A data-driven method for antiproton background measurement

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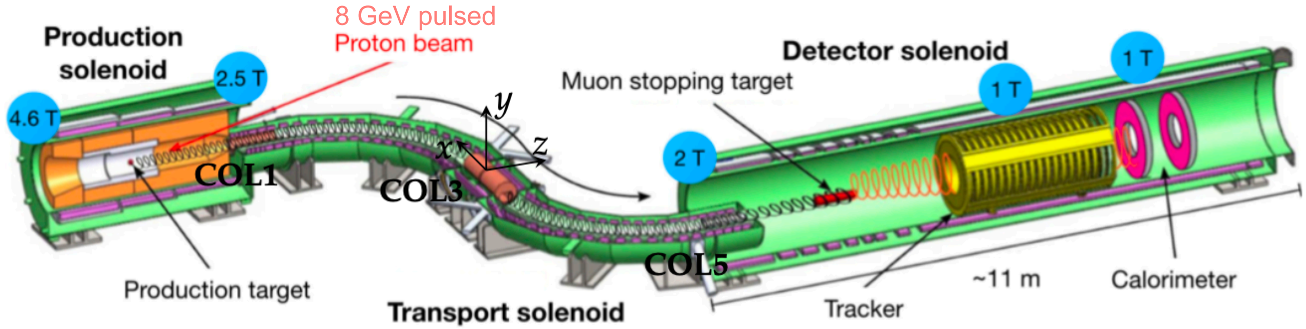
Mu2e : A quick Overview

- Goal : Search for CLFV neutrinoless, coherent conversion $\mu^- N \rightarrow e^- N$ on an Al target.
- Present experimental limit set by SINDRUM II experiment*

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A))} < 7 \times 10^{-13} (90\,\%\,CL)$$

- SM + massive neutrinos: CLFV allowed but highly suppressed ($< 10^{-50}$ BR). $\mu^- N \rightarrow e^- N$ would be clear proof for New Physics.
- Signal: Monochromatic conversion electron $E_{CE} = 104.97$ MeV for an Al nucleus.



The 8 GeV proton beam interacts with the Tungsten target and mostly produces pions. Pions decay into muons which spiral through the S-shaped Transport Solenoid. The μ^- beam will stop in the stopping target (ST) in the Detector Solenoid, where the conversion process to e^- may occur.

*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

Antiproton background

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmics	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

Background summary using 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 Production Solenoid can annihilate in the ST producing signal-like e^-s. It can also cause delayed RPC.
- Background induced by $\overline{p}$ cannot be efficiently suppressed by the time window cut used to reduce prompt background because $\overline{p}$s are significantly slower than other beam particles.
- Absorber elements placed at entrance and centre of the Transport Solenoid 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

Fermilab

Antiproton background

- $p\overline{p}$ annihilation at the ST can produce e^{-}s by $\pi^{0} \rightarrow \gamma\gamma$ decays followed by the photon conversions and $\pi^{-} \rightarrow \mu^{-}\overline{\nu}$ decays followed by the μ^{-}decays.

- In 10^{4} $p\overline{p}$ annihilation events, only about **0.15%** of the events contain single **electron tracks** with $\geq$ 20 straw hits and momentum in the range of 90-110 MeV/c.

- However, $p\overline{p}$ annihilation at rest in the ST can also produce events with $\geq$ 2 tracks with p $\sim$ 100 MeV/c for each track.

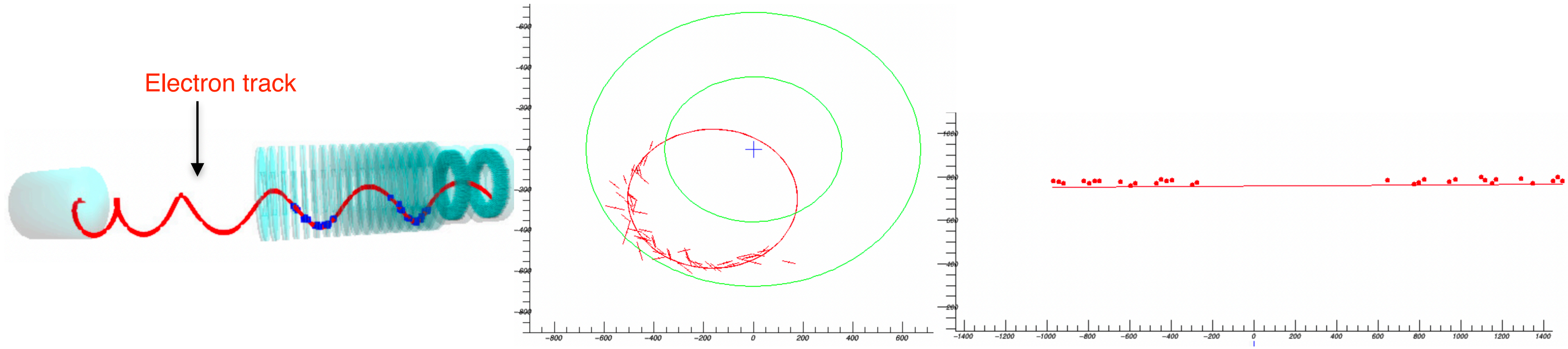
- About **3.8%** of the events contain **2 particle tracks** with $\geq$ 20 straw hits per particle.

- From simulations, we have estimated that the rate of such multi-track events is $\sim \times 500$ higher than the rate of events with 1 signal like e^{-}.

- Note: The uncertainties associated with these Branching Ratios need to be understood.

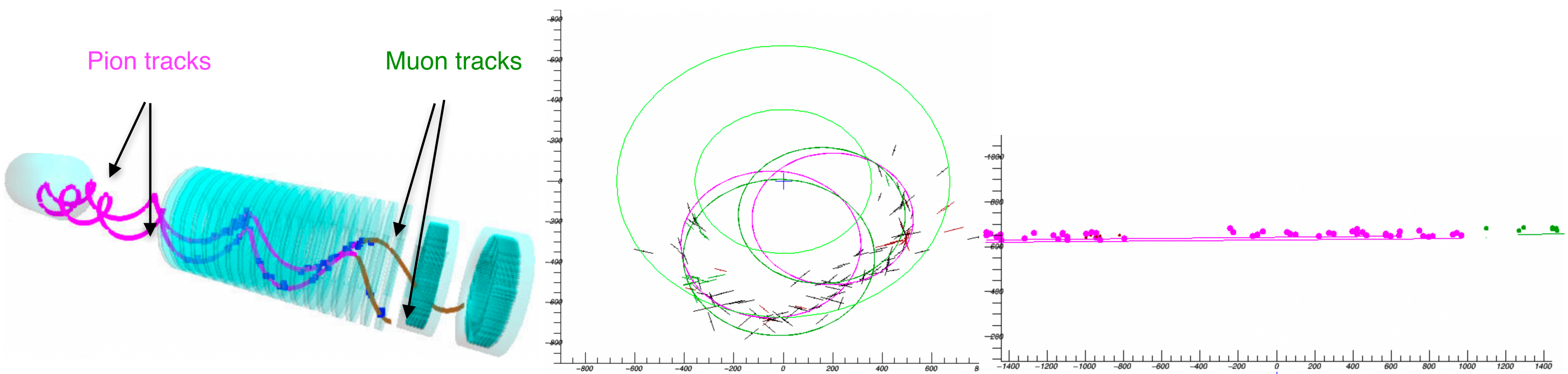
Our idea is to utilize and reconstruct the multi-track final state events and get an estimate of the CE like events by rescaling the ratio of the two final states.

$p\bar{p}$ annihilation events in the Mu2e detector



XY view   Time v/s z view

Events from $p\bar{p}$ annihilation in the ST. Red = electron, Green = Muon, Pink = Pion



XY view   Time v/s z view

Goal: Identify and reconstruct the multi-track final state events with good efficiency and estimate the $\bar{p}$ background by comparison.

Low-momentum electron identification

- The current algorithm 'FlgBkgHits' used in Offline to remove the low energy electron hits inadvertently removes a significant fraction of hits from the pion and muon tracks.

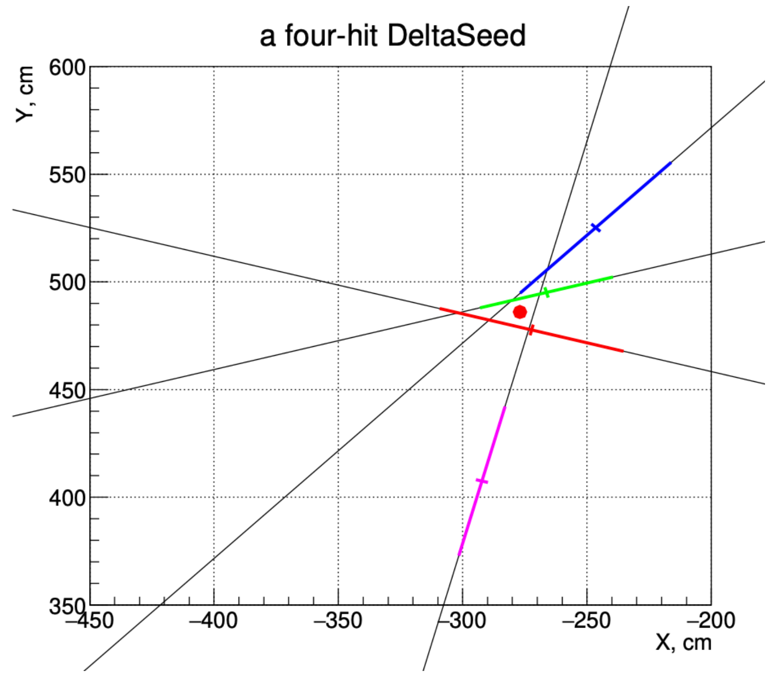
- So, many of the pion and muon hits do not even make it to the time clustering stage of reconstruction.

- A new algorithm called the DeltaFinder* (P. Murat) introduced.

- Logic of the algorithm:

  Build δe^- candidates out of "seeds": stereo intersections of the hit wires with close in time hits within one station. For low-momentum particles, a seed is better localised in space than the average of the reconstructed hit coordinates.

- With the new algorithm the rejection factor of pions and muons has been significantly reduced.

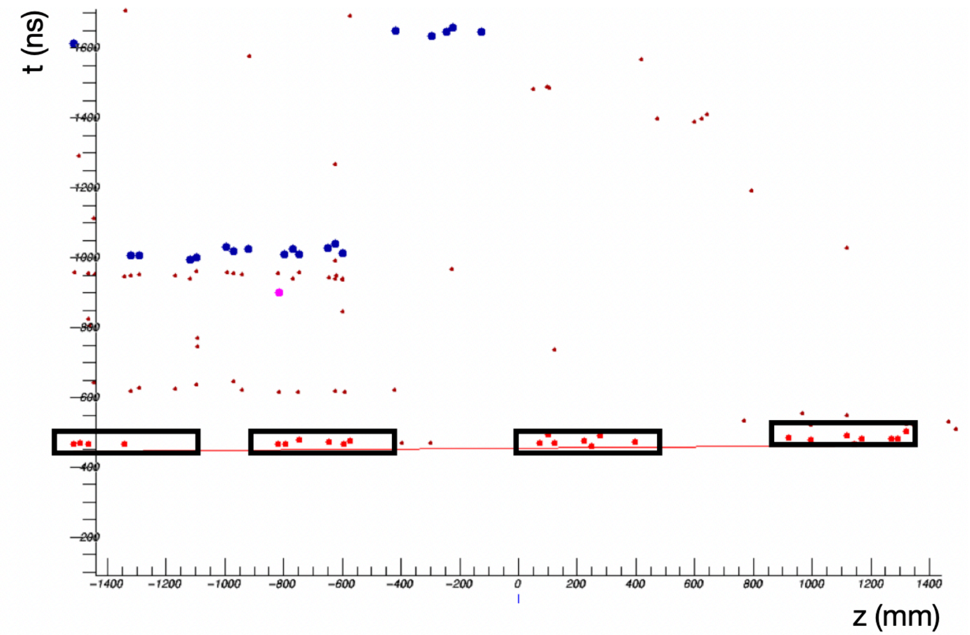


*https://mu2e-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=44935

Early Stage Time-Z Clustering

- The current TimeClusterFinder algorithm is is based on ANN hit selection. It is highly tuned for the CE search. The new algorithm TZFinder* (M.Stortini) is more agnostic, highly efficient for a wide spectrum of topologies.

- It uses the time and z information of the hits. It searches for hits that fit along a linear line in t vs. z space.

