Mu2e-II Experiment at Fermilab

Mete Yucel
Tau Lepton 2023
Interest in Mu2e-II

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass


ArXiv Link

ArXiv Link
What is Mu2e-II

• Current experiments searching muon sector of CLFV;

<table>
<thead>
<tr>
<th>Exp</th>
<th>Institut</th>
<th>Process</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEG II</td>
<td>PSI</td>
<td>$\mu^\pm \rightarrow e^\pm + \gamma$</td>
<td>$4.2 \times 10^{-14}$</td>
</tr>
<tr>
<td>Mu2e</td>
<td>FNAL</td>
<td>$\mu^- + N \rightarrow e^- + N$</td>
<td>$6.0 \times 10^{-17}$</td>
</tr>
<tr>
<td>COMET</td>
<td>JPARC</td>
<td>$\mu^- + N \rightarrow e^- + N$</td>
<td>$10^{-15} - 10^{-17}$</td>
</tr>
<tr>
<td>Mu3e</td>
<td>PSI</td>
<td>$\mu^\pm \rightarrow e^\pm + e^\pm + e^-$</td>
<td>$10^{-14} - 10^{-16}$</td>
</tr>
</tbody>
</table>

Increasing Mu2e capability

• Improve sensitivity.
• Probe higher mass scale.

Expanding upon Mu2e goals

• Change targets.
• Focus on excluding/including models.
  • $\mu^- + N \rightarrow e^+ + N'$
  • $\mu \rightarrow eX$

$\theta_D$ parametrizes relative Magnitude of dipole and four-fermion coefficients.
• Mu2e-II beam is delivered using CW of magnetically stripped $H^-$ directly from LINAC instead of slow extracted protons from delivery ring (DR).
• $1.4 \times 10^9$ $H^-$ per spill, 62 ns bunch width compared to 250 ns for Mu2e.
• $10^{-11}$ extinction is required for the beam compared to $10^{-10}$ for Mu2e.
# Mu2e vs Mu2e-II Beam Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mu2e</th>
<th>Mu2e-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton source</td>
<td>Slow extraction from DR</td>
<td>PIP-II Linac</td>
</tr>
<tr>
<td>Proton kinetic energy</td>
<td>8 GeV</td>
<td>0.8 GeV</td>
</tr>
<tr>
<td>Beam Power for expt.</td>
<td>8 kW</td>
<td>100 kW</td>
</tr>
<tr>
<td>Protons/s</td>
<td>$6.25 \times 10^{12}$</td>
<td>$7.8 \times 10^{14}$</td>
</tr>
<tr>
<td>Pulse Cycle Length</td>
<td>1.693 $\mu$s</td>
<td>1.693 $\mu$s</td>
</tr>
<tr>
<td>Proton rms emittance</td>
<td>2.7</td>
<td>0.25</td>
</tr>
<tr>
<td>Proton geometric emittance</td>
<td>0.29</td>
<td>0.16</td>
</tr>
<tr>
<td>Proton Energy Spread ($\sigma_E$)</td>
<td>20 MeV</td>
<td>0.275 MeV</td>
</tr>
<tr>
<td>$\delta p/p$</td>
<td>$2.25 \times 10^{-3}$</td>
<td>$2.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>Stopped $\mu$ per proton</td>
<td>$1.59 \times 10^{-3}$</td>
<td>$9.1 \times 10^{-5}$</td>
</tr>
<tr>
<td>Stopped $\mu$ per cycle</td>
<td></td>
<td>$1.2 \times 10^{5}$</td>
</tr>
</tbody>
</table>

[Diagram of Mu2e and Mu2e-II beam pulses with live and signal windows]
Solenoids

• Production solenoid (PS) needs to change (cold mass) to handle the increased power delivered by PIP-II beam line.
• Lower energy beam is deflected more in vertical direction entering PS.
• Replacing PS cold mass;
  - Superconducting;
    • Cable-in-conduit conductor (CICC).
    • Internally cooled Al cable.
    • High-temperature superconducting (HTS) coils.
  - Resistive;
    • Water cooled resistive Cu coil.
    • LN₂ cooled resistive Cu or Al coil.
• TS may require some modifications.
• DS will be used as is.
Production target

