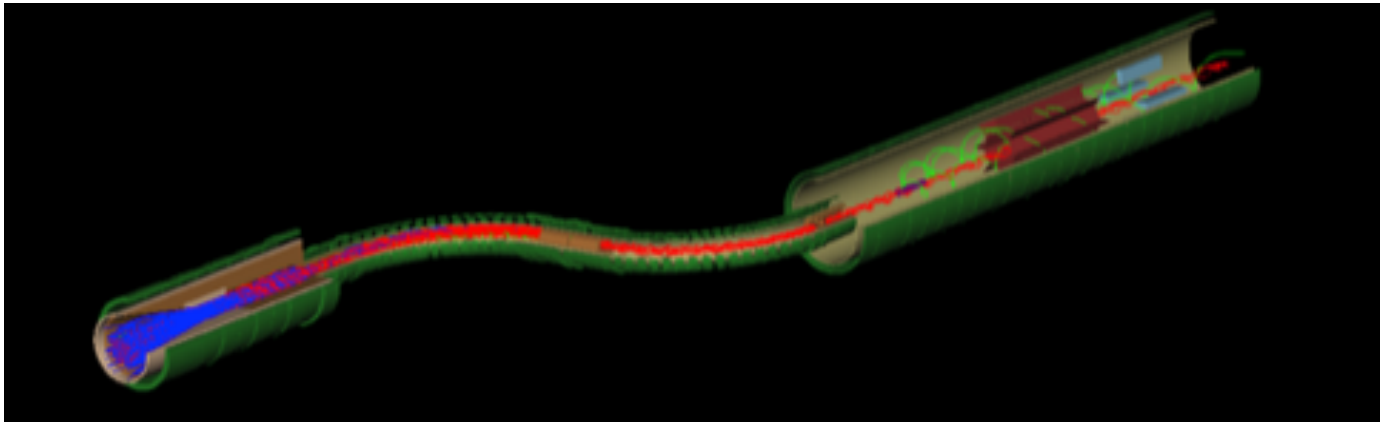

Mu2e : Developing the Offline Event Display and the Track Selection Algorithm

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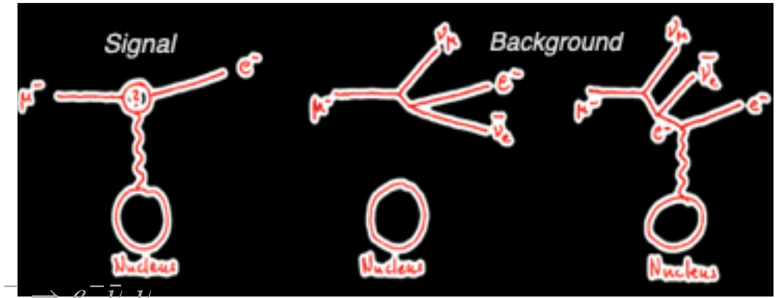
Overview

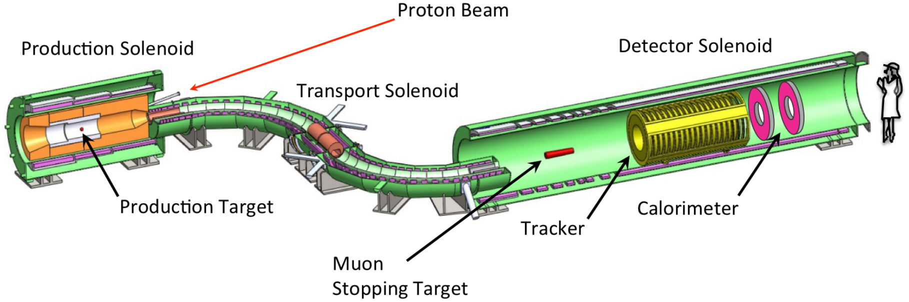
- Mu2e will search for the neutrino-less, coherent conversion $\mu \rightarrow e$ in the field of an Al nucleus, an example of the Charged Lepton Flavour Violation (CLFV) processes, by measuring the ratio :

$$R_{\mu e} = \frac{\mu^- + N(Z,A) \rightarrow e^- + N(Z,A)}{\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A)}$$

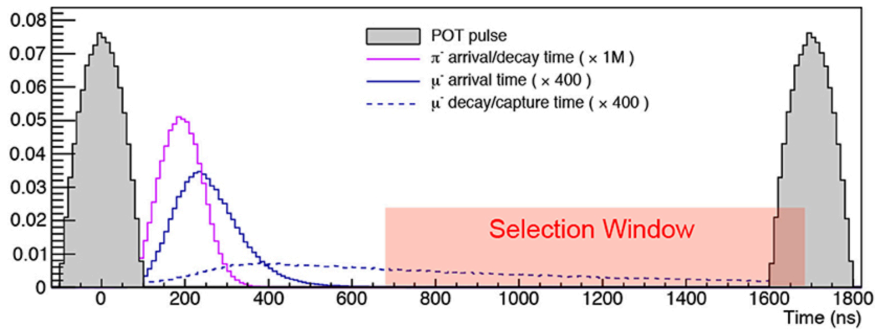


- Signal : Monochromatic Electron of energy $E_e = m_\mu - E_b - E_{recoil} \approx 104.97 MeV$
- Goal : Single-event sensitivity of $3 * 10^{-17}$
- Possible Background(s) :
  1. Intrinsic background : Decay of muons in the atomic orbit in the stopping target (DIO) $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
  2. Beam related : Radiative Pion Capture $\pi^- N \rightarrow \gamma N'$ or Radiative Muon Capture $\mu^- N \rightarrow \gamma N' \nu_\mu$
  3. Cosmic Rays

- The primary, pulsed 8 GeV proton beam with a pulse width of 250 ns FWHM with 1695 ns spacing will collide with the Tungsten Production target in the **Production Solenoid (PS)** and produce pions.
- The backward-going pions decay into muons which spiral through the S-shaped **Transport Solenoid (TS)**. Positive charges are filtered out by a collimator in the TS.
- The μ^- beam will collide with the Al stopping target in the **Detector Solenoid (DS),** where the conversion process may occur. The negative $\vec{\mathbf{B}}$ gradient guides the particles from the upstream (4.6T) to the downstream (1T) end of the last solenoid.



Mu2e Solenoid System

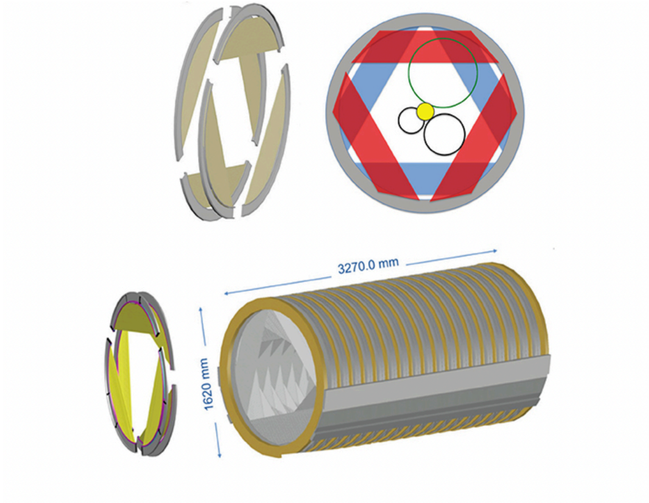


Mu2e beam timing and Event window

Mu2e Detectors

1. Straw-tube Tracker : High precision measurements of electrons with energy > 53 MeV with a momentum resolution < 200 KeV at 105 MeV are made using a low-mass, straw drift tube, annular tracker.

