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

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New Perspectives
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Overview

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  - Antiproton Annihilation in Mu2e
- Topology of Antiproton-Induced Events
- Antiproton (Pbar) Trigger
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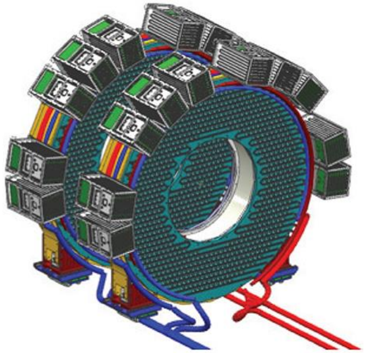
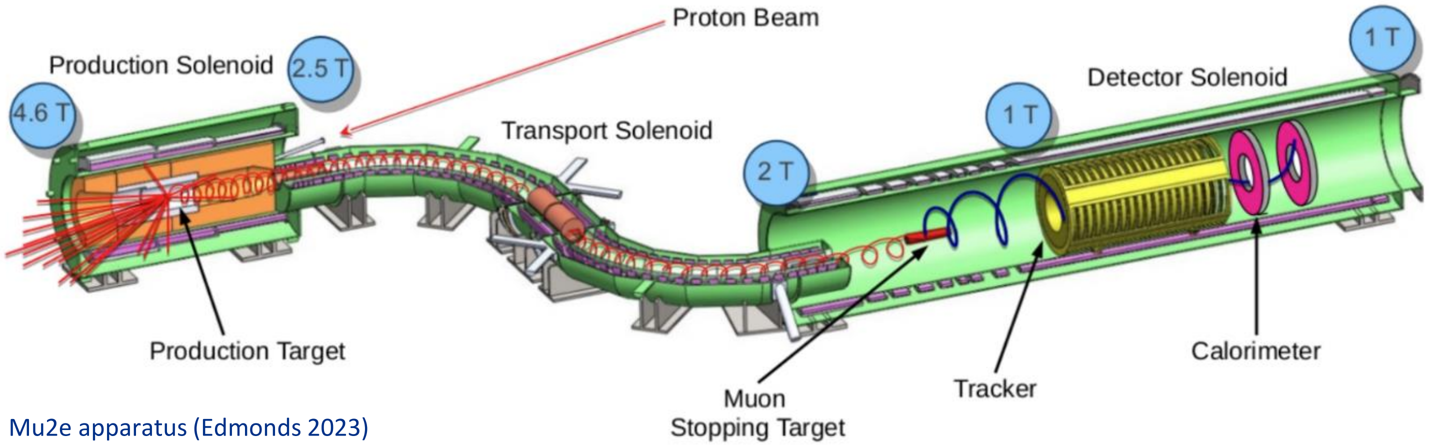
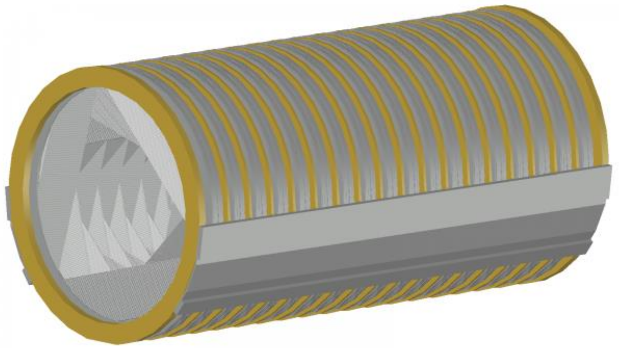
The Mu2e Experiment

- Search for neutrinoless muon-to-electron conversion in the field of an Al nucleus
- Monochromatic conversion electron signal of ~105 MeV
- Sensitivity goal of $3x10^{-17}$ (improvement from previous upper limit by 4 orders of magnitude)
- Muon beam supplied from pulsed proton beam incident on Tungsten target (~$3x10^{7}$ protons every 1.7 μs)
- Tracker composed of hollowed planes consisting of 23,000 straw tubes
  - Excellent momentum resolution
- Calorimeter comprised of two annular disks, each holding 674 CsI crystals
  - Excellent timing and energy resolution


Mu2e calorimeter (Bernstein 2019)



Mu2e apparatus (Edmonds 2023)


Mu2e tracker (Bernstein 2019)

Antiproton Annihilation in Mu2e

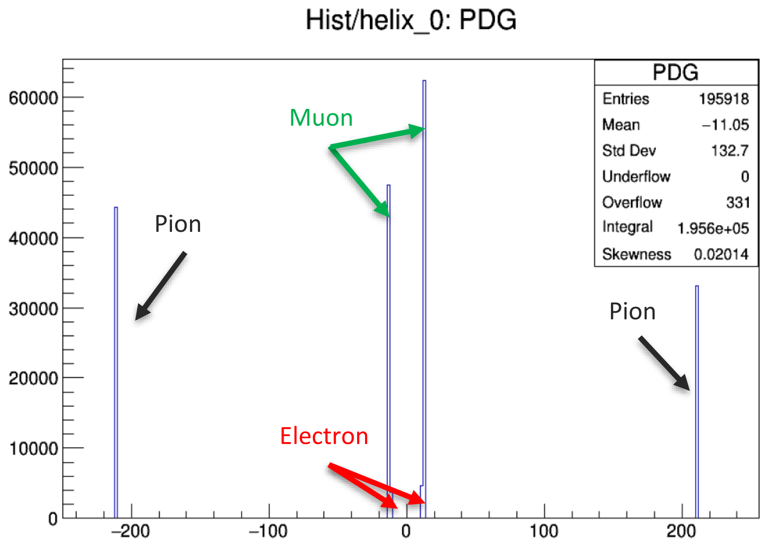
- Antiprotons are produced from proton beam's collision with Production Target at a low rate
- Some reach Detector Solenoid and annihilate with protons in Al Stopping Target
  - ~2 GeV available in annihilation
  - Produces pions, muons, and electrons
- Expect electrons that mimic conversion electron signal to be produced at a rate of 0.010 ± 0.010
  - Large systematic uncertainty due to theoretical model of antiproton production cross-section
  - This process can be better characterized experimentally by developing an efficient antiproton trigger

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (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

