FERMILAB-SLIDES-18-159-E

Probing charged lepton flavor violation with the Mu2e experiment

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DPG Spring meeting, Bochum, February 26, 2018

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MUSE

DRESDEN concept

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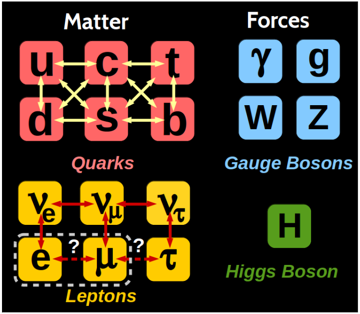
Motivation

The Standard Model of particle physics currently contains:

- Quark mixing
- Transitions between charged and neutral leptons of same flavor
- Neutrino oscillations

No charged lepton flavor violation (CLFV) observed so far!



Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \rightarrow eN$) with a projected

upper limit of 8×10^{-17} (90% CL)

Current limit by SINDRUM-II (PSI): B$(\mu Au \rightarrow eAu) < 7 \times 10^{-13}$(90% CL)

SM prediction via neutrino mixing is $\sim 10^{-54}$, but extensions of SM predict values up to $\sim 10^{-14}$ (Leptoquarks, SUSY, heavy neutrinos,...)

$\Rightarrow$ Unique possibility to test for New Physics

The Mu2e experiment

The **Mu2e** experiment will search for CLFV in the process ($\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$):

- Muons are produced by 8 GeV proton beam on tungsten target
  - 3×10^7 protons/pulse, pulse separation: 1.7μs
  - Gradient field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

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- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Toroidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

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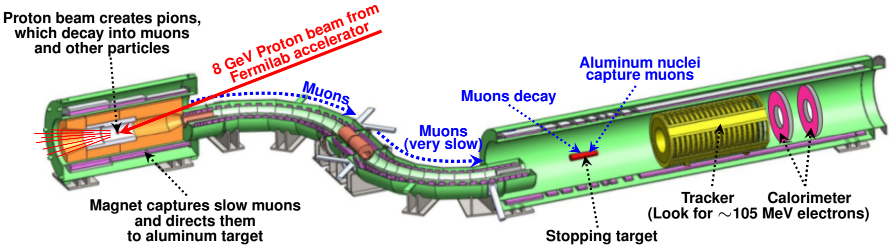
  - Collimators select low-momentum negatively-charged muons.
- Muons are stopped on aluminum target foils in Detector Solenoid
  - stopped muons decay in orbit or are captured by the Al nucleus
  - decay electrons are detected by a tracking detector and a calorimeter

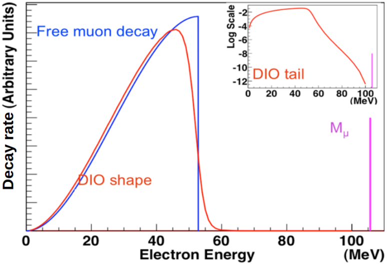
The Mu2e experiment



The Mu2e experiment

Stopped muons have a lifetime of $\sim$ 900ns in the 1s orbital of the Al nucleus

- about 60% of stopped muons undergo the muon capture reaction ($\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons stops around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives single mono-energetic electron
  - $E_e = 104.973$ MeV $\simeq M_\mu$



$$\text{Normalized ratio } R_{\mu e} = \frac{N(\mu^- + \text{Al} \rightarrow e^- + \text{Al})}{N(\mu^- + \text{Al} \rightarrow \nu_\mu + \text{Mg})}$$

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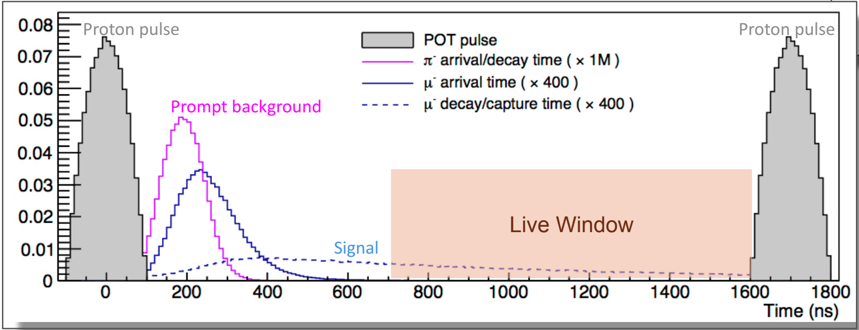
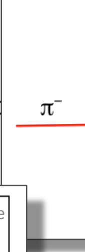
The Mu2e experiment

