Mu2e : A Search for Charged Lepton Flavour Violation in Muons

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INTENSE : particle physics experiments at the intensity frontier
Mid Term Review

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Introduction

- I was born in Kerala, India in 1997.
- Pursued Integrated MSc. (Bachelors + Masters) in Physics from S. V National Institute of Technology, Surat, India (Aug 2015 - 2020).
- Participated in summer schools/internships like in DESY, Hamburg; Weizmann Institute of Science; Inter-University Accelerator Centre, New Delhi; HZDR, Dresden.
- Master thesis research at Weizmann Institute of Science on “**Data-directed search for e/μ asymmetry**” .
- We developed a generalised methodology based on the test statistics approach to identify any significant e/μ asymmetry in the data collected from the ATLAS experiment. The test quantified its performance in terms of the expected efficiency to identify significant asymmetry versus the expected probability to detect statistical fluctuations.
- Joined the PhD program at the University of Pisa in April 2021.
- Attended the following courses at the University of Pisa (Feb 2022 - June 2022)
  1. Statistical Analysis Lab
  2. Introduction to Astrophysics
  3. Scientific Writing for Physicists

  The exams for these courses are scheduled from 4th - 6th July 2022 and a seminar on 28th June 2022.

Conferences

- 54th Annual FNAL Users Meeting (August 2-6, 2021) Poster “Mu2e Event Display Development using the TEve Framework”
- New Perspectives 2021 Conference (August 16-19, 2021) Talk
- Congresso Nazionale della Società Italiana di Fisica (September 13-17, 2021) Talk “Mu2e Event Display Development using the TEve Framework”
- APS April Meeting 2022 (April 9-12, 2022) Talk “Mu2e Event Display Development : Using the TEve and REve Frameworks”
- 15th Pisa Meeting on Advanced Frontier Detectors (May 22-28, 2022) Poster
- 55th Annual FNAL Users Meeting (June 13-19, 2022) Poster “Mu2e Event Visualisation using TEve and Eve-7”
- Mu2e Internal talks in the Comp-Soft meetings

Workshops

- Fermilab 2021 Summer Student School at LNF (August 2-4, 2021)
- International Workshop on Cosmic-Ray Muography, Ghent (November 24-26, 2021)
- muEDM Workshop, Pisa 2022.

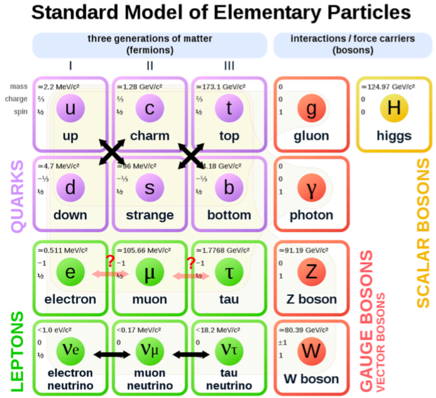
Mu2e : A search for Charged Lepton Flavour Violation in Muons

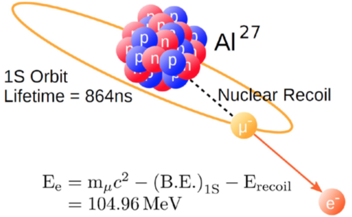
- According to the Standard Model (SM), muons like any other lepton conserve the lepton flavour.
- Flavour is not conserved in quarks (via quark mixing) and neutrinos (via neutrino oscillations). So, probably muons show flavour universality violation too?
- The SM with neutrino masses says it is unobservably rare ($R_{\mu\to e} < 10^{-52}$) but many Beyond the SM theories predict enhanced rates of CLFV ($R_{\mu\to e} \approx 10^{-15} - 10^{-17}$)
- The Mu2e experiment will look for the possible CLFV process of muon to electron conversion in the field of an Aluminium nucleus by measuring the ratio,