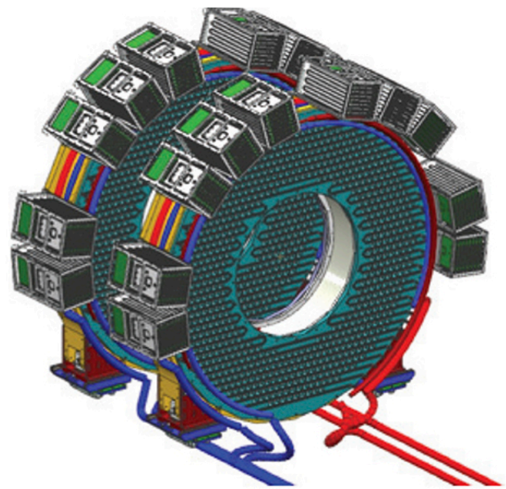
   It consists of 18 stations, evenly spaced along its whole length of 3m. Each station is made of two planes (36 planes total) and each plane consists of 6 panels (216 panels total) rotated by $30°$, on two faces of a support ring; there are three panels per face. Groups of 96 straws are assembled into panels.



Mu2e tracker : The upper left picture shows panels assembled into a plane and a station. The assembled tracker is shown in the bottom figure.

2. Calorimeter : Two disks made of CsI crystals form the calorimeter that measures the energy of the electron leaving the stopping target. In addition to providing precise timing ($\sigma_t \approx$ 100ps) and particle identification, the locations of showers in the calorimeter seed the tracker.

   The separation between the two disks is specifically chosen to be “half a wavelength” for the 105 MeV/c conversion electron in the 1 T field: if a conversion electron passes through the hole at the centre of the first disk, it will hit the second.

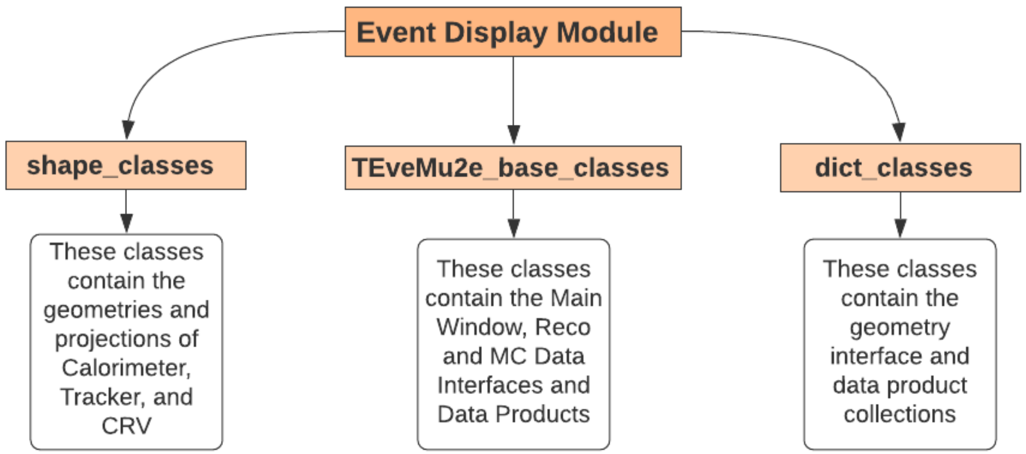


A schematic of the Mu2e calorimeter showing the two disks, location of readout modules, and part of the calibration system

Offline Event Display Development using TEve

- Motivation : Develop a sophisticated, 3-D visual interface useful for experts as well as the general users.
- The display should aid the Mu2e development discussions as well as the public engagement about the experiment.
- TEve https://root.cern/doc/master/group__TEve.html is a ROOT based 3-D event visualisation framework.
- It provides ready-made GUI and it allows to directly import the 3-D geometry from the basic mu2e.gdml.
- It maintains access to the raw art file making it convenient to go between the raw and reconstructed data within the TEve browser.
- The TEve display module fits in seamlessly with the Mu2e environment as it can access all the Mu2e objects and run directly on the art files , the outputs generated in Mu2e. The art file contains the complete information of the events like the HelixSeedCollection, CaloClusters, MC trajectory (MC truth) information.
- The TEveMu2e base classes provide the interface between TEve and the Mu2e Objects.

  For example: TEveMu2eCustomHelix inherits from TEveLine and contains a pointer to KalSeed which is a Mu2e object, TEveMu2eCluster inherits from TEvePointSet and has pointer to CaloCluster.
- TEve provides an easy to use event display with in-built zoom, rotation, perspective change, event navigation and 2-D projection functionalities.



Offline Event Display

We have developed and improved the Offline event display in the following manner :

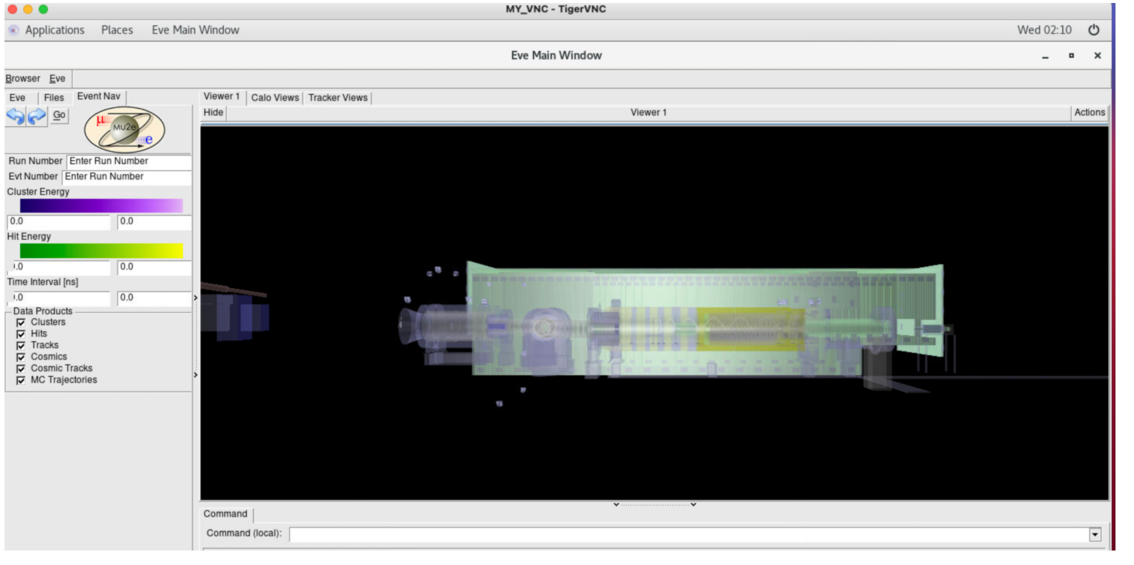
1. Addition of the upstream Monte Carlo truth trajectory (Production and the Transport solenoids) into the event display.

