A data-driven method for antiproton background measurement in Mu2e

N. Chithirasreemadam*, S.Donati, H. Kitagawa, P. Murat, G. Nigrelli, G. Pezzullo, A.M Ricci, M. Stortini
INFN, Pisa and University of Pisa

Mu2e

Search for neutrinoless, coherent conversion $\mu^- N \to e^- N$ in the field of an Al nucleus by measuring,

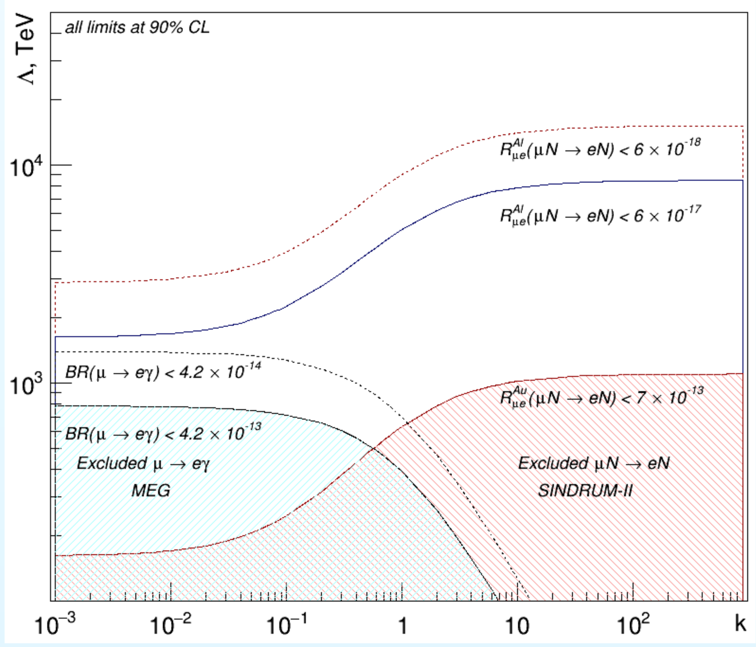
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \to e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \to \nu_\mu + N(Z-1,A))}$$

The $\mu^- N \to e^- N$ conversion channel has:

-> Best sensitivity to CLFV in a large range of NP scenarios.

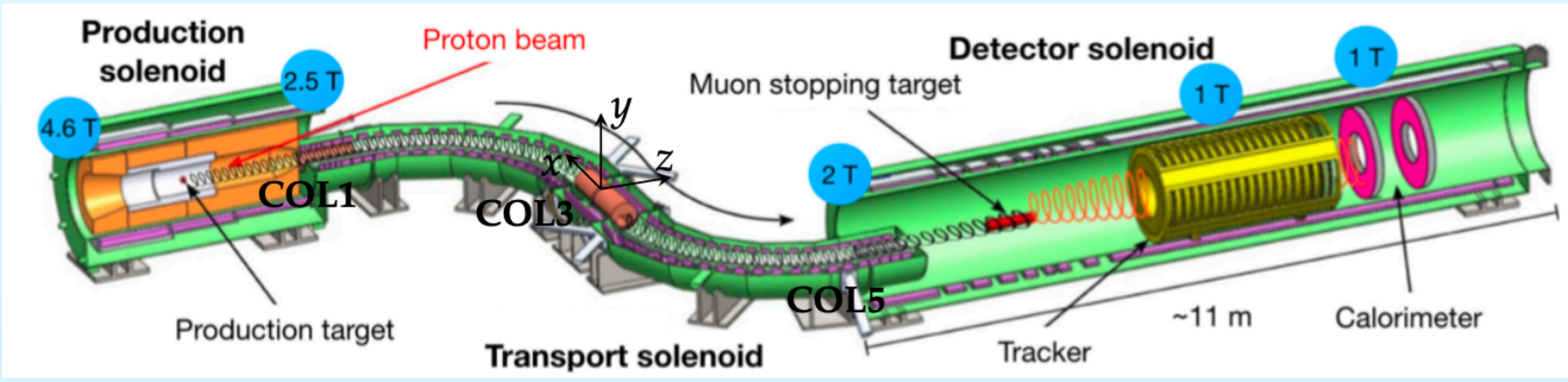
-> Can give unique information regarding underlying NP operators.

-> No combinatorial background.



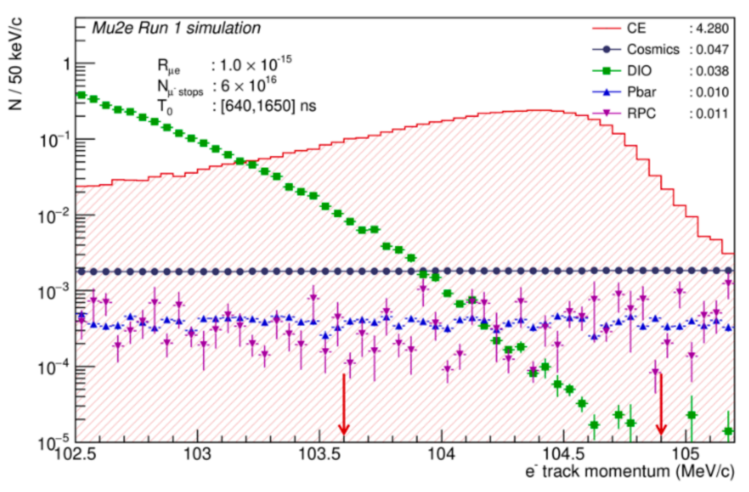
Λ is the effective mass scale and κ controls the relative contribution of the dipole moment term and the four fermion term

Signal: Monochromatic conversion electron (CE) with energy $E_{CE} = 104.97$ MeV



8 GeV pulsed proton beam interacts with the Tungsten target. Mostly produces pions.	Selects muons with p < 100MeV/c. Rotating collimator COL3 selects μ^- or μ^+ beam.	Muons stop in the Al stopping target (ST). Annular tracker and calorimeter to detect potential conversion e^-.

Background summary and expected sensitivity



Electron momentum distribution after optimisation of the signal momentum and time window.

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

The expected Run I 5σ discovery sensitivity is $R_{\mu e} = 1.2 \times 10^{-15}$. If no signal, the expected upper limit is $R_{\mu e} < 6.2 \times 10^{-16}$ at 90% CL.

Antiproton background

$\bar{p}$s are produced by the pW interactions in the Production Solenoid.

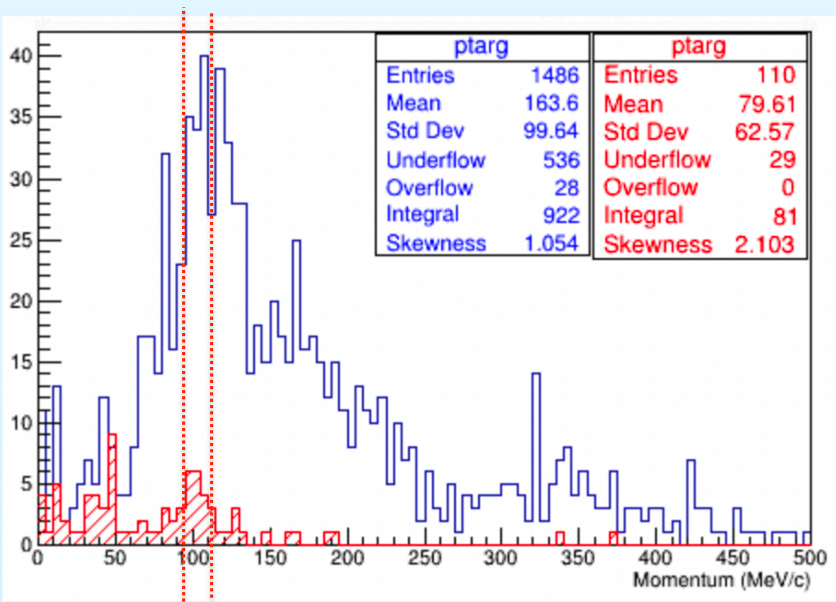
$p\bar{p}$ annihilation at the ST can produce e^-s by $\pi^0 \to \gamma\gamma$ decays followed by the photon conversions and $\pi^- \to \mu^- \bar{\nu}$ decays followed by the μ^- decays.

Background induced by $\bar{p}$ cannot be efficiently suppressed by the time window cut used to reduce prompt background because $\bar{p}$s are significantly slower than other beam particles.

Absorber elements placed at entrance and centre of the Transport Solenoid to suppress the $\bar{p}$ background.

Background expected from $\bar{p}$ is very low but highly uncertain.

We can exploit another final state with a much larger Branching Ratio to constrain the background by comparison.



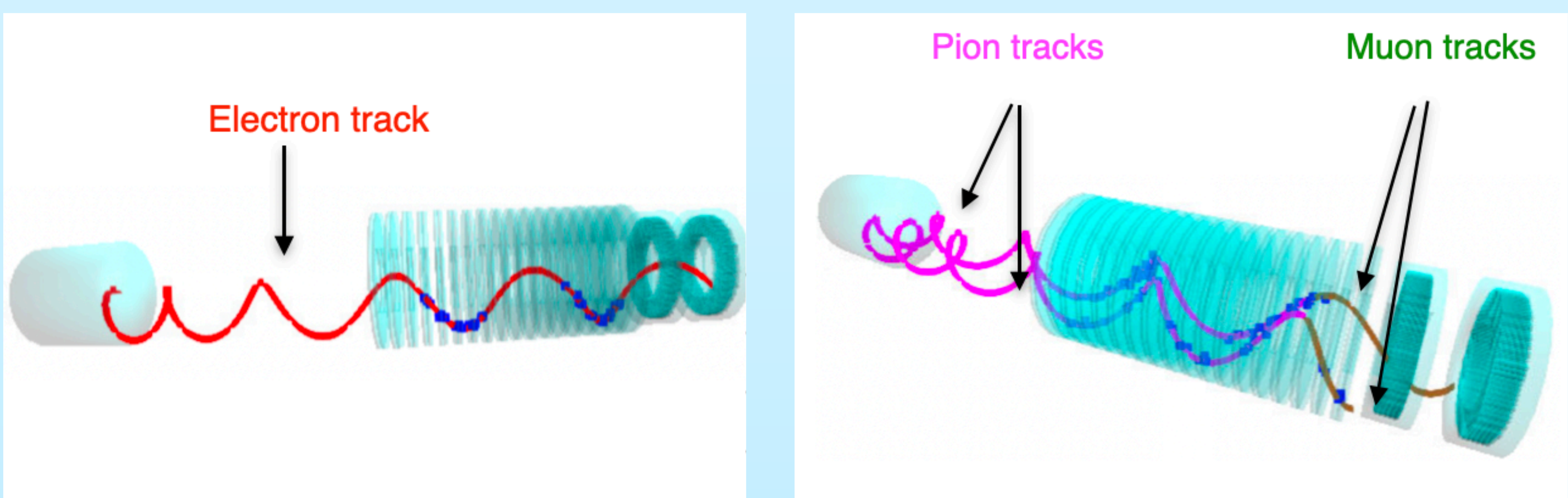
$$\frac{N_{e-perMeV}}{N_{multi-track}} \approx \frac{1}{500}$$

red: e^-
blue: multi-tracks

$p\bar{p}$ annihilation in the ST can give multiple tracks final state with p $\sim$ 100 MeV/c for each track at a much higher rate than signal like e^-.

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

About **480** of the events contain **$\geq$ 2 particles** with $\geq$ 20 straw hits per particle.



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

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

Mu2e event reconstruction

Mu2e event reconstruction is optimised to reconstruct single-track events with tracks coming from the ST.

From MC, > 90% of the hits in an event are from low energy e^-/e^+ and protons. They have to be flagged as background prior to the track reconstruction.

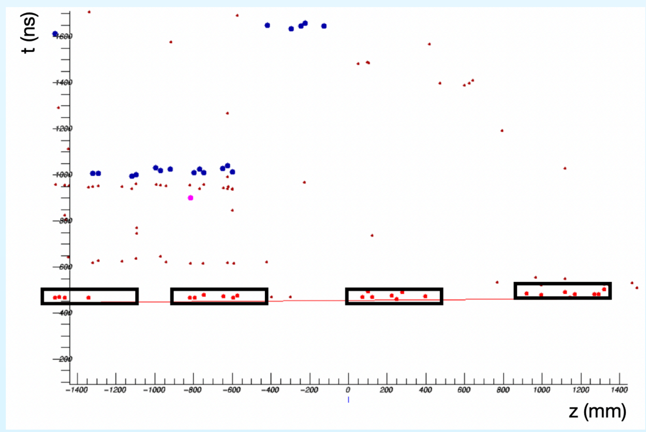
Background hit flagging and Time Clustering

Current algorithms to remove low energy hits and time clustering have an ANN layer trained for efficient signal e^- identification and reconstruction.

They remove a significant fraction of pion and muon hits.

We developed more physics neutral algorithms, highly efficient for a wide spectrum of particle topologies.

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



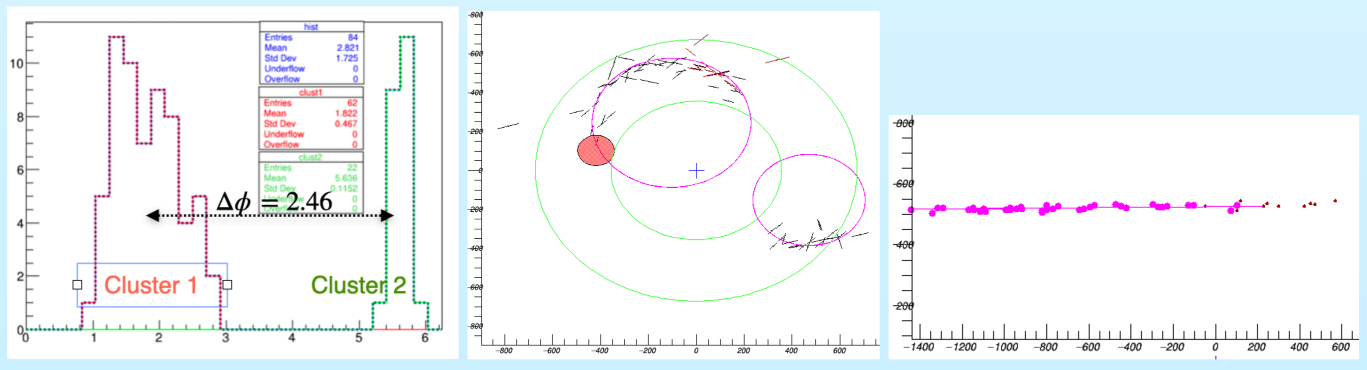
Time v/s z view of the hits in a CE + low intensity pileup event

The new time clustering performs a 2-D search using the time and z information of the hits.

Early Stage Hit Phi Clustering

Hits from different particles in the same time window could be well separated in ϕ or overlapping.

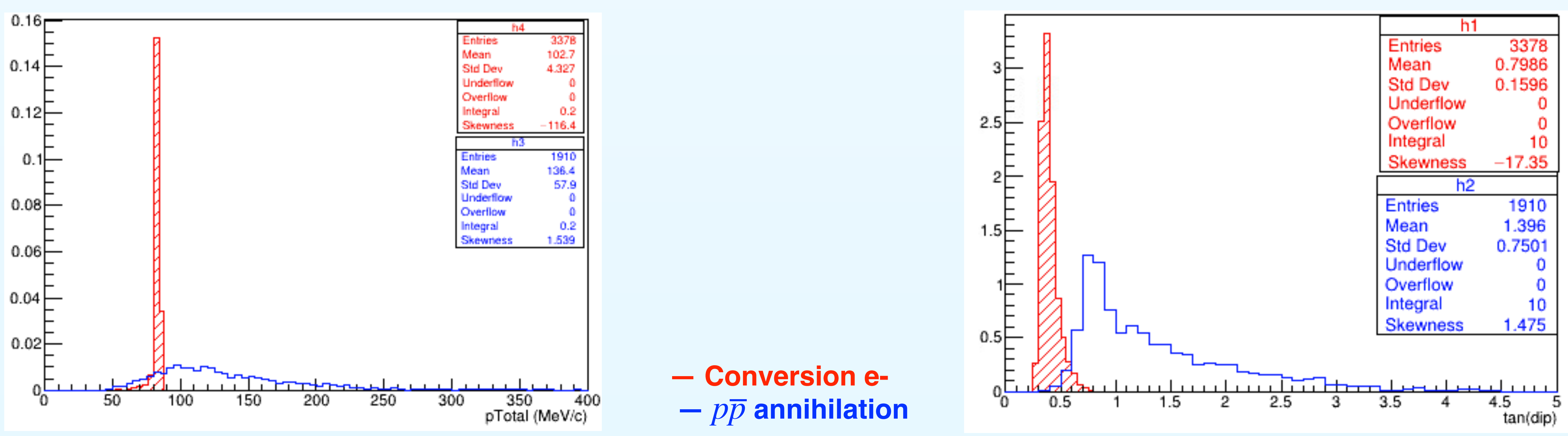
We developed a ϕ clustering algorithm to group hits of a $TimeCluster$ based on their ϕ distribution.



$\Delta\phi$ = 2.46 rad — XY view — Time v/s z view

Preliminary results

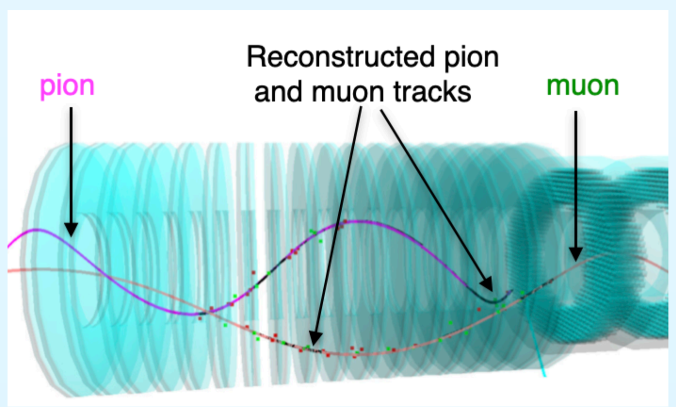
The topology of tracks from $p\bar{p}$ annihilation is much different from the expected CE tracks. Tracks from $p\bar{p}$ annihilation have a much wider total momentum distribution and most of these tracks have a lower pitch compared to the CE tracks.



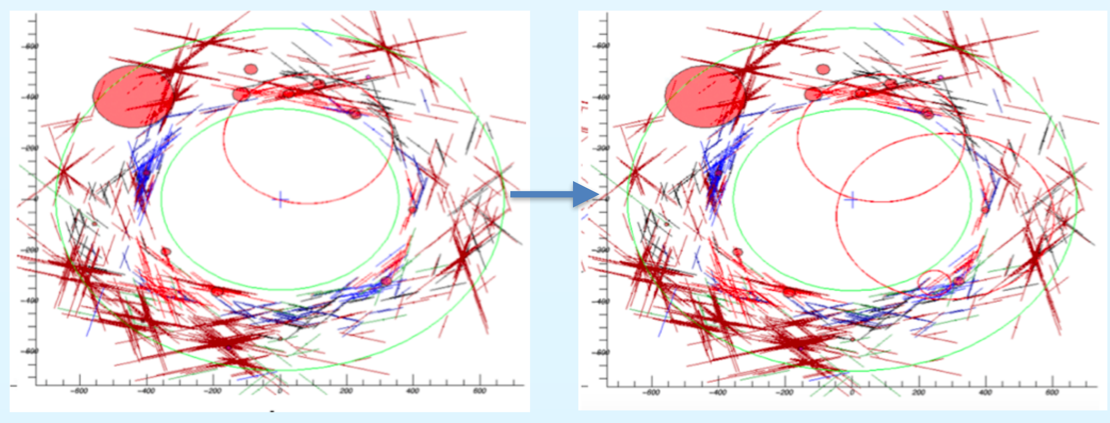
Total momentum — tan(λ)

Mu2e Run I will operate in a low intensity mode: mean intensity of 1.6×10^7 protons per pulse, $\sim 25{,}000$ muons per pulse stop in the ST. For the high intensity mode, the corresponding numbers are $\times 2.5$ higher.

We have generated and studied 10^4 $p\bar{p}$ annihilation + low intensity (1BB) and high intensity (2BB) pileup data samples respectively.



3-D view of a single interaction $p\bar{p}$ annihilation at the ST event with two reconstructed tracks



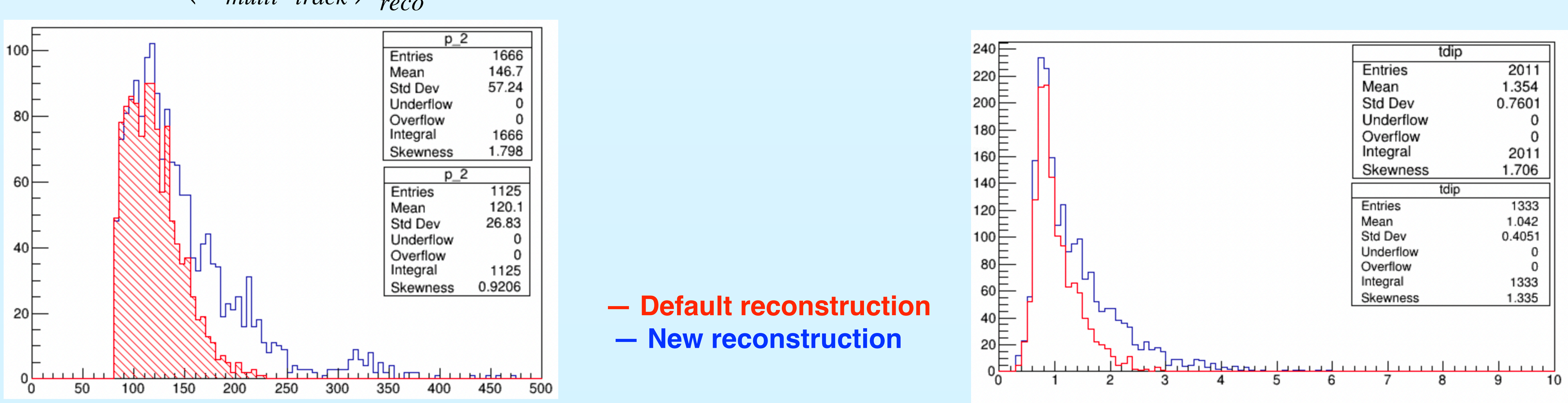
Mu2e standard reconstruction — New reconstruction

Transverse view of $p\bar{p}$ annihilation + 2BB pile-up data event.
red circle is the transverse view of the reconstructed track, segments are the "hit" straws.

Compared default v/s new reconstruction with 10^4single interaction $p\bar{p}$ annihilation, $p\bar{p}$ + 1BB and $p\bar{p}$ + 2BB pileup events respectively.

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

We obtained $\left(\frac{N_{e-perMeV}}{N_{multi-track}}\right)_{reco} \approx \frac{1}{140}$ for single interaction $p\bar{p}$ annihilation events.



Momentum (> 80 MeV/c) — tan(λ)

No. Of events with	>= 1 track			>= 2 tracks		
	0BB	1BB	2BB	0BB	1BB	2BB
Default reco	1138	1089	1046	50	46	39
New reco	1609	1579	1465	107	97	81
Improvement factor	x 1.4	x 1.4	x 1.4	x 2.1	x 2.1	x 2

Summary & next steps

- We are developing a novel data-driven approach to constrain the $\bar{p}$ background in Mu2e, creating new algorithms to reconstruct multi-track events.
- The Mu2e detector and the default event reconstruction procedure are designed for efficient reconstruction of single track events.
- The new algorithms significantly improve the efficiency of reconstructing $p\bar{p}$ annihilation events as well as improve the efficiency of single e^- track reconstruction. Using the new reconstruction sequence number of events with ≥ 2 tracks increased by $\sim \times 2$.
- Complete the proto analysis of the $\bar{p}$ background estimation: Improve the multi-track reconstruction further without reducing the CE track reconstruction efficiency. So, one can have one reconstruction path, irrespective of the particle topology and a single set of optimised event selection conditions in the Mu2e Trigger.

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