Probing charged lepton flavor violation with the Mu2e experiment

S. E. Müller, A. Ferrari, O. Knodel, and R. Rachamin for the Mu2e-collaboration

Helmholtz-Zentrum Dresden-Rossendorf

DPG Meeting Mainz, (virtual), March 31, 2022

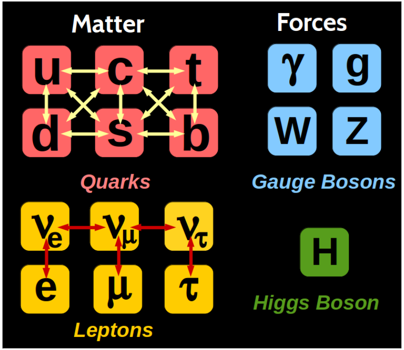
DRESDEN concept

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Motivation

The Standard Model of particle physics currently contains:

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

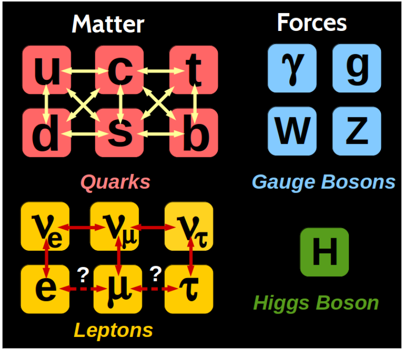


Motivation

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!

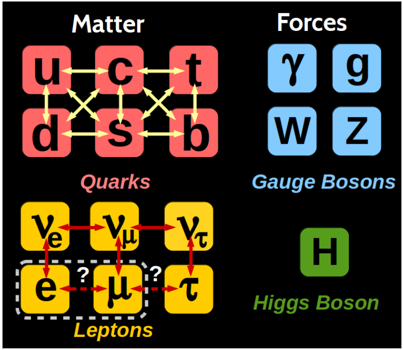


Motivation

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 6×10^{-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, heavy neutrinos, SUSY,...)

$\Rightarrow$ Unique possibility to test for New Physics

New physics

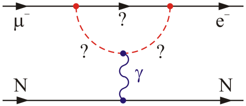
Model independent Lagrangian:

$$L_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Dipole term”}} + \underbrace{\frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)}_{\text{“Contact term”}}$$

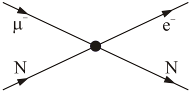
Λ: effective mass scale of New Physics

κ: relative contribution of contact term

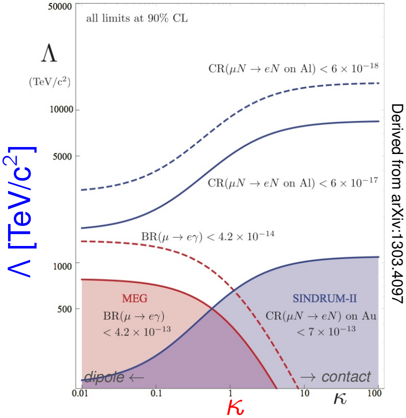
Dipole term: dominates for $\kappa \ll 1$



Contact term: dominates for $\kappa \gg 1$



Mu2e will probe $\Lambda \sim O(10^3\text{ -}10^4)$ TeV/c^2

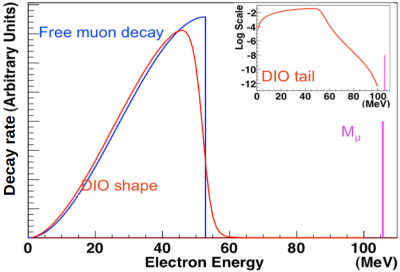


The Mu2e experiment

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

Stopped muons have a lifetime of 864ns in the 1s-orbital of the Al nucleus

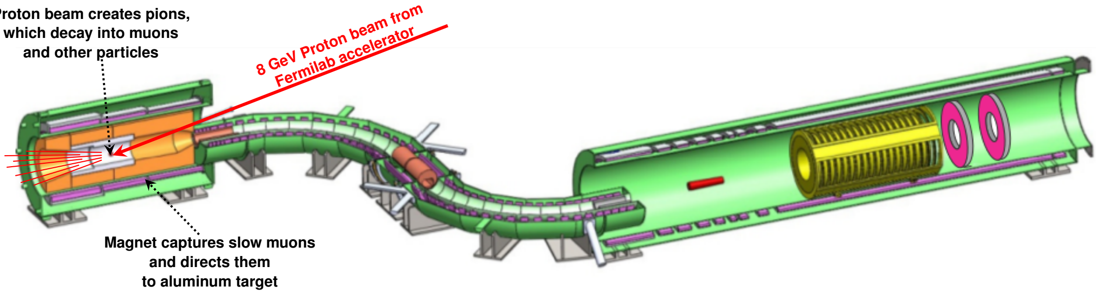
- about 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}\mathrm{Al} \rightarrow \nu_\mu + {}^{27}\mathrm{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons dies around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion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