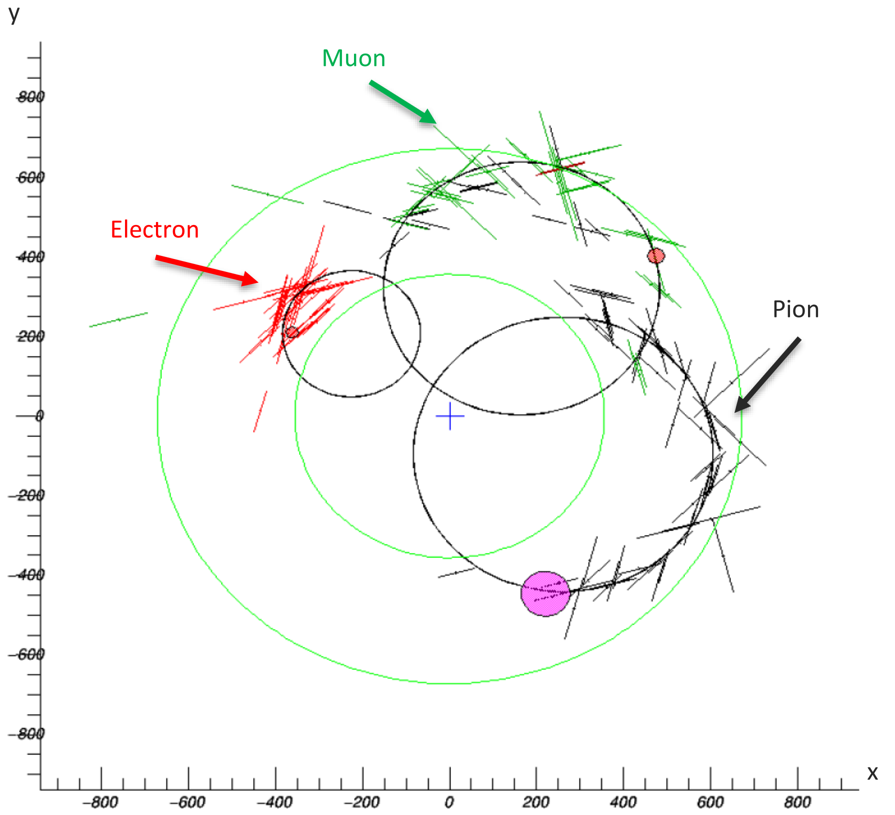
Projected background rates for Mu2e Run 1

Antiproton Annihilation in Mu2e

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

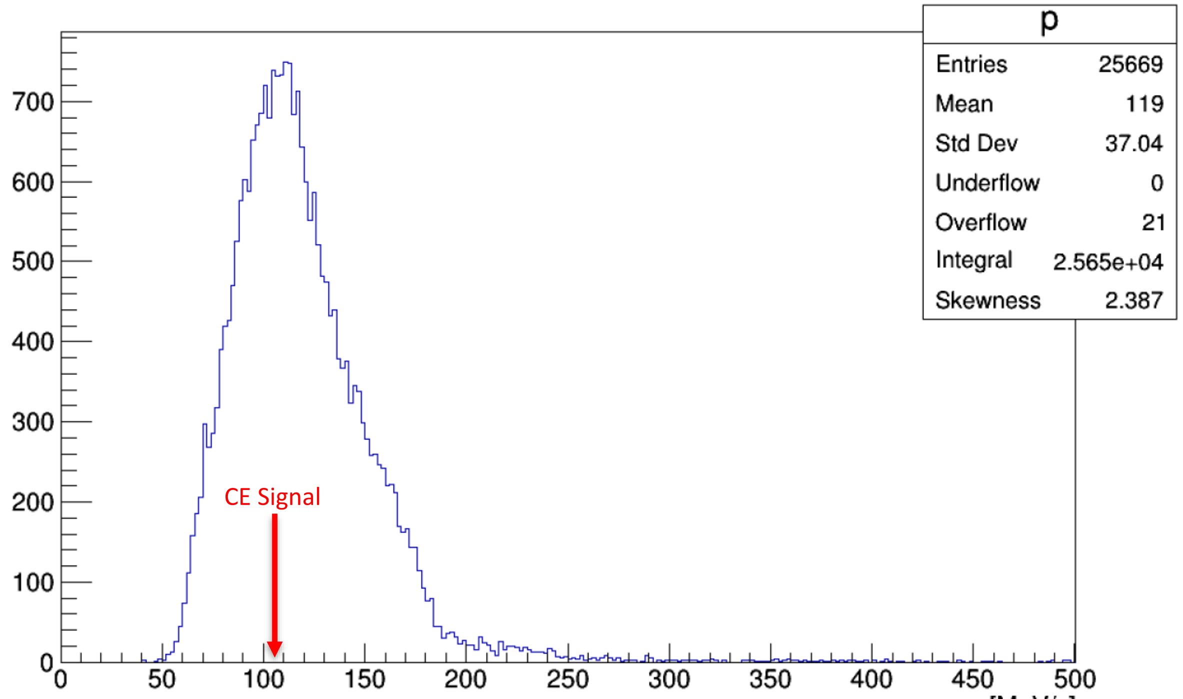


Agnostic reconstructed particle PDG of antiproton-induced events.