2. Addition of a user defined track selection feature, utilising the particle ID.

3. Improvement of the Monte Carlo truth and reconstructed helices alignment in the Detector solenoid region.

4. Enhancement of the 2-D projection to display the straw hits and the tracker sub-structures.

5. Addition of the Cosmic Ray Veto (CRV) system



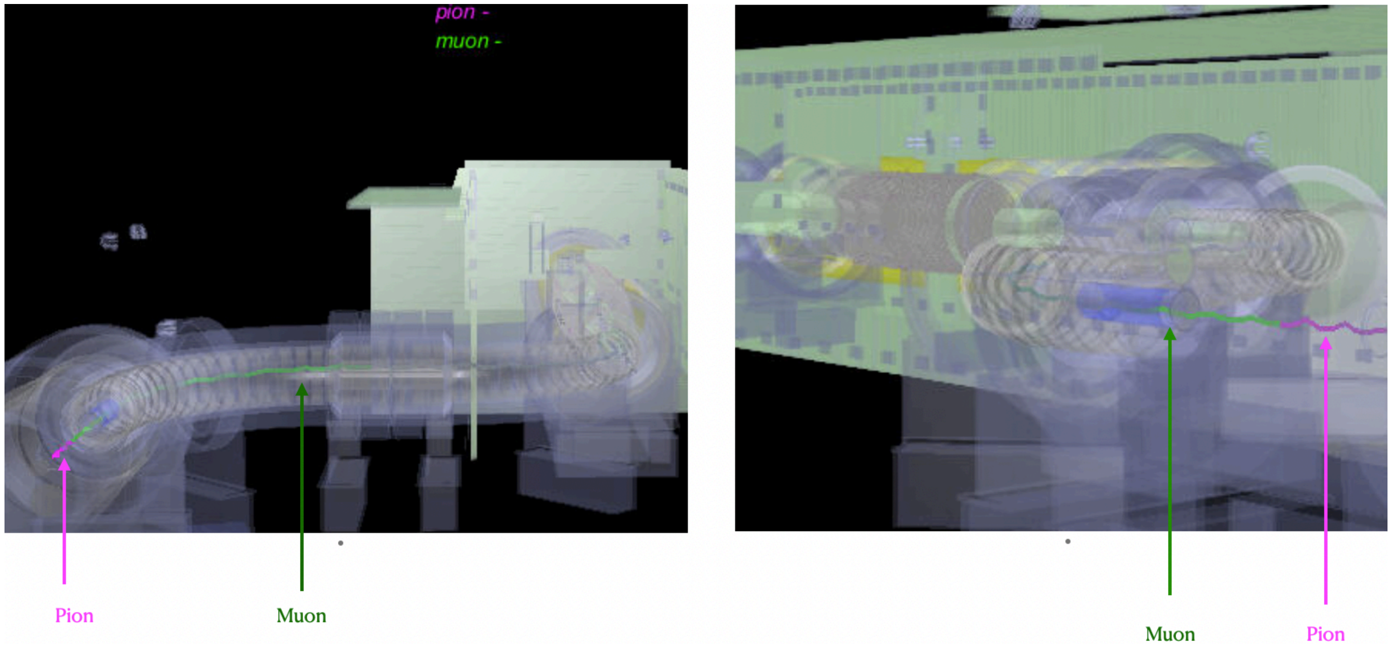
TEve Offline Display Main Window

In the right-hand column, there are buttons and tabs for navigation between events, time interval selection and the option to select the data products that the user would like to display. The user can also open the ROOT browser to peruse the finer details of the event.

The Calo and the Tracker view tabs display the 2-D projections of the respective detectors and the helices.

Upstream visualisation

- The Upstream module : Production and Transport solenoids, have been added to the display, which was solely focused on the Detector Solenoid before.
- The addition of the upstream Monte Carlo tracks enable a complete illustration of the experiment. It could be beneficial in understanding the processes occurring at the Production Solenoid more clearly.
- It helps the user to follow the trajectory of muons from the production region to the muon stopping target, where the conversion may take place or even the pion to muon decay in the TS region.



Pion to muon decay, Upstream Event Display

Track selection feature for the user

- A track selection feature was added into the GUI of the event display. This provides the user the option to select the track of their choice to be displayed. The selection is based on the particle ID.
- The tracks are colour coded and labeled according to their ID and sign.
- This feature works in all the solenoid sections.

```
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    showCRV : false
    showBuilding : false
    showDSOnly : true
    showEvent : true
    isMCOnly : false
    filler : {
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      CrvRecoPulseCollection      :  "CrvRecoPulses"
      CosmicTrackSeedCollection :  NULL
      CaloClusterCollection       :  "CaloClusterMaker"
      CaloHitCollection           :  NULL
      HelixSeedCollection         :  "HelixFinderDe:Negative'
      KalSeedCollection           :  ["KFFDeM"]
      TrkExtTrajCollection        : NULL
      MCTrajectoryCollection      :  "compressDigiMCs"
      addHits                     : true
      addTracks                   : true
      addCrvHits                  : true
      addCosmicSeedFit            : false
      addClusters                 : true
      addTrkExtTrajs              : false
      addMCTraj                   : true

    }
  particles :   [11,13,2212,2112,211,22,212]
  }
```

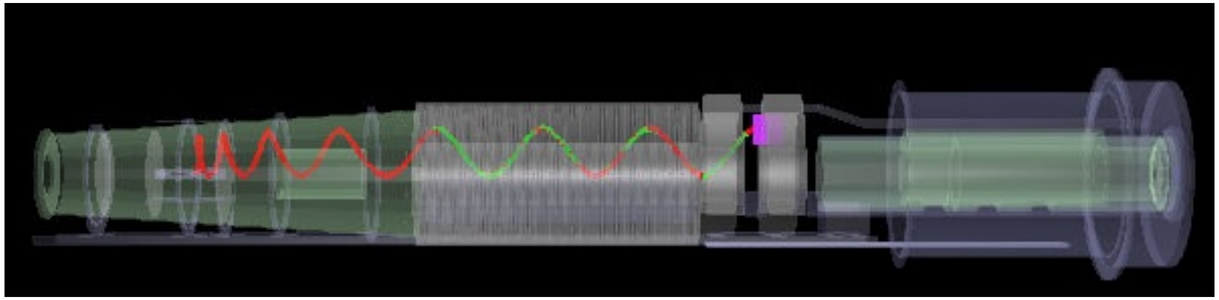
prolog.fcl
Track and other selection features for the end-user

Event X

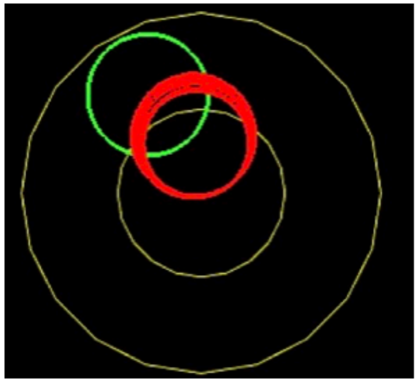
Event Y

Matching the MC truth and reconstructed helices

- The alignment of the MC truth and reconstructed helices has been improved.
- This was achieved by using a module called KalSegment which gives the segment by segment, Kalman filtered co-ordinate information of the reconstructed helix.
- The method initially followed was more an approximation technique where the position and momentum direction vectors at a point on the helical track are used to estimate the coordinates of the next point.

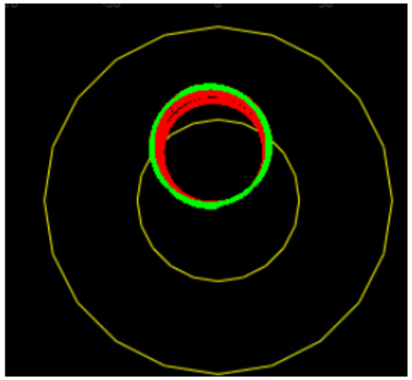


Conversion electron 3-D Event Display,
Red : MC truth track, Green : Reconstructed track



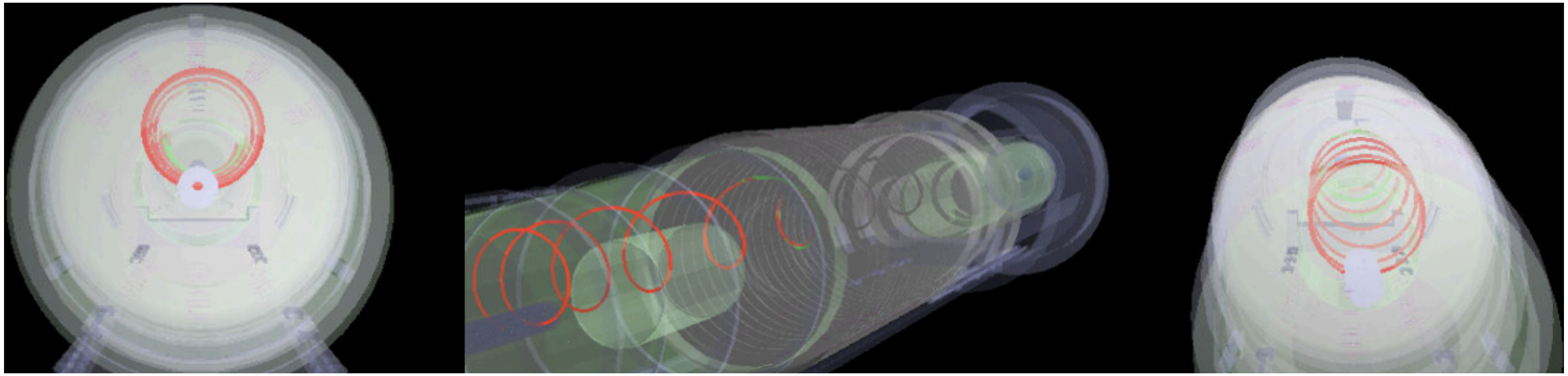
2-D display of the tracks (xy Tracker view)
Before correction