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

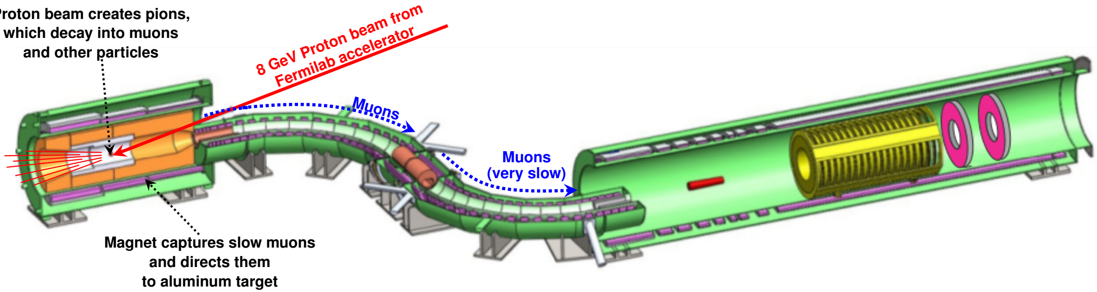
HZDR

The Mu2e experiment



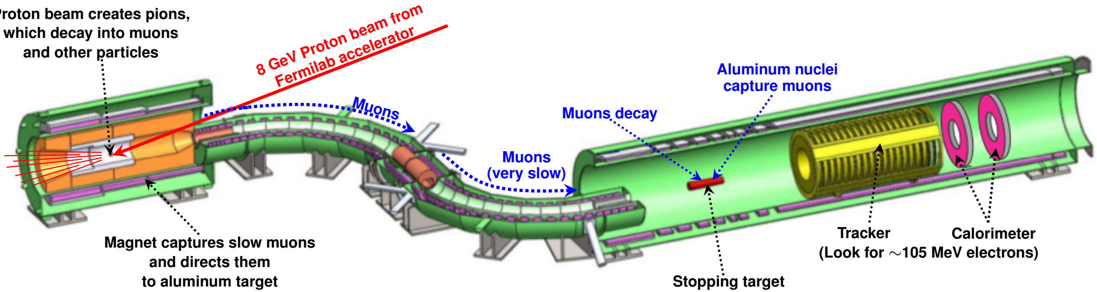
- Muons are obtained from 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1695ns
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



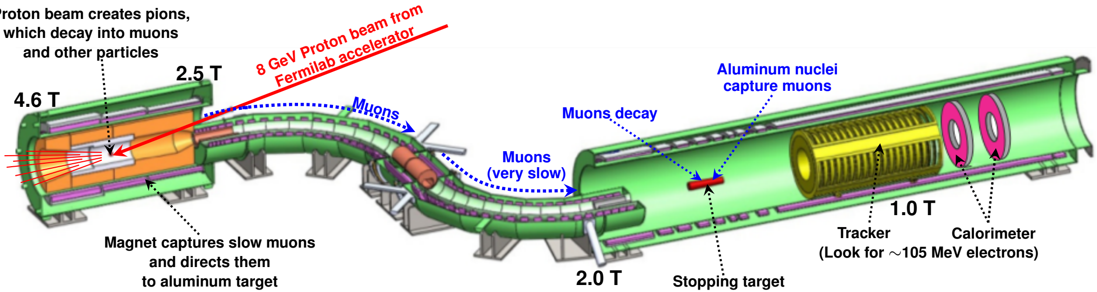
- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

The Mu2e experiment



- 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

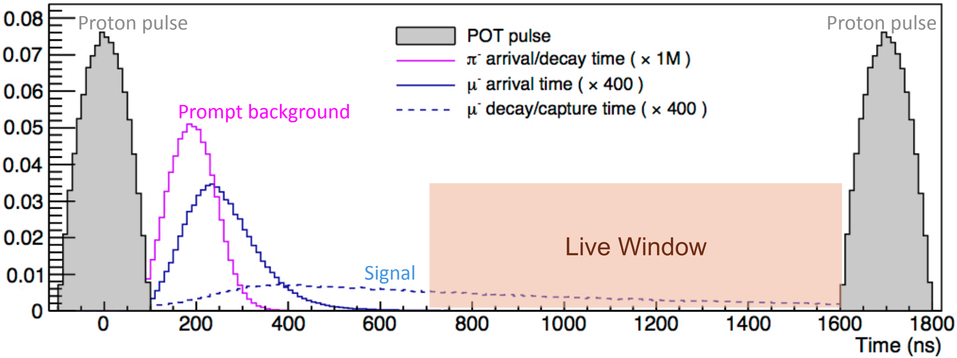
The Mu2e experiment



- Graded fields in the 3 solenoid systems are important
  - to increase muon yields
  - to suppress backgrounds
  - to improve geometric acceptance for signal electrons

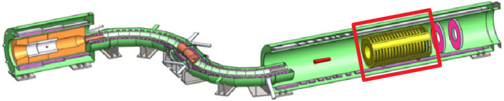
The Mu2e experiment

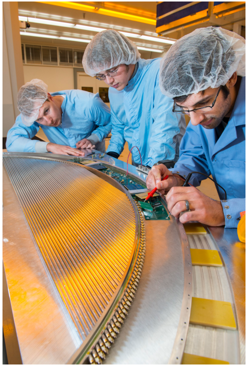
Pulsed proton beam allows definition of a "Live Window" for the signal to suppress prompt back-ground (1695ns peak-to-peak):



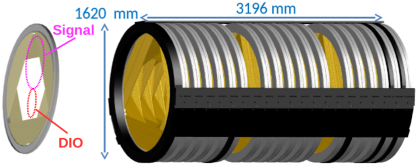
- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

Straw drift tube tracker



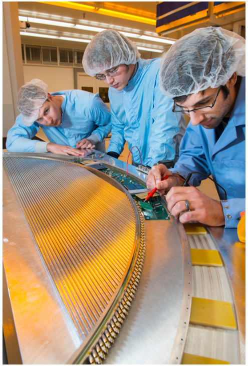


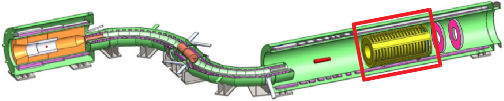
- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_p < 180$ keV/c

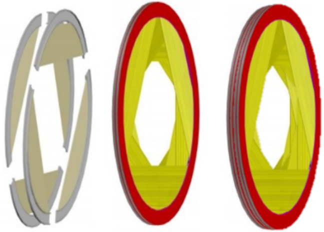


- inner 38 cm not instrumented
  $\rightarrow$ “blind” to low-momenta DIO electrons

