A data-driven method to constrain the antiproton background in Mu2e

Multi-track events from $p\bar{p}$ annihilation v/s Cosmics

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INTENSE
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Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmics	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
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

Background summary in the optimised signal momentum and time window 103.6<p<104.90 MeV/c and 640< T0<1650 ns*

- $\overline{p}$ produced by the pW interactions in the PS can annihilate in the ST producing signal-like e^-s.
- $\overline{p}$s are significantly slower than other beam particles. They cannot be efficiently suppressed by the time window cut used to reduce prompt background.
- Absorber elements placed at entrance and center of the TS to suppress the $\overline{p}$ background.
- The estimated $\overline{p}$ background for Run 1 is $0.01 \pm 0.003(stat) \pm 0.010(syst)$*.
  The systematic error is dominated by the uncertainty on the production cross section at 8 GeV/c proton momentum.

*Mu2e Collaboration MDPI Universe 2023 https://doi.org/10.3390/universe9010054

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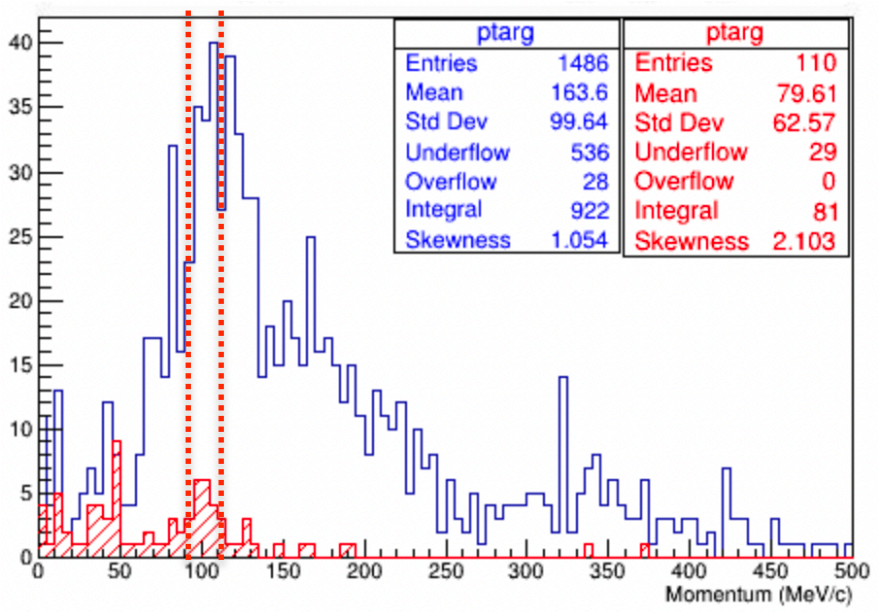
$$\frac{N_{e^-perMeV}}{N_{multi-track}} \approx \frac{1}{500}$$



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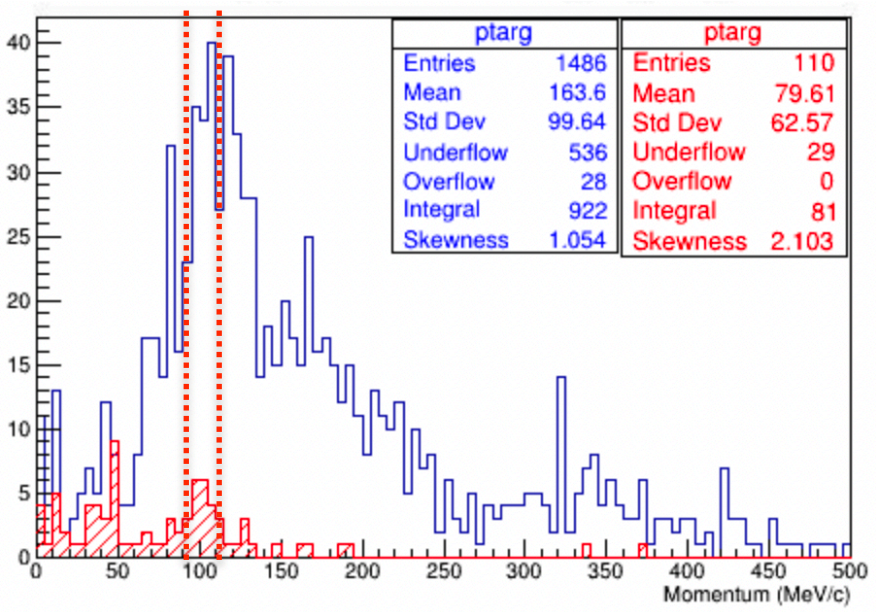

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Goal: Identify and reconstruct the multi-track final state events and get an estimate of the CE like events by rescaling the ratio of the two final states.

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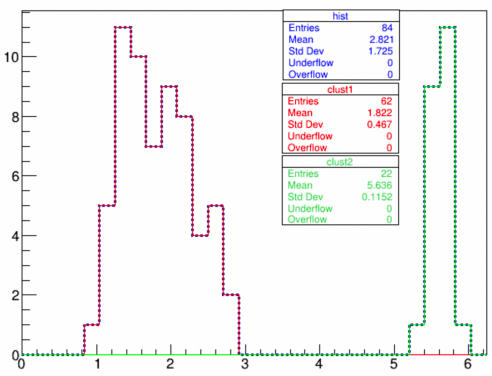

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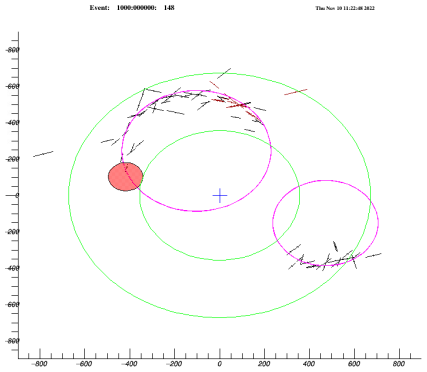

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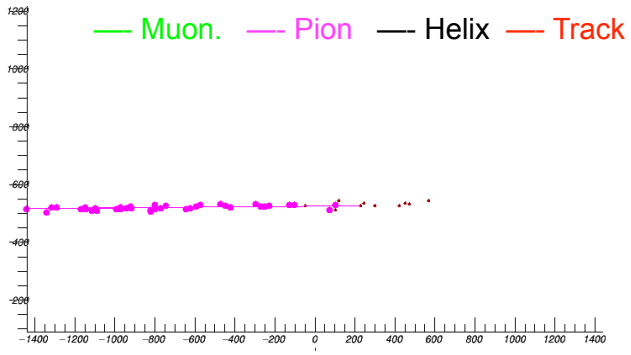

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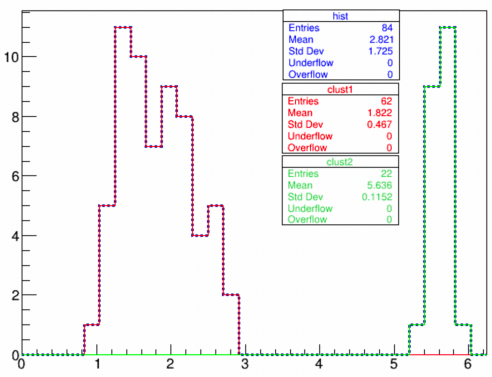

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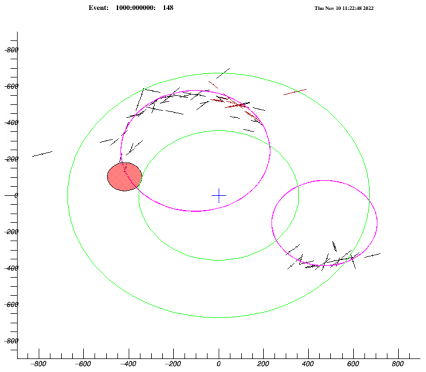

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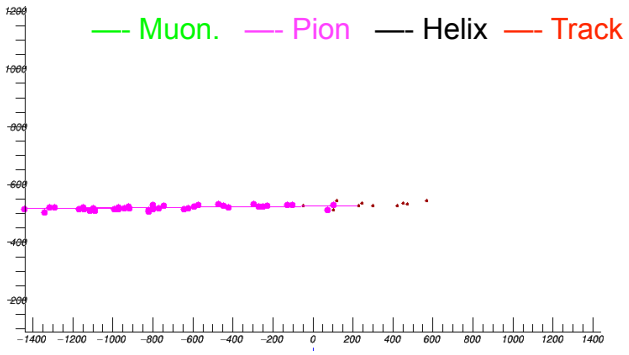

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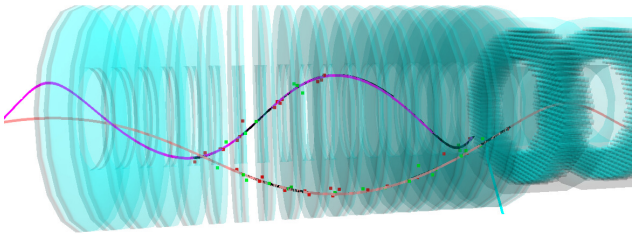

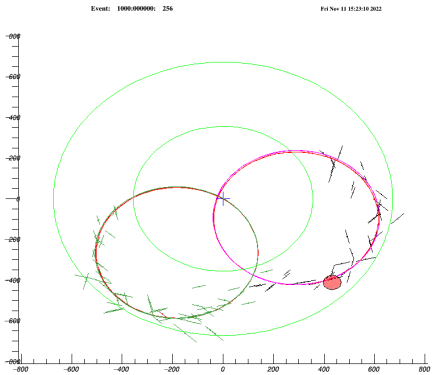

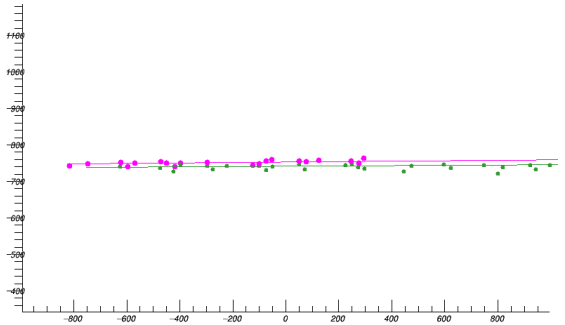

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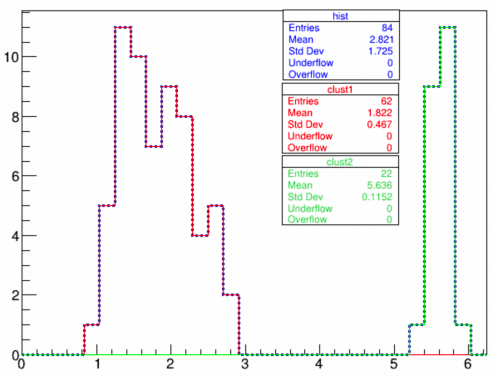

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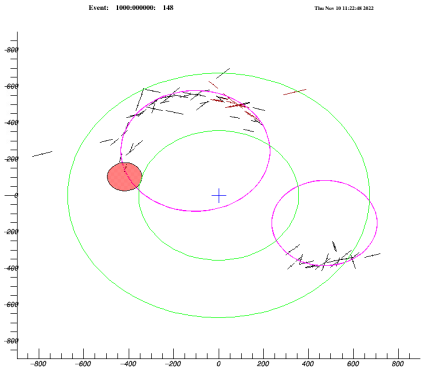

