The Mu2e experiment at Fermilab

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Helmholtz-Zentrum Dresden-Rossendorf

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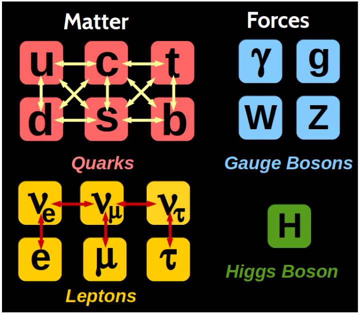
Motivation

The Standard Model of particle physics currently contains:

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



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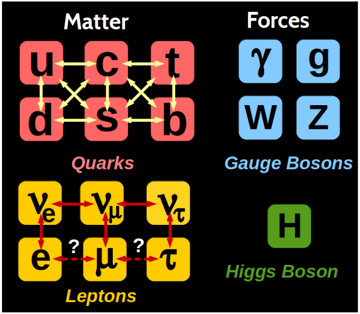
No charged lepton flavor violation (CLFV) observed so far!



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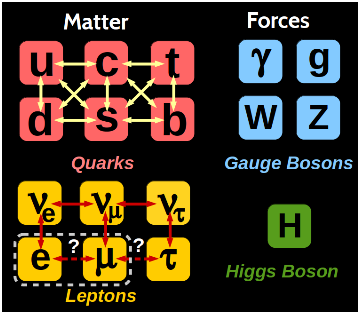


Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \to eN$) with a projected

upper limit of 6×10^{-17} (90% CL)

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

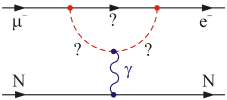
Model independent Lagrangian:

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

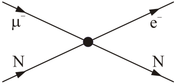
Λ: effective mass scale of New Physics

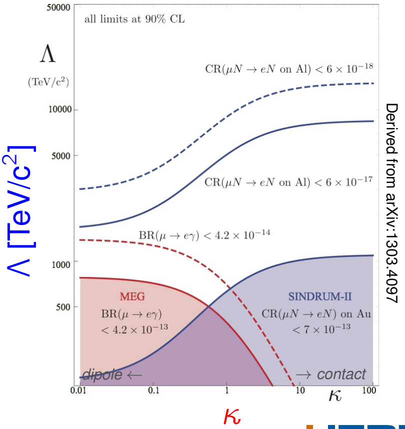
κ: relative contribution of contact term

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



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





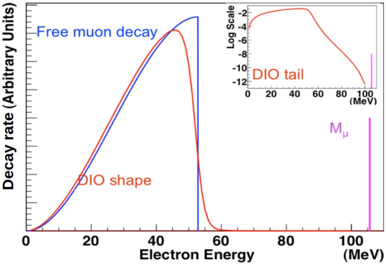
Mu2e will probe $\Lambda \sim O(10^3\text{ -}10^4)$ TeV/c^2

The Mu2e experiment

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

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

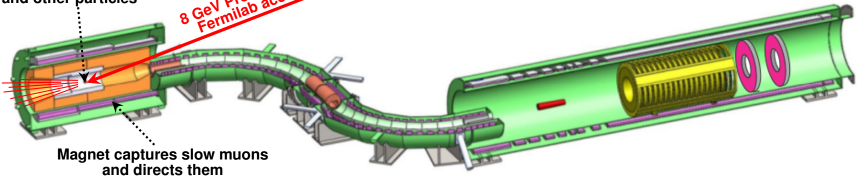
- about 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons dies around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives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