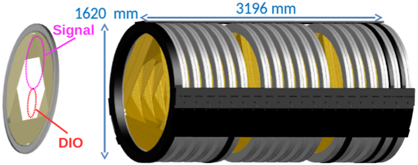
Straw drift tube tracker





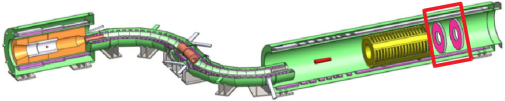


6 panels make a plane   2 planes a station

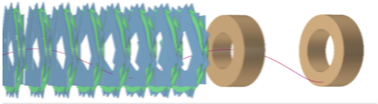


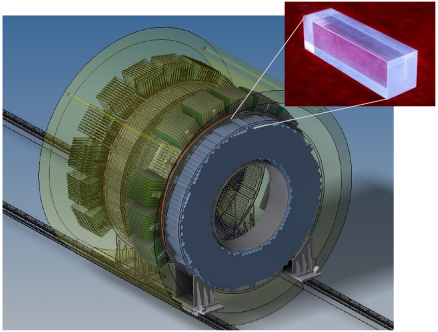
- inner 38 cm not instrumented
  → “blind” to low-momenta DIO electrons

Calorimeter



- composed of two rings separated by half a wavelength of signal electron trajectory helix
- each ring composed of ∼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
- calibration with activated liquid source

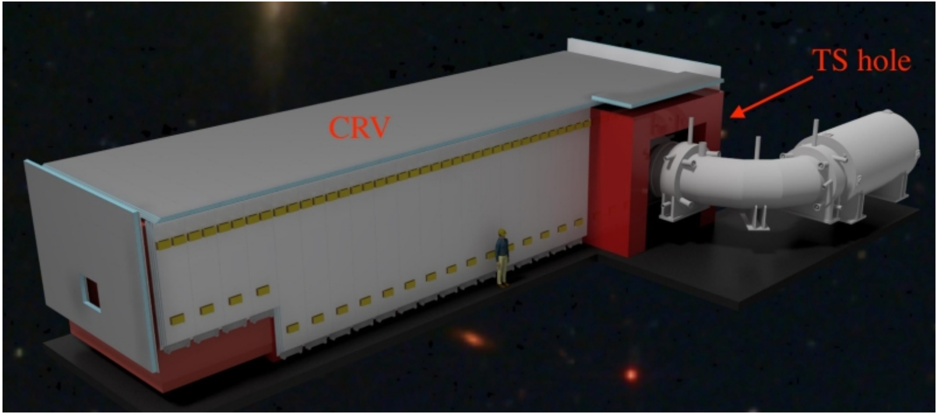




HZDR

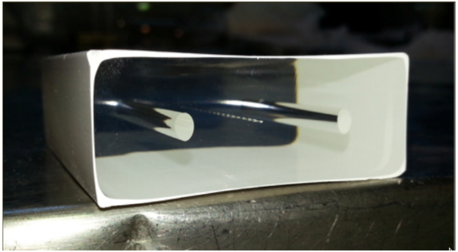
The cosmic ray veto detector

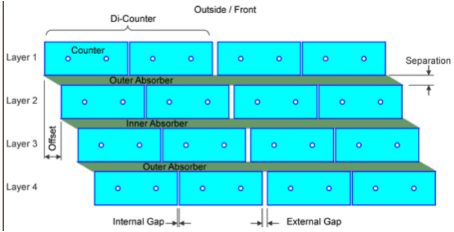
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



The cosmic ray veto detector

Without CRV, $\sim$ 1 background event per day mimicking signal produced by cosmic-ray muons

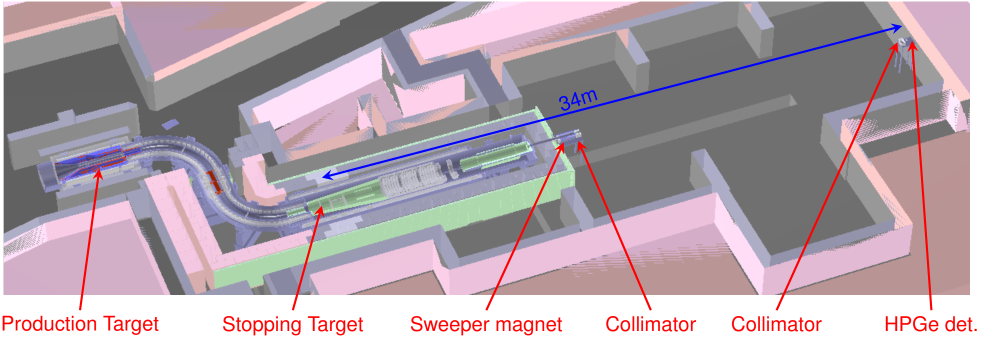




- 4 overlapping layers of scintillator bars ($5 \times 2 \times \sim 450$ cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

The Stopping-Target Monitor

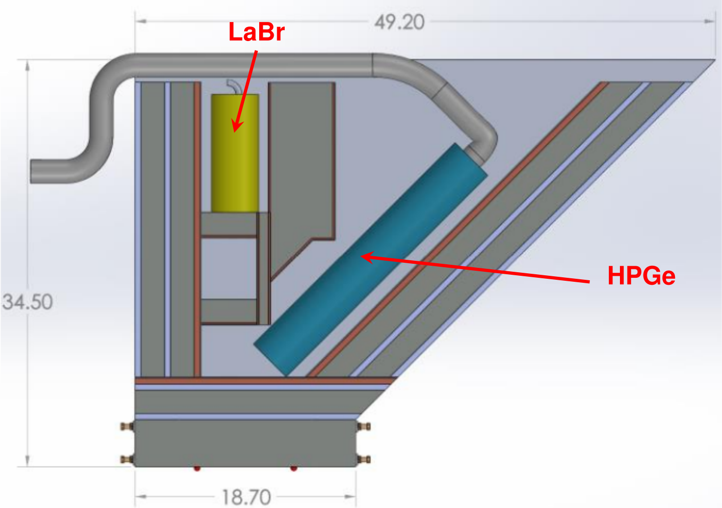
High-purity Germanium detector to determine overall muon-capture rate on Al to the level of 10%