Red : MC truth track
Green : Reconstructed track

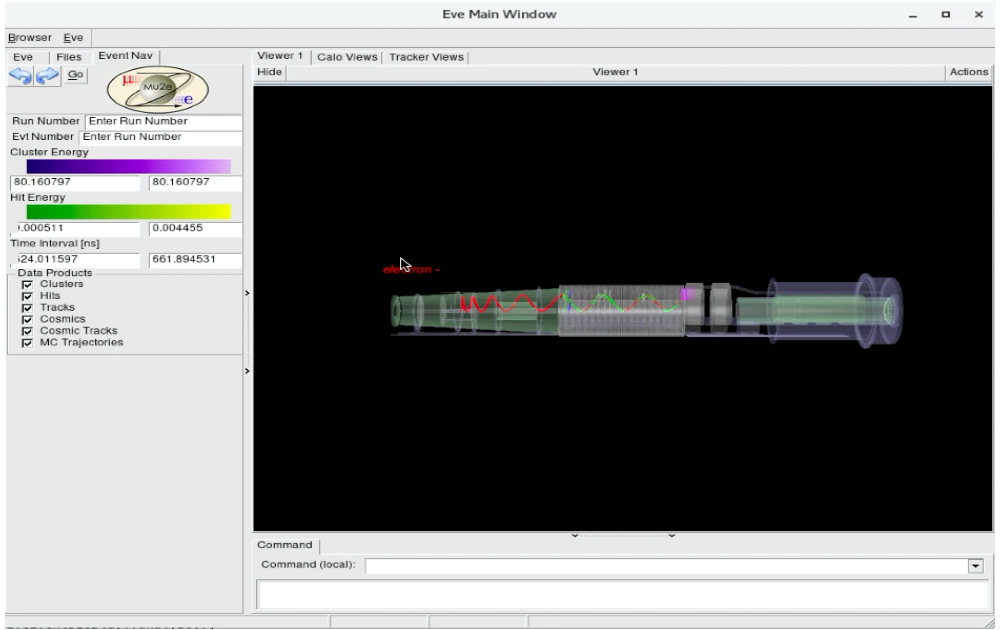


2-D display of the tracks (xy Tracker view
After KalSegment correction

Matching the MC truth and reconstructed helices

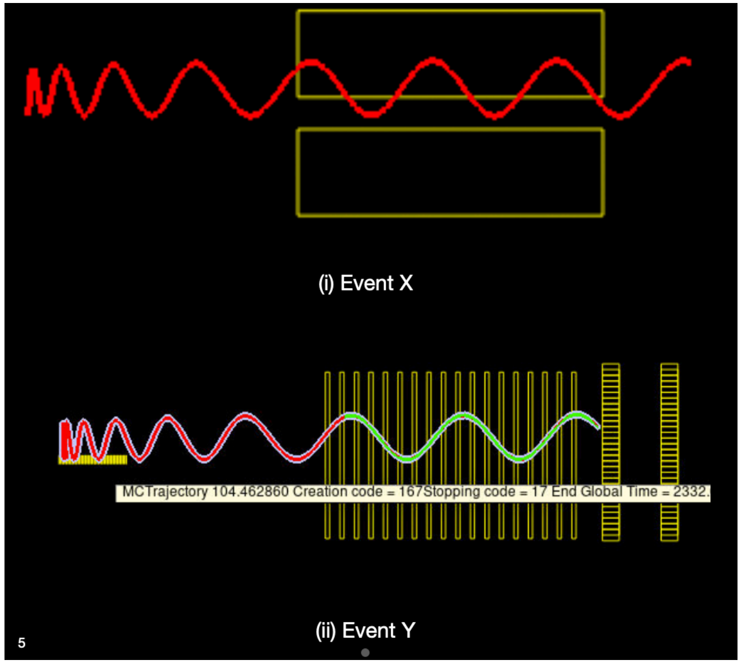


Various 3-D perspective views of the conversion electron helix
Red = MC truth track, Green = Reconstructed track

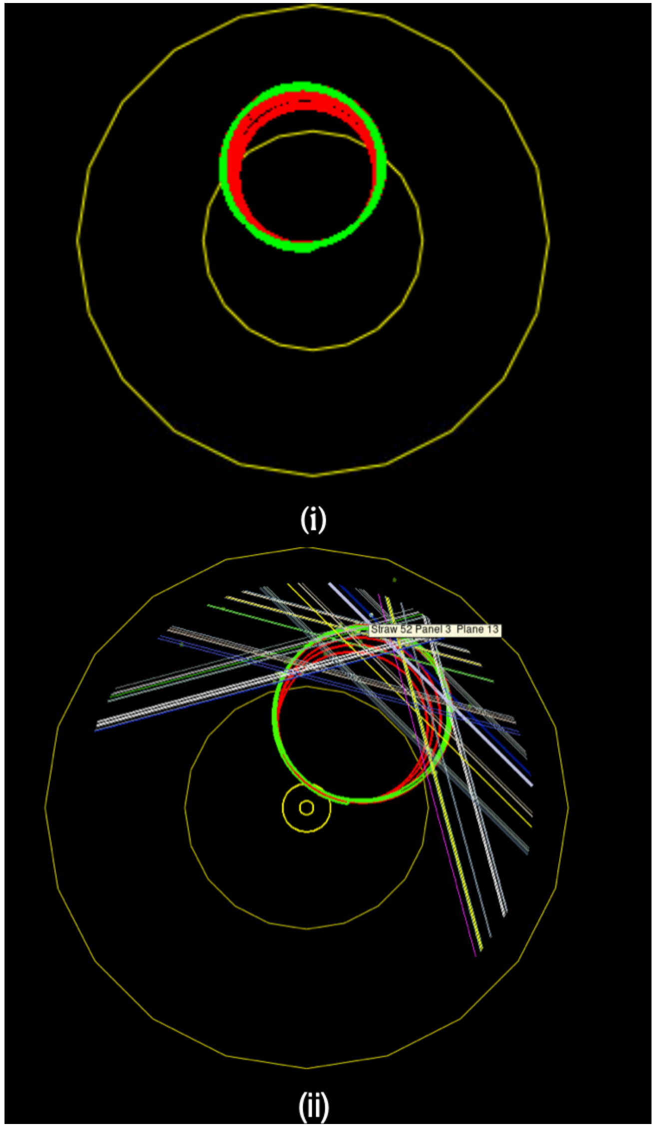


Enhancement of 2-D projection

- The 2-D Tracker view was improved with the addition of the stopping target, tracker planes and the calorimeter disk geometries.
- The straws which have been hit are highlighted along with a label which can be visualised when the pointer is placed on the straw. The label contains the straw, panel and plane information.
- The straws are highlighted and labelled in the 3-D view as well.
- The calorimeter hits are highlighted and labelled too.

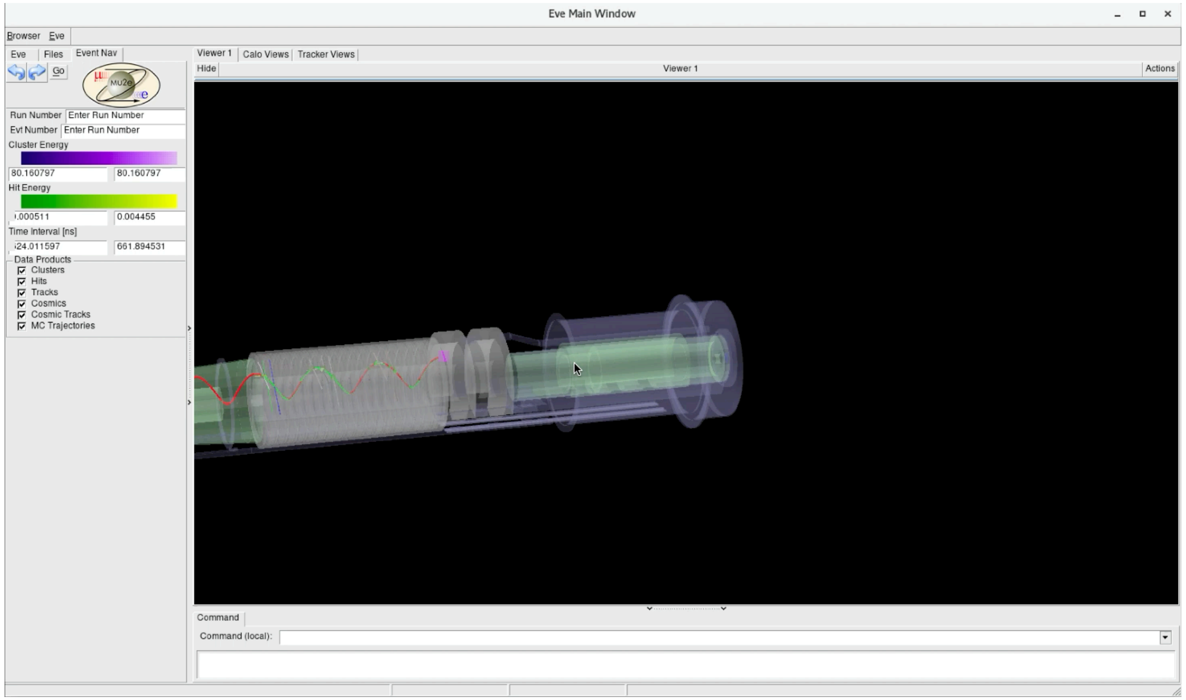


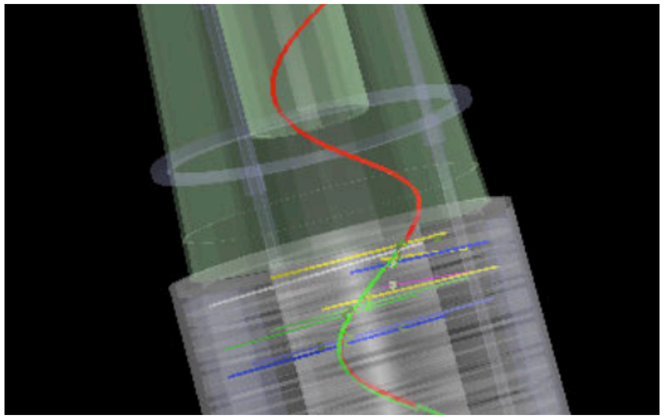
Addition of ST and panel details to the Tracker



“Hit” straws addition 2-D XY projection view

Addition of the “hit” straws to the 3-D view

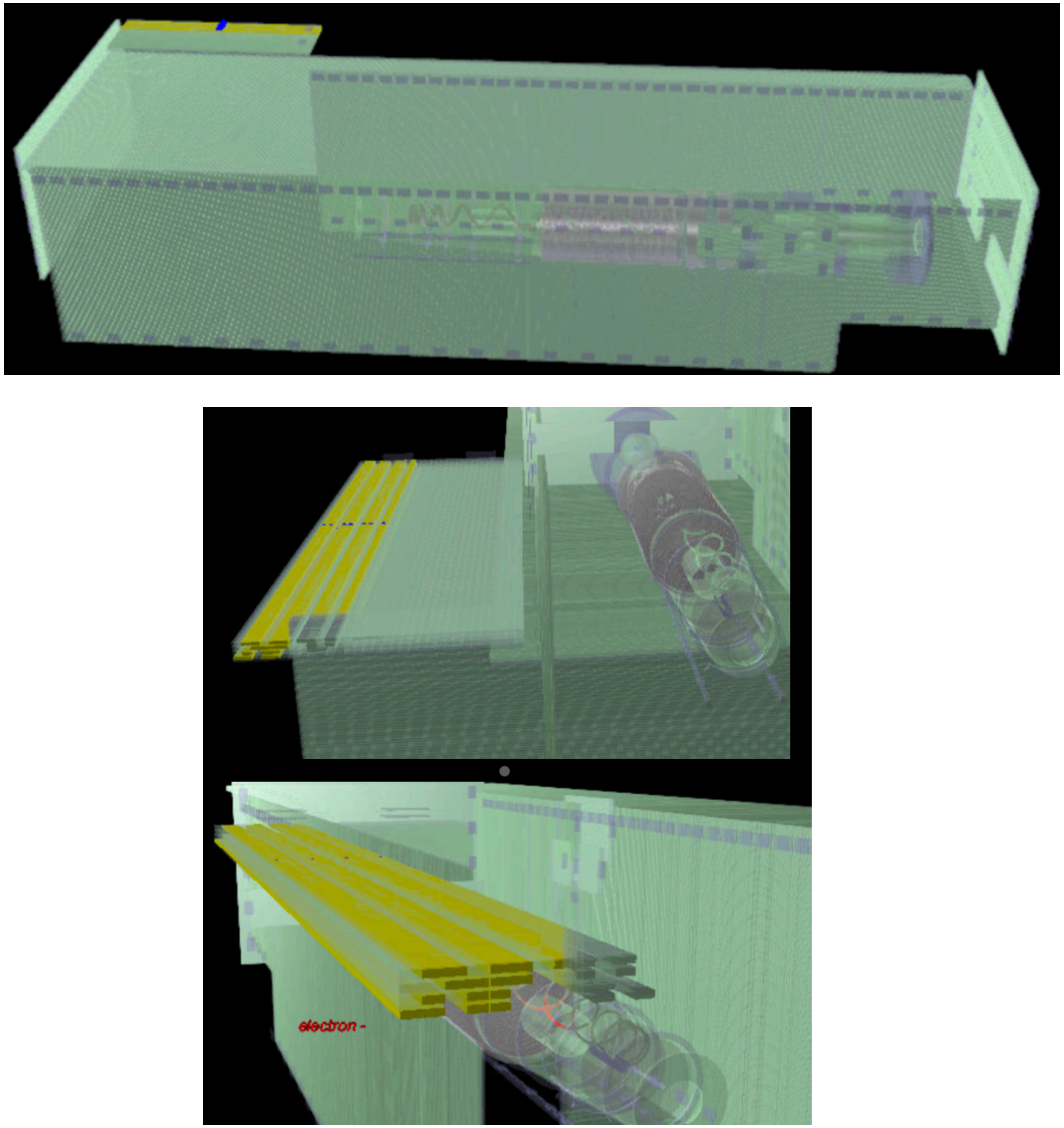




Zoomed-in view of the “hit” straw in the 3-d view

Cosmic hit display

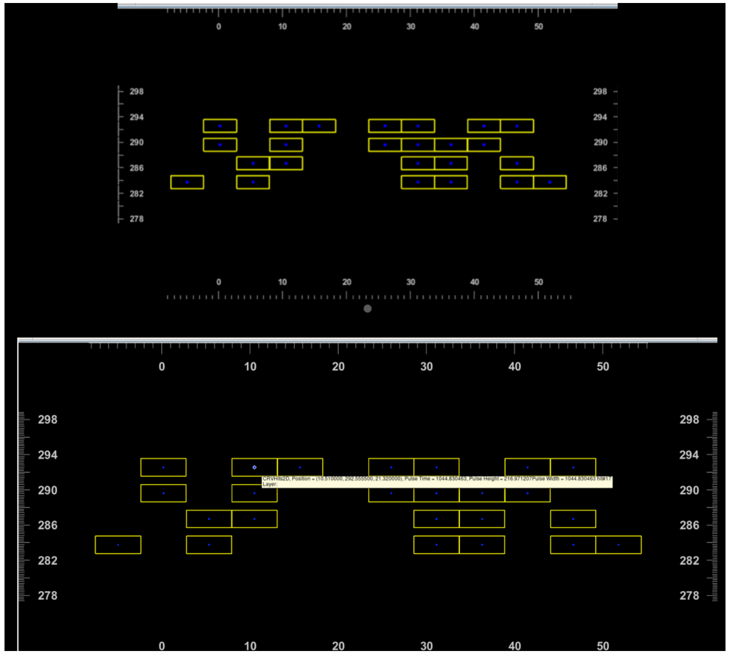
- The function to display the 3-D view of the Cosmic Ray Veto system and the hits was present. But, the hits were not displayed in the correct region of the CRV due to a co-ordinate transformation change in the Mu2e World which was not adapted to the CRV display module.
- The position of the CRV hits is corrected.
- The scintillation bars which are hit are displayed as well.



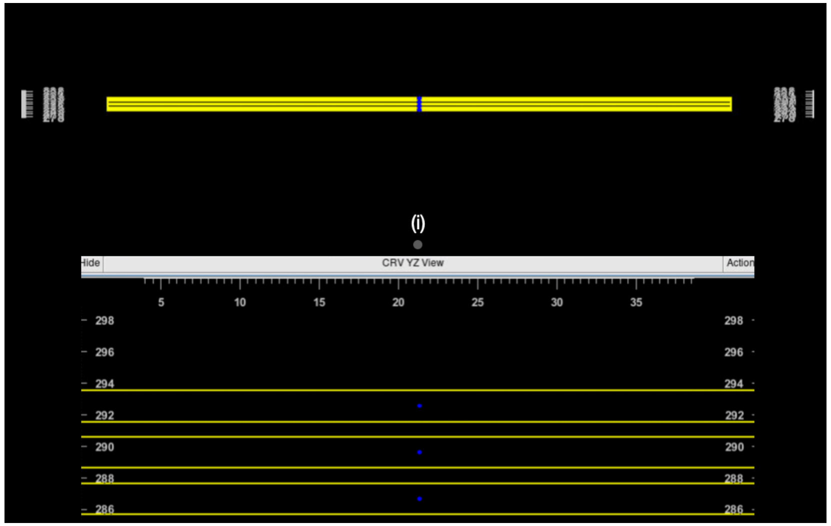
3-D view of the cosmic muon hit along with the display of the hit scintillation bars

CRV 2-D Projections

- 2-D XY and YZ projection tabs of the CRV are created.
- These tabs are displayed only when the user selects the “Show CRV hits” option.
- The scintillation bars which are hit are projected here.
- The hits are labelled. It contains information like the pulse position, time.



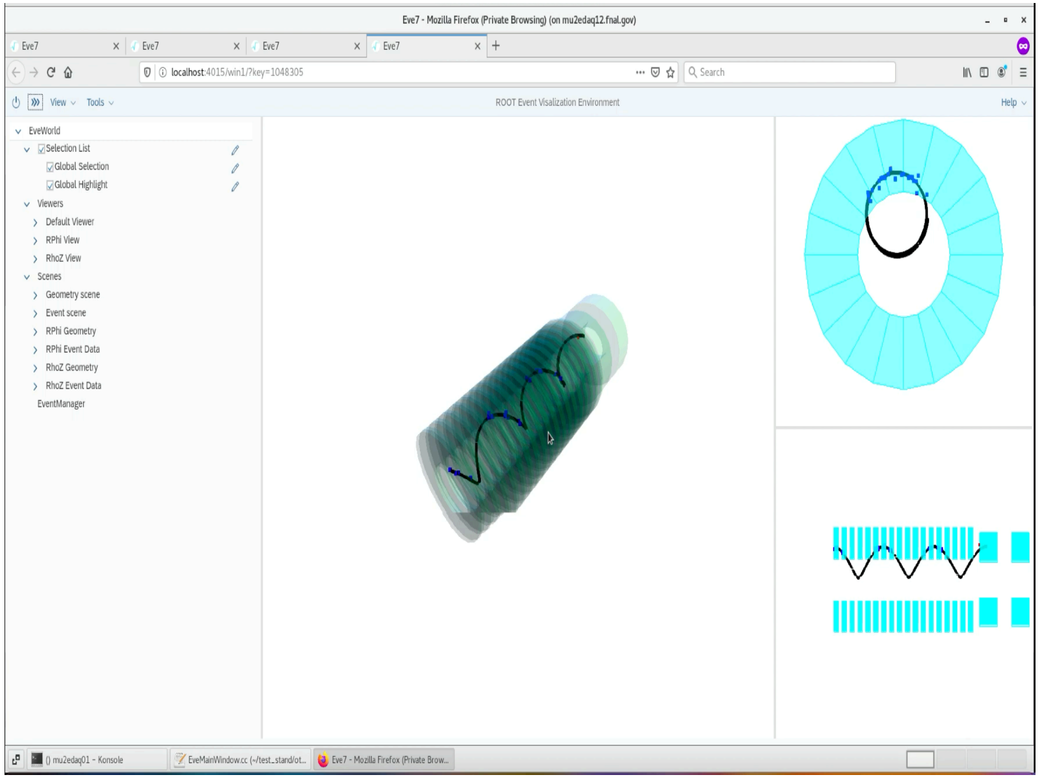
2-D XY view



2-D YZ view

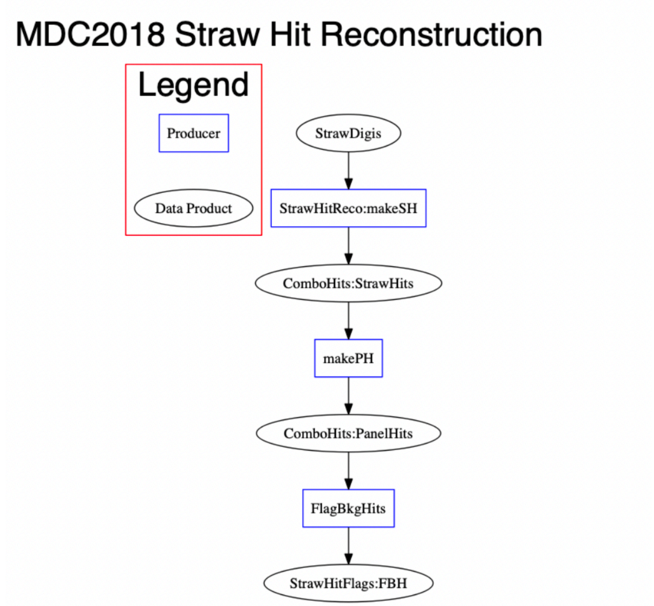
Online Event Display REve

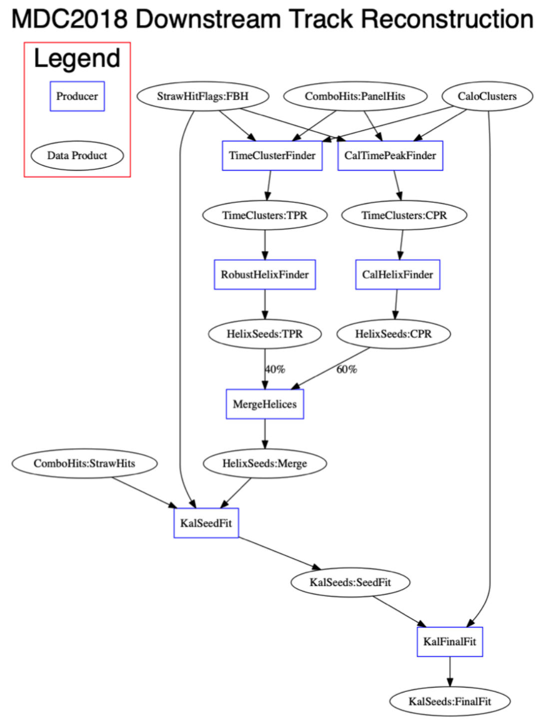
- REve is part of the ROOT7 upgrade.
- The bonus of REve is that it allows for remote access, and it has direct counterparts of most TEve objects so translating our already advanced TEve display to REve is not very difficult.
- It allows user to remotely access the display from anywhere (provided FNAL VPN).
- At present, we are in the process of translating all the Offline event display features to the Online version.



Track Reconstruction Pattern Algorithms

- Mu2e follows a targeted reconstruction sequence where the particles are distinguished by charge (which affects the Helicity),mass and direction(up and downstream).
- MakeStrawHits : Applies calibration to the raw digis to convert them to physical times and energy deposition in standard units.
- The collection of **ComboHits** in the tracker and the possible simultaneous presence of **Clusters** in the calorimeter are the starting ingredients necessary to reconstruct the helices.
- Separate instances of the Downstream reconstruction are run for positive and negative charge and for the electron and muon masses (Kalman filter).
- Each downstream sequence instance runs two pattern recognition algorithms, one based primarily on StrawHits (**TrkPatRec**), the other based on a combination of StrawHits and CaloClusters (**CalPatRec**).
- TrkPatRec can include CaloClusters, while CalPatRec requires them.
- Through both the algorithms we are trying to determine the helix parameters $\vec{n} \equiv (d_0, \phi_0, \omega, z_0, \tan(\lambda))$ which define the trajectory.





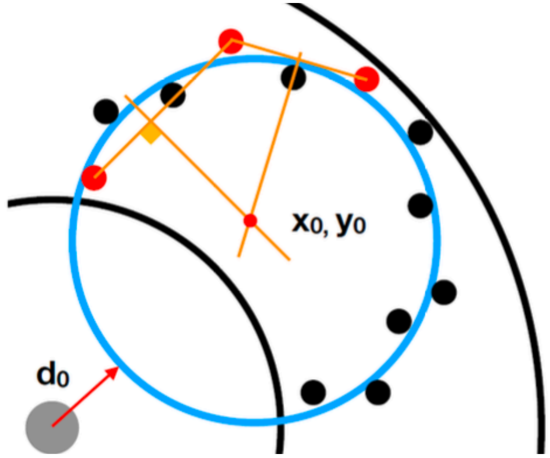
TrkPatRec : Tracker "only" Pattern Recognition

- XY plane : To determine the optimal circle compatible with the hit distribution, a loop on all possible triplets of ComboHits belonging to the same TimeCluster is performed. The centre and radius of all possible circle combinations is determined and the median value is taken as the centre and radius of the helix.
- ϕZ plane : Combinations of hits belonging to different panels are taken and $1/\lambda = d\phi/dz$ is estimated as :

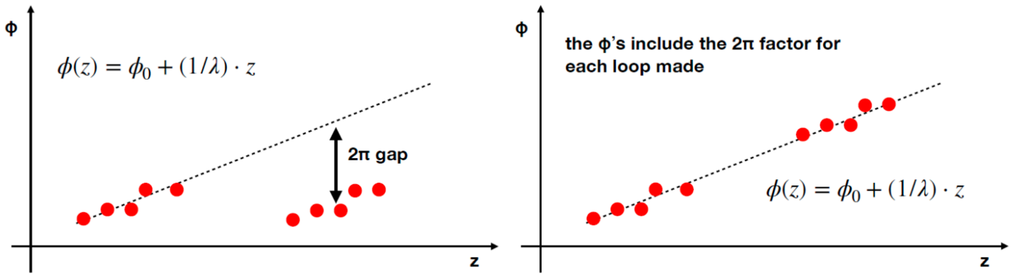
$$\frac{1}{\lambda_{i,j,k}} = \frac{\phi_j + 2\pi k - \phi_i}{z_j - z_i}$$

where i,j indicate the two different hits and k = number of full rotations.

- The peaks in the resulting distribution are used to assign hits to the corresponding k-th loop to resolve the 2π ambiguity and obtain the helix dϕ/dz and ϕ0 values.



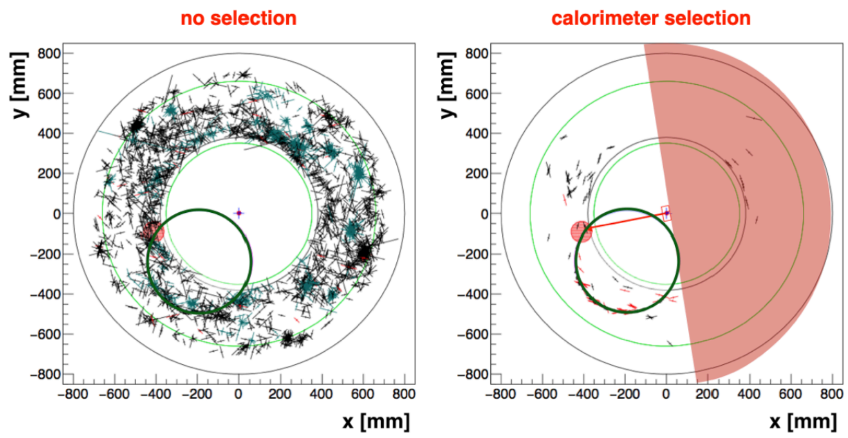
Circle fitting



2π ambiguity resolution

CalPatRec : Calorimeter seeded Pattern Recognition

- The calorimeter clusters are used as seeds for the helix reconstruction.
- The cluster's time and position are used to filter the collection of ComboHits: the hits are required to be in a ±40 ns window from the calorimeter cluster and in the same semi-plane.
- The algorithm takes the calorimeter cluster, one of the ComboHits and the solenoid centre as the starting points.
- The XY and ϕZ plane reconstruction is performed similar to the TrkPatRec but with increased sophistication.



Semi-Plane selection based on the CaloCluster position

Merge Helices : Track selection algorithm

- If helices from any input source share 10 or more hits the one with the most active hits (or best fit chi-squared) is kept in the MergeHelices output.
- Unique helices from either algorithm are always kept.

Issues with the present Track Selection algorithm

- The algorithm assumes that the helix with the greater number of hits is the better one which may not always be true like due to the presence of accidental hits : background hits mistaken for conversion electron hits leading to wrong track identification and reconstruction.
- The chi-square parameter which is used to select the better helix are computed through different algorithms in TrkPatRec and CalPatRec. This introduces a bias in this selection parameter.
- Duplication of tracks occur, that is, a single particle is found as two tracks. This is not tested by the present algorithm.

Steps taken to improve the Merge Helices algorithm

- Uniform χ^2 calculation : The χ^2 calculation method followed in the CalPatRec algorithm was adopted for the TrkPatRec helix as well. It is a least square fit based χ^2 minimisation approach [http://www.hep.ph.ic.ac.uk/~hallg/UA9/Karimaki_1991.pdf].

  1. Circle fit :

  $$\chi^2_{XY} = \sum_i (r_i^2 - r^2)^2 / \sigma^4_{r_i}$$

  Assuming $\Delta r/r << 1$,

  $$\chi^2_{XY} = (2r)^2 \sum_i (r_i - r)^2 / \sigma^4_{r_i}$$

  where $r_i = \sqrt{(x_o - x_i)^2 + (y_0 - y_i)^2}$, (x_0, y_0) is the helix centre, (x_i, y_i) is the straw hit position in the transverse plane and σ_{ri} is the error on r_i.

  2. ϕ-z fit : The relation between ϕ and z is linear, so the χ^2 minimisation is :

  $$\chi^2_{\phi z} = \sum_i (\phi_i - \phi)^2 / \sigma^2_{\phi_i}$$

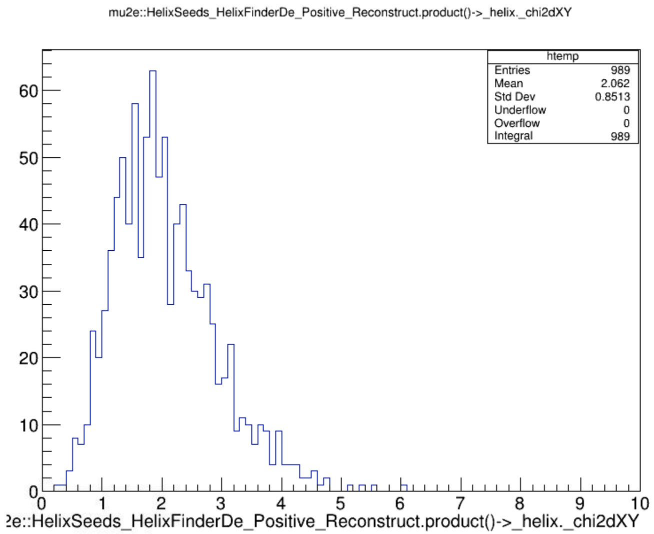
  $$\chi^2_{\phi z} = \sum_i (\phi_i - (\phi_0 + (z_i - z_0) d\phi/dz))^2 / \sigma^2_{\phi_i}$$

- Relax the criteria of number of hits.

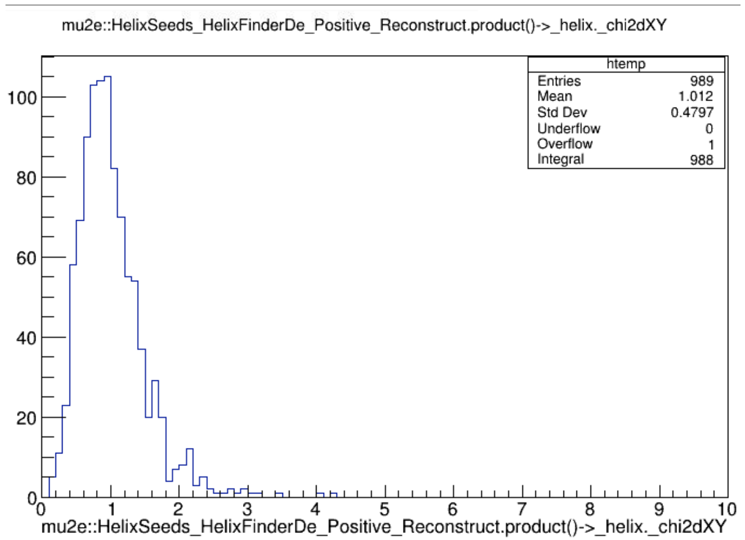
  1. Original criteria : If number of hits in helix 1 > number of hits in helix 2, select helix 1.
  2. Proposed new criteria : If (**difference of the number of hits between helices 1 and 2) < 5**, let χ^2 determine the helix selection.

Results for a trial run of 1000 events

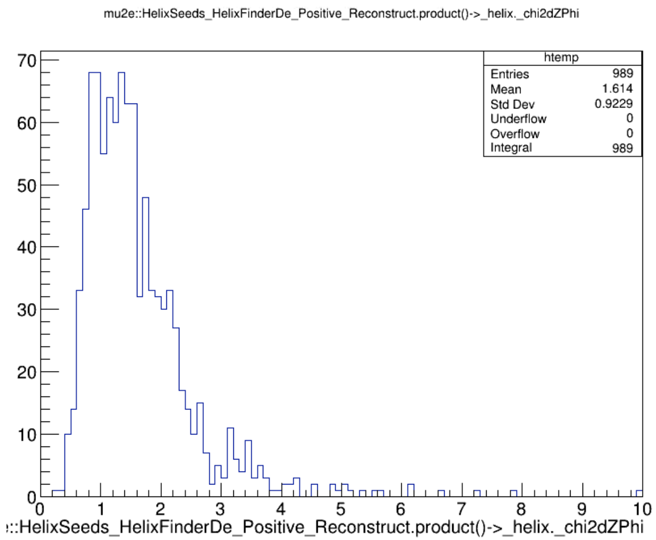
- 10 % of the tracks selected are **TrkPatRec** with the original algorithm.
- It increases to 24 % when the same χ^2 calculation is followed.
- 50 % of the tracks selected are **TrkPatRec** helices when the number of hits criteria is relaxed.



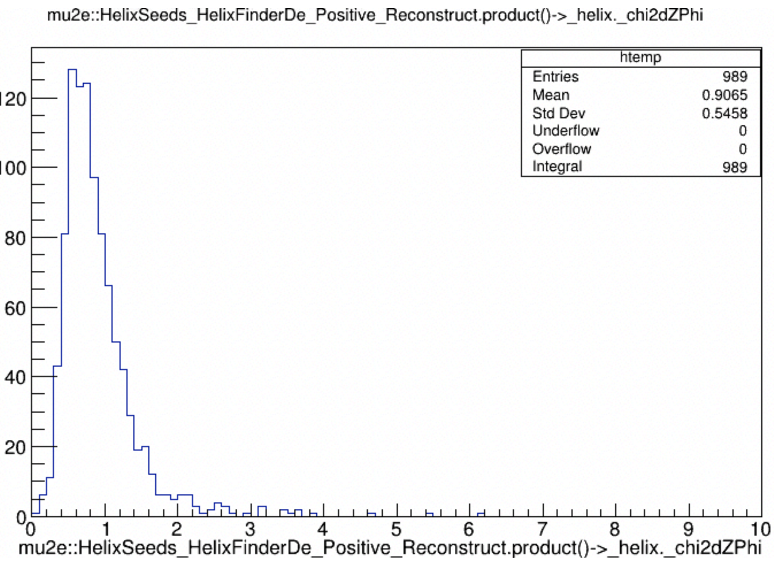
Chi-squareXY TrkPatRec Original



Chi-squareXY TrkPatRec New



Chi-squareZPhi TrkPatRec Original



Chi-squareZPhi TrkPatRec New

Future tasks

- Study the impact of the modified track selection on the final Kalman filtered output, the momentum and momentum resolution.
- Check the consistency of the results with the full10% MDC 2020 dataset.
- Improve the track selection algorithm further may be with the inclusion of more parameters and change it from the present simple “if else” conditional selection format.
- Develop the REve online event display.

Meetings/Conferences

- 107th SIF National Congress 13-17 Sep 2021
- New Perspectives 2021 conducted by Fermilab 13-17 Sep 2021
- Poster presentation at the 54th Fermilab Annual Users Meeting 2-6 Aug 2021
- Weekly comp/soft meetings Mu2e

Summer schools/PhD Courses

- Fermilab 2021 Summer Student School at LNF (2-4 August, 2021, INFN Laboratori Nazionali di Frascati)
- International Workshop on Cosmic-Ray Muography (24-26 November, 2021, Ghent);
- Short refresher course on C++ conducted by Fermilab
- PhD courses offered by the University of Pisa : Scientific Writing for Physicists, Introduction to Astrophysics, Statistical Data Analysis