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

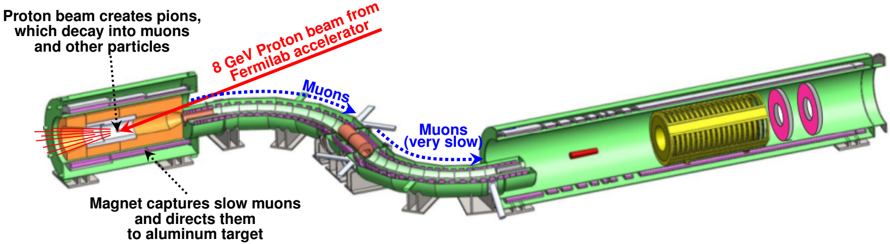
HZDR

The Mu2e experiment



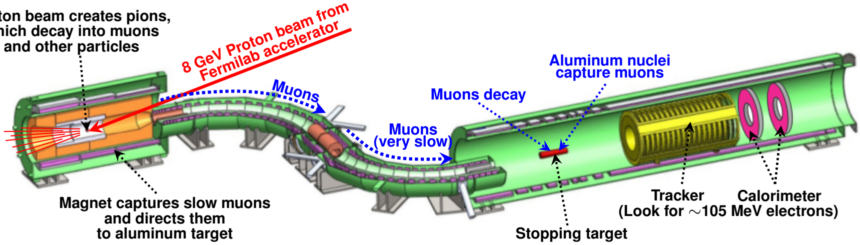
- Muons are obtained from 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1695ns
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



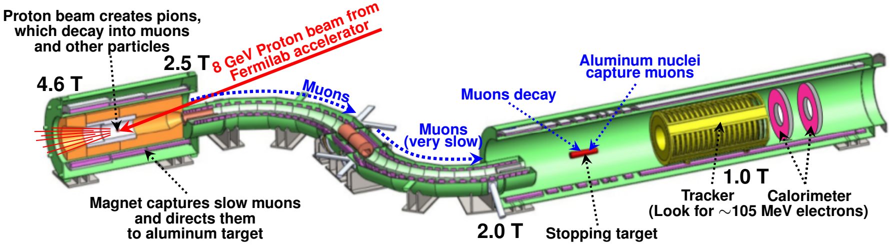
- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

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

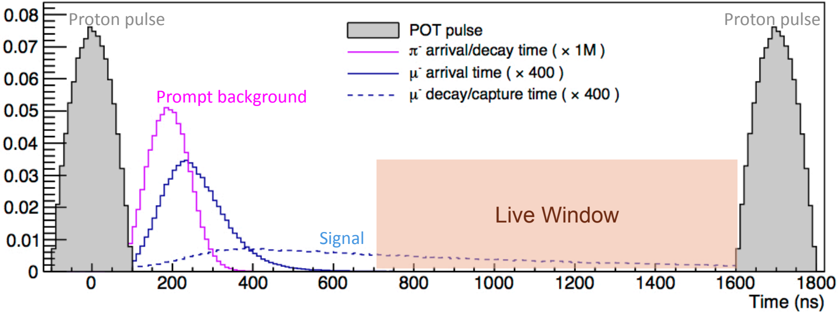
The Mu2e experiment



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

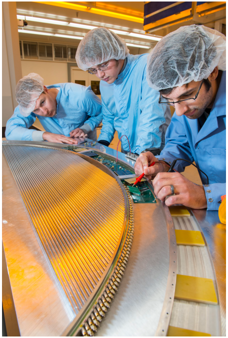
The Mu2e experiment

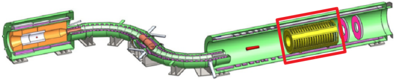
Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695ns peak-to-peak):



- 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) $\leq 10^{-10}$

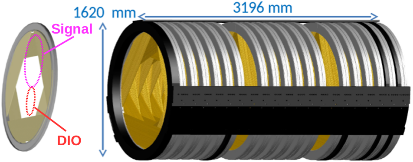
Straw drift tube tracker



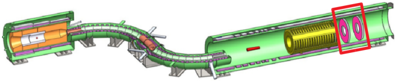


- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_{\rm p} < 180$ keV/c

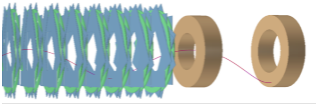
- inner 38 cm not instrumented
  $\rightarrow$ “blind” to low-momenta DIO electrons



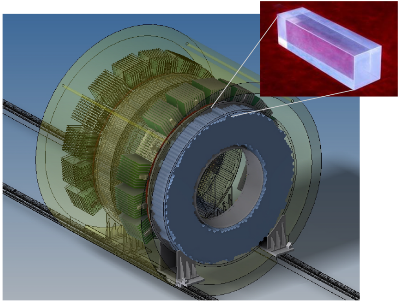
Calorimeter



- composed of two rings separated by half a wavelength of signal electron trajectory helix

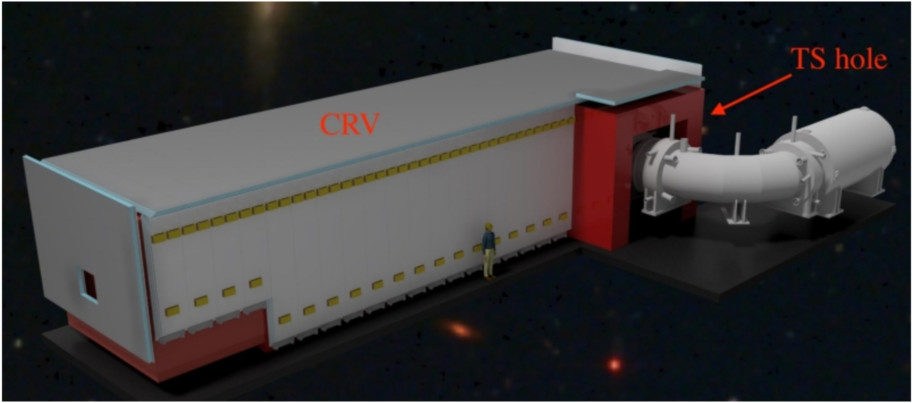


- each ring composed of ∼700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent trigger information
- particle ID



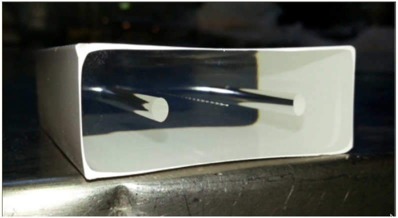
The cosmic ray veto detector

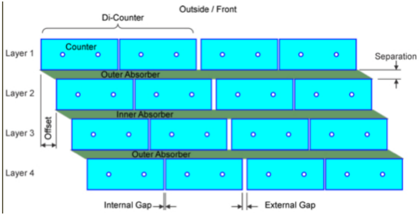
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



The cosmic ray veto detector

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

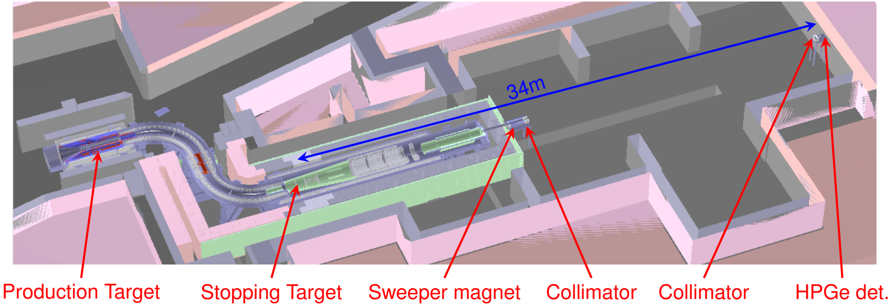




- 4 overlapping layers of scintillator bars (5 $\times$ 2 $\times \sim$ 450 cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

The Stopping-Target Monitor

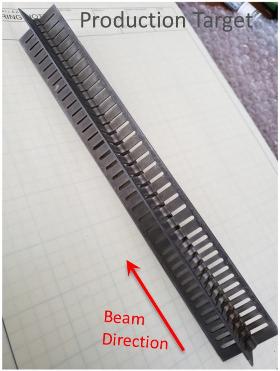
High-purity Germanium (HPGe) detector to determine overall muon-capture rate on Al to the level of 10%



- 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
- Recently it was decided to accompany the HPGe detector with a LaBr detector (worse energy resolution, but can take higher rates)

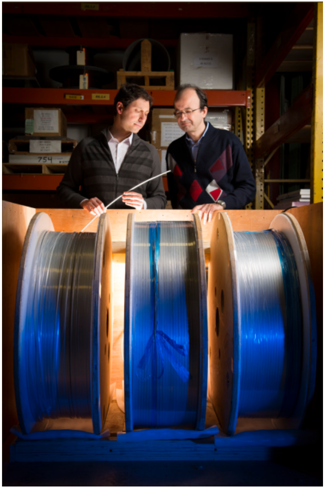
Production Target and HRS

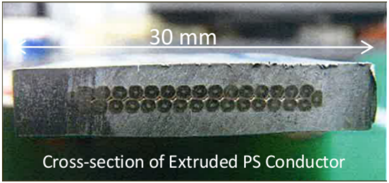
The production target and the bronze heat and radiation shield (HRS) have been manufactured:

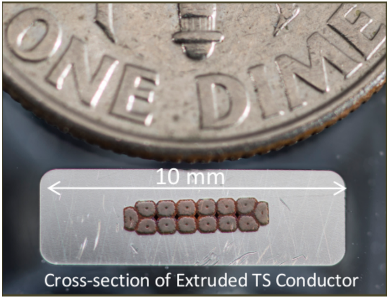


Magnet production

In total 75 km of conductor:







- Conductor production completed

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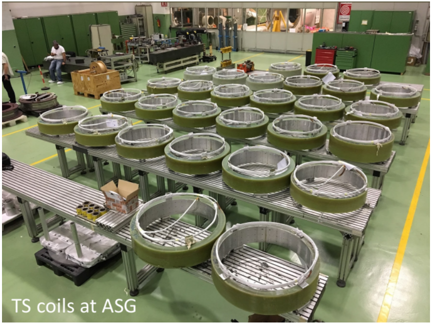
Magnet production

Transport solenoid production at ASG (Genova) and Fermilab:



- All TS units now at Fermilab and being tested (almost done)
- Upstream TS units assembled
- Upstream TS thermal shield delivered to Fermilab

Magnet production

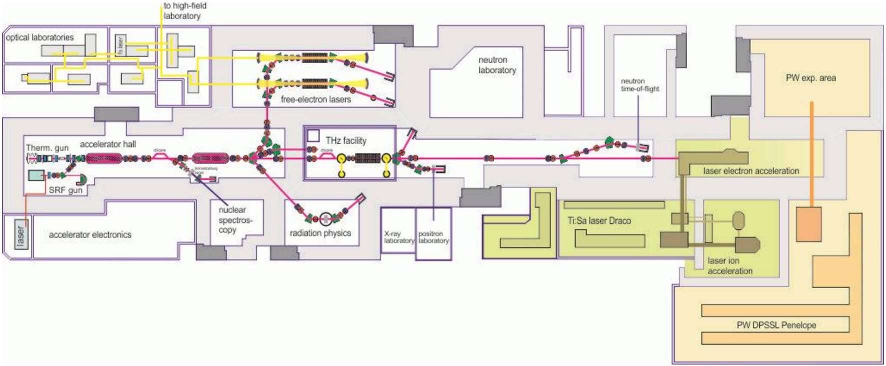
Production and Detector Solenoid production at General Atomics (Tupelo):

- Winding of PS coil:

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



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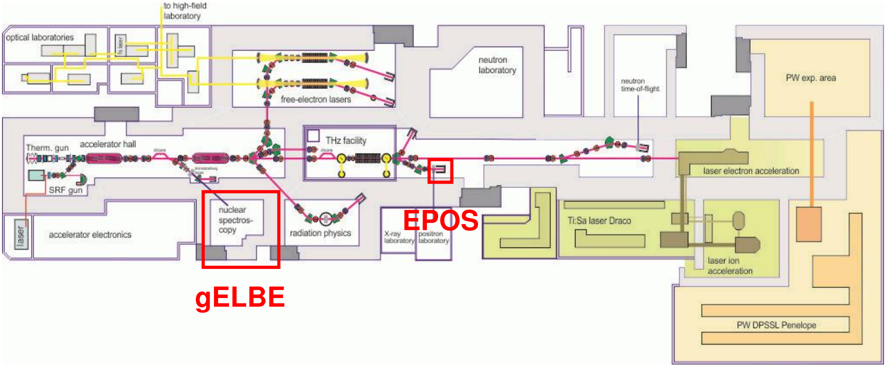

EPOS: Positron (+ Photoneutron) source (Radiation hardness tests)
gELBE: Gamma beam facility (HPGe detector design for STM and calorimeter board testing)

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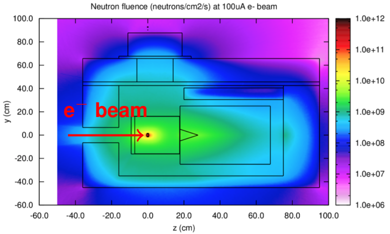
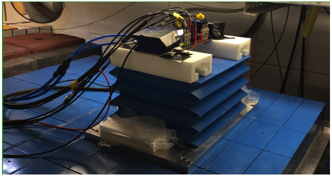
Testing radiation hardness of SiPMs at EPOS

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
- Routinely parasitic irradiation of SiPMs for quality assurance





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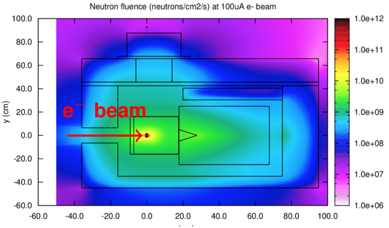
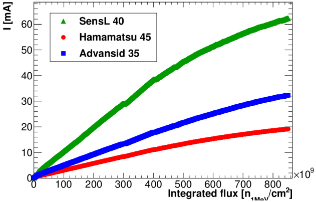
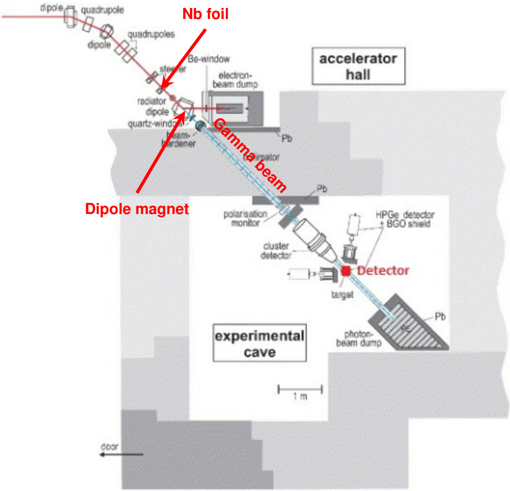




Cordelli et al.
JINST 13 (2018)
T003005

Studying HPGe detector response at gELBE

The gELBE bremsstrahlung facility was used to study HPGe detector performance. gELBE utilizes Bremsstrahlung production from an electron beam impinging on niobium radiator foils.



Studying HPGe detector response at gELBE

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

- gELBE pulse separation of 2.5μs close to Mu2e's 1.7μs proton pulse separation
- 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%)
- 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.
- Next beamtime scheduled in august 2021 to test DAQ chain for both HPGe and LaBr detectors
  - Analysis algorithms ported to FPGA firmware using HLS by HZDR

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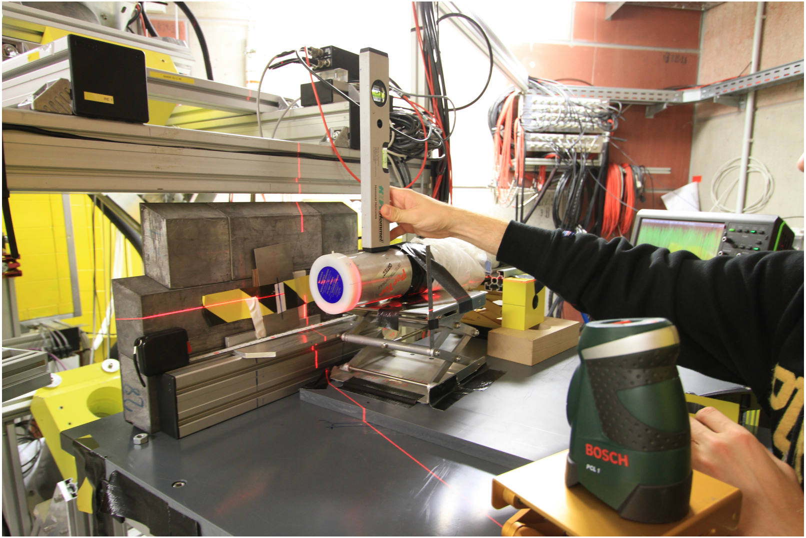
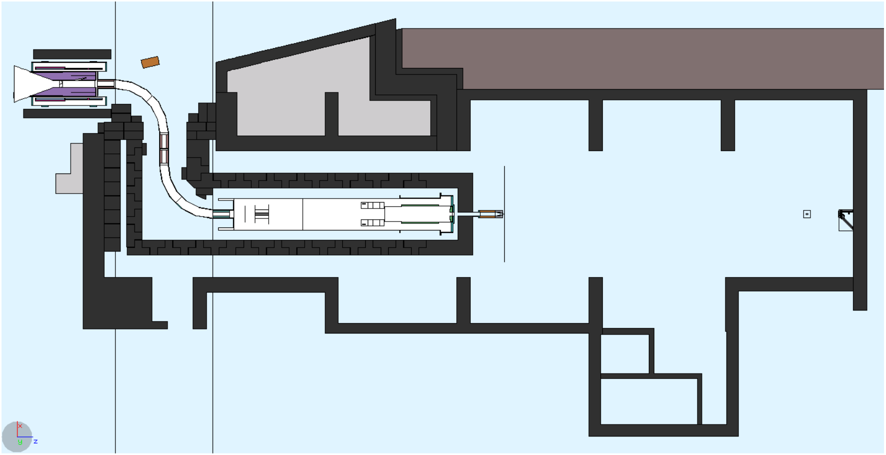


Mu2e MC simulations with FLUKA

The Mu2e offline simulation geometry has been ported to FLUKA:



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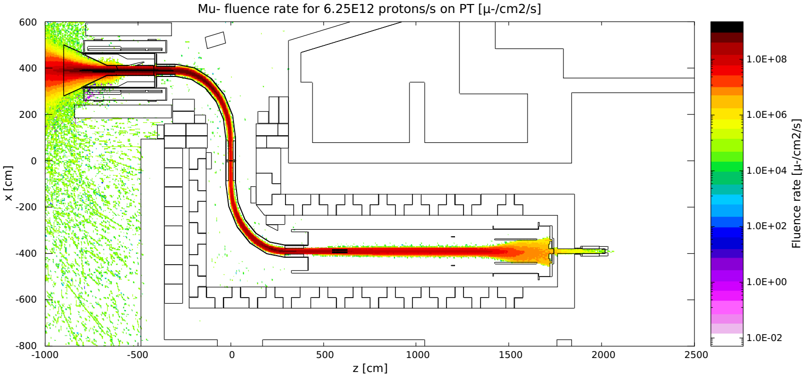
- Importing Mu2e magnetic fieldmaps allows to transport charged particles through the solenoid systems



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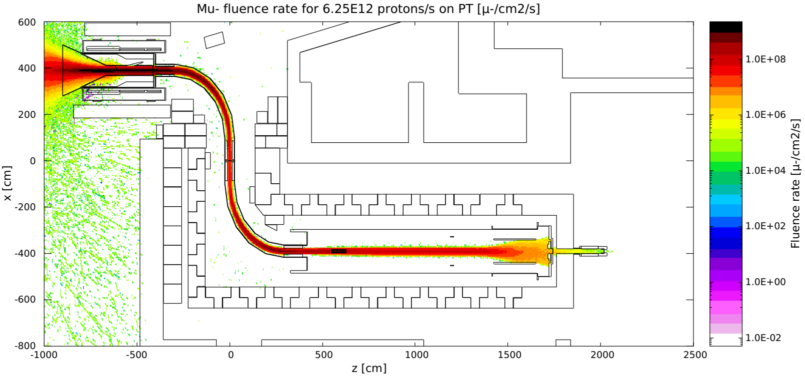

We have also started to compare results with MCNP6 simulation code

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 ongoing (TS units ready)
- HZDR contributes with beamtimes at the ELBE radiation source for tests of radiation hardness of calorimeter components and detector design for STM
- In addition studies with FLUKA and MCNP6 simulation codes are under way
  - production and stopping target rates
  - shielding assessment
- With physics datataking starting in 2023*, Mu2e will either unambiguously discover CLFV or push the limit on muon$\rightarrow$electron conversion by four orders of magnitude

* impact of COVID delays currently discussed

HZDR

Mu2e Collaboration

More than 200 scientists from 38 institutions: