Mu2e : A Search for Charged Lepton Flavour Violation in Muons

Developing a data driven method for antiproton background measurement

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Interim Review Meeting INTENSE

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Introduction

- Namitha Chithirasreemadam : From Kerala, India.
- BS + MS 5 year Dual Degree Programme in Physics at S.V . National Institute of Technology, Surat, India.
- Master thesis : Data directed search for e/μ asymmetry : A generalised method based on the test statistics approach was developed to identify any significant e/μ asymmetry in the data collected from the ATLAS experiment.

  Guide : Dr. Shikma Bressler at the Weizmann Institute of Science, Israel.
- Summer internships at various institutes like DESY, Hamburg; Weizmann Institute of Science, Israel; HZDR, Dresden; University of Giessen (DAAD Fellowship), IUAC, New Delhi; SINP, Kolkata
- Joined the PhD programme at the University of Pisa in April 2021.

Conferences/Workshops

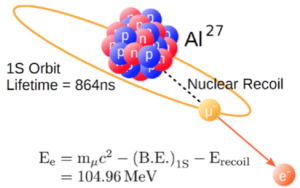
- 54th Annual Fermilab Users Meeting, Poster “Mu2e Event Display Development using the TEve Framework”, held online (Fermilab, August 2-6, 2021)
- New Perspectives 2021 Conference, Talk “Mu2e Event Display Development using the TEve Framework”, held online (Fermilab, August 16-19, 2021)
- Congresso Nazionale della Società Italiana di Fisica, Talk, held online (September 13-17, 2021)
- American Physical Society - April Meeting 2022, Talk , held online (April 9-12, 2022)
- 15th Pisa Meeting on Advanced Frontier Detectors – Edition 2022, Poster “Mu2e Event Visualization Development”, (La Biodola, Isola d’Elba, Italy, May 22-28, 2022)
- 55th Annual Fermilab Users Meeting, Poster “Mu2e Event Visualization Development” (Fermilab, June 13-19, 2022) : Won the Best Poster Presentation
- New Perspectives 2022, Talk “Mu2e Event Visualization Development using REve” (Fermilab, June 17, 2022).
- 21st International Workshop on Advanced Computing and Analysis Techniques in Physics Research, Poster (Bari, 23–28 Oct 2022)
- Mu2e Collaboration Meeting (Fermilab, 12- 19 Nov 2022)

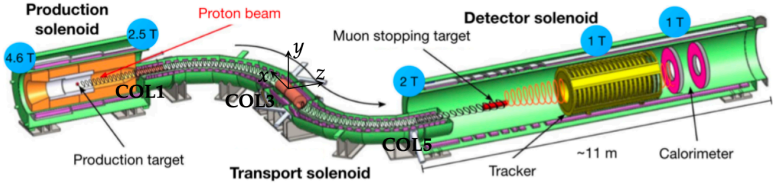
Courses completed

- Statistical Analysis Lab
- Introduction to Astrophysics
- Scientific Writing for Physicists
- Seminar on “Plasma Wakefield Accelerators”

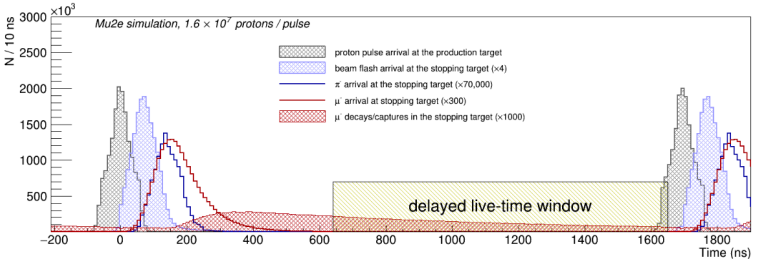
Mu2e

- The Mu2e experiment at Fermilab will search for the neutrinoless $\mu^- \rightarrow e^-$ conversion in the field of an aluminum nucleus.
- The expected Run I 5σ discovery sensitivity is $R_{\mu e} = 1.2 \times 10^{-15}$, with a total expected background of 0.11 ± 0.03 events.
- In the absence of a signal, the expected upper limit is $R_{\mu e} < 6.2 \times 10^{-16}$ at 90% CL.
- An 8 GeV pulsed proton beam is extracted from the Fermilab Delivery Ring.
- The beam interacts with the tungsten production target in the production solenoid (PS), producing mostly pions.
- Particles produced backwards travel through the S-shaped superconducting transport solenoid (TS) towards the superconducting detector solenoid (DS).
- Muons are mainly produced in $\pi^- \rightarrow \mu^- \nu$ decays.
- Muons stopped in the Stopping Target (ST) rapidly cascade to a 1s orbit in the Al atoms and could undergo the process of $\mu^- \rightarrow e^-$ conversion.





Mu2e Schematic Setup

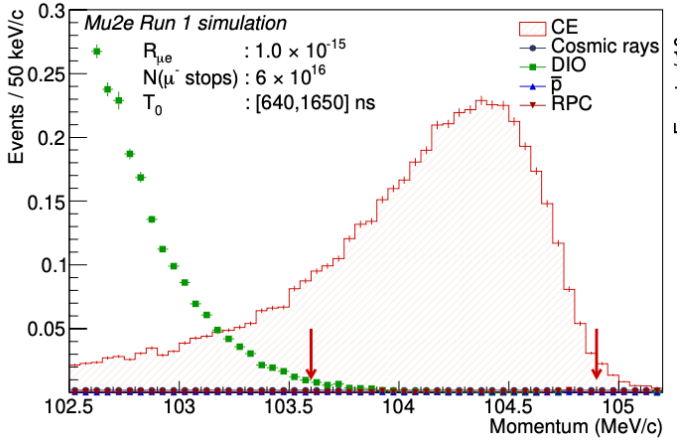


Proton pulses arrive at the production solenoid 1695 ns apart.
A delayed live-time window suppresses the beam-related background.

Main Background processes

- Cosmic Rays : A typical cosmic background event consists of a reconstructed downstream propagating e^- and a CRV stub.
- Muon Decays In Orbit : μ^- stopped in the ST form muonic atoms. The energy spectrum of electrons from decays of bound muons extends up to E_{CE}.
- Radiative Pion Capture : π^- stop within the ST and undergo $\pi^- + N(A,Z) \rightarrow \gamma^* + N(A,Z-1)$, followed by $\gamma \rightarrow e^-e^+$ producing e^- with an energy spectrum extending above 130 MeV.
- Radiative Muon Capture : $\mu^- + N(A,Z) \rightarrow \gamma^* + \nu_\mu + N(A,Z-1)$
- **Antiprotons :** $\bar{p}$ can pass through TS, enter DS, and **annihilate in the ST producing signal-like** e^-**.**

  $\bar{p}$ are significantly slower than the other beam particles. The only way to suppress $\bar{p}$ background is to use additional absorber elements, at the entrance and centre of the TS.



Electron momentum distribution.
The CE signal distributions correspond to Rμe = 1 × 10−15

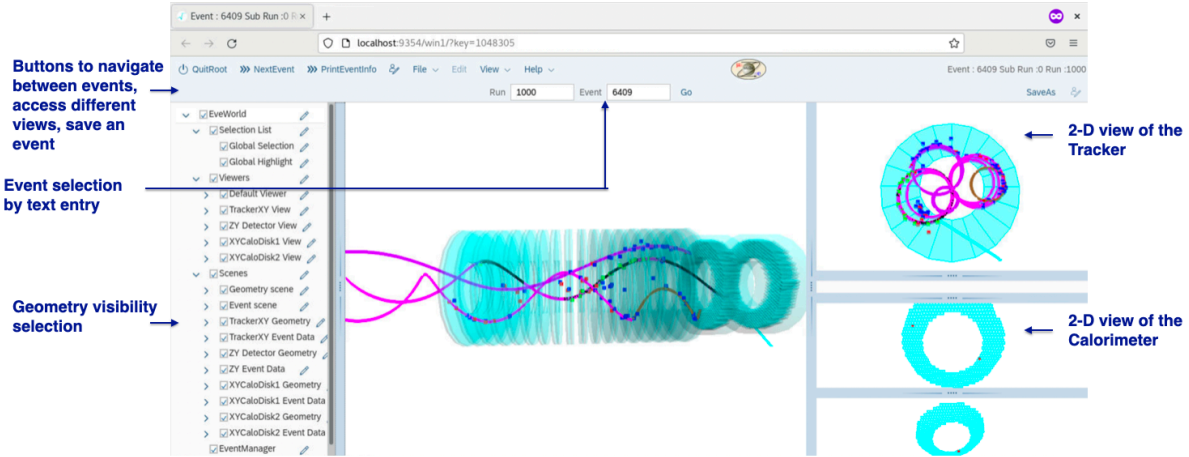
The background estimate numbers are the integrals over the optimized signal window, 103.60 < p < 104.90 MeV/c and 640 < T0 < 1650 ns. The error bars represent statistical uncertainties only.

Parameter	Total relative uncertainty	Dominant contribution
Signal acceptance	4%	Momentum scale
Antiproton background	100%	$\bar{p}$ production cross section
Cosmic background	20%	Cosmic flux normalization
DIO background	59%	Momentum scale
RPC background	29%	Pion production cross section
Muon flux	10%	Flux measurement

Systematic uncertainties used in the sensitivity optimisation procedure.

Mu2e Event Display development using Eve-7

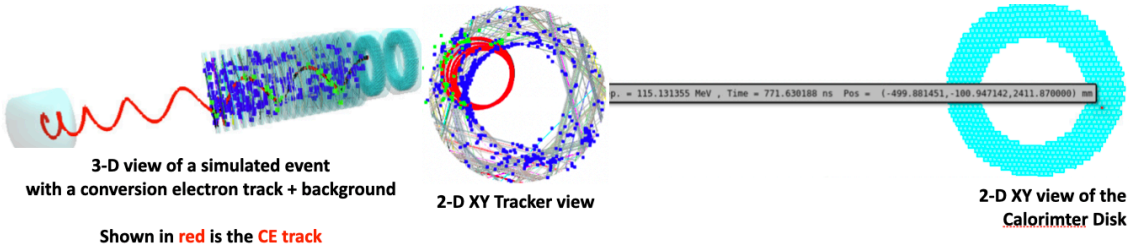
- Event display is the top layer of a robust framework. It helps to visualise the physics in each event.
- Crucial for monitoring and debugging during live data taking, offline analysis as well as public outreach.
- A custom, offline display prototype was developed first using **TEve**, a ROOT based 3-D event visualisation framework.
- The online display is being developed using **Eve-7**, an upgraded version of TEve which allows remote access for live data taking.
- It allows users to remotely access the display from anywhere (provided FNAL VPN).
- Multiple Users can simultaneously view and interact with display.



Main window of the online event display
Given here is an example event of $p\bar{p}$ annihilation at the Stopping Target in the Detector Solenoid

Features of the online display

- Reconstructed data like tracks, hits can be displayed within the detector geometries upon GUI request.
- User defined track selection and colour coding feature, using the particle ID.
  For example : **e-,** μ^-, π
- "hits" used in track reconstruction are highlighted in **green** and the unused hits are in **blue**.
- Relevant details about the simulated particle, reconstructed track, straw and calorimeter crystal "hits" can be obtained on tool-tip or printed.
- MC truth and reconstructed tracks can be displayed together, allowing visualisation of track resolution.
- Upstream visualisation : Production and Transport solenoids have been added to the display enabling complete illustration of the Mu2e world.
- A GUI "ShowCRV" option is added which lets the user view the CRV geometry and the cosmic muon tracks and hits.

