The Mu2e Transport Solenoid

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Mu2e Muon Beamline Requirements

• Pulsed beam
• Deliver high flux $\mu^-$ beam to stopping target
  • At FNAL, high proton flux $\sim 20 \times 10^{12}$ Hz, 8 GeV
  • Mu2e: use solenoidal muon collection and transfer scheme
  • muons $\sim 5 \times 10^{10}$ Hz, $10^{18}$ total needed
• Muon properties
  • low momentum and narrow momentum spread
    • stop max # muons in thin target
    • avoid $\sim 105$ MeV e$^-$ from in-flight $\mu^-$ decay (keep $p_\mu < 75$ MeV/c)
• Background particles from beam line must be minimized
  • especially $\sim 105$ MeV e$^-$ and high momentum $\mu^-$
  • a major factor driving design of muon beamline
Mu2e Muon Beamline - follows MECO design

Muons are collected, transported, and detected in superconducting solenoidal magnets:

- Muons are transported through the Muon Stopping Target.
- Muon Beam Collimators guide the muons.
- The Tracker and Calorimeter detect the muons.
- The Detector Solenoid provides magnetic fields for muon detection.

Production Solenoid:
- Selects low momentum $\mu^-$.
- Avoids straight line from production target to detectors.

Delivers 0.0025 stopped muons per 8 GeV proton.
Goals:
— Transport low energy $\mu^-$ to the detector solenoid
— Minimize transport of positive particles and high energy particles
— Minimize transport of neutral particles
— Absorb anti-protons in a thin window
— Minimize particles with long transit time trajectories

Pitch: $\frac{p_l}{p} = \cos \theta$

$$D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p \left( \frac{1}{\cos \theta} + \cos \theta \right).$$

Curved sections eliminate line of sight transport of n, $\gamma$.

Radial gradients ($dB_s/dR$) in toroidal sections cause particles to drift vertically; off-center collimator signs and momentum selects beam.

dB/dS < 0 in straight sections to avoid slow transiting particles

Collimation designed to greatly suppress transport of $e^-$ greater than 100 MeV.

Length decreases flux, by decay, of pions arriving at stopping target in measurement period.

To stopping target
Inner radius = 25 cm
Length = 13.11 m

TS1: L = 1 m
  coll. radius = 15 cm
  transverse p < 110 MeV/c

TS2: R = 2.9 m

TS3: L = 2 m
  coll. radius = 20 cm

TS4: R = 2.9 m

TS5: L = 1 m
  coll. radius = 15 cm
  transverse p < 90 MeV/c

TS3 Vertical cut: +5 cm to -19 cm

Antiproton absorber window
TS1: First straight section. Field grades linearly 2.5 to 2.4T. Axial ($B_s$) field on axis within 0.5% of expected value. $dB_s/ds < -0.02\,\text{T/m}$ for $R<15\,\text{cm}$.

TS2: First toroid. Ripple at outer radius $<1\%$ of $B_s$. Field rises from 2.4 T to 2.6 T along inner radius, then returns to 2.4 T. Field on outer radius follows a similar pattern but reduced by $1/R$.

* $dB_s/ds < -0.02\,\text{T/m}$ can be relaxed in transition regions from straight to curved sections whenever $|dB_s/dr| > 0.275 \,\text{T/m}$.
Separation of $\mu^-$ from $\mu^+$

\[
pitch = \frac{p_i}{p} = \cos \theta
\]

\[
D = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p(\frac{1}{\cos \theta} + \cos \theta).
\]
Vertical Drift Motion in a Toroid

Toroidal Field: $B_s = \text{constant} \times 1/R$. This gives a gradient $dB_s/dR$. Particle spiral drifts vertically (perpendicular to the plane of the toroid bend)

$$D = \text{vertical drift distance}$$

Pitch: $p_l = \cos(\theta)$

$$\rightarrow D = \frac{q}{0.3 \times B} \times \frac{s}{R} \times \frac{1}{2} p \left( \frac{1}{\cos \theta} + \cos \theta \right).$$

(Note: particles with small pitch have large $D$, and particles with opposite sign drift in opposite directions)

$p_l$

Production Target

Central Collimator

Stopping Target

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‘Acceleration’ in a Solenoid with a Gradient Field

- In a magnetic field, low momentum charged particles follow helical paths along the field lines.

- The magnetic moment of the particle associated with the helical motion is approximately constant. For a relativistic particle, \( p_t^2/B = \text{constant} \),

\[
\rightarrow \quad p_t \propto \sqrt{B} \quad \rightarrow \quad p_t = p_{t0} \sqrt{B/B_0}, \quad p_l = \sqrt{p^2 - p_{t0}^2 B/B_0}
\]

- **\( p_l \) is continuously increasing in the direction of decreasing field**
  - Particles ‘accelerate’ when spiraling to lower field: \( p_t \) decreases and \( p_l \) increases.
  - Particles ‘decelerate’ when spiraling to higher field: \( p_t \) increases and \( |p_l| \) decreases.

- **Particles are pushed in the direction of lower field**

\[
B_z = B_0 - |G_z| z \quad B_r = \frac{1}{2} |G_z| r
\]

Note that net \( q p_t \times B_r \) points downstream regardless of \( q \) (if \( q \) flips sign, \( p_t \) reverses direction)

\( B_z \) points out of page. Field decreases moving out of page, \( G_z < 0 \).
Magnetic Mirror

- If a particle spirals in the direction of higher field, $p_t$ increases and $|p_l|$ decreases:

$$p_t = p_{t0} \sqrt{B/B_0}, \quad p_l = \sqrt{p^2 - p_{t0}^2 B/B_0}$$

- If the field becomes large enough and the particle is reflected, spiraling back toward lower field $p_t \to p, p_l \to 0$.

For a particle born in the middle of the PS, where $B \sim 3.5$ T, the maximum pitch which can be reflected in the maximum $5T$ field upstream is (define $\theta = \text{angle between momentum and solenoid axis}$)

$$\sin \theta_{\text{min}} = p_{t0} / p = \sqrt{B_0/B_{\text{max}}} \approx \sqrt{3.5/5} = 0.84$$

$$\rightarrow 123^0 > \theta \rightarrow \text{Increases downstream flux of muons}$$

If a particle is born near the target where $B \sim 3.5$ T, then the maximum $\theta$ (corresponding to minimum pitch) at the downstream end of the PS, where $B = 2.5$ T, will be about $60^0$. 

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Long Transit Time Background

• Particles with low longitudinal velocity will take a long time to traverse the beam line, arriving at the stopping target during the measurement period
  ▪ Antiprotons and radiative pion capture:
    • Antiprotons are stopped by a thin window in middle of transport
    • Adjust measure start time until most long-transit time pions decay

• Example of a potential problem
  ▪ Pion decays into a muon early in the transport solenoid
  ▪ Muon can have small pitch and progress very slowly downstream
  ▪ Muon can decay after a long time into an electron
  ▪ Decay electron can be >100 MeV if \( p_\mu > 75 \text{ MeV}/c \)
  ▪ Electron could scatter in collimators, arriving at the target late during the measurement period, where it could scatter into the detector acceptance

• To suppress this…
  ▪ All straight sections of solenoids have <0 gradient, \( |dB_s/ds| > 0.02 \text{ T/m} \)
    • Greatly reduces number of particles (e.g. \( \pi \rightarrow \mu \)) with small pitch
    • Gradient criterion not necessary in curved solenoid sections, low pitch particles are swept away vertically by \( dB_s/dr \) field gradient.

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S-Shape Transport Solenoid

• Advantages
  - Second, reverse bend re-centers helices (on average) on the solenoid axis
  - Second, reverse bend cancels vertical dispersion due to first bend - could give more uniform stopping distribution on target and more stops on target (latter to be demonstrated)
  - Second bend gives added protection against neutrals scattering down solenoid from PS

• Disadvantages
  - Gives only half the dispersion of two bends in the same direction
Collimators

- Off-center collimator at TS midsection
  - **Advantages**
    - possible to alter geometry to change the distribution of transmitted particles
    - May be possible to get $\pi^+$ for calibrations by rotating collimator
    - Could be removed to allow + and – to pass: + for calibration, - to give some realistic background to see its effect on resolution
  - **Disadvantages**
    - Beam offset may require a larger TS diameter compared to dipole centering.

- Collimators at TS entrance and exit
  - **Advantages**
    - Can be modified to increase or decrease transmitted transverse momentum
    - Can be enlarge to pass $\pi^+$ at larger radii, stop them at larger radii, get better geometric coverage of detector from decay electron
Field Gradient in Straight Sections

- Advantages
  - Substantially reduces late-arriving particles at the stopping target
- Disadvantages
  - Increased cost
Antiproton Absorber

• Advantages
  ▪ Absorbs all antiprotons and effectively suppresses the background
  ▪ Separates ‘dirty’ upstream vacuum from ‘clean’ downstream vacuum
  ▪ Warm bore access is helpful in accessing that portion of the TS for other purposes, e.g. to rotate the collimators

• Disadvantages
  ▪ Need warm access to the thin absorber in case it breaks
  ▪ Probably need at least one toroid bend downstream to help eliminate the background from secondaries produced by antiproton capture on nuclei.
New Ideas/Other Issues

• Add adjustable vertical dipole fields inside the toroids to control the vertical offset of the helices; reversible for positive beam. Need ~ 500 gauss vertical field.
  - Control momentum of transmitted beam
  - Control sign of transmitted beam
  - May be difficult to put into toroid region

• Two bends in the same direction a la COMET?
Pions at the Stopping Target

![Graph showing pions on the target per proton against time of flight (ns).]
Muon Time Distribution at the Stopping Target

![Graph showing muon stop time distribution](image-url)
Vertical Drift Motion in a Toroid

Toroidal Field: Axial field $B_s=\text{constant} \times 1/r$. This gives a large $dB_s/dr$.

Particle spiral drifts vertically (perpendicular to the plane of the toroid bend).

$D=\text{vertical drift distance}$ \hspace{1cm} $R=\text{major toroid radius}=2.9 \text{ m}$,

$p_l=\text{longitudinal momentum}$ \hspace{1cm} $s/R=\text{total toroid bend angle}=90^0$

$p_t=\text{transverse momentum}$ \hspace{1cm} $D[m]=\text{distance, B[T], } p[\text{GeV/c}]$

Define pitch $\alpha = \frac{p_l}{p}$


d_{\text{vertical drift distance}} = \frac{1}{2} \times \frac{q}{0.3 \times B} \times \frac{s}{R} \times p\left(\frac{1}{\alpha} + \alpha\right)$.
Cosmic Ray Background

- Well-studied and controlled by previous muon conversion experiments
- Reactions which could produce a fake conversion electron:
  - Scattered electrons from cosmic ray muons in target or detectors
  - Muons decaying in-flight in the Detector Solenoid
  - Muon scattering from the target, then mistaken for an electron
  - Muons interacting in shielding, producing hadrons or photons which may not register in a veto counter.

- MECO design
  - 0.5 m steel, 2 m concrete shielding
  - Active $4\pi$ scintillator veto, 2 out of three layers report, $10^{-4}$ inefficiency
  - From simulations with $\sim$70x cosmic flux, expect 0.021 events in $2\times10^7$ seconds running at FNAL
Sensitivity of Mu2e

- For $R_{\mu e} = 10^{-15}$
  - $\sim 40$ events / 0.4 bkg (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
- $\sim 4$ events / 0.4 bkg $R_{\mu e} < 6 \times 10^{-17}$ 90% CL

<table>
<thead>
<tr>
<th>Source</th>
<th>Number/3.6 $\times$ $10^{20}$ POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay-In-Orbit</td>
<td>0.225</td>
</tr>
<tr>
<td>Radiative $\pi$ capture</td>
<td>0.063</td>
</tr>
<tr>
<td>Muon Decay-In-Flight</td>
<td>0.063</td>
</tr>
<tr>
<td>Scattered $e^-$</td>
<td>0.036</td>
</tr>
<tr>
<td>$\pi$ Decay-In-Flight</td>
<td>&lt; 0.004</td>
</tr>
</tbody>
</table>
Supersymmetry

In some models,

rate $\sim 10^{-15}$

Access SUSY through loops:

signal at Terascale seen by LHC implies

$\sim 40$ event signal in this experiment
Radiative Pion Capture Background

- $\pi^-$, like $\mu^-$, stop in stopping target and form atoms
  - reaction of $\pi^-$ with nucleus is fast: occurs mid-cascade
    \[ \pi^- + A(N, Z) \rightarrow A'(N', Z') + X + \gamma \]
    \[ \pi^- + _{13}^{27} Al \rightarrow _{12}^{27} Mg + \gamma, \ E \sim 137 \ MeV \]
  - BR 2% for photon > 55 MeV, peak prob ~110 MeV, endpoint~137 MeV
  - $\gamma$ + material (e.g. target) $\rightarrow e^+e^-$

Calculation:
- BR~0.02
- $(\text{stopped pions}) / (\text{proton on primary target}) = 3 \times 10^{-7}$
- Probability: $e^- (101.5 < E < 105.5 \) \ produced \ in \ target = 3.5 \times 10^{-5}$
- Detector acceptance ~0.8
- This gives $(0.02)(3 \times 10^{-7})(3.5 \times 10^{-5})(0.8) = 1.7 \times 10^{-13}/\text{proton}$
- For $4 \times 10^{20}$ protons, there would be $7 \times 10^7$ potential false conversion $e$'s over the entire measurement.
Experimental Advantage of $\mu \rightarrow e$

- Electron energy, 105 MeV, is far above the bulk of low energy decay electron background. Considerable improvement in the ultimate sensitivity is quite likely.
- Contrast with $\mu \rightarrow e\gamma$:
  - $e$ and $\gamma$ each have energies of 53 MeV, right at the maximum flux of electron energies from ordinary muon decay. This background is believed to limit future improvements in achievable limits on the branching ratio.
Electrons from Production Target

- Electrons present largest flux of particles during the proton injection
  - Most traverse the beam line quickly compared to muons, pions, etc.
  - Suppression depends on extinction + suppression in the beam line.
- Beamline and collimators are designed to strongly suppress electrons > 100 MeV from arriving at stopping target
- Simulation: With $10^7$ electrons starting at the production target, none made it to the stopping target.
- Electrons >100 MeV entering the Detector Solenoid from the Transport Solenoid will have the wrong (too large) pitch when arriving at the detector compared to a conversion electron, due to gradient field in the stopping target region, except for target scatter.
  - $45<\Theta_{\text{max}}<60$ degrees for electrons from stopping target
  - $\Theta_{\text{max}}<45$ degrees for electrons from entrance of Detector Solenoid
- Estimate: 0.04 background events
MECO Simulations

- Full GEANT simulations of all particles traversing muon beam line: e, π, μ, γ, n, K…
- Full GEANT tracking of particles in detector region
- Separate studies of long transit time particles
  - pions, K0, K+, K-, pbars
  - K_L live a long time, ~52 ns
    - Separate simulation, following decays of low energy K_L from production region; number of background electrons at the stopping target was found to be tiny.
    - neutrons: can energetic neutrons survive many bounces down the beam line and be delayed enough in time to arrive in the measurement period? Study needed
- As part of the process of absorbing the MECO knowledge, Mu2e is setting up a general simulation apparatus and will repeat the MECO calculations
Neutrino Oscillations and $\mu \rightarrow e$

- $\nu$'s have mass! Individual lepton numbers are not conserved
- Therefore lepton flavor violation also occurs in charged leptons. In the SM:

$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 \lesssim 10^{-54}$$

- SM: BR($\mu N \rightarrow eN$)$<10^{-52}$
- This is way below any experimental sensitivity
- Other CLFV are similarly suppressed
- Any observation of CLFV is evidence for new physics
Power of Signal in Muon-Electron Conversion

neutrino mass via the see--saw mechanism, analysis in SO(10) framework

**Neutrino-Matrix Like (PMNS)**

**Minimal Flavor Violation (CKM)**

$$\text{BR}(\mu \rightarrow e) \times 10^{12}$$

measurement can distinguish between PMNS and MFV

$$\tan \beta = 10$$

Current Mu2e
Tracker measures energy of electrons to <1MeV FWHM, high-side tail $\sigma \sim 300$ keV

Calorimeter after the tracker: provides fast trigger, confirms energy and trajectory

2.4-2.9 m long, 0.5 cm diameter straws

Specs: $\sigma_z \sim 1.5$ mm, $\sigma_r \sim \sigma_\phi \sim 200$ $\mu$m
Detector Solenoid: Stopping Target and Detectors

- Tracker measures energy of electrons to <1 MeV FWHM, high-side tail $\sigma \sim 300$ keV
- Calorimeter after the tracker: provides fast trigger, confirms energy and trajectory
- 2.4-2.9 m long, 0.5 cm diameter straws
- Specs: $\sigma_z \sim 1.5$ mm, $\sigma_r \sim \sigma_\phi \sim 200$ $\mu$m
• Projection of helical track

• Conversion electron has high momentum ($p_T$) and has $R$ large enough to pass outside octagon and be tracked

• DIO ($p_T < 55$ MeV/c) does not!

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τ LFV at Belle

Belle and BABAR

BABAR Pub-07057 < 9 x 10^{-8}
Energy Calibration

- Mu2e resolution: $\sigma \sim 300$ keV on high-side tail, FWHM $\sim 1$ MeV
  - Response function needs to be well established
- Proposed energy integration region: 103.6-105.1 MeV
- Proposed absolute energy calibration: $\sigma \sim 0.1-0.2$ MeV
- Calibration approaches:
  - $\pi^+ \rightarrow e^+ + \nu_e$, $E(e^+) \sim 70$ MeV
- Stop $\pi^+$ in the stopping target
- Lower solenoid field to improve geometric overlap with detector
- Gives energy response function and energy calibration but at lower energy
- Reverse field to transport positive particles, or rotate collimator
- Use DIO spectrum to monitor calibrations
- Calibrate with a 100 MeV electrons from a dedicated accelerator
Antiproton-induced background

- Cross section for production by 8 GeV protons is small
- Only very low energy antiprotons are transported.
  - Can move very slowly through beam line.
- When material is encountered, forms atom, annihilates producing energetic pions, gammas, etc.
- Potentially dangerous background source.
- Eliminated by stopping all antiprotons in a very thin window in the middle of the Transport Solenoid
- Simulation: Secondary particles from antiproton annihilation tracked.
- Estimate: 0.006 counts
- Background is fairly continuous in time, unlike muons and pions
Staging Approach to Search for Muon to Electron Conversion

Phase 1: COMET

\[ B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16} \]
- without a muon storage ring.
- use a slowly-extracted pulsed proton beam.
- medium proton beam power (60 kW)
- can be done at the J-PARC NP Hall.
- Early realization

Phase 2: PRISM

\[ B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18} \]
- with a muon storage ring.
- use a fast-extracted pulsed proton beam.
- very high beam power (>1 MW)
- need a new beamline of fast extraction.
- Ultimate search
Magnetic Spectrometer:
Rates vs. Time

Rates start at 6 MHz/wire but ≤ 180 kHz/wire in live time window
• Each muon capture produces $2\gamma$, 2n, 0.1p