A data-driven method to estimate the $\bar{p}$ background in Mu2e

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Abstract

The Mu2e experiment will search for the CLFV process of neutrinoless, coherent conversion of muon to electron in the field of an Al nucleus. One of the expected backgrounds is antiprotons produced by the proton beam at the Production Target and annihilating in the Stopping Target to produce signal-like electrons. Although not a dominant background, it has a large uncertainty and cannot be suppressed by the timing cuts used to reduce the prompt background. However, at Mu2e energies, $p\bar{p}$ annihilation is the only source of events with multiple, simultaneous particles coming from the Stopping Target. We utilized this unique feature and developed a novel approach to reconstruct multi-track events and estimate the antiproton background.

1 Introduction

The Mu2e experiment at Fermilab will search for the CLFV process of coherent, neutrinoless $\mu^- \to e^-$ conversion in the field of an atomic nucleus, by measuring the ratio $\mathbf{R}_{\mu e}$:

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

For an Al target, the expected signal is a monochromatic ∼104.97 MeV/c electron (CE) [1]. The main backgrounds to this search are cosmic muons interacting or decaying within the detector, decays in orbit of muons stopped in the Stopping Target (ST), radiative capture of stopped pions (RPC), and $\bar{p}$ annihilation in the ST. A schematic view of the experiment is given in Fig.1. Mu2e will use an 8 GeV pulsed proton beam which interacts with a tungsten (W) target in the Production Solenoid (PS), and produces pions which decay to muons. These particles drift towards the S-shaped Transport Solenoid (TS). The curved magnetic field of the TS causes the oppositely charged particles to drift vertically in opposite directions. A rotating collimator in the center of the TS will be used to select the μ^+/μ^- beam. The muons enter the Detector Solenoid (DS) and stop in the Al ST. The main detectors include a straw tracker and an electromagnetic calorimeter, positioned after the ST.

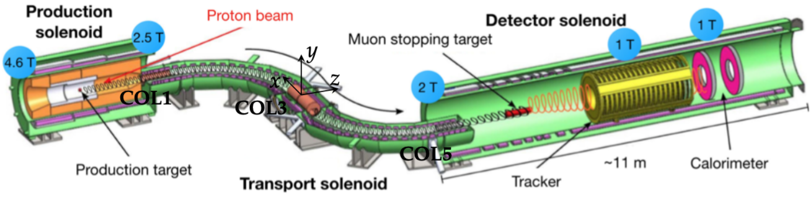

Figure 1: Schematic view of the Mu2e experiment [2].

2 Antiproton background in Mu2e

$\bar{p}$'s are produced in the interactions of the proton beam with the production target in the PS. They can pass through the TS, unaffected by the center collimator. $\bar{p}$ absorbers are present at the entrance and center of the TS. Most of the $\bar{p}$s that make it to the DS, stop within the first few ST foils as shown in Fig.2, at $\sim$ 6m.

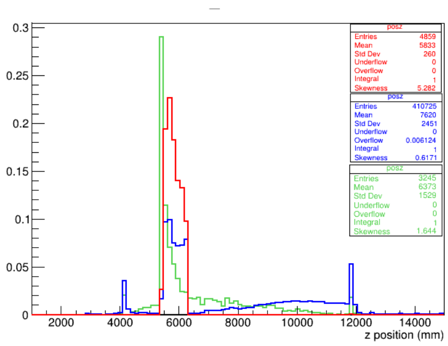

Figure 2: z-coordinate of the start position of the MC true trajectories of particles from $p\bar{p}$ annihilation (green), interactions of the cosmic rays in the DS (blue) and $\mu^- \to e^-$ conversion (red).

$p\bar{p}$ annihilation at the ST can produce electrons via $\pi^0 \to \gamma\gamma$ decays followed by photon conversions, and $\pi^- \to \mu^- \bar{\nu}$ decays followed by muon decay. In addition, radiative capture of the pions produced in $p\bar{p}$ annihilation along the beamline increases the overall RPC background. $\bar{p}$s are significantly slower than the other beam particles so they cannot be efficiently suppressed by a time window cut. The estimated $\bar{p}$ background for Run I is $0.01 \pm 0.003(stat) \pm 0.010(syst)$ [2]. The large systematic error is dominated by the uncertainty on the $\bar{p}$ production cross section that has never been measured at the Mu2e beam energy. However, the $\bar{p}$ background in Mu2e has a unique feature: $p\bar{p}$ annihilation at rest in the ST can produce events with two or more simultaneous particles. From the Geant4 simulation, only about 0.2% of the simulated $p\bar{p}$ annihilation events have an electron producing at least 20 straw hits in the tracker and with momentum in the range of 90-110 MeV/c. At the same time, $\sim$ 5% of events have more than 1 particle with at least 20 straw hits per particle. Therefore, our idea is to identify and reconstruct the multi-track events and estimate the $\bar{p}$ background by exploiting the large ratio of the production rates of the two final states.

3 Mu2e Event Reconstruction

The event reconstruction in Mu2e is optimized for single electron track events. From MC studies, we have observed that about 90% of the hits in an event are from low energy electrons, positrons and protons. They are flagged as background prior to the track reconstruction. Assuming that hits produced by the same particle have close reconstructed times, the hits are clustered in time. These time clusters are input for the pattern recognition which searches for 3-D helical trajectories. The default Mu2e algorithms to flag the background hits and form the time clusters use an Artificial Neural Network (ANN) trained for efficient CE search, which inadvertently removes a large fraction of pion and muon hits. This reduces the efficiency of reconstructing tracks from $p\bar{p}$ annihilation significantly. Thus, we have developed new algorithms, without any ANN, highly efficient for a wide spectrum of particle topologies. However, simple time clustering alone is insufficient for $p\bar{p}$ annihilation events as the tracks are mostly simultaneous in time. We observed that hits from different particle trajectories could be well separated in $\phi = tan^{-1}(y/x)$. We developed a ϕ clustering algorithm to group hits of a time cluster based on their ϕ distribution. Fig.3 is an event display of one of the $p\bar{p}$ annihilation

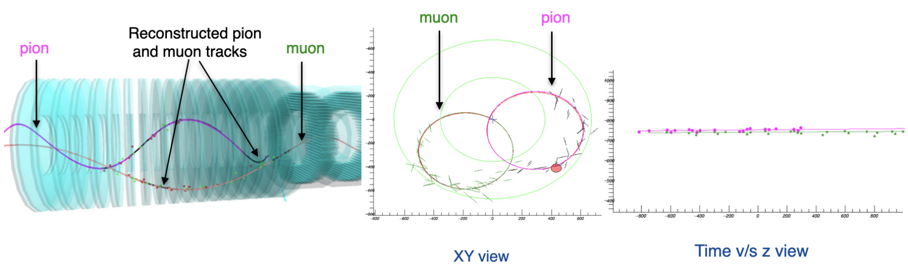

Figure 3: An example event showing successful multi-track reconstruction. The MC true trajectories are given in magenta (pion) and green (muon). The reconstructed track is shown in black (3-D view) and in red (2-D views), respectively.

at the ST events where both the particle trajectories are close in time but well separated in ϕ and have been reconstructed successfully.

4 Contribution from other backgrounds to multi-track events

4.1 Decay in Orbit (DIO)

According to the Run I plan [2], about 75% of the total protons on target (POT) will be delivered in the low intensity running mode, with a mean intensity of 1.6×10^7 protons/pulse and about 25% in the high intensity running mode with a mean intensity of 3.9×10^7 protons/pulse. The average number of stopped muons/POT determined from the muon beam simulations is 1.6×10^{-3}. Thus, for Run I we expect a total of $\sim 6.0 \times 10^{16}$ muon stops at the ST. About 39% of the stopped muons decay in orbit, so an average Mu2e event includes about 10^4 DIO electrons, and in Run I, we can expect about 2.3×10^{16} DIO electrons. We search for multi-track events with each track momentum ~ 100 MeV/c. Requiring the DIO electron momentum to be above 90 MeV/c and integrating over the DIO momentum spectrum [1] gives an estimate of the total number of events with two DIO electrons,

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

Assuming a track reconstruction efficiency of ~ 0.1 [2], we reconstruct about 10^{-4} events with two electron tracks from DIO. Further, assuming a uniform distribution in time and the same efficiency of reconstruction for multi-track events as single-track events, the number of events with two DIO electrons within a time window of 100 ns is $\sim 10^{-5}$ for Run I. Therefore, the contribution of the DIO background to the multi-track event signature is negligible.

4.2 Cosmic rays

Mu2e has a Cosmic Ray Veto (CRV) surrounding the DS to suppress the cosmic ray background. The cosmic background events could be from:

- Cosmic rays passing through the CRV and striking the detector or beamline components. Most of these events can be vetoed using the CRV signal. The distribution of the timing residuals $\Delta T_{CRV} = T_0 - T_{CRV}$ between the reconstructed track and the CRV stub is shown in Fig.4. Cosmic event candidates are identified by the timing window $-50 < \Delta T_{CRV} < 80 ns$.
- Cosmic rays entering the DS through regions not covered by the CRV.

Most of the cosmic ray interactions occur at the ST (at $\sim$ 6 m) and the calorimeter disk (at $\sim$ 12 m), as shown in Fig.2. From our preliminary analysis, the multi-track events from cosmic

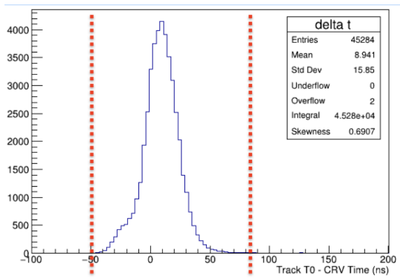

Figure 4: Distribution of timing residuals $\Delta T_{CRV} = T_0 - T_{CRV}$ between the reconstructed track and the CRV stub. Dotted red lines represent the timing window used in the event selection.

rays can be classified into the following categories:

- Cosmic muons interacting with a detector element like the calorimeter disk, producing an e^-/e^+ which first travels upstream towards the ST and then returns back. Given in Fig.5 is one such event. The μ^- passes through the CRV (the 'hit' scintillation bars are shown in red), interacts with a detector element, generating an e^- that travels upstream to the ST and returns back.
- Cosmic muons interacting with the ST producing electrons or positrons.
- Cosmic muons trapped in the magnetic bottle structure of the DS and performing helical motion.

In most of the above mentioned events, each event contains a single particle trajectory with an upstream and downstream leg that are reconstructed as two distinct trajectories with a ΔT of about 50-100 ns between them. Such multi-track events can be well distinguished from the $\bar{p}$ events as $p\bar{p}$ annihilation at the ST mostly produces pion and muon trajectories, simultaneous in time, moving downstream in the tracker. Therefore, we can veto most of the multi-track events from cosmic rays using the CRV signal and the Δt between the reconstructed trajectories.

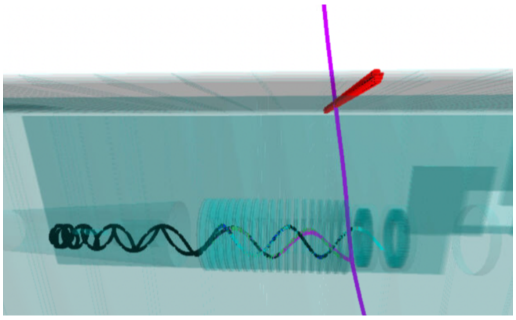

Figure 5: Event display of a multi-track event from cosmic ray interactions in the DS.

5 Conclusion

We have developed a novel data-driven approach to constrain the $\bar{p}$ background to the neutrinoless μ^- to e^- conversion search. The new algorithms significantly improve the reconstruction efficiency of $p\bar{p}$ annihilation events. 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, respectively. Compared to the default reconstruction, the number of events with two or more tracks increased by $\times 2.1$ times. We have estimated that the contribution of DIO and cosmic rays to the multi-track event signature is negligible. Currently, we are working on improving the reconstruction efficiency further and getting a final estimate on the $\bar{p}$ background in Mu2e.

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References

[1] A. Czarnecki, X. Garcia i Tormo and W. J. Marciano, *Muon decay in orbit: Spectrum of high-energy electrons*, Phys. Rev. D **84**, 013006 (2011), doi:10.1103/PhysRevD.84.013006.

[2] M. Collaboration, *Mu2e run 1 sensitivity projections for the neutrinoless $\mu^- \to e$ conversion search in aluminum*, Universe **9**(1) (2023), doi:10.3390/universe9010054.