The Mu2e-II experiment at Fermilab

S. E. Müller
for the Mu2e-II collaboration

Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

4th International Conference on Charged Lepton Flavor Violation, Heidelberg, June 20-22, 2023

DRESDEN concept

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Snowmass White Paper & CALTECH Workshop

Contributed paper for Snowmass:

arXiv:2203.07569

- 109 authors
- 34 institutions
- 6 countries

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

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Workshop on a Future Muon Program At Fermilab:

https://indico.fnal.gov/event/57834

- Caltech, Mar 27 - 29, 2023
- Many sessions devoted to **Mu2e-II**
- Synergies with Muon collider community explored

Mu2e-II: Muon to electron conversion with PIP-II
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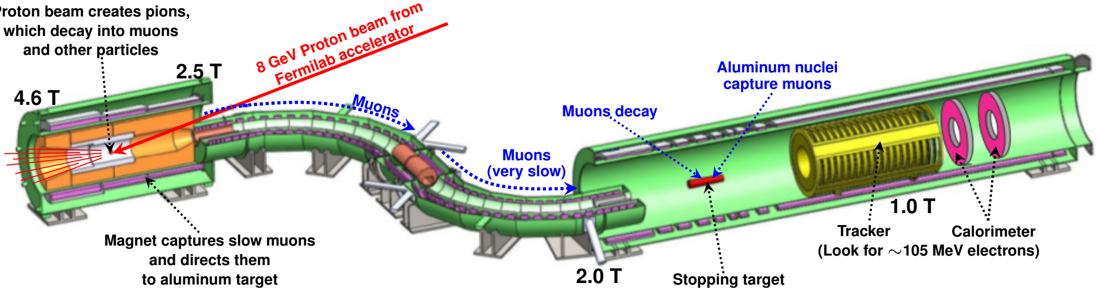
Mu2e reminder



- 8 GeV proton beam hits tungsten target and produces pions
- Pions are transported in s-shaped Transport Solenoid where they decay into muons
- Muons are stopped on aluminum target foils in Detector Solenoid
- Detectors (tracker and calorimeter) search for 105 MeV conversion electrons
- Not pictured: Cosmic Ray Veto system (CRV) and Stopping Target Monitor (STM)

Motivation

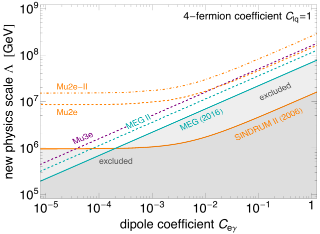
Mu2e-II will be the natural extension of the **Mu2e** experiment, using the **PIP-II** facility at FNAL to obtain more and cleaner muons, with the goal to achieve at least one order of magnitude in sensitivity over **Mu2e**.

Two scenarios:

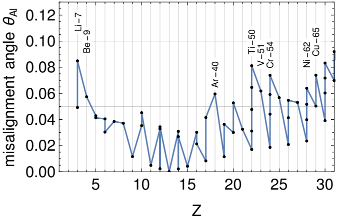
- **Mu2e** does not find a signal
  - improve sensitivity
  - probe higher mass scales
- **Mu2e** discovers CLFV in aluminum
  - measure with different target materials
  - pin down NP parameters

In addition, search for

- $\mu^- + N \to e^+ + N'$
- $\mu \to eX$



K. Byrum et al., **arXiv:2203.07569**

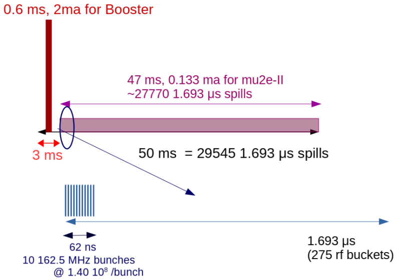


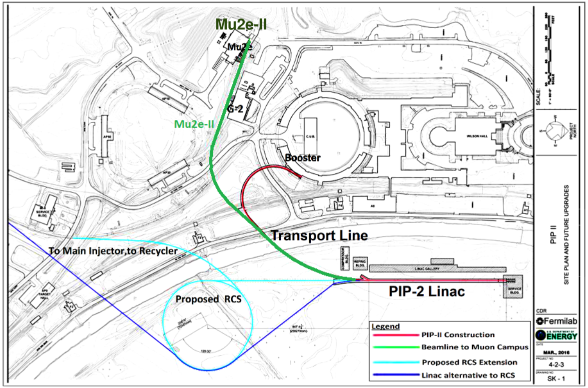
J. Heeck et al., **arXiv:2203.00702**

PIP-II

Mu2e-II will be using H^- beam from **PIP-II** LINAC instead of slow extracted protons from delivery ring (DR) via a direct transport line from **PIP-II** Linac to **Mu2e** M4 beamline. Foil stripping to get 800 MeV protons incorporated already in transport line.

- 3ms of beam out of 50ms for 20 Hz Booster injection, remaining beam available to Muon Campus
- 10 PIP-II bunches at 162.5MHz (62ns long, 1.4×10^9 H^-) followed by 265 empty bunch buckets form 1.693µs **Mu2e-II** spill





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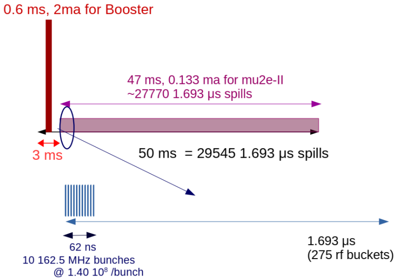


Mu2e and Mu2e-II Proton beam parameters:

Parameter	Mu2e	Mu2e-II
Proton source	Slow extraction from DR	PIP-II Linac
Proton kinetic energy	8 GeV	0.8 GeV
Beam Power for expt.	8 kW	100 kW (minimum)
Protons/s	6.25×10^{12}	7.8×10^{14}
Pulse Cycle Length	1.693 μs	1.693 μs (variable)
Proton bunch width	250ns	62ns
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}

Extinction (N_{p+} out of bunch)/(N_{p+} in bunch) $\leq 10^{-11}$

(factor 10 better than required for Mu2e).

800 MeV beam gets deflected in magnetic field:

- Beam trajectory to PT will be significantly different
- Beam will be dumped at different postion

PIP-II upgrade to 2 GeV very welcome!

HZDR

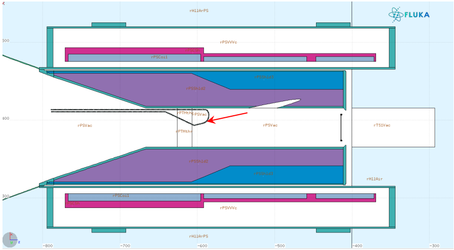
Production target

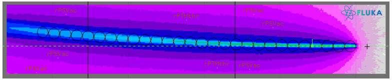
Due to the higher proton beam intensity, Mu2e-II needs a pion production target which involves active cooling. The current target designs are based on a conveyor idea in which carbon or tungsten balls are circulated to and from the proton beam.

Two major designs:

- target made out of 28 carbon spheres (0.75cm radius each)
- target consisting of 11 tungsten spheres (0.5 cm radius each)

Extensive MC studies using different radiation transport codes to estimate pion and muon yield, energy deposition and DPA in the spheres as well as overall radiation levels in progress.





800 MeV proton beam gets deflected in Mu2e magnetic field.

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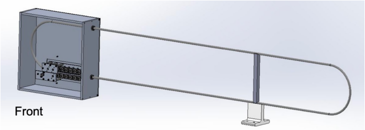

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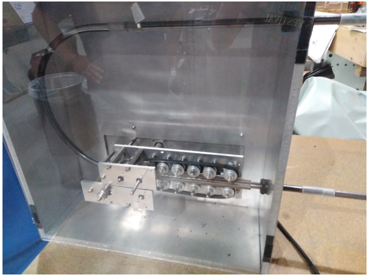

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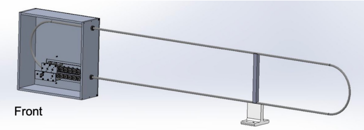

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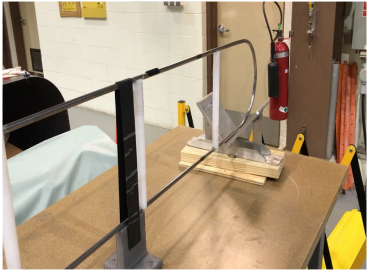

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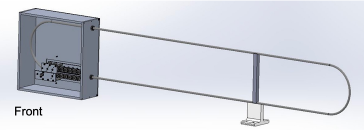