$$R_{\mu e} = \frac{\mu^- N \to e^- N}{\mu^- N \to all\ muon\ captures}$$

- Signal : ≈ 105 MeV monochromatic electron

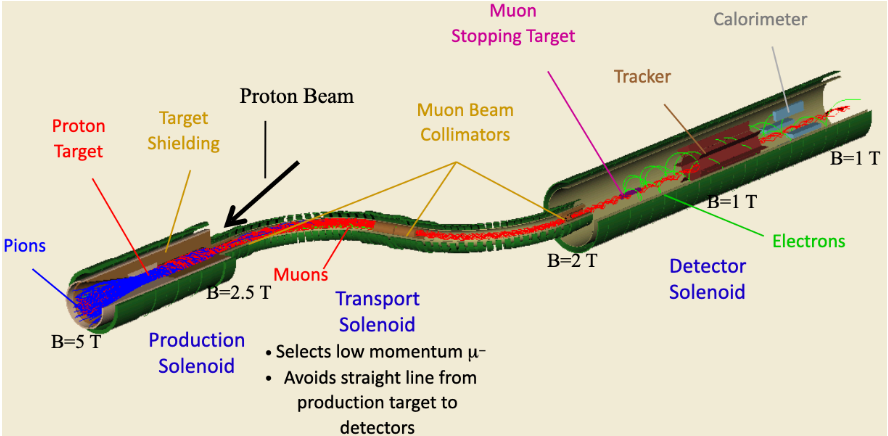
	μ^-	$\to$	e^-	$\bar{\nu}_e$	ν_μ
L_μ:	+1		0	0	+1
L_e:	0		+1	-1	0

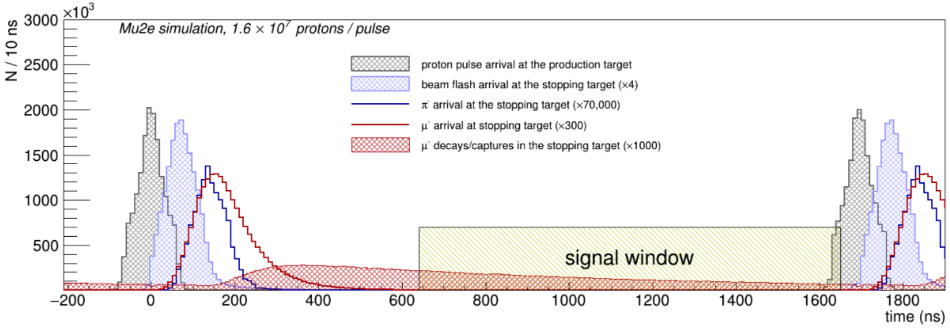




Experimental Setup

- 3-part solenoid system guides the particles from the **Production Solenoid** (PS), through the S-shaped T**ransport Solenoid** (TS) to the **Detector Solenoid** (DS).
- $\approx 3.9 \times 10^7$ protons per pulse will collide with the Production Target, produce pions.
- Backward-going pions decay into muons which spiral through the TS.
- The μ^- beam will collide with the stopping target (thin Al foils) in the DS, where the conversion process to e^- may occur.
- The e^- are detected by a straw-tube tracker and an electromagnetic calorimeter.
- Taking advantage of muonic atom's long lifetime and using a pulsed proton beam greatly reduces the beam related backgrounds. The signal would be emitted in the gaps between the proton pulses.





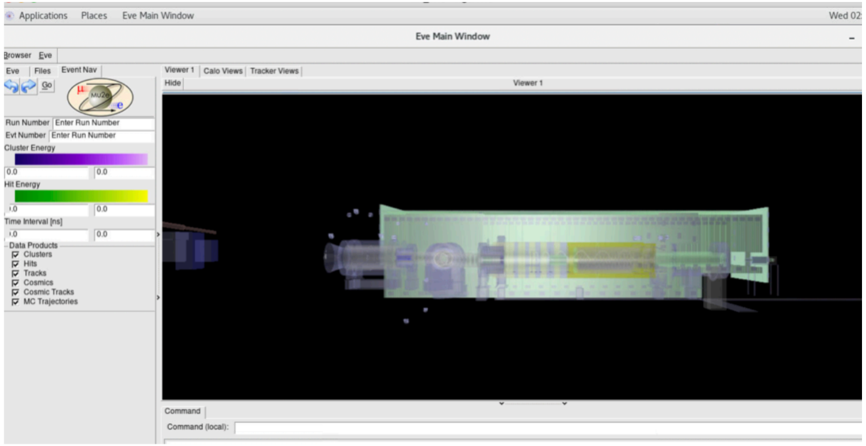
Event Visualisation Development using TEve and Eve-7