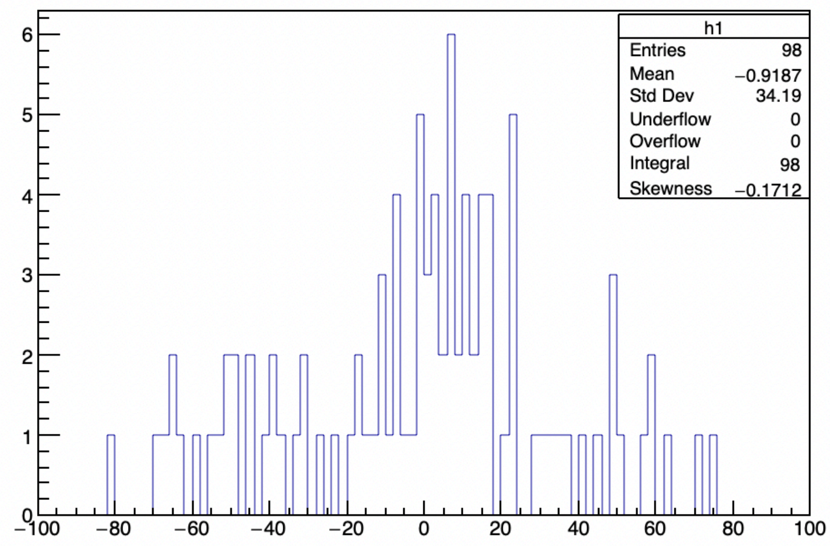


Time v/s z view of the hits in a CE + 1BB pile up event

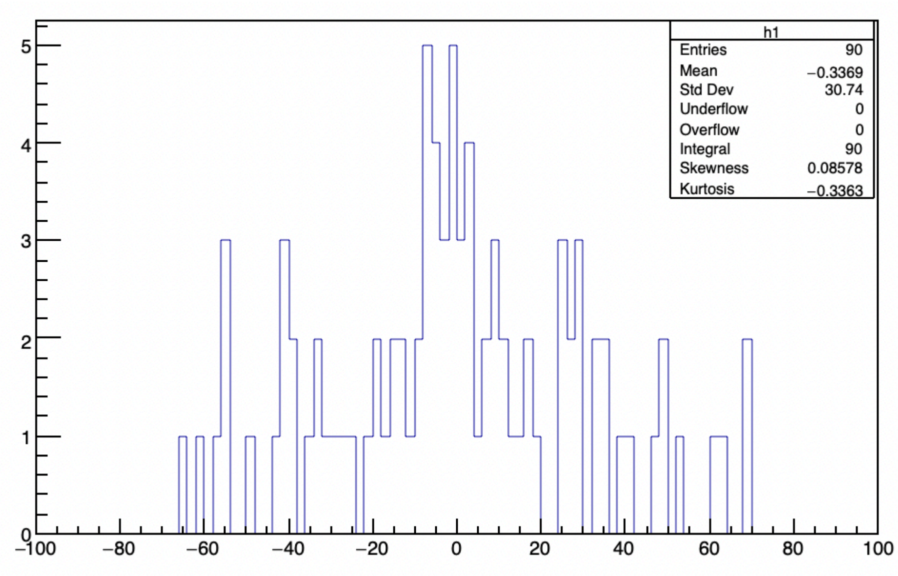
*https://mu2e-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=43999

Δt between the tracks of two-track events

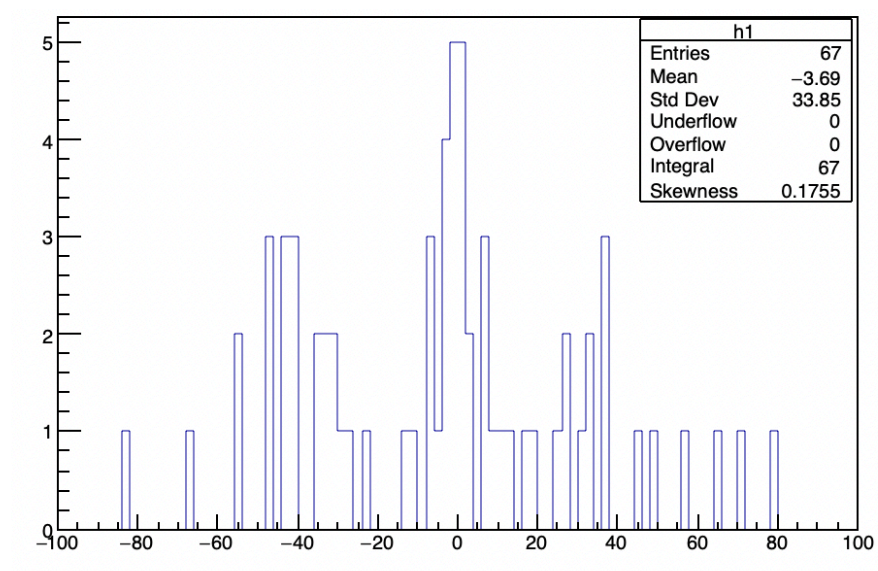
- Given here are the Δt distributions for two-track final state $p\bar{p}$ annihilation events where each reconstructed track has a momentum > 80 MeV/c.
- Tracks from the same $p\bar{p}$ interaction could be close in time, but could also be up to 100 ns apart.
- The events with track hits separated in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



Δt (Pure $p\bar{p}$ events)



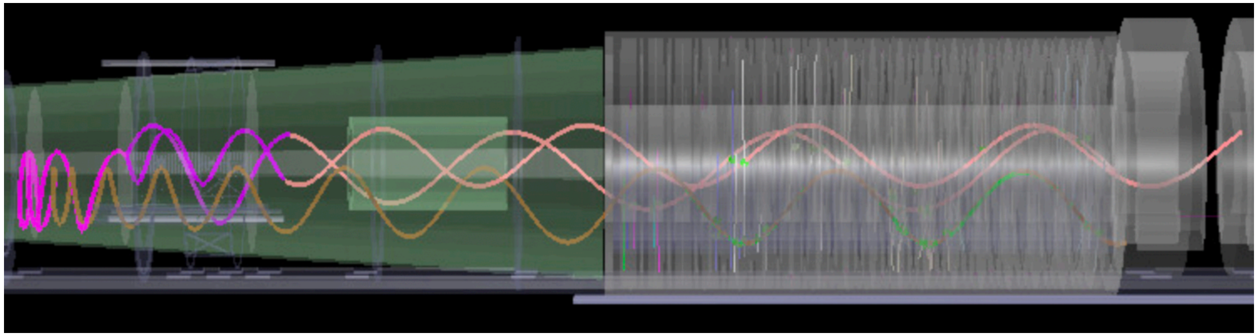
Δt ($p\bar{p}$ + 1BB pile-up events)

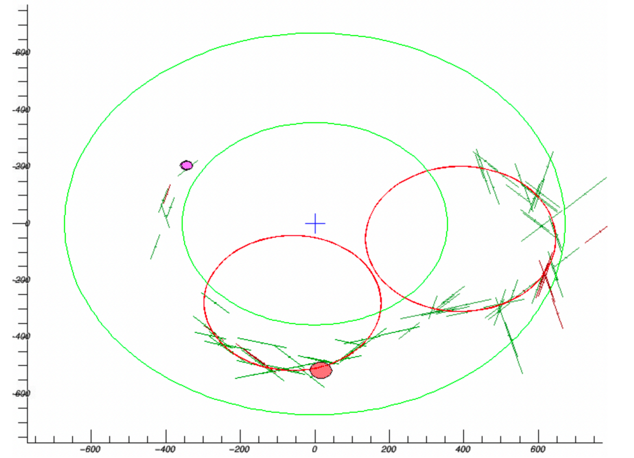


Δt ($p\bar{p}$ + 2BB pile-up events)

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

Event: 527

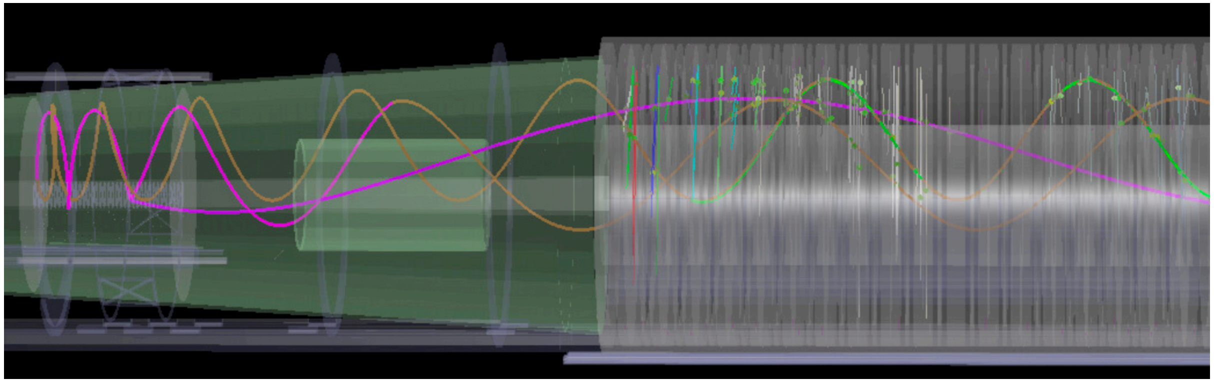


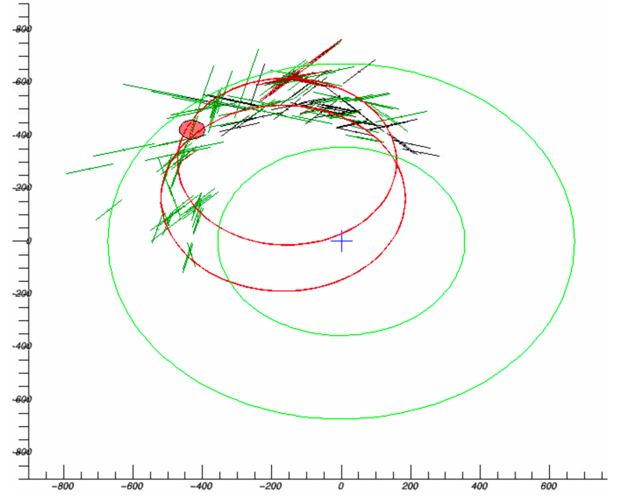


$\Delta t = 63ns$

track 1 = μ^+, track 2 = $\mu-$

Event: 676





$\Delta t = 32ns$

track 1 = μ^-, track 2 = $\mu-$

XY view

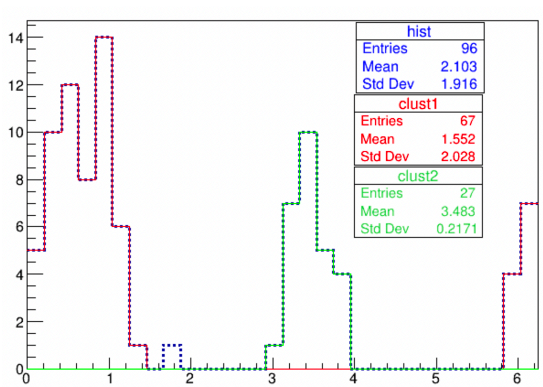
$p\overline{p}$ annihilation event with two reconstructed tracks

Green = Muon, Pink = Pion in 3-D view

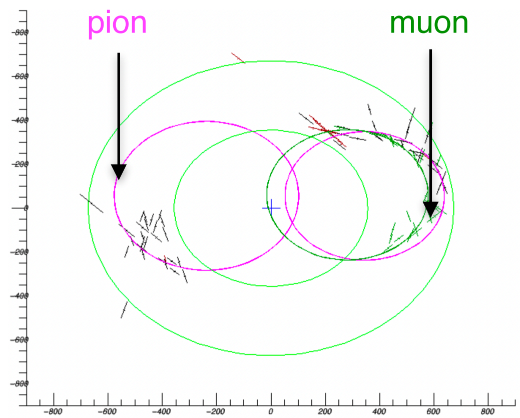
Red = Reconstructed track in 2-D view

Early Stage Hit Phi Clustering

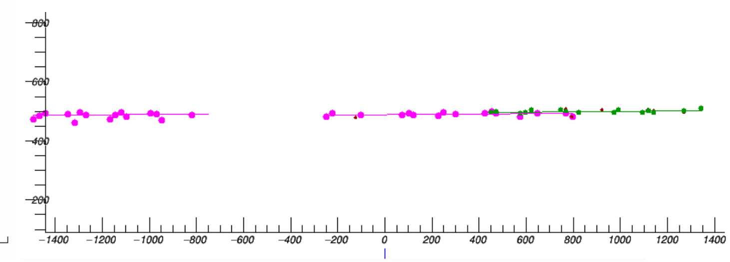
- Aim: To reconstruct the events where the tracks are within one time cluster.
- In some of these events, hits from the different tracks could be well separated in ϕ.
- We developed a ϕ clustering algorithm to group hits of a time cluster based on their ϕ distribution.