Mu2e Project scope includes

- Modifications to the accelerator complex

Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background:



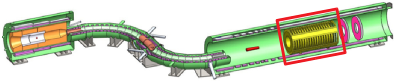


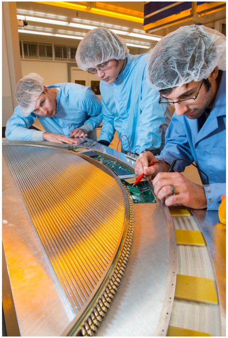
- Fermilab accelerator complex provides ideal pulse spacing for Mu2e.
- Pulsed beam allows to suppress prompt background during proton-pulses
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

Suppress prompt backgrounds by many orders of magnitu
beam and a delayed live gate

- Proton pulses must be narrow
- Out-of-time protons must be suppressed

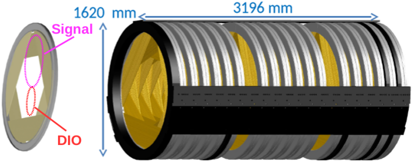
Straw drift tube tracker





- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_\text{p} < 180$ keV/c

- inner 38 cm not instrumented
  $\rightarrow$ “blind” to low-momenta DIO electrons



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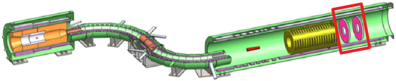
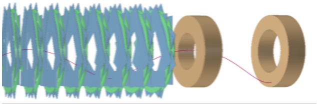
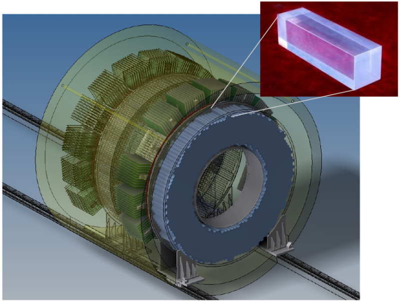
Calorimeter



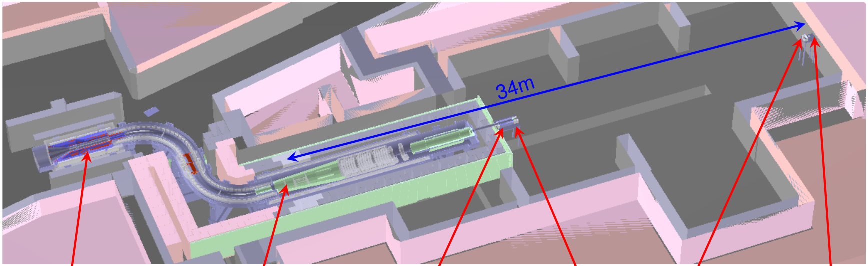


- composed of two rings separated by half a wavelength of electron trajectory helix
- each ring composed of $\sim$700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent trigger information
- particle ID



The Stopping-Target Monitor

High-purity Germanium (HPGe) detector to determine overall muon-capture rate on Al to about the 10% level



- measures X- and γ-rays from muonic Aluminum

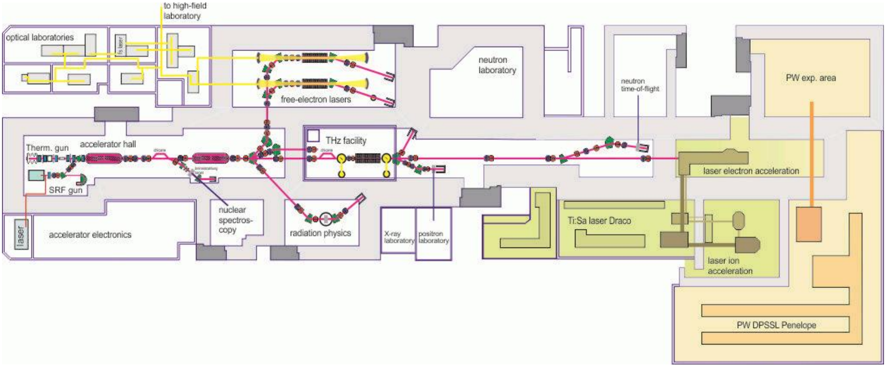
  347 keV 2p-1s X-ray (80% of muon stops)
  844 keV delayed γ-ray (5% of muon stops)
  1809 keV γ-ray (30% of muon stops)

- line-of-sight view of Muon Stopping Target
- sweeper magnet to reduce charged particle background and radiation damage to detector

The ELBE radiation source

The ELBE “Electron Linac for beams with high Brilliance and low Emittance” delivers multiple secondary beams.

- $E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t < 1$ μs



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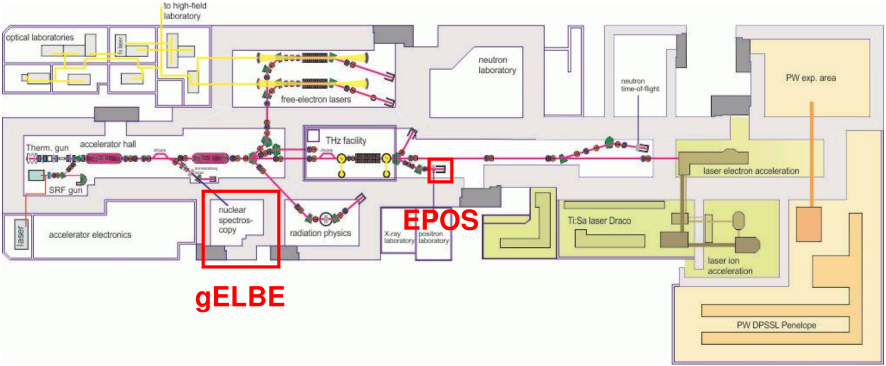


gELBE: Gamma beam facility (HPGe detector design for STM)

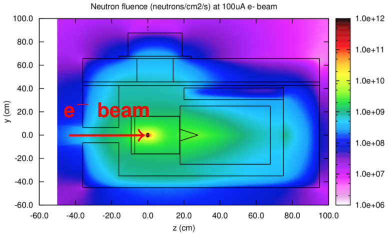
EPOS: Positron (+ Photoneutron) source (Radiation hardness tests)

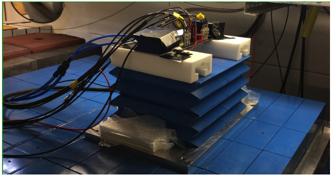
Testing radiation hardness of SiPMs at EPOS

Positron production by ELBE 30 MeV electron beam on tungsten target is accompanied by a large amount of photoproduced neutrons with an energy spectrum which peaks at $\sim$1 MeV.

$\rightarrow$ this matches the expected radiation conditions at Mu2e

- expected neutron fluence has been simulated using FLUKA
- SiPMs from 3 suppliers have been installed on top of the EPOS target bunker for a parasitic beamtime
- dark current of SiPMs has been monitored (stabilized at 20°C)
- integrated fluence of more than 8×10^{11} 1-MeV-equiv. neutrons/cm^2 has been accumulated





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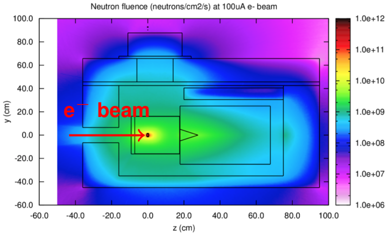

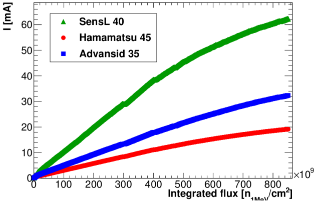

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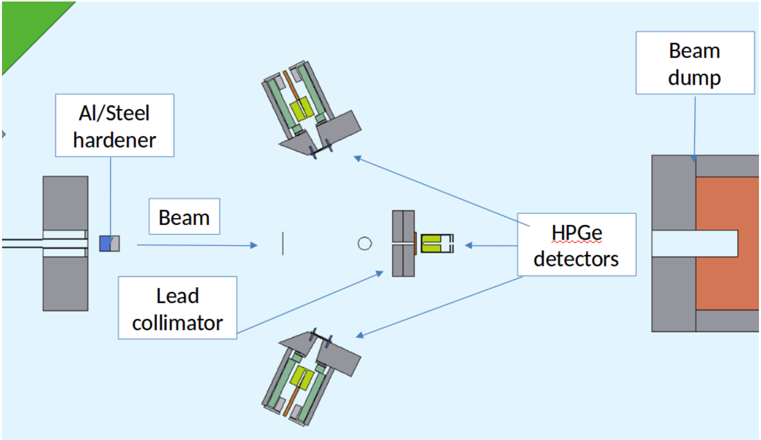
Studying HPGe detector response at gELBE

