DPG Frühjahrstagung – Gießen, 14 March 2024

The search for Charged Lepton Flavour Violation with the Mu2e experiment at Fermilab

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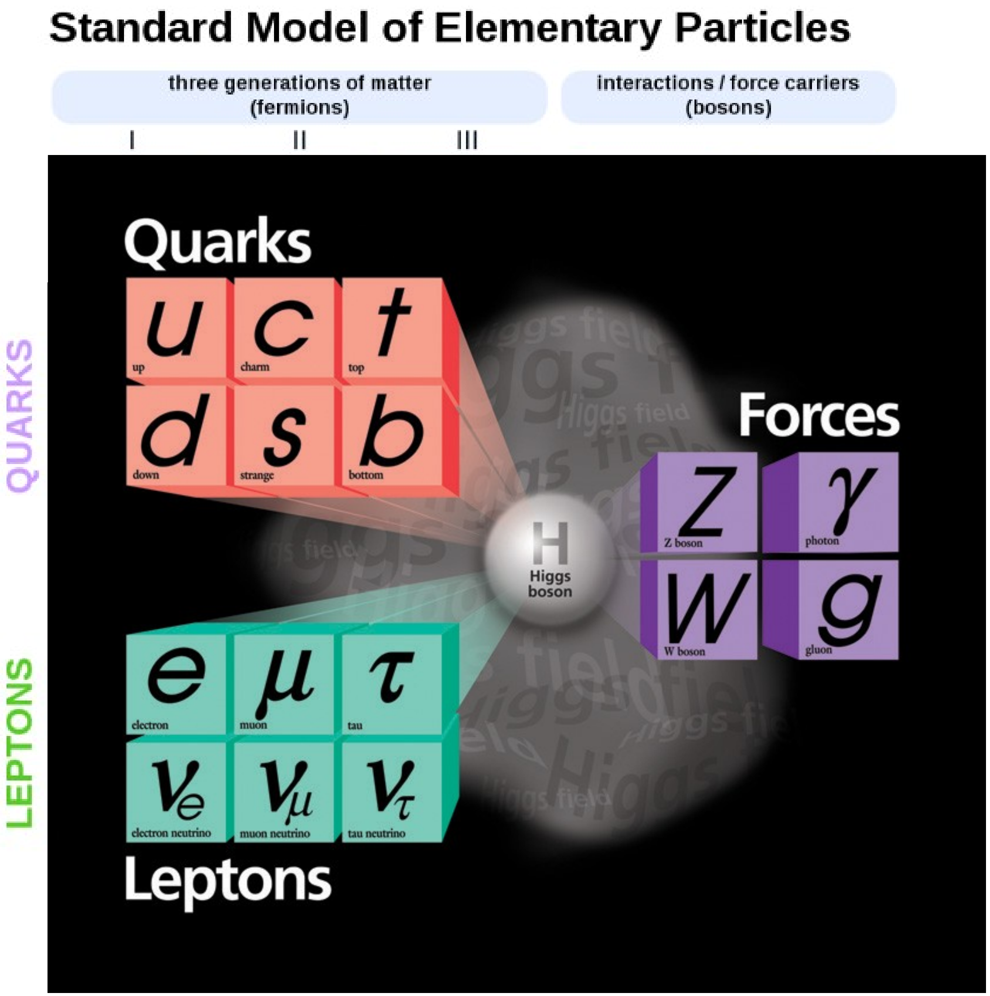
for the Mu2e Collaboration

Motivation of the experiment



The current Standard Model of particle physics contains:

- Quark Mixing
- Neutrino oscillations
- Transitions between charged and neutral leptons with same flavor

No flavor violation of charged leptons has been observed so far!

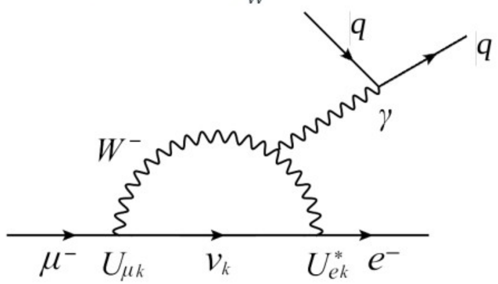
Charged Lepton Flavor Violation (CLFV)

The Standard Model with neutrino masses (νSM) says its unobservably rare...

...but many Beyond Standard Model (BSM) theories predict enhanced rates of CLFV

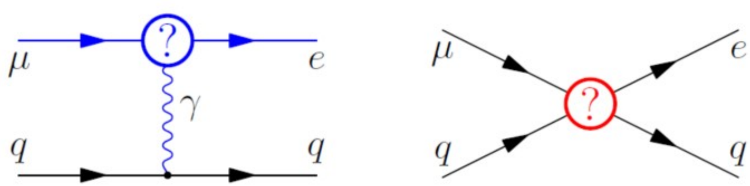
νSM Prediction

$$R_{\mu\to e} \propto \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 < 10^{-52}$$



BSM Predictions

$$R_{\mu\to e} \sim 10^{-17} - 10^{-15}$$



Mu2e will search for neutrino-less Muon-to-Electron conversion in the Coulomb field of a nucleus: ($\mu^- + Al \rightarrow e^- + Al$) with a projected

upper limit of 8 x 10^{-17} (90% CL)

Current limit by SINDRUM-II at PSI (on Au): < 7 x 10^{-13} (90% CL)

Aim of the experiment is to reach a single event sensitivity of **3 x 10^{-17}** on the conversion rate