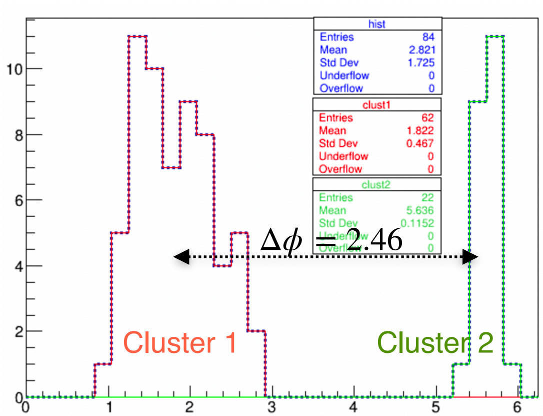
$\Delta\phi$ = 2.96 rad



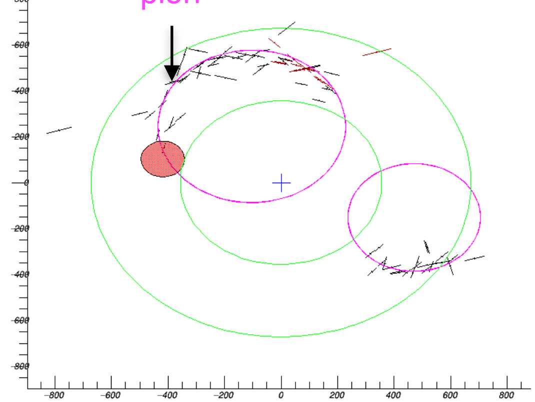
XY view



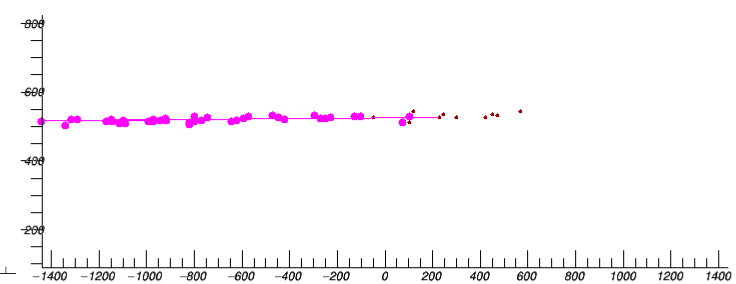
Time v/s z view



$\Delta\phi$ = 2.46 rad

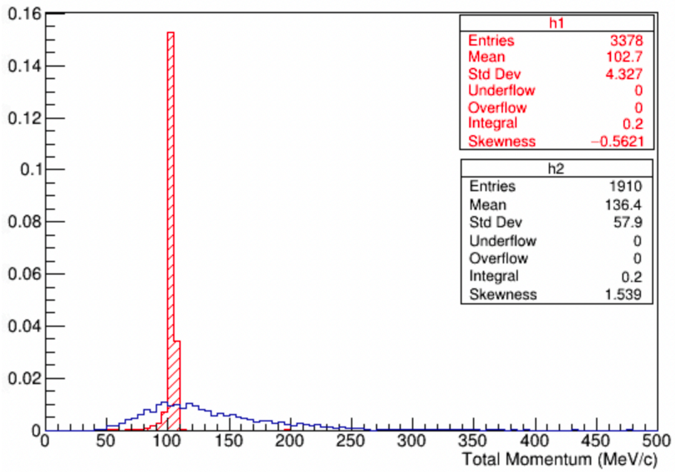


XY view

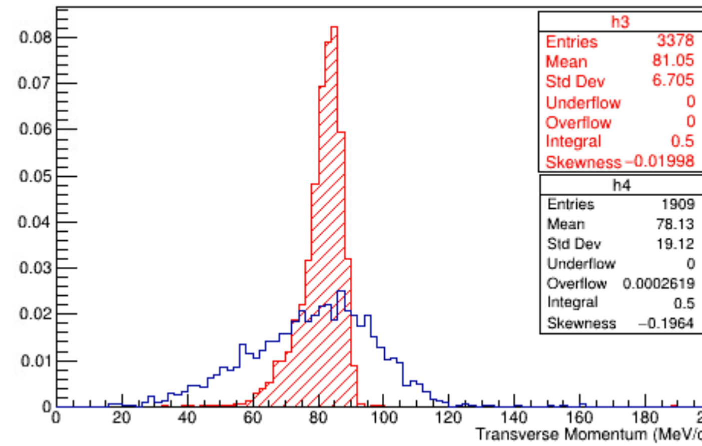


Time v/s z view

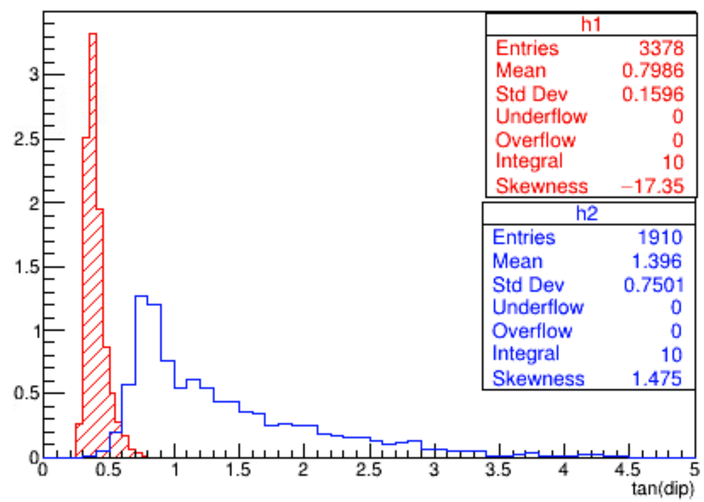
Comparing single interaction $p\bar{p}$ annihilation with CE events



Total momentum



Transverse momentum



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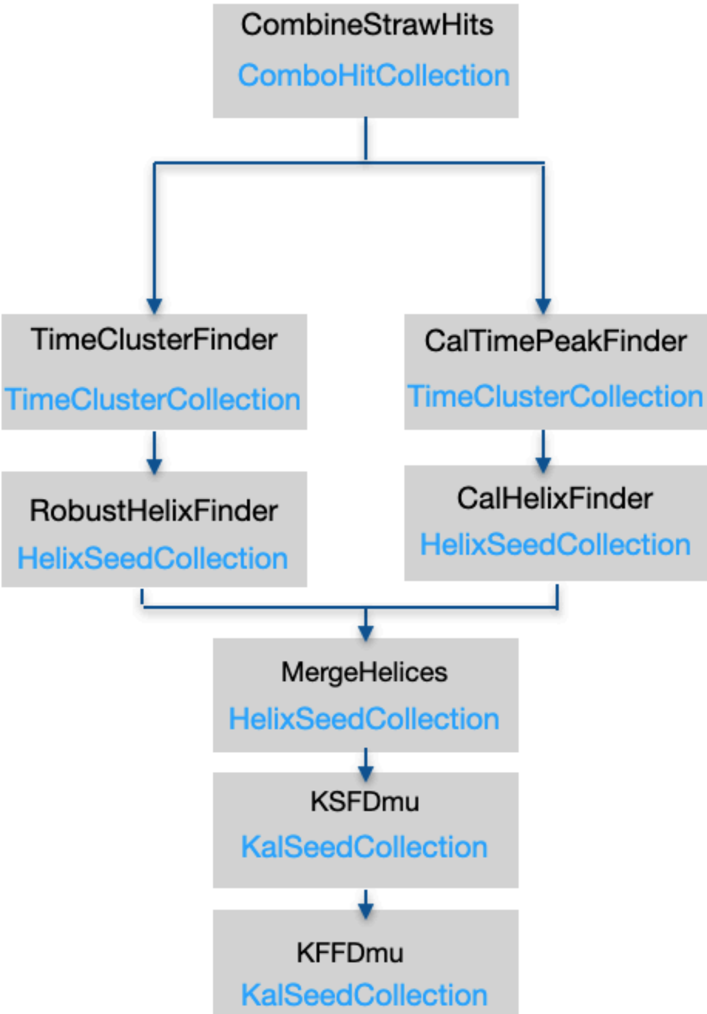
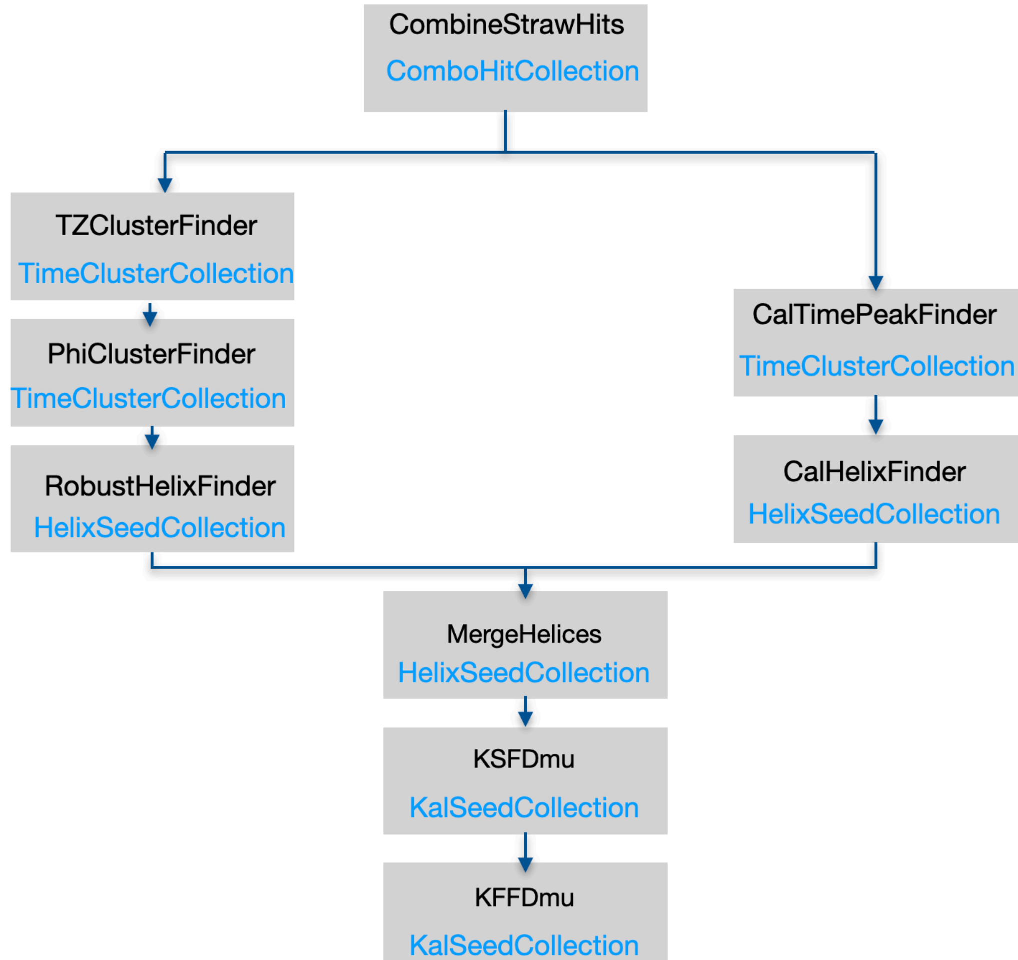
— Conversion electron
— $p\bar{p}$ annihilation

- 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.

Default Mu2e Offline v/s New Reconstruction workflow

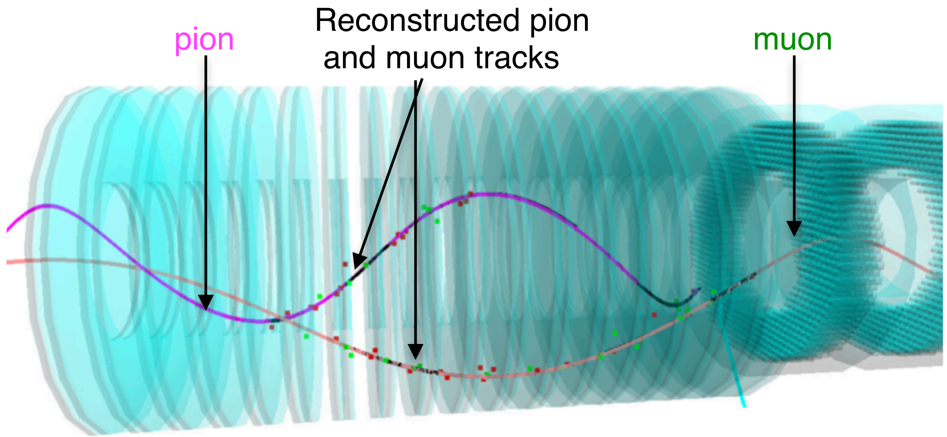


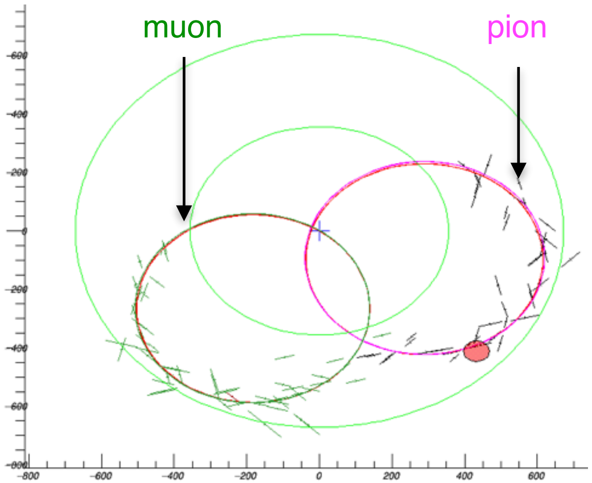
Default reconstruction chain



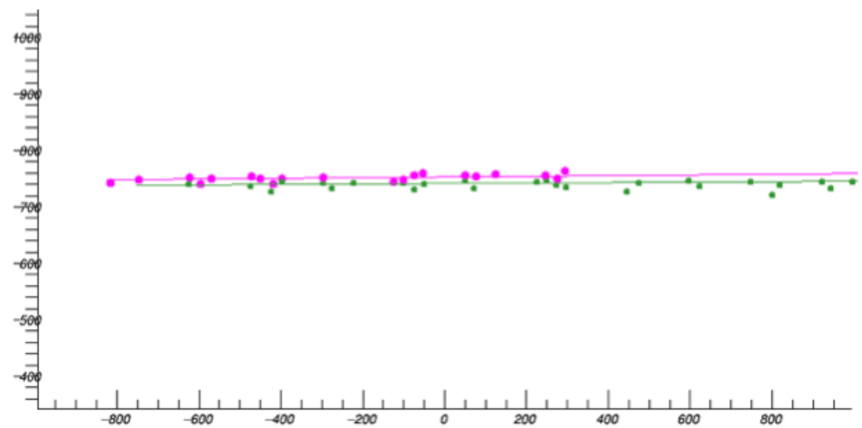
New Reconstruction chain using the DeltaFinder, TZFinder and PhiClusterFinder

Preliminary results (single interaction $p\bar{p}$ annihilation events)





XY view



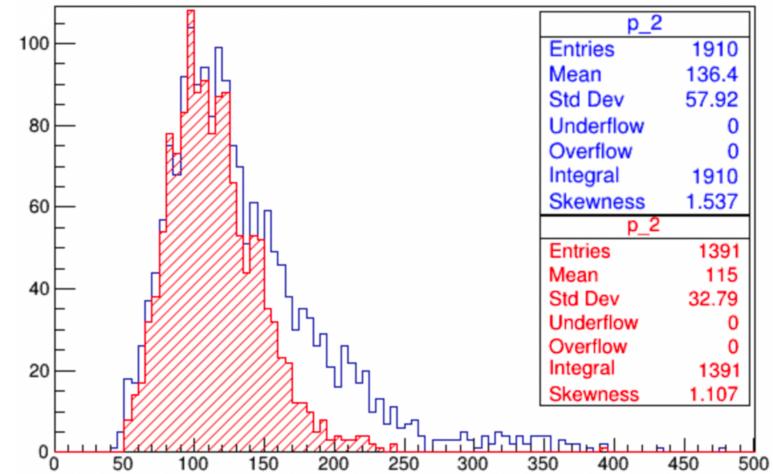
Time v/s z view

A $p\bar{p}$ annihilation event with two reconstructed tracks

Green = Muon, Pink = Pion, Black = Reconstructed track in 3-D view
Red = Reconstructed track in 2-D views

Comparison of default v/s new reconstruction with 10^4 pure $p\bar{p}$ annihilation events

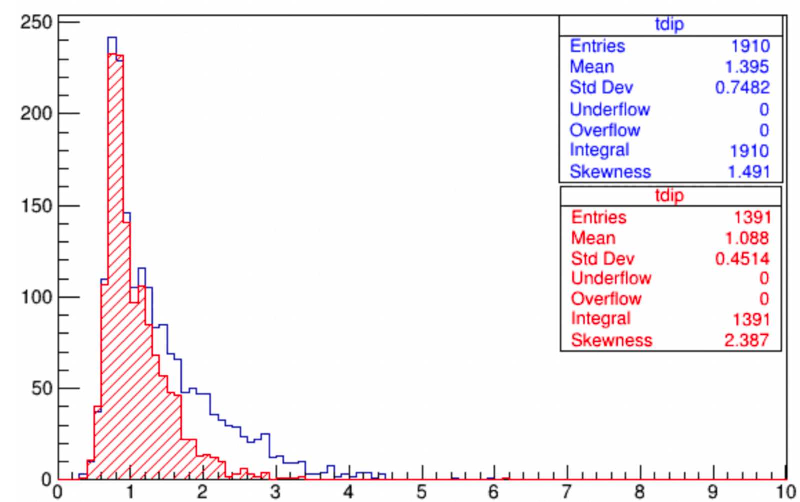
- The new reconstruction chain uses the "DeltaFinder" instead of "FlgBkgHits", "TZClusterFinder" instead of the "TimeClusterFinder" and the "PhiClusterFinder" after the time clustering stage.



