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

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Summary. — The Mu2e experiment will search for the charged lepton flavour violating process of neutrinoless coherent muon to electron conversion in the field of an Al nucleus. The expected signal is a 104.97 MeV/c electron. One of the expected backgrounds is due to $\bar{p}$s produced by the proton beam at the Production Target and annihilating in the Stopping Target (ST). The background from $\bar{p}$ annihilation is not a dominant one, but it has a large uncertainty and it 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 tracks coming from the ST. We exploit this unique feature and reconstruct the multi-track events to estimate the $\bar{p}$ background.

1. – Introduction

The Mu2e experiment will search for coherent, neutrinoless conversion of muon to electron in the presence of an atomic nucleus, an evidence for Charged Lepton Flavour Violation, 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 Stopping Target (ST), the expected signal is a monochromatic ∼104.97 MeV/c electron [1]. The main backgrounds to this search are cosmic muons interacting or decaying within the detector, decays in orbit of muons stopped in the 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 production 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

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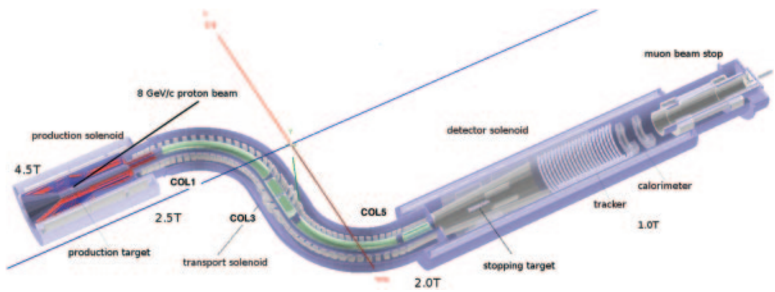

Fig. 1. – Schematic view of the Mu2e experiment.

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 DS also contains the main detectors: a straw tracker and an electromagnetic calorimeter.

2. – Antiproton background in Mu2e

$\bar{p}$s are produced in the interactions of the 8 GeV proton beam with the production target. They can pass through the TS, unaffected by the center collimator in the TS. $\bar{p}$ 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. $p\bar{p}$ 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. However, the $\bar{p}$ background 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 and 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, the 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

Mu2e event reconstruction is optimized for single electron track events. From the MC studies, 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. Finally, the reconstructed track parameters are determined by the Kalman fit. The default Mu2e algorithms to flag the background hits and form the time clusters use an Artificial Neural Network (ANN) trained for efficient conversion electron search, which inadvertently removes a large fraction of pion and muon hits.

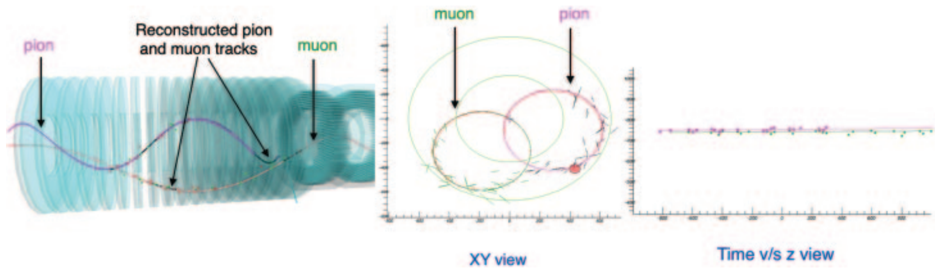

Fig. 2. – An example event showing successful multi-track reconstruction. The MC true trajectories are given in magenta (pion) and green (muon). The reconstructed track is shown in black (3 D view) and in red (2 D views), respectively.

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 have developed a ϕ clustering algorithm to group hits of a time cluster based on their ϕ distribution.

Figure 2 is an event display of one of the $p\bar{p}$ annihilation 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 of 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 the mean intensity 1.6×10^7 protons/pulse and about 25% in the high intensity running mode with the 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 the DIO momentum spectrum shown in fig. 3 gives an estimate of the total number of events with two DIO electrons,

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

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.

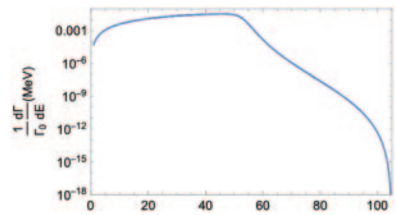

Fig. 3. – Leading Order DIO energy spectrum (MeV) on Al [1].

4˙2. *Cosmic ray muons.* – An estimate of the contribution of the cosmic ray muons to the multi-track event signature is currently in progress. Mu2e has a Cosmic Ray Veto surrounding the DS to suppress the cosmic ray background. Our preliminary study indicates that the multi-track events due to cosmic ray muons are of the following types: 1) muons interacting with the calorimeter disk, producing an electron or positron which first travels upstream towards the ST and then returns back, 2) muons interacting with the ST, producing electrons or positrons. Both of these types of multi-track events can be well distinguished from the $\bar{p}$ background events as $p\bar{p}$ annihilation at rest mostly produces pions and muons moving downstream in the tracker.

5. – Summary

We are developing a novel data-driven approach to constrain the antiproton background to the search for the muon to electron conversion. 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 at least one reconstructed track has increased by $\times 1.4$ times and with two and more tracks increased by $\times 2.1$ times. We have estimated that the contribution of DIO to the multi-track event signature is negligible. Currently, we are working on improving the reconstruction efficiency further and estimating the contribution of the cosmic rays to the multi-track event signature.

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