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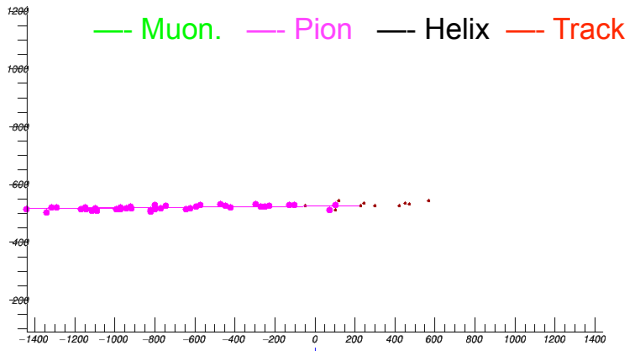

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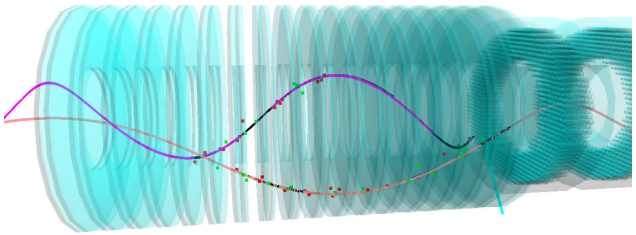

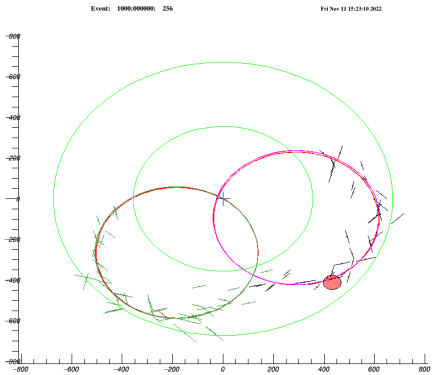

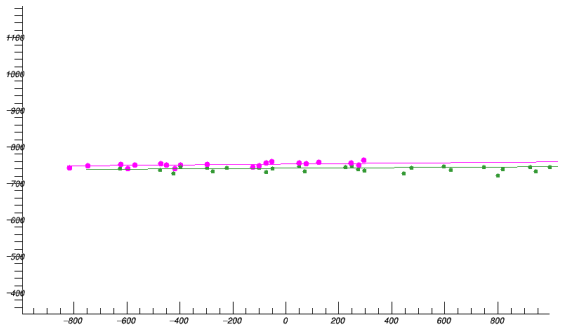

- The default algorithms to flag background hits and $TimeClustering$ trained for efficient CE search, did not work well for tracks from $p\bar{p}$ annihilation.

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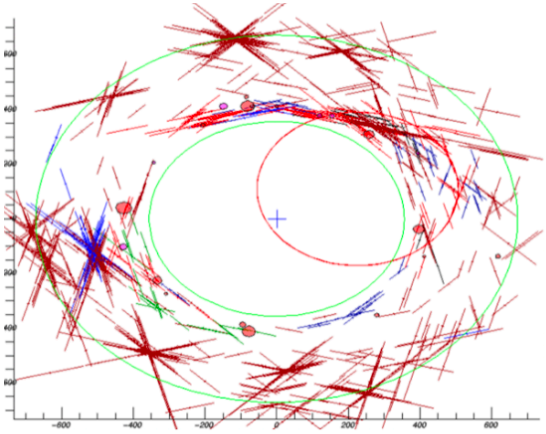
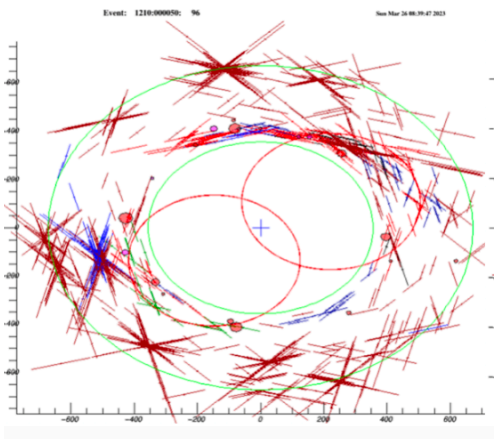


XY view, Default reconstruction



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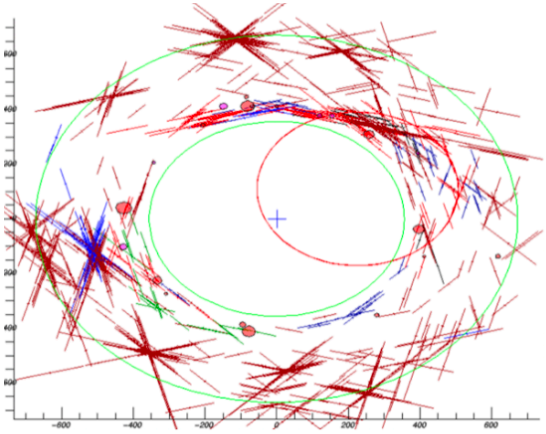

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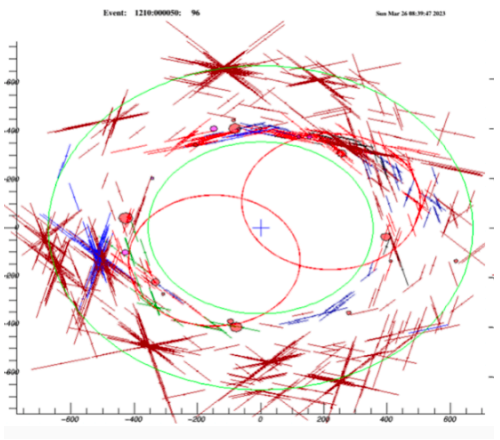

XY view, New reconstruction

Dataset	0 BB		1 BB		2 BB	
No. Of events with	> 0 track	> 1 track	> 0 track	> 1 track	> 0 track	> 1 track
Default reco	1272	58	1089	46	1046	39
New reco	1734	113	1579	97	1465	81
Improvement	**x 1.4**	**x 2**	**x 1.4**	**x 2.1**	**x 1.4**	**x 2**

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- $N_{POT/pulse} = 1.6 \times 10^{7},\ N_{\mu^- stops/POT} = 1.59 \times 10^{-3} \Rightarrow N_{\mu^- stops/pulse} = 2.54 \times 10^{4}$

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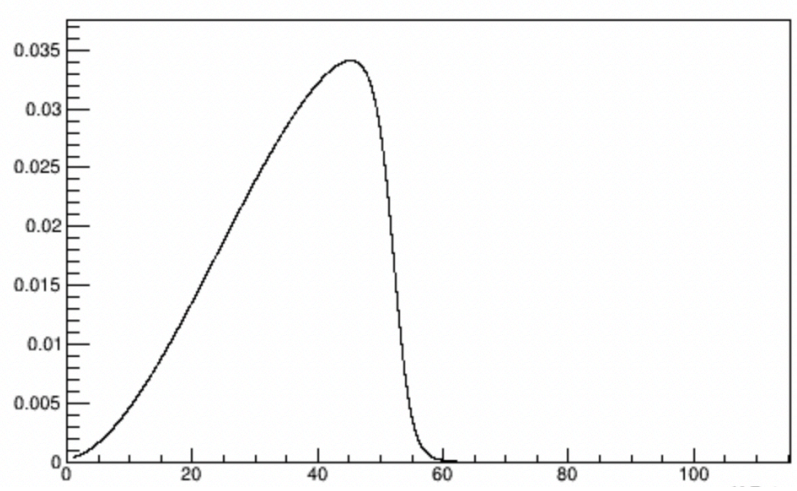

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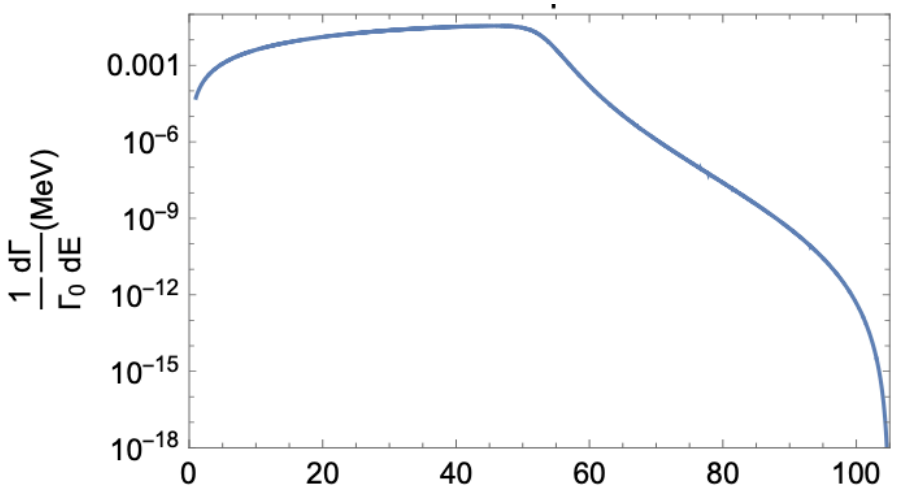

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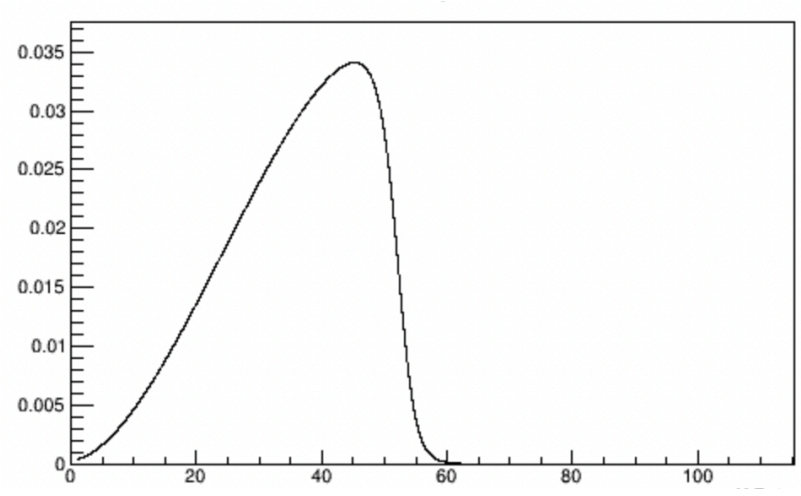
- $N_{2DIO>80MeV/c} = 1.8 \times 10^{16} \times 3.68 \times 10^{-15} = 66.24$



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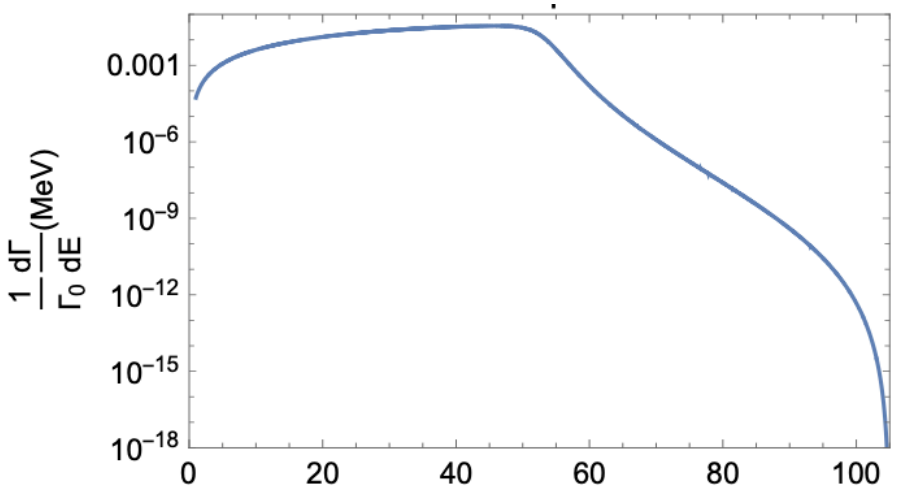

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- Thus, if one asks for the track to have at least 85 MeV/c momentum then the probability of a two DIO tracks event is negligible.

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- The new CRY lo dataset can be found:

  samweb list-files --summary "dh.dataset=**dts.mu2e.cry4lb0s31r0000.pbar2m.art**"
  File count: 1000
  Total size: 249751538458 (200GB)
  Event count: 18007806

Cosmics Dataset

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- The 1BB mixed CRY4 Lo dataset can be found:

  samweb list-files --summary "dh.dataset=**dig.mu2e.cry4lb1s41r0000.pbar2m.art**"
  File count: 498
  Total size: 1803711346022
  Event count: 1014574

Cosmics Dataset: An oversampling issue

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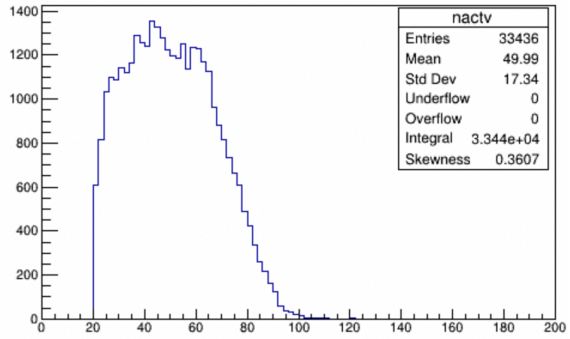
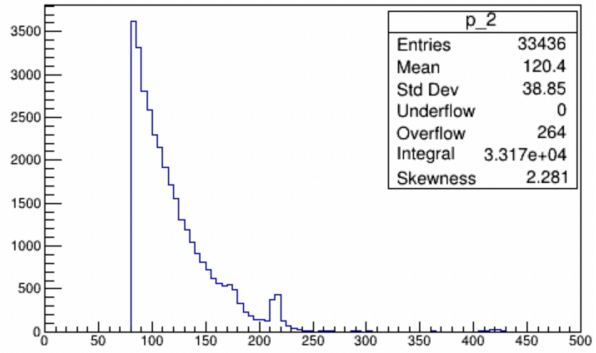


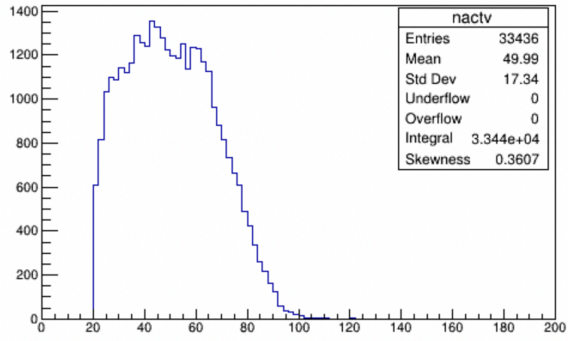
NHits > 20



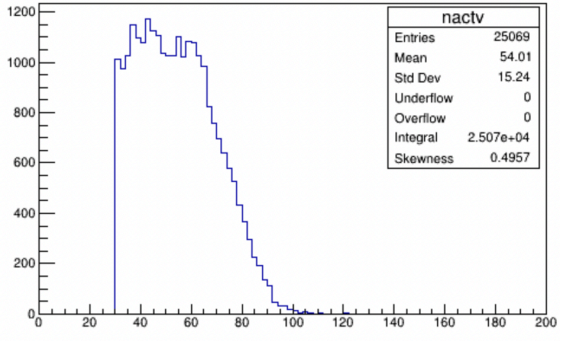
Momentum (Mev/c)

Cosmics Dataset: An oversampling issue

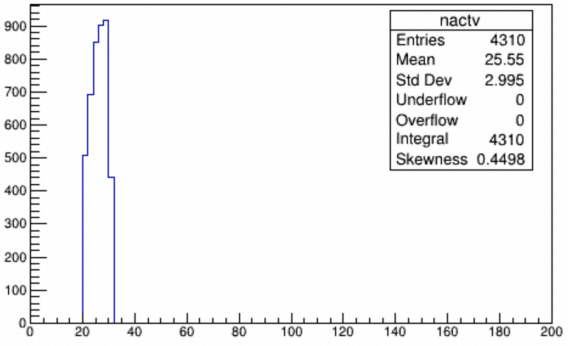
- Ran reconstruction on some of the Cosmics + 1BB digi files.
- Observed a bump in the 210-220 MeV/c momentum range of reconstructed tracks.
- We noticed that most of these tracks have 20 < nStrawhits < 30.



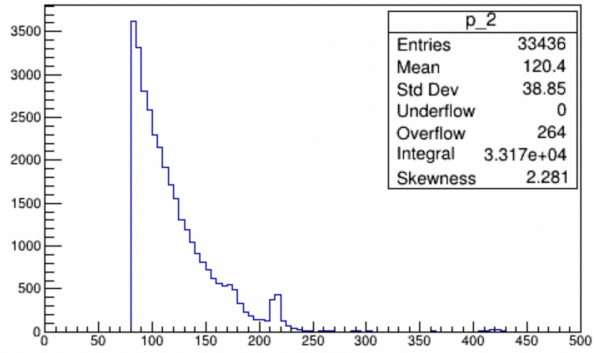
NHits > 20



NHits > 30



20 < NHits < 30



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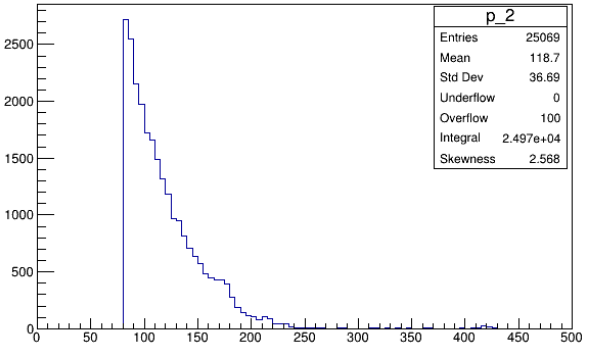

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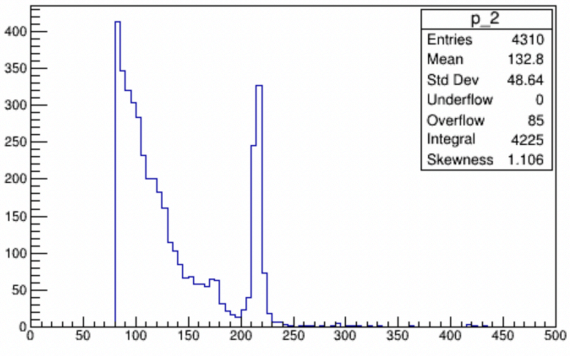

Momentum (Mev/c)

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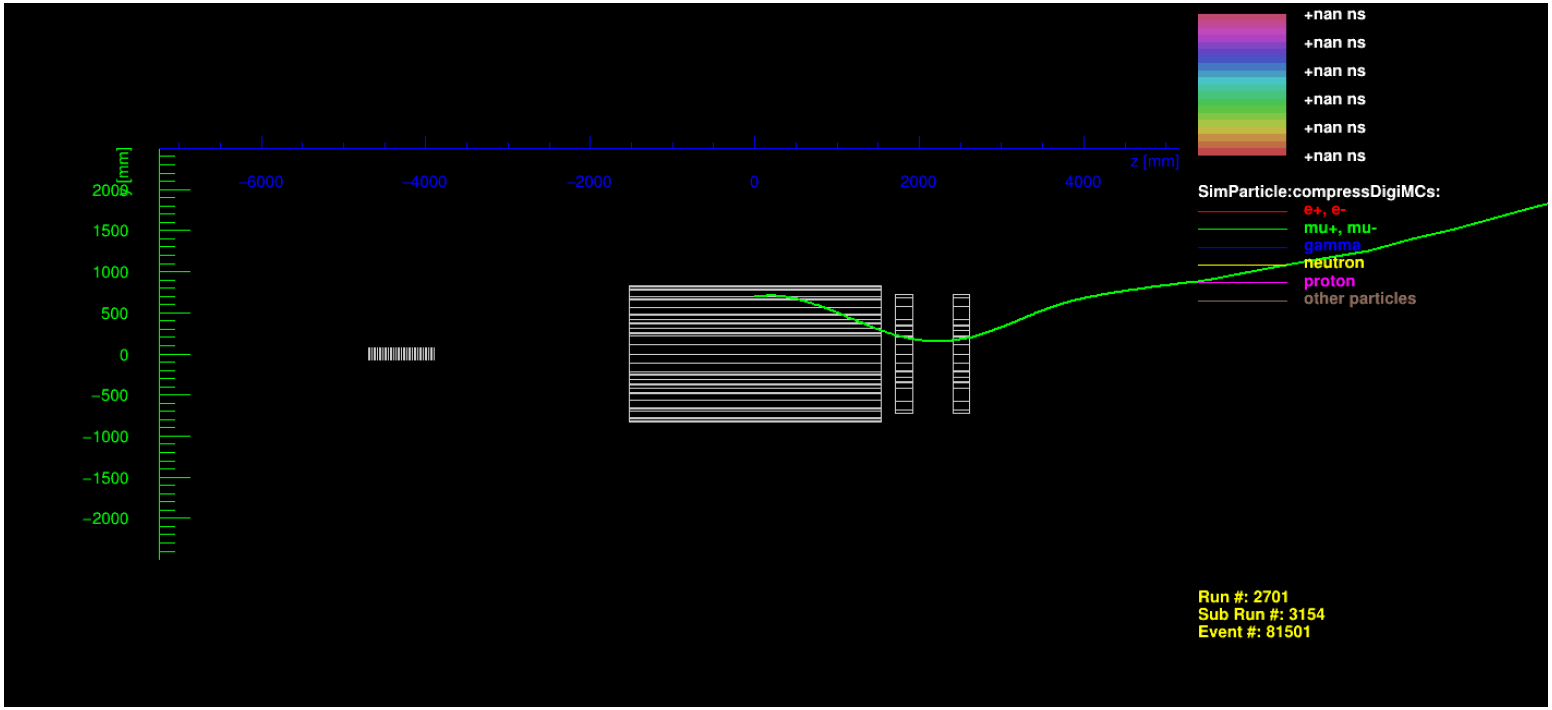
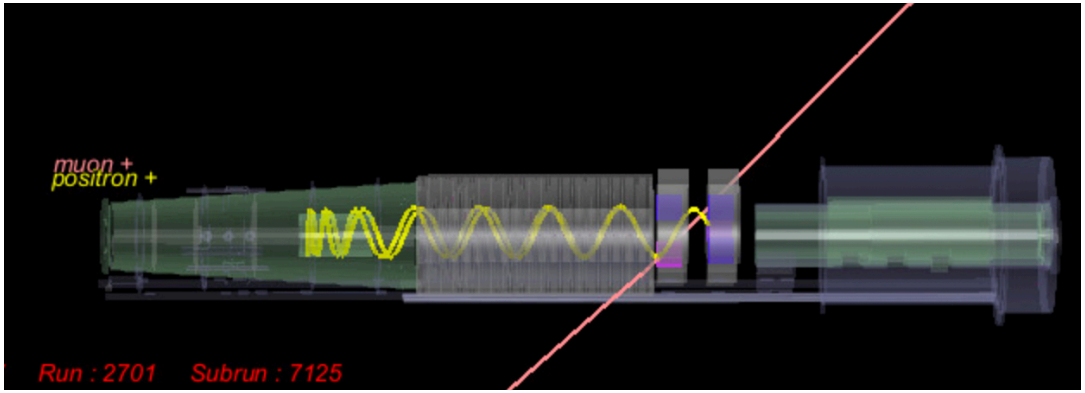
- This is an event with a cosmic muon entering from the back, not interacting with the Calorimeter and making about 20-30 hits in the Tracker.
- Such an event occurs about 30-50 times every ∼15000 events or so.

