Cosmic Ray Veto(CRV) R&D for Mu2e experiment

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Outline

• Mu2e overview and motivation
• Cosmic Ray Veto (CRV) overview
• Cosmic rays (CR) background
• CRV
  – PMT based prototype
  – SiPM based single counter test beam studies
• Summary

Goal is 99.99% CR veto efficiency
Mu2e overview

• Mu2e is the muon-to-electron conversion experiment
  – Proposed start date of 2018 and two years of data taking.

• Goal:
  – Search for neutrino-less muon decay in the field of nucleus
  – Single event sensitivity!
  – Measure $R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$
  – Designed sensitivity of $R_{\mu e} < 6 \times 10^{-17}$ at 90% CL
  – 4 orders of magnitude more sensitive than existing limit.

• WHY?
  – Any signal is a sign of new physics
  – Both complementing and extending LHC
  – Testing mass scales at $10^4$ TeV, not directly reachable on any collider
  – Many models beyond Standard Model predict CLFV at observable rates for Mu2e
Mu2e overview

- Protons produce pions in the production target
- Pions transported in the transport solenoid. Pions decay to muons
- Muons captured in the stopping target
- Conversion electrons are detected and measured in the tracker
- CRV system (not shown) surrounds detector solenoid and rejects events associated with cosmic rays
- To achieve required sensitivity we need CR induced background under control
CRV overview

- **CRV system:**
  - Covers detector solenoid
    - more than 1000m² needs to be covered
    - Challenge: outstanding veto efficiency at reasonable cost
  - Purpose is to veto conversion-like events produced by cosmic muons
  - Proposed design of three layers of plastic scintillators read out by wavelength shifting (WLS) fibers and photomultipliers
CRV requirement

- Using GEANT4 detector simulation and Daya Bay package to generate cosmic rays
  - Generated $0.5 \times 10^9$ CR muons in [3-300] GeV window
  - Only 2 events survive final event selection cuts
  - To limit CR background events to less than 0.05 events, we need an inefficiency of $2 \times 10^{-4}$ or better

- Perfect CR background event example
  - Muon produces an electron in the stopping target
  - Decays before entering bottom CRV - one chance to veto.
To achieve desired inefficiency we will require 2 out 3 coincidence in CRV module.

Assuming each layer is independent, it will result in single layer efficiency of 99.4%.
Prototype test stand

- Mid 2009 shipped CRV prototype from William & Mary
- Commissioned CRV test stand at CDF
- Does not meet 99.99% veto efficiency requirement
- Set up two trigger paddles above and below CRV prototype
- Perform various measurements:
  - Light yield at various points from readout(RO) end
  - Efficiency versus the angle of incidence
- Studies are performed by summer students
CRV prototype results

- To meet the requirements of 99.99% efficiency we will need an improved light yield
- Various improvements will be considered
  - More fibers per counter
  - Thicker scintillator. Already produced
  - Holes instead of grooves
  - Different type of WLS fiber
  - Photomultiplier with higher Quantum Efficiency. SiPM?
Neutron Sensitivity

- The neutron flux in mu2e cavern is expected to be high
  - Make sure the neutron flux is not significant source of fake BG in CRV
  - CRV not more than 1% deadtime

- Portable CRV prototype to test the sensitivity to neutrons
  - BCF-92 WLS fiber and Hamamatsu PMT
  - Box commissioned and 10-15 <PE> achieved

- Neutron generator
  - ~2.8 MeV neutrons with flux of ~10^6 n/s

- Data collected and needs to be analyzed.
To improve the photo electron statistics we built and tested single counter strip.