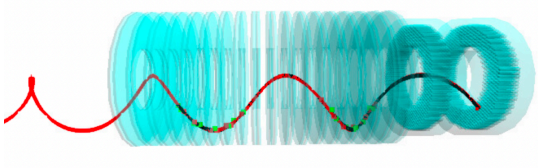


3-D view of a simulated event with a conversion electron track + background

Shown in red is the CE track

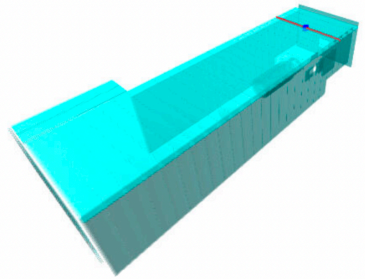
2-D XY Tracker view

2-D XY view of the Calorimter Disk



Conversion electron event
Red : MC true track, Black : Reconstructed track
Green : Hits used in reconstruction

PS, TS and DS displayed



CRV display : "hit" scintillation bars highlighted in red, hits are shown in blue

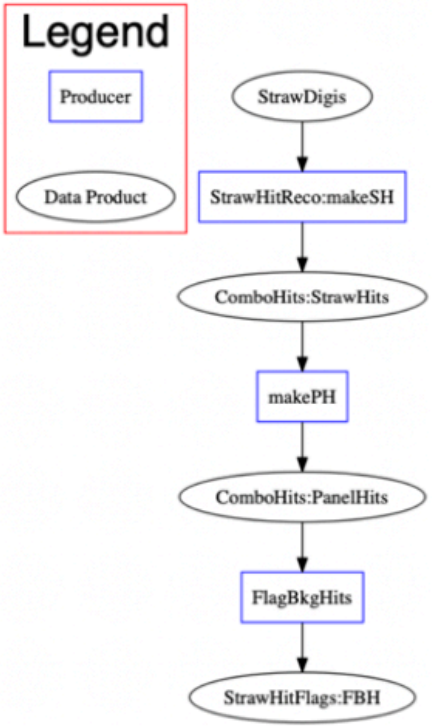
Motivation to study the $\bar{p}$ background

- $p\bar{p}$ annihilation at rest in the ST can produce events with more than one track with p~100 MeV/c , and we want to utilize this unique feature.
- At present, we do not have a good way to constrain $\bar{p}$ background from data.
- **Our idea is to identify and potentially reconstruct these two particle final state events and estimate the antiproton background by comparison.**
- For the "$p\bar{p}$ annihilation in the ST" events, we estimated $\frac{N_{e^-perMeV}}{N_{>=2particle}} \sim \frac{1}{500}$.
- From SU2020, the estimated antiproton background for Run 1 is $0.01 \pm 0.003(stat) \pm 0.010(syst)$, where the systematic error is dominated by the uncertainty on the production cross section.
- Successful identification and reconstruction of the two and more particle final state events could help to constrain the antiproton background.

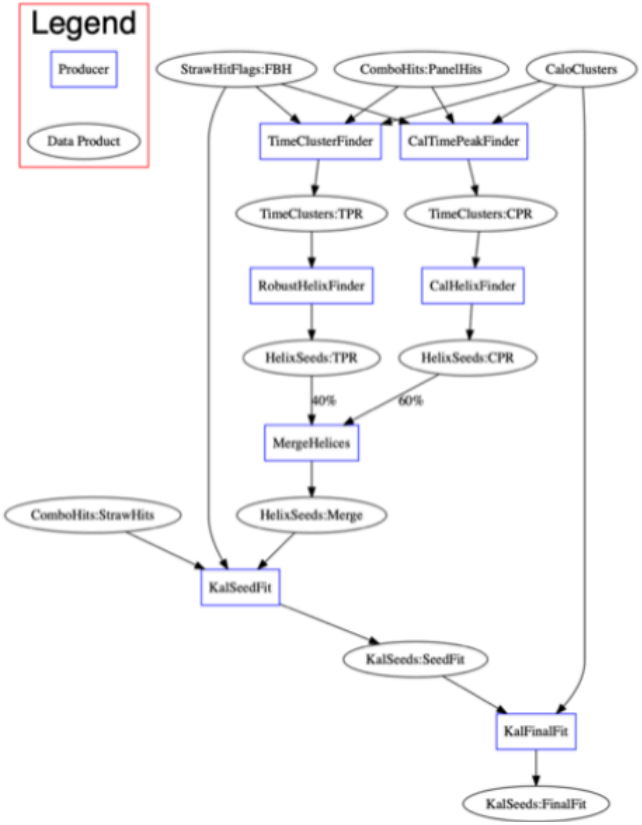
Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat)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

Background summary and SES using the optimized signal momentum and time window, $103.60 < p < 104.90$ MeV/c and $640 < T_0 < 1650$ ns

Offline Reconstruction Workflow



Straw hit reconstruction

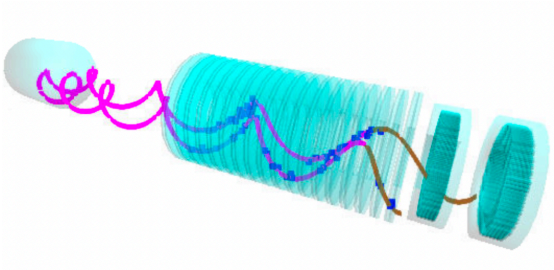


Downstream track reconstruction

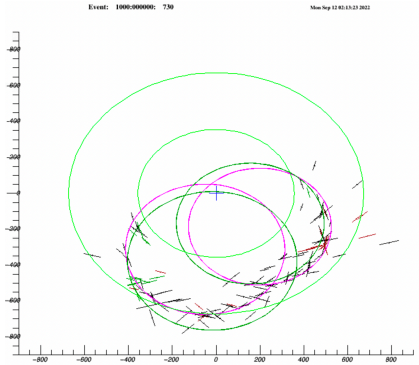
Motivation to develop tools for identification and reconstruction of events with >= 2 particle tracks

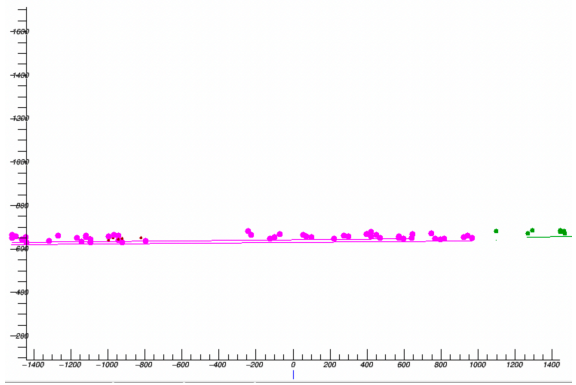
- The present Offline reconstruction algorithm is designed to identify single final particle events and tuned particularly for efficient conversion electron event reconstruction :
  - The present TimeClusterFinder settings could remove hits which do not look like CE hits.
  - TrkPatRec takes an input time cluster and forms a helix. In the case of two particle final state events from $p\bar{p}$ annihilation, the tracks would fall within the same time window.
  - CalPatRec could identify two helices if each helix has a calo cluster associated to it but this may not be the case for most of the events.

Some interesting events

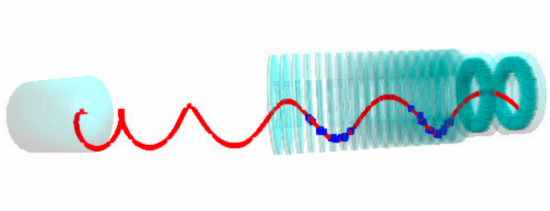


Event : 730

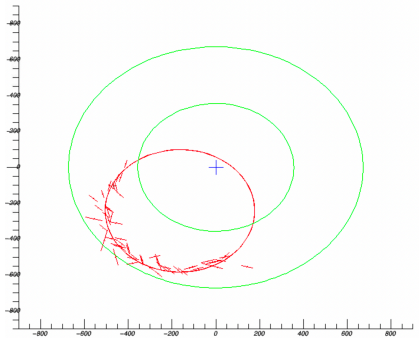




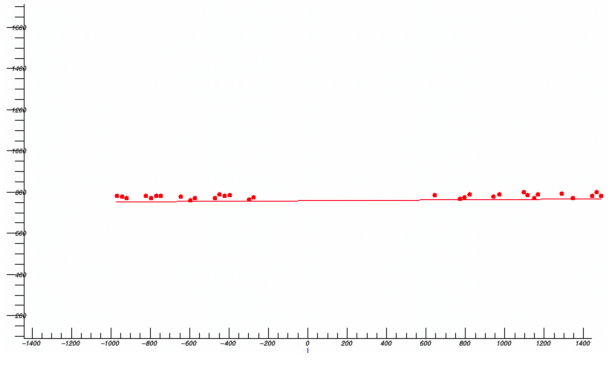
—- Muon. —- Pion. —- Electron



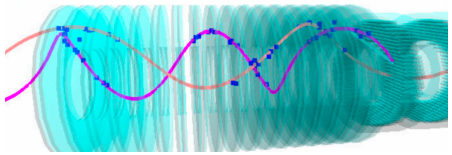
Event : 11



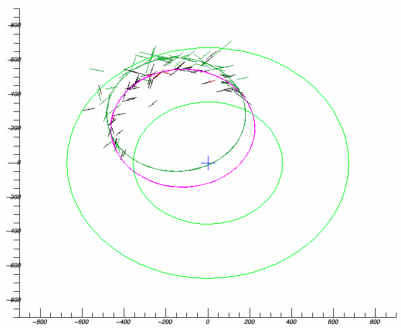
XY view

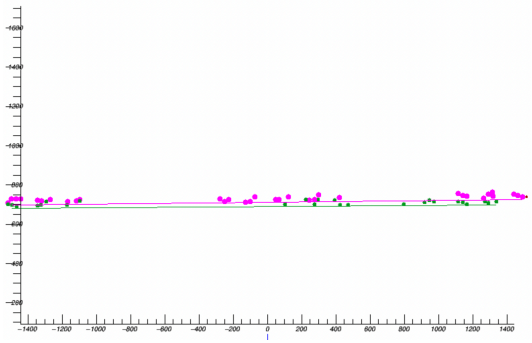


TZ view

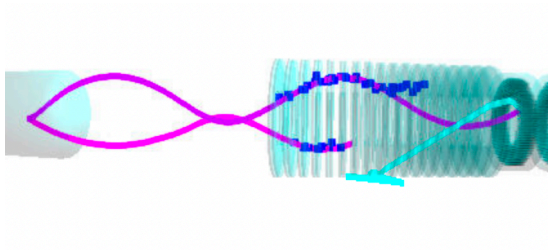


Event : 106

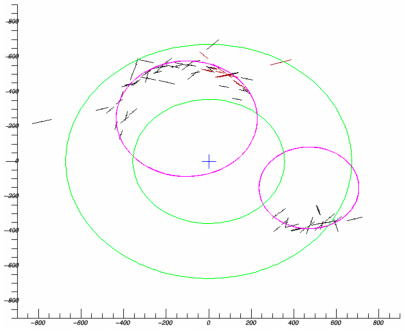




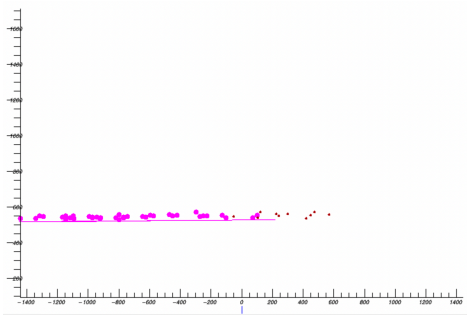
— Muon. — Pion. — Electron



Event : 148



XY view



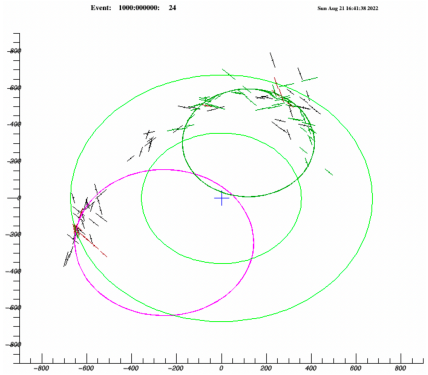
TZ view

Aim : Reconstruct events with two helices corresponding to two particles produced at the same time and understanding the efficiency of reconstruction which may tell us whether this approach is feasible.

