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Multi-track event reconstruction to constrain the <mml:math xmlns:mml="http://www.w3.org/1998/Math/MathML" altimg="si6.svg" display="inline" id="d1e125"><mml:mover accent="true"><mml:mrow><mml:mi>p</mml:mi></mml:mrow><mml:mrow><mml:mo>■</mml:mo></mml:mrow></ ver></mml:math> background in Mu2e

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

Namitha Chithirasreemadam [a,b,*], Simone Donati [a,b], Pavel Murat [c], on behalf of the Mu2e Collaboration

[a] Università di Pisa, Largo B. Pontecorvo, 3, I-56127, Pisa, Italy
[b] INFN, Sezione di Pisa, Largo B. Pontecorvo, 3, I-56127, Pisa, Italy
[c] Fermi National Accelerator Laboratory, Batavia, IL, United States of America

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ABSTRACT

Mu2e experiment will search for the neutrinoless, coherent conversion of $\mu^- \to e^-$ in the field of an Al nucleus. One of the expected backgrounds is $\bar{p}$'s annihilating in the stopping target to produce signal-like e^-'s. 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 way to reconstruct multi-track events and estimate the $\bar{p}$ background.

1. Introduction

The Mu2e experiment will search for the Charged Lepton Flavour Violating process of coherent, neutrinoless $\mu^- \to e^-$ conversion in the field of an atomic nucleus. For Al target, the expected signal is a monochromatic ∼104.97 MeV/c electron (CE). 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 target in the Production Solenoid (PS), and produces pions which decay to muons. The curved $\vec{B}$ of the S-shaped Transport Solenoid (TS) causes the oppositely charged particles to drift vertically in opposite directions. A rotating collimator is used to select the μ^+/μ^- beam. The muons enter the Detector Solenoid (DS) and stop in the Al Stopping Target (ST). The main detectors are a straw tracker and an electromagnetic calorimeter, located in the downstream end of the DS, in a uniform $\vec{B}$ of 1 T. A Cosmic Ray Veto (CRV) system surrounds the DS to identify the cosmic ray background events.

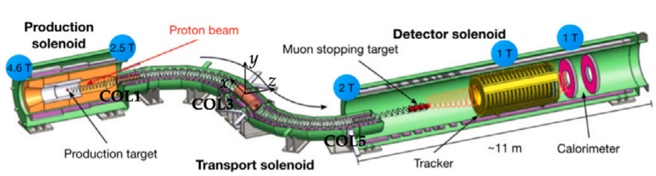

Fig. 1. Schematic view of Mu2e experiment [1]. The Mu2e reference frame center is at COL3 collimator center, y-axis points upwards, z-axis is parallel to DS axis and points downstream.

2. Antiproton background in Mu2e

$\bar{p}$s are produced in the proton beam interactions with the production target. They can pass through the TS, unaffected by the center collimator and reach the ST. $\bar{p}$ absorbers are present at the entrance and center of the TS. $p\bar{p}$ annihilation at the ST can produce e^-s via $\pi^0 \to \gamma\gamma$ decays followed by γ conversions, and $\pi^- \to \mu^-\bar{\nu}$ decays followed by μ^- decay. $\bar{p}$s are much slower than the other beam particles so they cannot be efficiently suppressed by a time windo cut. The estimated $\bar{p}$ background for Run I, in the optimized signal momentum and time window, $103.60 < p < 104.90$ MeV/c and $640 < T_0 < 1650$ 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 for Mu2e beam energy in the relevant angular region. However, $p\bar{p}$ annihilation at rest 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 e^- producing at least 20 straw hits in the tracker and with momentum in the range of 90–110 MeV/c. Meanwhile, ∼ 5% of events have two or more particles with at least 20 straw hits per particle. So, 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. Mu2e event reconstruction

The Mu2e event reconstruction is optimized for single e^- track events. From MC studies, about 90% of the hits in an event are from

* Corresponding author at: Università di Pisa, Largo B. Pontecorvo, 3, I-56127, Pisa, Italy.
E-mail address: namithac@pi.infn.it (N. Chithirasreemadam).

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low energy e^-/e^+ and p's. They are flagged as background prior to the track reconstruction. Assuming that hits made 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 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 particles

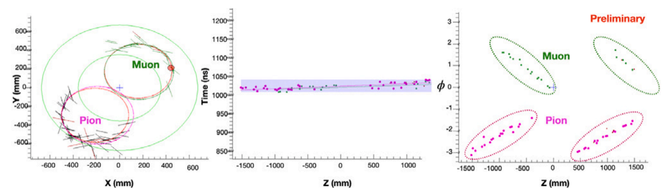

Fig. 2. An example multi-track $p\bar{p}$ background event, with pion (in magenta) and muon (in green) trajectories. The reconstructed tracks are shown in red.

could be well separated in $\phi = tan^{-1}(y/x)$. So, 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 $p\bar{p}$ annihilation at the ST, generating a pion and muon trajectory. From the tz view, we can see all the hits in this event are part of one time cluster. But, from the xy and ϕz views, the hits of the two particles can be well distinguished.

4. Contribution of other backgrounds to multi-track events

4.1. Muon decay in orbit (DIO)

According to the Run I plan [1], about 75% of the total protons on target (POT) will be delivered in the low intensity mode, with a beam intensity of 1.6×10^7 protons/pulse and 25% in the high intensity mode with 3.9×10^7 protons/pulse. The average number of stopped muons/POT determined from the simulations is 1.6×10^{-3}. About 39% of the stopped muons decay in orbit, so an average Mu2e event has about 10^4 DIO electrons. We expect about 2.3×10^{16} DIO electrons in total for Run I. We search for multi-track events with each track having $p \simeq 100$ MeV/c. Requiring the DIO electron momentum to be above 90 MeV/c and integrating the DIO energy spectrum shown in Fig. 3 gives an estimate of two DIO electrons for Run I:

$$N_{2\,DIO}(E > 90) = 2.3 \times 10^{16} \times (7.3 \times 10^{-10})^2 \approx 0.01 \quad (1)$$

Assuming a track reconstruction efficiency of ~ 0.1 [1] and a uniform DIO distribution in time, the number of two reconstructed DIO electrons with $p > 90$ MeV/c each and within a time window of 100 ns is $\sim 10^{-5}$ for Run I.

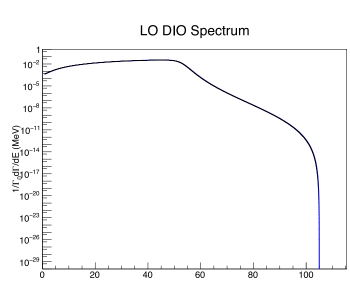

Fig. 3. Leading Order DIO energy spectrum (MeV) on Al [2].

4.2. Cosmic rays

Cosmic ray interactions in the DS can generate multi-track events when cosmic ray muons interact with the calorimeter disks and generate e^-/e^+'s which first travel upstream towards the ST and then returns back due to the magnetic bottle structure of the DS. The upstream and downstream legs of the trajectory are reconstructed as two distinct tracks. Meanwhile, $p\bar{p}$ annihilation at the ST mostly produces pion and muon tracks, simultaneous in time, moving downstream in the tracker. We can veto about 99.98% of the multi-track events from cosmic rays

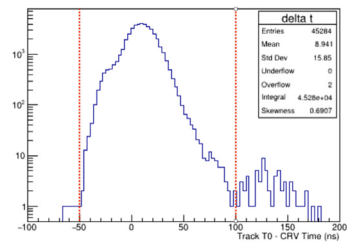

Fig. 4. $\Delta T_{CRV} = T_0 - T_{CRV}$ between reconstructed track and CRV signal.

using the CRV signal. The distribution of the timing residuals $\Delta T_{CRV} = T_0 - T_{CRV}$ between the reconstructed track and the CRV signal is shown in Fig. 4. Cosmic event candidates are identified by the timing window of $-50 < \Delta T_{CRV} < 100$ ns.

5. Conclusion

We have developed a novel data-driven approach to constrain the $\bar{p}$ background to the neutrinoless μ^- to e^- conversion search. We have 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. Currently, we are working on getting a final estimate on the $\bar{p}$ background in Mu2e.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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