IL NUOVO CIMENTO **47 C** (2024) 110
DOI 10.1393/ncc/i2024-24110-4

Colloquia: IFAE 2023

Developing a data-driven method to constrain the antiproton background in the Mu2e experiment(*)

N. Chithirasreemadam(1)(**), S. Donati(1), P. Murat(2), G. Pezzullo(3) and M. Stortini(3) on behalf of the Mu2e Collaboration

(1) *Dipartimento di Fisica, Università di Pisa - Pisa, Italy*
(2) *Fermi National Accelerator Laboratory - Batavia, IL 60510, USA*
(3) *Department of Physics, Yale University - New Haven, CT 06520-8120, USA*

received 13 February 2024

Summary. — The Mu2e experiment will search for CLFV neutrinoless coherent muon to electron conversion in the field of an Al nucleus. The expected signal is a 104.97 MeV/c monochromatic e^- (CE). CE-like e^-'s could also come from $\bar{p}$'s annihilating in the Stopping Target (ST). The background induced by $\bar{p}$'s is expected to be low but has a large systematic uncertainty. It cannot be suppressed by the time window cut used to reduce the prompt background. However, $p\bar{p}$ annihilation in the ST is the only source of events in the Mu2e detector with multiple tracks coming from the ST, simultaneous in time, each with a momentum in the signal window region. We exploited this unique feature and developed algorithms to identify and reconstruct multi-track events. This paper discusses the status and prospects of this data-driven method to constrain the $\bar{p}$ background at Mu2e.

1. – Introduction

Mu2e is a new, high-intensity frontier experiment under development at Fermilab that will search for the CLFV process of neutrinoless coherent muon to electron conversion in the presence of an atomic nucleus by measuring the ratio $\mathbf{R}_{\mu e}$.

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

For an Al target, the expected signal is a ∼104.97 MeV/c monochromatic e^- [1]. A schematic view of the experiment is given in fig. 1. Mu2e will use an 8 GeV pulsed proton beam which interacts with the tungsten (W) target in the Production Solenoid (PS), and mostly produces pions. The pions decay in flight, producing muons.

(*) IFAE 2023 - "Poster" session
(**) Corresponding author. E-mail: `namithac@pi.infn.it`

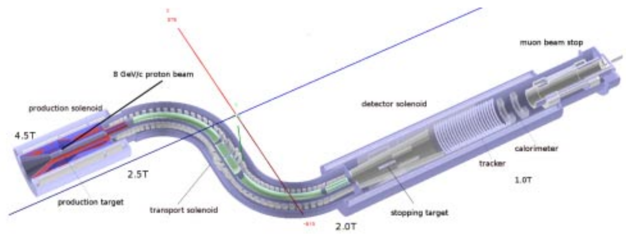

Fig. 1. – Schematic view of the Mu2e apparatus.

These particles drift towards the S-shaped Transport Solenoid (TS). The curved magnetic field of the TS causes the opposite charged particles to drift vertically in opposite directions. The rotating collimator in the TS center selects a μ^+ or μ^- beam. The muons enter the Detector Solenoid (DS) and stop in the Al Stopping Target (ST). The DS also contains the main detectors: the straw-tube Tracker and the electromagnetic Calorimeter. The tracker consists of 18 stations with 1152 straws per station. The straws are filled with 80%:20% Ar:CO_2 mixture. The calorimeter consists of 2 disks covering radii 37 cm - 66 cm. Each disk consists of 674 undoped CsI crystals. Main backgrounds to the conversion search are due to cosmic muons interacting or decaying within the detector, decays in orbit of muons stopped in the ST, radiative capture of stopped π^-'s, and $\bar{p}$ annihilation in the ST.

2. – Antiproton background in Mu2e

$\bar{p}$s can be produced in the pW interactions in the PS. They can pass through the TS, unaffected by the center collimator used to select the μ^- beam.

$\bar{p}$ absorbers positioned at the entrance and center of the TS suppress the $\bar{p}$'s. Most of $\bar{p}$'s reaching the DS stop in the first ST foils. $p\bar{p}$ annihilation at the ST can produce e^-'s via $\pi^0 \to \gamma\gamma$ decays followed by photon conversions and $\pi^- \to \mu^-\bar{\nu}$ decays followed by the μ^- decays. In addition, radiative capture of pions produced in $p\bar{p}$ annihilation along the beamline and reaching the ST increases the overall RPC background. The $\bar{p}$ background cannot be efficiently suppressed by the time window cut used to reduce the prompt background because $\bar{p}$'s are significantly slower than the other beam particles. 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.

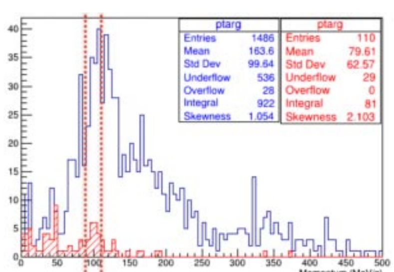

Fig. 2. – Tracks in multi-track events (blue) *vs.* single e^- tracks (red) from $p\bar{p}$ annihilation.

However, $\bar{p}$ background in Mu2e has a unique feature: $p\bar{p}$ annihilation at rest in the ST can produce events with $\geq$1 track with momentum $\sim$ 100 MeV/c. From the Geant4 simulation, only about 0.2% of simulated $p\bar{p}$ annihilation events have an e^- with $\geq$ 20 straw hits and momentum in the range of 90-110 MeV/c. At the same time, $\sim$ 5% of events have $\geq$ 2 particles with $\geq$ 20 straw hits per particle. Figure 2 shows the momentum distribution of the tracks from multi-track events in blue and the single e^- tracks from $p\bar{p}$ annihilation at the ST in red. So, $N_{e^- perMeV}/N_{multi-track} \approx 1/500$. Therefore, the idea is to identify and reconstruct the multi-track events and estimate the $\bar{p}$ background by re-scaling the ratio of the two final states.

3. – Mu2e Event Reconstruction

The Mu2e event reconstruction is optimized for single-track events. From MC studies, > 90% of the hits in an event are from low energy e^+/e^- and protons. They are flagged as background prior to the track reconstruction. Assuming that hits produced by the same particle have close reconstructed times, hits in the tracker are clustered in time. Time clusters are used as input for the pattern recognition which searches for 3-D helical trajectories. Finally, parameters of the reconstructed track are determined by the Kalman fit. The default Mu2e algorithms removing hits of low energy e^+/e^- and performing the time clustering use an ANN which inadvertently remove a significant fraction of pion and muon hits. This significantly reduces the efficiency of reconstructing tracks from $p\bar{p}$ annihilation.

We have developed more physics-neutral algorithms, highly efficient for a wide spectrum of particle topologies to remove the low energy background hits [3] and time clustering. The new time clustering [4] algorithm searches for time clusters using the hit time and z coordinates. With the new algorithms, the rejection factor of pions and muons have significantly reduced. However, most tracks from $p\bar{p}$ annihilation are simultaneous in time. So, a simple time clustering alone is insufficient. Hits from different particle trajectories could be well-separated in $\phi = tan^{-1}(y/x)$ or overlapping. We began with the simple case of well-separated tracks and developed a ϕ clustering algorithm [5] to group hits of a time cluster based on their ϕ distribution. An example event is shown in fig. 3 where the two pion tracks are simultaneous in time but separated in ϕ. New algorithms have been included into the standard event reconstruction chain. Figure 4 is an event display of one of the $p\bar{p}$ annihilation at the ST events where both particle trajectories were successfully reconstructed.

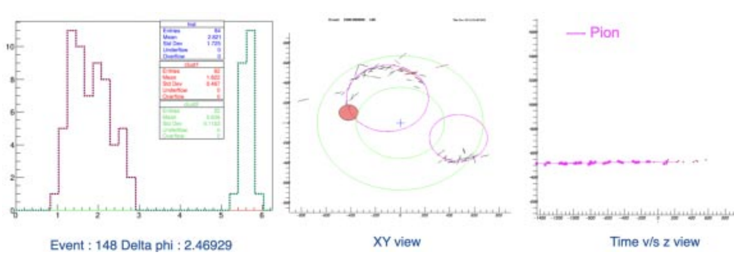

Fig. 3. – An example event with two pion tracks coming from the $p\bar{p}$ annihilation at the ST. The $\Delta\phi = 2.46$ rad between the two ϕ clusters formed by the hits of each track.

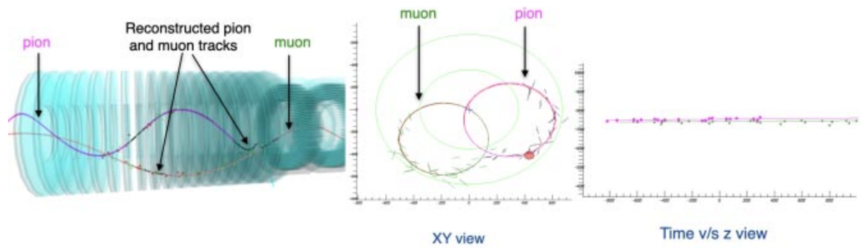

Fig. 4. – An example event showing successful two track reconstruction. The MC true trajectories are given in magenta (pion) and green (muon) respectively. The reconstructed track is given in black (3-D view) and in red (2-D views).

4. – Results

We tested the new algorithms with three datasets: (1) 10^4 single-interaction $p\bar{p}$ annihilation tracks (2) 10^4 $p\bar{p}$ annihilation tracks mixed with low-intensity background (mean intensity of 1.6×10^7 protons/pulse) and (3) 10^4 $p\bar{p}$ annihilation tracks in high-intensity mode (mean intensity of 4.0×10^7 protons/pulse). We observed that using the new reconstruction sequence number of events with ≥ 1 track increased by $\sim$40% and the number of events with ≥ 2 reconstructed tracks increased by $\sim \times 2.1$ compared to the default reconstruction sequence, across all the three datasets.

5. – Summary

The Mu2e detector and the default event reconstruction procedure are designed for efficient single track event reconstruction. The topology of $p\bar{p}$ annihilation tracks is very different from a signal e^- track. The new algorithms not only significantly improve the efficiency of reconstructing $p\bar{p}$ annihilation events, but they also improve the efficiency of single e^- track reconstruction. At present, $N_{e^- perMeV}/N_{multi-track} \approx 1/140$ (after reconstruction) for single interaction $p\bar{p}$ annihilation events.

* * *

This work was supported by the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement Nos. 734303, 822185, 858199, 101003460.

REFERENCES

[1] Czarnecki A. *et al.*, *Phys. Rev. D*, **84** (2011) 013006.
[2] Mu2e Collaboration, *Universe*, **9** (2023) 54.
[3] Murat P., *Flagging hits of Compton electrons*, Mu2e-DocDB 44415 (2023).
[4] Stortini M., *TZCLusterFinder*, Mu2e-DocDB 43999 (2022).
[5] Chithirasreemadam N., *PhiClusterFinder*, Mu2e-DocDB 43996 (2022).