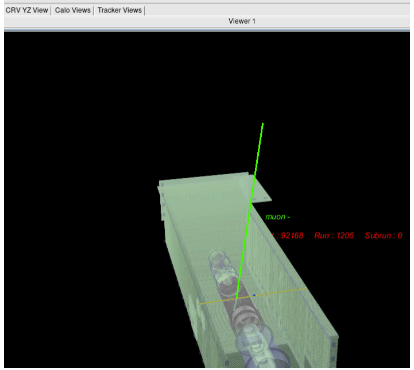
- **Offline** is the core of Mu2e computing with simulations of the entire Mu2e geometry, algorithms for reconstruction and analysis.
- All reconstructed objects (e.g. straw hits, calorimeter clusters) are stored in the event as art data products which can be accessed and created in C++ modules.
- An Event Display helps to visualise the physics in each event, crucial for monitoring and debugging during live data taking, offline analysis as well as for public outreach.
- A **custom display** for Mu2e has been developed using **TEve**, a ROOT based 3-D event visualisation framework.
- It maintains access to the raw art file making it convenient to go between the raw and reconstructed data within the browser.
- It fits well with the Offline environment and can run directly on the .art files, the outputs generated in Mu2e.

Event Navigation

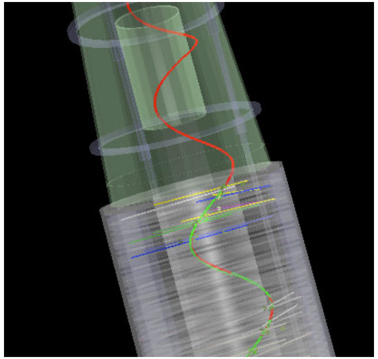
Event selection by entry

Data product visibility selection





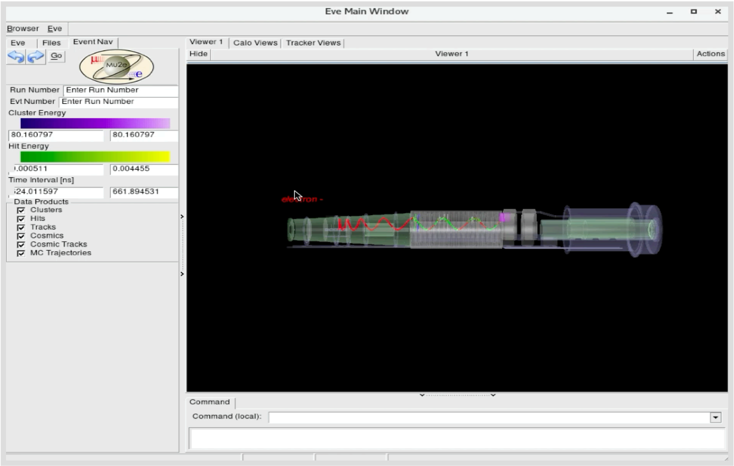
Cosmic muon track

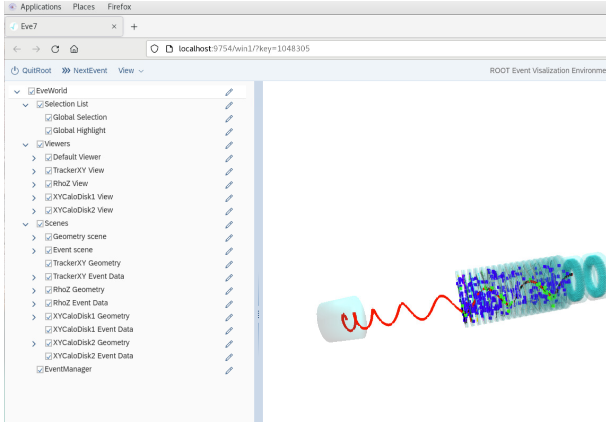


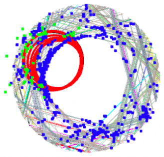
3-D view of “hit” straws

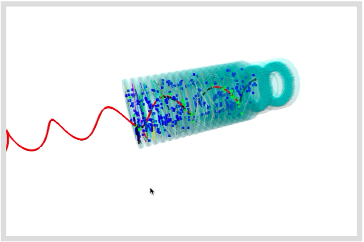
Features of the Offline and Online event visualisation

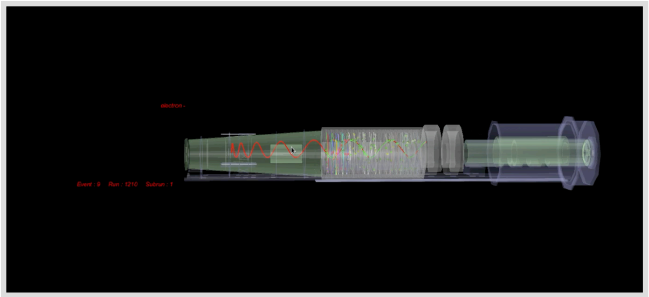
- Selective display upon GUI request. User defined track selection.
- Remove/add data based on energy deposited in a detector or arrival time.
- Upstream visualisation enabling complete illustration of the Mu2e world.
- The MC truth and reconstructed tracks displayed together, allowing visualisation of the track resolution.
- “hit” straws and crystals highlighted with relevant information. Active hits can be displayed in green and background hits in red.
- The online display is currently under-development using **Eve-7** which allows remote access for live data taking.
- Allows users to remotely access the display from anywhere (provided FNAL VPN) and multiple users can simultaneously view and interact with display.





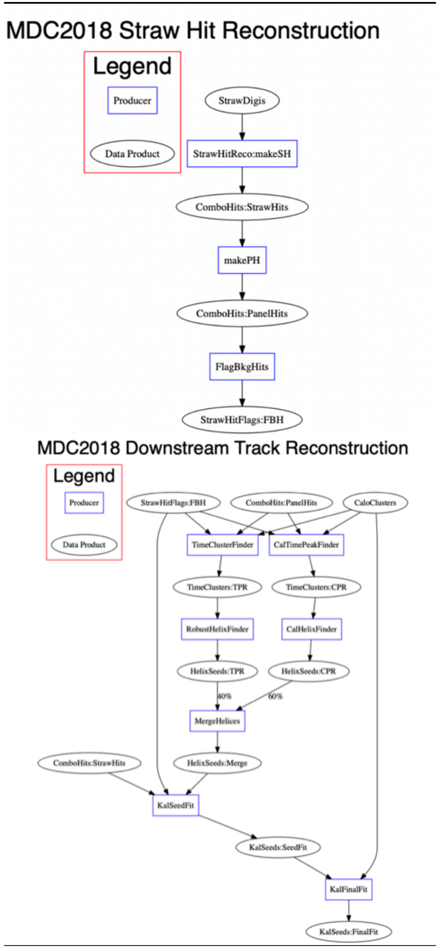






Track reconstruction using Pattern Recognition algorithms

- Mu2e follows a targeted reconstruction sequence. Particles are distinguished by charge (helicity),mass and direction(up and downstream).
- MakeStrawHits : Converts raw digital signals to physical times and energy deposition.
- MakeComboHits : Combines the straw hits of nearby panels to form a single hit.
- The collection of **ComboHits** in the tracker and the possible simultaneous calorimeter **Clusters** are the starting ingredients for the helix reconstruction.
- Each downstream reconstruction sequence runs two pattern recognition algorithms :
  TrkPatRec : Based primarily on the StrawHits,
  CalPatRec : Uses the combination of StrawHits and CaloClusters.
- TrkPatRec can include CaloClusters, while CalPatRec requires them.



TrkPatRec and CalPatRec

1. TrkPatRec

- Transverse plane : All possible triplets of ComboHits belonging to the same TimeCluster are checked to find the optimal circle. The median centre and radius value of all the circles is saved.
- ϕZ plane : Pairs of hits belonging to different panels are taken and 1/λ = dϕ/dz is estimated as,

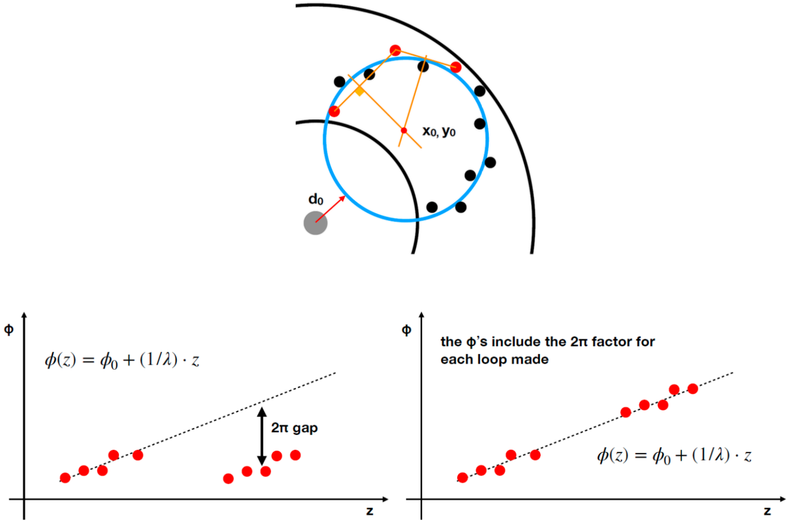
$$\frac{1}{\lambda_{i,j,k}} = \frac{\phi_j + 2\pi k - \phi_i}{z_j - z_i}$$

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

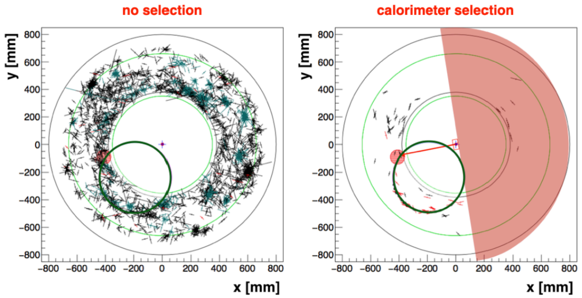
- The peaks in the resulting distribution are used to assign hits to the corresponding k-th loop to resolve the 2π ambiguity and obtain the helix dϕ/dz and ϕ_0 values.

2. CalPatRec

- 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 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.



TrkPatRec



CalPatRec

Helix Selection Algorithm

- If helices from either of the input sources (TrkPatRec or CalPatRec) share 10 or more hits the one with the most hits (or best fit chi-squared) is selected and moves ahead in the reconstruction. The selection criteria is :

  1. Select the helix candidate with a CaloCluster associated to it.

  2. If both the candidates have CaloCluster then select the helix with the greater number of hits.

  3. If the number of hits is equal then select the helix with the lower chi-squared value.
- The unique helices, cases with only one candidate, are always selected.
- The issues with this algorithm are :

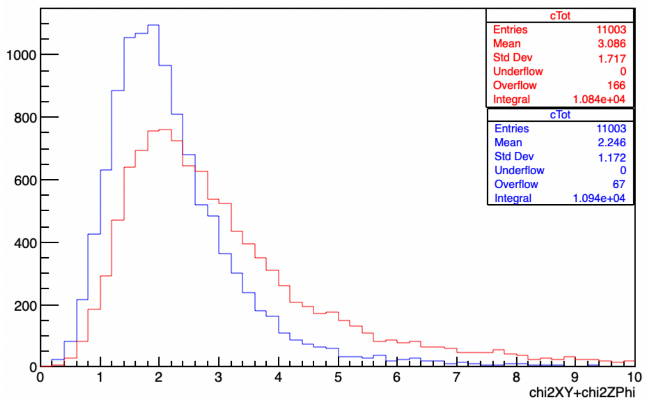
  1. It assumes that the helix with the greater number of hits is the better one, which may not be true always.

  2. The chi-square parameter used to select the better helix are computed using different algorithms in TrkPatRec and CalPatRec leading to biased selection.

  3. Possible duplication of tracks in some events.
- The solution that we have adopted to solve the above issues is :

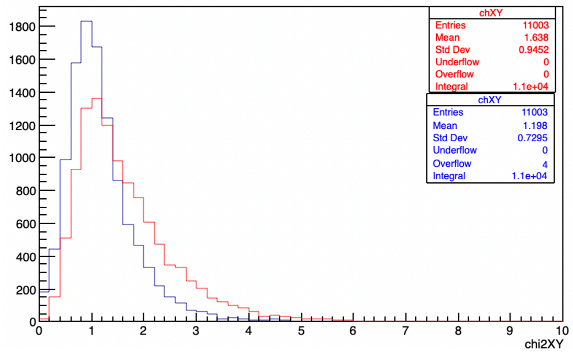
  1. Uniform chi-square calculation for all helices, irrespective of their source.

  2. Relax the "greater the number of hits, better the helix" criteria to " If the difference in the number of hits < 5, use the chi-square " of the helices as the selection parameter.



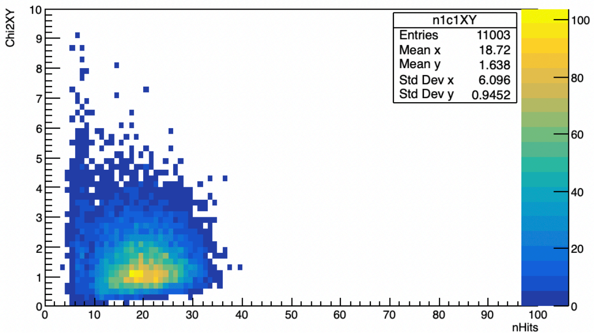
Chi2/n.d.o.f
red = Original, blue = New

Results with the new Helix Selection algorithm

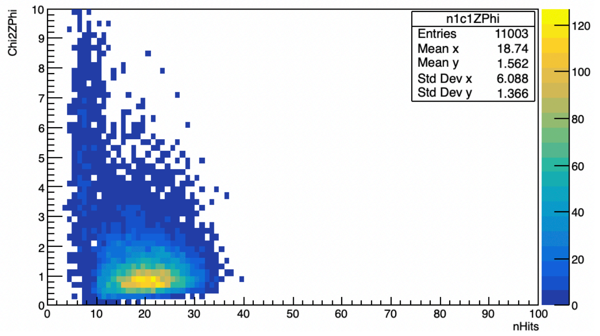


Chi2XY

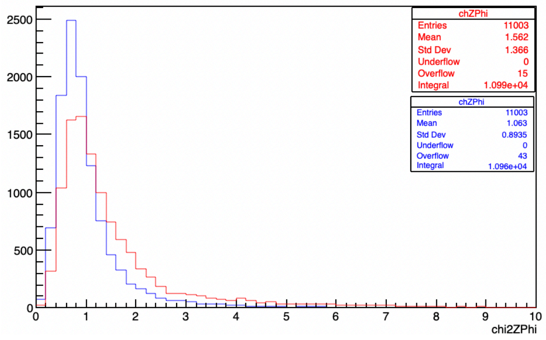
red = Original, blue = New



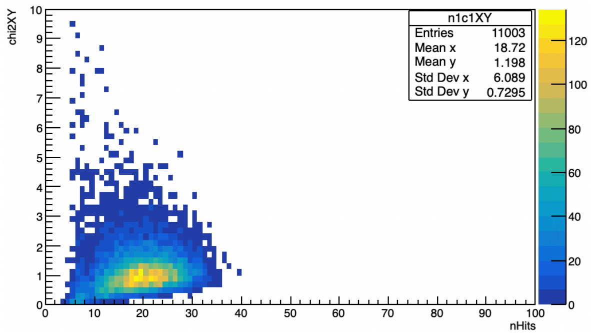
Original Chi2XY v/s nHits



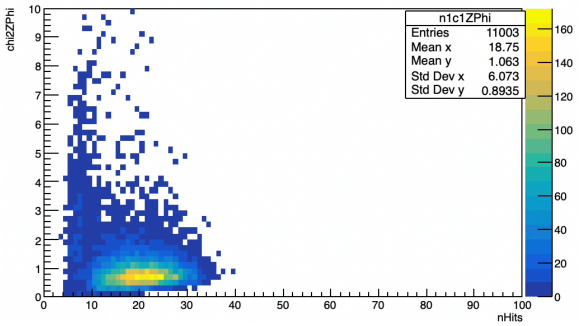
Original Chi2ZPhi v/s nHits



Chi2ZPhi



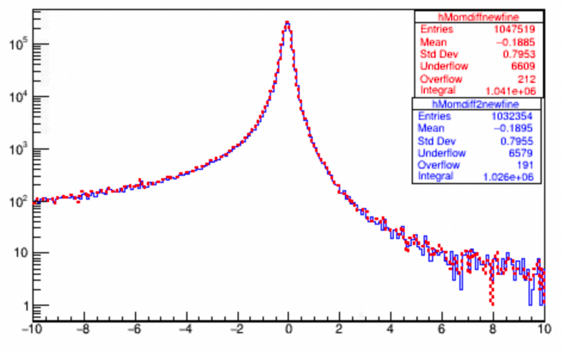
New Chi2XY v/s nHits



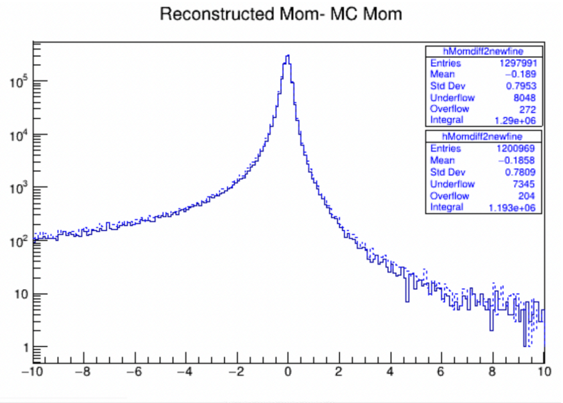
New Chi2ZPhi v/s nHits

Results with the new Helix Selection algorithm

- With the new helix selection, about 60% of the selected helices come from the TrkPatRec algorithm now which was about 27% earlier.
- This change in the helix origin does not seem to effect the final momentum resolution of the tracks much. We had hoped to see an improvement the high-end tail of the momentum resolution.
- So, we checked with data that contained only “TrkPatRec” and only “CalPatRec” helices and noticed that the momentum resolution of the final tracks are not very different.
- In conclusion, the two pattern recognition algorithms result in very similar helices most of the times.



Momentum resolution comparison
red = Original, blue = New



Momentum resolution with only “—TrkPatRec” and “- - CalPatRec” helices

Future tasks

- Study of the antiproton background, a potentially dangerous source for fake signals.
- Develop a 2 tracks reconstruction algorithm which identifies two well defined tracks from the hits.
- Improve the time clustering algorithm.

Back up Slides

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 :

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

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

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

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 :

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

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