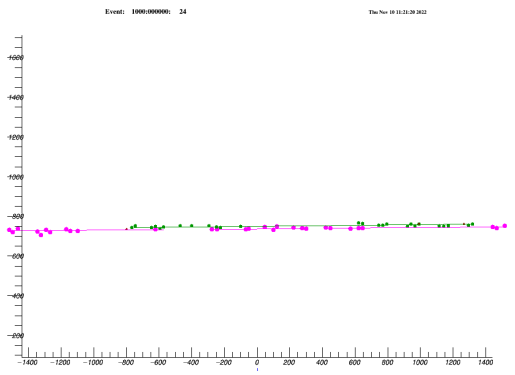
Step 1 : From the visual inspection of the events, we decided to start with the simple cases where two distinct groups of hits separated in ϕ could be identified.

ϕ cluster finder algorithm

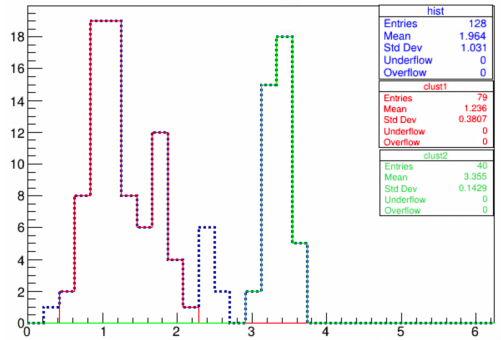
- Input : Combo hits (or Time Clusters)
- Loop through the hits, fill ϕ histogram.
- Find peak bin and go through the bins around it with content > threshold.
- This gives ϕ_{min} and ϕ_{max} for a cluster.
- Repeat the above procedure for the rest of the hits.
- Form time clusters (algorithm borrowed from the present Offline TimeClusterFinder) from the hits of a ϕ cluster.
- If the time cluster has > 10 straw hits, add it to the event.



XY View



TZ view

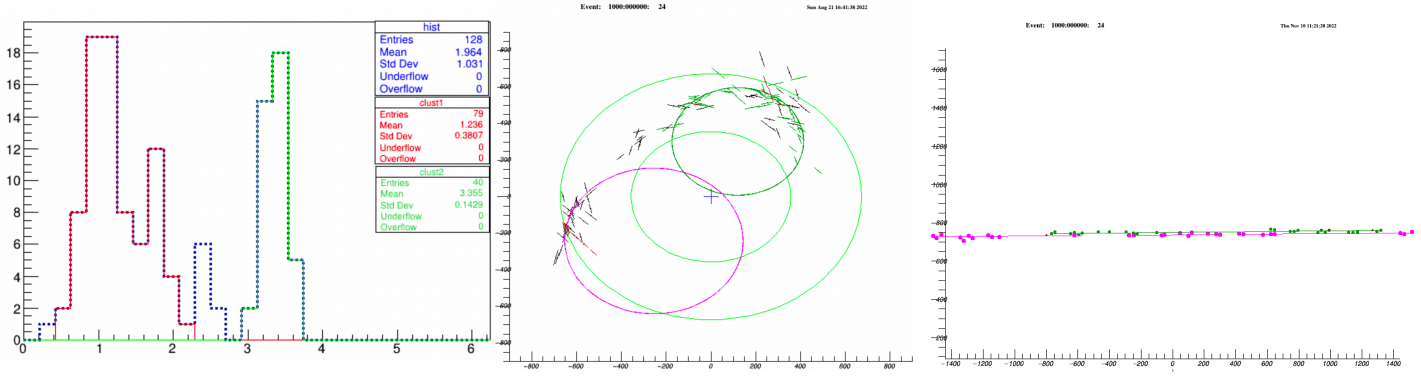


Event : 24 $\Delta\phi$ = 2.11854

— Muon — Pion

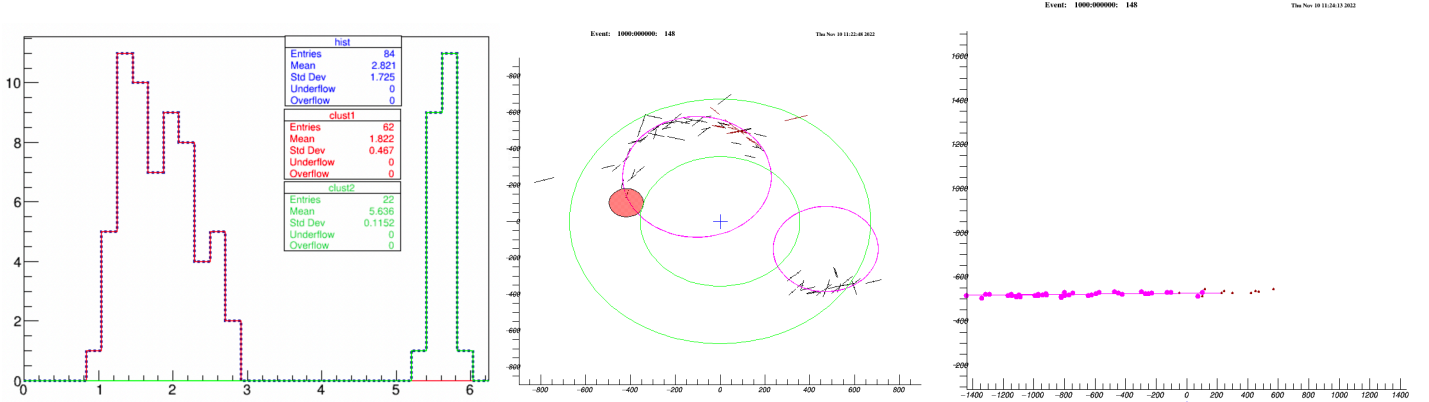
ϕ clusters

- Event 24
  Cluster 1 : 79 straw hits
  Cluster 2 : 40 straw hits
  $\Delta\phi$: 2.12



Event : 24 Delta phi : 2.11854

- Event 148
  Cluster 1 : 62 straw hits
  Cluster 2 : 22 straw hits
  $\Delta\phi$: 2.47

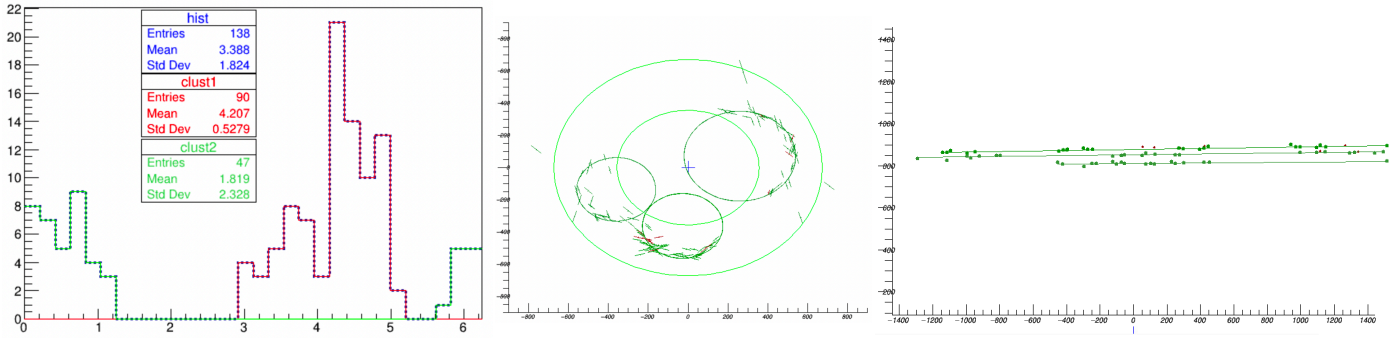


Event : 148 Delta phi : 2.46929

—— Muon —— Pion

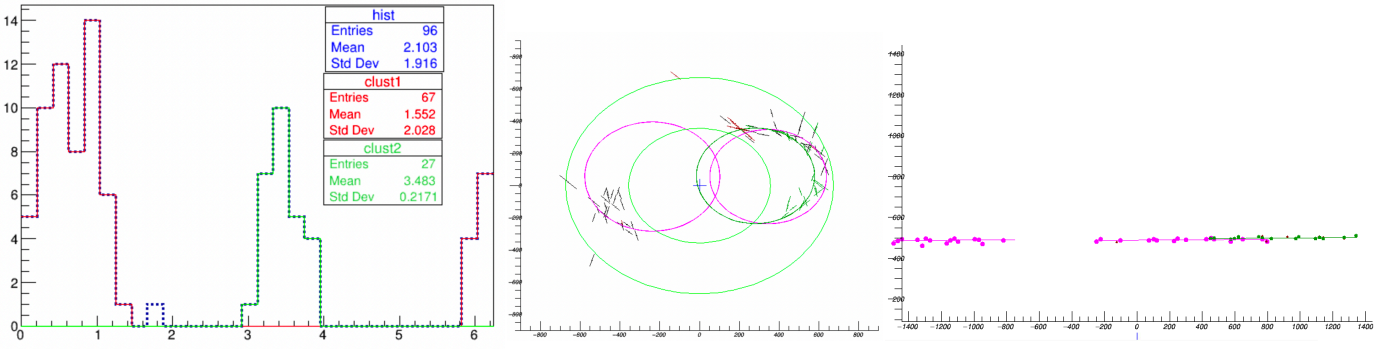
ϕ clusters

- Event 258
  Cluster 1 : 90 straw hits
  Cluster 2 : 47 straw hits
  $\Delta\phi$: 2.43



Event : 258 Delta phi : 2.42506

- Event 259
  Cluster 1 : 67 straw hits
  Cluster 2 : 27 straw hits
  $\Delta\phi$: 2.6



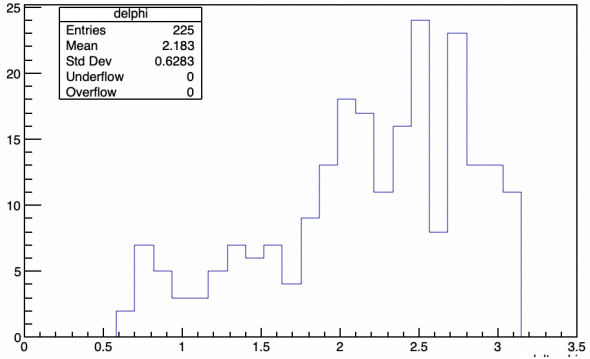
Event : 259 Delta phi : 2.96271

— Muon — Pion

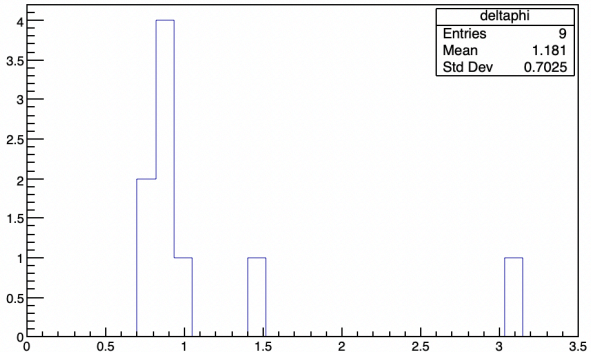
$\Delta\phi$ comparison between $p\bar{p}$ and conversion e^- events

- $\Delta\phi$ distribution is filled with events where two time clusters are found with each time cluster having > 10 straw hits