• 100 kW on Mu2e-II target needs active cooling.
  - Carbon or Tungsten spheres on a conveyer belt.
  - Switch from copper to tungsten for HRS.
  - Need in situ monitoring of the target.
• R&D platform for AMF experiments and the Muon Collider.
Potential stopping targets

- Misalignment angle probes different Wilson coefficients.
- Preferably, for a complementary study one requires large angle -> heavy Z.
- Need muon lifetime > 250 ns, therefore Z < 25.

\[ \theta_{\text{Al}} \]

\[ Z \]

J. Heeck, R. Szafron, and Y. Uesaka, [2203.00702]

J. Heeck, R. Szafron, and Y. Uesaka, [2110.14667]

<table>
<thead>
<tr>
<th>spin NA/%</th>
<th>E_{end}/MeV</th>
<th>B/MeV^{-6}</th>
<th>( \tau_\mu/\text{ns} )</th>
<th>( \Gamma_{\text{cap}}/\text{s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^6\text{Li} )</td>
<td>1</td>
<td>7</td>
<td>104.64</td>
<td>( 1.3 \times 10^{-19} )</td>
</tr>
<tr>
<td>( ^7\text{Li} )</td>
<td>( ^3/2 )</td>
<td>93</td>
<td>104.78</td>
<td>( 1.3 \times 10^{-19} )</td>
</tr>
<tr>
<td>( ^{27}\text{Al} )</td>
<td>( ^{1}/2 )</td>
<td>100</td>
<td>104.97</td>
<td>( 8.9 \times 10^{-17} )</td>
</tr>
<tr>
<td>( ^{46}\text{Ti} )</td>
<td>0</td>
<td>8</td>
<td>104.25</td>
<td>( 5.2 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{47}\text{Ti} )</td>
<td>( ^{5}/2 )</td>
<td>7</td>
<td>104.26</td>
<td>( 5.3 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{48}\text{Ti} )</td>
<td>0</td>
<td>74</td>
<td>104.26</td>
<td>( 5.3 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{49}\text{Ti} )</td>
<td>( ^{7}/2 )</td>
<td>5</td>
<td>104.26</td>
<td>( 5.4 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{50}\text{Ti} )</td>
<td>0</td>
<td>5</td>
<td>104.26</td>
<td>( 5.4 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{51}\text{V} )</td>
<td>( ^{7}/2 )</td>
<td>100</td>
<td>104.15</td>
<td>( 6.3 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{52}\text{Cr} )</td>
<td>0</td>
<td>4</td>
<td>104.04</td>
<td>( 7.1 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{53}\text{Cr} )</td>
<td>0</td>
<td>84</td>
<td>104.04</td>
<td>( 7.2 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{54}\text{Cr} )</td>
<td>( ^{3}/2 )</td>
<td>10</td>
<td>104.05</td>
<td>( 7.1 \times 10^{-16} )</td>
</tr>
<tr>
<td>( ^{54}\text{Cr} )</td>
<td>0</td>
<td>2</td>
<td>104.05</td>
<td>( 6.9 \times 10^{-16} )</td>
</tr>
</tbody>
</table>

J. Heeck, R. Szafron, and Y. Uesaka, [2110.14667]
Tracker

Biggest difference is the reduced straw thickness from 15 μm to 8 μm

<table>
<thead>
<tr>
<th>Mu2e</th>
<th>Mu2e-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall thickness (μm)</td>
<td>18.1</td>
</tr>
<tr>
<td>Al thickness (μm)</td>
<td>0.1</td>
</tr>
<tr>
<td>Au thickness (μm)</td>
<td>0.02</td>
</tr>
<tr>
<td>Linear Density (g/m)</td>
<td>0.35</td>
</tr>
<tr>
<td>Pressure limits (atm)</td>
<td>0–5</td>
</tr>
<tr>
<td>Elastic Limit (gf)</td>
<td>1600</td>
</tr>
</tbody>
</table>

R&D needed for:
- Straw handling.
- Module production.
-Leaks.

Consider other tech:
- NA62/COMET 12 μm ultrasound weld.
- Microform Al extrusion 2 μm
Comparison using thinner straws

15 μm vs 8 μm

Mu2e-II CE momentum resolution at the Tracker front

Mu2e-II CE reconstructed momentum

<table>
<thead>
<tr>
<th>New Tracker</th>
<th>Old Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.04646</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.3693</td>
</tr>
<tr>
<td>Integral</td>
<td>0.9389</td>
</tr>
<tr>
<td>Constant</td>
<td>0.01192 ± 0.00003</td>
</tr>
<tr>
<td>Mean</td>
<td>0.005185 ± 0.000224</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.1048 ± 0.0002</td>
</tr>
</tbody>
</table>

FWHM = 900 keV/c

FWHM = 850 keV/c
Conversion electron

15 $\mu$m straws (Mu2e)  

8 $\mu$m straws (Mu2e-II)

10% improvement on CE efficiency

R&D is needed to improve pattern recognition and track finding
Alternative tracker geometry

Blue is 25 μm W sense wire, red is 50 μm Al and orange is 40 μm Al field wires. Alternatively 5 μm metalized mylar foils can replace the field layer.

• No glueing is needed as there is no need to eliminate leaks.
• He is needed for the drift gas to minimize multiple scattering.
• However He is ×2 slower than ArCO₂ and will reduces rates.
Calorimeter

- Crystal needs to withstand 0.1-1 Mrad;
  - BaF$_2$ met requirements but long wavelengths must be suppressed.
  - LYSO:Ce also met requirements but is slower (40 ns decay time).
- Photosensors has the same rad requirements;
  - For BaF$_2$ they must be sensitive to 220 nm fast component and insensitive to 300 nm slow component.
  - AlGaN photocathode works well with BaF$_2$.
  - R&D is underway to improve radiation hardness of these SiPMs.

BaF$_2$ Crystal Response
Cosmic ray veto

- Polystyrene scintillators coated with TiO2 sandwiched between Al absorbers.
- 4 overlapping layers of scintillators.
  - 3 layer coincidence veto
- Readout through WLS fibers & 2x2 mm² SiPMs on both ends.

Cosmic background \(\approx 1\) bg event per day. Covers all DS and part of TS.

- Improve concrete shielding with Barite and Boron loaded concrete.
- Change geometry to further minimize gaps between scintillators and increase granularity.
- SiPMs with better PDE and potted fibers to increase light yield.
Trigger and Data Acquisition (TDAQ)

- $\times 6$ event size @ 1MB/s.
- Reduced period with no beam.
- $\times 5$ better Mu2e trigger rejection.
- $\times 10$ Rad dose.
- 14 PB/y data.

Track reconstruction:
3. Track fit.

Use FPGA for L1 hardware trigger

Use GPUs for software trigger

Development can start now!
# Backgrounds and sensitivity

- **Mu2e-II results are for a C production target.**
- **More R&D and software optimization is needed.**
- **This estimate is considered to be conservative.**

<table>
<thead>
<tr>
<th>Results</th>
<th>Mu2e</th>
<th>Mu2e-II (5-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backgrounds</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DIO</td>
<td>0.144</td>
<td>0.263</td>
</tr>
<tr>
<td>Cosmics</td>
<td>0.209</td>
<td>0.171</td>
</tr>
<tr>
<td>RPC (in-time)</td>
<td>0.009</td>
<td>0.033</td>
</tr>
<tr>
<td>RPC (out-of-time)</td>
<td>0.016</td>
<td>&lt; 0.0057</td>
</tr>
<tr>
<td>RMC</td>
<td>&lt; 0.004</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>0.040</td>
<td>0.000</td>
</tr>
<tr>
<td>Decays in flight</td>
<td>&lt; 0.004</td>
<td>&lt; 0.011</td>
</tr>
<tr>
<td>Beam electrons</td>
<td>0.0002</td>
<td>&lt; 0.006</td>
</tr>
<tr>
<td>Total</td>
<td>0.41</td>
<td>0.47</td>
</tr>
</tbody>
</table>

\[
N(\text{muon stops}) = 6.7 \times 10^{18} \quad 5.5 \times 10^{19}
\]

\[
\text{SES} = 3.01 \times 10^{-17} \quad 3.25 \times 10^{-18}
\]

\[
R_{\mu e} (\text{discovery}) = 1.89 \times 10^{-16} \quad 2.34 \times 10^{-17}
\]

\[
R_{\mu e} (90\% \text{ CL}) = 6.01 \times 10^{-17} \quad 6.39 \times 10^{-18}
\]

[Arxiv link](#)
Schedule Prediction

Mu2e-II scenario:
- CD-0 by 2028
- Construction 2028-2032 (5 years)
- Data 2033-2037... (5... years)
Summary

• Mu2e-II is a worthwhile follow up to Mu2e in all cases with respect to Mu2e result.
• PIP-II will provide a much finer beam allowing Mu2e-II and other muon experiments to flourish.
• However more intense beam brings a harsher environment in terms of radiation. All subsystems will require significant R&D to meet this criteria.
• Mu2e-II offers many challenges and opportunities to work on regardless of the subsystem.
BACKUP
Extinction

- Extinction is measure of out-of-time beam
- Mu2e-II requires extinction < $10^{-11}$
  - cf Mu2e requirement < $10^{-10}$
- PIP-II specification is $10^{-4}$
  - Likely will be better
- Second stage ($10^{-9}$ with safety margin) with resonant dipoles and collimators, modified from Mu2e
  - Lower momentum means larger deflection
  - No beam halo from Mu2e’s slow extraction septum
  - Lower momentum means lower punch through at collimator
Extinction monitor

Mu2e’s extinction monitor is integrated into beam dump shielding
- Sees about one $\sim 4$ GeV/c particle per $10^6$ protons on target
- Statistical measurement of extinction over several hours
- Monitor adaptable to Mu2e-II (800 MeV beam)
- Acceptance of channel is a challenge since trajectory much different
- Reworking requires R&D
Radiation

Radiation around production target

- Displacements/atom (DPA) damage to PS coil
  - FOM is ratio of muon stops in stopping target to hottest DPA rate in PS coil
  - For Mu2e-II beam this FOM is close to or better than for Mu2e 8 GeV beam
  - DPA level around $4 \times 10^{-5}$ DPA/yr
  - Allows to run without annealing for ~1 yr

Beam power may imply different HRS

- W HRS with 25 cm inner bore radius would tolerate 100 kW beam

Radiation at the detector

- Doses ~20 times Mu2e at electronics and equipment alcoves
- Scaling by beam power yields estimated hadron fluxes (E > 30 MeV):
  - $3.7 \times 10^5$ h/cm²/yr at rack electronics
  - 750 h/cm²/yr tracker and calorimeter electronics
- Estimates will be improved, but will require radiation-tolerant electronics

Environmental radiation

- MARS simulations suggest approximately 20 times Mu2e
- Mitigation to be evaluated, may require, e.g.,
  - Increasing berm
  - Fencing a controlled area
Stopping Target Monitor

Stopping Target Monitor (STM) measures denominator of $R_{\text{me}}$
- Monitors X-ray and g-ray emission from stopping target during muon capture
- 10% accuracy
- For Al target:
  - 347 keV from 2p to 1s transition, prompt with muon stop
  - 1809 keV from nuclear capture, with 864 ns muon lifetime in Al
  - 844 keV from $^{26}\text{Mg}^*$ capture product, lifetime 9.5 minute
- Mu2e uses HPGe detector (excellent resolution) and LaBr$_3$ crystal (high rate, radiation hard) at 34 m from target
- To continue to use in higher rate and higher dose Mu2e-II may:
  - Increase absorber in STM beamline to reduce “beam flash”
  - Use HPGe at low intensity to calibrate LaBr$_3$
  - Move detectors off-axis
  - Replace some calorimeter crystals with LaBr$_3$ or LYSO
  - Create tertiary photon beam and measure that
- Subject of further R&D
AMF concept

Proton Driver  Front End  Muon Beams  Experiments

SC Linac  Proton Compressor

$100\text{kW-1MW target in a Capture Solenoid}$  FFA to create pure, cold muon beam

$\pi \rightarrow \mu$

$\mu^+ \rightarrow e\gamma, 3e$

$\mu^- N \rightarrow e^- N$
High Temperature Superconductor (HTS)

Thinking about HTS for production solenoid

- Cable more costly than LTS
  - But gap is closing
  - Can operate at higher current density
- R&D will cost more than for LTS
  - Thanks to fusion, already high on learning and availability curves
  - What we learn is of interest to others
  - E.g., muon collider “prototype”, maybe AMF
- Operating cost lower than for LTS
  - Higher temperature operation
  - Gaseous cooling
  - Cryostable (hard to quench)
    - Quench detection harder
- Radiation damage limits similar with LTS
  - HTS conductor (REBCO) can be annealed; Nb3Sn can not

Conductor cost

Grateful thanks to fusion!

Thanks to Zachary Hartwig and Luca Bottura!
Accelerator Evolution (ACE) formerly known as PIP-III

- Booster replacement.
  - Extend SRF or a new RCS.
  - Supply 8 GeV up to 2.4 MW.
  - New science spigots;
    - 2 GeV continuous wave.
    - 2 GeV pulsed (~1 MW).
    - 8 GeV pulsed (~1 MW).
- AMF can work with both options.
  - Needs accumulator ring in both cases.

What we want!
Mu2e(-II) physics besides $\mu \rightarrow e$

$\Delta L=2$ in $\mu^-N \rightarrow e^+N'$
Majorana neutrinos, matter-antimatter asymmetry
Currently $<1.2 \times 10^{-12}$ [SINDRUM II, on Ti, PLB 422(1998)334]
Needs further study, potential for gains similar as $\mu^-\rightarrow e^-$ conversion (RMC background, Ti target)

e.g., Geib et al., PL B764 (2017)157
Berryman et al., PRD 95 (2017)115010
Lee&MacKenzie, 2110.07093

New light boson in $\mu^{\pm}[N(A,Z)] \rightarrow e^{\pm}X[N(A,Z)]$
Currently $<5.8 \times 10^{-5}$ [TWIST, 1409.0638]

"calibration mode", sensitivity according to priority

Plestid, Caltech workshop 2023

"Heavy" (20-50 MeV) neutral lepton in $\pi^+ \rightarrow e^+X$ at rest
Possible dark matter “portal”

"calibration mode", plus degrader, sensitivity according to priority

Sensitivity to right-handed neutrinos mixing with e-flavor in “calibration” data with degrader

Plestid, Caltech workshop 2023 (credit S. Huang)
Tracker LDRD R&D

Achieving higher sensitivity requires better resolution
- Discriminate to higher momentum in decay-in-orbit tail
- Tracking LDRD has been extremely useful so far
  - Low mass straws 15 μ Mu2e → 8 μ Mu2e-II
- Investigating challenges
  - Collapse under own weight or static forces
  - Keep inflated once terminated
  - Metallization important to lowering leak rate
  - Paper removal, Alloy formation
  - Finding companies willing to make samples
    - 3 μ straws?

8 m Mylar straws using spiral winding
8 μ straws with terminations

B. Casey, LDRD talk

Gold/aluminum alloy Formation (μ2e straw)
High power target LDRD R&D (future)

- (Continue to) study configurations in simulation
- Additional realism in prototyping
  - (prototype 3 with realistic materials)
- Investigate other options, perhaps jointly with muon collider
  - Fluidized tungsten powder
  - Liquid heavy metal
- Cooling plant, remote handling

Estimate $2M
Discussion with K.Lynch:
- Good for designs, prototypes, long-term testing
- Likely to need more, but would be good start
- Additional work also may have additional sources (university program, GARD, LDRD for novel ideas, SBIR/STTR, some on FNAL ops, etc)
- Preparing a list of R&D items
RPF Experiment Targetry – R&D Approach for Muon Collider

DESIGN
- FEA simulations

PHYSICS
- Evaluate physics performance

MATERIAL
- Material Sciences
- Radiation Damage

Packed bed or Fluidized powder target
Liq. Target
Mu2e-II-like target (liquid)
Neutrino-like target (solid C)
Mu2e-like target

R&D Phase up to 2030

Demonstration Phase up to 2040

Selected Target Design

Prototype