Total Momentum (MeV/c)

All reconstructed tracks

No. Of events with	>= 1 track	>= 2 tracks
Default reco	1298	48
New reco	1817	137
Improvement factor	**x 1.4**	**x 2.8**



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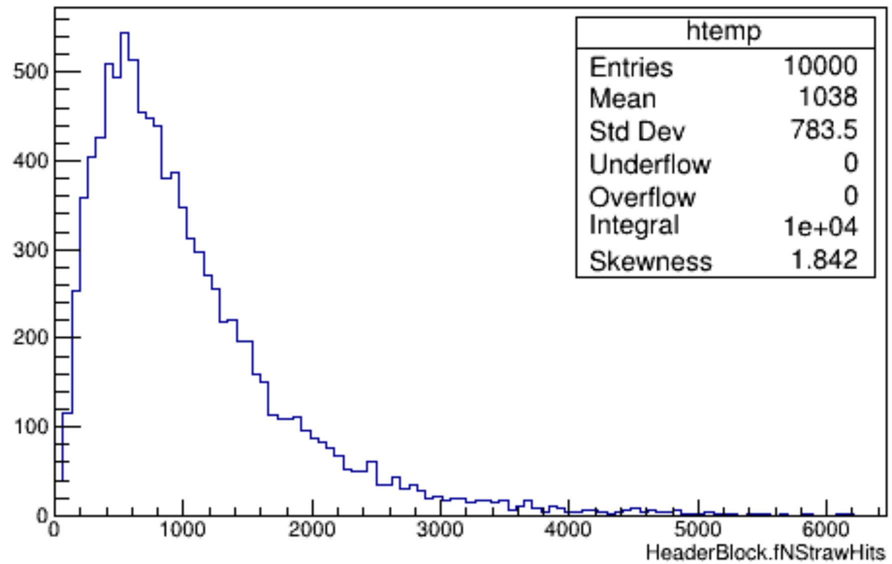
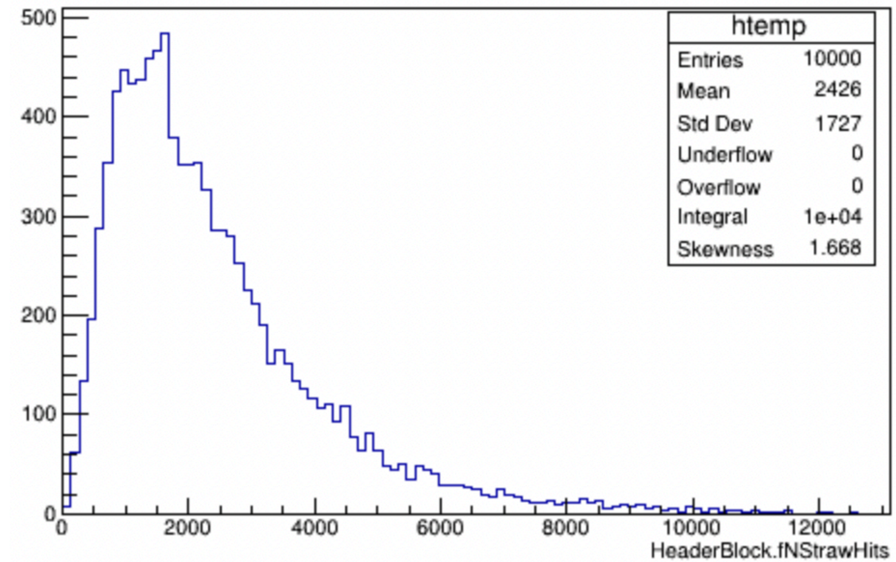
$p\overline{p}$ annihilation + pileup data samples



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

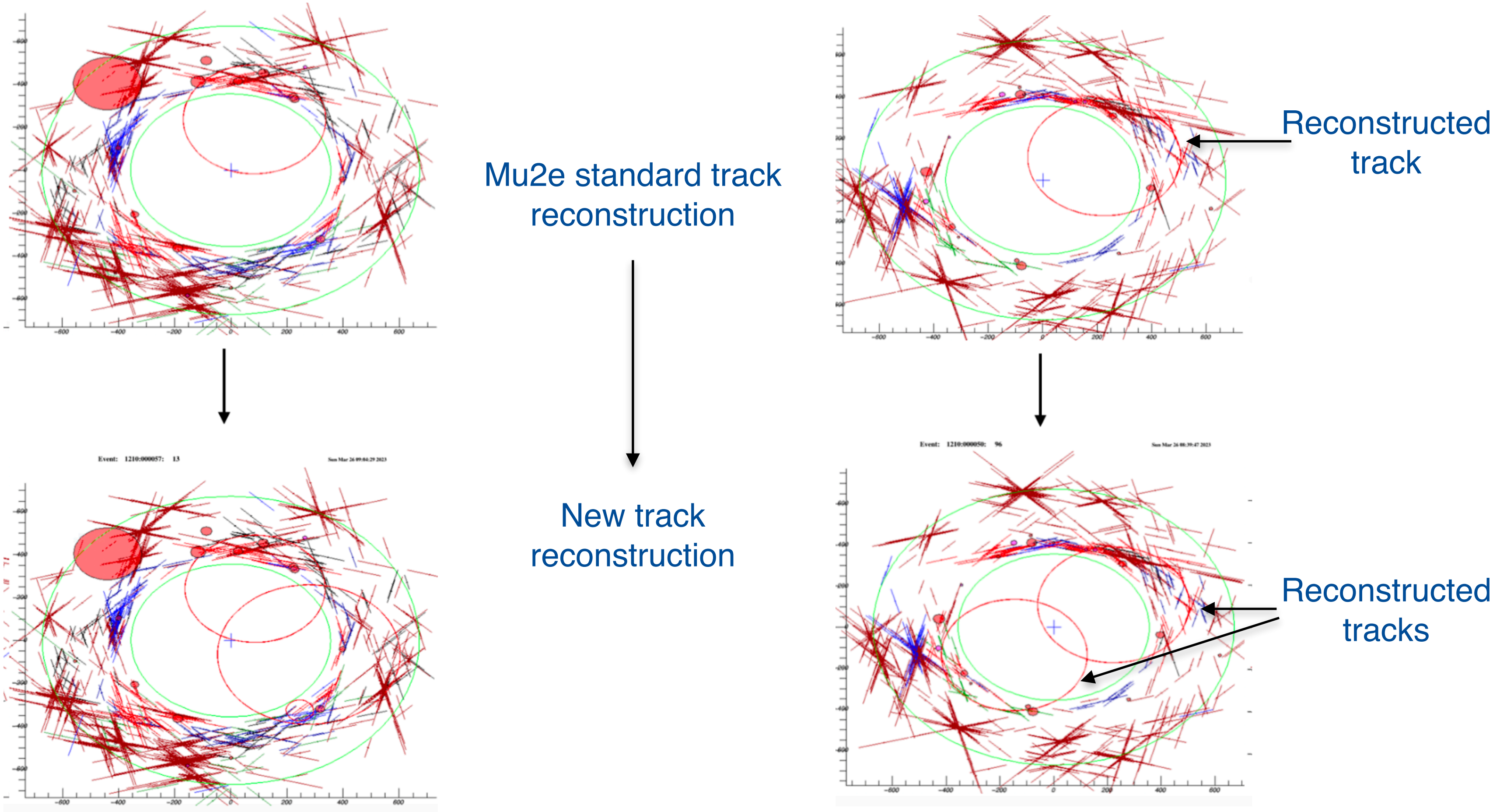


Number of Straw Hits
$p\overline{p}$ + 2BB data sample

- We have generated 10^4 $p\overline{p}$ 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.

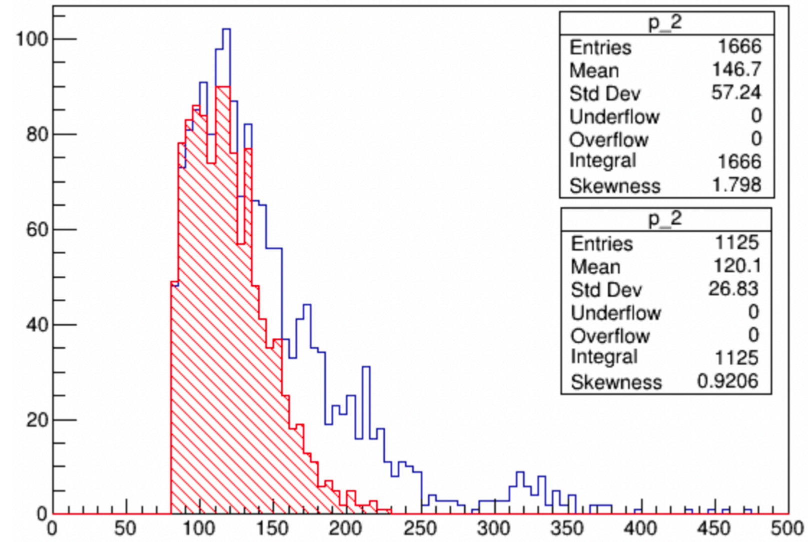
Fermilab

Preliminary results with $p\bar{p}$ annihilation + 2BB pile-up data sample



Transverse view of two events from the $p\bar{p}$ annihilation + 2BB data sample.
The red circle is the transverse view of the reconstructed track.
The segments are the “hit” tracker straws.
The red circles are calorimeter clusters.

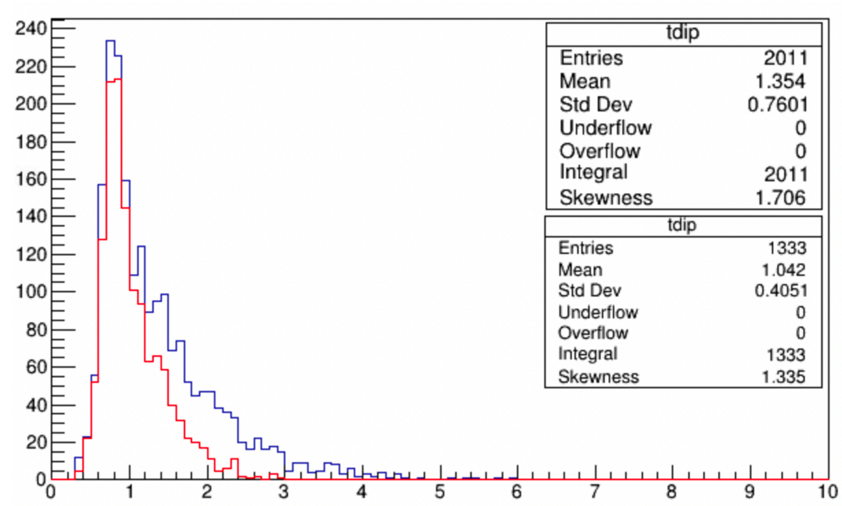
Comparison of default v/s new reconstruction with $p\bar{p}$ annihilation +1BB pileup events



Momentum (> 80 MeV/c)

- A momentum cut at 80 MeV/c was introduced to not count the low energy e^{-}/e^{+} reconstructed tracks.

No. Of events with	>= 1 track	>= 2 tracks
Default reco	1261	70
New reco	1848	158
Improvement factor	**x 1.46**	**x 2.2**



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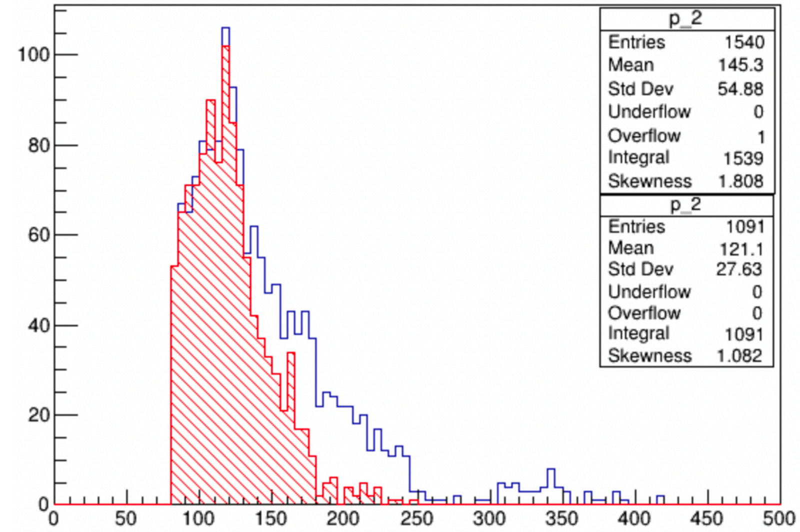
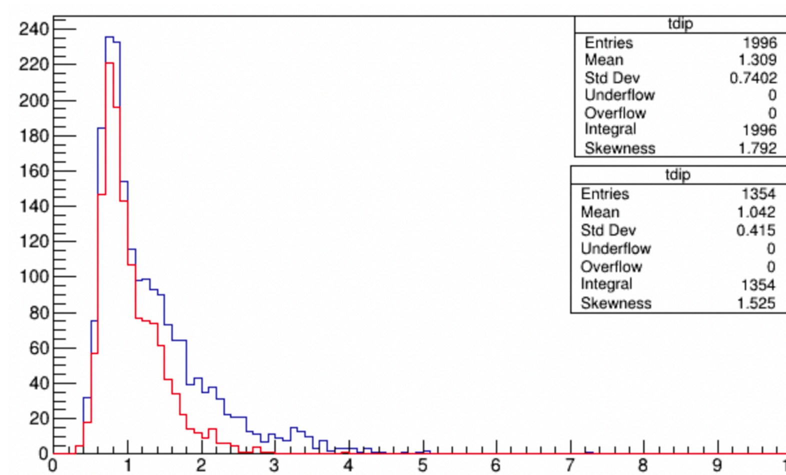
Comparison of default v/s new reconstruction with $p\bar{p}$ annihilation + 2BB pileup events

- A momentum cut at 80 MeV/c was introduced to not count the low energy e^-/e^+ reconstructed tracks.



Momentum (> 80 MeV/c)

No. Of events with	>= 1 track	>= 2 tracks
Default reco	1271	80
New reco	1837	144
Improvement factor	**x 1.44**	**x 1.8**



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Summary

- We are developing new algorithms to reconstruct multi-track events.
- These new algorithms are more physics neutral. They not only significantly improve the efficiency of reconstructing $p\bar{p}$ annihilation events, but they also would improve the efficiency of single e^- track reconstruction.
- Using the reconstruction sequence with the 'DeltaFinder', 'TZ' and the 'PhiClusterFinder' number of events with ≥ 2 tracks increased by:
  -> $\sim \times 2.8$ for the single interaction $p\bar{p}$ annihilation events.
  -> $\sim \times 2.2$ for the $p\bar{p}$ annihilation + 1BB events.
  -> $\sim \times 1.8$ for the $p\bar{p}$ annihilation + 2BB events.
- Next tasks:

  -> Estimate the contribution of the other background processes that can give multi-track events.
  -> Generate and test with a larger data sample of $p\bar{p}$ annihilation events.

This work was supported by the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement Nos. 734303, 822185, 858199, 101003460.

Extra slides

Datasets and code developed for the antiproton background study

- The generation of the $\overline{p}$s in the production target and tracing them from the Production to the Detector Solenoid was done using the Mu2e Offline software.

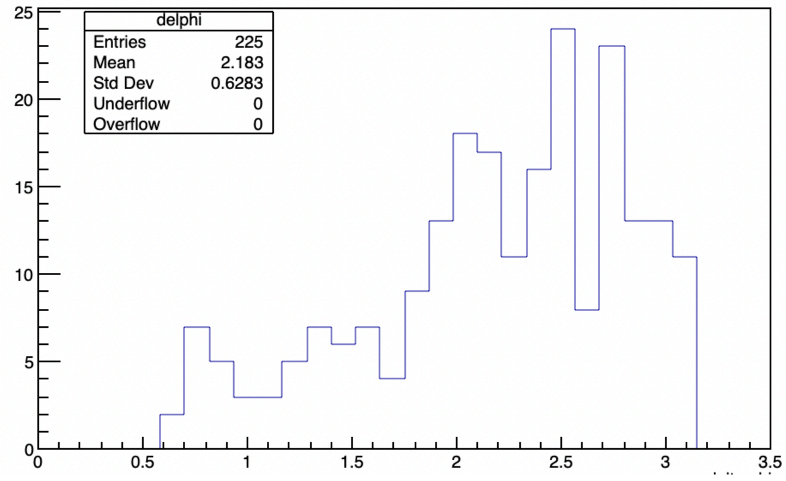
- A dataset containing the position and time of the stopped $\overline{p}$s at the ST from the SU 2020* work was the starting point of our study.

- A data sample with 10^4 pure $p\overline{p}$ annihilation events in the ST was created. Most of the reconstruction algorithm was developed based on the test results obtained with this pure $p\overline{p}$ data.

- Further, 10^4 $p\overline{p}$ annihilation events with low intensity $(1.6 \times 10^7$ protons/pulse) and high intensity pile-up modes were generated as well.

- The simulation, digitisation and reconstruction fcl files can be found at https://github.com/Mu2e/pbar2m.

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



$\Delta\phi$

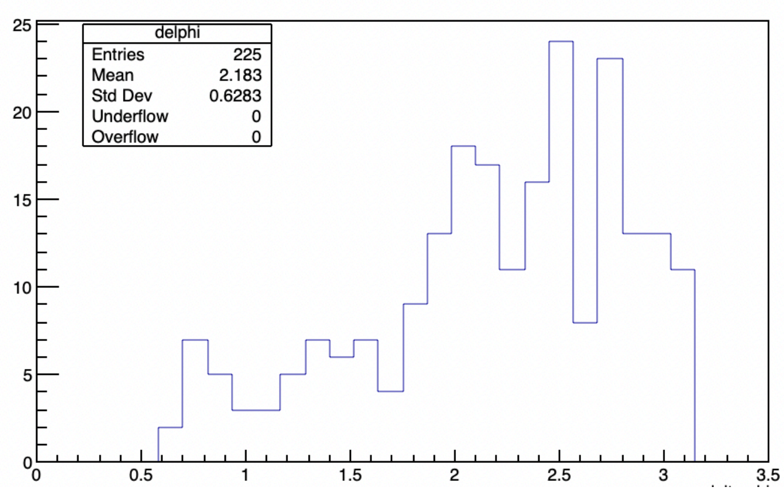
$p\bar{p}$ data sample (10^4 generated events)

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

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

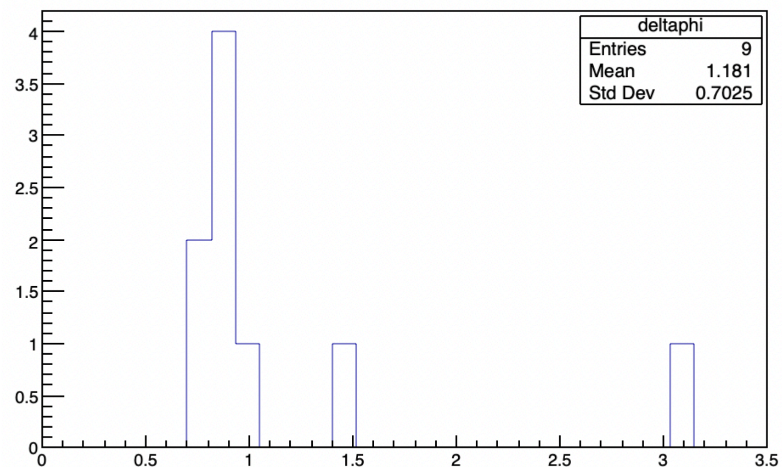
- Studying the $\Delta\phi$ distributions we decided to set a $\Delta\phi_{min} = 1.5$ rad cut to select events for the two tracks per event reconstruction.

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



$\Delta\phi$

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



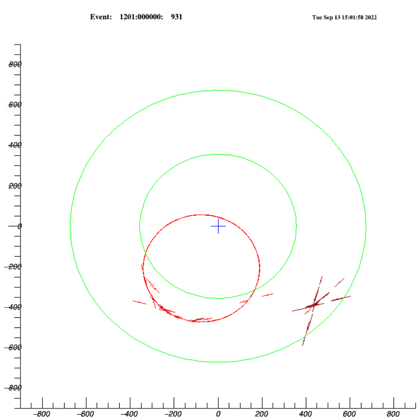
$\Delta\phi$

Conversion e- data sample (10^4 generated events)

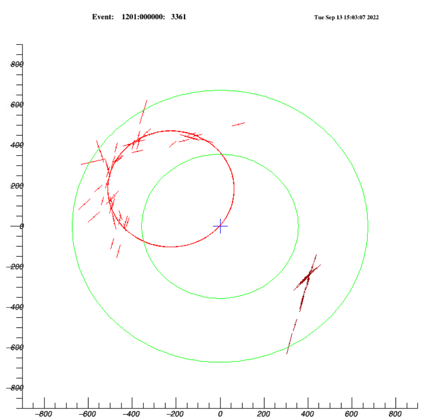
- The events with two output time clusters after the PhiClusterFinder stage were used to fill the above histogram.

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

- 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.



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



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

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		

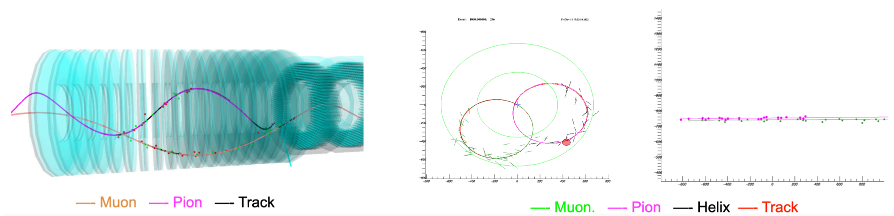
$p\bar{p}$ data with default Offline workflow

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

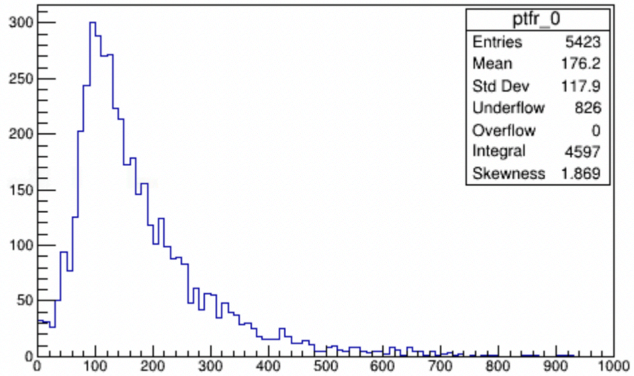
$p\bar{p}$ data with DeltaFinder -> TZFinder -> New PhiCusterFinder -> HelixFinder



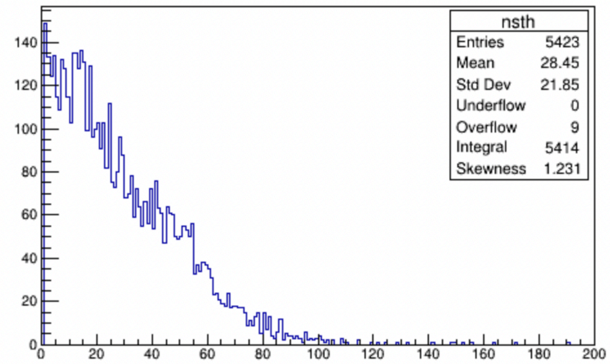
3-D and 2-D XY, tZ displays of an event with two reconstructed tracks

- 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.

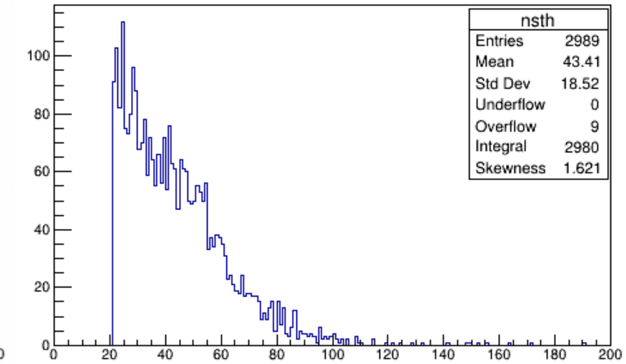
SimParticles



Momentum(MeV/c) at VD 13

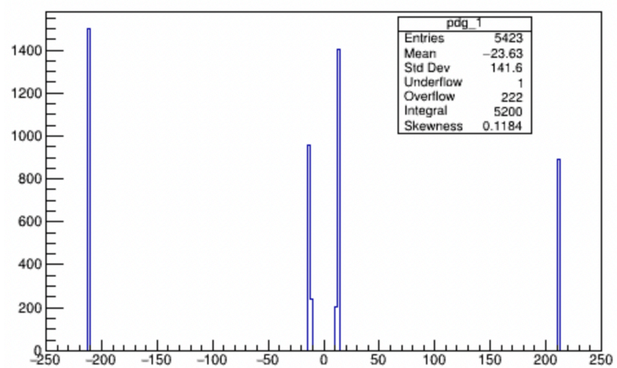


N straw hits

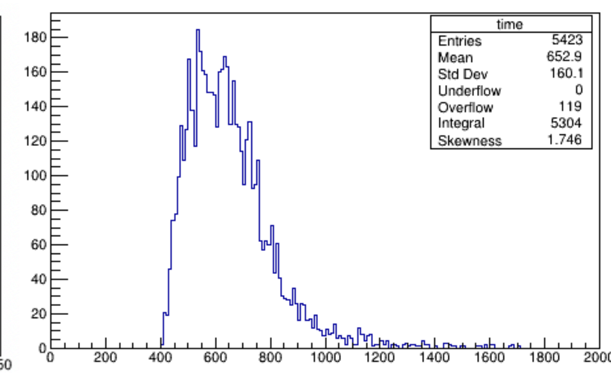


N straw hits

- 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.

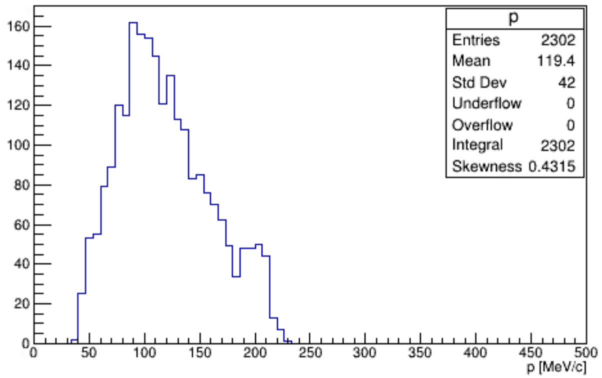


PDG code

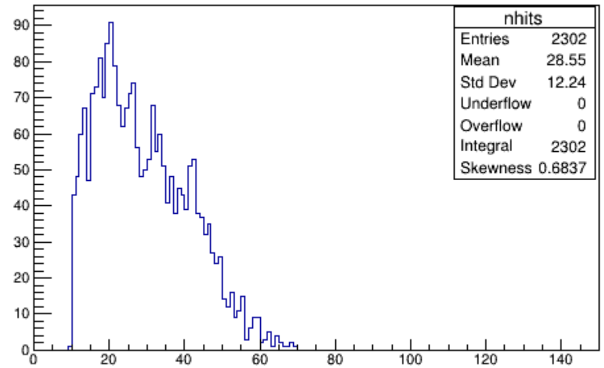


Time (ns)

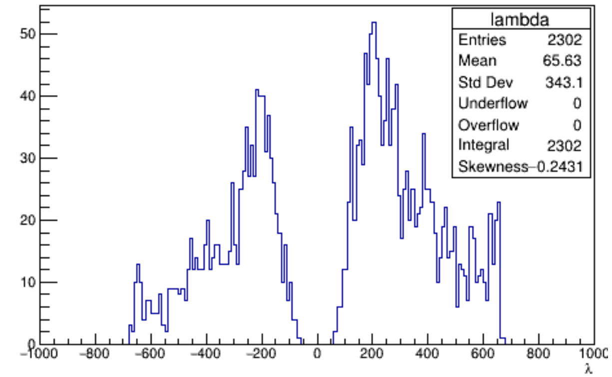
All Helices



Total momentum (MeV/c)

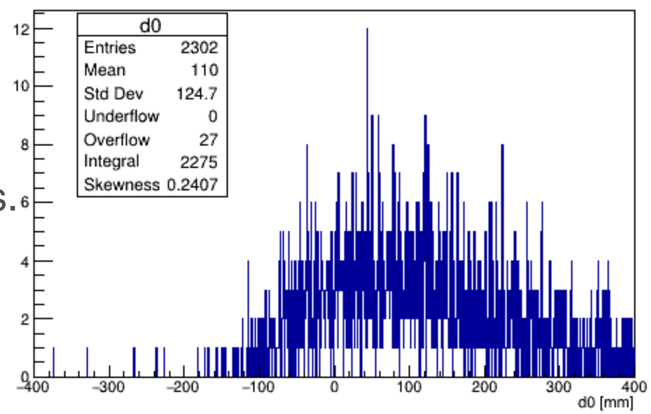


N straw hits

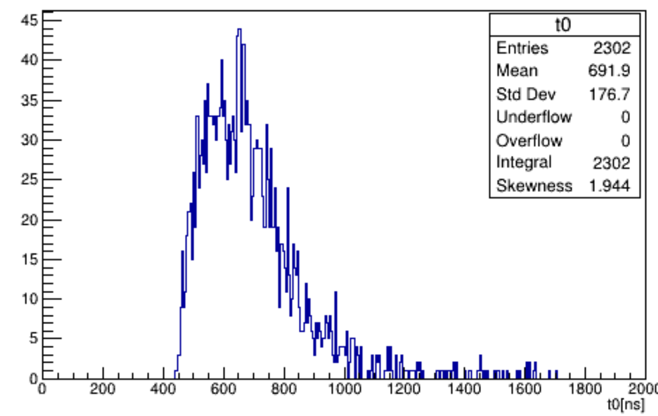


Lambda

- 1978 events with 1 helix
- 133 events with 2 helices
- 50 events with 3 sim particles.
- But only 345 events pass the HS filter of the standard TPR trigger path.



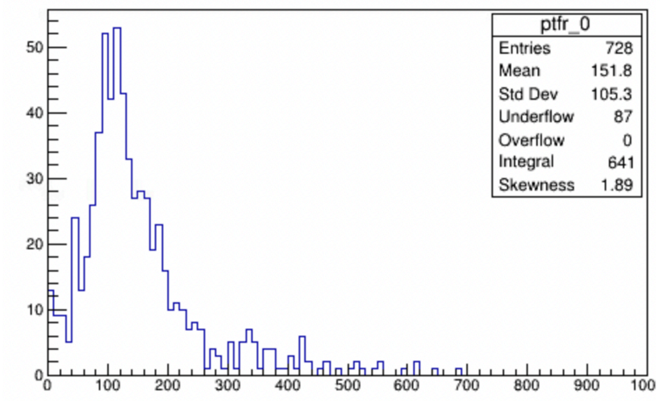
D0



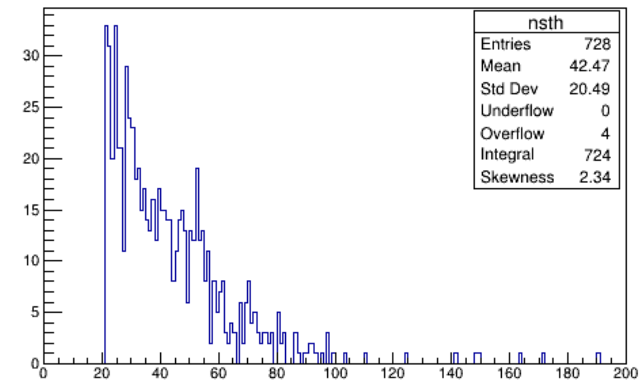
T0

SimParticles

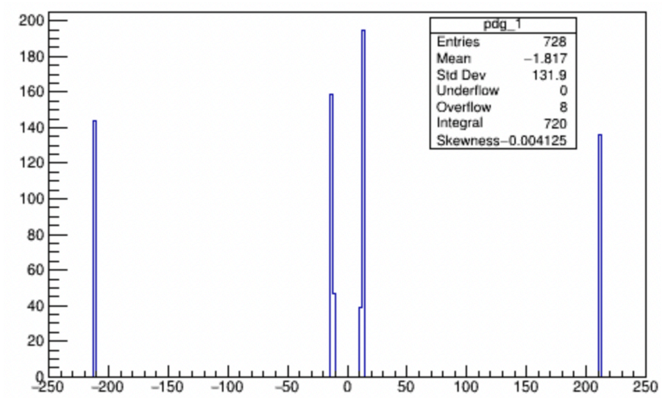
- 364 events with 2 SimParticles with each particle having > 20 straw hits.



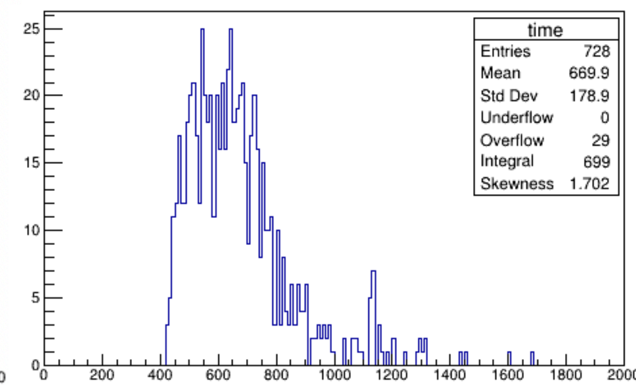
Momentum(MeV/c) at the Tracker entrance



Straw hits

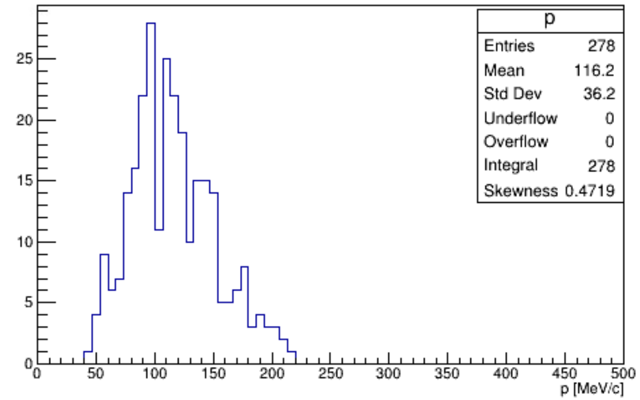


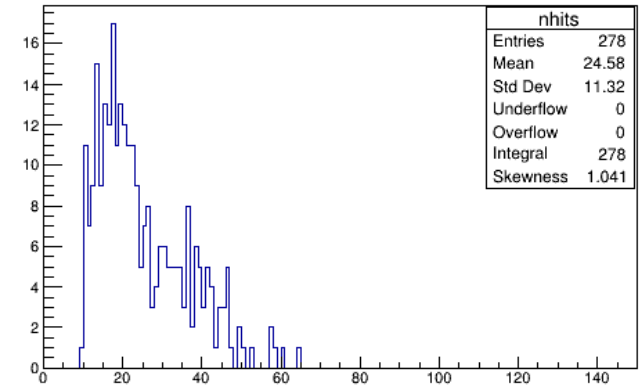
PDG code

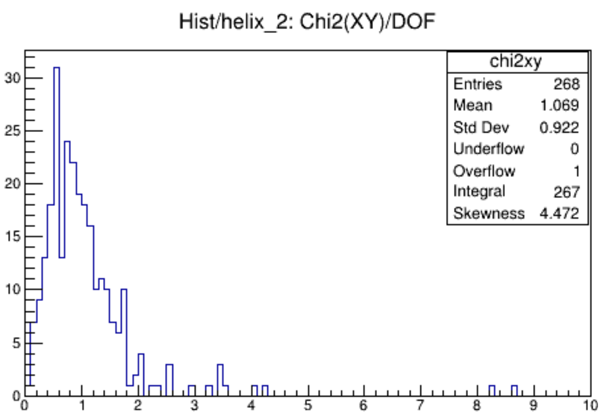


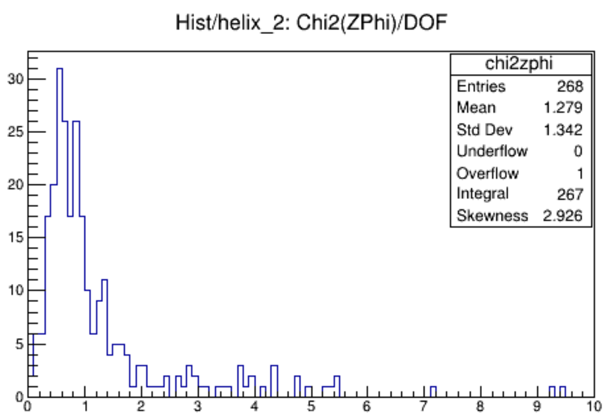
Time (ns)

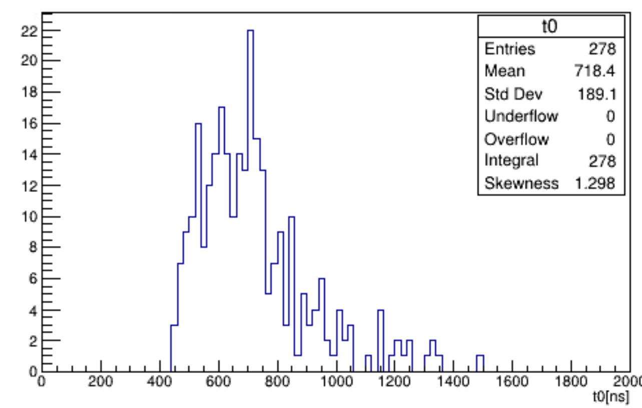
2 helices per event



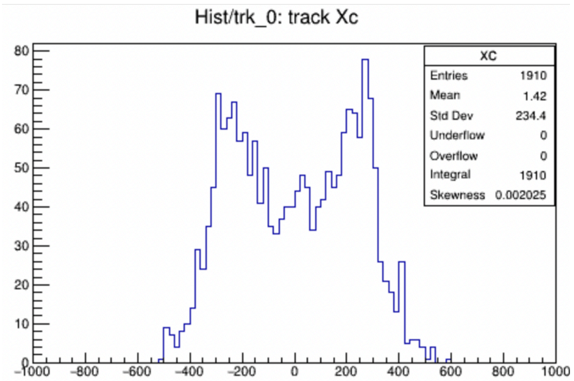


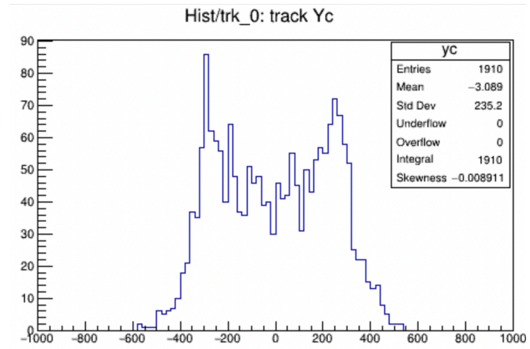


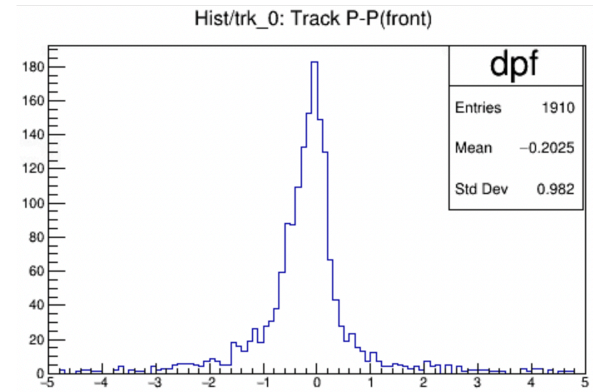




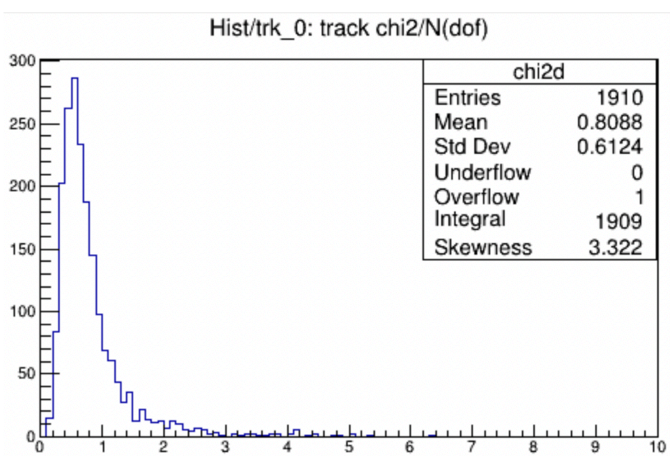
Preliminary results with the single interaction $p\bar{p}$ annihilation at the ST events

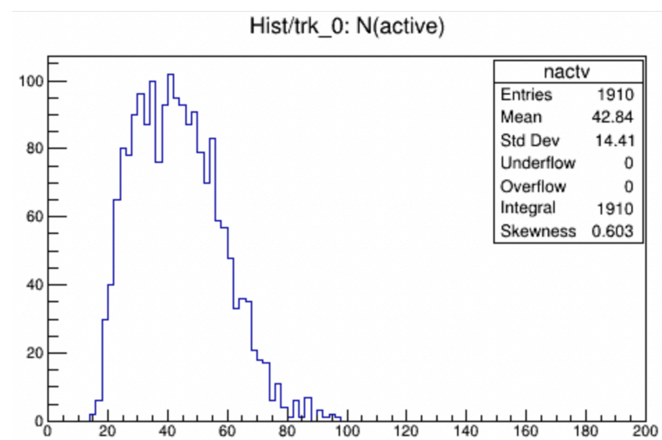






Momentum resolution



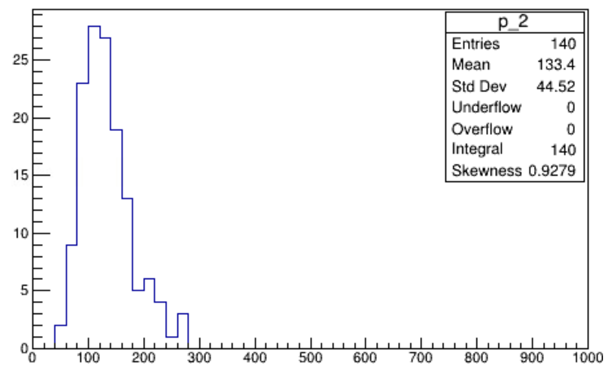


Straw hits

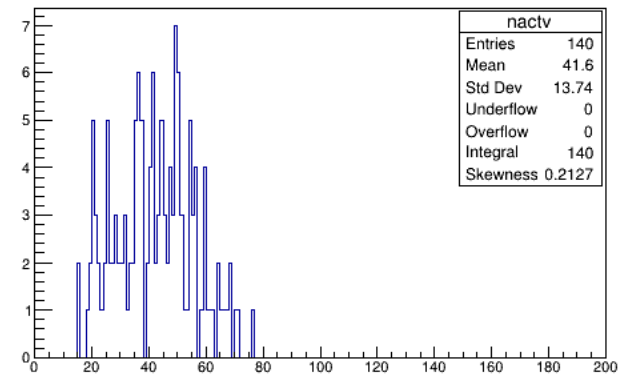
Fermilab

Some relevant distributions of two track per event cases

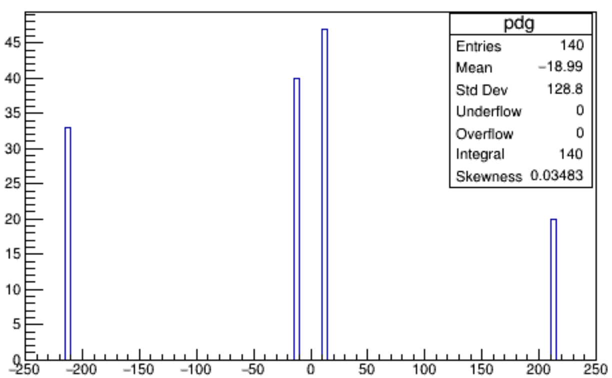
- 70 events with two reconstructed tracks per event
- Most of the tracks are in the high momentum range.
- The tracks are mostly muon and pion tracks, as expected.



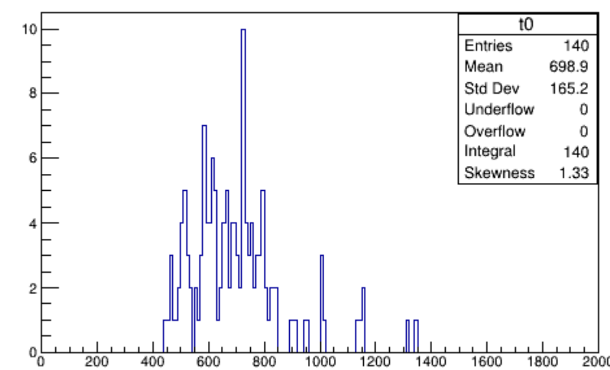
Momentum



N(active) hits

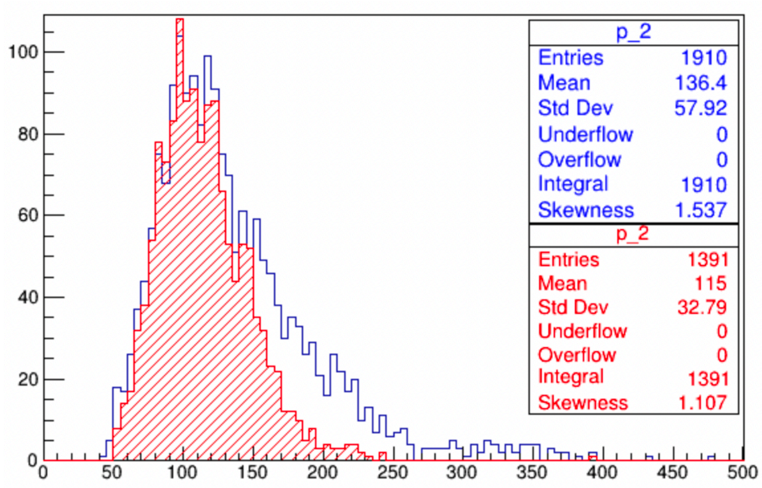


PDG code

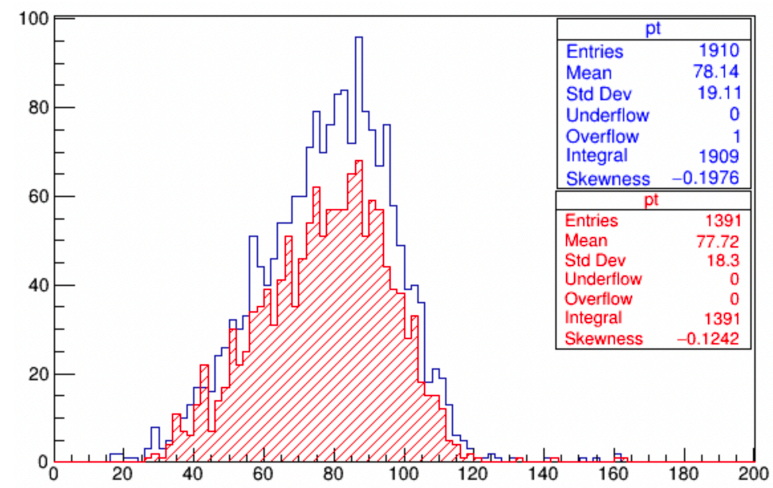


Trk T0

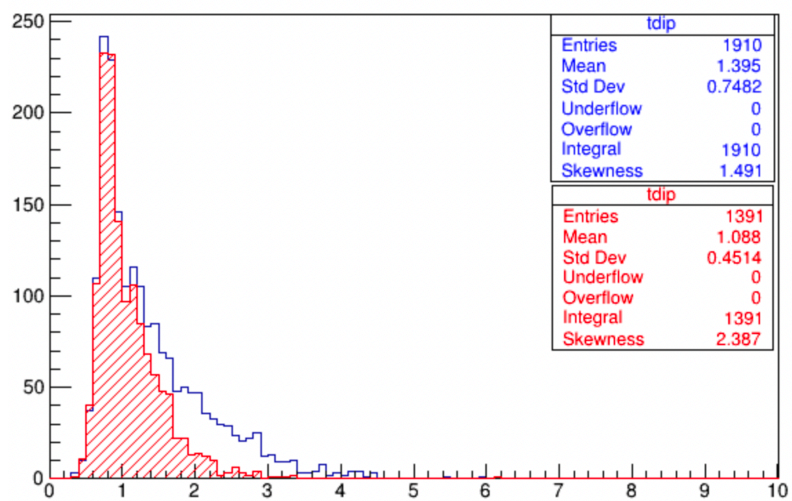
Comparison of default v/s new reconstruction with pure $p\bar{p}$ annihilation events



Total Momentum (MeV/c)



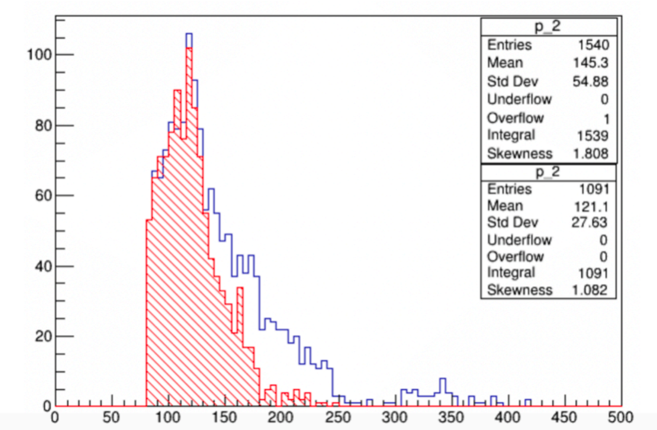
Transverse Momentum (MeV/c)



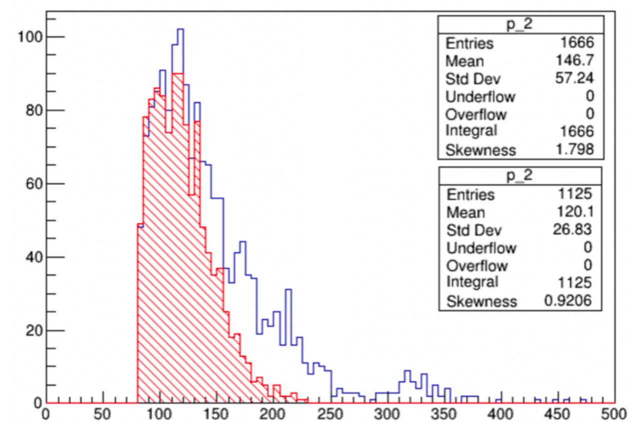
tan(λ)

- Given here are all the reconstructed tracks with no quality cuts.
- Most of the reconstructed tracks are of pions and muons as expected.

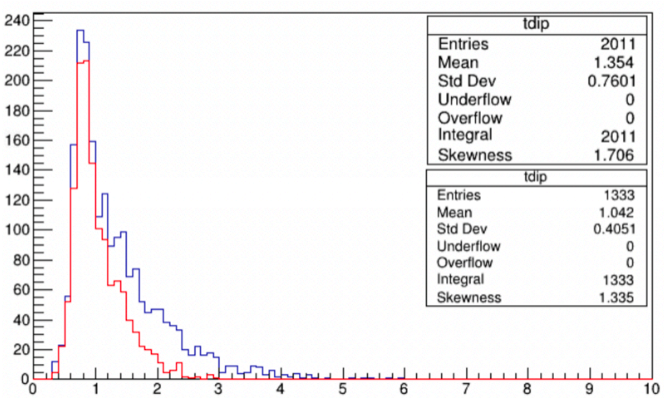
Preliminary results with $p\bar{p}$ annihilation + low intensity pile up data sample



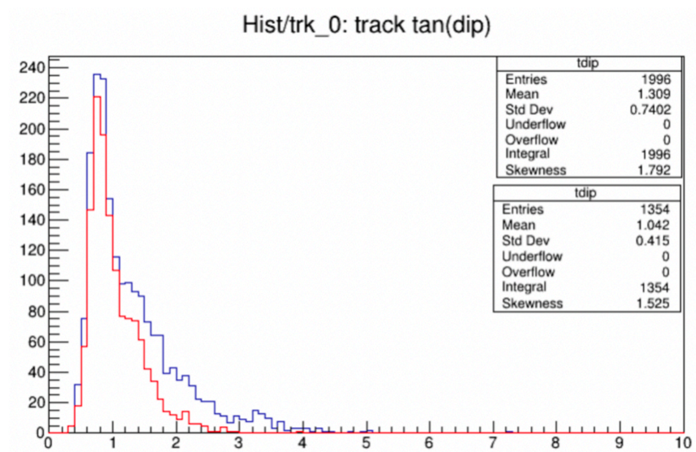
Momentum > 80 MeV/c



Momentum > 80 MeV/c cut



tan(dip)



tan(dip)

Red = Default reconstruction
Blue = New reconstruction chain developed for the $\bar{p}$ background study

Red = Default reconstruction
Blue = New reconstruction chain developed for the $\bar{p}$ background study

Preliminary results with $p\bar{p}$ annihilation + low intensity pile up data sample

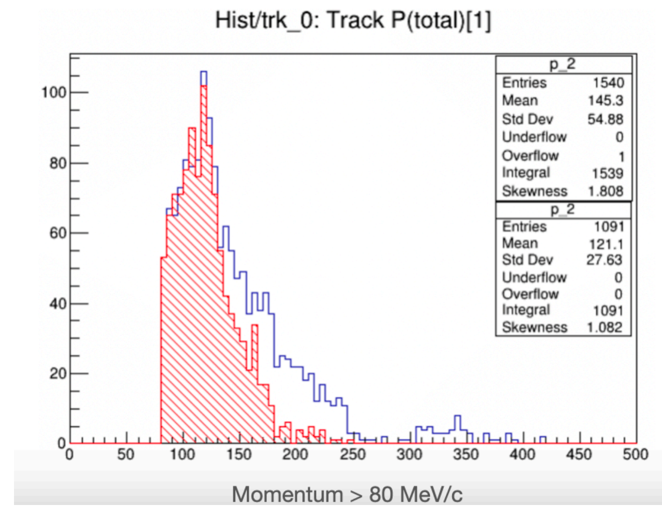
Events with	0	1	2	3	4	> = 5
SimParticle	442	951	1299	1270	1225	4813
Time	2513	2870	1901	1027	627	1062
Helix	7153	2318	412	83	29	5
Track	8739	1191	68	2		

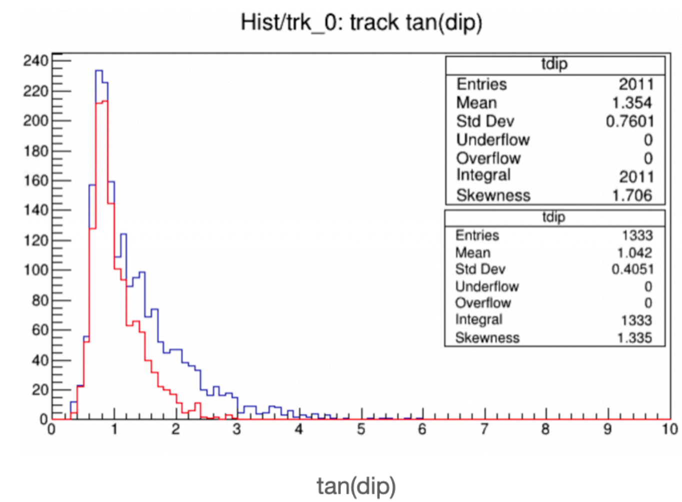
Default Mu2e Offline reconstruction chain

Events with	0	1	2	3	4	>= 5
Sim Particle	442	951	1299	1270	1225	4813
TZCluster	2179	2366	1729	1128	806	1792
PhiCluster	2791	2781	1727	1095	609	604
Helix	5614	3005	1012	271	73	25
Track	8152	1690	153	5		

DeltaFinder + TZFinder + PhiClusterFinder reconstruction chain

- 10^4 generated events.
- A sim particle is defined as a particle making at least 15 straw hits in the Tracker and having a momentum > 40 MeV/c.



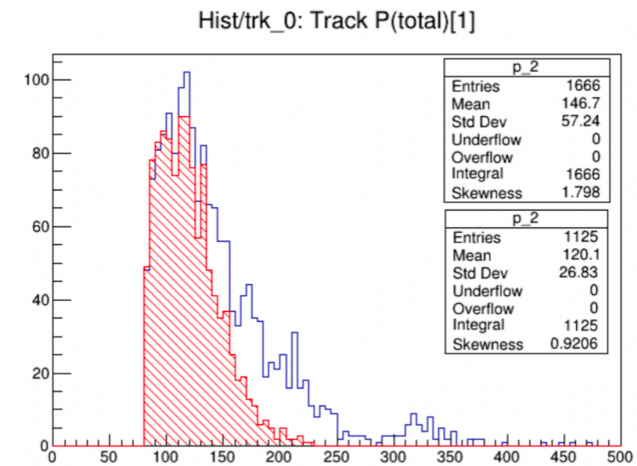


Red = Default reconstruction
Blue = New reconstruction chain developed for the $\bar{p}$ background study

Preliminary results with $p\overline{p}$ annihilation + high intensity pile-up data sample

Event with	0	1	2	3	4	5 and more
Sim	59	185	330	465	579	8382
Time	776	1351	1352	1155	989	4377
Helix	5729	2663	958	381	144	125
Track	8729	1191	77	3		

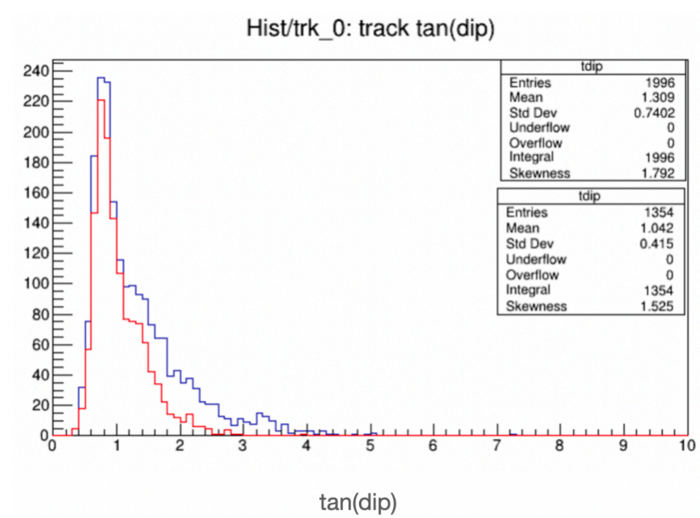
Default Mu2e Offline reconstruction chain



Momentum > 80 MeV/c cut

Events with	0	1	2	3	4	5 and more
Sim Particle	59	185	330	465	579	8382
Helix	3527	3150	1836	823	391	161
Track	8163	1693	131	11	2	

DeltaFinder + TZFinder + PhiClusterFinder reconstruction chain



- 10^4 generated events.
- A sim particle is defined as a particle making at least 15 straw hits in the Tracker and having a momentum > 40 MeV/c.

Red = Default reconstruction
Blue = New reconstruction chain developed for the $\overline{p}$ background study

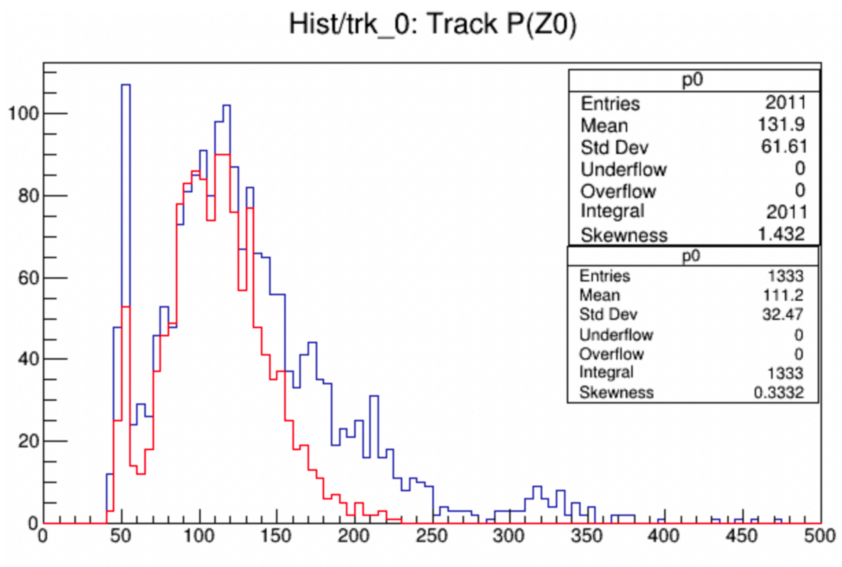
Fermilab

- **Comparing the default reconstruction chain**
- **With the pure $p\overline{p}$ data (10^4 events), the number of reconstructed tracks increased from 1348 to 1910.**

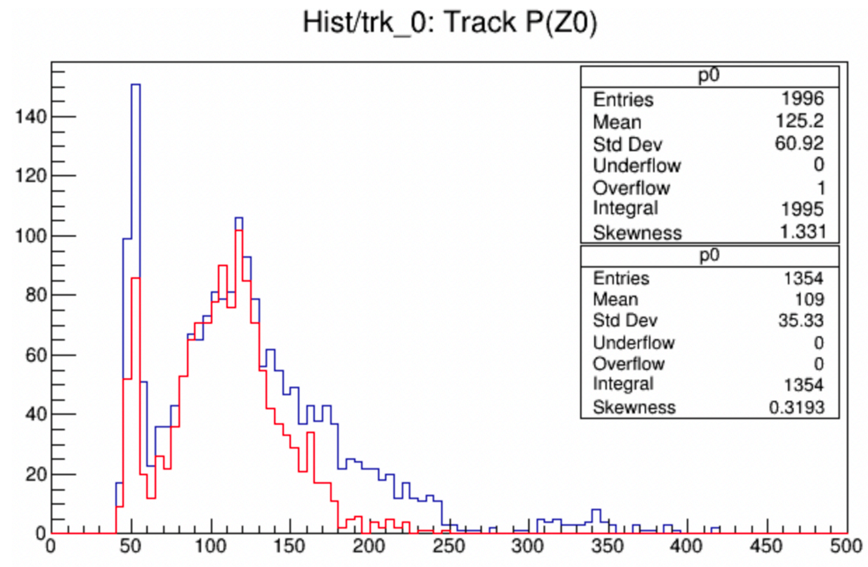
- **With the 1 BB $p\overline{p}$ data (10^4 events), the number of reconstructed tracks increased from 1333 to 2011.**
- **With a momentum cut at 80 MeV/c for each track, the number of events with two tracks increased from 44 to 90**
- **With a momentum cut at 80 MeV/c for each track, the number of events with one track increased from 1012 to 1419.**

- **For the 2 BB $p\overline{p}$ data (10^4 events), about 0.15% of the events have CE like tracks and 6.6 % of the events have 2 particle tracks with each track having > 15 straw hits and > 80 MeV/c momentum.**

- **For the 2 BB $p\overline{p}$ data (10^4 events), the number of reconstructed tracks increased from 1354 to 1996**
- **With a momentum cut at 80 MeV/c for each track, the number of events with two tracks increased from 44 to 67**
- **With a momentum cut at 80 MeV/c for each track, the number of events with one track increased from 969 to 1330.**

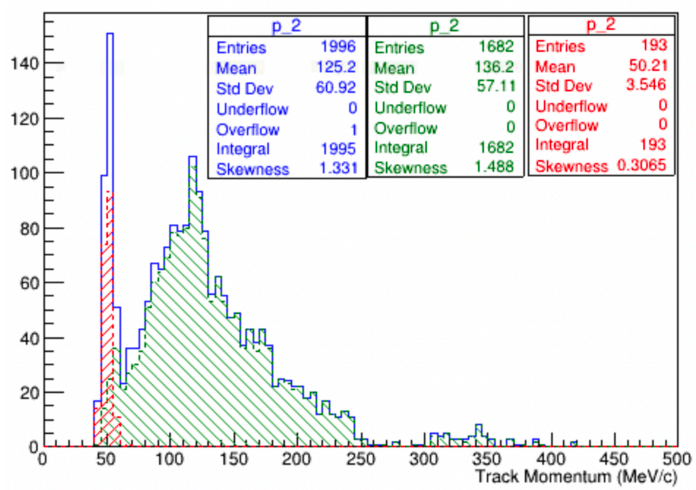


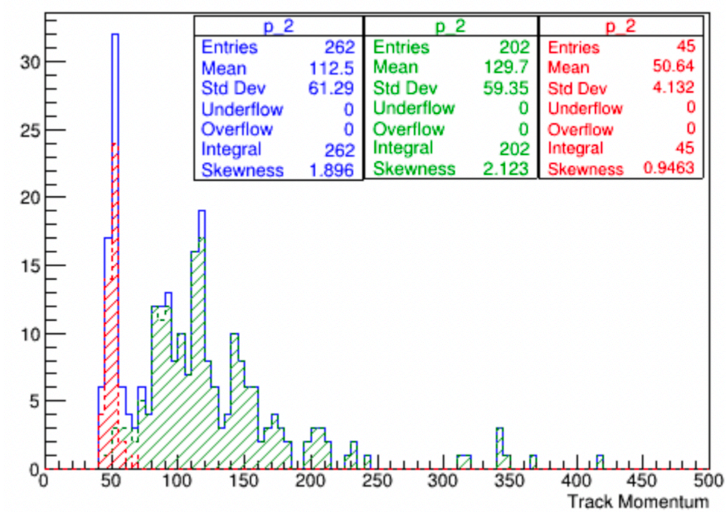
Hist/trk_0: Track P(Z0)
p0
Entries 2011
Mean 131.9
Std Dev 61.61
Underflow 0
Overflow 0
Integral 2011
Skewness 1.432
p0
Entries 1333
Mean 111.2
Std Dev 32.47
Underflow 0
Overflow 0
Integral 1333
Skewness 0.3332

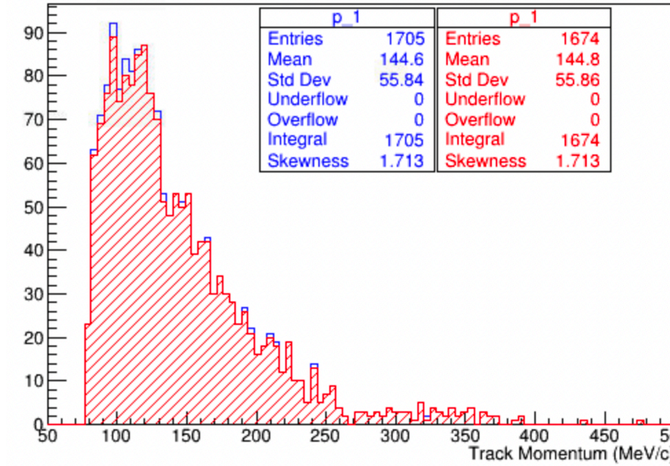


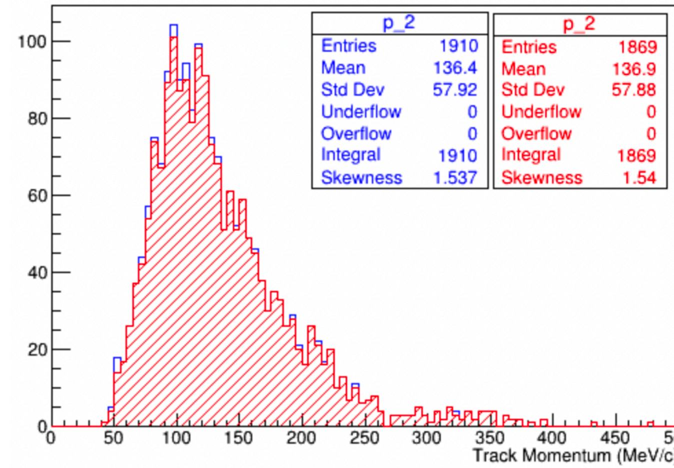
Hist/trk_0: Track P(Z0)
p0
Entries 1996
Mean 125.2
Std Dev 60.92
Underflow 0
Overflow 1
Integral 1995
Skewness 1.331
p0
Entries 1354
Mean 109
Std Dev 35.33
Underflow 0
Overflow 0
Integral 1354
Skewness 0.3193

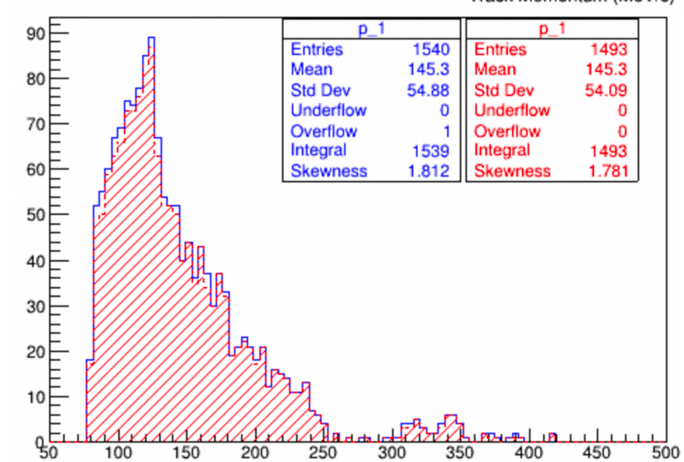
Ascertaining the legitimacy of the tracks











Ascertaining the legitimacy of the tracks