Input : ComboHit Collection

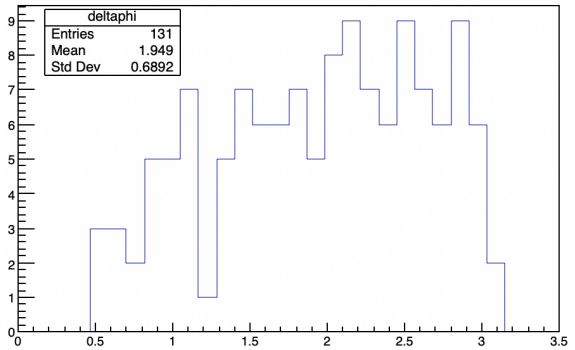


$p\bar{p}$ data

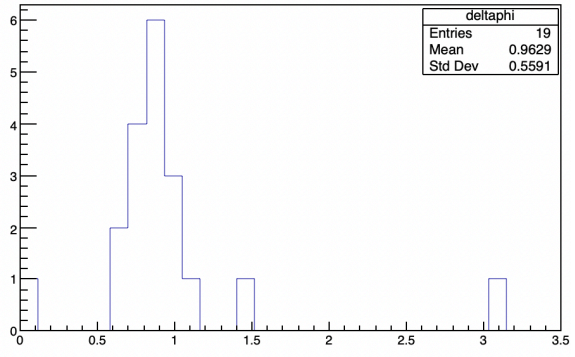


Conversion e-

Input : TimeCluster Collection

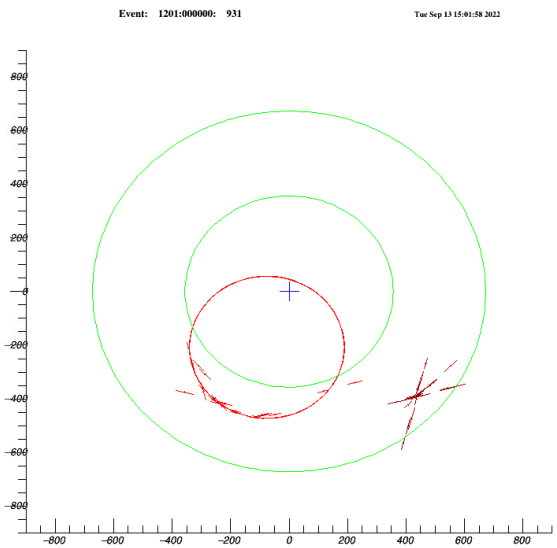


$p\bar{p}$ data

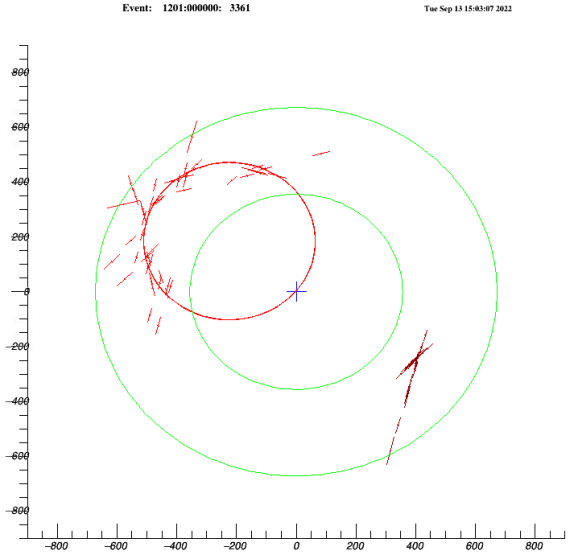


Conversion e-

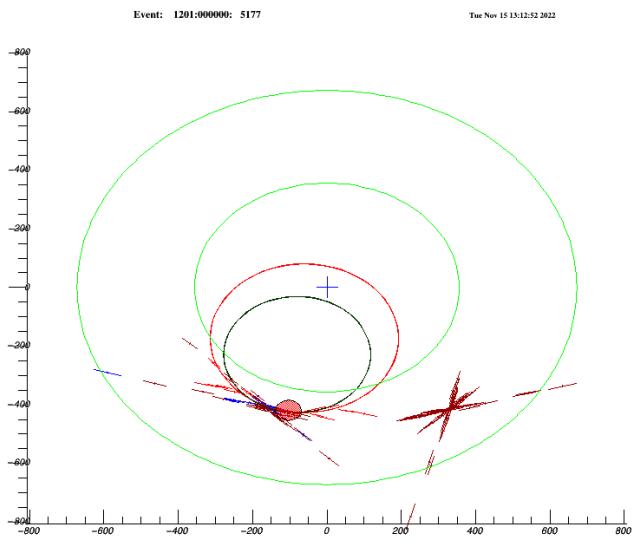
Conversion e^- events with $\Delta\phi \geq 1$ rad



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



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

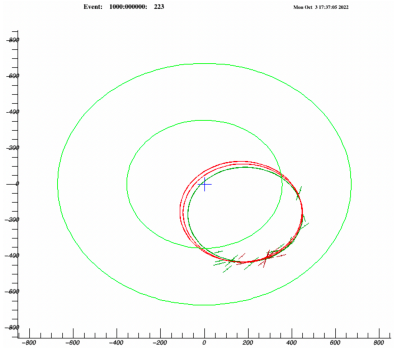


Event : 5177, $\Delta\phi$ = 1.06 rad

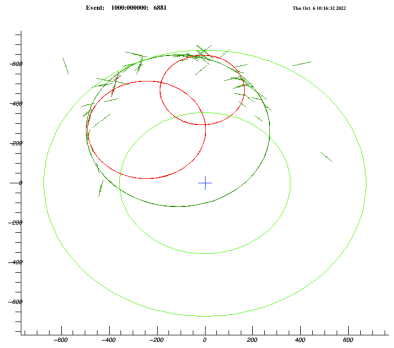
Note : The compton e+/e- forms the second ϕ cluster.
But they are not saved.

Some cuts/enhancements made to the PhiClusterFinder

- Issue 1 : 1 cluster found by the PhiClusterFinder but 2 helices. Issue at the MergeHelices nOverlap criteria as no. of overlapping hits < 10.
- Solution : Changed the criteria from " if nOverlap > 10 AND overlap fraction > 0.5 " to just " if overlap fraction > 0.5 " then compare the helix candidates.

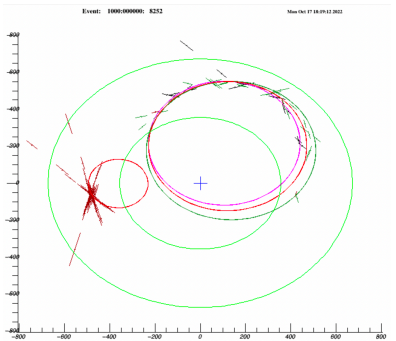


Example of Issue 1



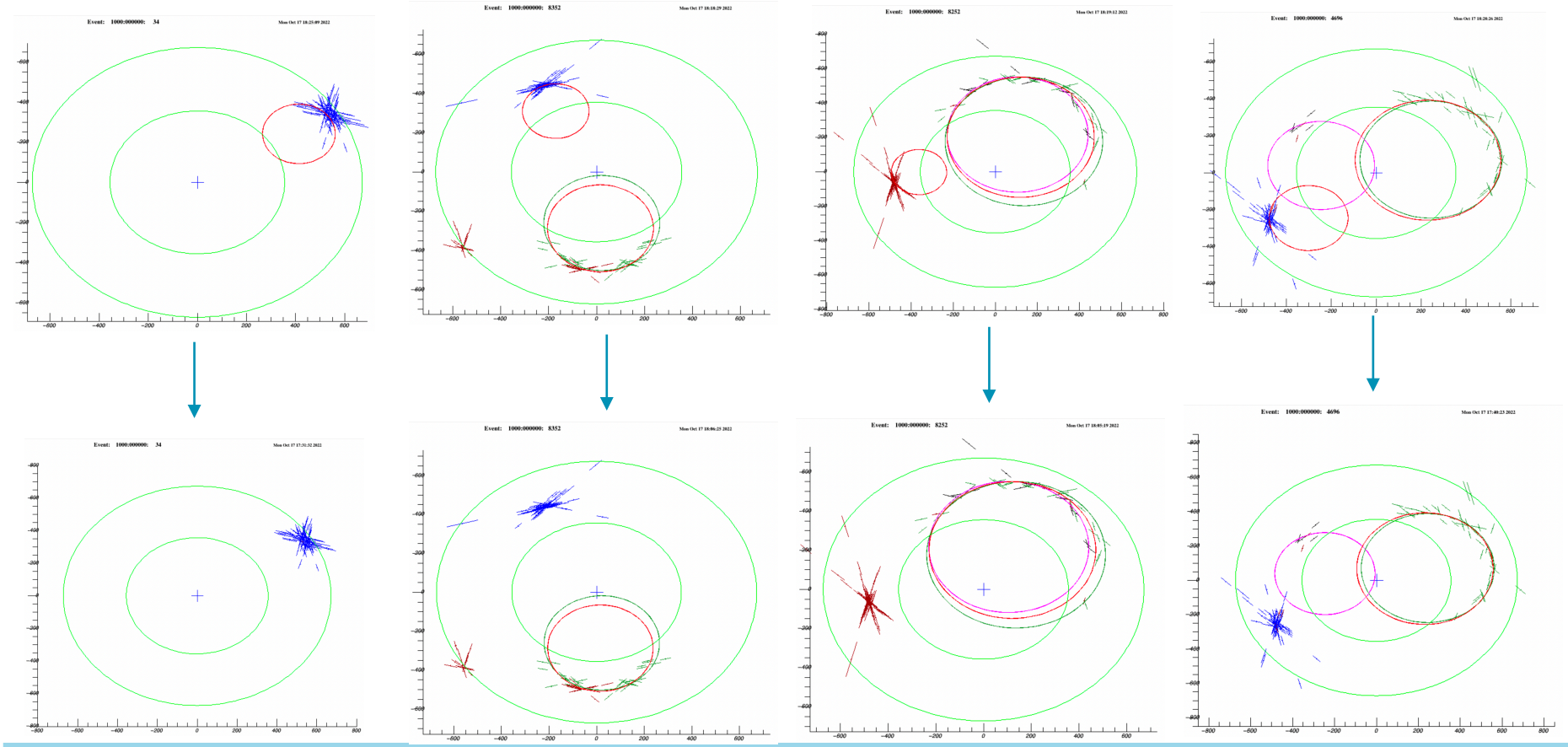
Example of Issue 2

- Issue 2 : Two clusters found with $\Delta\phi < 1.5$ are mostly events with a single off-axis produced particle with large radius.
- **Solution : $\Delta\phi$ cut at 1.5 rad.**
- Issue 3 : Two clusters found with $\Delta\phi > 1.5$ but one of the clusters is formed by a delta e-/+.
- Solution : When a cluster has > min straw hits (40) check the sigma of its ϕ distribution. If sigma < min. limit (0.1) it is vetoed as a compton e-/e+.



Example of Issue 3

The compton electron issue is resolved



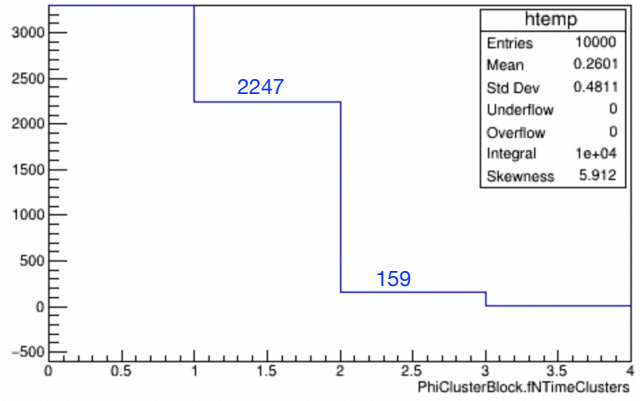
Time cluster(s) per event

- After a $\Delta\phi > 1.5$ cut, we obtain 159 events with two clusters in each event.