- measure 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
- It was decided to accompany the HPGe detector with a $LaBr_3$ detector (worse energy resolution, but can take higher rates)

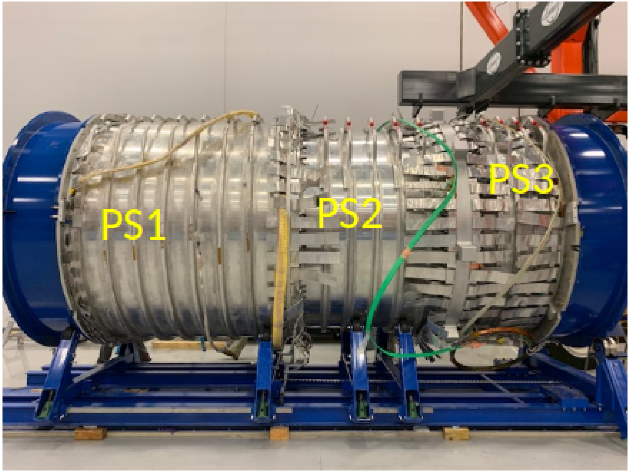
The Stopping-Target Monitor shieldhouse design

HPGe detector needs to be in an angled position due to limited space. Detectors “see” the Aluminum stopping target through collimator holes in tungsten shielding block.



Magnet production

Production Solenoid (PS) coil fabrication completed (General Atomics):



Magnet production

Upstream Transport Solenoid (TSu) cold mass assembled and thermal shield fitted:

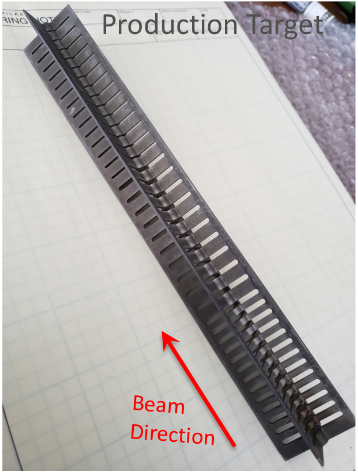
Downstream Transport Solenoid (TSd) assembly close behind.

The Heat and Radiation Shield (HRS)

The bronze heat and radiation shield was delivered to Fermilab, and was lowered into the PS area inside the Mu2e building:

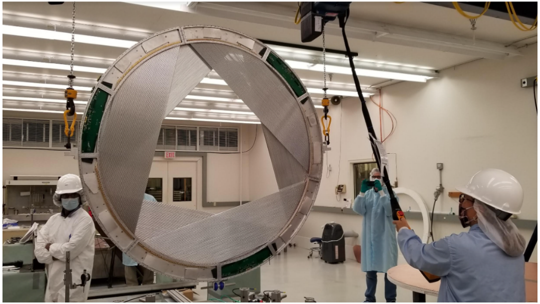
Production Target

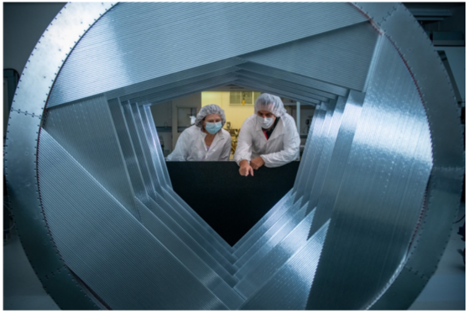
The tungsten production target absorbs about 10% of beam power ($\simeq$700 W):



Tracker panel production

166 out of 240 tracker panels produced, 12 of the 36 planes assembled.





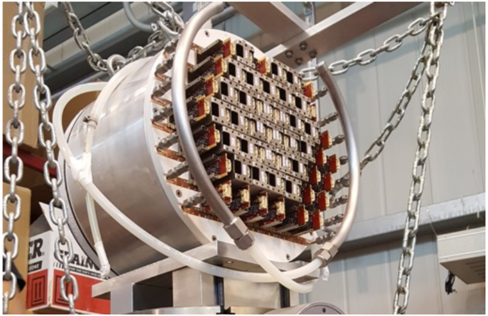
Panels shipped to Fermilab for further quality assurance and full tracker assembly.

Calorimeter status

- Production of CsI crystals finished
- All SiPMs are tested
- FEE boards delivered, undergoing quality control

Prototype with 51 crystals and 102 SiPMs and FEE boards has been built

- Successful beamtime with e^- beam at BTF, Frascati
- 5.4% at 100 MeV energy resolution
- Timing resolution < 150 ps



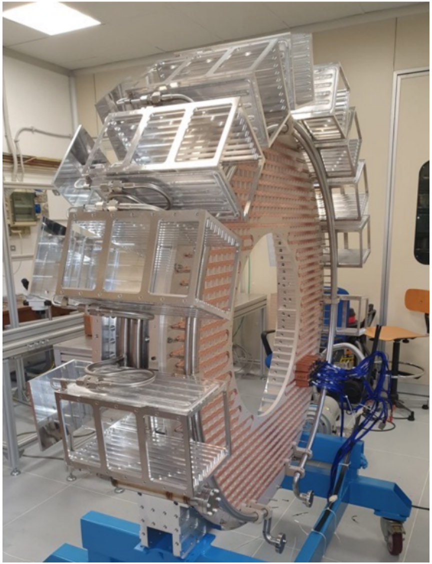
Calorimeter status

- Production of CsI crystals finished
- All SiPMs are tested
- FEE boards delivered, undergoing quality control

Mechanical integration tests:

- Upstream disk
- 2 FEE/Back plates
- 10 electronics crates and manifolds

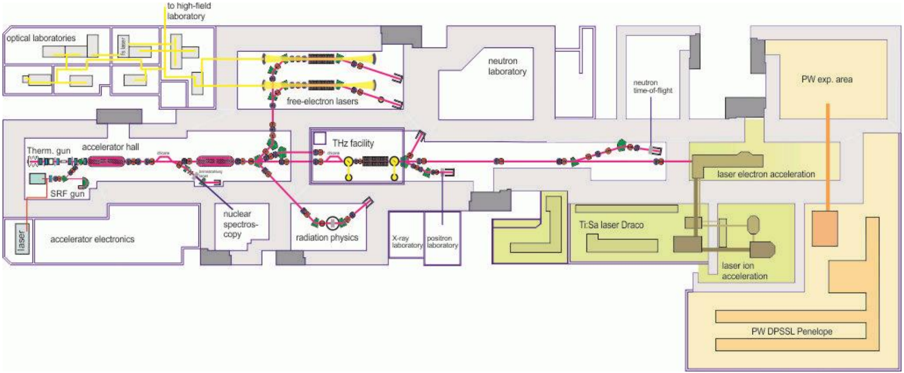
Source system DT generator delivered to Fermilab



Mu2e@HZDR: The ELBE radiation source

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

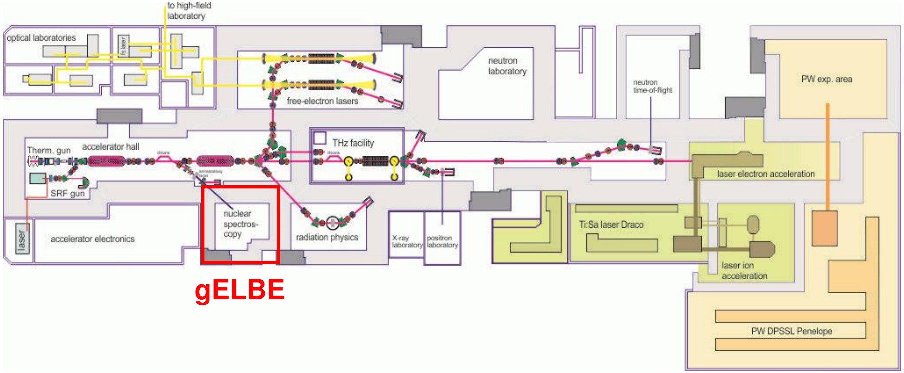
- $E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t <$ 1 μs



Mu2e@HZDR: The ELBE radiation source

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

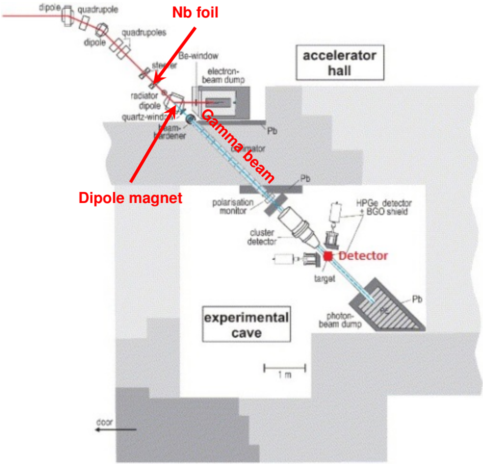
- $E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t <$ 1 μs



gELBE: Bremsstrahlung gamma beam facility (detector design for STM and calorimeter board testing)

Studying HPGe & $LaBr_3$ detector response at gELBE

gELBE utilizes bremsstrahlung production from an electron beam impinging on niobium radiator foils. A dipole magnet sweeps away charged particles in the beam.



HZDR

Studying HPGe & $LaBr_3$ detector response at gELBE

Use of gELBE's pulsed bremsstrahlung γ-beam with max. energy of 15 MeV.

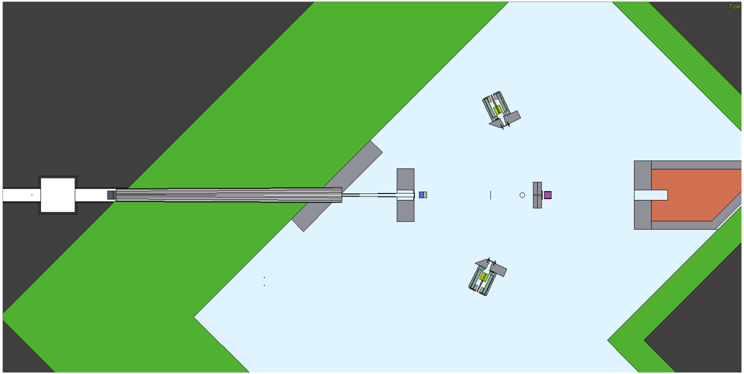
- gELBE pulse separation of 1.23µs or 2.46µs close to Mu2e's 1.7µs proton pulse separation
- 150kcps of gamma rates expected for Mu2e Stopping-Target Monitor detectors during nominal beam pulse
  - high average γ energy ($\sim$ 5 MeV)
  - high beam pulse occupancy ($\sim$ 20%)
  - large beam intensity fluctuations might occur (up to a factor of 6)
- First beamtime in 2017:
  - Measure HPGe detector performance in the gELBE beam (energy resolution, radiation damage,...)
  - Understand best beam and detector geometry and position (including absorbers)
  - HZDR provided radiation transport simulations using the FLUKA code to estimate γ energy spectrum, energy deposit in crystal etc.
- Second beamtime in September 2021 to test $LaBr_3$ detector performance
  - running in “streaming” and “veto” mode to test detector response to beam fluctuations (up to 800kcps)
- Third beamtime scheduled end of April 2022
  - test DAQ chain for both the HPGe and $LaBr_3$ detector