The gELBE bremsstrahlung facility was used to study HPGe detector performance in the presence of high beam pulse occupance.
gELBE delivers a pulsed γ-beam with max. energy of 15 MeV.

- Up to 125kHz of gamma rates expected for Mu2e Stopping-Target Monitor HPGe detector during beam pulse
  - high average γ energy ($\sim$ 5 MeV)
  - high beam pulse occupancy ($\sim$ 20%)
- gELBE pulse separation of 2.4μs close to Mu2e's 1.7μs proton pulse separation
- Goals of the beamtime:
  - Measure HPGe detector performance in the gELBE beam (energy resolution, radiation damage,...)
  - Understand best beam and detector geometry and position (including absorbers)
- HZDR provides radiation transport simulations using the FLUKA code to estimate γ energy spectrum, energy deposit in crystal etc.

Studying HPGe detector response at gELBE

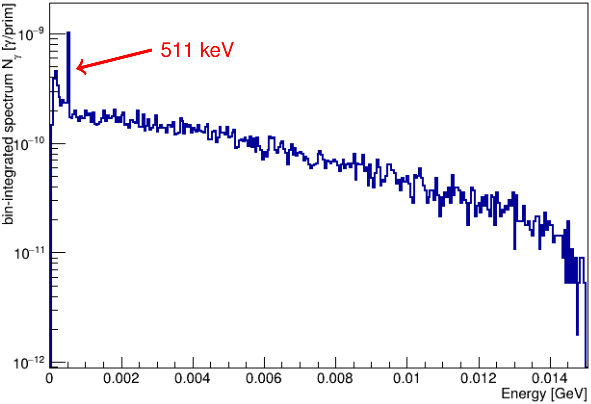
Setup during the gELBE beamtime:



Studying HPGe detector response at gELBE

Studying energy deposition in crystal:

- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it till HPGe detector position
- HPGe detector behind lead wall with 1cm^2 collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



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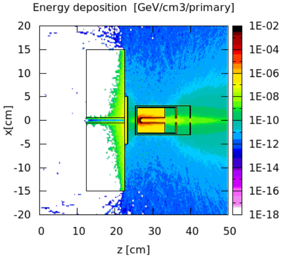
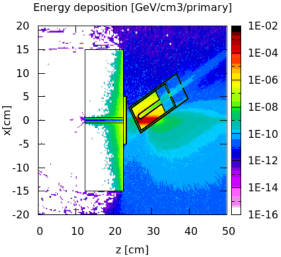
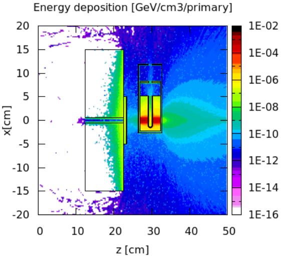


Average energy deposition
(508.68$\pm$0.11) keV
per primary γ



Average energy deposition
(1846.3$\pm$0.16) keV
per primary γ



Average energy deposition
(1759.4$\pm$0.08) keV
per primary γ

Conclusion & Outlook

- The Mu2e experiment at FERMILAB will search for the neutrinoless conversion of a muon into an electron in the coulomb field of an Aluminum nucleus
  - projected upper limit: 8×10^{-17} (90% CL)
- Detector design ready, construction started
- Solenoid design ready, coil fabrication started
- Beamtimes at HZDR's ELBE radiation source for tests of radiation hardness of calorimeter components and HPGe detector design for STM
- With dataking starting in 2021, Mu2e will either unambiguously discover CLFV or push the limit on muon$\rightarrow$electron conversion by four orders of magnitude

Mu2e Collaboration

More than 200 scientists from 37 institutions: