Multi-track event reconstruction to constrain the $\bar{p}$ background in Mu2e

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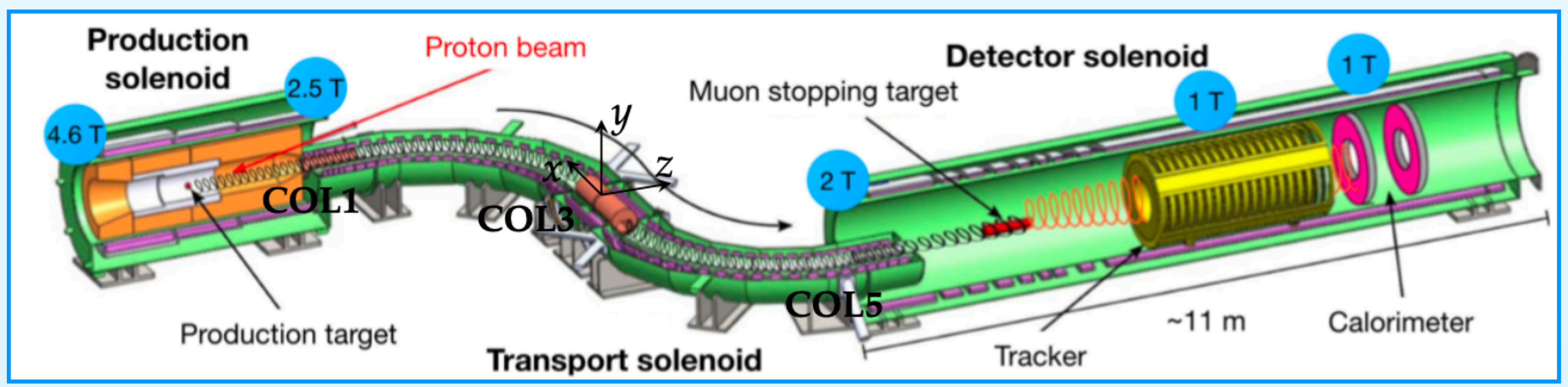
Mu2e: An Overview

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

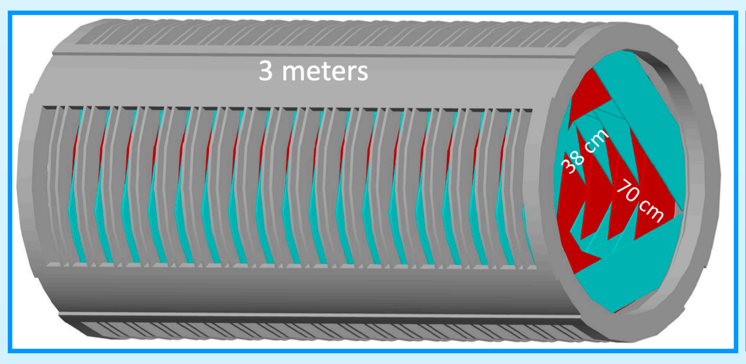
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(Z,A) \rightarrow e^- + N(Z,A))}{\Gamma(\mu^- + N(Z,A) \rightarrow \nu_\mu + N(Z-1,A))}$$

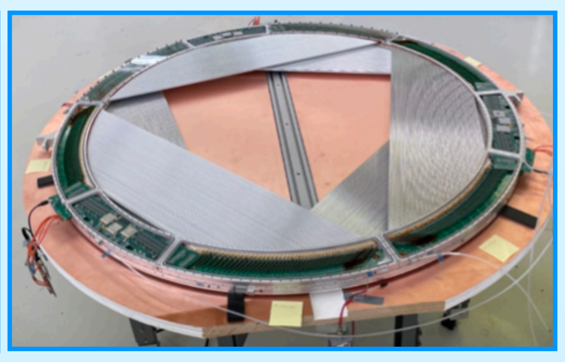
Signal: Monochromatic, 104.97 MeV/c e^-.



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. Annular tracker and calorimeter to detect potential conversion e^- (CE).

The tracker consists of 18 stations with 1152 straws per station. The straws are filled with 80%:20% $Ar : CO_2$ mixture.

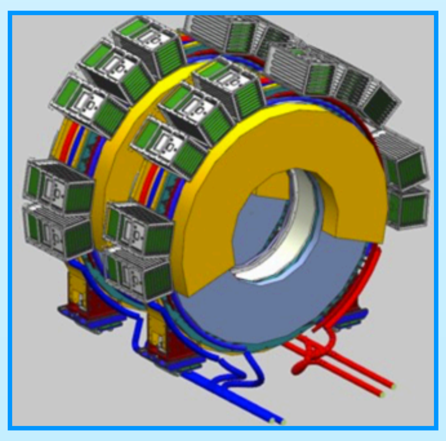


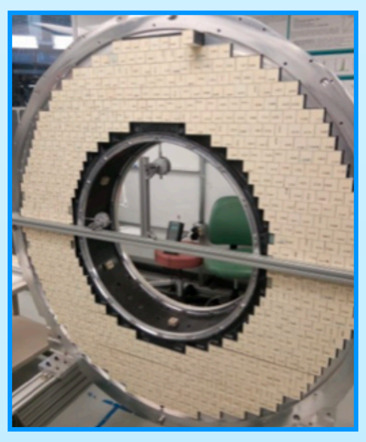


The calorimeter has 2 disks covering radii 37 cm-66 cm. Each disk has 674 pure CsI crystals.

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.

The estimated $\bar{p}$ background for Run 1 is $0.01 \pm 0.003(stat) \pm 0.010(syst)$***.**
The systematic error is dominated by the uncertainty on the $\bar{p}$ production cross section.



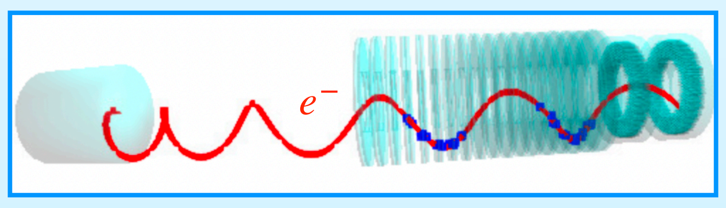


Antiproton background in Mu2e

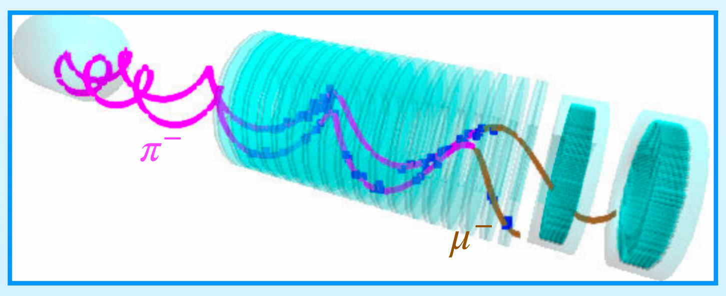
$\bar{p}$s are produced by the pW interactions in the Production Solenoid.

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

It cannot be efficiently suppressed by the time window cut 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.



Red: e^-
Magenta: π^-
Brown: μ^-

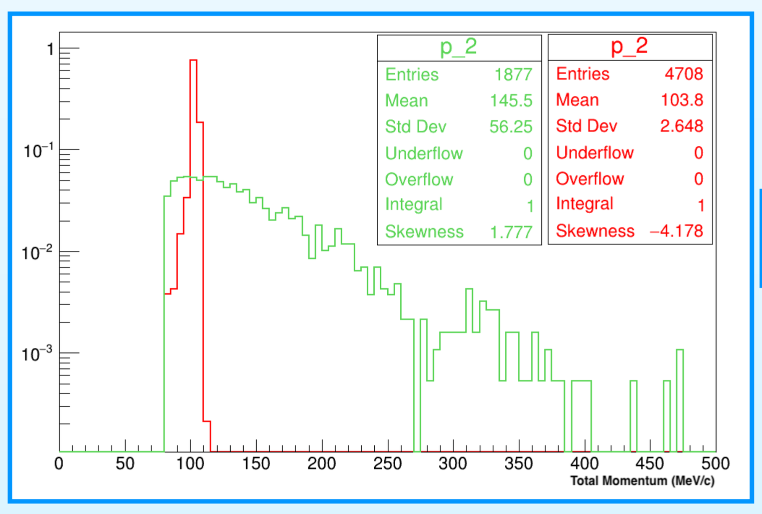


$p\bar{p}$ annihilation at ST can give multi- tracks final state with p ~ 100 MeV/c for each track at much higher rate than signal-like e^-. From Geant4 simulations, only 0.2 % of the simulated $\bar{p}$ annihilation events have an e^- with momentum in the range of 90-110 MeV/c, making ≥ 20 straw hits and ~ 5% of events have > 1 particle with ≥ 20 hits per particle.

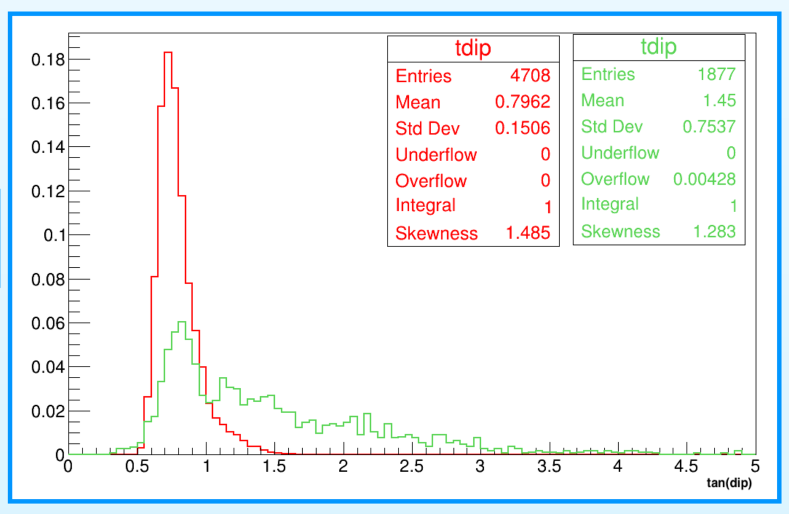
Goal: Identify and reconstruct the multi-track final state events and get an estimate of the CE like events by rescaling the ratio of the two final states.

Mu2e event reconstruction

Mu2e event reconstruction is optimised for single e^- track events.



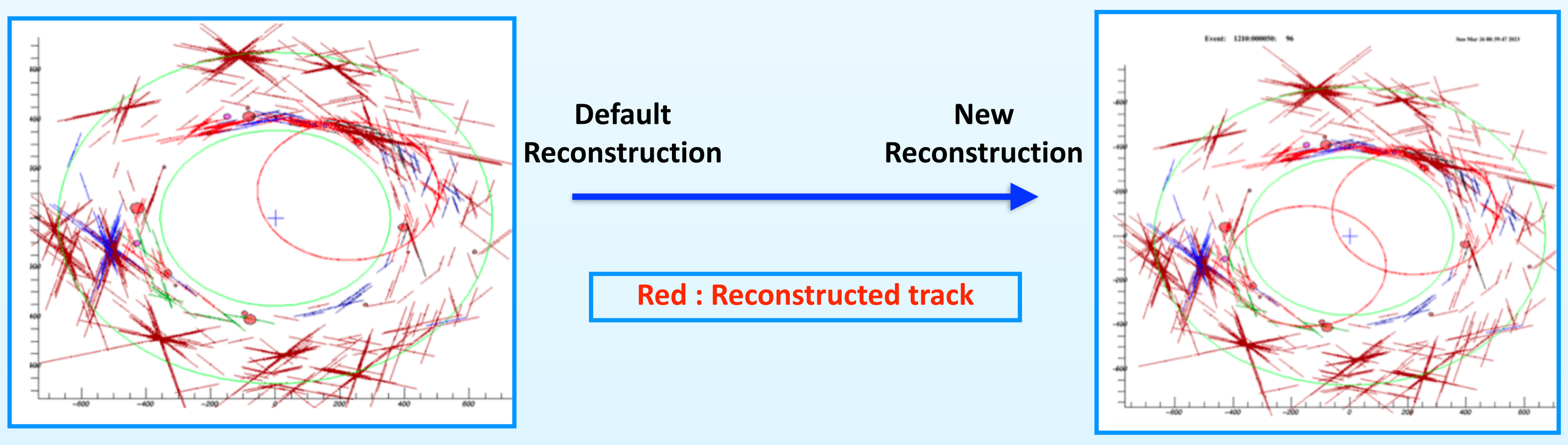
Red: CE
Green: $p\bar{p}$



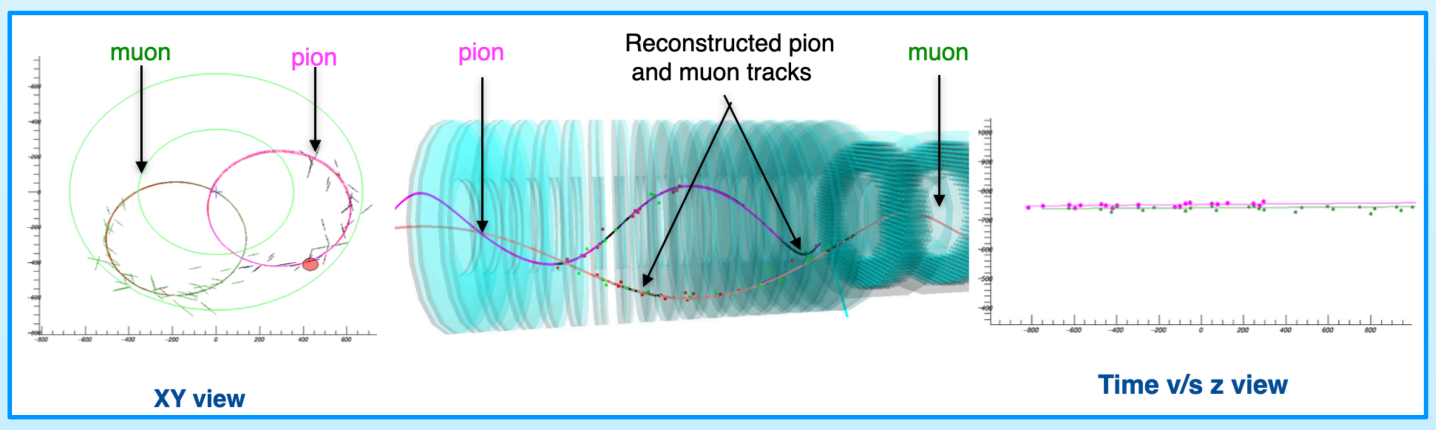
From MC studies, 90% of hits in an event are from low energy e^-, e^+, p. They are flagged background prior track reconstruction. Assuming the hits produced by same particle have close reconstructed times, they are clustered in time. $TimeClusters$ are input for the pattern recognition which search for 3-D $Helices$. Finally, the reconstructed track parameters are determined by the Kalman fit.

The default Mu2e algorithms to flag background hits and form $TimeClusters$ use an ANN trained for efficient CE search, which removes a large fraction of pion and muon hits. This reduces the efficiency of reconstructing tracks from $p\bar{p}$ annihilation significantly.

We developed new algorithms, without any ANN, highly efficient for a wide spectrum of particle topologies.



Simple time clustering alone is insufficient for $\bar{p}$ annihilation events as the tracks are mostly simultaneous in time. We observed that hits from different particles could be well separated in $\phi = tan^{-1}(y/x)$. We developed a ϕ clustering algorithm to group hits of a $TimeCluster$ based on their ϕ distribution.



Contribution from other backgrounds to multi-track events

1. Decay in Orbit (DIO)

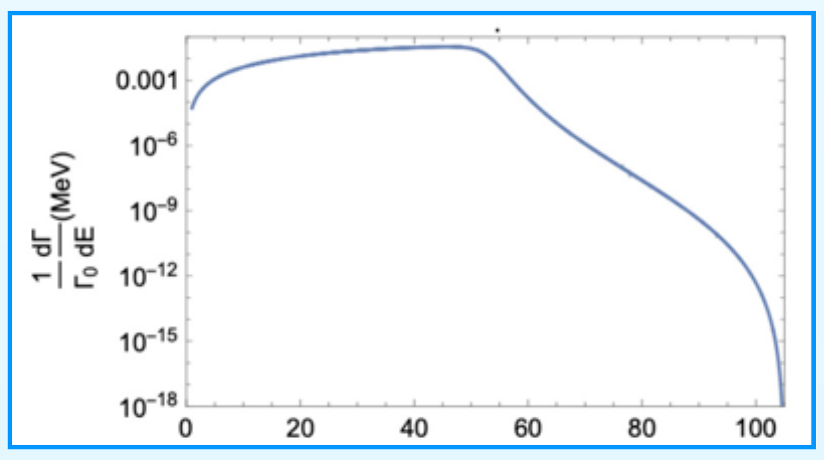
For Run I, we expect about 75% of the total protons on target (POT) in low intensity mode (1BB), mean intensity of 1.6×10^7 protons/pulse and 25% in high intensity (2BB), 3.9×10^7 protons/pulse.

$$N_{\mu^- stops/POT} = 1.6 \times 10^{-3}$$

39% of stopped μ^- DIO, so an average Mu2e event includes about 10^4 DIO e^-s.

In Run I, we expect about 2.3×10^{16}DIO e^-s. We search for multi-track events with each track $p \sim 100$ MeV/c. Requiring $p > 90$ MeV/c and integrating the DIO momentum spectrum,

$$N_{2DIO} = 2.3 \times 10^{16} \times (7.3 \times 10^{-10})^2 \approx 0.01$$



DIO Spectrum

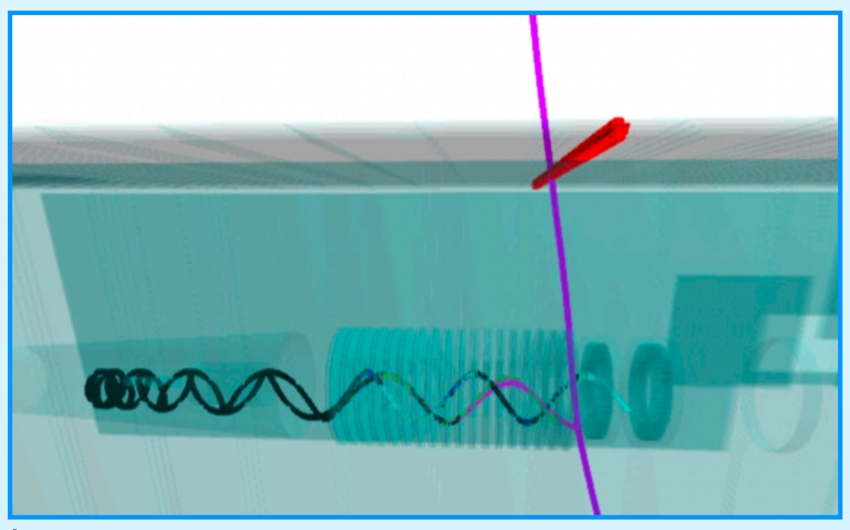
Assuming track reconstruction efficiency of ~ 0.1, we reconstruct about 10^{-4} events with two e^- tracks from DIO. Assuming a uniform distribution in time and same efficiency of reconstruction for multi-track events as single-track events, **number of events with two DIO e^-s within a time window of 100 ns is $\sim 10^{-5}$ for Run I.**

2. Cosmic rays

A cosmic ray veto (CRV) system built from scintillator counters surrounds the detector solenoid to identify the cosmic rays.

The multi-track events from cosmic rays are:

1) Muons interacting with the calorimeter, producing e^-/e^+ that travels upstream towards the ST and then returns back.
2) Muons interacting with ST producing e^-/e^+.
3) Muons trapped in the magnetic bottle structure of the DS, travel towards the ST and back in helical motion.

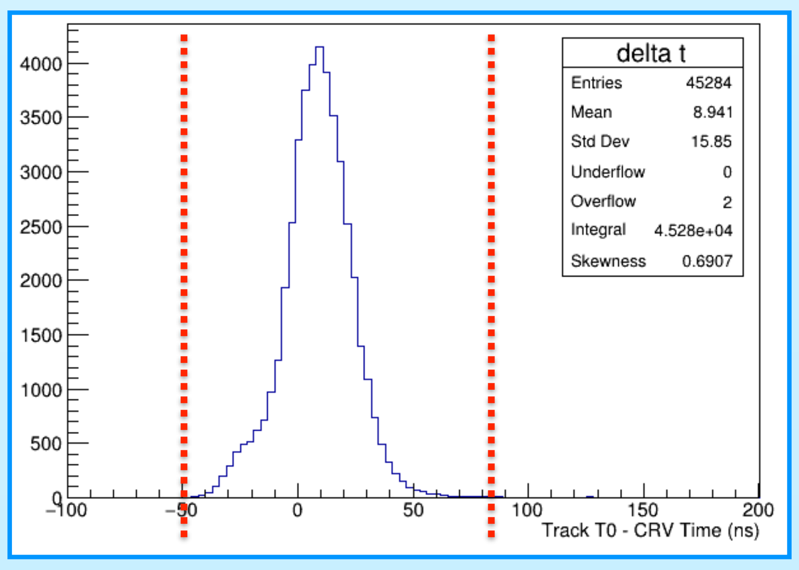


Cosmic μ^- hits the CRV scintillation bars (shown in red), performs helical motion due to the magnetic bottle structure of the DS.

About 98% of these multi-track events can be vetoed using the signal from the CRV. Cosmic event candidates are identified by the timing window $-50 < \Delta T_{CRV} < 80ns$ where $\Delta T_{CRV} = T_0 - T_{CRV}$.

Most cosmic multi-track events are composed of an upstream and downstream moving trajectory of the same particle while $\bar{p}$ annihilation at the ST gives multiple particles moving downstream with the staring position consistent with the ST.

We have identified track parameters: pitch($tan(\lambda)$), impact parameter ($D0$), time ($T0$), (Δp, Δt) between the reconstructed tracks, that can be used to distinguish tracks from cosmic muons from $\bar{p}$ background events.



Conclusion

We are developing a novel data-driven approach to constrain the $\bar{p}$ background in Mu2e.

We tested the reconstruction procedure with datasets containing only $p\bar{p}$ annihilation events and with $p\bar{p}$ annihilation events mixed with low and high intensity backgrounds. **Compared to the default reconstruction, the number of multi-track events increased by × 2.1 times.**

We have estimated that the contribution of DIO and cosmic rays to the multi-track event signature expected from the $\bar{p}$ background is negligible.

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