HZDR

Studying HPGe & $LaBr_3$ detector response at gELBE

Beamtime simulations with FLUKA:

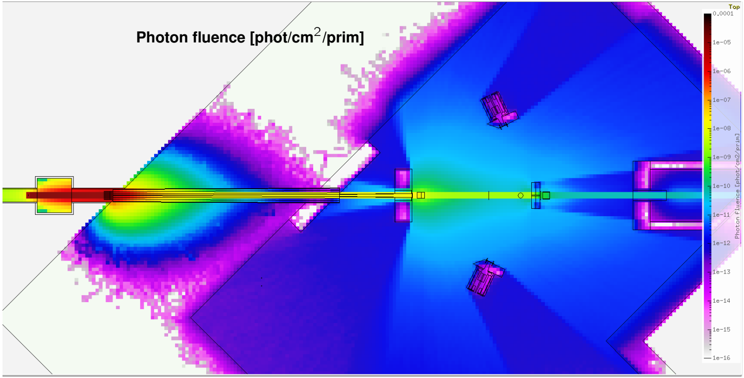
- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it to detector position
- Detector behind lead wall with $1cm^2$ collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



Studying HPGe & $LaBr_3$ detector response at gELBE

Beamtime simulations with FLUKA:

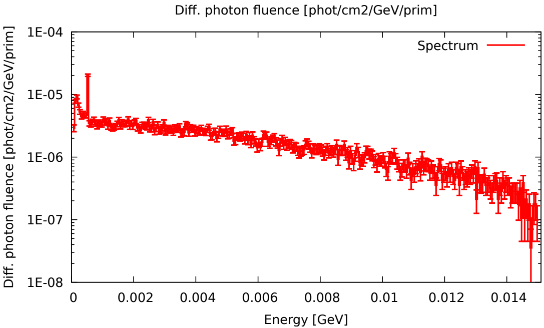
- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it till detector position
- Detector behind lead wall with $1cm^2$ collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



Studying HPGe & $LaBr_3$ detector response at gELBE

Beamtime simulations with FLUKA:

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



Testing the $LaBr_3$ detector at the gELBE beamline

The goal of the beamtime was to test whether the $LaBr_3$ detector system can deal with the rate fluctuations anticipated at the Mu2e experiment.

Detector was shipped from Purdue University to Dresden and setup by the HZDR experimental team. Purdue colleagues were connected remotely via video link during the beamtime.

Testing the $LaBr_3$ detector at the gELBE beamline

The goal of the beamtime was to test whether the $LaBr_3$ detector system can deal with the rate fluctuations anticipated at the Mu2e experiment.

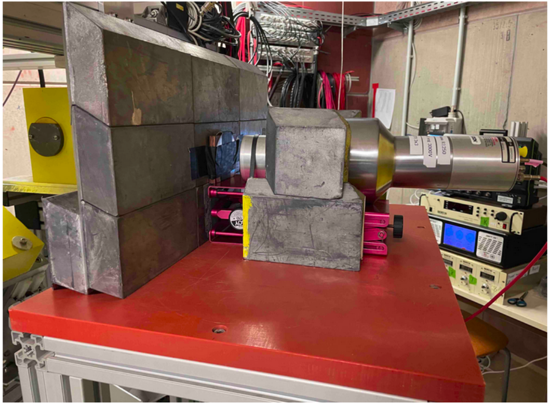
Detector was shipped from Purdue University to Dresden and setup by the HZDR experimental team. Purdue colleagues were connected remotely via video link during the beamtime.

HZDR

Testing the $LaBr_3$ detector at the gELBE beamline

The goal of the beamtime was to test whether the $LaBr_3$ detector system can deal with the rate fluctuations anticipated at the Mu2e experiment.

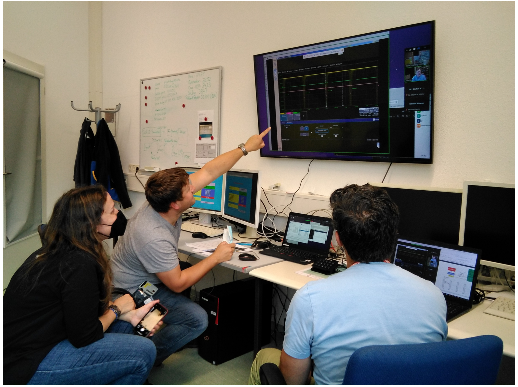
Detector was shipped from Purdue University to Dresden and setup by the HZDR experimental team. Purdue colleagues were connected remotely via video link during the beamtime.



Testing the $LaBr_3$ detector at the gELBE beamline

The goal of the beamtime was to test whether the $LaBr_3$ detector system can deal with the rate fluctuations anticipated at the Mu2e experiment.

Detector was shipped from Purdue University to Dresden and setup by the HZDR experimental team. Purdue colleagues were connected remotely via video link during the beamtime.



Testing the $LaBr_3$ detector at the gELBE beamline

A calibration source including Y-88 line at 1836 keV was used to mimick the muon capture on Aluminum emission at 1809 keV.

→ determine energy resolution for 1836 keV line over Bremsstrahlung spectrum at increasing levels of **gELBE** electron current

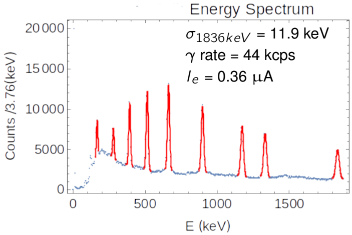
Streaming mode: Take data at 406 kHz and 813 kHz pulse frequency at 500 MHz sampling with increasing electron current (for 813 kHz, overlay a 0.2s-on/4s-off window to protect PM tube)

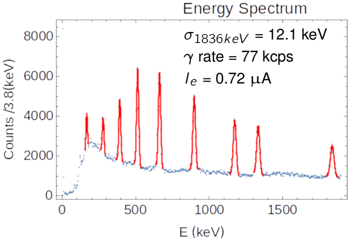
Veto mode: Take data at 813 kHz and 1625 kHz pulse frequency at 500 MHz sampling with increasing electron current, overlay a 0.2s-on/4s-off window and veto the Bremsstrahlung flash pulses to bring the "flash" background down

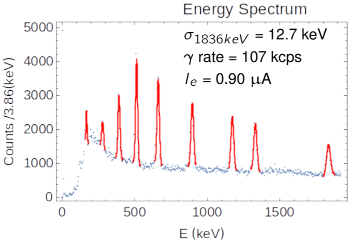
"Nominal" expected **Mu2e** conditions were found at a pulse frequency of 813 kHz and 1.1 uA electron current:
150 kcps with 3.8 MeV average photon energy.

