Design considerations for the cosmic-ray-veto system of the Mu2e experiment at Fermilab

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...on behalf of the Mu2e collaboration.
http://mu2e.fnal.gov
Mu2e

Experiment with preliminary approval that is proposed to begin data taking in 2019 at Fermilab.

• Goal: Search for
  
  \[ \mu^- N \rightarrow e^- N \]

  – Measure ratio:
  
  \[ R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})} \]

  – With sensitivity to R at 90% C.L. of \(6 \times 10^{-17}\)
    
    → 4 orders of magnitude better than current limits
    
    → Need more than \(10^{17}\) stopped muons!
      
      -- \(3.6 \times 10^{20}\) protons on target (3 year run \(\sim 1 \times 10^7\) s)
    
    → Need to keep background small and well understood
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Background Processes

- Signal is a single mono-energetic 105 MeV e-.
- Many possible sources of background events:
  - Muon decay in Coulomb orbit (DIO)
  - Radiative muon/pion capture
    - Photon produced that can convert asymmetrically
  - Beam electrons can scatter in target
  - Muon/pion decay in flight
  - Antiprotons and other late arriving particles
  - Cosmic-ray induced electrons

These can all be controlled and none produce a sharp peak at 105 MeV!
GOAL: single event sensitivity $\Rightarrow N_{\text{background}} < 1$ event:

- Current expected background is 0.4 events
- Expected background from cosmic muons $\sim 0.05$ event
  $\Rightarrow$ Assumes 99.99% cosmic ray veto efficiency

Without the CRV there would be hundreds of background events!
Sensitivity to “new physics”

**Example: CLFV from SUSY**

Supersymmetry

\[
\text{rate} \sim 10^{-15}
\]

In Mu2e, a signal of Terascale physics at LHC implies:

- 40 signal events
- \(~\) 0.4 background events

Sensitive also to many other models of “new physics”. (Contact interactions as well as loops)
Mu2e Experimental Setup

1) Proton beam hits production target in Production Solenoid.
2) Pions captured and accelerated towards Transport Solenoid (TS) by graded field.
3) Pions decay to muons.

(for sense of scale)
2) Transport Solenoid performs sign and momentum selection.
   Eliminates high energy negative particles, positive particles and line-of-sight neutrals.
• Muons stop in target and decay.
• Conversion electron trajectory measured in tracker, validated in calorimeter.
• Cosmic Ray Veto (CRV) surrounds Detector Solenoid.
Major sources of neutrons and gamma rays:
• 8 GeV protons striking the Production target.
• Pions, muons, etc. strike the collimators in the TS.
• Muons interacting with the Stopping Target or the Muon Beam Stop.

In addition to beam sources, low energy neutrons may produce gammas with energy up to 10 MeV through the process of neutron capture anywhere in the detector hall.
• The CRV surrounds the Detector Solenoid and part of the TS
• The CRV must:
  • Reject cosmic ray muons with high efficiency ($> 99.99\%$)
  • Produce little dead time ($< 1\%$ is the stated requirement)
  • Operate in a high-radiation environment
    • $10^{18}$ muons will be stopped, and it takes more than $10^{20}$ protons on target to produce these muons
    • Note that the Detector Solenoid and some regions of CRV are in somewhat close proximity to the Production Solenoid
Detector Solenoid surrounded on 5 sides by the CRV modules.  
(no bottom)

Modules are approximately 5m long and 1m wide.
Detector Solenoid surrounded on 5 sides by the CRV modules. (no bottom)
Modules are approximately 5m long and 1m wide.
CRV Modules

Modules composed of 3 layers of plastic scintillator counters. (10 counters wide)

Each counter read out by WLS fibers and SiPMs using a plastic fiber guide bar and SiPM manifold
Requirements on Muon Veto

Modules composed of 3 layers of plastic scintillator counters. (10 counters wide)

• Mu2e CDR plan is to require 2-out-of-3 coincidence.
• Simulations suggest 99.99% veto efficiency required.
• 2-out-of-3 requires 99.4% single-counter efficiency. (ignoring the effect of cracks between counters)
• We achieved 15 photo-electrons (PE) with a 1 cm thick counter (test beam studies at Fermilab in 2010)
• We plan to use a 2 cm thick counter, so 30 PE is expected
• Cutting at ~6 PE should achieve desired efficiency (~ 1 MeV) (assuming Poisson statistics)
The CRV is not blind to neutrons!

a) Radiative Capture

Capture gamma ray may be detected.

b) Inelastic Scattering

Gamma ray or recoil nucleus may be detected.

c) Elastic Scattering

Recoil nucleus may be detected.

Note: - Each neutron can produce one (or more) gamma ray.
- Recoil nucleus may just be proton.
Coincidental hits from gammas or neutrons:

→ Based on a 1% deadtime from the CRV we estimate a tolerable hit rate of: $2 \cdot 10^8 \text{ [hits/cm}^2\text{]}$

Correlated hits from a single particle:

(For example delta rays (a), or double Compton scatter (b))

→ We estimate a tolerable hit rate of: $6 \cdot 10^5 \text{ [hits/cm}^2\text{]}$

Note: hit limits assume uniform distribution of hits.
G4BEAMLINE: Simple Counter

  
  A "Swiss Army Knife" for Geant4, optimized for simulating beamlines
- We first use G4BEAMLINE to study counter efficiencies to neutrons and gamma rays.
- Simple 3-counter geometry:
  
  - Example: 10 eV neutrons “beam” (directed at counter center)
  - Blue bar – Counter polystyrene
  - Silver bar – Aluminum absorber
Gamma and Neutron efficiencies

• For varying energies we shoot a beam of neutrons (gammas) at the counter configuration from the previous slide and study the energy deposition.

• For a 2 cm thick counter we estimate our energy threshold will be ~1 MeV which will correspond to several photo electrons (~ 6 PE) for minimum ionizing particle (MIP).

• Birk’s law is important for interpreting the energy deposit in terms of light yield for protons and other non-MIP particles.
Example: Energy Deposition

Energy deposition from 5 MeV gamma ray.

Note:
- Not very sensitive to the threshold value
- That the peak at 4 MeV corresponds to the “double escape peak” from pair production.
Neutron and Gamma Efficiencies

We study the single counter efficiencies as a function of incident energy and approximate them as follows for rate calculations:

<table>
<thead>
<tr>
<th>Neutron energy</th>
<th>$E_N &lt; 1\text{e-6}$</th>
<th>$1\text{e-6} &lt; E_N &lt; 2 \text{ MeV}$</th>
<th>$2 \text{ MeV} &lt; E_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>0.5%</td>
<td>0.1%</td>
<td>10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\gamma$ energy</th>
<th>$E &lt; 1.0 \text{ MeV}$</th>
<th>$1.0 \text{ MeV} &lt; E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>0.0%</td>
<td>10%</td>
</tr>
</tbody>
</table>

We also study the efficiency for a 2-out-of-3 coincidence cause by an incident gamma:

<table>
<thead>
<tr>
<th>$\gamma$ energy</th>
<th>$E &lt; 5.0 \text{ MeV}$</th>
<th>$5.0 \text{ MeV} &lt; E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection efficiency</td>
<td>0.0%</td>
<td>1%</td>
</tr>
</tbody>
</table>
First step - produce “beam file”:
- Hit 8 GeV protons on production target
- Record all particles on virtual plane at first collimator (white square)
- Particles split into two categories:
  - Charged particles - Beam source
  - Neutrons - PS only source

Second step - run simulation from “beam file”:
- Simulate and propagate particles from the virtual plane
First look at rates from all neutrons

Rate limit from earlier calculation: $2 \times 10^8$

Rates too high in region closest to TS

(TS counter position)
We should require hits to satisfy: $670 \text{ ns} < t < 1595 \text{ ns}$
(in each beam pulse and also tracking particles through future pulses)
Timing cut: neutron hit rates

Neutron rates: random coincidence

Fast neutrons can be reduced by an order of magnitude from the timing requirement!
Gamma rates: random coincidence

DS: Beam source

TS: Beam source

DS: PS source

TS: PS source
Gamma rates: correlated hits

DS: Beam source

TS: Beam source

DS: PS source

TS: PS source

8/2013 C. Group - Mu2e Cosmic Ray Veto - 2013 DPF Meeting
Summary from rate studies

• Neutrons are under reasonable control with current Mu2e shielding.
• Gammas from random coincidence are near the limit imposed by a 1% deadtime from the CRV.
• Gammas causing correlated hits in 2-out-of-3 CRV layers occur at a rate about 10 times too high.

Note: comparison between MARS and G4BEAMLINE yield compatible conclusions.
Possible solutions

• Thicker absorber layers will reduce efficiencies for correlated hits from gammas.

• Changing the concrete around the DS to a heavy concrete loaded with Barite reduces the rate by about a factor of 10.

• Adding 5 cm of lead around the DS concrete also would reduce the rate by about a factor of 10.

• Adding a 4th layer to the CRV improves the rate due to correlated hits from gammas by about two orders of magnitude.
Summary

• The cosmic ray veto must operate with high efficiency while producing low deadtime in a high-radiation environment.

• Expected hit rates in the CRV due to gamma rays and neutrons were studied using G4BEAMLINE.

• Current proposed version of shielding effectively suppresses neutrons. Exploring options to address remaining challenges generated by gammas.
• For overview of Mu2e see Rob Kutschke’s talk
  (Tomorrow, in the session on ”Quark and Lepton Flavor Physics”)

• Mu2e Conceptual Design Report:

• http://mu2e.fnal.gov/
Tolerable CRV rates

Coincidental hits from gammas or neutrons:

Pairwise coincidence rate:
\[ n_{pc} = 2\Delta t_c \cdot n_s^2 \]

Single counter time resolution: 5 ns

Single counter singles rate

Total pairwise coincidence rate:
\[ n_{tpc} = N_{cl} \cdot N_{pp} \cdot n_{pc} \]

1% Deadtime fraction:
\[ f_v = \Delta t_v \cdot n_{tpc} = 2\Delta t_c \cdot N_{cl} \cdot N_{pp} \cdot 2\Delta t_c \cdot n_s^2 \]

A valid cosmic-ray muon event is 2/3 adjacent counter hits. Number of possible pairwise coincidences per counter: 11.

Veto time: 50 ns

\[ n_s = \sqrt{\frac{f_v}{\Delta t_v \cdot N_{cl} \cdot N_{pp} \cdot 2 \cdot \Delta t_c}} \]

= 50 kHz per counter

Experimental lifetime of \(1.06 \times 10^7\) s and counter area of 470x5 cm²
\[ \rightarrow \text{tolerable hit rate} \sim 2 \cdot 10^8 \text{ [hits/cm}^2\text{]} \]
Correlated hits from a single particle:
(For example delta rays from gammas, or double Compton scatter)

- **Upper limit hit rate estimation from 2-out-3 hits**
  - Assuming:
    - $f_\nu = 0.01$ - the deadtime fraction CRV produces is less than 1%
    - $\Delta t_\nu = 50\,\text{ns}$ - Veto time window
    - $N_c = 696$ - number of counters per layer
    - $\epsilon_2$ - 2-out-3 detection efficiency.
    - $n_p$ - particles rate per counter

  $$f_\nu = [n_p \cdot N_c \cdot \epsilon_2] \cdot \Delta t_\nu = 0.01$$

  $$n_p = \frac{1}{\epsilon_2 \Delta t_\nu \cdot N_c} = \frac{1}{\epsilon_2} \quad 300 \, \text{Hz}$$

- The total lifetime of the experiment is $1.06E+7 \, \text{s}$
- Counter area $4700 \, \text{cm}^2$

$$\text{Total hits} = \frac{1.06 \cdot 10^7 \cdot n_p \cdot \epsilon_2}{4700} = 6 \cdot 10^5 \, \text{[hits/cm}^2\text{]}$$
- Neutrons and gammas arrival time at DS left
- Neutrons in TS region (not shown) are even more prompt
- Large fraction of higher-energy neutrons arrive well before the signal time window
- Large fraction of gammas arrive delayed
CLFV in $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- N \rightarrow e^- N$

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Model independent effective CLFV Lagrangian

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu} R \sigma_{\mu \nu} e_L F_{\mu \nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu} L \gamma_\mu e_L$$

Loops

$\kappa << 1$

magnetic moment type operator

$\mu \rightarrow e\gamma$ rate $\approx 300X$

$\mu N \rightarrow eN$ rate

Contact Interactions

$\kappa >> 1$

four-fermion interaction

$\mu N \rightarrow eN >> \mu \rightarrow e\gamma$ rate

Mass scales probed $\sim 10,000$ times that probed directly by LHC
Model Independent Parameterization

$$L_{CLFV} = \frac{m_\mu}{(\kappa + 1)} \bar{\mu} R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)} \Lambda^2 \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Loops

Contact terms

Contributes to $\mu \rightarrow e\gamma$

Does not produce $\mu \rightarrow e\gamma$

SUSY and massive neutrinos

Exchange of a heavy particle

Dominates if $\kappa \ll 1$

Dominates if $\kappa \gg 1$
Other “new physics” also provide Mu2e signal

Supersymmetry
- Rate $\sim 10^{-15}$

Compositeness
- $\Lambda_c \sim 3000$ TeV

Leptoquark
- $M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2}$ TeV/c²

Heavy Neutrinos
- $|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$

Second Higgs Doublet
- $g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$

Heavy Z’
- Anom. Z Coupling
- $M_{Z'} = 3000$ TeV/c²