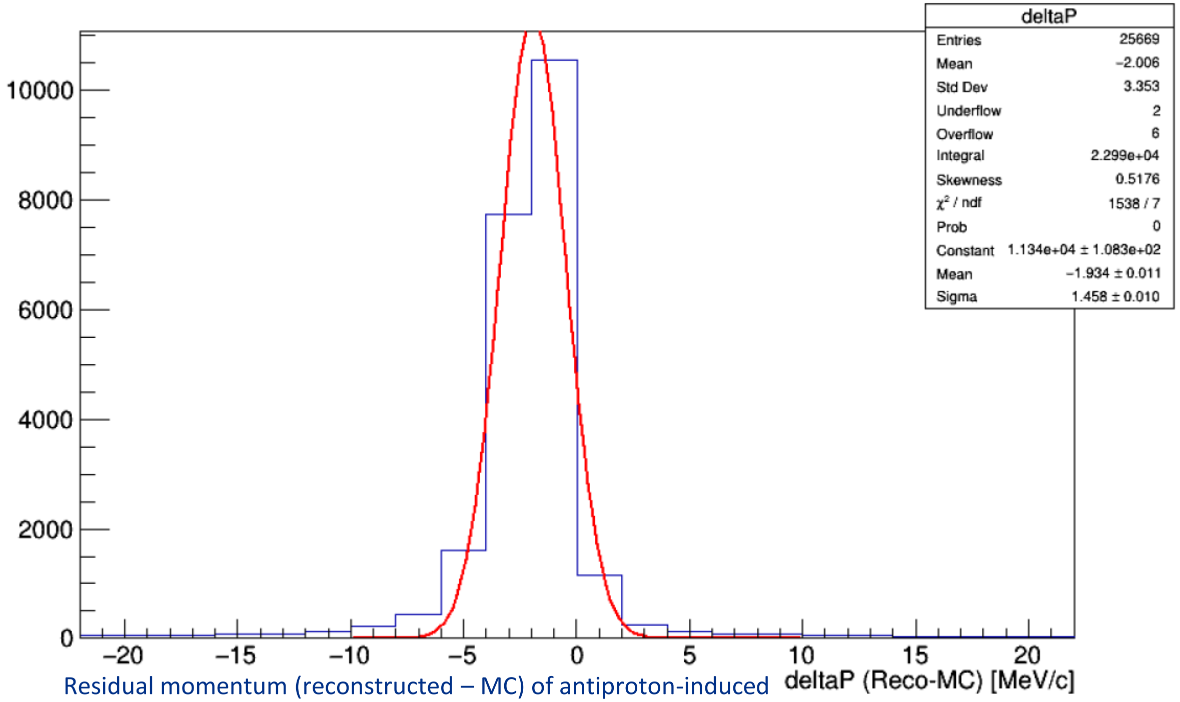


Antiproton-induced event display in the transverse plane of the tracker showing reconstructed particle trajectories.

Topology of Antiproton-Induced Events: Momentum



Reconstructed momentum of antiproton-induced events.

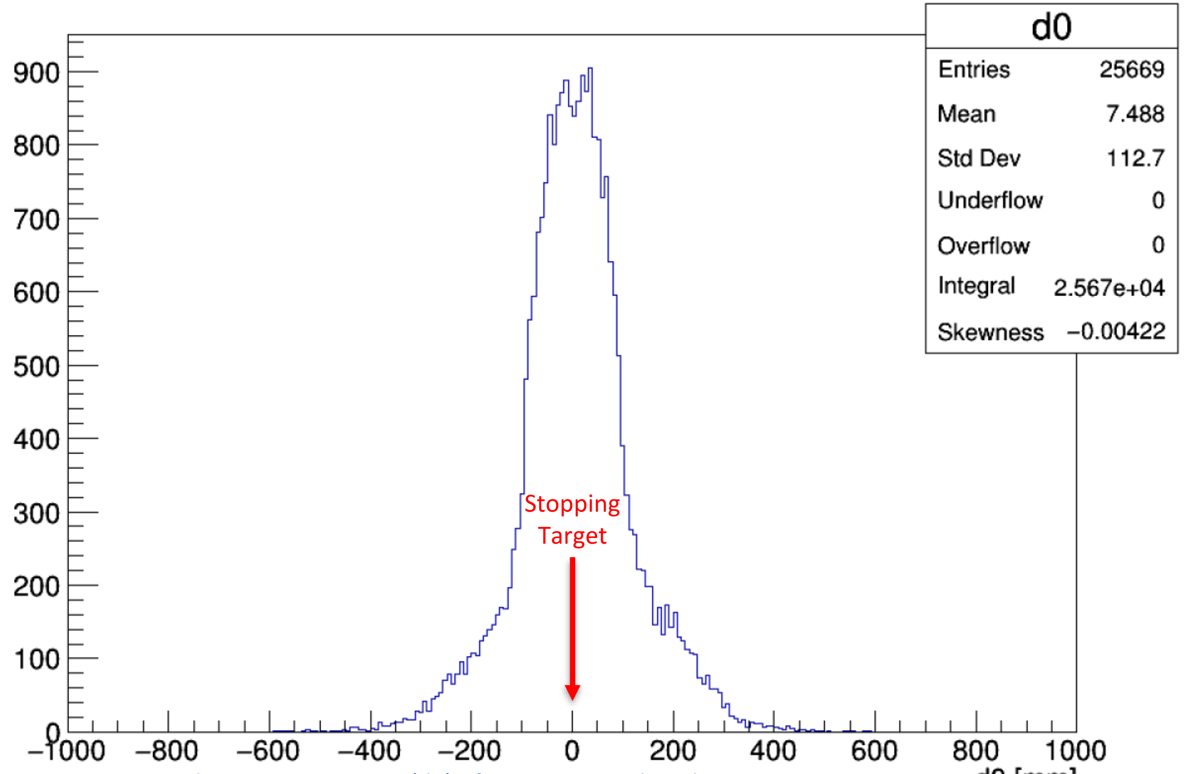


Residual momentum (reconstructed – MC) of antiproton-induced events (blue) with Gaussian fit (red).

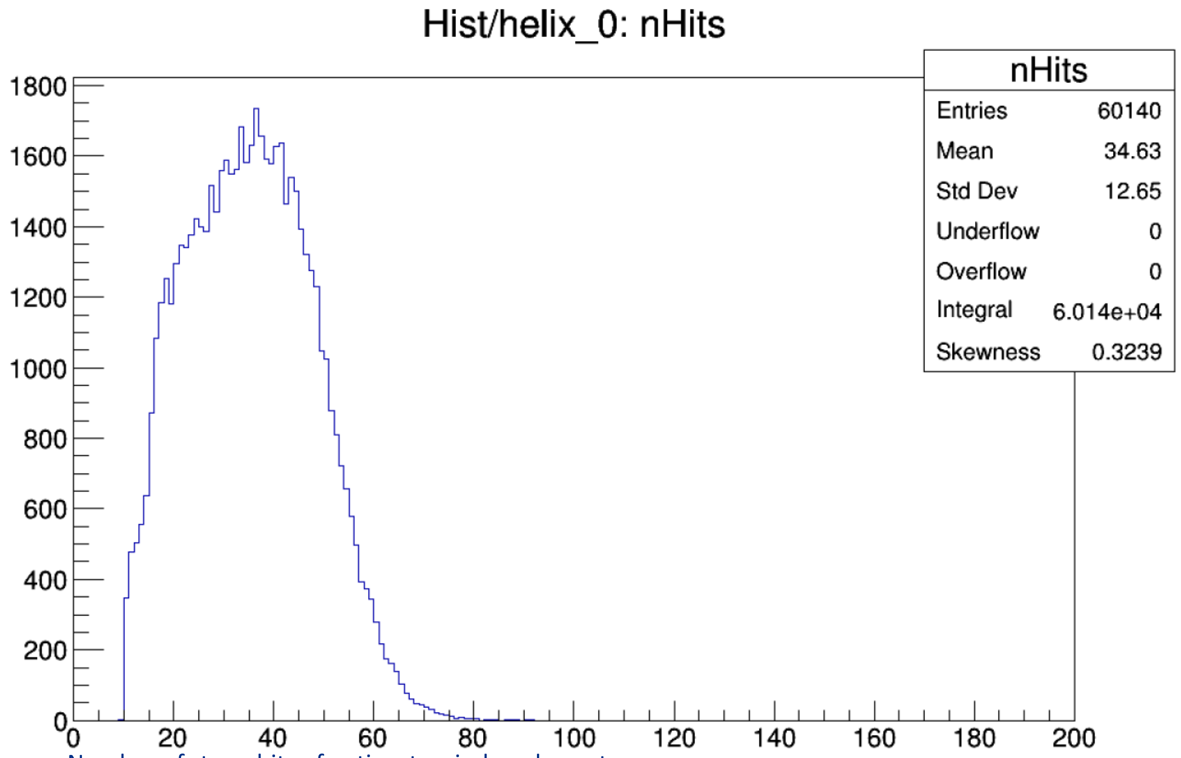
- Large momentum compared to conversion electron signal
  - Mean of 119 MeV/c
- Shape of distribution due to tracker geometry

- 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 (d0) of antiproton-induced events.



Number of straw hits of antiproton-induced events.

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

- 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 assumptions

Antiproton (Pbar):

- Agnostic reconstruction
  - Agnostic Pattern Recognition (APR) + Calorimeter Pattern Recognition (CPR)
- Does not require charge or upstream vs downstream assumption
- Selects events with multi-track topology using lower momentum cut

Trigger Philosophy:

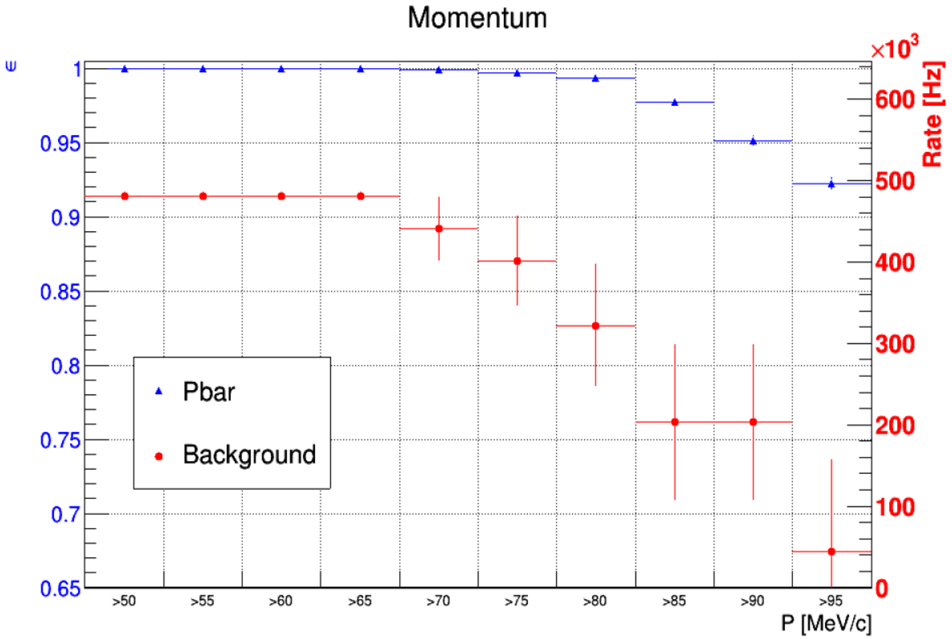
- Maximize signal efficiency
- Minimize rate of fake events
- Take advantage of signal event topology

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.

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

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

- Efficiency evaluated with antiproton-induced events
- Rate evaluated with background events
- Rate drops by ~30% with 80 MeV/c momentum cut

Performance of Pbar Trigger Selection: Efficiency

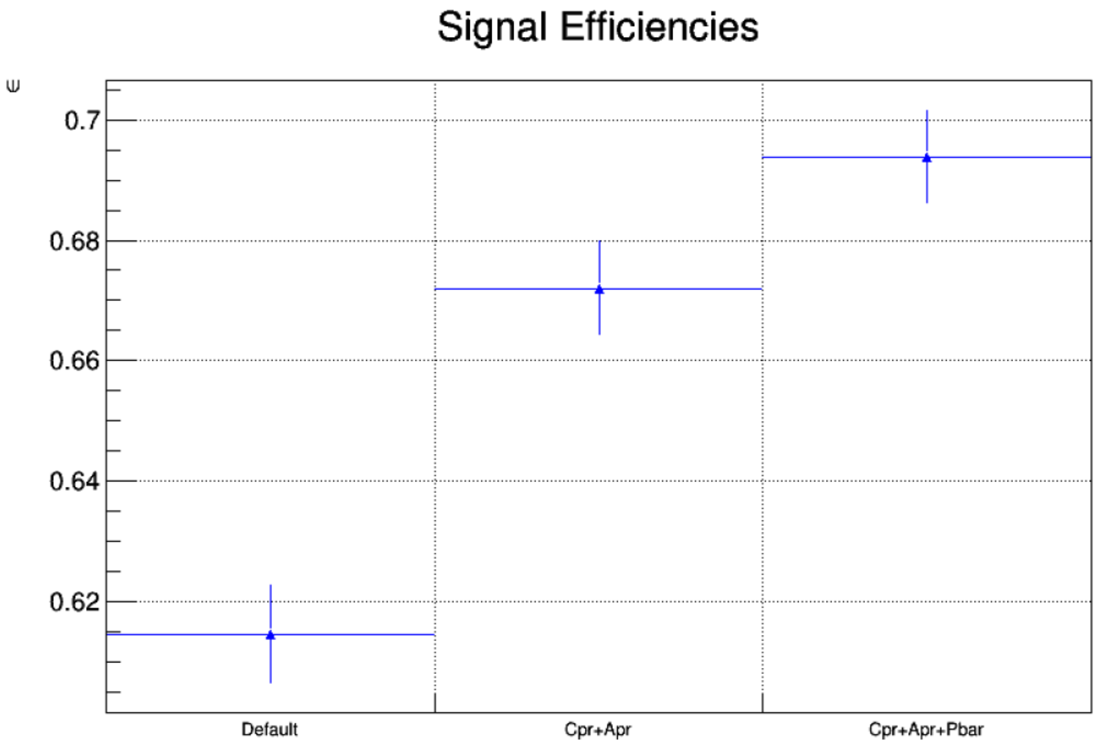
Efficiency Definition:

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

- Good events have at least 2 tracks with at least 80 MeV/c and 15 straw hits
- Evaluated with antiproton-induced events

Performance:

- Highest efficiency achieved with antiproton trigger selection
  - ~70% at best
- Agnostic (CPR + APR) outperforming conversion electron (default) reconstruction by ~10%



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

Performance of Pbar Trigger Selection: Rate of Fake Events

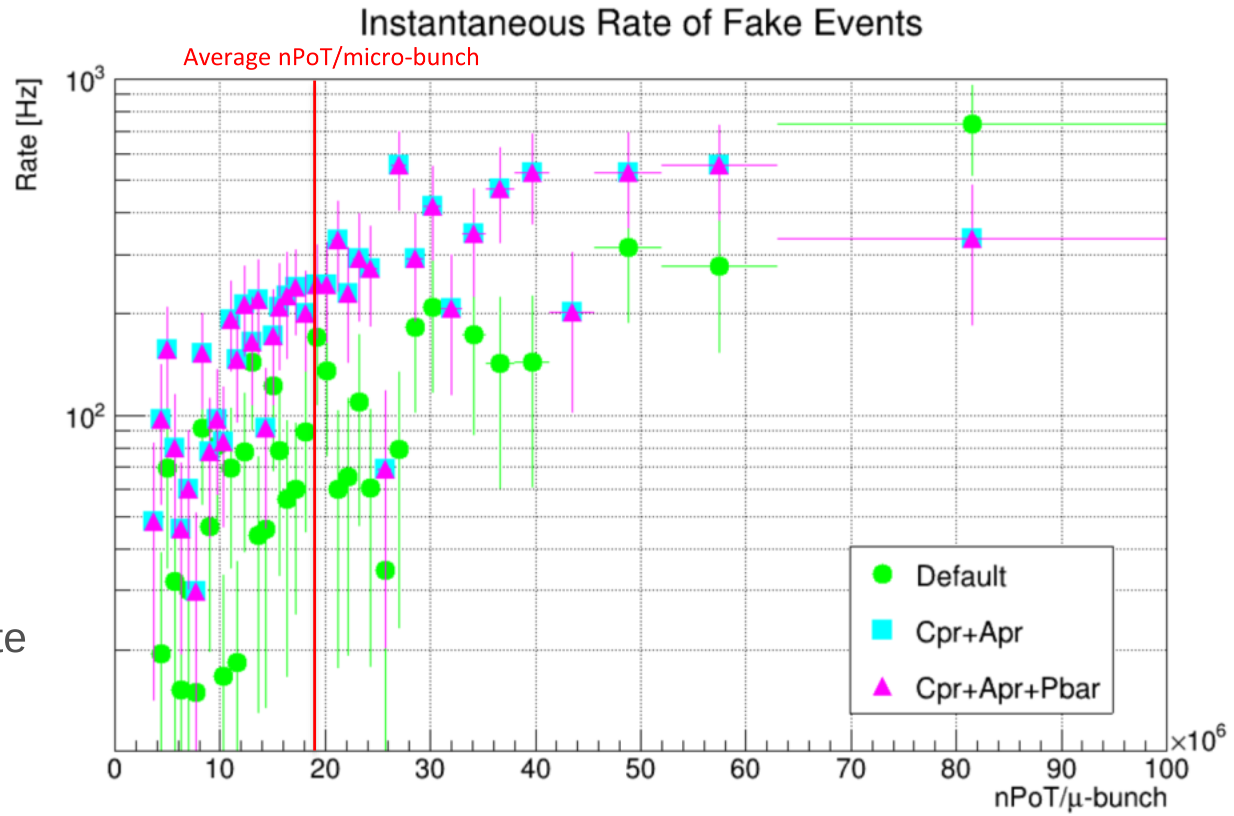
Rate Definition:

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

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

Performance:

- Agnostic trigger rate performs within 1kHz limit
  - Required to limit the total amount of data we store
- Additional antiproton-induced selection does not increase rate



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

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Conclusion and Next Steps

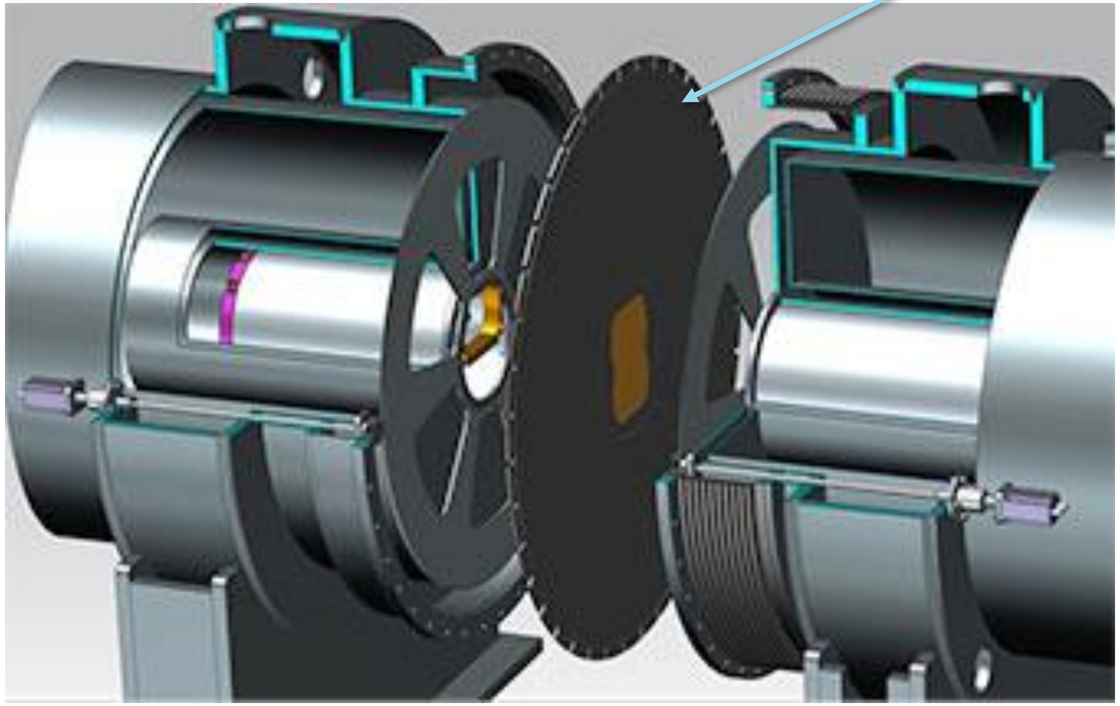
- Agnostic reconstruction and multi-track selection are necessary to develop an efficient antiproton trigger to better characterize this process
- We will continue to optimize selection cuts to boost signal efficiency
- We will further optimize agnostic reconstruction to reduce rate of fake events
  - Consider introducing new cuts (timing, tracker-related observables)

THANK YOU!

Backup

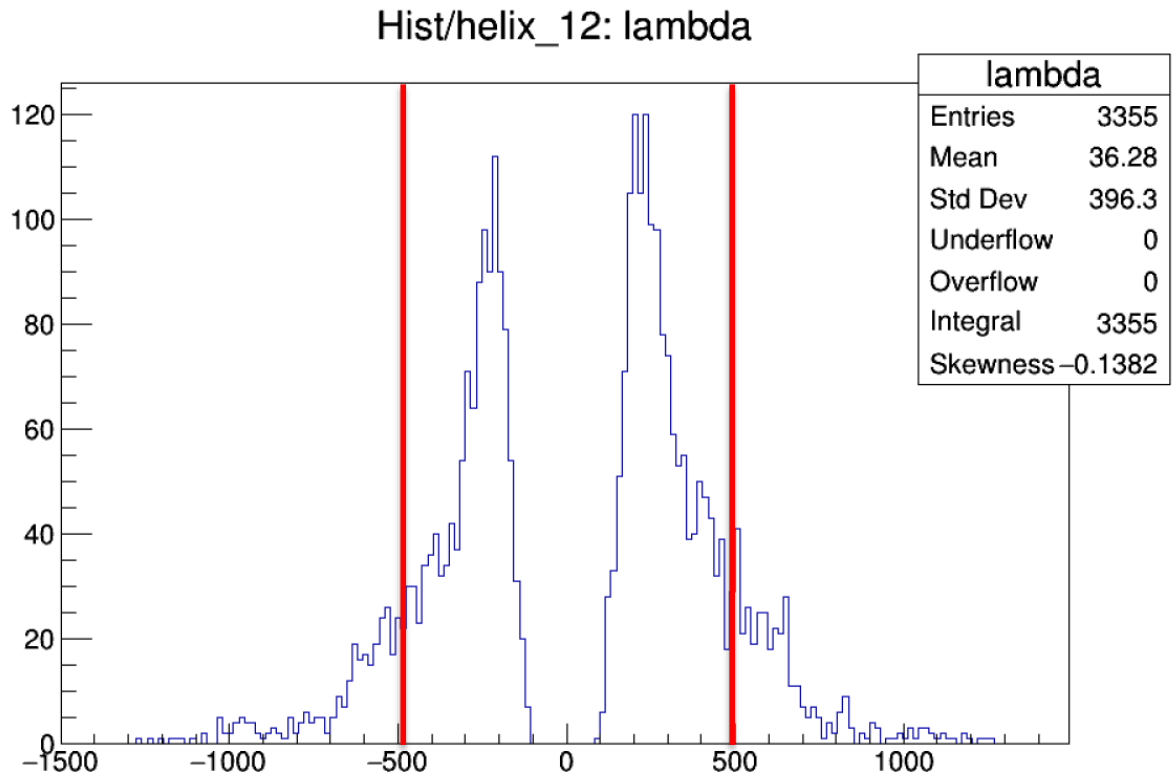
Antiproton Stopping Windows

- Thin Beryllium wedge-shaped plate 200-1300 μm thick
- Placed in between collimators located in the Transport Solenoid
- Designed to absorb antiprotons while avoiding reduction of the muon stopping rate



Preliminary design of the collimators COL3u and COL3d assembly inside the Transport Solenoid cryostat in an assembled cross-section view.

Helix Lambda of Failed Antiproton-Induced Events



Helix lambda of good antiproton-induced events which failed the pbar trigger selection.

```
aprLowPStopTargMultiTrkHSFilter: {
   doHelicityCheck: false
   helicity: 1
   helixSeedCollection: "TTAprHelixMerger"
   maxAbsLambda: 500
   maxChi2PhiZ: 8
   maxChi2XY: 8
   maxD0: 150
   maxMomentum: 500
   maxNLoops: 30
   minAbsLambda: 50
   minD0: -150
   minHitRatio: 4e-1
   minMomentum: 50
   minNLoops: 0
   minNStrawHits: 15
   minPt: 0
   module_type: "HelixFilter"
   prescaleUsingD0Phi: false
   requireCaloCluster: false
   minNHelices: 2
}
```

Definitions of cuts placed at the helix level of the pbar trigger selection.

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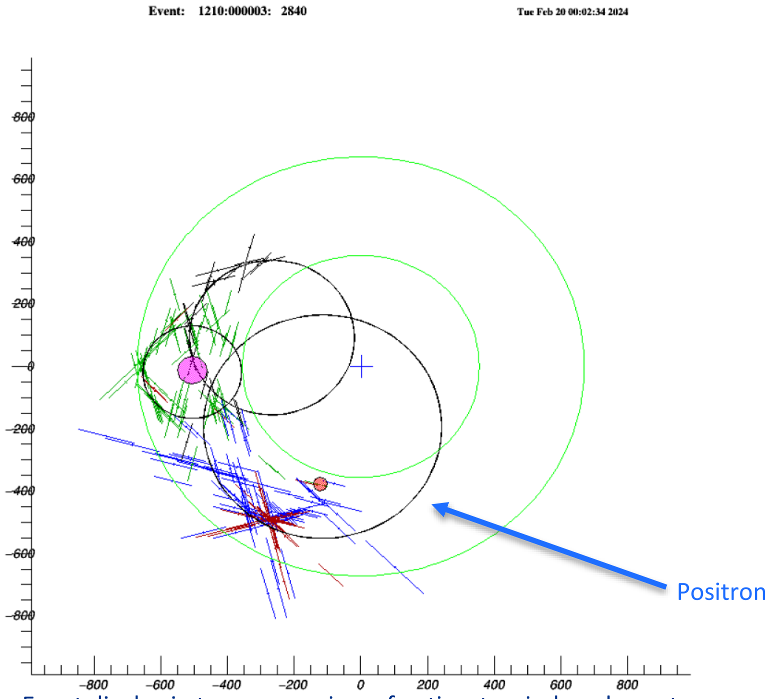
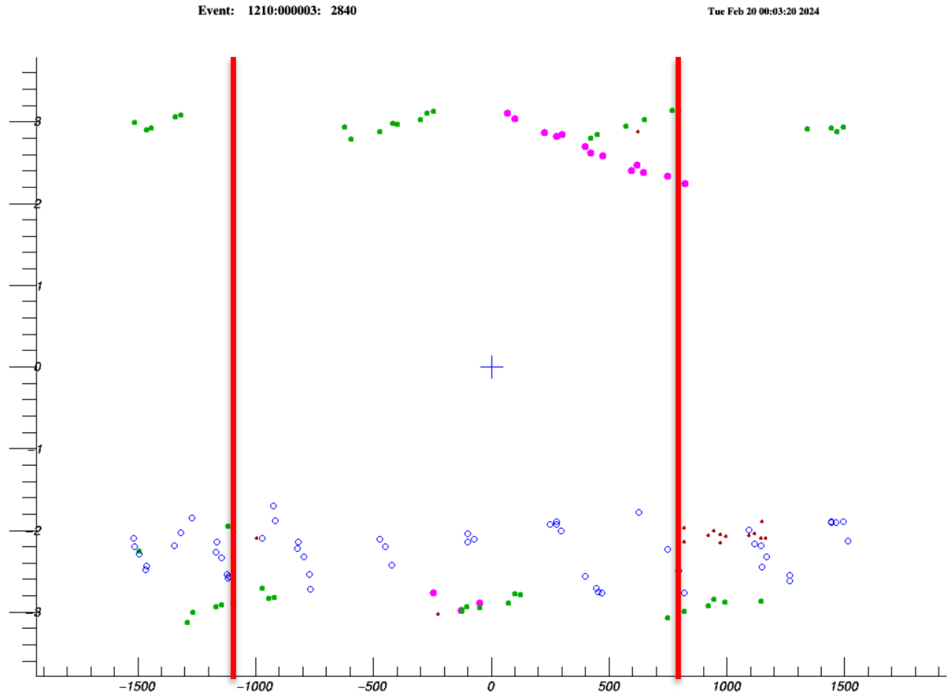
Antiproton-Induced Events with Large NHitsRatio



Event display in transverse view of antiproton-induced event.



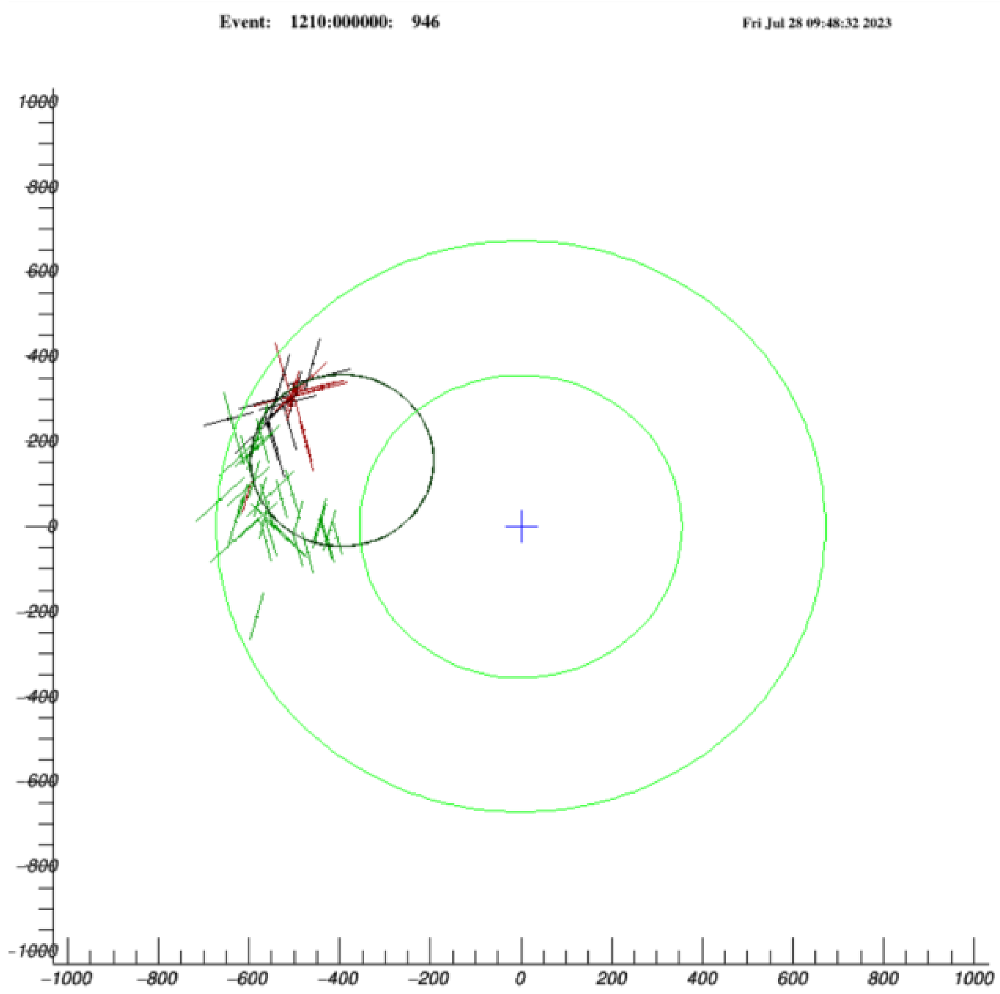
Event display in the Phi-Z view of antiproton-induced event.

-1 0x16e404e0 9 1 9 158.116 107.553 763.282 1.225 -133.378 0.434 -115.412 -193.298 -386.338 358.509 -1.000 0.134 1.572 00000008

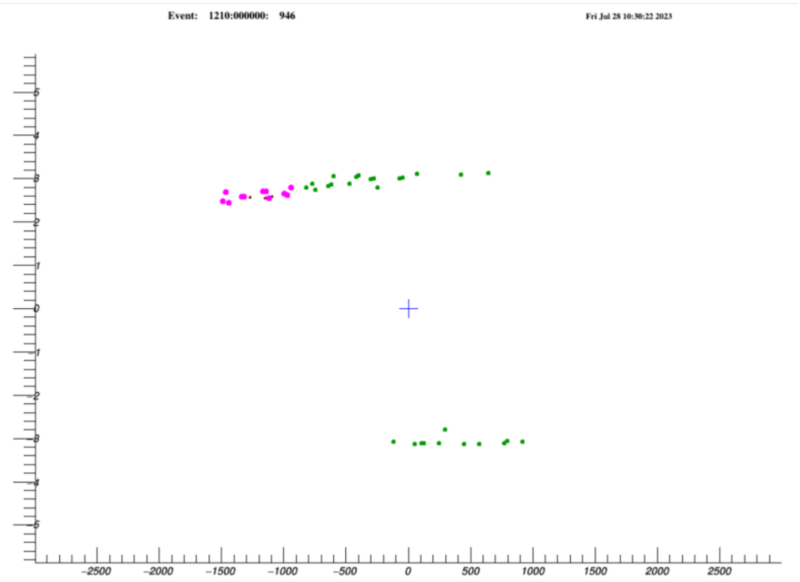
I	NSH	SHID	Flags	Pl	Pn	L	S	x	y	z	phi	Time	eDep	PDG	PDG(M)	GenID	SimID	p	pT	pZ
	2	32062	00000000	31	2	0	62	-392.224	-421.390	1167.614	-2.448	775.805	0.004	-11	-2212	-1	112	51.397	48.093	18.129
	3	31894	00000000	31	1	0	22	-341.931	-477.858	1144.178	-2.248	783.539	0.002	-11	-2212	-1	112	51.486	47.972	18.695
	2	29750	00000000	29	0	0	54	-321.266	-483.643	971.080	-2.192	791.918	0.006	11	-2212	-1	117	0.564	0.447	-0.344
	1	27957	00000000	27	2	1	53	-227.197	-544.433	816.908	-1.874	779.750	0.002	11	-2212	-1	117	1.731	1.730	-0.033
	2	5129	00000000	5	0	1	9	-457.565	-303.153	-1114.214	3.444	785.532	0.001	-11	-2212	-1	112	54.272	51.762	16.314
	2	5133	00000000	5	0	1	13	-490.049	-309.008	-1116.920	3.433	774.789	0.001	-11	-2212	-1	112	54.318	51.618	16.911
	1	5138	00000000	5	0	0	18	-473.632	-324.730	-1119.626	3.486	779.711	0.000	-11	-2212	-1	112	54.380	51.533	17.365
	3	142	00000000	0	1	0	14	-322.921	-448.185	-1514.712	4.021	781.606	0.000	-11	-2212	-1	112	54.649	52.395	15.531
	2	138	00000000	0	1	0	10	-293.415	-505.983	-1518.320	4.191	771.586	0.001	-11	-2212	-1	112	54.666	52.469	15.342

Printout of reconstructed helix information.

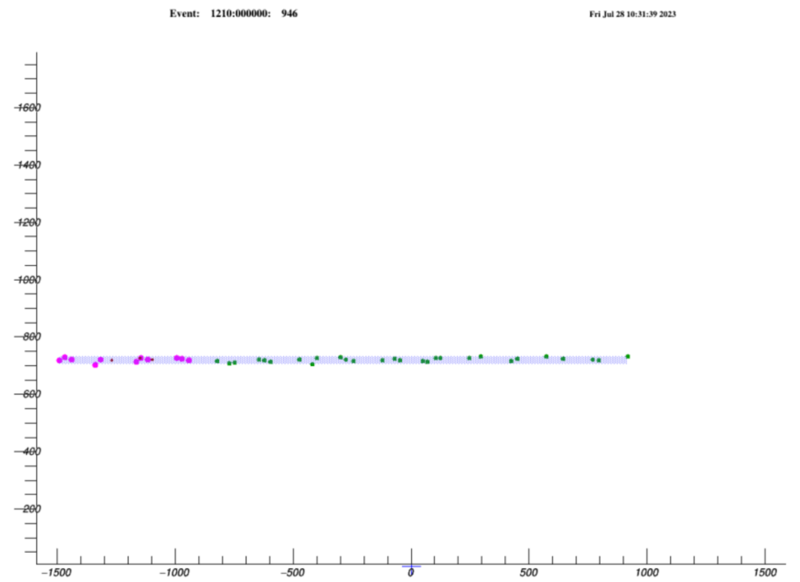
Decay-In-Flight Event



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.