Testing the $LaBr_3$ detector at the gELBE beamline: Prel. results

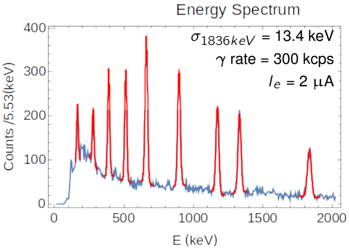
Data taken in streaming mode shows stable energy resolution (406 kHz pulse frequency):





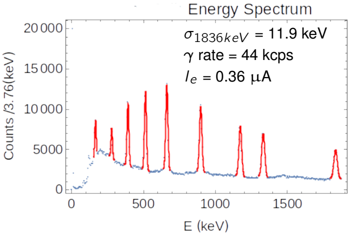


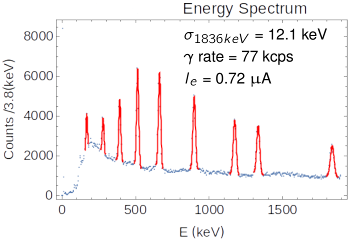
Detector system can handle date taken at twice the expected photon rate (813 kHz pulse frequency):

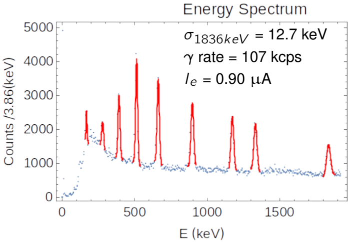


Testing the $LaBr_3$ detector at the gELBE beamline: Prel. results

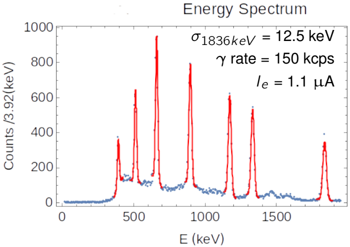
Data taken in streaming mode shows stable energy resolution (406 kHz pulse frequency):





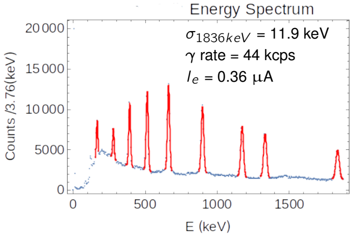


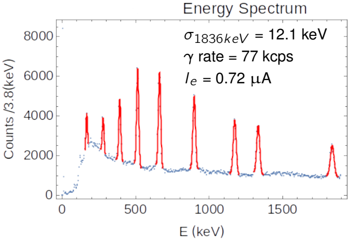
Data taken in veto mode shows that detector system can handle the rates using the pulse veto to suppress flash background (813 kHz pulse frequency):

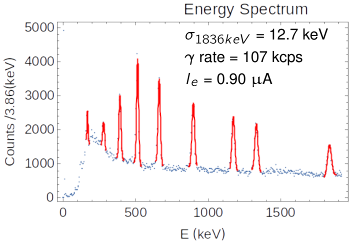


Testing the $LaBr_3$ detector at the gELBE beamline: Prel. results

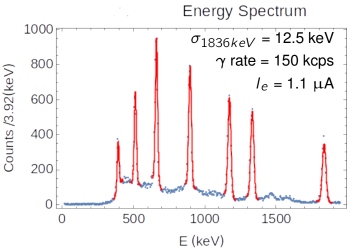
Data taken in streaming mode shows stable energy resolution (406 kHz pulse frequency):







Data taken in veto mode shows that detector system can handle the rates using the pulse veto to suppress flash background (813 kHz pulse frequency):

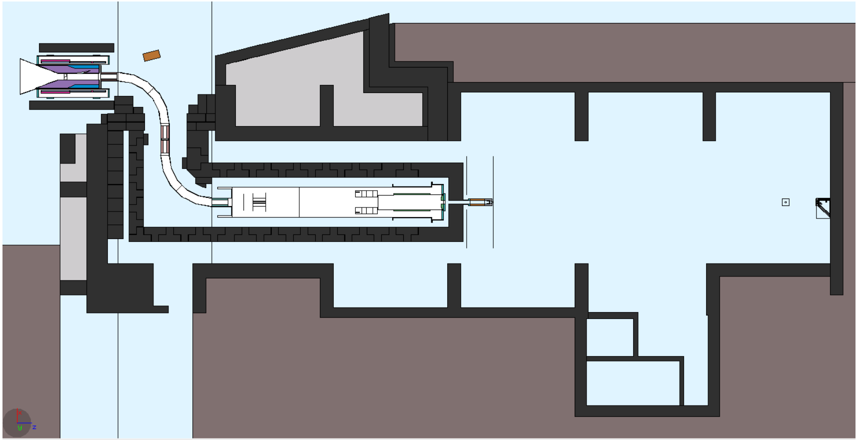


The origin of a time-dependent gain drift in the runs with 0.2s-on/4s-off structure still to be understood (for $t > 5$ ms).