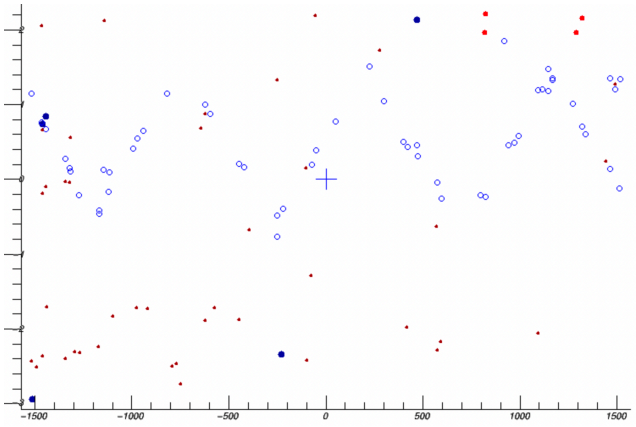


Courtesy: Y. Oksuzian

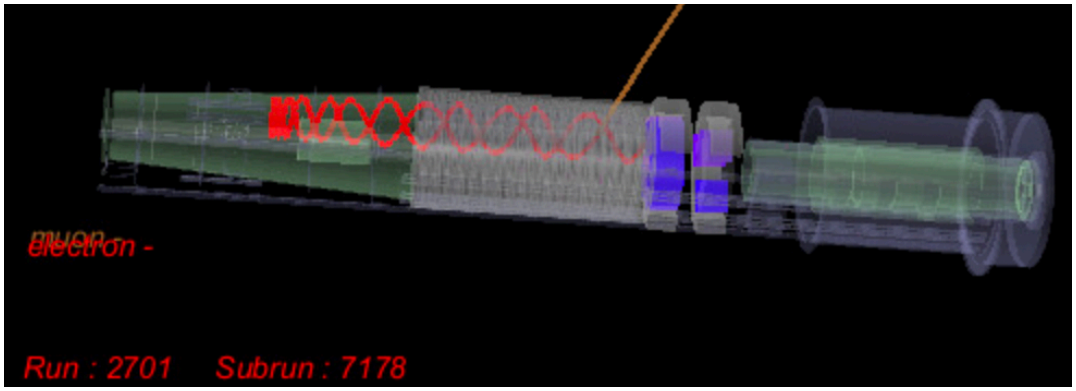
Multi-track events from Cosmics



3-D view



ϕ v/s Z view



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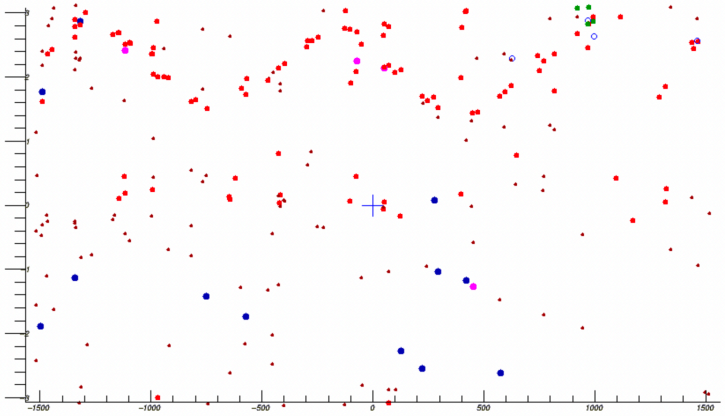

ϕ v/s Z view

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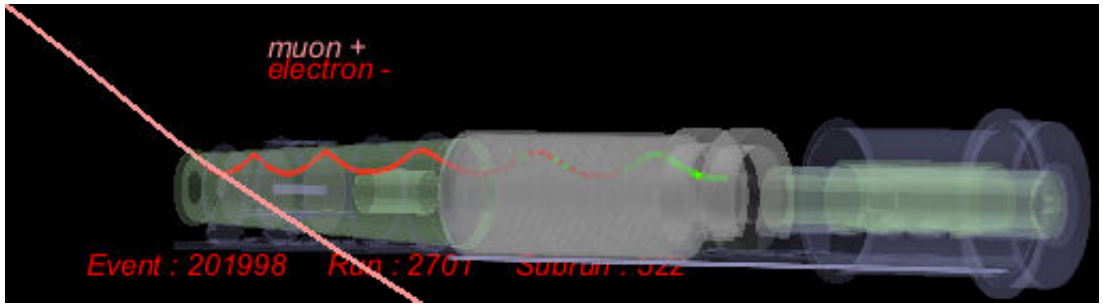
- Observed hundreds of events with a duplicate track.



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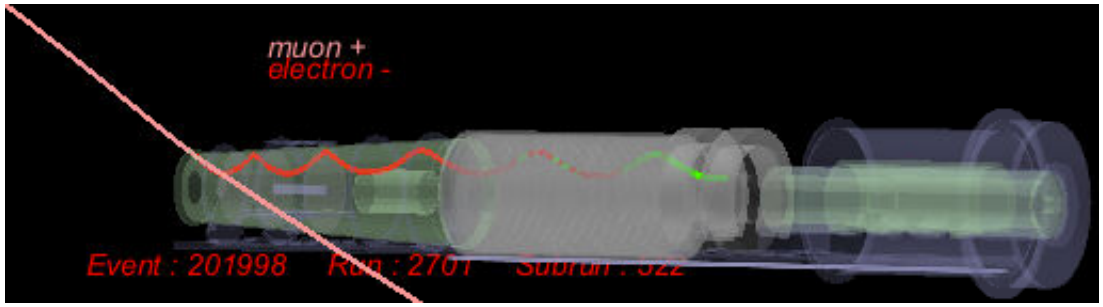
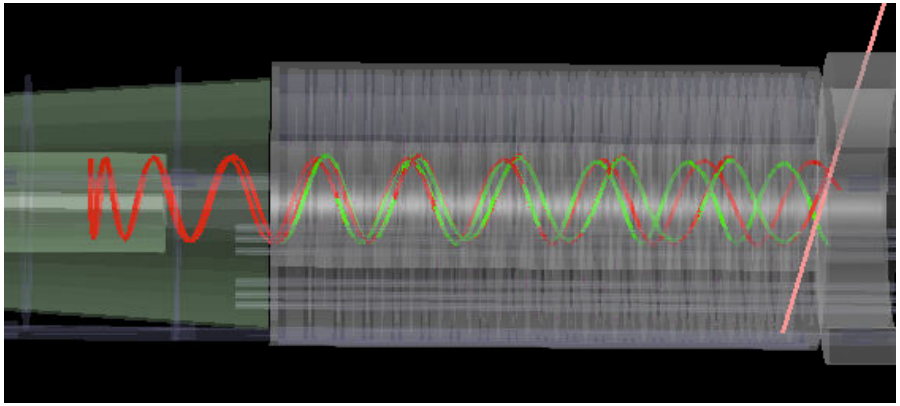


- Most of the Cosmics multi-track events are:

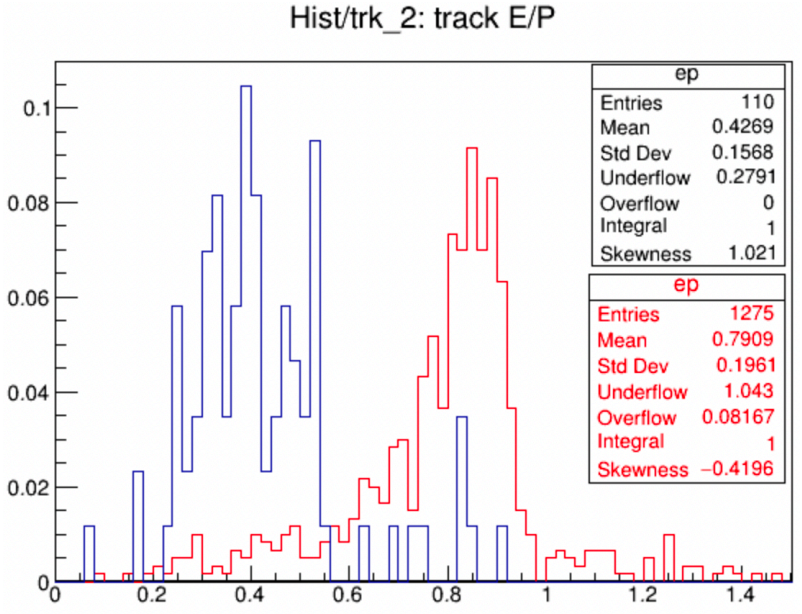
(1) Cosmic muons interacting with the calorimeter disk, producing an e^+/e^- which first travels upstream towards the ST and then returns back.

(2) Cosmic muons interacting with the ST, producing e^+'s and e^-'s.



Cosmics v/s $p\bar{p}$ annihilation multi-track events

- Only events with > 1 track considered. Each track with $p > 80$ MeV/c and $nHits > 20$ and $\chi^2/dof < 5$.
- The E/p distribution of the reconstructed tracks from Cosmics is centred around 0.8. Most are e-/e+ tracks.
- The E/p distribution of the reconstructed tracks from $p\bar{p}$ annihilation at the ST is centred around 0.4. Most of the tracks here are pions and muons.
- A selection cut of $E/p < 0.6$ should help to eliminate many of the tracks from Cosmics.



Red: Cosmics

Blue: $\bar{p}$

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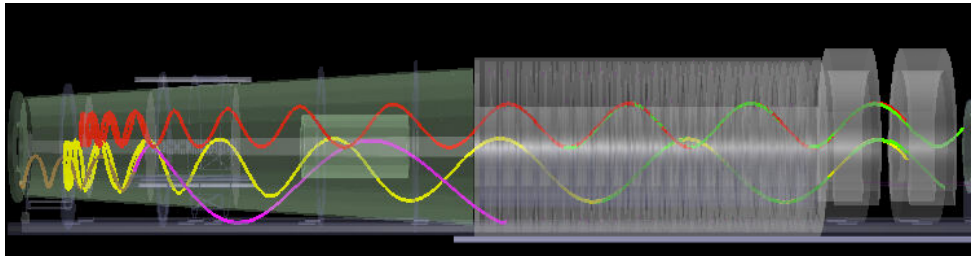
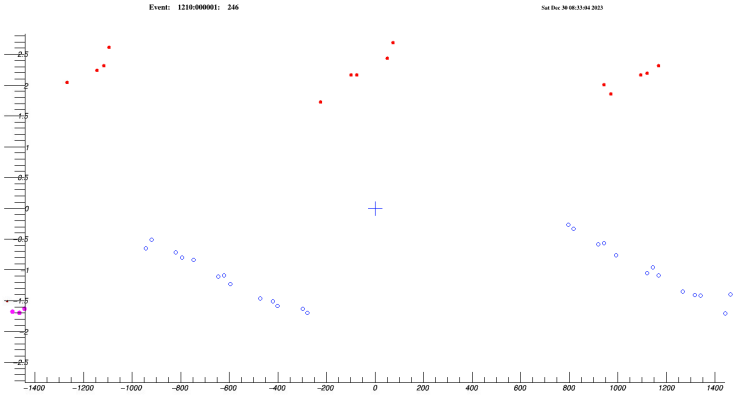
- Next task: Estimate the contribution of Cosmics to the multi-track event signature expected from the $\bar{p}$ background.

Extra slides

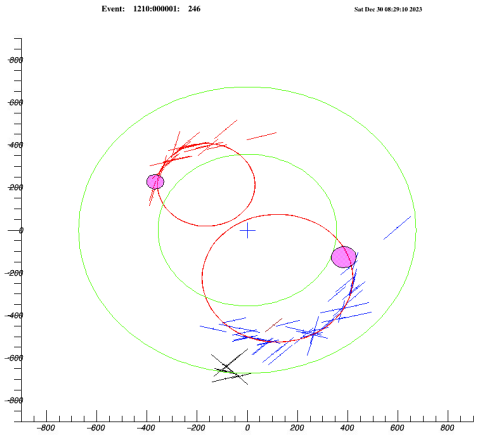
Pbar1b0 Event 1210:0:246 (E/p > 0.8)

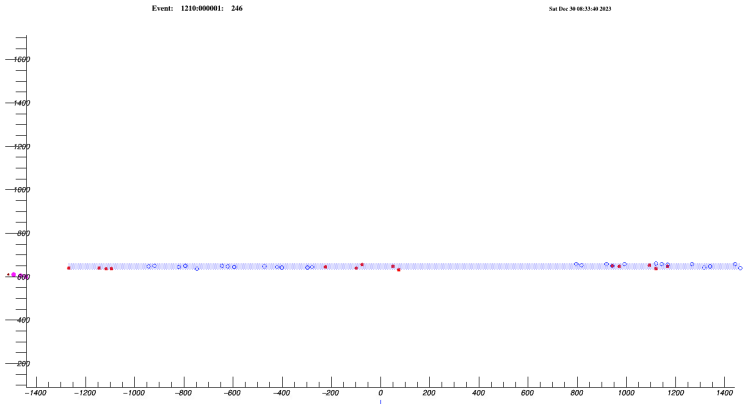


3-D view: e- and e+ tracks



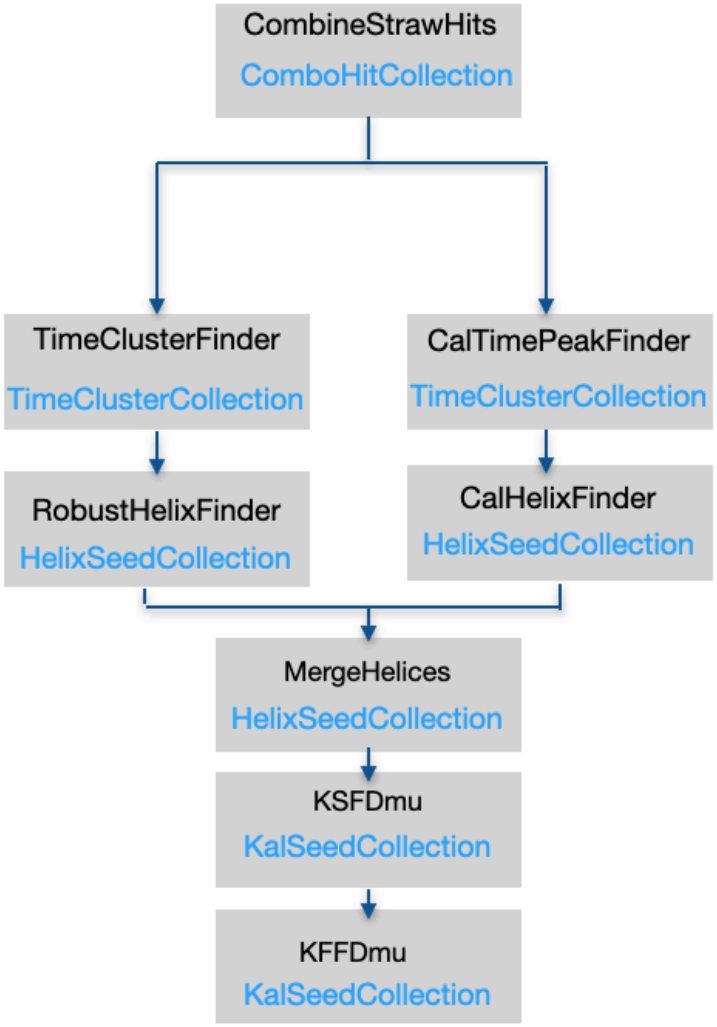
ϕ v/s z



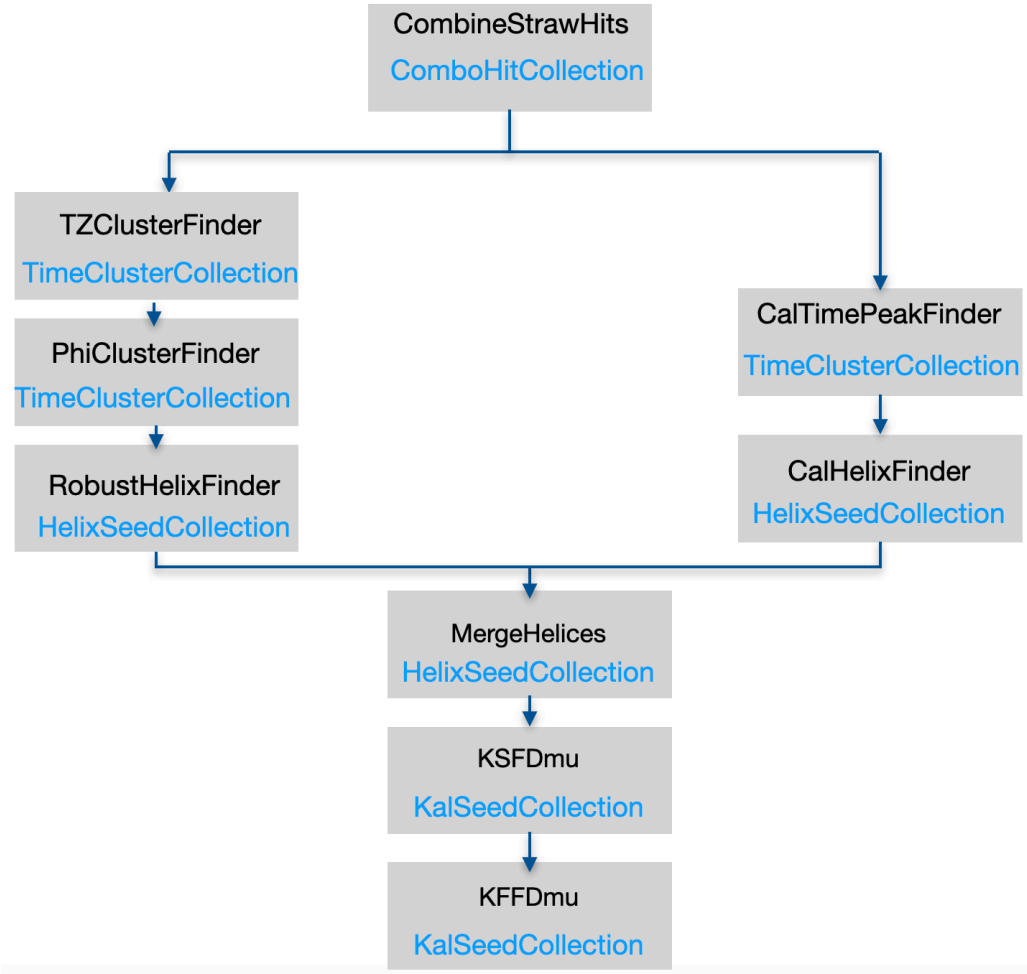


Time v/s z

Default Mu2e Offline v/s New Reconstruction workflow



Default reconstruction chain



New Reconstruction chain using the DeltaFinder, TZFinder and PhiClusterFinder

$\Delta\phi$ distribution for single interaction $p\bar{p}$ annihilation events

- The events with two output time clusters after the PhiClusterFinder stage were used to fill the above histogram.

$$\Delta\phi = \phi_1 - \phi_2$$

- Studying the $\Delta\phi$ distributions we decided to set a $\Delta\phi_{min} = 1.5$ rad cut to select events for the two tracks per event reconstruction.

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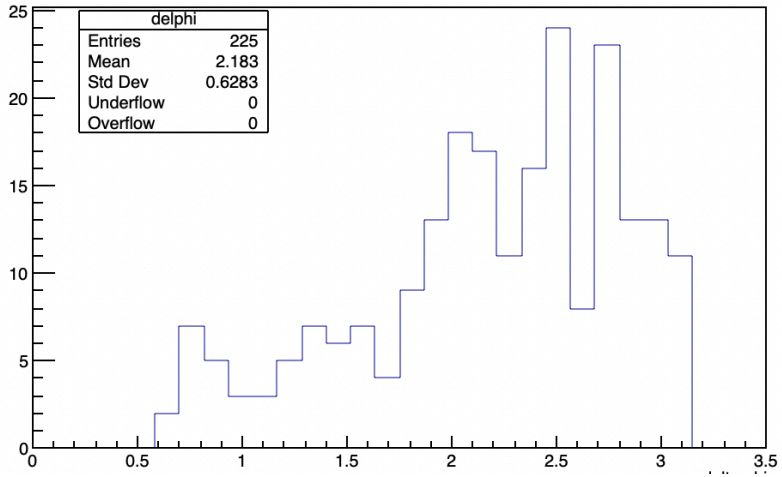

$p\bar{p}$ data sample (10^4 generated events)

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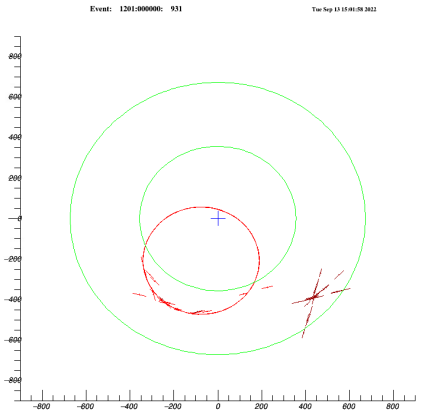
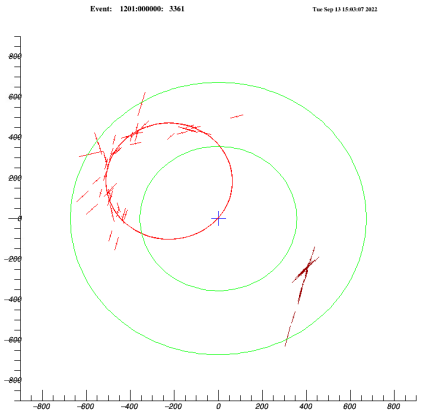
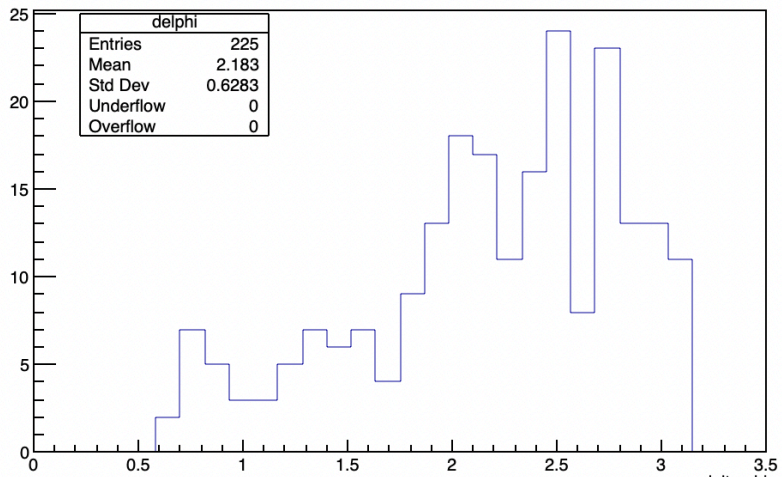


Event : 931, $\Delta\phi$ = 1.5 rad



Event : 3361, $\Delta\phi$ = 3.05 rad

$\Delta\phi$ comparison between $p\bar{p}$ and conversion e^- events



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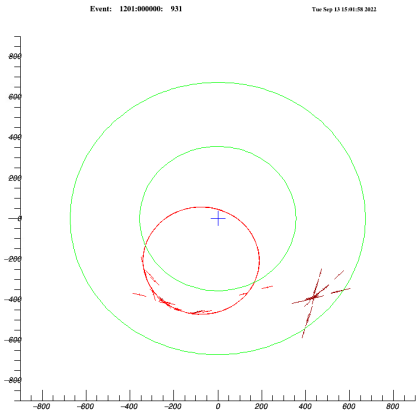

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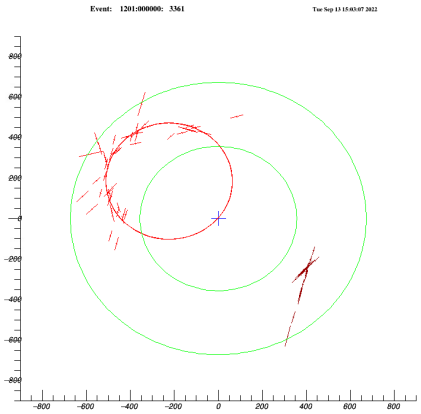

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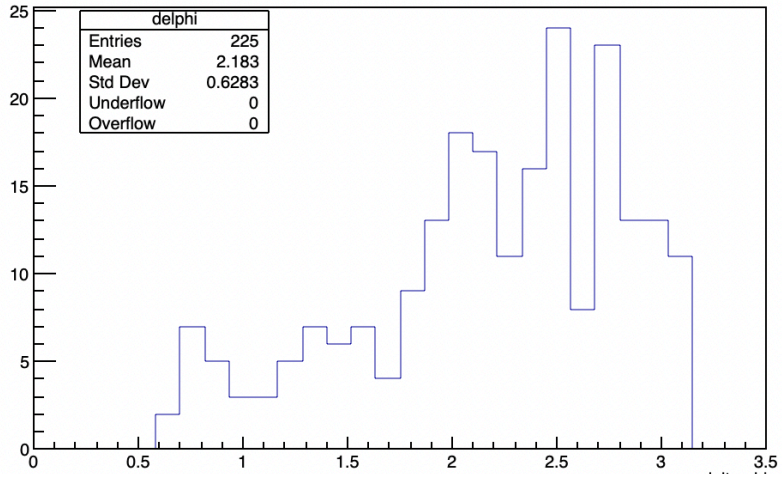
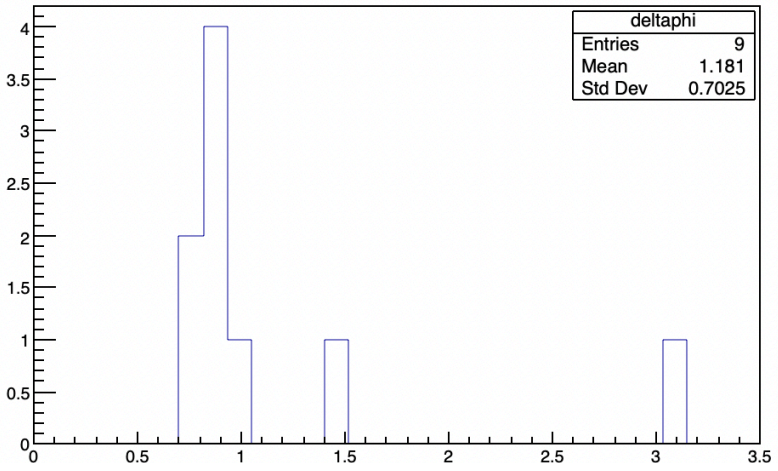


$\Delta\phi$
$p\bar{p}$ data sample (10^4 generated events)



$\Delta\phi$
Conversion e- data sample (10^4 generated events)

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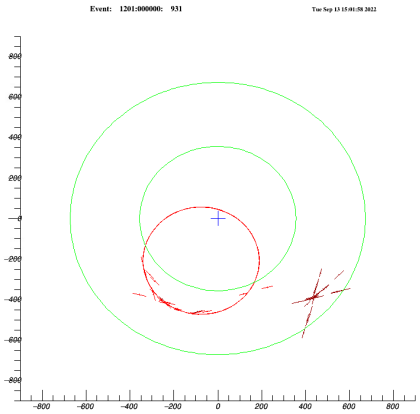

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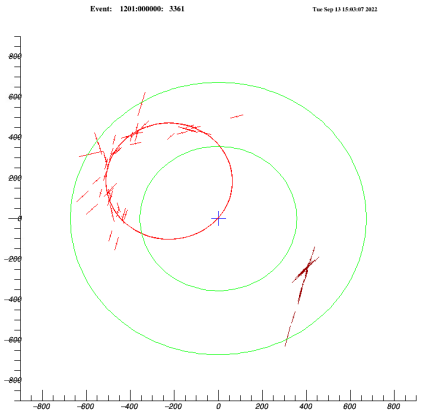

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Results with the single interaction $p\bar{p}$ annihilation at the ST events

Events with	0	1	2	3	4	5
Sim	7405	2159	381	50	4	1
TimeCluster	7913	1871	194	14	7	1
Helix	8287	1596	110	5	2	
Track	8702	1250	46	2		

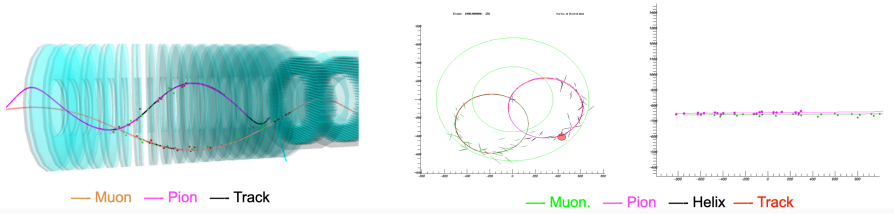
$p\bar{p}$ data with default Offline workflow

Events with	0	1	2	3	4	5
Sim	7405	2159	381	50	4	1
TimeCluster	7913	1871	194	14	7	1
Phi	8036	1685	244	23	10	1
Helix	8349	1508	132	10	1	
Track	8791	1152	55	2		

$p\bar{p}$ data with FlgBkgHits -> TimeClusterFinderDmu -> New PhiCusterFinder -> HelixFinder

Events with	0	1	2	3	4	>=5
Sim	7405	2159	381	50	4	1
TZ	7120	2564	284	23	4	
Phi	7276	2229	416	47	27	5
Helix	7677	2007	289	23	4	
Track	8187	1680	128	4	4	1

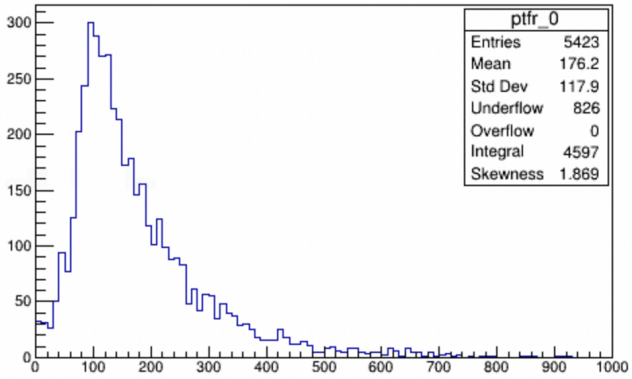
$p\bar{p}$ data with DeltaFinder -> TZFinder -> New PhiCusterFinder -> HelixFinder



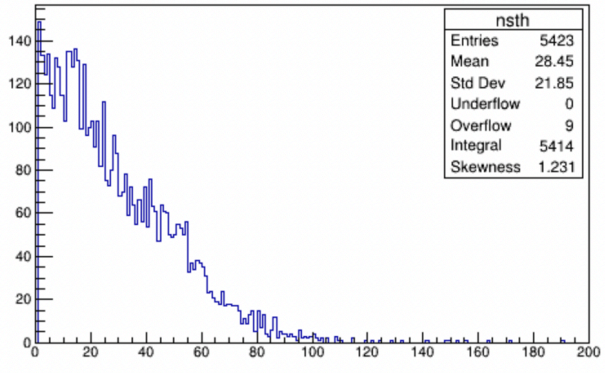
3-D and 2-D XY, tZ displays of an event with two reconstructed tracks

- Tested on 10^4 pure $p\bar{p}$ annihilation events.
- A sim particle is defined as a particle making at least 20 straw hits in the Tracker and having a momentum > 40 MeV/c. In this sample, there are 381 events with two particles each.
- The tables compare the number of events at each stage of reconstruction using the default and new chains of reconstruction
- The number of events with two helices increased from 110 to 289, number of events with two reconstructed tracks per event increased from 46 to 128 with the new reconstruction chain.

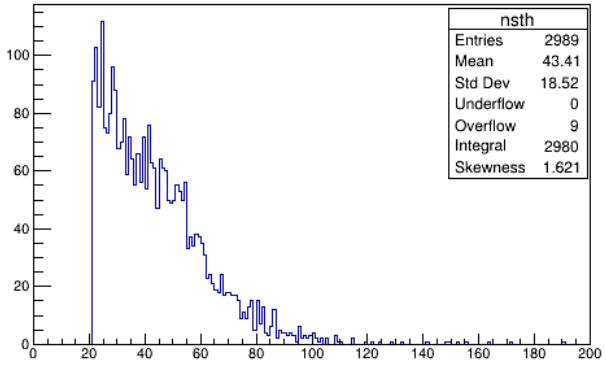
SimParticles



Momentum(MeV/c) at VD 13

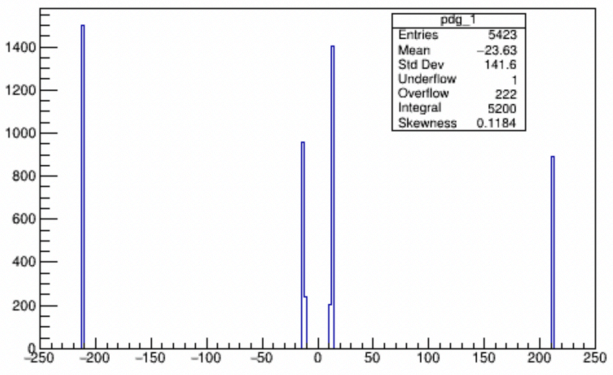


N straw hits

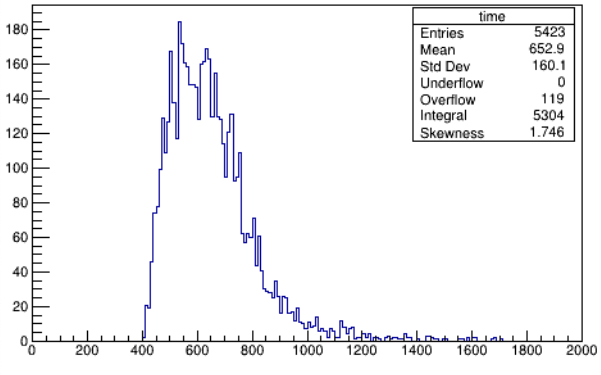


N straw hits

- 2150 events with 1 sim particle having > 20 straw hits
- 364 events with 2 sim particles each having > 20 straw hits
- 50 events with 3 sim particles.
- But only 1252 events pass the TC filter of the standard TPR trigger path.



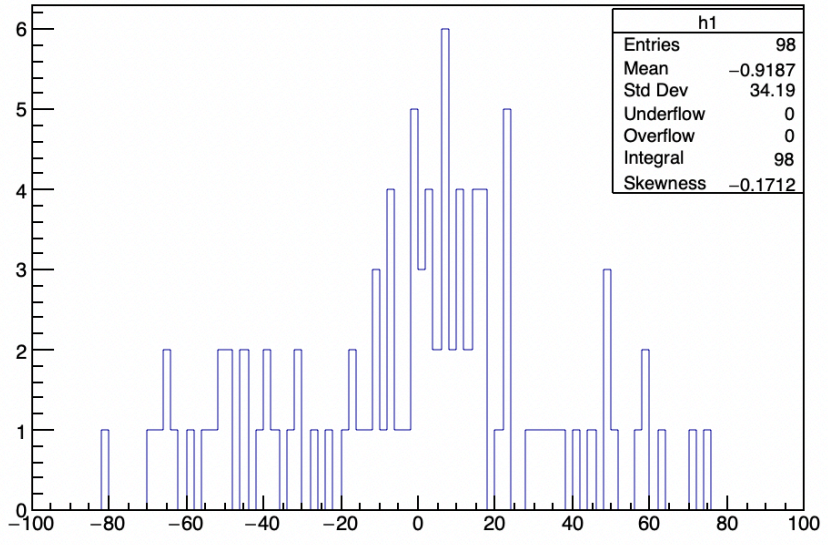
PDG code



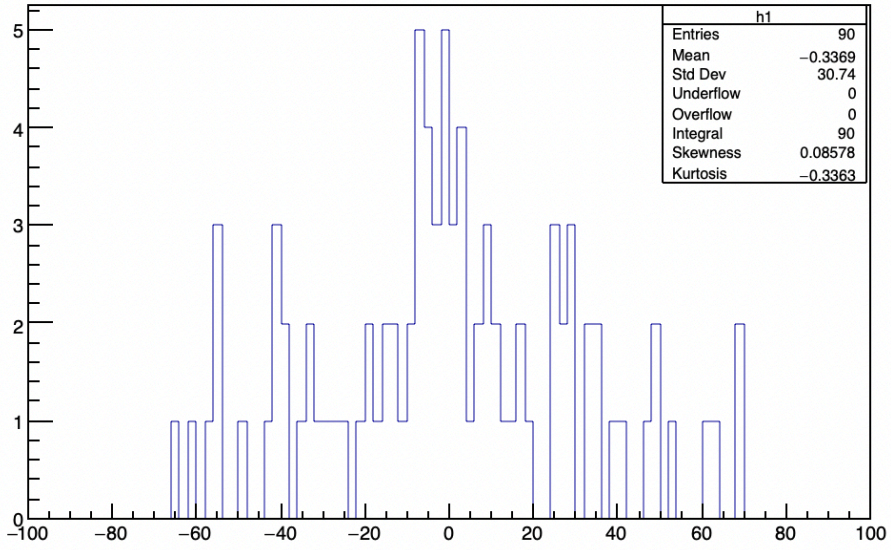
Time (ns)

Δt between the tracks of two-track events

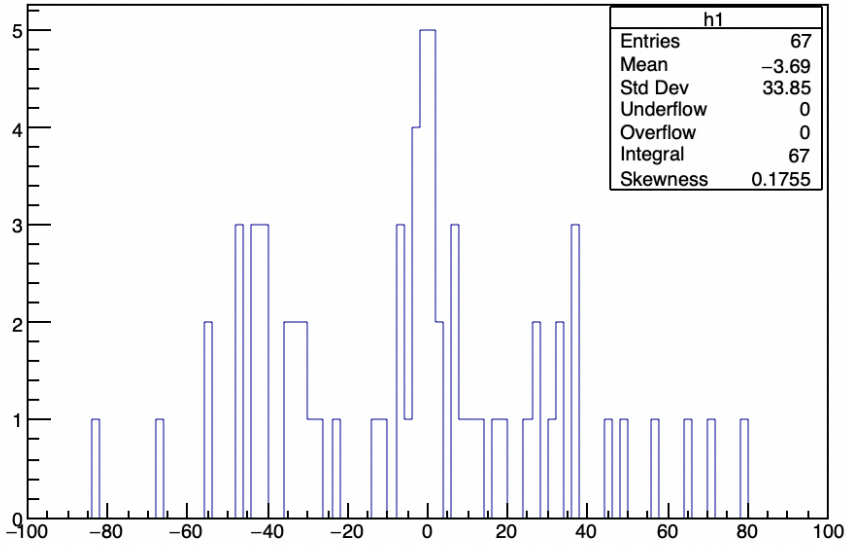
- Given here are the Δt distributions for two-track final state $p\overline{p}$ annihilation events where each reconstructed track has a momentum > 80 MeV/c.
- Tracks from the same $p\overline{p}$ interaction could be close in time, but could also be up to 100 ns apart.
- The events with track hits separated in time make different time clusters.



Δt (Pure $p\overline{p}$ events)



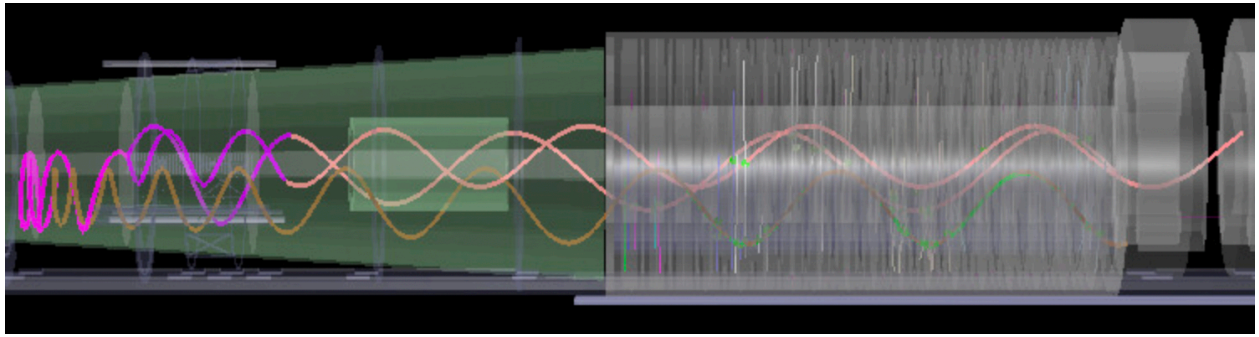
Δt ($p\overline{p}$ + 1BB pile-up events)

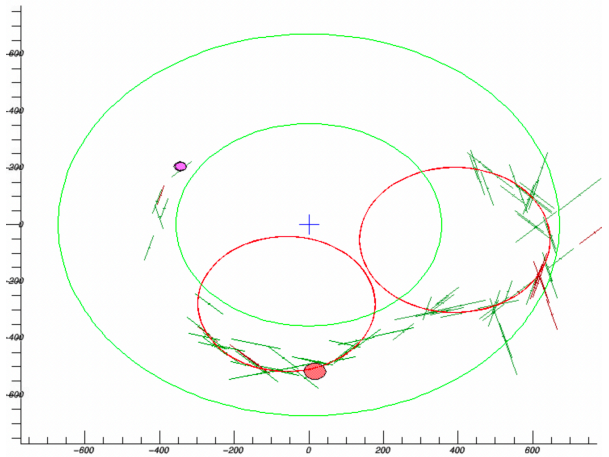


Δt ($p\overline{p}$ + 2BB pile-up events)

Some examples of two-track events with large Δt between the particle tracks

Event: 527

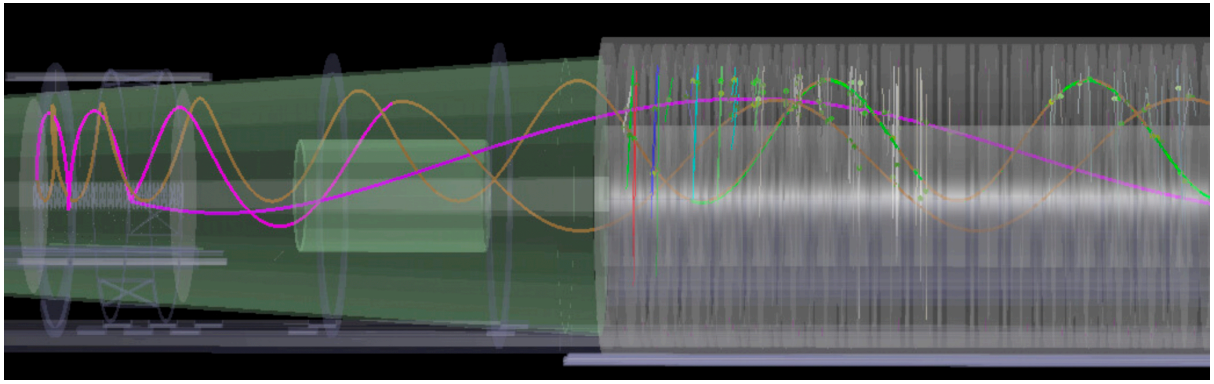


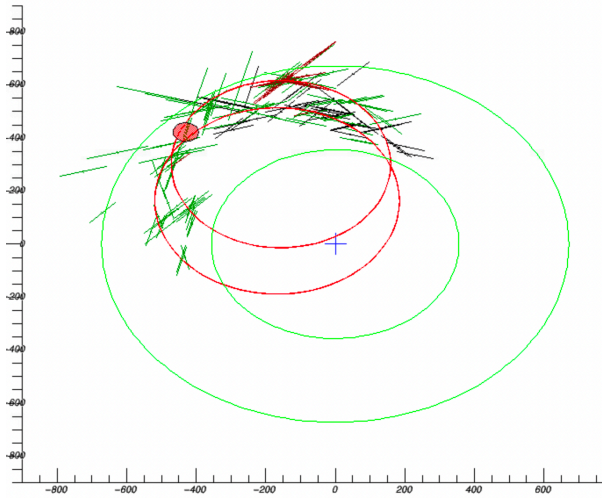


$\Delta t = 63ns$

track 1 = μ^+, track 2 = $\mu-$

Event: 676





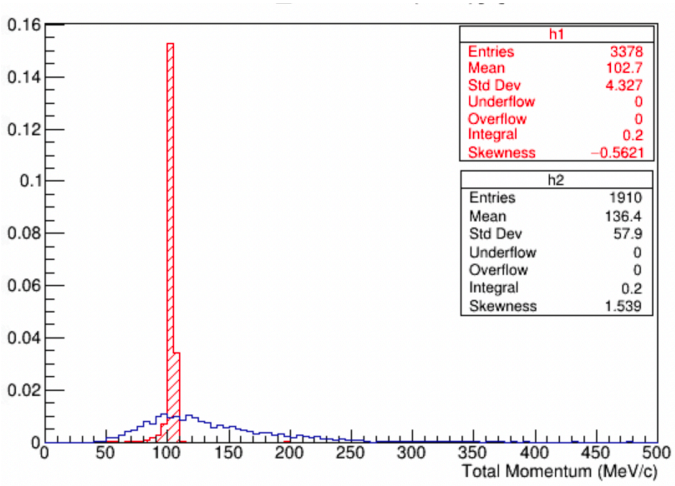
$\Delta t = 32ns$

track 1 = μ^-, track 2 = $\mu-$

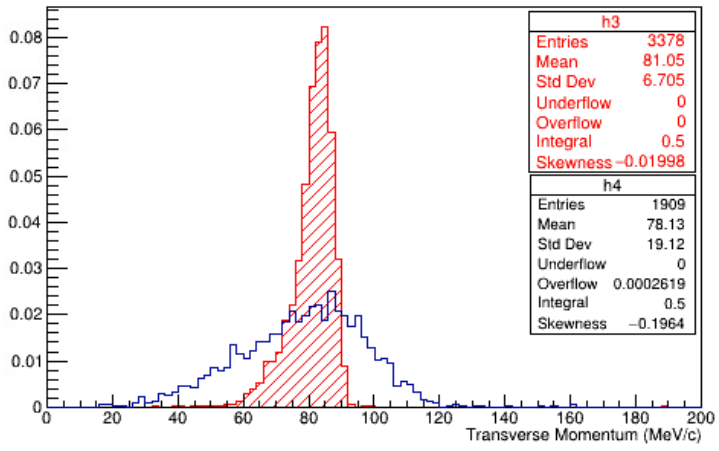
XY view

$p\bar{p}$ annihilation event with two reconstructed tracks
Green = Muon, Pink = Pion in 3-D view
Red = Reconstructed track in 2-D view

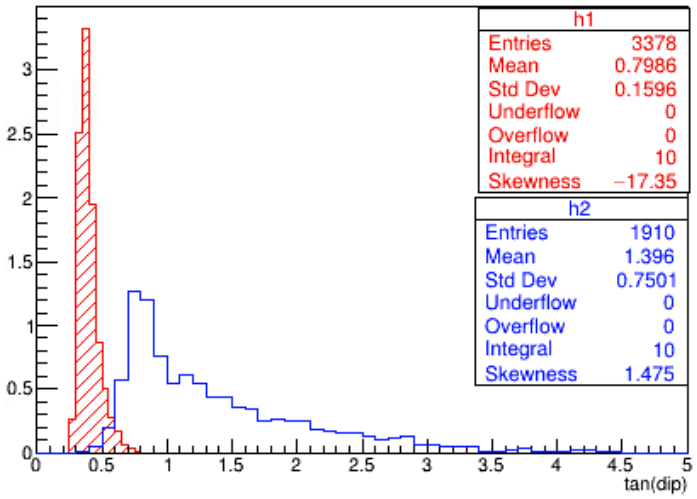
Comparing single interaction $p\bar{p}$ annihilation with CE events



Total momentum



Transverse momentum

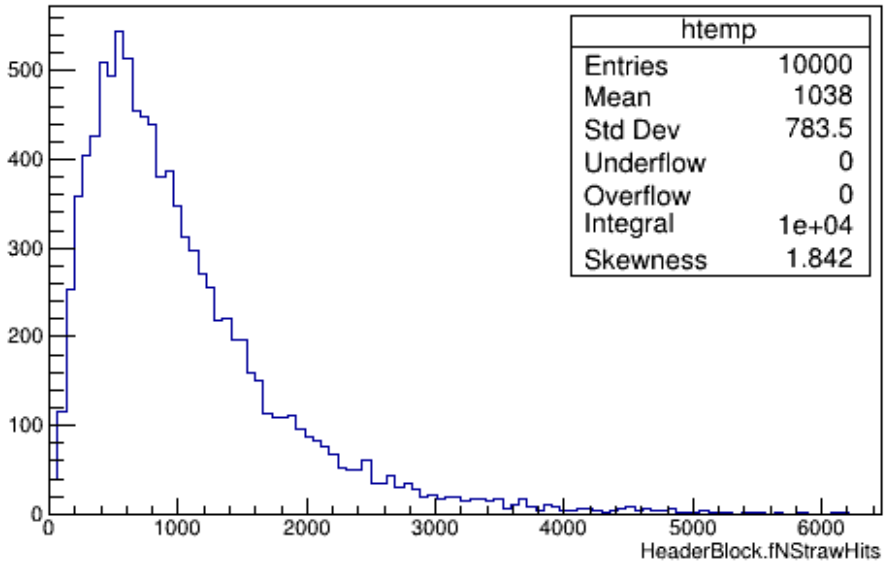


tan(λ)

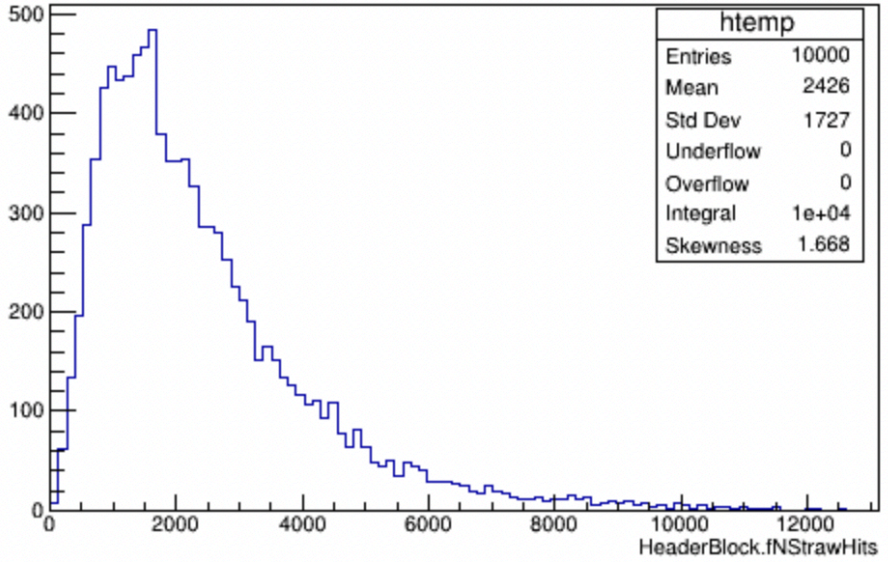
— Conversion electron
— $p\bar{p}$ annihilation

- Given here are all the reconstructed tracks with no quality cuts.
- Most of the reconstructed tracks from $p\bar{p}$ annihilation are pions and muons, as expected.

$p\bar{p}$ annihilation + pileup data samples

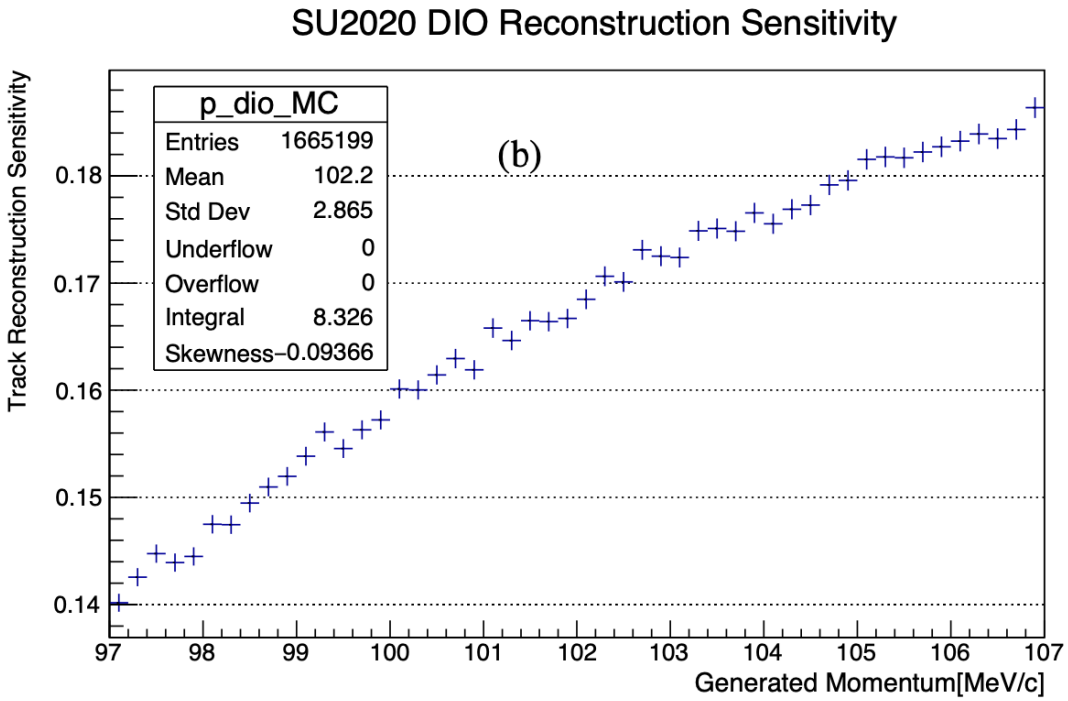


Number of Straw Hits
$p\bar{p}$ + 1BB data sample



Number of Straw Hits
$p\bar{p}$ + 2BB data sample

- We have generated 10^4 $p\bar{p}$ annihilation + 1BB and 2BB pileup data samples respectively.
- The fcl files and dataset locations can be found at https://github.com/Mu2e/pbar2m.
- The number of straw hits and combo hits per event are as expected for a data sample with pile-up.



Track reconstruction efficiency, defined as the ratio of the number of single electron events with tracks passing all selections over the number of generated events, is a function of the track momentum