➡ **Unique possibility to test for New Physics**

The Mu2e experiment

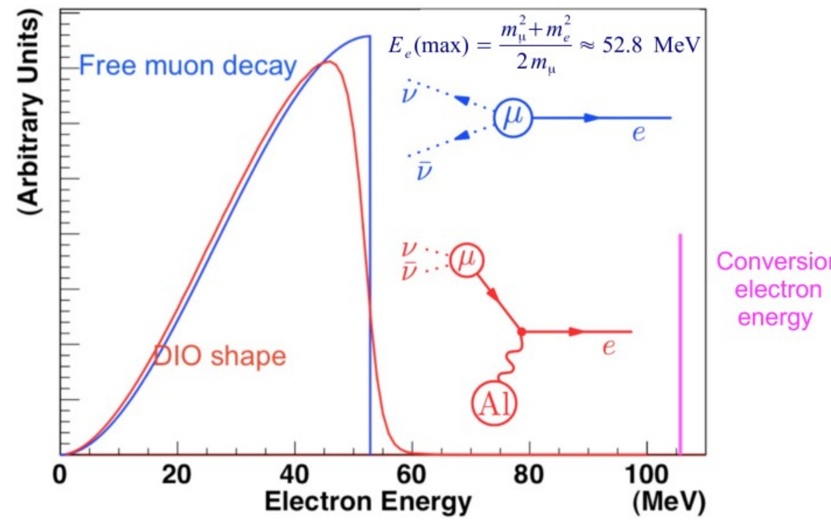
The Mu2e experiment will search for CLFV in the process ($\mu^- + Al \rightarrow e^- + Al$)

Muons stopped in Al have a lifetime of <u>864 ns</u> in the orbital 1s of the Al nucleus

- ~ 60% of stopped muons undergo muon capture reaction (i.e. $\mu^- + {}^{27}Al \rightarrow \nu + {}^{27}Mg$)

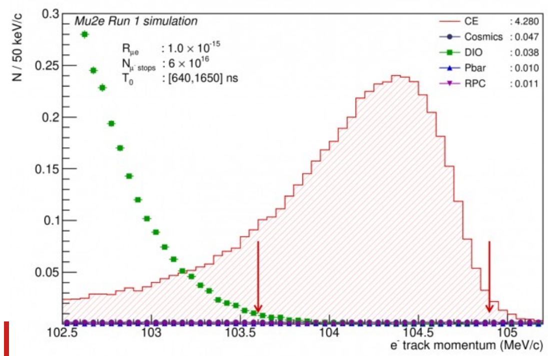
- ~ 40% of muons bound in the muonic Al decay in orbit (DIO) to an electron and two neutrinos:

$$(\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e)$$



Nuclear recoil modifies energy spectrum:

- peak still at ~ 50 MeV, but
- tail extends up to the conversion energy

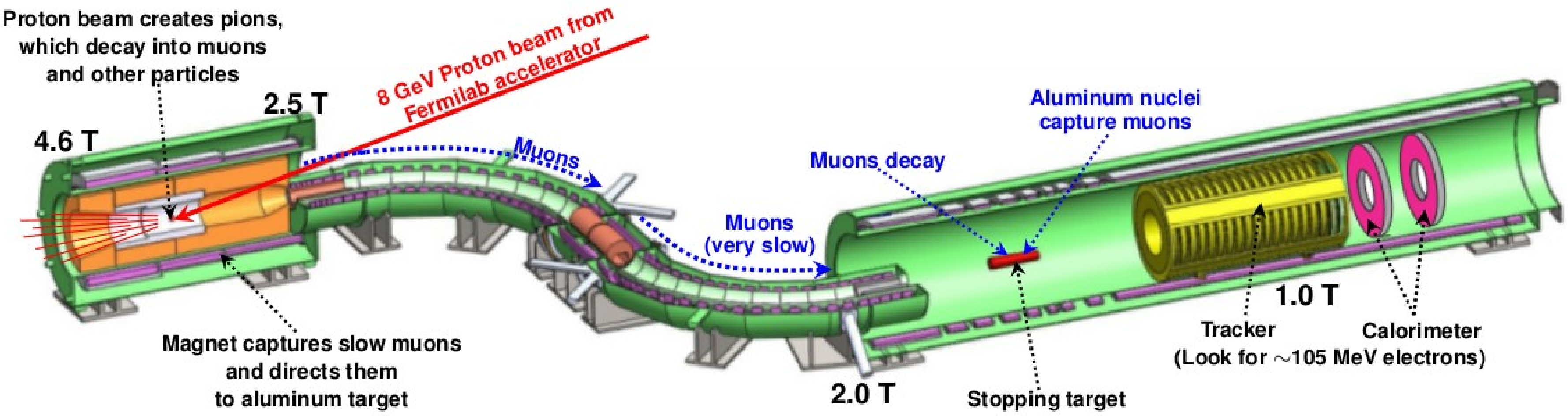


- Signal of CLFV conversion process gives a single monochromatic electron with

$$E_e = 104.973 \text{ MeV} \simeq M_\mu$$

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

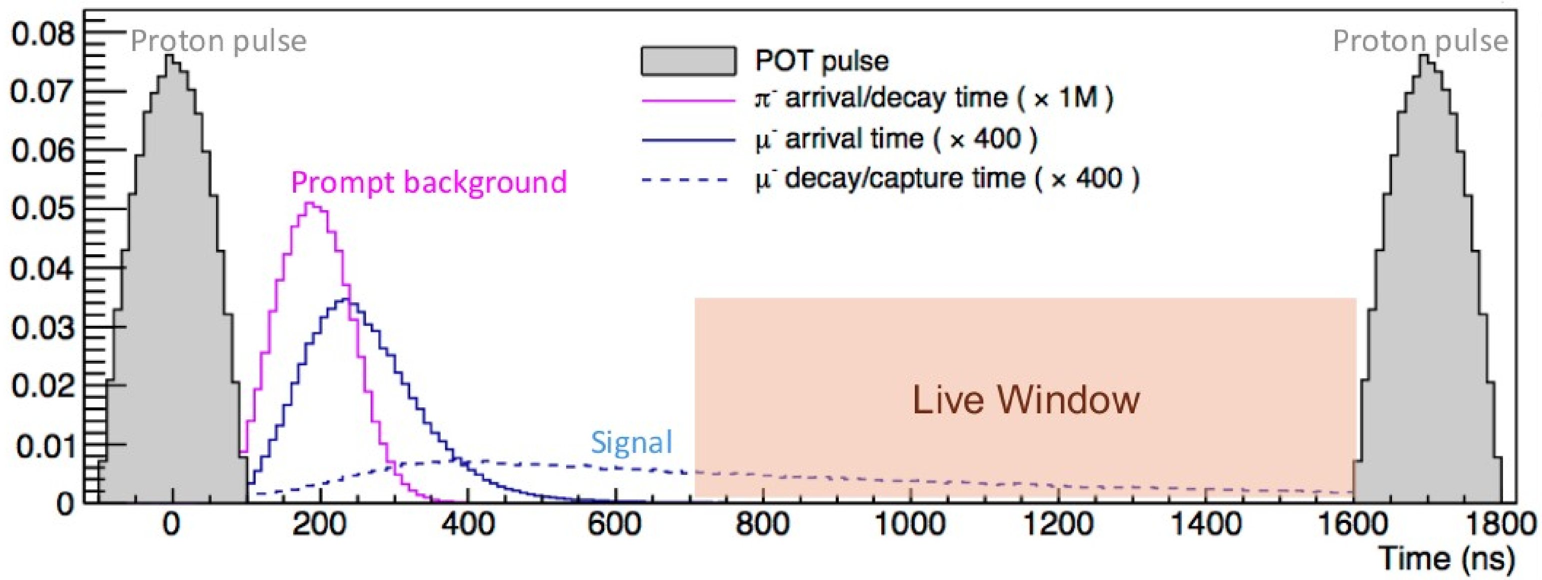
The Mu2e experiment



- The 8 GeV **proton** beam hits tungsten target and produces **pions**
- **Pions** are transported in the s-shaped **Transport Solenoid**, where they decay in **muons**
- **Muons** are stopped on Al target foils in **Detector Solenoid**
- **Detector system** (*Tracker* and *Calorimeter*) search for *104.97 MeV Conversion Electrons*

The Mu2e experiment

Pulsed proton beam allows definition of a "Live Window" for the signal to suppress prompt back-ground (1695 ns 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) $\leq 10^{-10}$

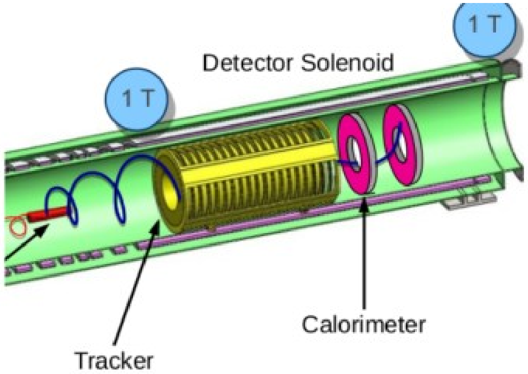
DRESDEN concept HZDR

The Mu2e tracker

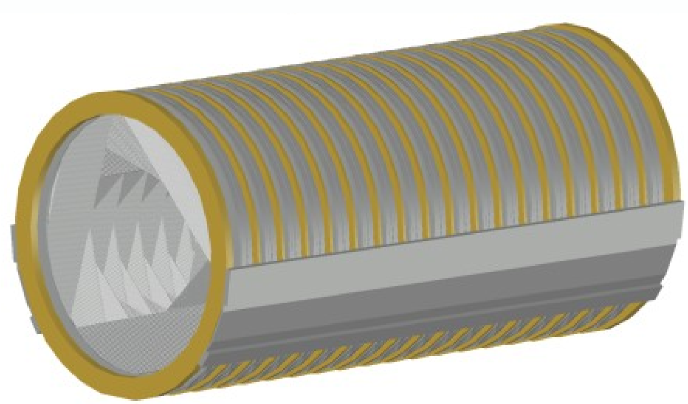
Goal: high-resolution momentum measurement

(< 180 keV/c @ 105 MeV/c)

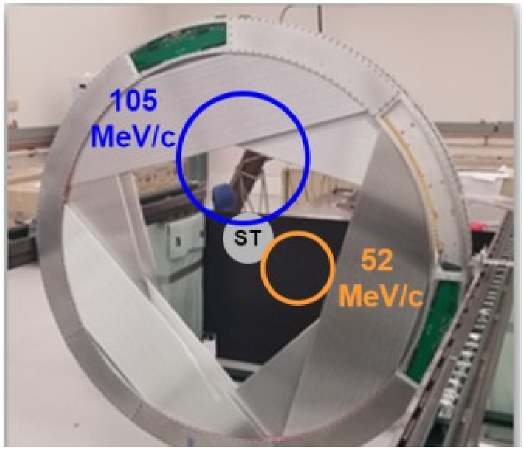
- minimize energy loss by operating in vacuum and using low mass straws
- extra hit position information with high-angle stereo overlaps and readout on both ends of straw
- reduce background hits with a central hole



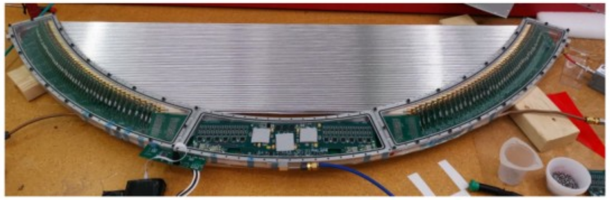
5 mm diameter, 15 μm thick walls



plane with central hole

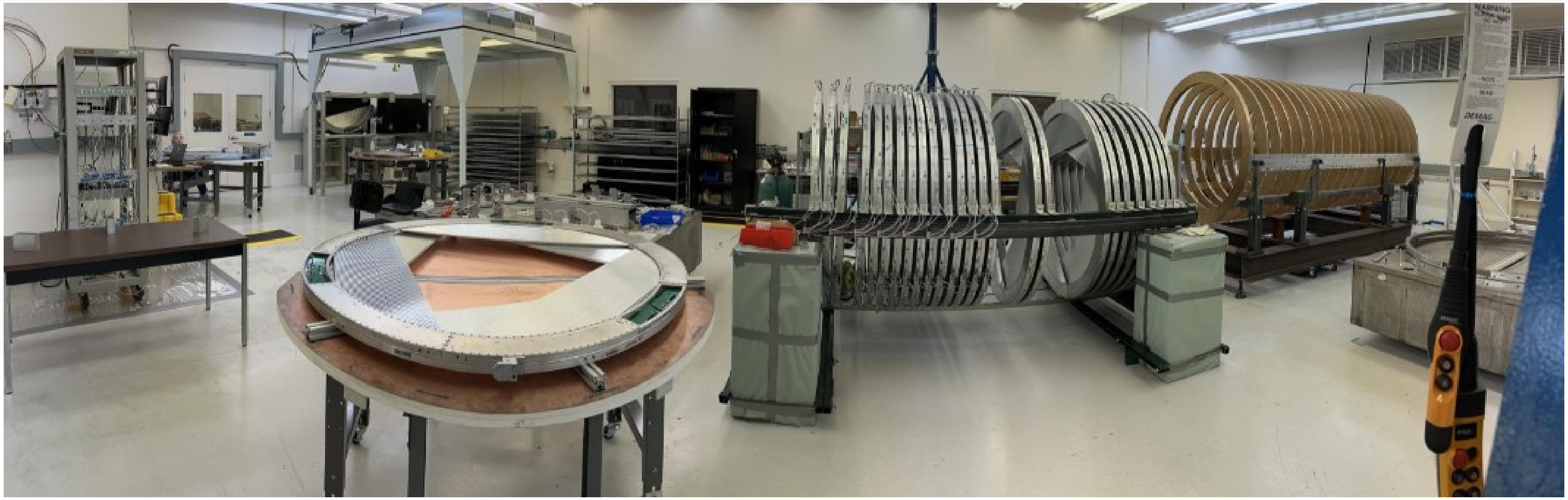


- 96 straws per panel
- 6 panels per plane
- 36 planes
→ ***20736 straws***



1 panel = 96 straws

Status of the Mu2e tracker



Completed:

- All 20736 straws produced
- All 216 panels ready
- 33/36 planes built

On going:

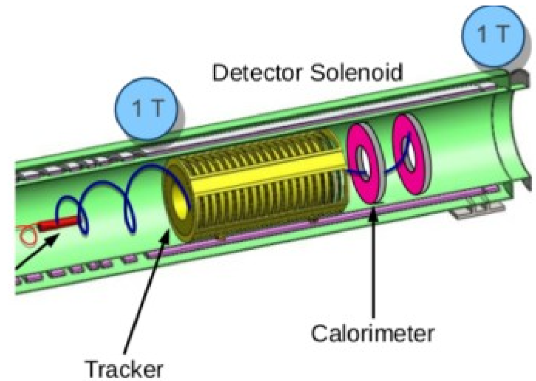
- Assembled Planes under long term leak test
- Electronics installation
- Cooling system (cooling ring) and gas system under construction

Installation of electronics units (August 2024)

The Mu2e calorimeter

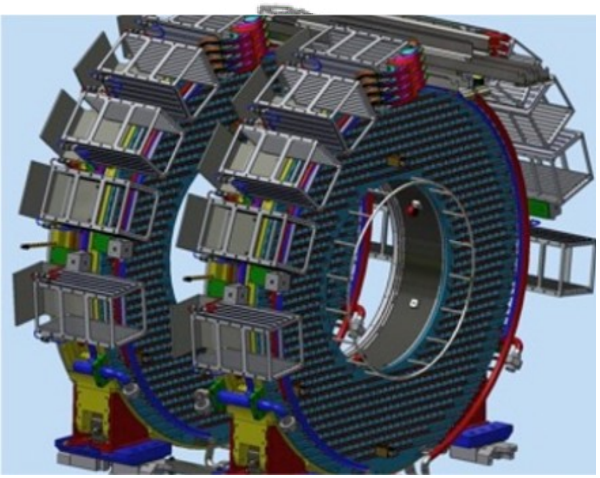
Goal: fast energy measurement

(Time resolution: < 150 ps @ 100 MeV)

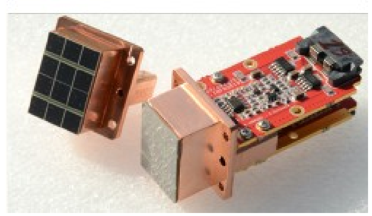


- can be used for the trigger
- combine with momentum measurement for e/μ separation
- energy clusters can also be used to seed the track fit

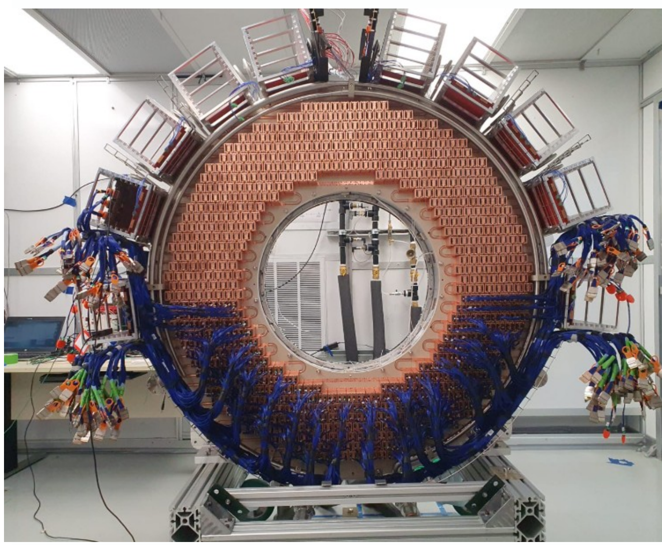
Two disks, each 674 crystals



undoped CsI crystals
(20 x 3.4 x 3.4 cm^3)

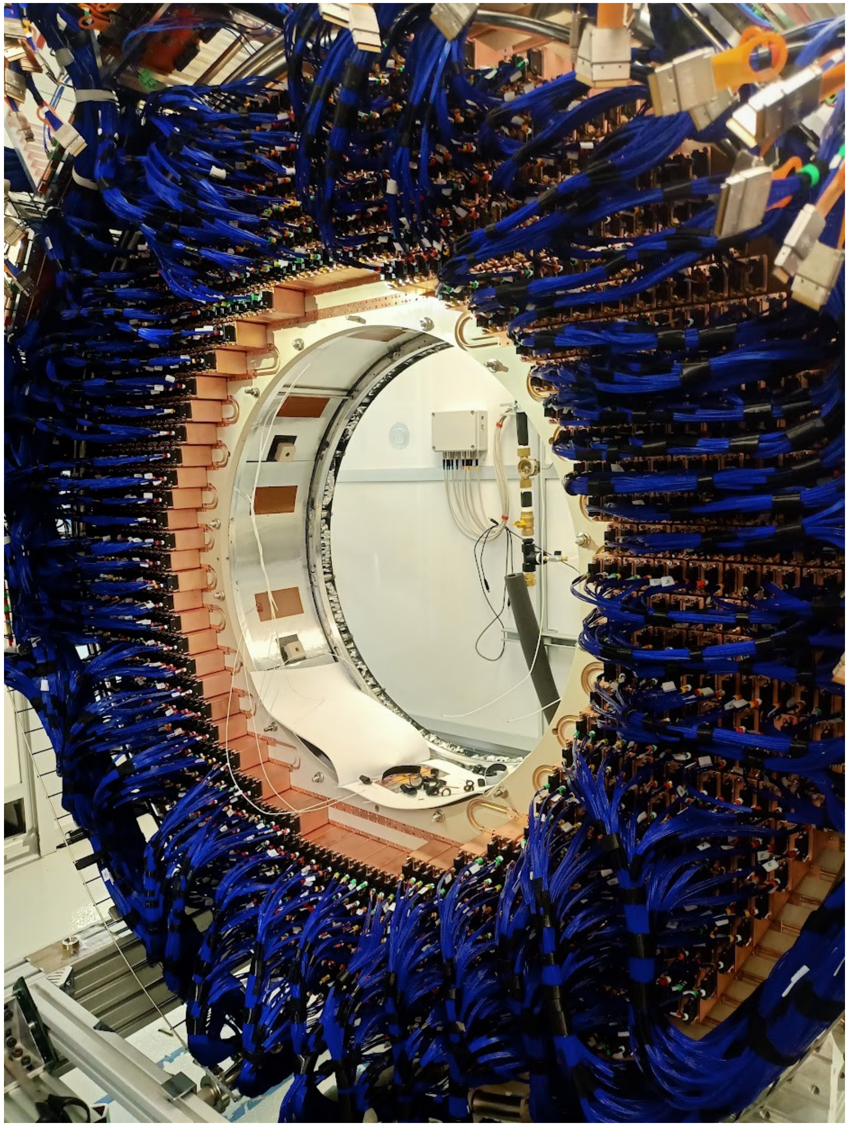


SiPM readout with FEE boards

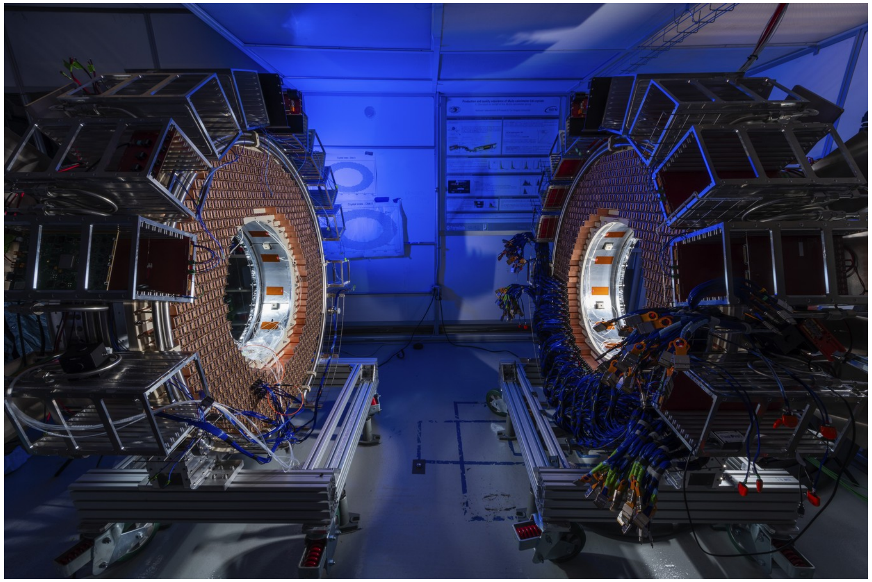


First disk status in December 2023

Status of the Mu2e calorimeter



March 2024

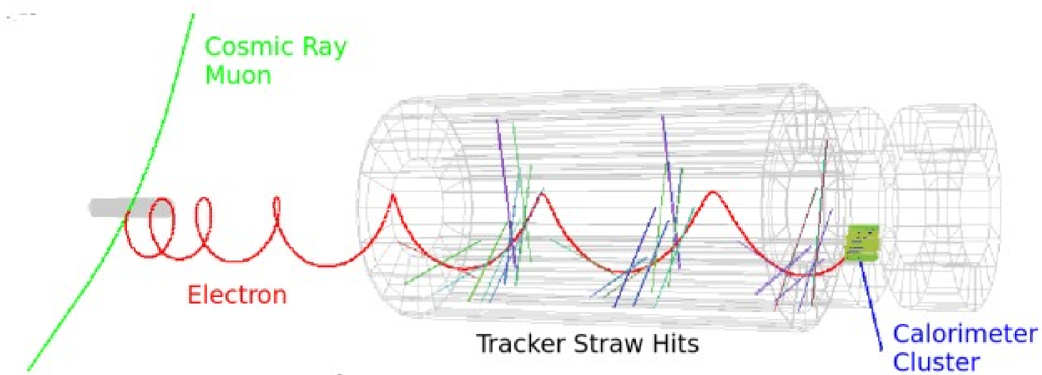


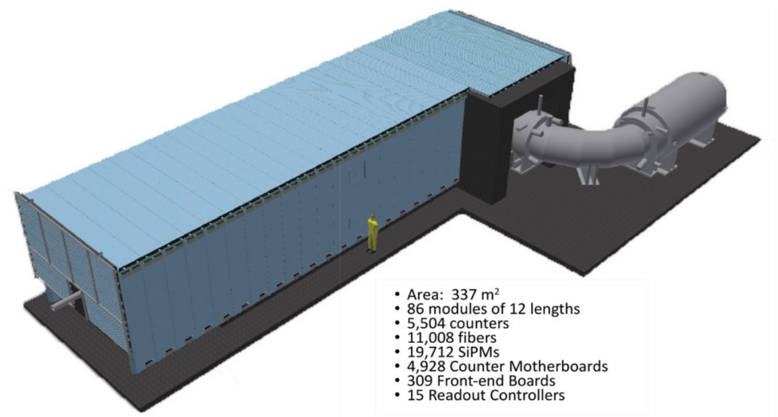
- Two discs completed with all CsI crystals and SiPMs installed
- FEE units installed
- 1 disk cabled (HV/LV distribution completed), cabling in progress for the second one
- Electronics (DAQ boards) under test

The Cosmic-Ray veto

A nearly hermetic cosmic ray veto suppresses the background due to the cosmic rays that could hit the Mu2e stopping target and knock out an electron with the conversion energy (this effect would result in **~1 background event per day**).

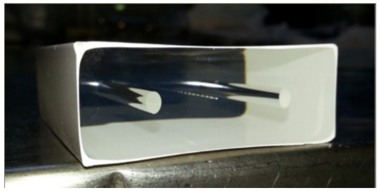
In addition, an electron from a cosmic muon with the conversion energy could be trapped in the field of the TS, propagate in the stopping target region and be reconstructed

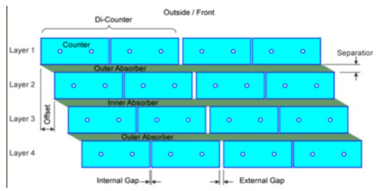




The CRV must be **99.99% efficient**

It covers therefore entire Detector Solenoid and half of the Transport Solenoid





4 overlapping layers of scintillator bars, with 2 wavelength-shifting fibers/bar

Status:

- 81/83 CRV modules produced
- cabling and electronics test on-going
- testing with cosmic rays

Status of the Mu2e hall: Transport Solenoid installation

- Upstream part of TS installed in December 2023
- Downstream part of TS transported to the Mu2e hall on 20 Feb 2024

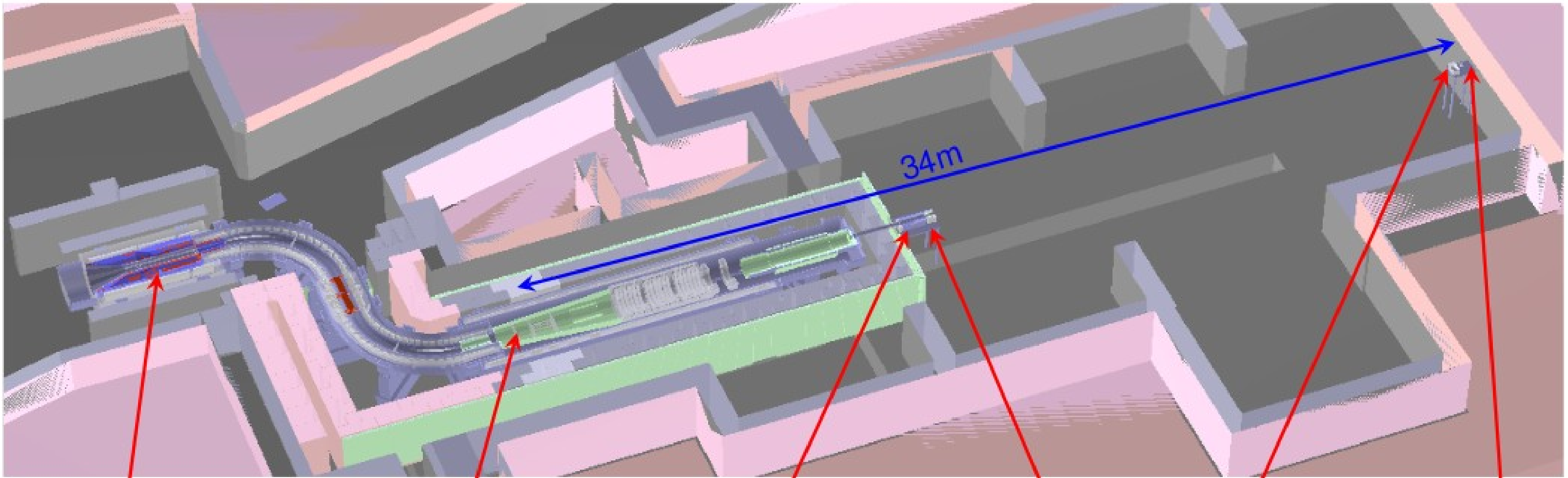
20 Feb 2024

1st week of March 2024

Normalization of signal events: the Stopping Target Monitor

Goal: monitoring the muon capture rate in Aluminum at the 10% level

Detector system: High Purity Germanium detector + $LaBr_3$ detector
LaB_3 has worse energy resolution, but can sustain higher rates

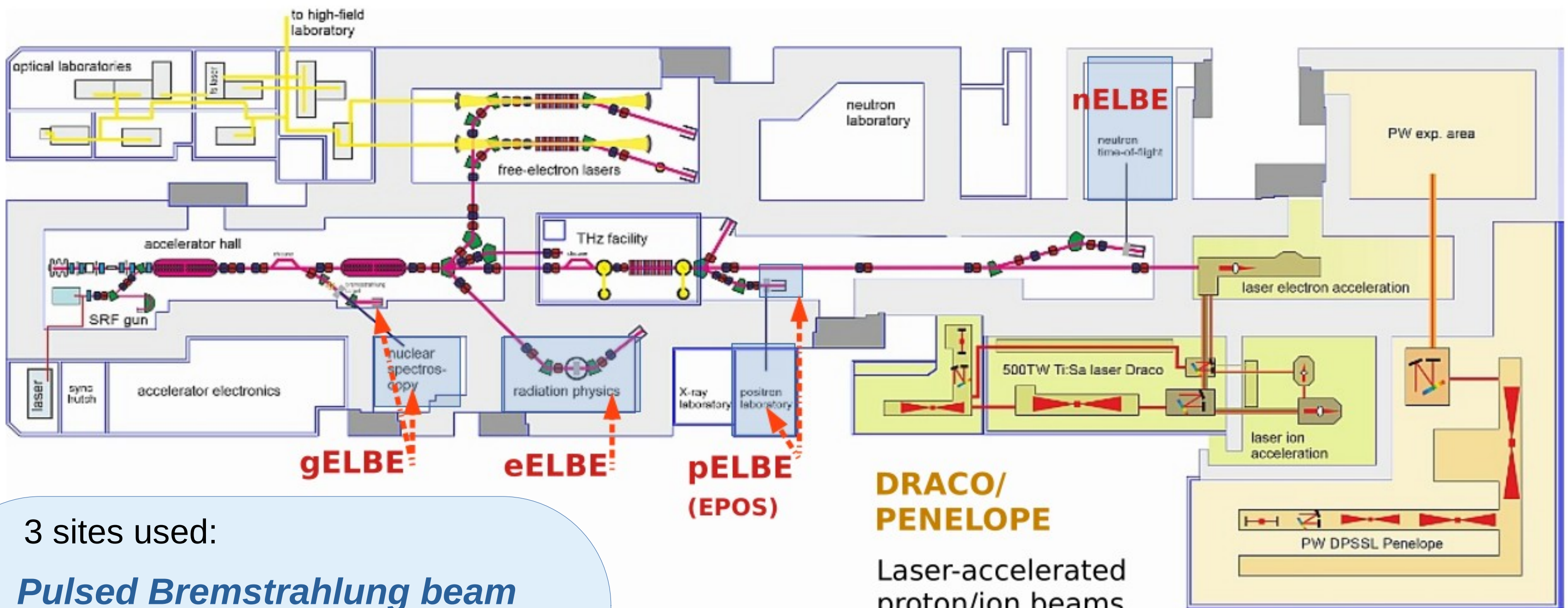


Production Target Stopping Target Sweeper magnet Collimator Collimator HPGe det.

- 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
- behind tungsten collimator with 0.5 cm^2 holes
- sweeper magnet to reduce charged particle background and radiation damage to detector

DRESDEN concept HZDR

Contribution of the ELBE Center for High Power Radiation Sources to Mu2e



3 sites used:

- ***Pulsed Bremstrahlung beam*** **in the gELBE experimental cave**
  $\sim 2.5 \times 10^{7}\ \gamma\ cm^{-2}\ s^{-1}$
  @1 μA e- beam current, E_{e-}=15 MeV
- **High-dose site along the gELBE beamline for TID studies**
  1-2 order of magn. higher γ rate
- **Neutron irradiation site** outside the EPOS cage
  up to 10^{12} n_{1MeV} /cm² in one day

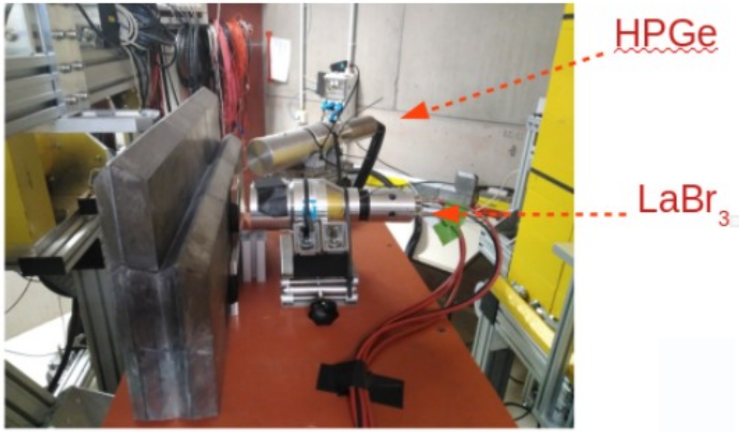
ELBE ("*Electron Linac for high Brilliance and low Emittance*") is based on a superconducting linear accelerator, which accelerates electrons to energies in the interval **[5, 40] MeV** at a beam current of up to **1 mA**

Guiding the electron beam on suitable targets allows the production of secondary radiation:

- in addition to **electrons**, intense **photon, positron and neutron beams** are available to the users in dedicated caves
- a unique feature: **pulsed beams**, with a pulse width between 10 ps and 1 μs, a repetition rate of 26 MHz/2^n (n=1,...,7) and a charge load up to ~77 pC/pulse.

Beamtime results of the last campaigns in a glance

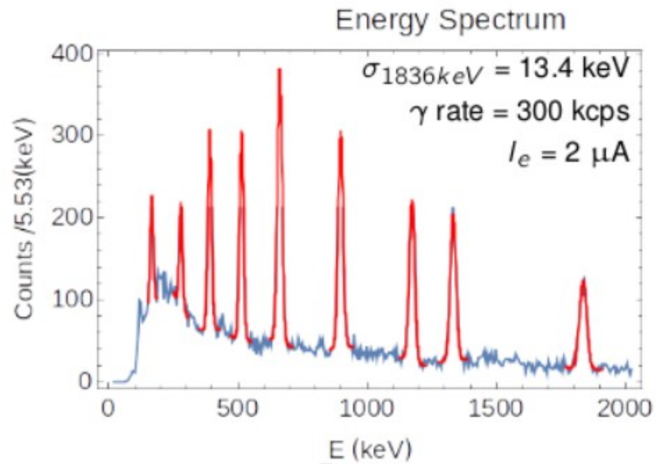
Testing the STM detector system at gELBE in pulsed beam conditions similar to Mu2e



HPGe test of energy resolution, radiation damage and sustained rate

Energy resolution between

3 keV and **6 keV**



LaBr3 response to a set of radioactive sources that mimic the X- and γ-ray signals in Mu2e

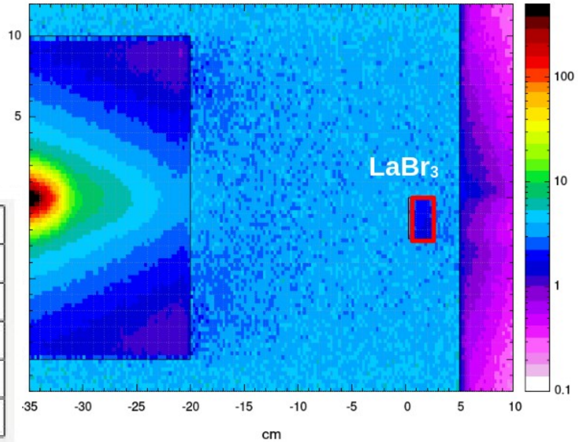
$LaBr_3$ can handle data taking at twice the expected photon rate

Pulse frequency: **813 kHz**

Testing radiation damage to new crystals for Mu2e-II at gELBE

	CsI	LYSO	BaF_2	PbF_2	CRY18	GAGG	LaBr
Light Yield (γ /MeV)	1700	33200	13000, 1700	~20	30000	Up to 50000	63000
Wavelength [nm]	310	420	300,220	-	425	520	380
Decay time [ns]	26	40	600,0.9	-	45	90	16
Density [g/cm^3]	4.51	7.4	4.89	7.77	4.5	6.63	5.08
Radiation length [cm]	1.86	1.14	2.03	0.93	2.74	TBA	1.88

Dose rate [kGy/h] at 500 μA e$^-$ current



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Conclusion

- The Mu2e experiment at FERMILAB will search for the neutrino-less conversion of a muon into an electron in the field of an Al nucleus,
  with a projected upper limit: 8×10^{-17} (90% CL)

- Detector production is concluding, installation and commissioning efforts are growing

- The ELBE High Power radiation sources at HZDR contributed to the Mu2e effort with several beamtime campaigns:

  - to *optimize the detector design of the Stopping Target Monitor* (STM), which will provide the normalization of the final measurement by measuring the total number of muon captures
  - to *study radiation hardness of crystals end electronics* for the Calorimeter system

- With a first run of physics data taking starting in the end of 2026,
  Mu2e will either unambiguously discover CLFV
  or push the limit on muon → electron conversion by nearly four orders of magnitude

⇒ **Exciting period to work in Mu2e!**

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