<table>
<thead>
<tr>
<th></th>
<th>WLS(multi-clad)</th>
<th>Photo Multiplier</th>
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</thead>
<tbody>
<tr>
<td>CRV prototype</td>
<td>1.4mm Bicron BCF-92</td>
<td>4x4 Hamamatsu H8711 PMT</td>
</tr>
<tr>
<td>Single counter</td>
<td>1.2 mm Kuraray Y-11 1500 ppm</td>
<td>1.2mm diameter IRST SiPM</td>
</tr>
<tr>
<td>Difference</td>
<td>Y-11 has longer attenuation length and better match for scintillator light emission</td>
<td>SiPM has higher Photo Detection Efficiency</td>
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</tbody>
</table>
• Joined T995 collaboration in May
• Use proton beam at MTest to study single scintillator counter
  – 120 GeV protons, 4s spill every minute, 1-10KHz intensity
  – Trigger on coincidence 1x1 cm\(^2\) upstream and 10x10 cm\(^2\) downstream
• Advantages:
  – 1000 ev/spill: 15 minutes(beam) vs 2 days(cosmics)
  – Known beam position. Take vertical scans
  – Known angle of incidence
• 2 test beam runs in May and Sep of 2010
Setup

Proton Beam

1 cm² Trigger Counter T2

Motion Table

Points to scan
• Fermilab-based electronics
• 300 digitization/sampling
• 12-bit ADC
  - Sample input signal at 4.7ns interval
  - ADC in time information
  - Dark current and signal pulses on the left picture
• Total charge is calculated in the signal region
• Front porch (FP) region is used for self calibration: to extract pedestal and single PE value

(Black) - pedestal and SPE from FP
(g, b, r) - number of PE in signal

60cm from RO

# of PE
• Fewer $<\text{PE}>$ from test beam data expected:
  - Test beam protons hit head on. Cosmic muons have wide range of angle of incidence
• Reminder:
  – Using 3 layers of scintillator, we need CR veto efficiency of 99.99%
  – Translates into 99.4% single layer efficiency

• Plots on the right show:
  – Sum of PE from three fibers in the signal region
  – Sum of PE from three fibers in the Front Porch (FP) background region
  – Signal and noise (dark current) rejection efficiency at 3.2 PE

• We can achieve required efficiency

• Not the final result and room to improve

We can reach 99.4% single layer efficiency
Summary

• Mu2e will perform a measurement 4 orders of magnitude better than the current limits
  – Complements and extends LHC results and probes physics at mass scales up to \(10^4\) TeV
• Plan to have an approved Conceptual Design Report by the end of 2011
• CRV prototypes studies
  – Does not meet required efficiency yet, but room for improvement.
• Test beam studies
  – Observe promising increase in PE statistics, using SiPMs
  – 99.4% single layer efficiency seems achievable
Attenuation curve

Channel 1

Channel 2

Not an optimal light yeild: bad glueing, polishing, mirroring...?
Setup at Lab 6

- 3.5mm SiPM
- Fiber end
- Keithley 2400 SourceMeter
- HP8112A Pulse Generator
- Scintillator
- LED
- HP8112A Pulse Generator
- 20 LED
- Scintillator
Fiber studies

- Study the angular light distribution from WLS fibers
  - Fiber/SiPM size matching
- Studies on
  - 1.2mm double-clad Kuraray(Y11) WLS Fiber
  - 1.4mm single-clad Bicron(BFC-92) WLS Fiber
- Summer student’s project

As expected, more light is trapped at higher angles for 1.2mm multi-clad fiber
Test beam in May

- Far from optimal scintillator strip in May:
  - 1.4 mm BFC-92 single-clad fiber
    - Smaller trapping efficiency => smaller(50%) light yield
  - 1.2 mm IRST SiPM
    - bad match for the fiber size
  - Lower SiPM gain
    - Smaller quantum efficiency

~300 ns time windows
PE yield at \( \sim 4\text{m} \)

### Histograms

**NPE**

- Ch. 8: Mean 3.7
- Ch. 9: Mean 3.7
- Ch. 10: Mean 3.4
- Sum: Mean 6.4

<table>
<thead>
<tr>
<th>Month</th>
<th>Si_Sum</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
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<tbody>
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<td>May</td>
<td></td>
<td>5351</td>
<td>13.2</td>
<td>4.916</td>
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<tr>
<td>Sep</td>
<td></td>
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