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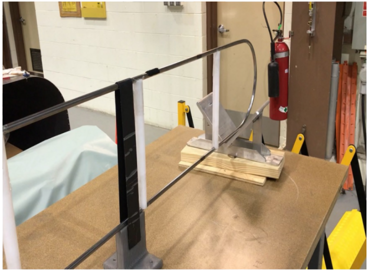

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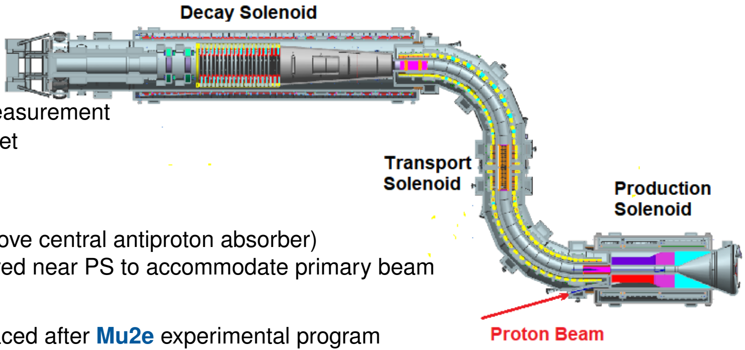
Alternative designs (CALTECH workshop):

- fluidized tungsten powder
- liquid heavy metal (e.g. liquid lead)

$\Rightarrow$ Synergies with Muon Collider community.

Solenoids

Mu2e-II will reuse as much as possible Mu2e's beamline configuration of three solenoidal magnets.



Detector (Decay) Solenoid:

- Focus e^- towards detectors
- Provides field for momentum measurement
- Possibility to re-use Mu2e magnet

Transport Solenoid:

- Muon selection and transport
- Re-use Mu2e magnet (may remove central antiproton absorber)
  - Modification may be required near PS to accommodate primary beam

Production Solenoid:

- Existing PS will need to be replaced after **Mu2e** experimental program
  - high activation of components prevents upgrade or modification
  - design updated PS to improve sensitivity (lessons learned from **Mu2e**)
- New Tungsten Heat- and Radiation Shield (HRS) to cope with higher radiation loads
- Explore options for SC coils
  - Cable-in-conduit conductor (CICC), internally cooled Al cable, HTS coils
- Increase overhead shielding

Tracking detector

The tracker must efficiently identify 105 MeV/c conversion electrons while rejecting the high energy tail of DIO background events. Since the DIO background scales with the number of stopped muons, for **Mu2e-II** this background would increase 10-fold respect to **Mu2e**.

Improvements to meet design goals:

- Increase tracker resolution by reducing mass
  - Thinner straws (8μm thickness vs. 18μm)
  - Drop 200 angstrom gold layer inside of straw
- Move the lower bound of momentum acceptance window for CE candidates to optimize S/B ratio
- Improve track reconstruction algorithms (ML)

R&D started to investigate 8μm straws:

	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0-5	0-3
Elastic Limit (gf)	1600	500

Efficiency improved by $\sim$ 10% in MC performance studies.

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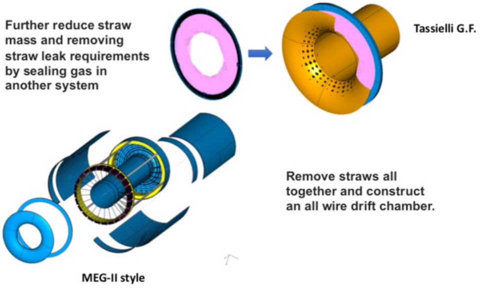
Alternative detector designs:

- enclose drift tracker in ultra-light gas vessel
  - reduce straw leakage requirements
- construct all-wire drift chamber without straws

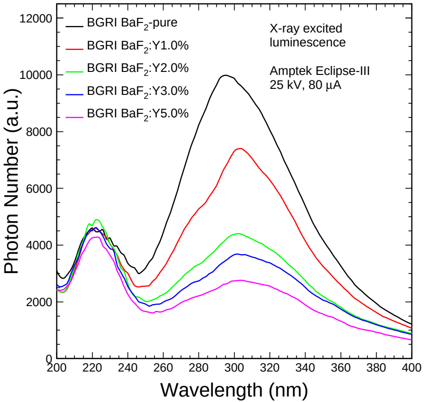


Calorimeter

The **Mu2e-II** calorimeter has same energy ($< 10\%$) and timing resolution requirements (< 500ps) as **Mu2e**, but much higher radiation environment (up to 10kGy, $\sim 10^{13}$ neutrons(1 MeV eq.)/cm^2).

Existing CsI crystals in front disk need to be replaced

- BaF_2 is excellent candidate
  - radiation hard
  - fast UV component at 220nm
  - need to suppress slow component at 300-320nm
- Yttrium doping effective in suppressing the slow component
- R&D on UV sensitive, solar-blind photosensors



Alternative solutions under study:

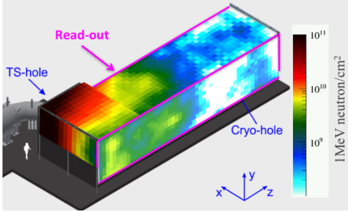
- PbF_2 crystals (rad-hard, but reduced lightyield)
- LYSO crystals (expensive, equip only inner part of disk)

Cosmic Ray Veto

Mu2e CRV system needs to be replaced due to light yield degradation over experiment's lifetime. Factor 3 in live time results in 3 times higher Cosmic Ray backgrounds for **Mu2e-II**. Noise rates in CRV due to primary protons and muons give rise to dead time in CRV and high radiation rates in front-end electronics.

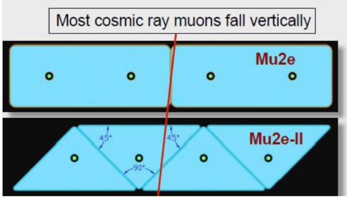
Requirements:

- Suppress CR backgrounds to the fraction of event
- Keep beam-induced readout noise below 1 MHz
- Reduce beam-induced deadtime to better than 10%
- Radiation on front-end electronics $< 10^{10}$ neutrons(1 MeV eq.)/cm^2



R&D efforts:

- Improve shielding with barite and boron loaded concrete
- Increased light yield using potted fibers and SiPMs with better efficiency
- Enhanced CRV design with triangular shaped counters
  - Improved efficiency due to reduced gaps
  - Lower rate on each counter thanks to reduced size



Cosmic Ray Veto

Mu2e CRV system needs to be replaced due to light yield degradation over experiment's lifetime. Factor 3 in live time results in 3 times higher Cosmic Ray backgrounds for **Mu2e-II**. Noise rates in CRV due to primary protons and muons give rise to dead time in CRV and high radiation rates in front-end electronics.

Requirements:

- Suppress CR backgrounds to the fraction of event
- Keep beam-induced readout noise below 1 MHz
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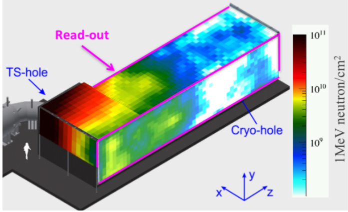

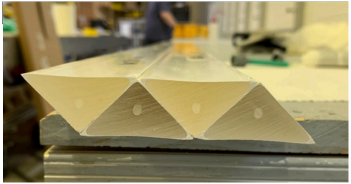

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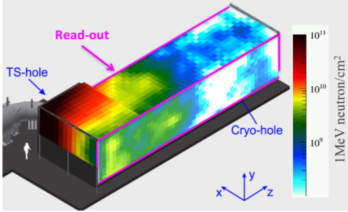

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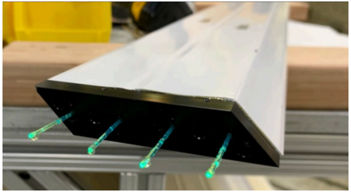
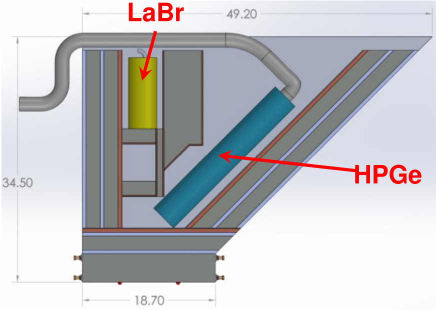


Normalization

Normalization of the CLFV signal is done by registering the number of stopped muons in the Stopping Target by detecting the characteristic X- and γ-rays when muons are stopped or captured.

Mu2e Stopping Target Monitor (STM) consists of a detector system made of an HPGe and a $LaBr_3$ detector looking at the Stopping Target from $\sim$ 35m distance.

- Especially HPGe detector will not be able to handle the higher rates and radiation at **Mu2e-II**
  - add absorber material in STM beamline
  - use HPGe detector only during dedicated low-intensity runs
  - move detector system off-axis



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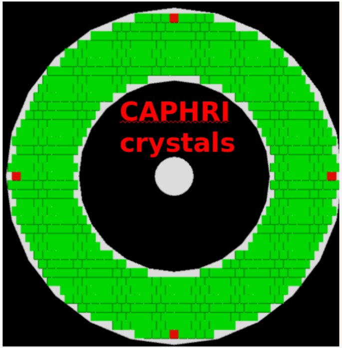
Alternative/Additional solution:

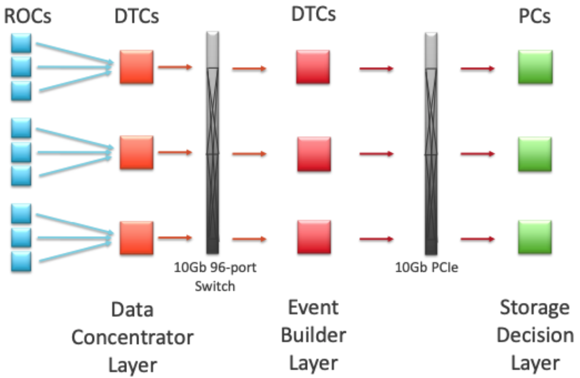
- Equip first disk with 4 $LaBr_3$ crystals to detect characteristic 1.8 MeV line when muons are captured on Aluminum (LYSO for **Mu2e**)
- CAPHRI (Calorimeter Precise High-Resolution Intensity) detector
- R&D ongoing



Trigger and DAQ

- factor 6 increase of event data size respect to **Mu2e** amounting to $\sim$1 MB/event
  - factor 3 increase in duty cycle due to reduced beam-off period
  - factor 2 increase in number of channels
- factor 10 increased dose on electronics
- available storaged capacity $\sim$ 14 PB/year
  - trigger rejection needs to be a factor of $\sim$5 better than in **Mu2e**

Mu2e readout topology



Mitigation strategies:

- 2-level trigger with L1 hardware trigger on FPGA + HLT
  - exploit High-Level-Synthesis (HLS) tools
- software trigger with GPUs
  - implement reconstruction algorithms on GPUs

Preliminary Sensitivity Study

A preliminary sensitivity study has been carried out using the **Mu2e-II** production target design based on carbon spheres together with the nominal **Mu2e** aluminum stopping target.

- Straw tube tracker with 8μm straws
- Calorimeter as **Mu2e** with CsI replaced with BaF_2
- Antiproton-absorbers removed in TS
- signal window for **Mu2e-II**:
  $104.05 < p < 104.90$ MeV/c and
  $690 < t < 1650$ ns
  (**Mu2e**: $103.85 < p < 104.90$ MeV/c and
  $700 < t < 1695$ ns)

Estimates can be considered conservative, more R&D and software optimization needed.

Summary table for the expected background rates:

Results	Mu2e	Mu2e-II (5-year)
Backgrounds		
DIO	0.144	0.263
Cosmics	0.209	0.171
RPC (in-time)	0.009	0.033
RPC (out-of-time)	0.016	< 0.0057
RMC	< 0.004	< 0.02
Antiprotons	0.040	0.000
Decays in flight	< 0.004	< 0.011
Beam electrons	0.0002	< 0.006
Total	0.41	0.47
N(muon stops)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}

Summary

- **Mu2e-II** is a natural follow-up to the **Mu2e** experiment
  - If **Mu2e** discovers CLFV in aluminum, **Mu2e-II** can measure with different target materials to pin down NP parameters
  - If **Mu2e** does not find a signal, repeat the measurement to push limits even further
- reuse as many components of **Mu2e** as possible
- still many challenges for **Mu2e-II**:
  - rates
  - radiation
  - resolution
- many R&D activities already ongoing
  - prototype for conveyor target
  - tracker R&D prototype straws with thickness reduced to 8μm
  - studies on BaF_2 crystals for calorimeter
  - CRV prototype with triangular shaped counters
- **Mu2e-II** can act as a bridge to Advanced Muon Facility
  - also synergistic R&D with Muon Collider on Production Target and Production Solenoid