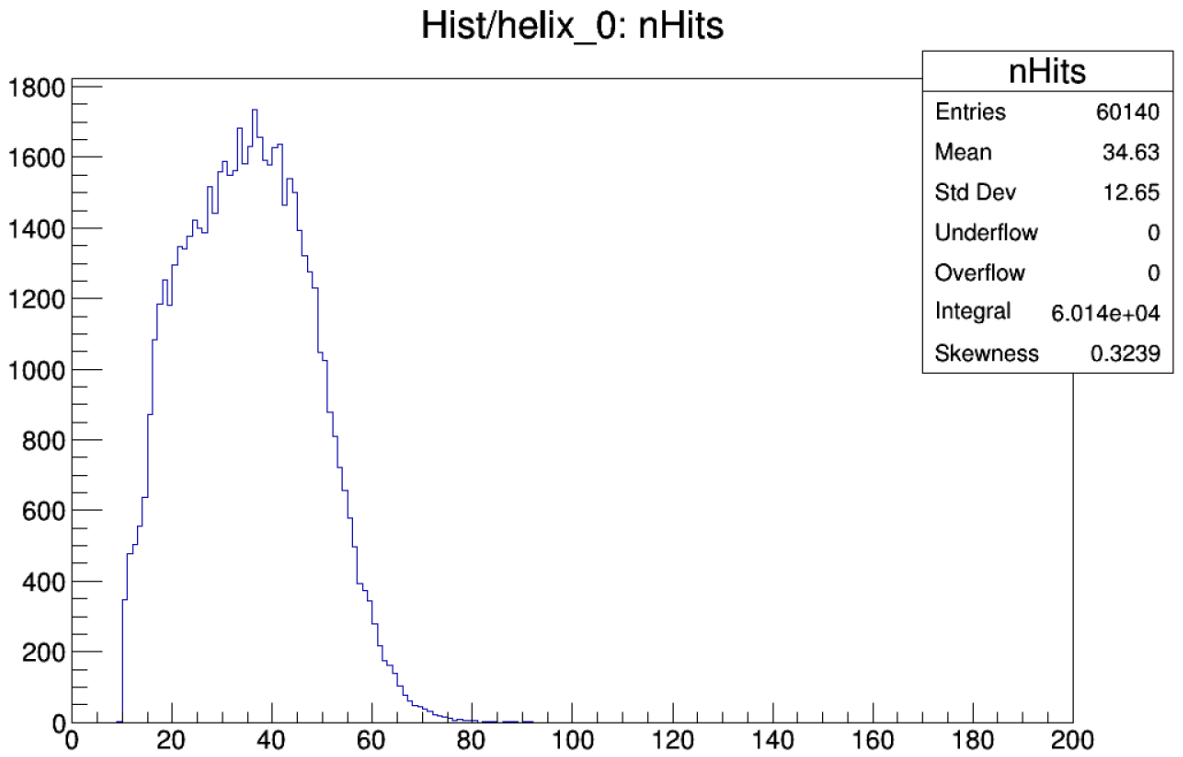
- Large momentum compared to conversion electron signal
  - Mean of 119 MeV/c
- Shape of distribution due to tracker geometry

- Efficient reconstruction of antiproton-induced event
  - Sigma of ~1.5 MeV/c

Topology of Antiproton-Induced Events: Impact Parameter and Number of Straw Hits



Reconstructed impact parameter of antiproton-induced events.



Number of straw hits of antiproton-induced events.

- Distance from particle trajectory to center of tracker
- Events originate from Stopping Target
  - Distribution centered around 0

- Large number of straw hits in tracker
- Important factor to reduce rate of events with fake tracks

Trigger Sequences in Mu2e

Default:

- Conversion electron reconstruction
  - Tracker Pattern Recognition (TPR) + Calorimeter Pattern Recognition (CPR)
- Requires charge and upstream vs. downstream assumption

Pbar:

- Agnostic reconstruction (APR) instead of TPR
- Selects events with multi-track topology using lower momentum cut
- Does not require charge or upstream vs downstream assumption

Trigger Philosophy:

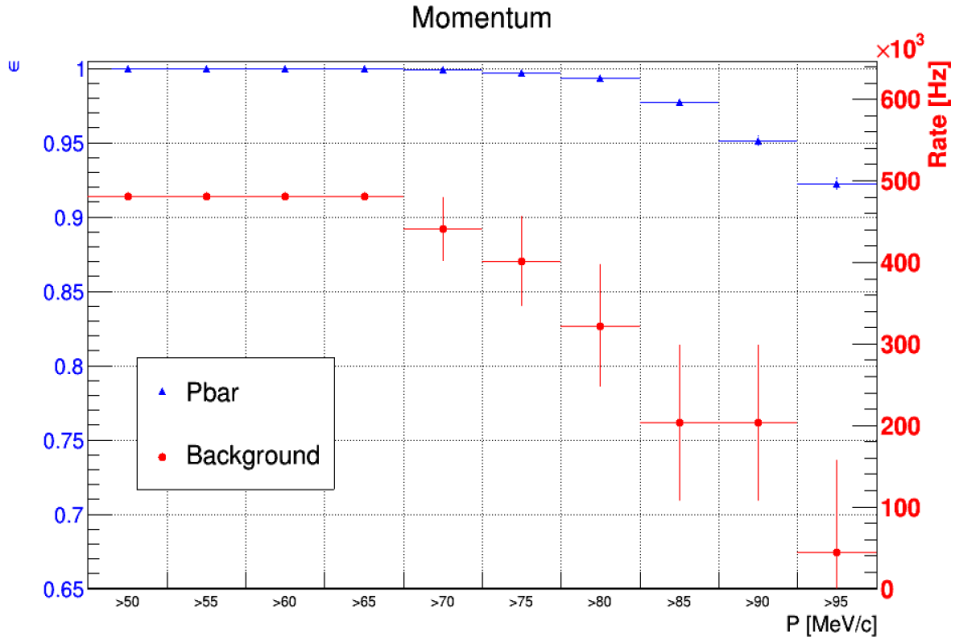
- Maximize signal efficiency
- Minimize rate of fake events
- Take advantage of signal event topology

Definition of Pbar Trigger Selection

- Take advantage of antiproton-induced event topology
  - Especially particle multiplicity
- Define cuts which reduce rate of fake events by significant fraction

Parameter	Cut
Momentum (MeV/c)	P > 80
Impact Parameter (mm)	-150 < D0 < 150
Number of Hits	N ≥ 15
Number of Tracks	N ≥ 2

Cuts not shown: Transverse momentum, number of loops, hit ratio, helix lambda, and chi2.



Antiproton-induced signal efficiency and rate of fake events of pbar trigger at varying momentum cuts.

$$\epsilon = \frac{NumberOfEventsPassed}{NumberOfGoodEvents} \quad Rate = InputRate * \frac{NumberOfEventsPassed}{NumberOfEvents}$$

- Good events have at least 2 good tracks
- Efficiency evaluated with pbar-induced events
- Rate evaluated with background events
- Rate drops by ~30% with 80 MeV/c momentum cut

Performance of Pbar Trigger Selection: Efficiency

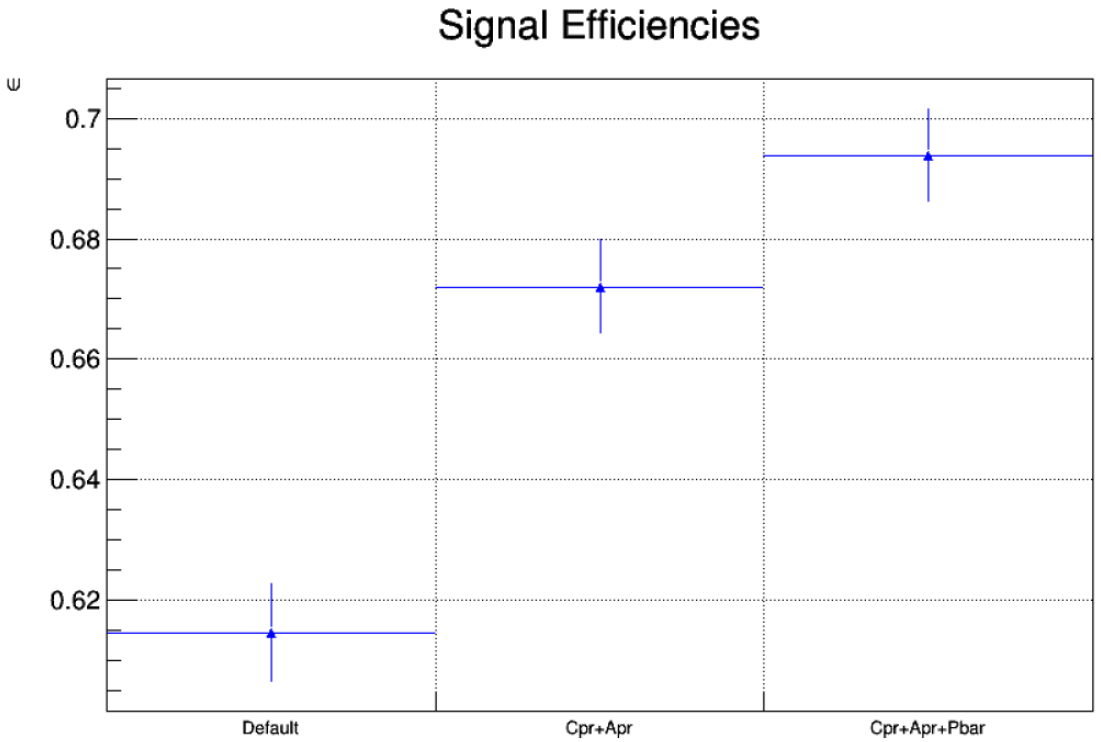
Efficiency Definition:

$$\epsilon = \frac{NumberOfEventsPassed}{NumberOfGoodEvents}$$

- Good events have at least 2 good tracks
- Evaluated with pbar-induced events

Performance:

- Highest efficiency achieved with pbar trigger selection
  - ~70% at best
- Agnostic outperforming conversion electron reconstruction by ~10%



Signal efficiencies of three trigger selection sequences: Default, Agnostic, and Agnostic + Pbar.

Performance of Pbar Trigger Selection: Rate of Fake Events

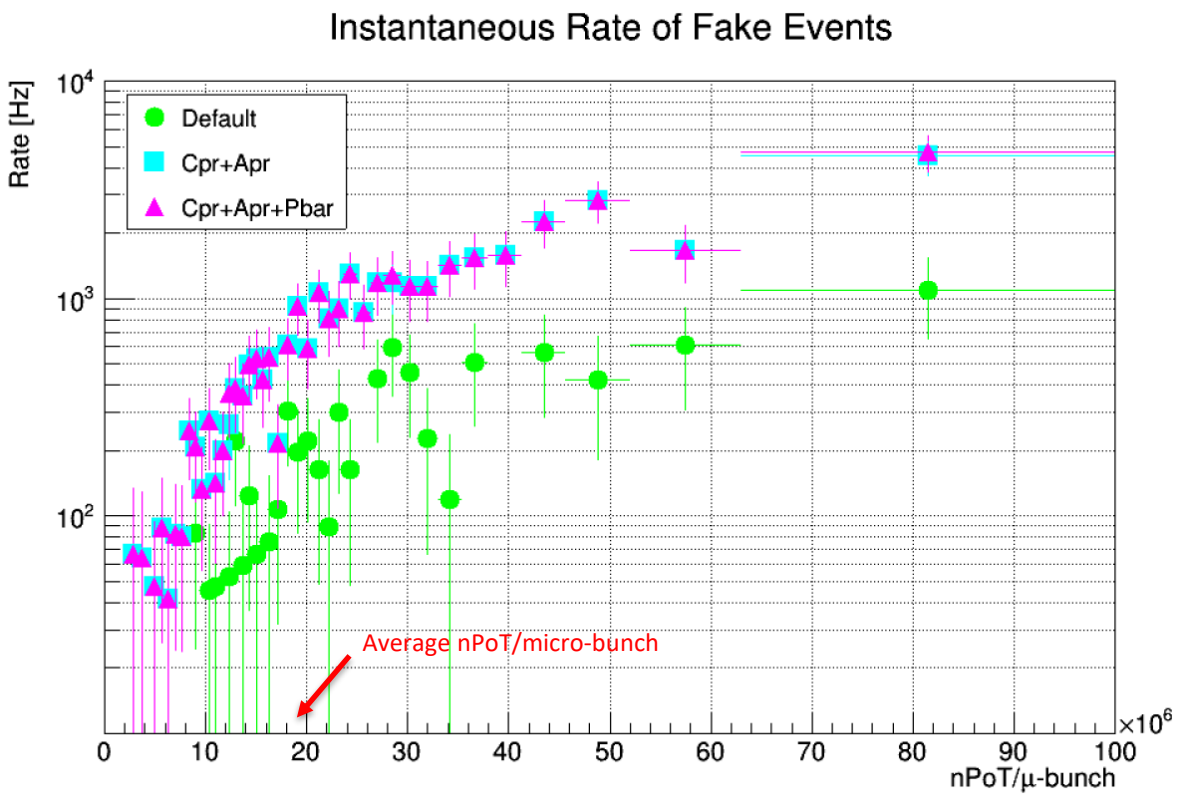
Rate Definition:

$$Rate = InputRate * \frac{NumberOfEventsPassed}{NumberOfEvents}$$

- Plotted as a function of number of protons on target
- Evaluated with background events

Performance:

- Agnostic reconstruction increases rate by at most 1kHz
  - Could be reduced by a factor of 2 with a higher cut on the number of tracking planes crossed
- Additional pbar selection does not increase background rate



Instantaneous rate of fake events of three trigger selection sequences: Default, Agnostic, and Agnostic + Pbar.

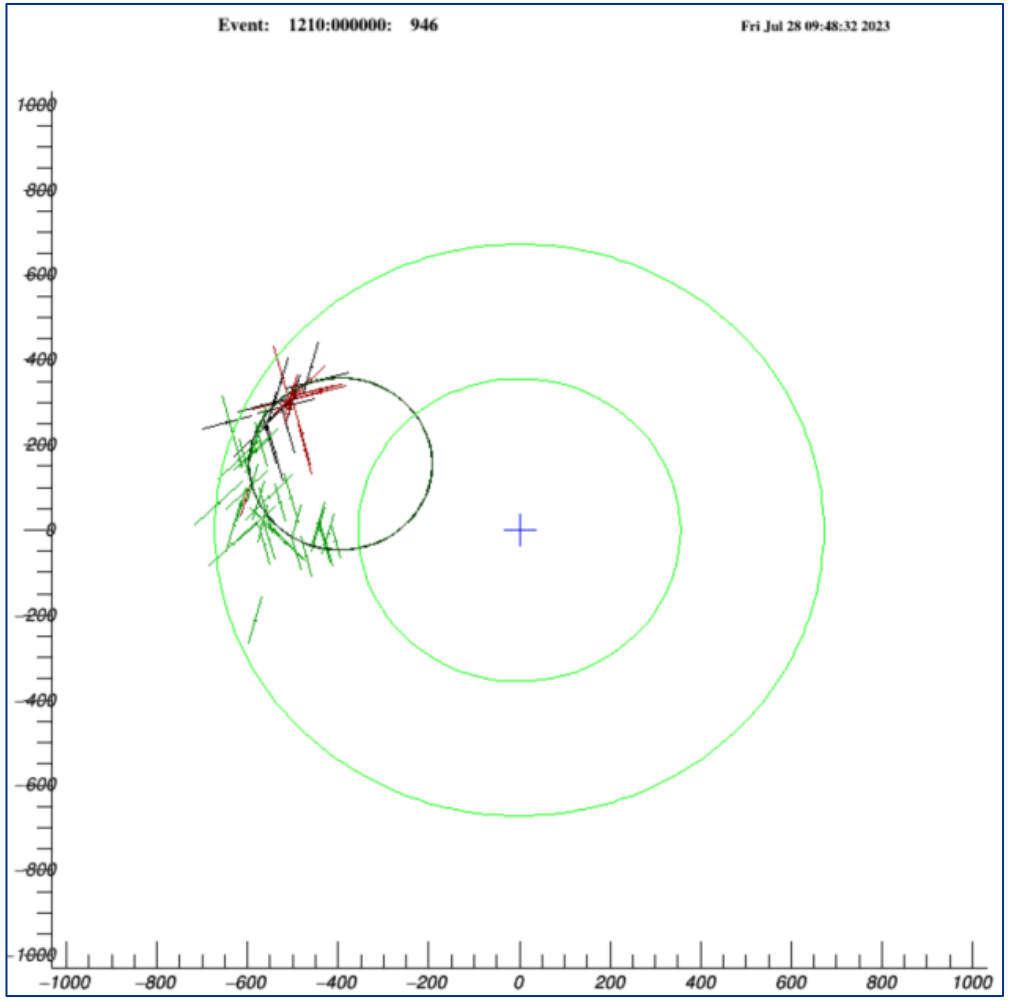
Conclusion and Next Steps

- Agnostic reconstruction and multi-track selection are necessary to develop an efficient antiproton trigger to better characterize this background
- We will continue to study antiproton-induced events that failed selection to improve trigger performance
- We will further optimize agnostic reconstruction to reduce rate of fake events
  - Consider making changes to the logic
  - Consider introducing new cuts (timing, tracker-related observables)

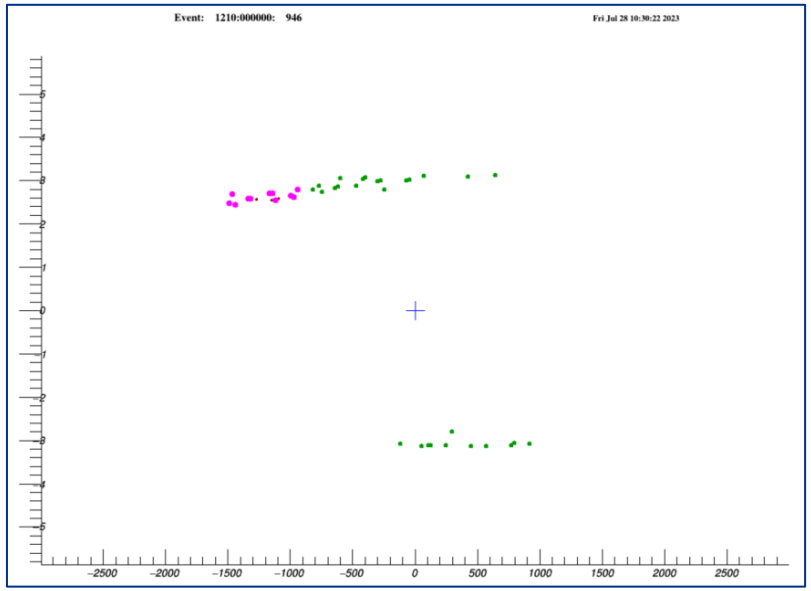
THANK YOU!

Backup

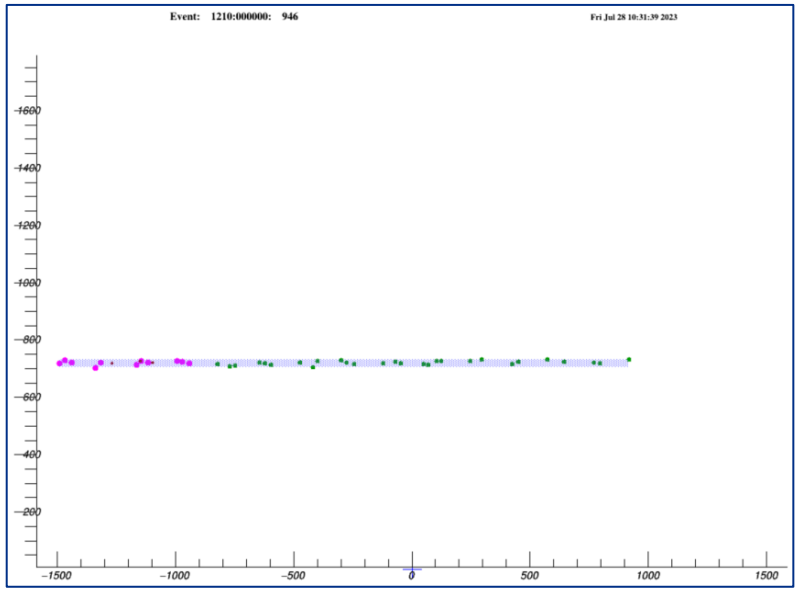
Decay-In-Flight Event



Event display in the transverse view of the tracker showing trajectory of decay-in-flight particles from antiproton-induced event.



Event display in phi-z view of the tracker.



Event display in t-z view of the tracker.