Mu2e MC simulations with FLUKA

The Mu2e offline simulation geometry has been (partly) ported to FLUKA:

- Simulate production and stopping target rates and perform shielding assessment

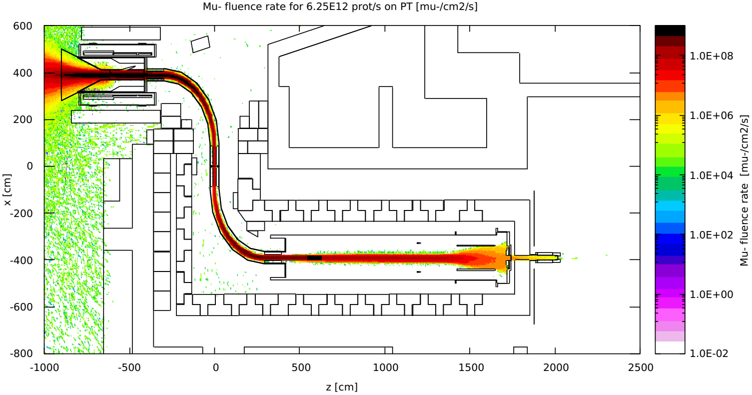


Mitglied der Helmholtz-Gemeinschaft
S. E. Müller | HZDR | https//www.hzdr.de

Mu2e MC simulations with FLUKA

The Mu2e offline simulation geometry has been (partly) ported to FLUKA:

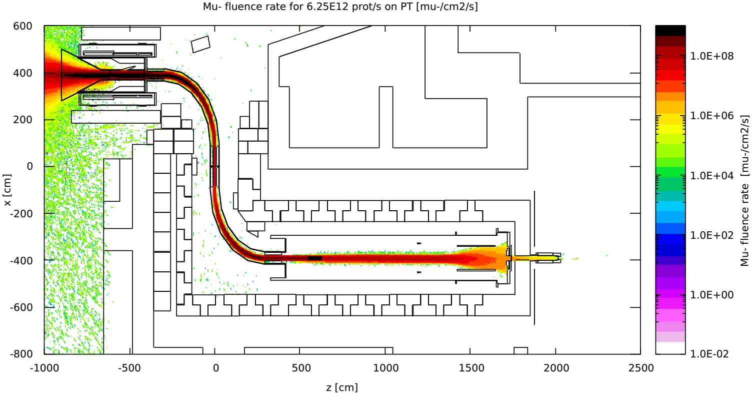
- Importing Mu2e magnetic fieldmaps allows to transport charged particles through the solenoid systems



Mu2e MC simulations with FLUKA

The Mu2e offline simulation geometry has been (partly) ported to FLUKA:

- Importing Mu2e magnetic fieldmaps allows to transport charged particles through the solenoid systems



We have also started to compare results with MCNP6 simulation code

Development of FPGA firmware using HLS

Idea is to analyze the detector data directly in hardware on FPGA.

- Use High-Level-Synthesis (HLS) to port analysis algorithms to FPGA
- Integrate into designated STM Read-Out-Controller FPGA firmware

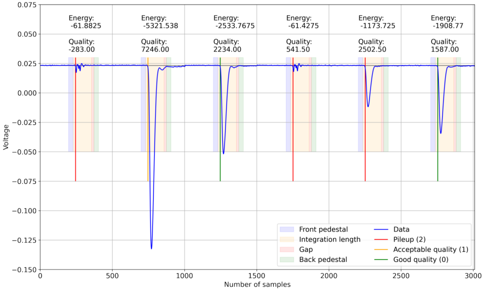
Development of FPGA firmware using HLS

Idea is to analyze the detector data directly in hardware on FPGA.

- Use High-Level-Synthesis (HLS) to port analysis algorithms to FPGA
- Integrate into designated STM Read-Out-Controller FPGA firmware

Pulse-Integration with quality analysis to identify pile-up for $LaBr_3$-detector data acquisition:

- takes up to 400 MegaSamples/s as input
- outputs for each pulse trigger time, energy and pile-up flag



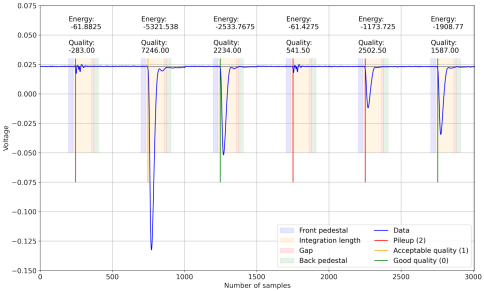
Development of FPGA firmware using HLS

Idea is to analyze the detector data directly in hardware on FPGA.

- Use High-Level-Synthesis (HLS) to port analysis algorithms to FPGA
- Integrate into designated STM Read-Out-Controller FPGA firmware

Pulse-Integration with quality analysis to identify pile-up for $LaBr_3$-detector data acquisition:

- takes up to 400 MegaSamples/s as input
- outputs for each pulse trigger time, energy and pile-up flag



Further algorithms studied include a zero-suppression & cutout algorithm and a Moving-Window-Deconvolution algorithm for the analysis of HPGe data.

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: 6×10^{-17} (90% CL)
- Detector construction advancing (despite COVID)
- Solenoid construction in good shape (PS units fabricated, TS units thermal shield assembly, DS units fabrication started)
- Beamtimes at HZDR's ELBE radiation source for tests of STM detector design
  - Test of $LaBr_3$ detector's response to anticipated Mu2e beam fluctuations September 2021
  - Next month's beamtime will concentrate on DAQ chain for HPGe and $LaBr_3$ detectors
- Studies with FLUKA and MCNP6 simulation codes are under way
  - production and stopping target rates
  - shielding assessment
- Development of FPGA firmware using HLS for STM data acquisition
- With a first run of physics dataking starting in 2026, Mu2e will either unambiguously discover CLFV or push the limit on muon $\rightarrow$ electron conversion by four orders of magnitude

HZDR

Mu2e Collaboration

More than 200 scientists from 38 institutions: