Effects of Single Counter Efficiencies on Mu2e Sensitivity and Mitigation Strategy for Individual Counter Efficiency Deficits

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Introduction

The mission of the Mu2e (muon-to-electron-conversion) experiment is to observe a muon to electron conversion. This observation would be evidence of a charged lepton flavor violation process, thereby putting into question some parts of the Standard Model.

Positive and negative pions, protons, and neutrons will be produced in the Production Solenoid. Negative pions will be guided through the Transport Solenoid and into the Detection Solenoid. During this process, the pions will decay into negative muons which will slow to nearly a stop in the aluminum stopping target located within the Detector Solenoid. The muons will convert into electrons and photons which will propagate out towards the tracker and calorimeter located within the Detector Solenoid (see Figure 1). The tracker will measure the momenta of the particles and the calorimeter will record timing and energy information to check results and improve the experiment's efficiency. Most of the muons will decay into the traditional muon decay instead of converting into electrons. These decays represent a potential source of error in Mu2e.

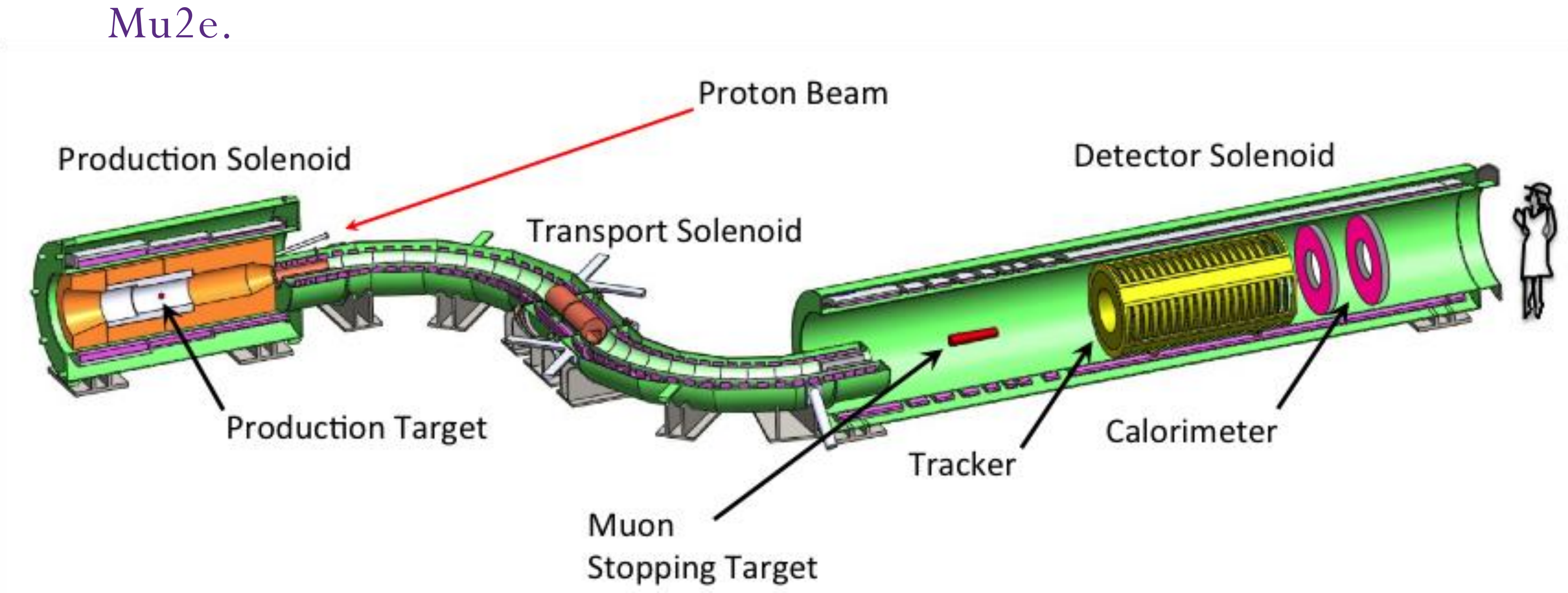

Figure 1: Mu2e Experiment Overview

The momenta associated with the decays are lower than the momenta of the converted electrons, but not by much (Figure 2). Other sources of error can shift the decay momentum peak which will obstruct the converted electron signal.

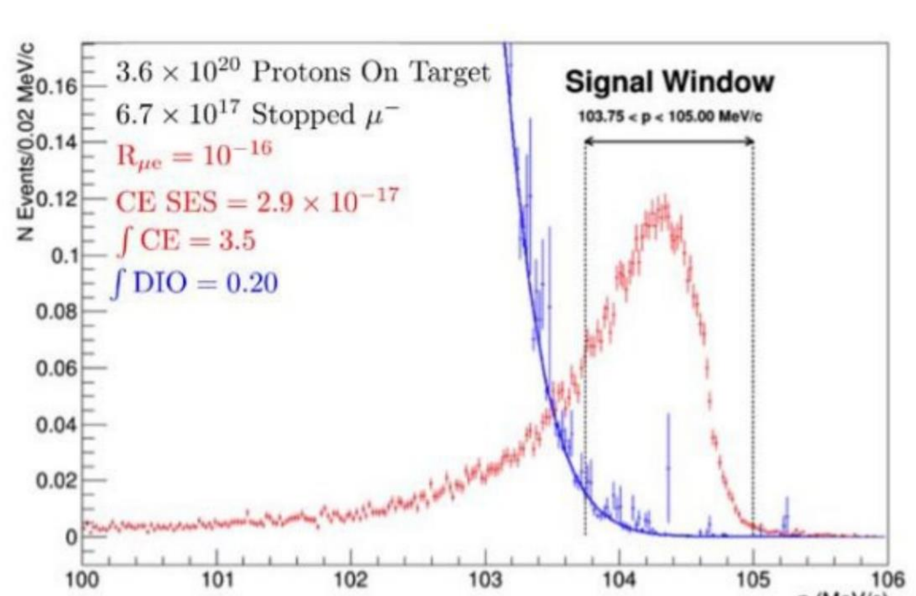

Figure 2: Momentum histogram showing the electron conversion signal in red and the accidental decay events in blue.

Cosmic Ray Veto

One such source of error comes from cosmic rays. Cosmic rays can produce signals in the tracker that are similar to converted electron signals and can hide conversion data. The Cosmic Ray Veto was designed to fix this problem.

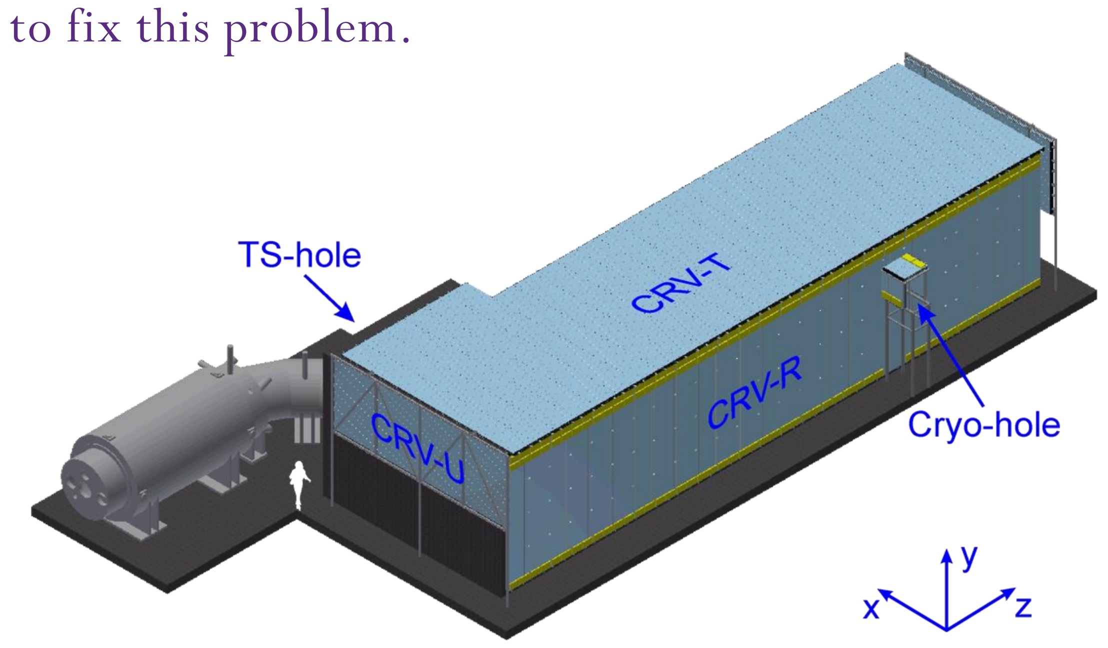

Figure 3: The Cosmic Ray Veto covering the transport solenoid of the Mu2e Experiment

The cosmic ray veto covers the entire Detector Solenoid (Figure 3). It is comprised of modules with four layers of scintillation counters (Figure 4). Cosmic rays hit the counters and send signals to silicon photomultipliers through the optical fibers that run along the length of the counter. If a signal is detected, in at least three of the four layered counters and in the tracker, it is vetoed from the results of the experiment. To reduce the number of vetoed events in the experiment, and to be sure all cosmic ray error is accounted for, the cosmic ray veto must be incredibly efficient.

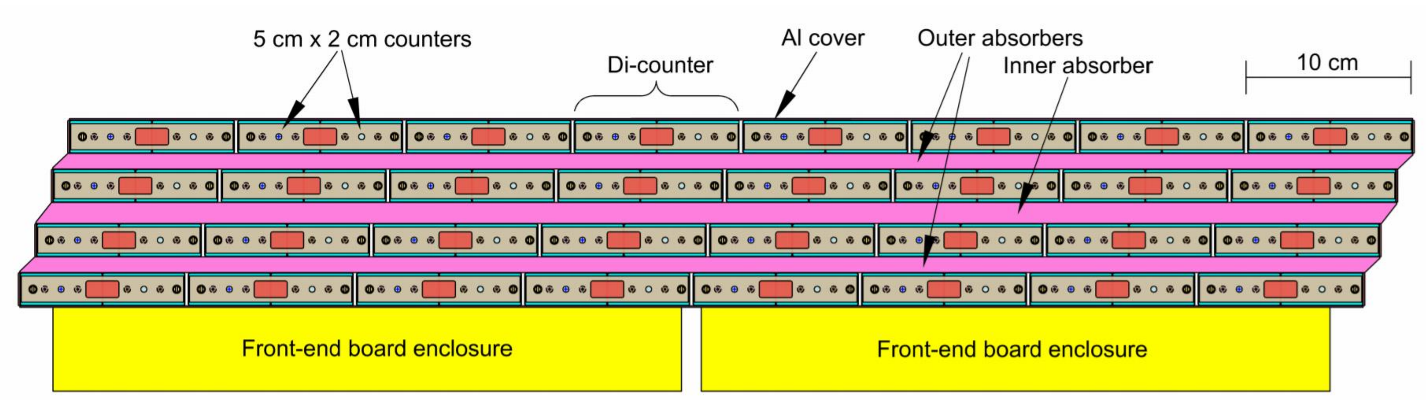

Figure 4: Cross section of a Cosmic Ray Veto module, showing the four layers of scintillation counters.

The efficiency of each counter contributes to the overall efficiency of the cosmic ray veto. The individual counter efficiencies can be affected by anything from electronics to manufacturing failures.

References

Mu2e WebMaster. Mu2e Material for Speakers. February 3, 2017. Fermi National Accelerator Laboratory Website.

Technical Design Report. Mu2e Document 4299-v15. March, 23, 2015. Mu2e Document Database.

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Sensitivity

To determine the effects of individual counter sensitivity on the overall efficiency of the cosmic ray veto we must simulate a cosmic ray hitting the counters. To do this, we generated an event which consists of a random number generation that represents a cosmic ray striking a counter. If this number is less than or equal to the individual counter efficiency, a hit variable is incremented and the counter is considered to have been hit. There are 1,000,000 events per simulation.

The counter strike process happens four times in each event, corresponding to the four counter layers that make up the Cosmic Ray Veto. There is a 0.37% chance that the cosmic ray will pass through a gap instead of one of the counters. To account for this, we included a gap correction. If the gap random number generation meets the 0.37% chance criteria, the number of counter strike processes is dropped to three. Using this simulation, we found that the lowest individual counter efficiency needed to meet the 99.99% overall efficiency requirement is 99.65% (See Figure 5.)

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Passing Events
4 / 4 hits: 982286
3 / 4 hits: 17607
Failing Events
2 / 4 hits: 107
1 / 4 hits: 0
0 / 4 hits: 0
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Figure 5: Overall efficiency is calculated by taking a ratio of passing events to total events. This is a Pass/Fail event printout for a simulation using a 99.65% individual counter efficiency.

There is also a possibility of counter failure, where one or more counters is dead, meaning the individual efficiency drops to 0% for the failed counter. We incorporated this into our simulation by generating a random number and testing various percentages of dead counters in the cosmic ray veto. We found that a 99.8% individual counter efficiency with a 0.2% rate of dead counters will give an overall efficiency of 99.99%.

Local Drop

It is useful to have ways to work around systematic failures. One such way is to drop the Pass/Fail event rate. Generally, three or four hits per event is counted as a passing event, and 2 or fewer hits is counted as a failing event. If we drop the pass rate to two or three hits per event and the fail rate to one or no hits per event, the individual counter efficiency can again be 99.65% with a dead counter rate of 0.2% to meet the overall efficiency of 99.99%. This fix will work for up to 2% of the total number of counters in the cosmic ray veto being dead.

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