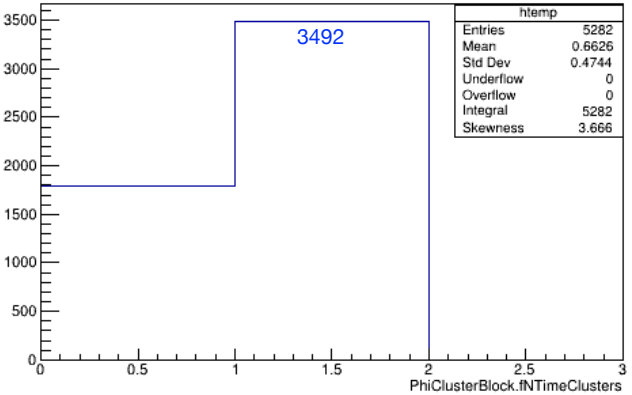
- With the ϕ cluster finder,

  1. For 10^4 generated $p\bar{p}$ events : 159 events with two clusters.

  2. For CE events : 3492 events with single cluster.

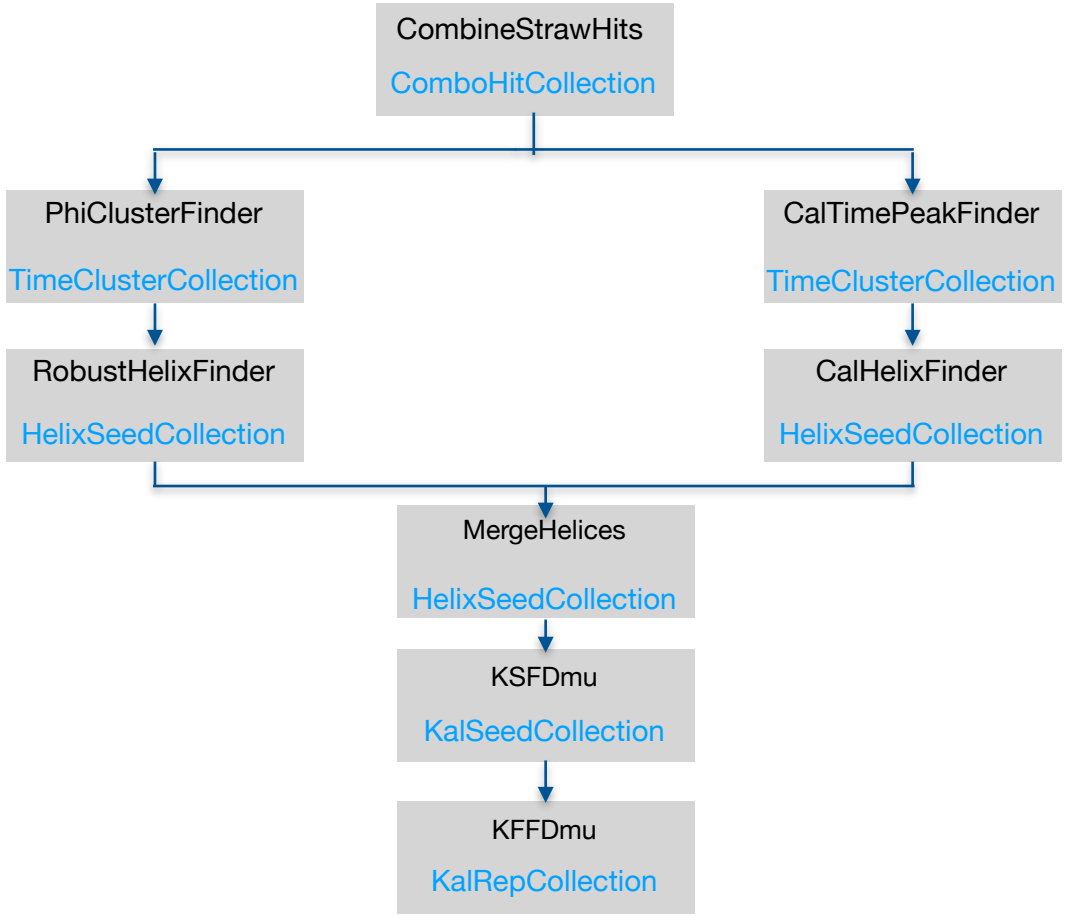


$p\bar{p}$ data

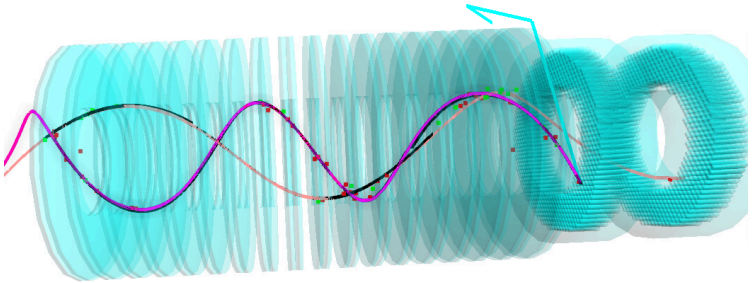


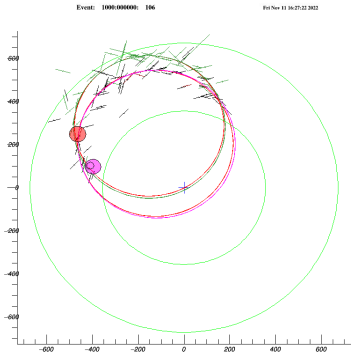
Conversion e-

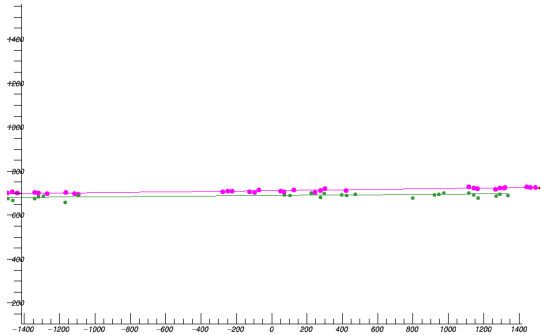
Reconstruction workflow

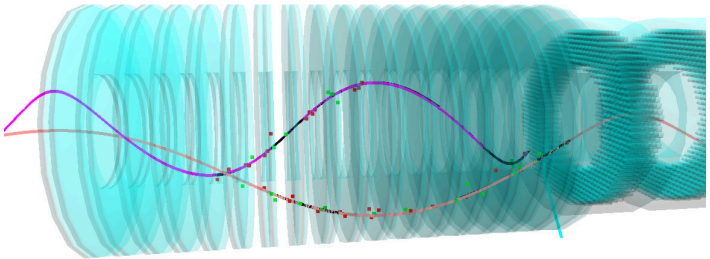


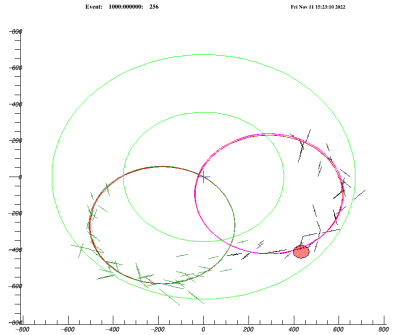
Some events with two reconstructed tracks

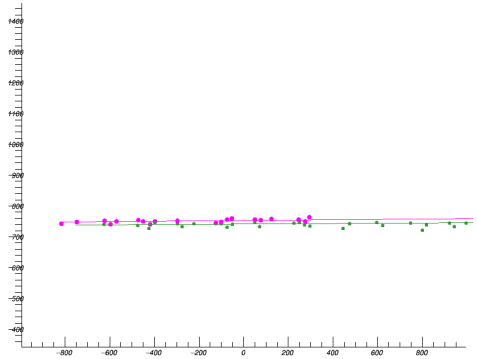












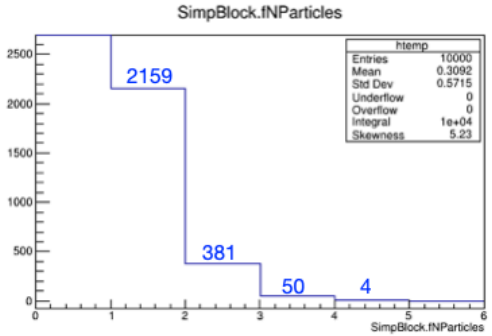
—– Muon —– Pion —– Track

—– Muon. —– Pion —– Helix —– Track

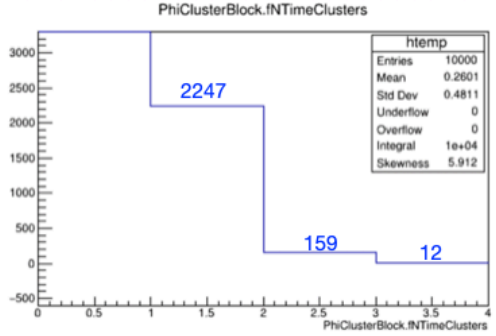
Sim Particles -> Time Clusters -> Helices ->Tracks

- 381 events with two sim particles with > 20 straw hits associated to each particle.
- 159 events with two time clusters.
- About 67% of these events are correctly identified 2 particle track events.
- 133 events with two helices.
- 71 events with two tracks.
- 90% of these two track events are events with two sim particles.

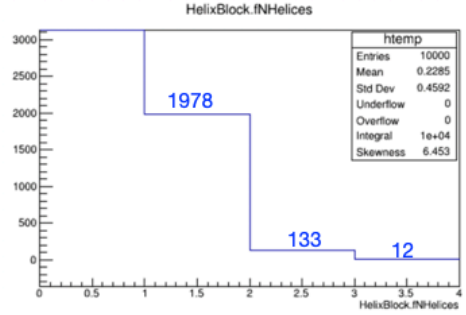
- Overall, about 19% of the two sim particle events are correctly identified and reconstructed.



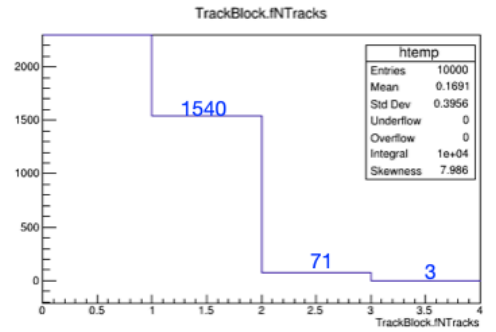
I



II



III



IV

Conclusion

- With the PhiClusterFinder we can identify particle trajectories which are simultaneous in time but separated in ϕ.
- In the study of the $p\bar{p}$ events,

  -> In 10^4 generated events, about **3.7 %** of the events contained **2 particle tracks** with > 20 straw hits per particle and about **0.15%** of the events contain single **electron tracks** with > 20 straw hits and momentum in the range of 90-110 MeV/c.

  -> With a $\Delta\phi > 1.5$ cut, 159 events with two clusters are selected.

  -> After complete reconstruction, we found 71 events with 2 tracks. 90% of these events are events with two sim particles.

  -> So, about 19% of the two sim particle events are correctly identified.

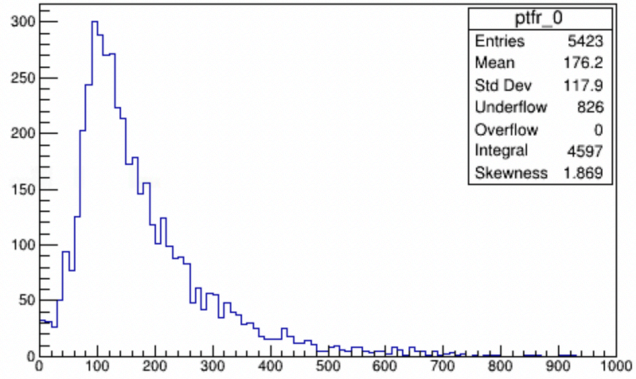
- **At present,** $\frac{N_{>=2particle}}{N_{e^-perMeV}} \sim \frac{71 * (110 - 90)}{15} \sim 10^2$**. The expected background is small** $\sim 10^{-2}$**, so the expectation is that we will end up with an upper bound on the** $p\bar{p}$ **background.**

Next Steps

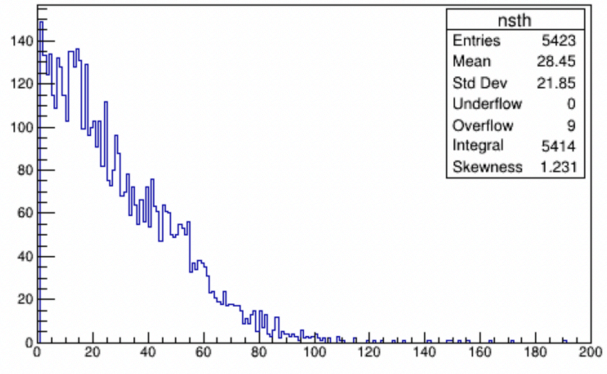
- We continue to investigate the efficiency of the standard triggers for $p\bar{p}$ events. If the efficiency of one-track trigger turns out to be high enough, that would be ideal.
- If the efficiency turns out to be insufficient, we may have to think about a two-helix trigger (so far, this is the only proposal)
- Generate $p\bar{p}$ data mixed with background and test the PhiClusterFinder.

Back up Slides

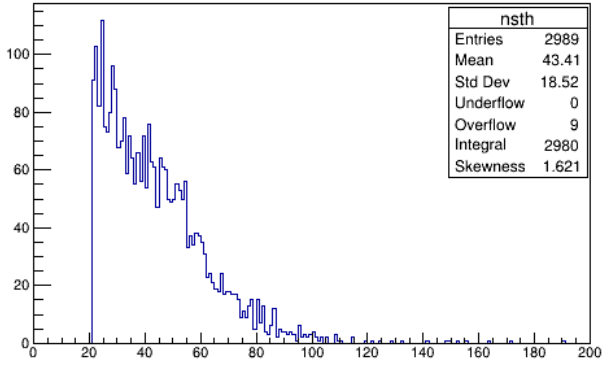
SimParticles



Momentum(MeV/c) at VD 13

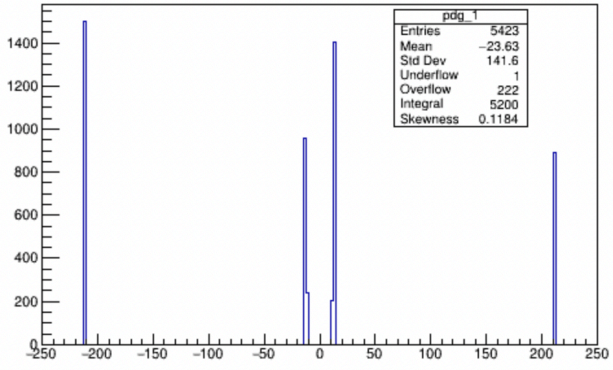


N straw hits

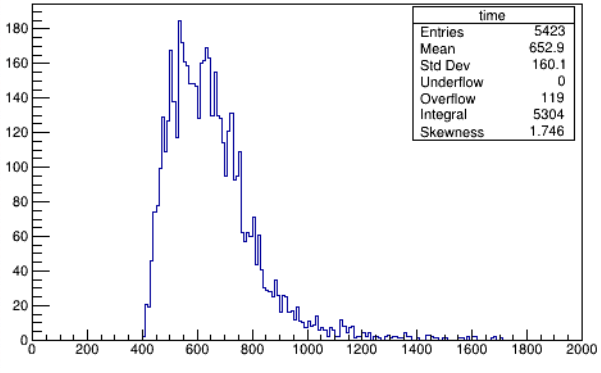


N straw hits

- 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.

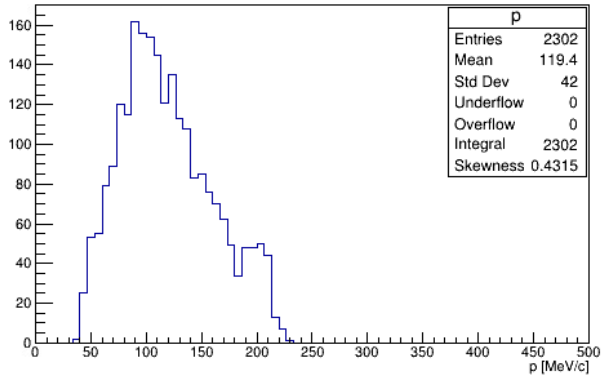


PDG code

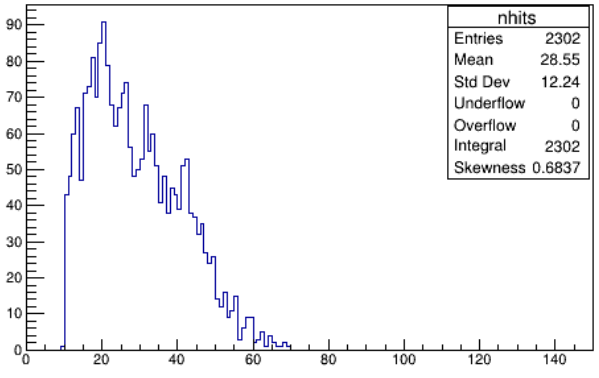


Time (ns)

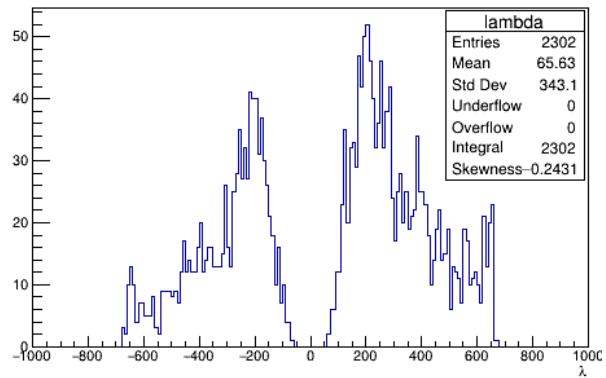
All Helices



Total momentum (MeV/c)

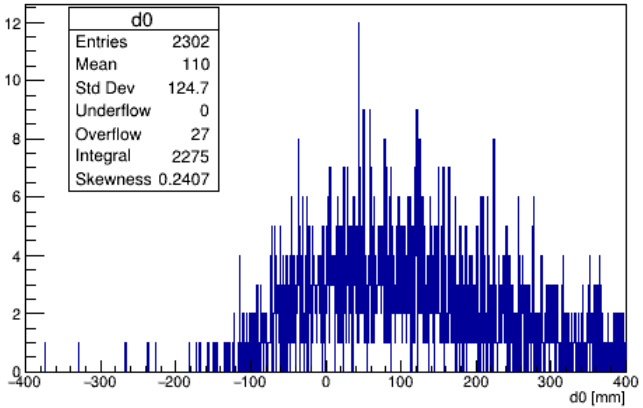


N straw hits

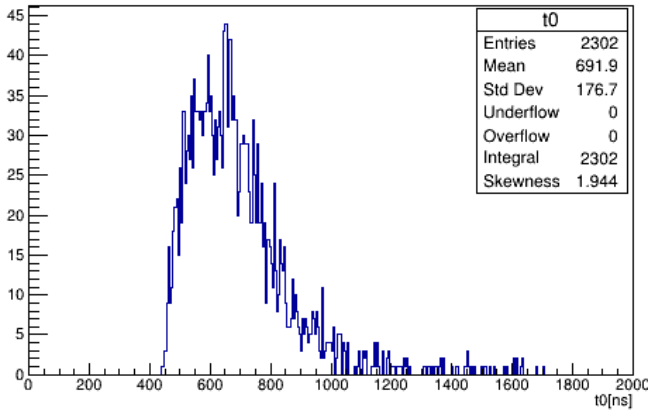


Lambda

- 1978 events with 1 helix
- 133 events with 2 helices
- 50 events with 3 sim particles.

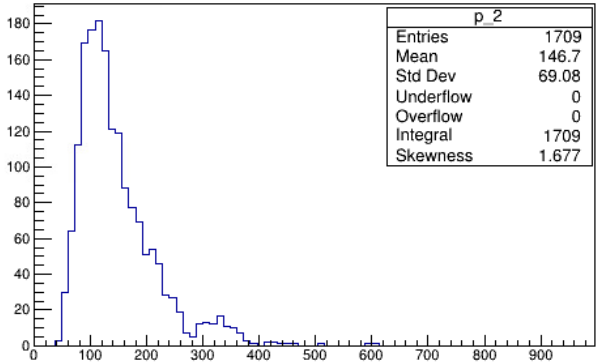


D0

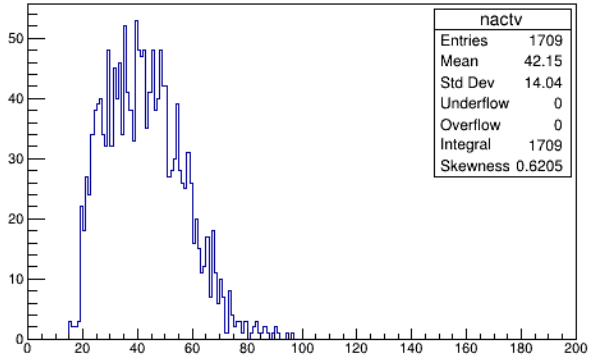


T0

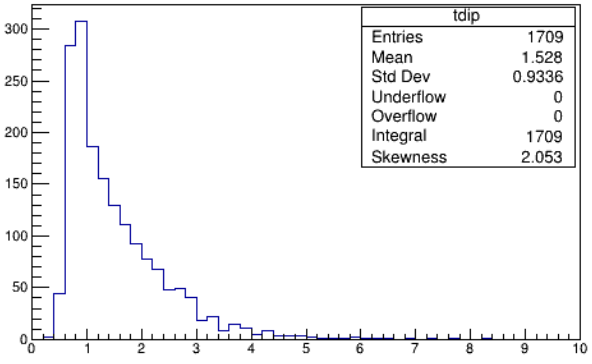
All reconstructed tracks



Total momentum (MeV/c)

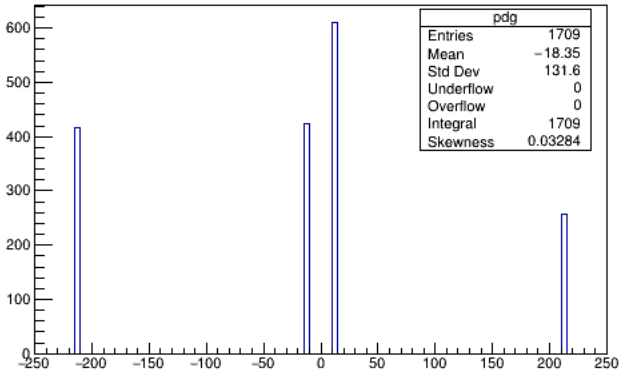


N(active) hits

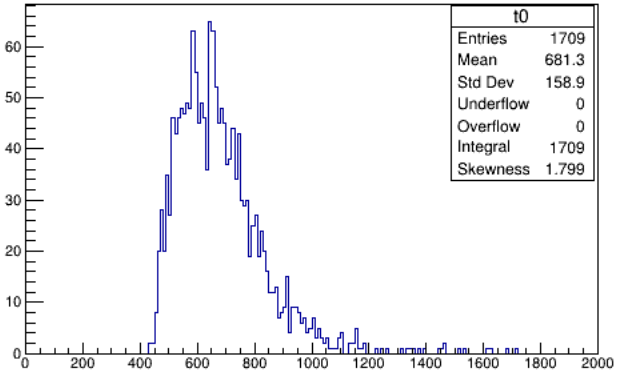


tan(dip)

- 1540 events with 1 track.
- 71 events with 2 tracks.



PDG code



Trk T0

Time clustering from the found ϕ clusters

- Calculate the time of each combo hit of a ϕ cluster and fill the time spectrum (no. of bin entries = no. of straw hits forming the combo hit)
- Find the T0 of this spectrum.
- Assign/push back the combo hits to the time cluster if they belong to the time/phi spectrum after checking that the combo hit time - T0 < maxdT.
- Create the time cluster with these combo hits and calculate the T0 as the weighted median of the sum combo hit time where the weight on each combo hit time is the no. of straw hits.

```
PhiCluster : { module_type : PhiClusterFinder
  ComboHitCollection     : "makePH"
  #TimeClusterCollection  : "TimeClusterFinderDmu"
  DiagLevel              : 0
  DebugLevel             : 0
  MinNStrawHits          : 10
  MinCount               : 10
  Threshold              : 2 # 4
  Phimin                 : 0.0
  Phimax                 : 6.238
  Phibin                 : 0.207
  DeltaPhimin            : 1.5
  Tmin                   : 0.0
  Tmax                   : 100000.0
  Tbin                   : 15.0
  AveragePitch           : 0.6
  Ymin                   : 5.0
  PeakWidth              : 100
  MaxdT                  : 150
  MinSigma               : 0.1
  T0Calculator           : {}
}
```

Issues with the time cluster as input

- 2 time clusters were found in some events with repeated hits.
- Some hits were left out due to $\Delta\phi < 1.5$ and peak width = 1 conditions

```
TimeClusterFinder : {
  module_type            : TimeClusterFinder

  ComboHitCollection     : "makePH"
  StrawHitFlagCollection : "FlagBkgHits:ComboHits"
  CaloClusterCollection  : "CaloClusterMaker"
  ClusterMVA             : { MVAWeights : "Offline/TrkPatRec/data/TimeCluster.weights.xml" }
  ClusterCaloMVA         : { MVAWeights : "Offline/TrkPatRec/data/TimeClusterCalo.weights.xml" }
  HitSelectionBits       : ["EnergySelection","TimeSelection","RadiusSelection"]
  HitBackgroundBits      : @local::PatRecBackground
  UseCaloCluster : true
  UseCaloClusterPosition : true
  CaloClusterWeight      : 10.0
  TestFlag               : true
  CaloClusterMinE        : 50.0
  CaloClusterWeight      : 10.0
  T0Calculator           : {}
  DtMax                  : 25
  MinNHits               : 10
  MinKeepHitMVA          : 0.2
  MinAddHitMVA           : 0.2
  MaxdPhi                : 1.5
  Tmin                   : 0.0
  Tmax                   : 100000.0
  Tbin                   : 15.0
  AveragePitch           : 0.6
  Ymin                   : 5.0
  RefineClusters         : true
  PrefilterCluster       : true
  RecoverHits            : true
  PeakWidth              : 1
}
```

Solution

- Now we find single time clusters with most of the combo hits.
- But in some events we still observe the loss of combo hits (examples in the next slide)

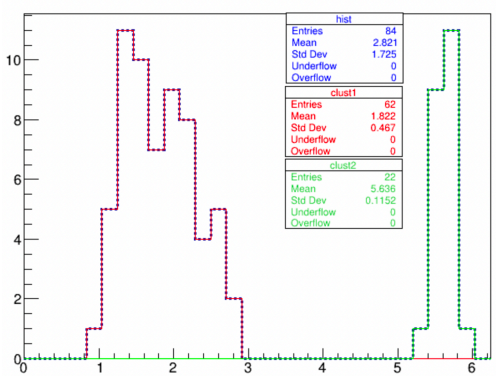
```
#------------------------------------------
physics.producers.TimeClusterFinderDmu :
    ComboHitCollection     : "makePH"
    UseCaloCluster         : false
    TestFlag               : false
    MinNHits               : 10
    MinKeepHitMVA          : -1.0
    MinAddHitMVA           : -1.0
    MaxdPhi                : 100.0
    PeakWidth              : 100
}
```

Changes made to the TimeClusterFinder settings

Examples of events where the effect of the loss of hits is observed

Event : 148
Input straw hits = 84
2 output ϕ clusters with 62 and 22 hits
$\Delta\phi$ = 2.47

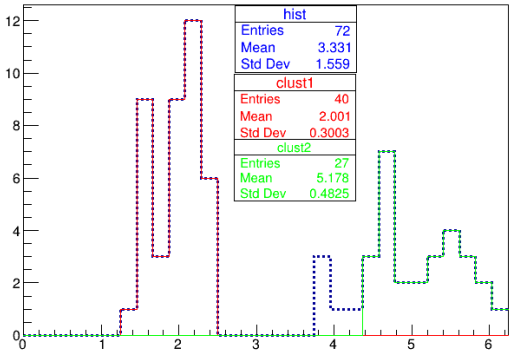
Input time cluster straw hits = 76
2 output ϕ clusters with 61 and 15 hits



So, for this study we need a physics-neutral time clustering.

Event : 1385
Input straw hits = 72
2 output ϕ clusters with 40 and 27 hits
$\Delta\phi$ = 3.11

Input time cluster straw hits = 62
2 output ϕ clusters with 42 and 19 hits



```
physics : {

    producers : { @table::Reconstruction.producers
        PhiCluster    : { @table::PhiCluster
          #  TimeClusterCollection : "TimeClusterFinderDmu"
        }

        MHFinderDmu   : { @table::TrkReco.producers.MergeHelices
            HelixFinders: [ "MHDmuM", "MHDmuP" ]
        }

        KSFDmu : { @table::KSFDmuM
            SeedCollection : "MHFinderDmu"
            CheckHelicity  : false
        }

        KFFDmu : { @table::KFFDmuM
            SeedCollection : "KSFDmu"
        }
    }
```

No. of Time cluster(s) per event

- With ϕ cluster finder,

  1. For $p\bar{p}$ events : 159 events with two clusters

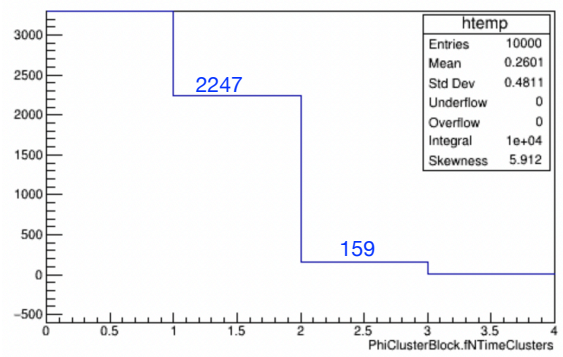
  2. For CE events : 3492 events with single cluster

- With TZ cluster finder,

  1. For $p\bar{p}$ events : 70 events with two clusters

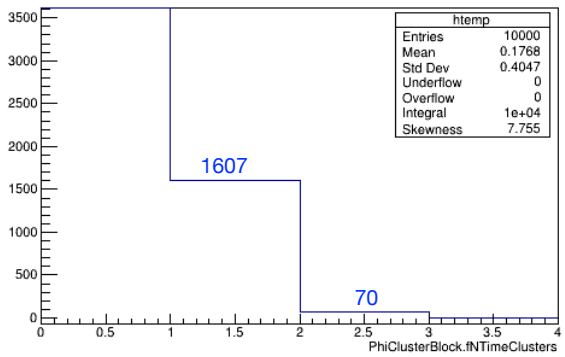
  2. For CE events : 3624 events with single cluster

PhiClusterFinder

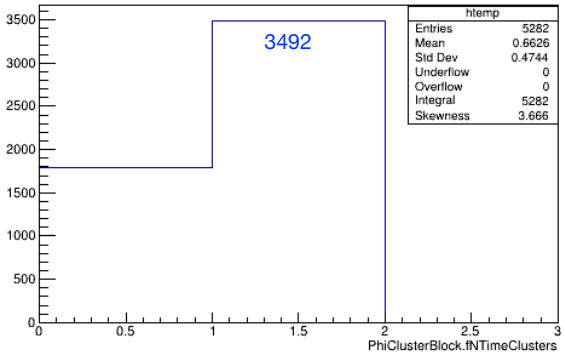


$p\bar{p}$ data

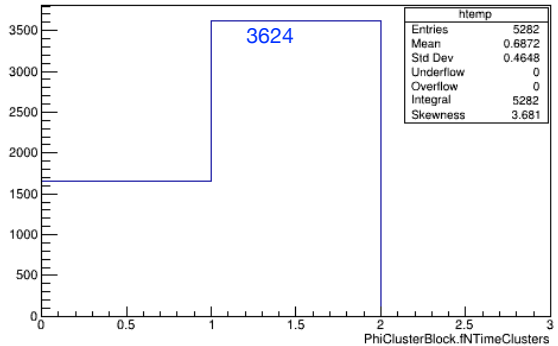
TZClusterFinder



$p\bar{p}$ data



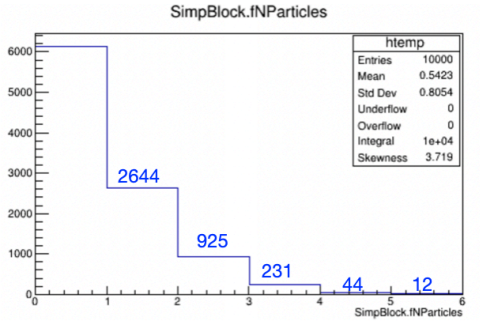
Conversion e-

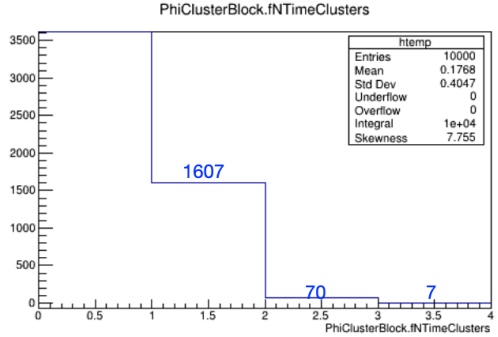


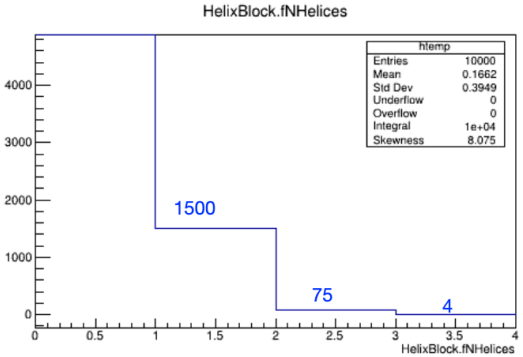
Conversion e-

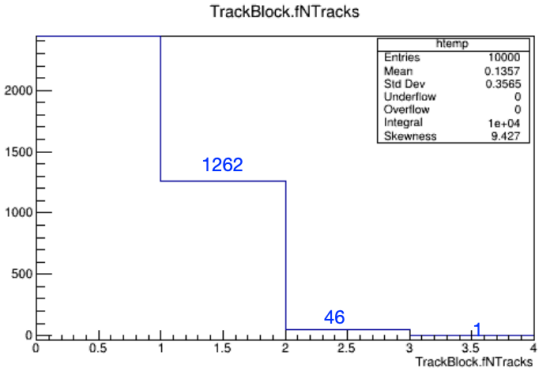
Sim Particles -> Time Clusters -> Helices ->Tracks (with TZClusterFinder)

- 364 events with two sim particles with > 20 straw hits associated to each particle.
- 70 events with two time clusters.
- 75 events with two helices.
- 46 events with two tracks.



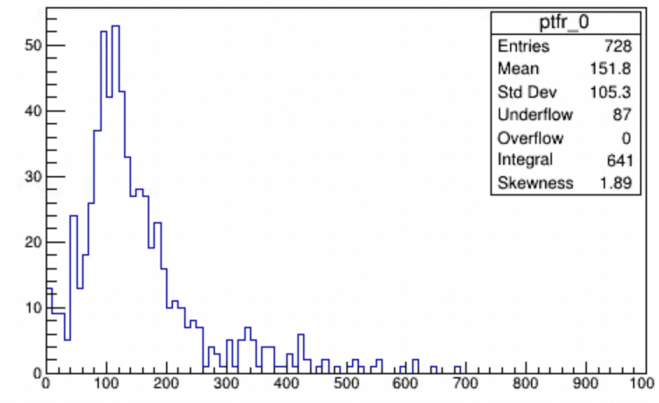


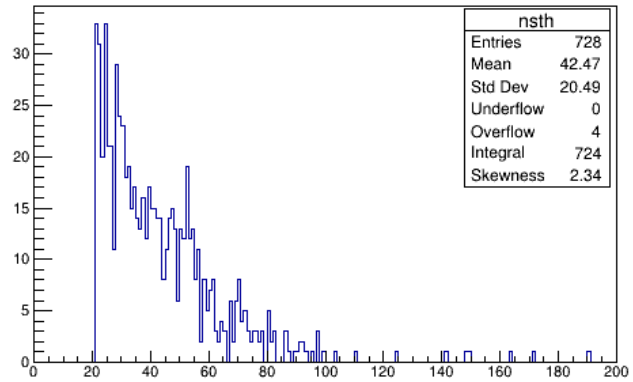


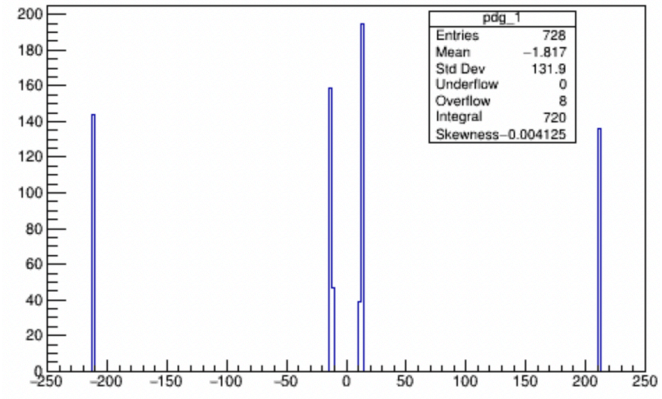


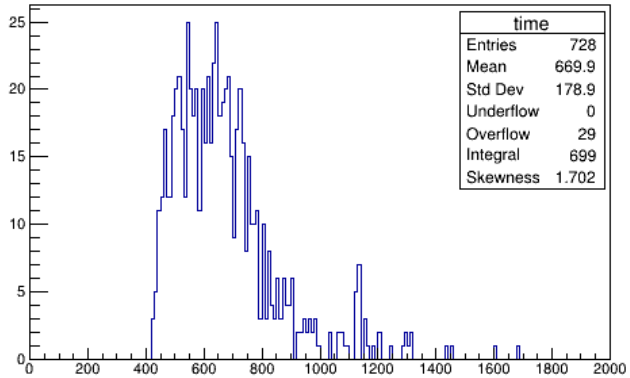
SimParticles

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

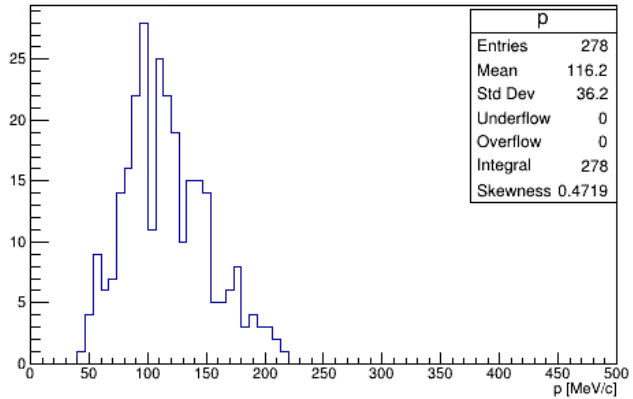


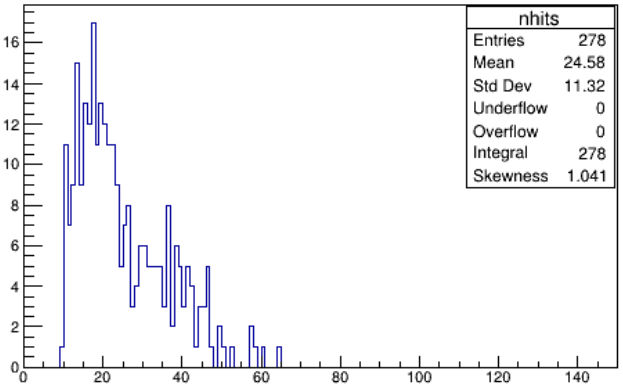


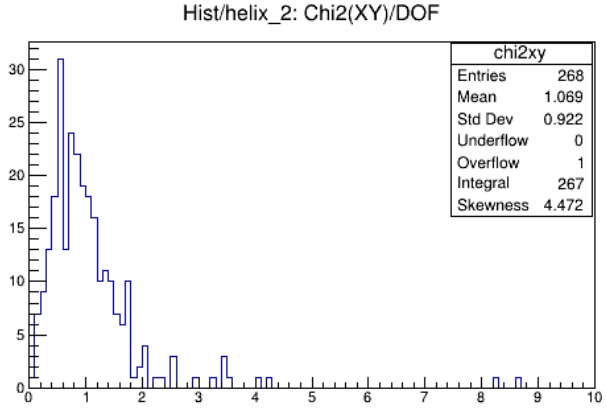


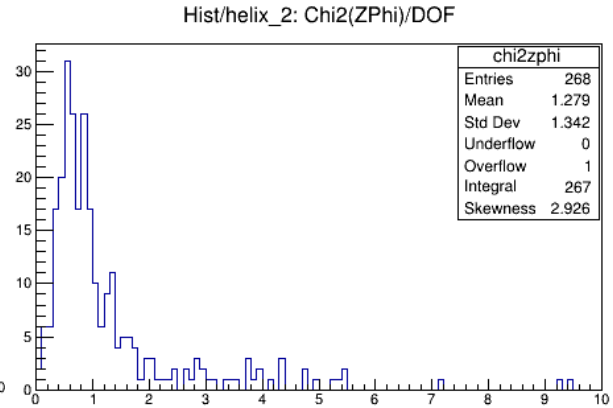


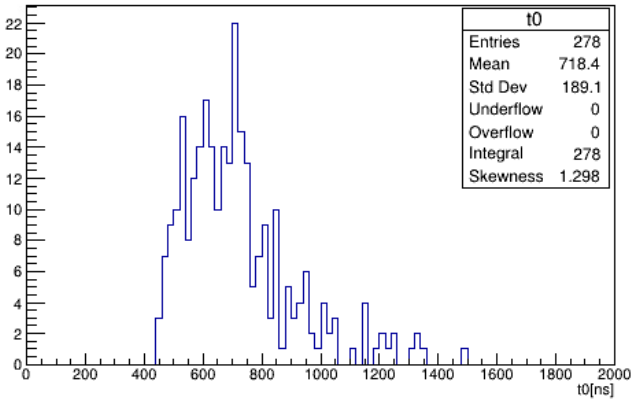
2 helices per event





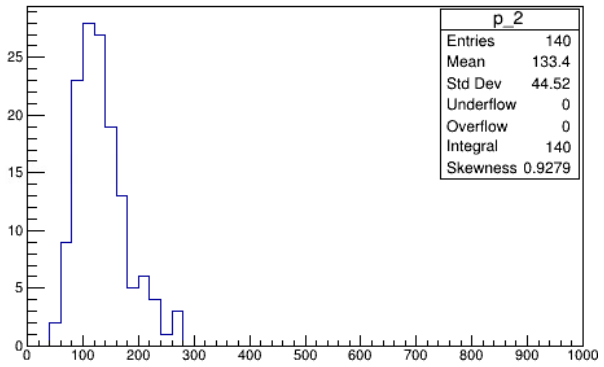




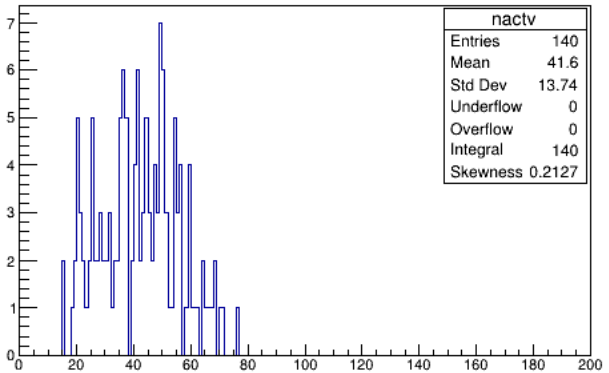


Some relevant distributions of two track per event cases

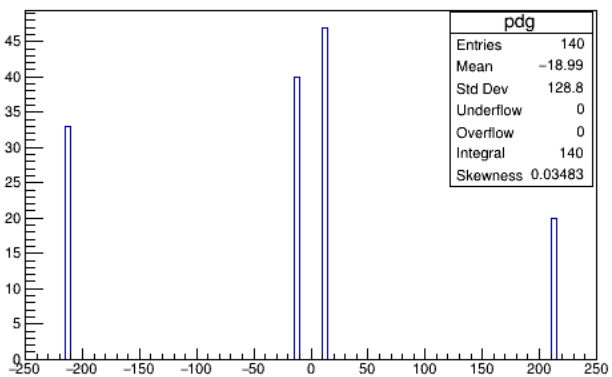
- 70 events with two reconstructed tracks per event
- Most of the tracks are in the high momentum range.
- The tracks are mostly muon and pion tracks, as expected.
- Track T0 is good too?



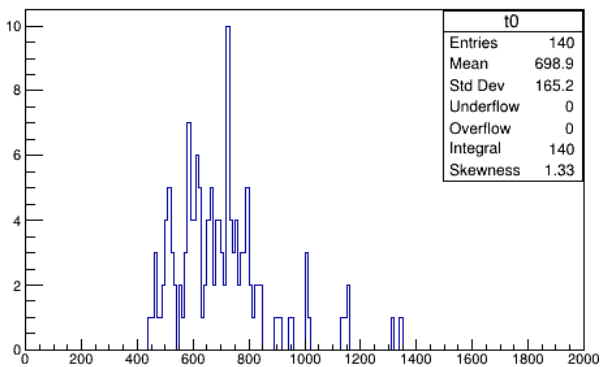
Momentum



N(active) hits

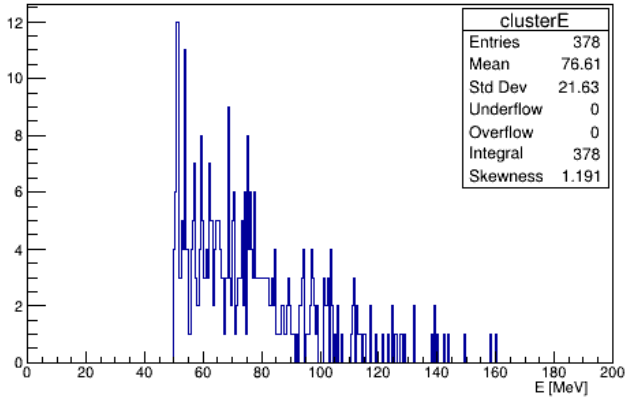


PDG code

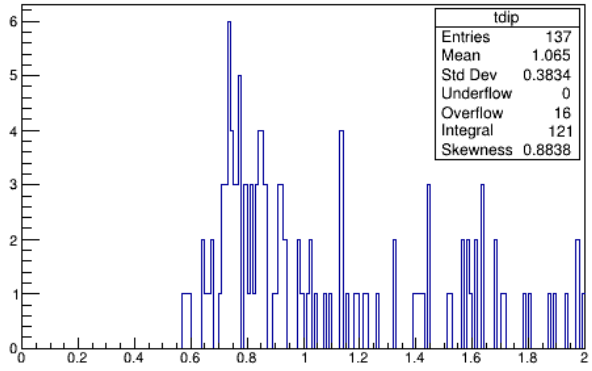


Trk T0

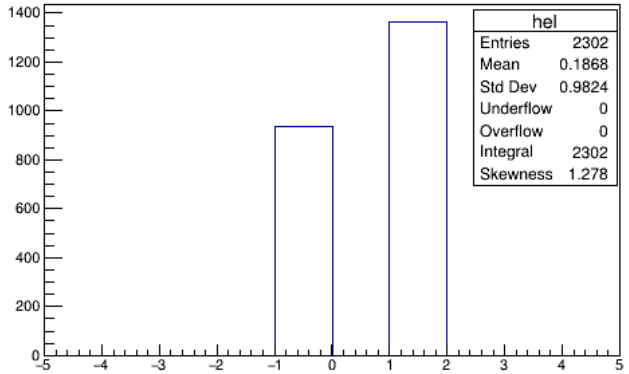
Hist/helix_0: cluster energy



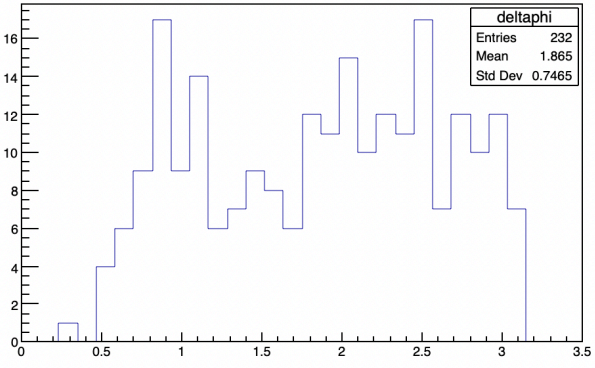
Hist/trk_4: track tan(dip)



Hist/helix_0: Helicity



deltaphi



deltaphi