A Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab

Yuri Oksuzian on behalf of Mu2e
Fermilab is actively pursuing the searches with high intensity beams: NOvA, Short-baseline neutrino, DUNE, Muon g-2, Mu2e…

Mu2e will search for neutrino-less, coherent muon conversion into an electron

\[ \mu^- + N \rightarrow e^- + N \]

In the SM, \( \mu \rightarrow e \) occurs at the rate of \(<10^{-50}\)

- Signal observation at Mu2e is unambiguous sign of new physics
- Indirectly probing high mass scales (>10^4 TeV)
(1) Pulsed 8 GeV proton beam strikes production target to produce $\pi^-$
   - Graded B-field reflects pions toward the transport solenoid
(2) Transport solenoid:
   - Transports $\pi^-/\mu^-$, selects particle's momentum and charge, avoids direct line of sight
(3) Muons stop on Al stopping target
   - Conversion electron momentum and energy are measured in the tracker and calorimeter

See Marc BUEHLER talk
Various components of Mu2e are covered at DPF

- Four talks and two poster on Cosmic Ray Veto

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Presenter and Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tue 16:45</td>
<td>A Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab</td>
<td>Yuri OKSUZIAN, University of Virginia</td>
</tr>
<tr>
<td>Tue 17:00</td>
<td>Performance of Scintillation Counters with Silicon Photomultiplier Readout</td>
<td>Yongyi WU, University of Virginia</td>
</tr>
<tr>
<td>Tue 17:15</td>
<td>Radiation Damage Testing of Silicon Photomultipliers for the Mu2e Experiment</td>
<td>Vishnu ZUTSHI, Northern Illinois University</td>
</tr>
<tr>
<td>Tue 17:40</td>
<td>The Mu2e Experiment at Fermilab</td>
<td>Marc BUEHLER, Fermi National Accelerator Laboratory</td>
</tr>
<tr>
<td>Wed 15:54</td>
<td>Beam Extinction and Monitoring at the Upcoming Mu2e Experiment</td>
<td>Ryan HOOPER, Lewis University</td>
</tr>
<tr>
<td>Wed 16:45</td>
<td>A Straw Tube Tracker for the Mu2e Experiment</td>
<td>Daniel AMBROSE, University of Minnesota</td>
</tr>
<tr>
<td>Fri 14:30</td>
<td>The Mu2e electromagnetic calorimeter</td>
<td>Tomonari MIYASHITA</td>
</tr>
<tr>
<td>Fri 14:45</td>
<td>Studies of Beam Induced Radiation Backgrounds at the Mu2e Experiment and Implications for the Cosmic Ray Veto Detector Operations</td>
<td>Yuri OKSUZIAN, University of Virginia</td>
</tr>
</tbody>
</table>
Mu2e Sensitivity

Mu2e will measure the ratio of $\mu \rightarrow e^-$ conversions to the number of muon captures by Al nuclei:

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

- Mu2e single event sensitivity: $R_{\mu e} = 2.5 \times 10^{-17}$
  - Almost 4 orders of magnitude improvement to the current best limit
  - Expect 40 events at $R_{\mu e} = 10^{-15}$
- Need to keep background small and well understood
  - Total expected background 0.4 events
  - Total expected background from cosmic rays 0.08 events
- Mu2e expects 1 signal-like event per day induced by cosmic rays
- Need to build the detector several km under the ground
- ...or cover Mu2e detector solenoid with an active shielding
- Cosmic rays can interact with detector components producing 105 MeV electron, faking a conversion signal
- We simulated 28 billion cosmic ray muons, only 2% of total number expected over experiment lifetime
- In addition we simulated the full experiment lifetime for the region with poor CRV coverage
- To achieve experiment’s designed sensitivity, cosmic ray veto inefficiency is required to be no worse than $10^{-4}$
Cosmic Ray Veto

- Cosmic Ray Veto (CRV) consists of 4-layer scintillating counters
- We require hit coincidence in at least 3 out of 4 layers localized in time and space for a cosmic ray muon track
- We veto 125 ns from the signal window after each coincidence in the CRV

CRV details:
- Area: 323 m²
- 82 modules
- 55 tons of counters
- 50 km of fibers
- 18,944 SiPMs
Top-view at the CRV

Top region of the CRV consists of
- Extra-long (6.6 m) counters in transport solenoid region read out from one side
- Long counters (5.6 m) counters in detector solenoid region readout from both sides
CRV design (side-view)

- Side-view at the right region of CRV
- Right region of the CRV consists of
  - Medium (4.5 m) counters
  - Special size counter modules are designed for cryo penetration region

Diagram:
- CRV-U
- CRV-T
- CRV-R
- CRV-D
- Cryo-notch
- Narrow modules
- Cryo-modules
- 5.6 m
- Extruded polystyrene scintillator counters: 50 x 20 x 900-6600 mm$^3$
- Two Kuraray Y11 non-S type, 1.4-mm diameter wavelength shifting fibers
- Readout: 2x2 mm$^2$ SiPMs on each fiber end
  - Two fibers per extrusion, up to four SiPMs for readout
  - Each counter (except TS region) read out on both ends
- Glue two extrusions together to form di-counters
  - Each di-counter is read out by one counter motherboard
Four layers of counters with 3 layers of Al absorbers sandwiched between them: 16 counters/layer

Layers are offset to avoid projective gaps between layers

Total: 82 modules; two widths, five different lengths
CRV shielding

- CRV needs to be shielded from the beam induced radiation backgrounds
- CRV is mounted on 1 yd of concrete wall
- T-shaped concrete blocks are designed to avoid direct cracks
- Region close to PS/TS is enhanced with heavy barite enriched concrete
Neutron and gamma fluxes from beam interactions cause problems to CRV operations

- Produce hits at the CRV, faking cosmic ray muons, increasing the dead-time

The first detailed simulation results show the expected CRV dead-time is 12% (Y. Oksuzian)
- Neutrons damage the CRV read-out components
- The modules in the hottest region are read-out only from one side
- The radiation level at the CRV readout is $> 5 \times 10^9$ n/cm$^2$
- No significant impact to read-out components at this level (V. Zutshi)
- Using MC, estimate the required light for the CRV efficiency of 99.99%
  - Vary the light yield, gaps and offsets between the counters
- The light yield of 14/SiPM from far end is required in order set a threshold at 7 PE
  - The thresholds and coincidence reconstruction is applied offline
- The test beam results suggest that we get adequate light yield (Y. Wu)
Mu2e has a great discovery potential and can reveal New Physics

Mu2e will improve over previous conversion experiments by 4 orders of magnitude

Cosmic ray veto is an essential component for the Mu2e experiment by suppressing the backgrounds by 4 orders of magnitude

CRV design is challenging, but mature and advanced

Exciting R&D time of prototyping, test beams, simulations

Plan to start the production in 2016

Further details in Mu2e TDR