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A data-driven method to estimate the antiproton background in Mu2e

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Mu2e experiment at Fermilab will search for the Charged Lepton Flavour Violating (CLFV) process of neutrinoless conversion of muon to electron in the field of an Aluminum nucleus. The experimental signature is a monochromatic 104.97 MeV conversion electron. One of the expected backgrounds to the conversion electron search is antiprotons produced by the proton beam at the Production Target and annihilating in the Stopping Target (ST). The background expected from antiprotons is low but highly uncertain due to the uncertainty in the antiproton production cross section for the Mu2e beam energy in the relevant angular region. Antiprotons are significantly slower than the other beam particles, so they cannot be efficiently suppressed by the time window cut used to reduce the prompt background. At Mu2e energies, antiproton annihilation at rest in the ST is the only source of events with multiple, simultaneous particle trajectories. We utilized this unique feature and developed a novel way to reconstruct the multi-track events and estimate the antiproton background in situ.

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[*] Speaker

1. Introduction

The Mu2e experiment will search for the CLFV process of coherent, neutrinoless $\mu^- \to e^-$ conversion in the field of an Al nucleus. A schematic view of the experiment is given in Fig.1.

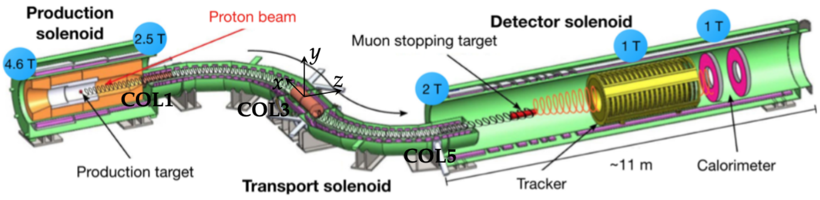

Figure 1: Schematic view of the Mu2e experiment [1].

Mu2e will use an 8 GeV pulsed proton beam which interacts with a tungsten target in the Production Solenoid, and produces pions which decay to muons. The curved $\vec{B}$-field of the S-shaped Transport Solenoid (TS) causes oppositely charged particles to drift vertically in opposite directions. A rotating collimator selects the sign of the μ^+/μ^- beam. Muons enter the Detector Solenoid (DS) and stop in the Al Stopping Target (ST). The detectors, the straw tracker and the electromagnetic calorimeter surrounded by the cosmic ray veto system are located downstream of the ST.

2. Antiproton background in Mu2e

Antiprotons are produced in the proton beam interactions with the production target. They pass through the TS, unaffected by the center collimator and reach the ST. Antiproton absorbers are present at the entrance and center of the TS. Antiproton annihilation at the ST can produce electrons via $\pi^0 \to \gamma\gamma$ decays followed by γ conversions, and $\pi^- \to \mu^- \bar{\nu}$ decays followed by μ^- decay. Antiprotons are significantly slower than other beam particles so they cannot be efficiently suppressed by the time window cut used to reduce prompt background. The antiproton background estimated for Run I in the optimized signal momentum ($103.60 < p < 104.90$ MeV/c) and time window ($640 < T_0 < 1650$ ns) is $0.01 \pm 0.003(stat) \pm 0.010(syst)$ events [1]. The large systematic error is dominated by the uncertainty on the $\bar{p}$ production cross section. However, $\bar{p}$ annihilation in the ST can produce events with multiple simultaneous particles. From the Geant4 simulation, only about 0.2% of the simulated $\bar{p}$ annihilation events have an electron with momentum $90 < p < 110$ MeV/c. Meanwhile, $\sim 5\%$ of events have multiple reconstructible particle tracks. Therefore, we plan to 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. Multi-track event reconstruction

The Mu2e event reconstruction is optimized for single track events. From MC studies, about 90% of the hits in an event are from low energy e^-/e^+ and p's. They are flagged as background prior to track reconstruction. Assuming that hits made by the same particle have close reconstructed times, they are clustered in time. The time clusters are input for pattern recognition algorithms which search for 3-D helical trajectories. However, time clustering alone does not help in finding the tracks from $\bar{p}$ annihilation events as the daughter tracks are mostly simultaneous in time.

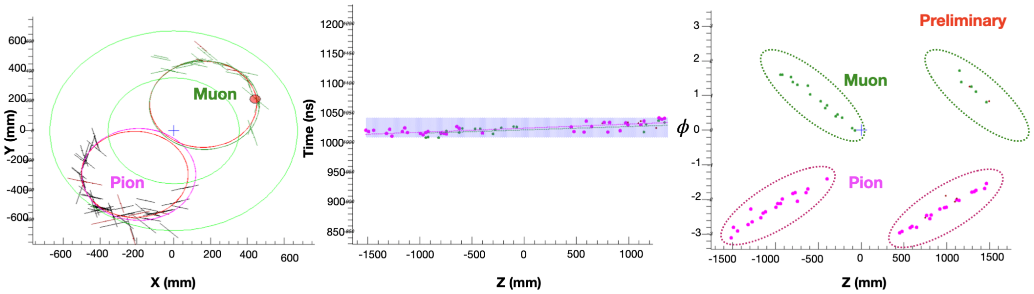

Figure 2: An example multi-track $\bar{p}$ background event, with pion (in magenta) and a muon (in green) track coming from the ST. The reconstructed tracks are shown in red.

We observed that in most $\bar{p}$ annihilation events hits from different particles could be well separated in $\phi = tan^{-1}(y/x)$. We developed a ϕ clustering algorithm to group the hits of a time cluster based on their ϕ distribution. Given in Fig.2 is an example event of $\bar{p}$ annihilation at the ST, generating a pion and a muon trajectory. From the tz view, we can see that all the hits in this event are part of a single time cluster. But, from the xy and ϕz views, hits of two particles can be well distinguished.

4. Conclusion

We have developed a novel data-driven approach to constrain the antiproton background to the neutrinoless muon to electron conversion search. We tested the reconstruction procedure successfully with single-interaction $\bar{p}$ annihilation events and $\bar{p}$ annihilation events mixed with low-intensity (beam intensity of 1.6×10^7 protons/pulse) and high-intensity (4.0×10^7 protons/pulse) pileup respectively. Currently, we are working out the systematic uncertainties and getting a final estimate on the antiproton background in Mu2e.

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[1] Mu2e Collaboration, Mu2e run 1 sensitivity projections for the neutrinoless $\mu^- \to e^-$ conversion search in aluminum, Universe 9 (2023). URL: `https://www.mdpi.com/2218-1997/9/1/54`. doi:`10.3390/universe9010054`.