The MU2E experiment at Fermilab

Stefan E. Müller

Department of Information Services and Computing - Computational Science Group and Institute of Radiation Physics
Helmholtz-Zentrum Dresden-Rossendorf

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DRESDEN concept

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Motivation

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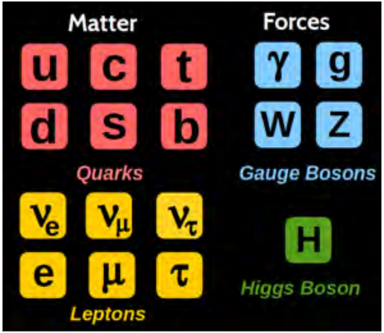

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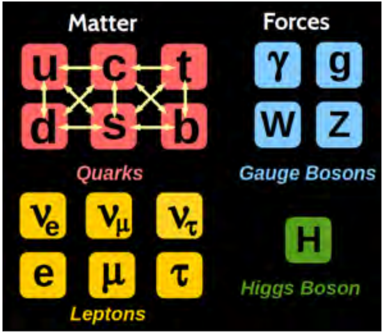

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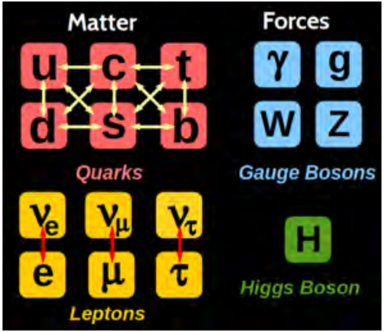

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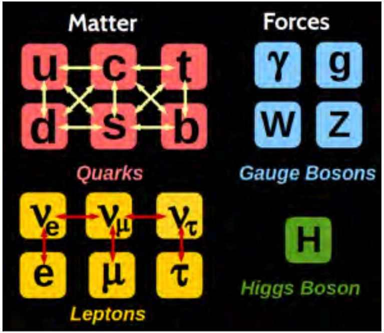

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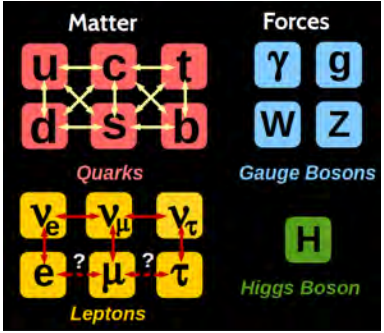

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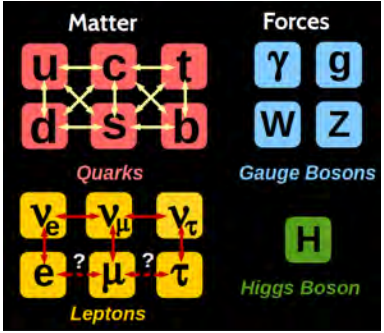

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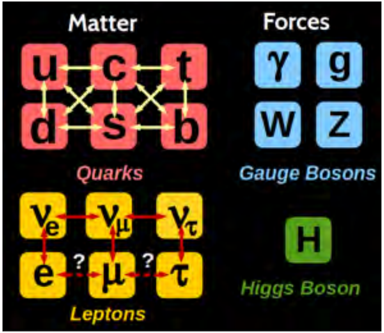

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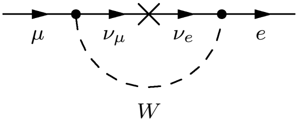

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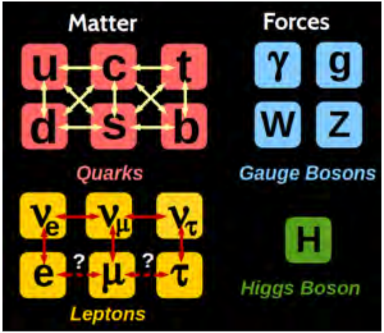

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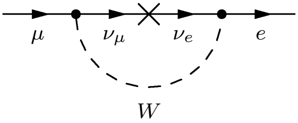

However, this graph is forbidden since it violates energy and momentum conservation. We need additional particles to carry away the momentum!

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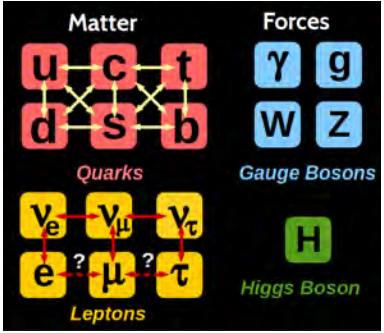

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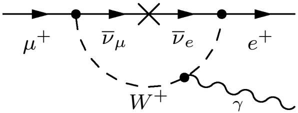

$\mu^+ \to e^+ + \gamma$: MEG and MEG-II experiments at PSI

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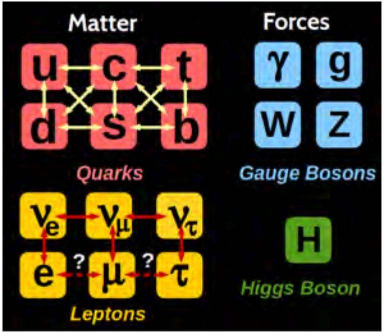

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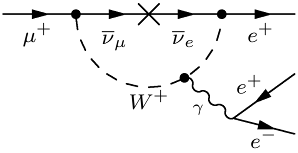

$\mu^+ \to e^+e^+e^-$: Mu3e experiment at PSI

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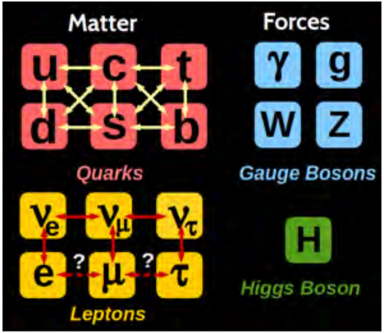

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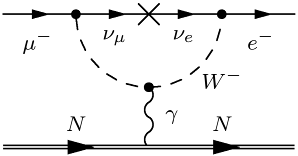

$\mu^- + N \rightarrow e^- + N$: Mu2e experiment at FNAL, COMET experiment at J-PARC.

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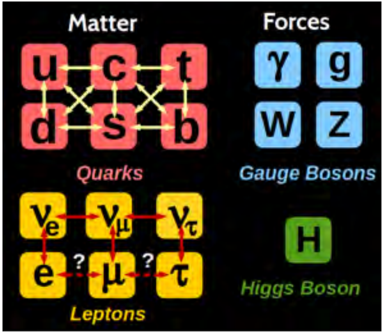

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$$Br(\mu \to e\gamma)_{SM} = \frac{\Gamma(\mu \to e\gamma)_{SM}}{\Gamma(\mu \to e\nu\overline{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}$$

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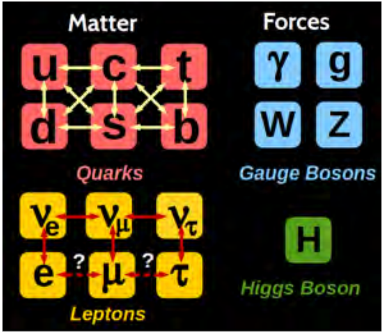

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Unmeasurably small!

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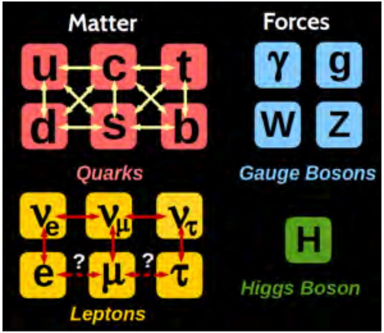
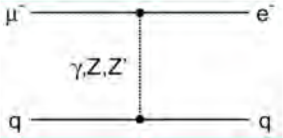
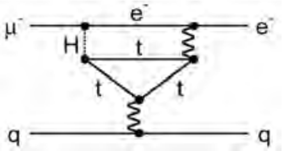


Extensions of SM predict values up to 10^{-14}:

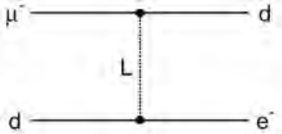
Heavy Z’, anomalous Z coupling



Second Higgs doublet



Leptoquarks



Models taken from Marciano, 2008

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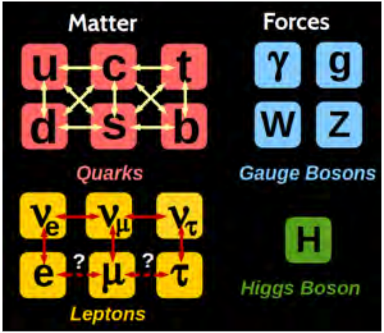
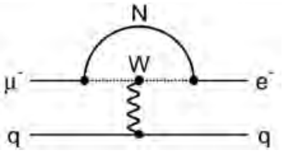
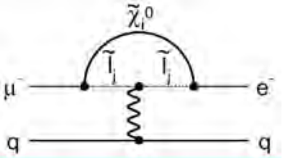


Extensions of SM predict values up to 10^{-14}:

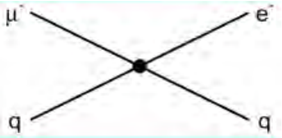
Heavy Neutrinos



Supersymmetry



Compositeness



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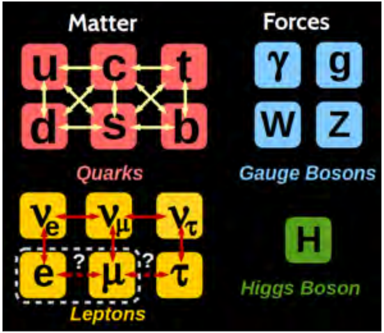


The **Mu2e** experiment will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \rightarrow eN$) with a projected

upper limit of 8x10^{-17} (90% CL)

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

Motivation (2)

CLFV in the muon sector can make a difference:

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Altmannsdorfer *et al.*, arXiv:0909.133 [hep-ph]

HZDR

New physics

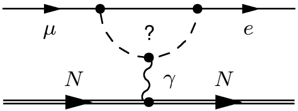
Model independent Lagrangian:

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

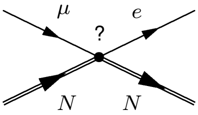
Λ: effective mass scale of New Physics

κ: relative contribution of contact term

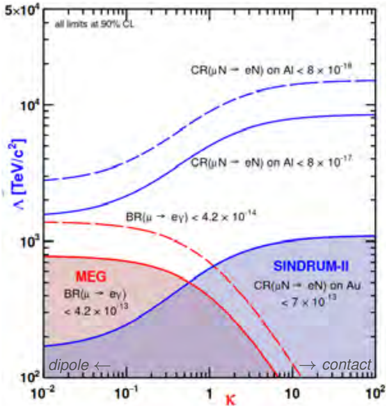
Dipole term: dominates for $\kappa \ll 1$



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



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



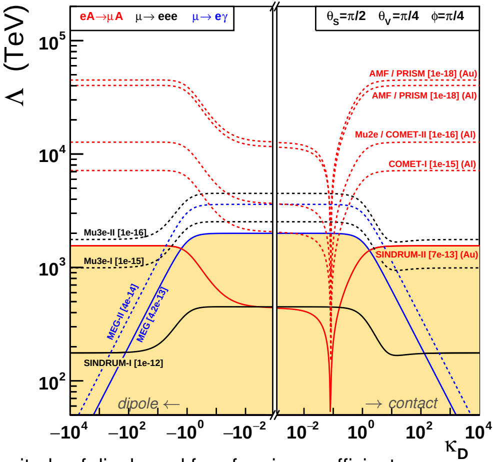
Derived from arXiv:1303.4097

HZDR

New physics (2)

Slightly more involved Lagrangian from Davidson & Echenard (arXiv:2204.00564):

$$\begin{aligned}\delta\mathcal{L} = \frac{1}{\Lambda_{LFV}^2}\Big[& C_D(m_\mu \bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} \\ & + C_S(\bar{e}P_R\mu)(\bar{e}P_R e) \\ & + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_R e) \\ & + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_L e) \\ & + C_{Alight}\mathcal{O}_{Alight} \\ & + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]\end{aligned}$$



The angle θ_D parametrizes the relative magnitude of dipole and four-fermion coefficients

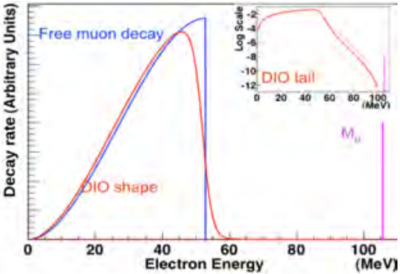
$$2\sqrt{2}C_D \approx \frac{cos\theta_D}{\Lambda_{LFV}^2} \text{ and } \kappa_D = \cot(\theta_D - \pi/2).$$

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 864 ns 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

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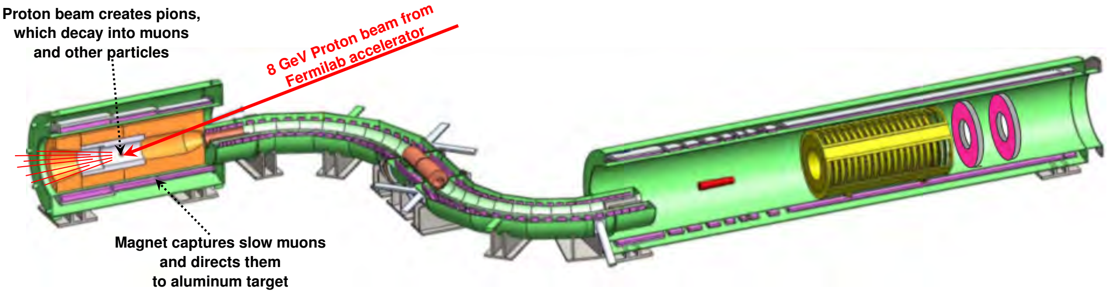
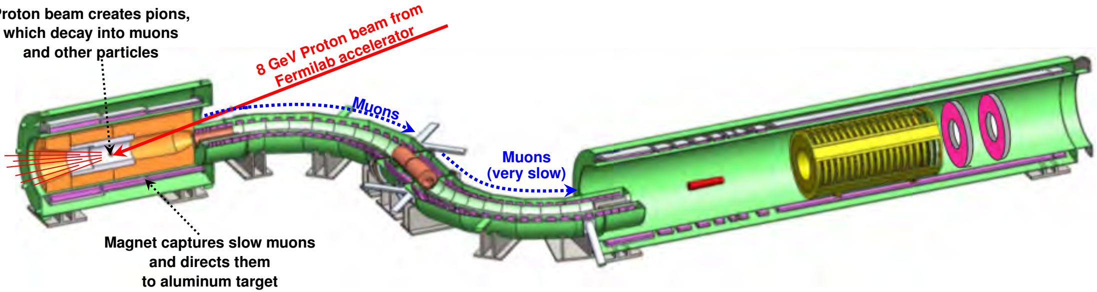


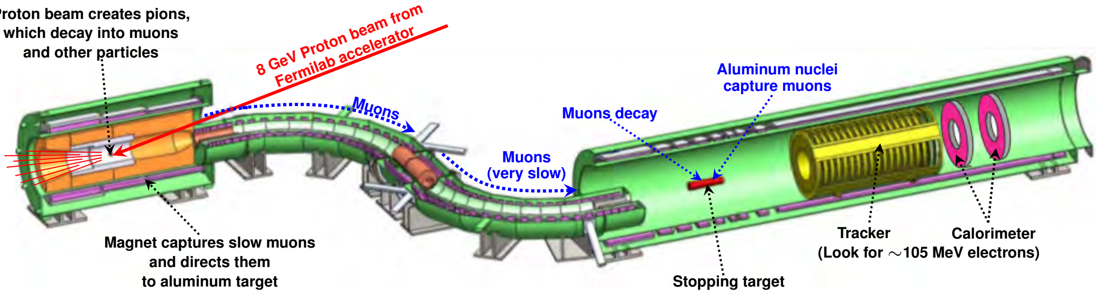
- Muons are produced by 8 GeV proton beam on production target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1.695μs
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



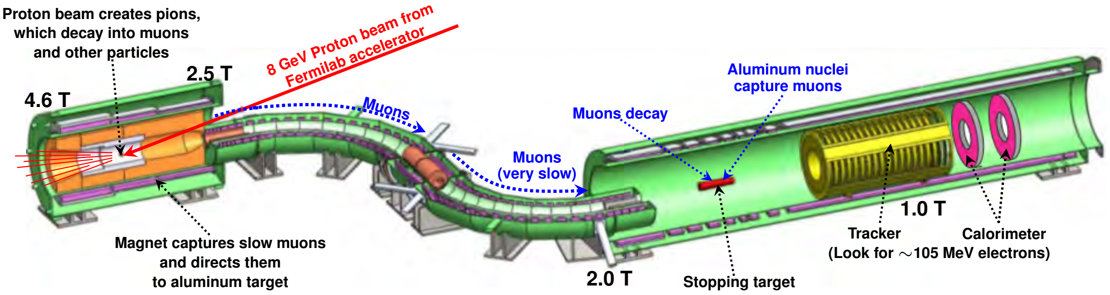
- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

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

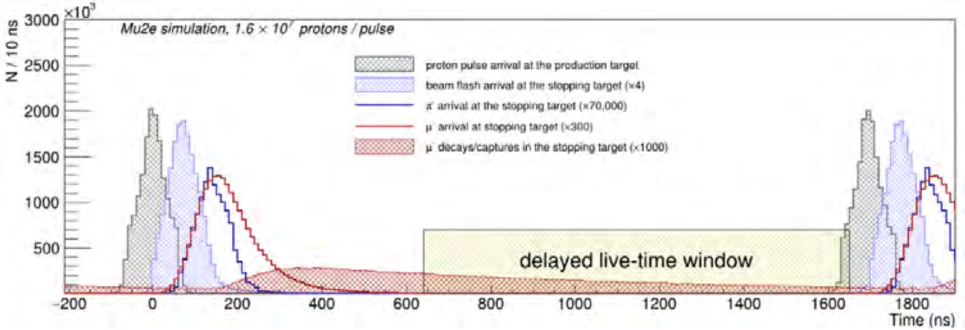
The Mu2e experiment



- 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 background (1695 ns peak-to-peak):

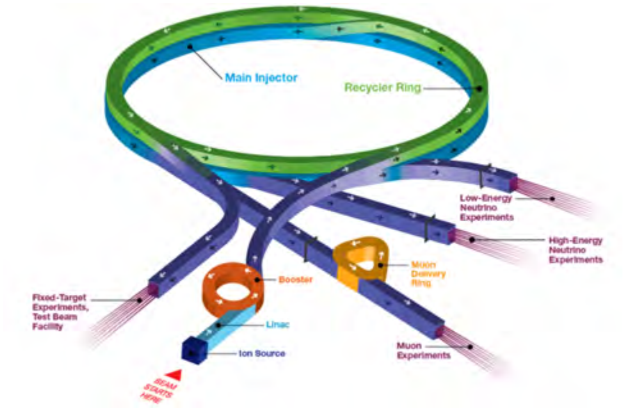


- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- Delayed live-time window allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

Proton beam

1. 400 MeV protons from the LINAC are injected into the **Booster Ring** where they are accelerated to 8 GeV and grouped into batches
2. each 67 ms, a booster batch is sent to the **Recycler Ring** and re-bunched into four bunches of 1e12 protons each
   - Eight 67ms buckets for Mu2e (only 2 filled), 12 for other experiments (NOVA)
3. Eight Mu2e bunches are sent to **Delivery Ring** from which they are resonantly extracted each 1.695 μs to create the proton pulses directed to **Mu2e** beam line (4E7 protons/pulse)

Beam is delivered to Mu2e during 380 ms over a full RR cycle of 1440 ms (remaining time beam is delivered to other experiments)



Initially, Mu2e will use only 1 batch from the Recycler Ring before switching to the full 2-batch-mode.

The pion Production Target

Mu2e's Production Target needs to fulfill the following requirements:

- Needs to have a sufficiently high cross section for pion production
  - Pions decay along the TS to produce muons
- PT absorbs about 10% of the 7.3 kW proton beam
  - passive radiative cooling design requires large surfaces ("fins")
- Needs to cope with thermal shocks due to pulsed proton beam
- Needs to have sufficient radiation hardness
- Needs to last for one year in beam
  - robotical replacement takes 1-2 months

A first prototype made from tungsten has been built, but still other material options (carbon, Inconel,...) and geometrical designs are explored.

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The muon Stopping Target

Mu2e's "Stopping Target" consists of 37 aluminum discs

- thickness 100 μm
- r_{ou} = 7.5 cm
- r_{in} = 2.15 cm
  - holes to reduce "beam flash" background
- distance between foils $\sim$ 2 cm

Muons are slowed down and stopped inside the aluminum discs (then undergo muon capture, decay-in-orbit or **direct conversion**).

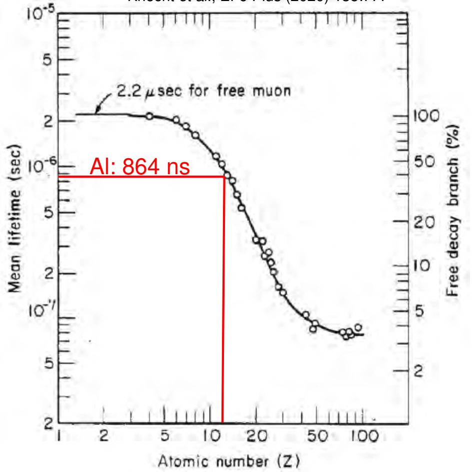
HZDR

Why aluminum as stopping material?

Why aluminum as stopping material?

- The lifetime of the muon on ${}^{27}_{13}Al$ of 864 ns matches the pulsing of the proton beam (1.695 μs)
  - allows the definition of a "Live Window"-gate in time to suppress prompt background from e.g. pion decays
- studying the muon conversion on lighter nuclei may give complementary information in terms of New Physics
  - the SINDRUM-II experiment used ${}^{197}_{97}Au$ (with a cw proton beam)
- Ti (Z=22) would be another option

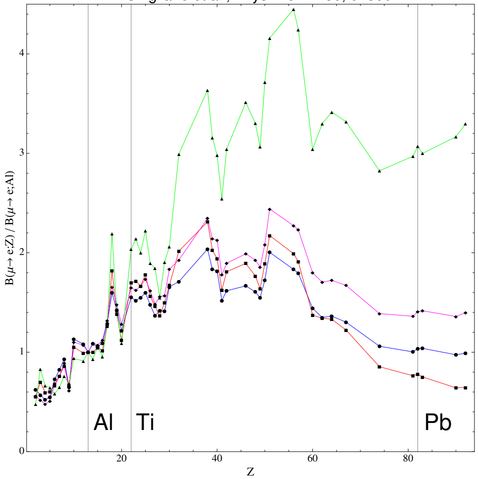
Knecht *et al.*, EPJ Plus (2020) 135:777



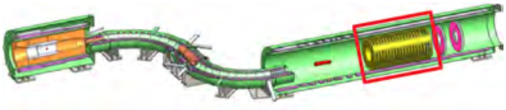
Why aluminum as stopping material?

- The lifetime of the muon on $^{27}_{13}$Al of 864 ns matches the pulsing of the proton beam (1.695 μs)
  - allows the definition of a “Live Window”-gate in time to suppress prompt background from e.g. pion decays
- studying the muon conversion on lighter nuclei may give complementary information in terms of New Physics
  - the SINDRUM-II experiment used $^{197}_{97}$Au (with a cw proton beam)
- Ti (Z=22) would be another option

Cirigliano *et al.*, Phys. Rev. D 80, 013002



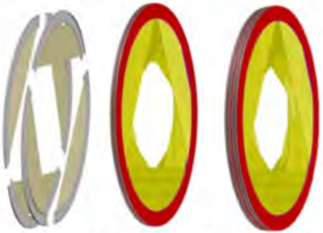
Straw drift tube tracker

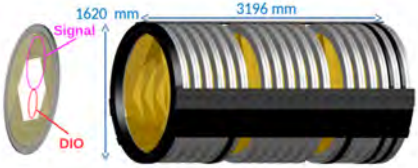


- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- in vacuum and at $\sim$1 T magn. field
- straws operate at 1 atm of Ar-CO_2 mixture (80/20)
- momentum resolution $\sigma_p < 180$ keV/c

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

Straw drift tube tracker





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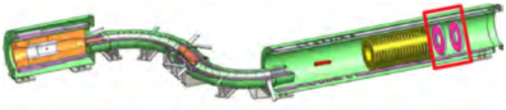
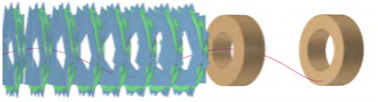
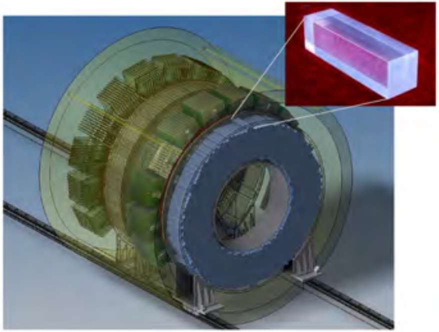
Calorimeter



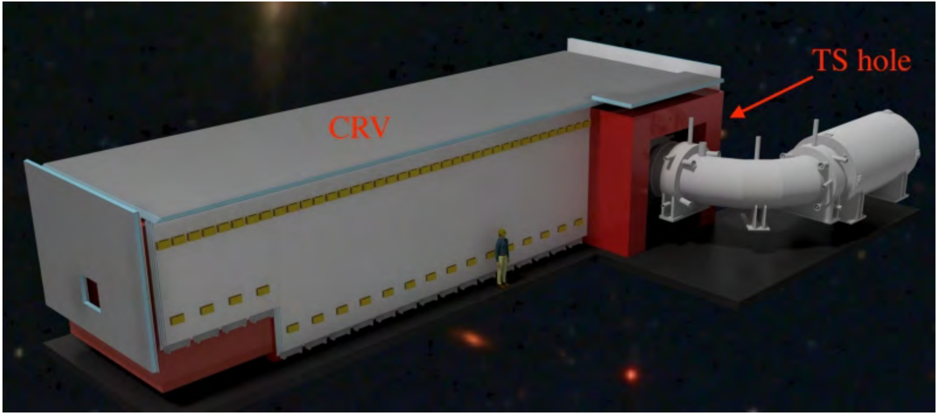
- composed of two rings separated by half a wavelength of signal electron trajectory helix
- each ring composed of ~700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent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





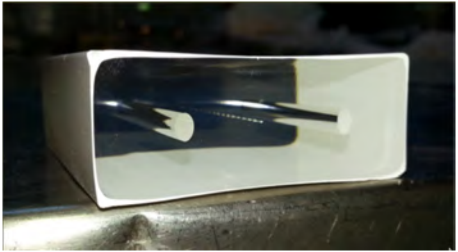
The cosmic ray veto detector

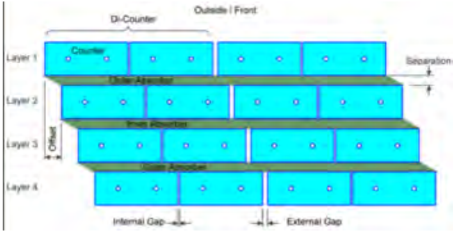
The cosmic ray veto system (CRV) covers entire Detector Solenoid and half of the Transportation Solenoid (TS)



The cosmic ray veto detector

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

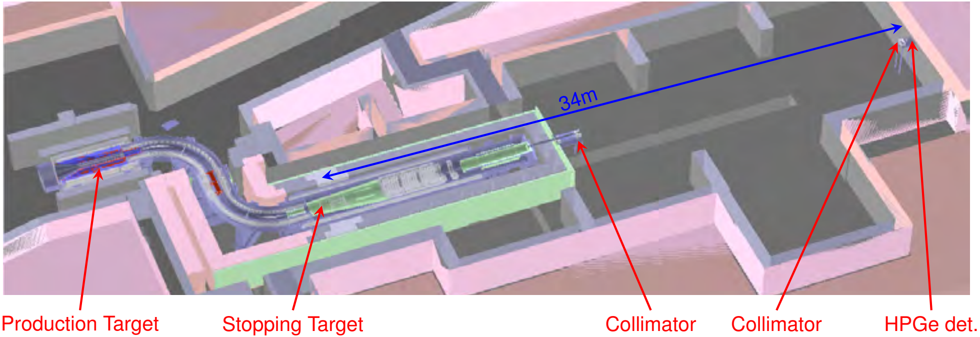




- 4 overlapping layers of scintillator bars ($5 \times 2 \times \sim 450$ cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- required inefficiency $\sim 10^{-4}$

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
- behind tungsten collimator with 1 cm^2 holes
- It was decided to accompany the HPGe detector with a $LaBr_3$ detector (worse energy resolution, but can take higher rates)

Mu2e status: Transport Solenoid magnet

S-shaped Transport Solenoid has arrived at FNAL on 12/23 (upstream part) and 2/24 (downstream part).

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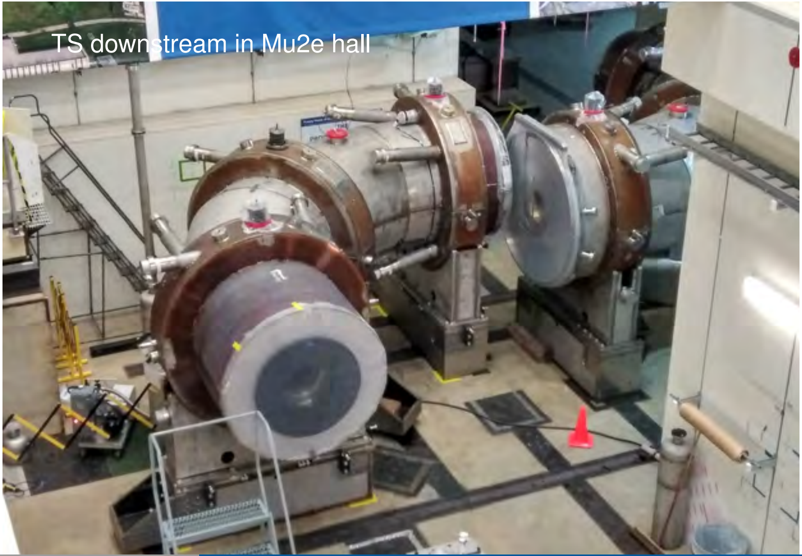

Mu2e status: Transport Solenoid magnet

S-shaped Transport Solenoid has arrived at FNAL on 12/23 (upstream part) and 2/24 (downstream part).

- installed in final position in Mu2e hall
- Rotating collimator installed and tested
- Upstream and downstream part welded together
- Installation of Anti-Proton absorber blade planned
- Cryogenic system connection in progress

HZDR

Mu2e status: Production Solenoid magnet

Production Solenoid has arrived at FNAL in June 2025, and was lifted into Mu2e hall August 2025:

Mu2e status: Production Solenoid magnet

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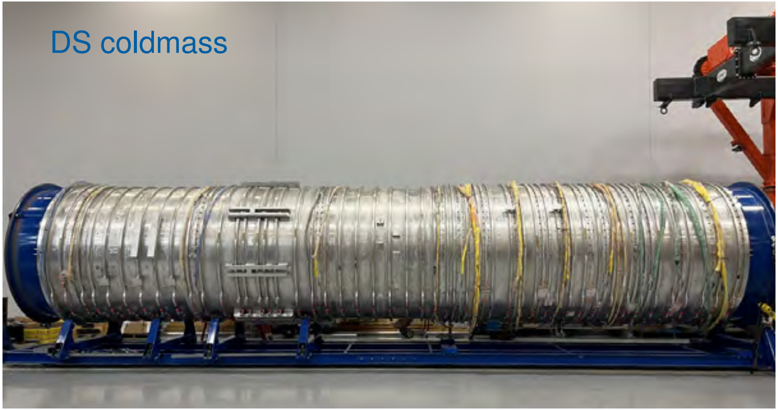
Heat- and Radiation Shield (HRS) has been inserted into PS.

Mu2e status: Detector Solenoid magnet

All 11 coils assembled into cold mass. Dry run of insertion of cold mass into vacuum vessel completed. Expected delivery date to FNAL: Spring 2026.



DS needs to undergo cold and leak tests after coldmass insertion and closing of vacuum vessel.

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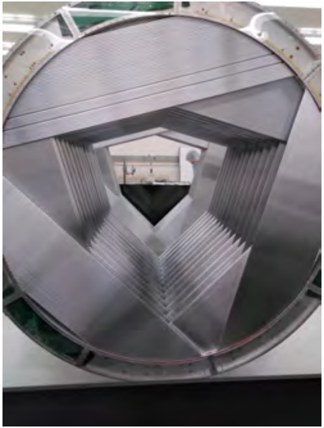
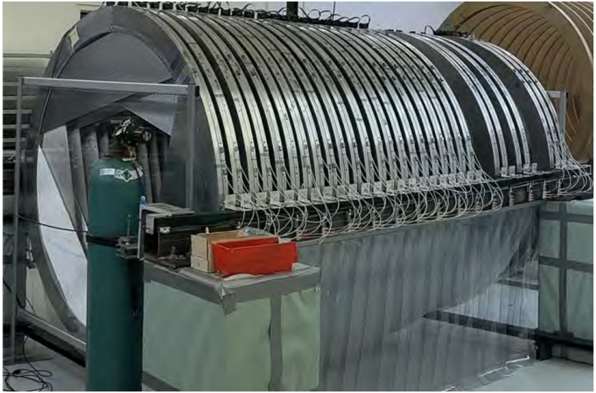
Mu2e status: Tracker

- All 20736 straws and 216 panels produced
- All 36 planes assembled
- 15 out of 18 stations built
- Electronics delivered and installed
- Quality Control and leak testing ongoing
- Preparing for transport to Mu2e hall





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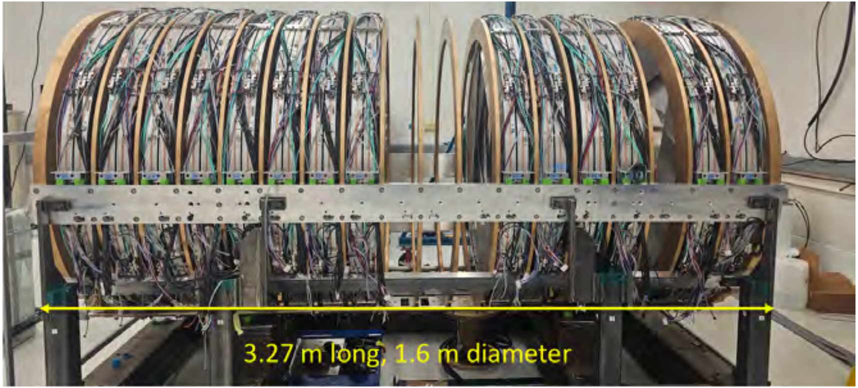
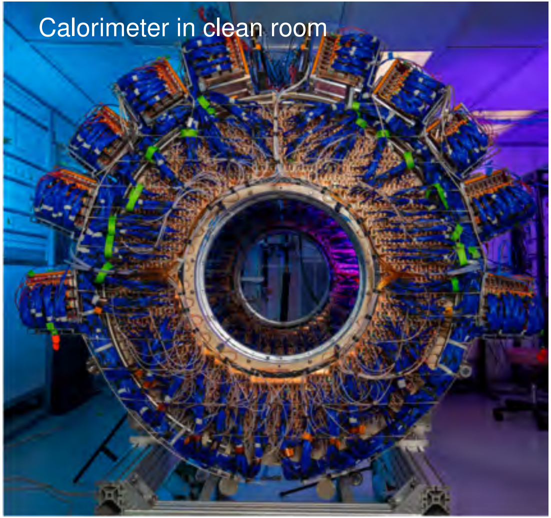


Mu2e status: Calorimeter

- Both Disk0 and Disk1 completed
  - Assembly terminated February 2025
- Final Commissioning completed
  - Feb 2025 (Disk1)
  - June 2025 (Disk0)
- both disks transported and installed in Mu2e hall in September 2025



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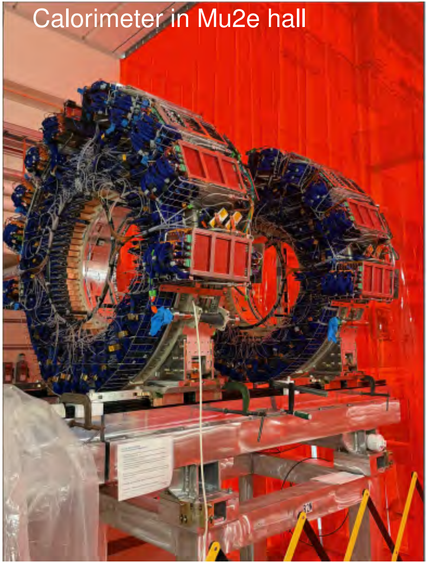
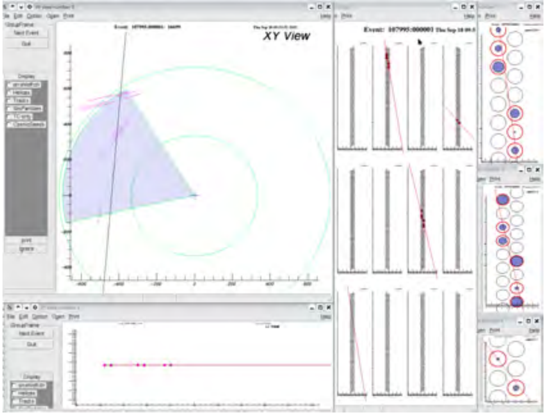


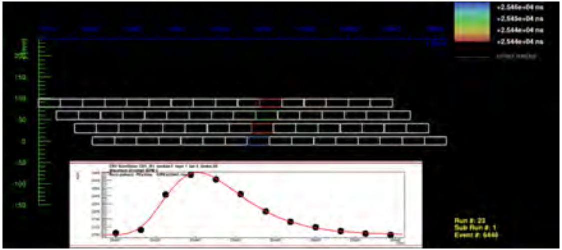
Mu2e status: CRV

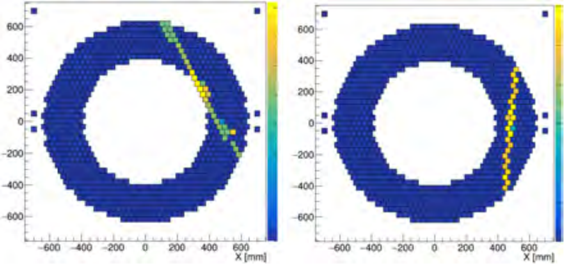
All 5344 counters and 83 CRV modules built and tested - 8 modules for cosmic ray run installed in **Mu2e** hall:

Cosmic ray data-taking

- Cosmic rays are used to commission tracker, calorimeter and CRV
- This allows to perform noise studies and commissioning of the DAQ infrastructure

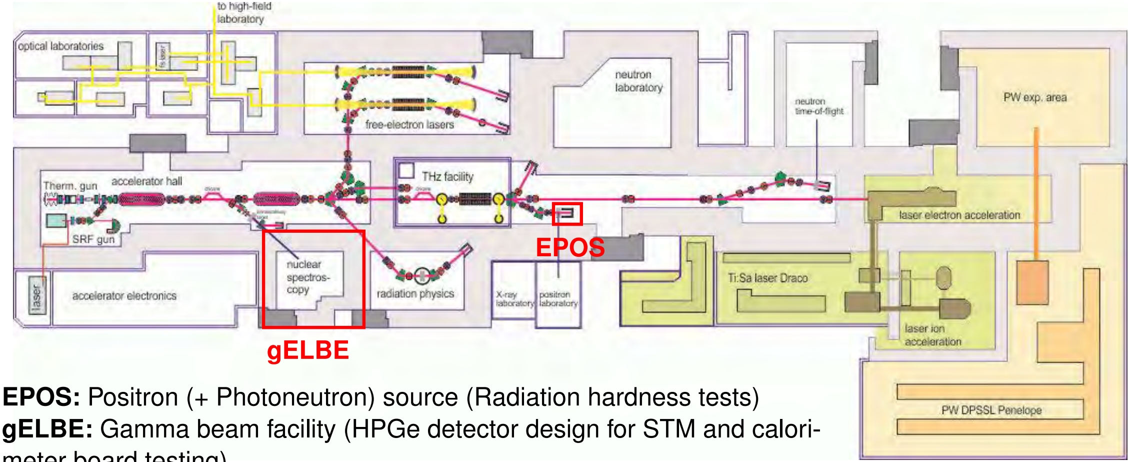






HZDR contributions: ELBE beamtimes

Several beamtimes for **Mu2e** have been conducted at the **ELBE** (Electron Linac for beams with high Brilliance and low Emittance) radiation source at **HZDR**.



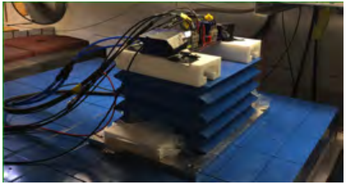
EPOS: Positron (+ Photoneutron) source (Radiation hardness tests)
gELBE: Gamma beam facility (HPGe detector design for STM and calorimeter board testing)

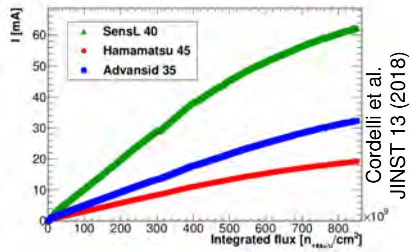
HZDR contributions: ELBE beamtimes

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

- 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 and crystals





Cordelli et al.
JINST 13 (2018)
T003005

HZDR contributions: ELBE beamtimes

Use of gELBE's pulsed bremsstrahlung γ-beam with max. energy of 15 MeV to study HPGe & $LaBr_3$ detector response for STM:

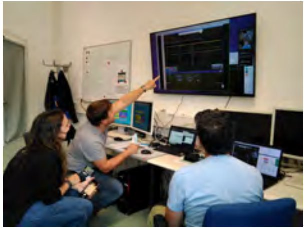
- The muons hitting the aluminum disks of the Stopping Target will produce a bremsstrahlung "flash" background on top of which one needs to detect the characteristic lines emitted when the muons stop or are captured
- gELBE pulse separation of 1.23μs or 2.46μs close to Mu2e's 1.7μs proton pulse separation
- 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)
- Use of calibration sources (^{137}Cs, ^{60}Co, ^{88}Y) together with the pulsed bremsstrahlung spectrum of gELBE allows to simulate Mu2e conditions

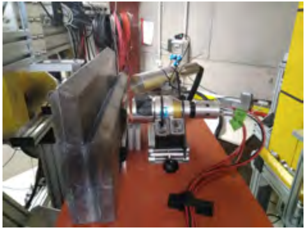
HZDR

HZDR contributions: ELBE beamtimes

Three beamtimes dedicated to STM detector studies (partially heavily affected by COVID!):

- First beamtime in August 2017:
  - Characterization of HPGe detector, design of STM shielding house
- Second beamtime in September 2021:
  - Test of $LaBr_3$ detector's response to anticipated Mu2e beam fluctuations
- Third beamtime in April 2022:
  - Further tests with the $LaBr_3$ detector
  - Testing the DAQ chain for HPGe and $LaBr_3$ detectors





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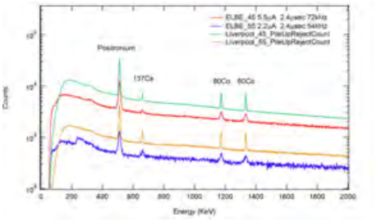
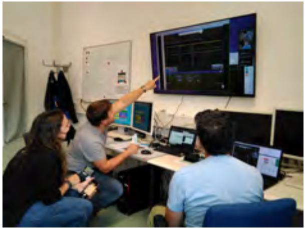
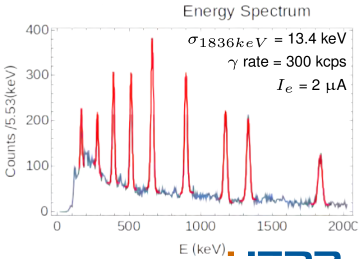


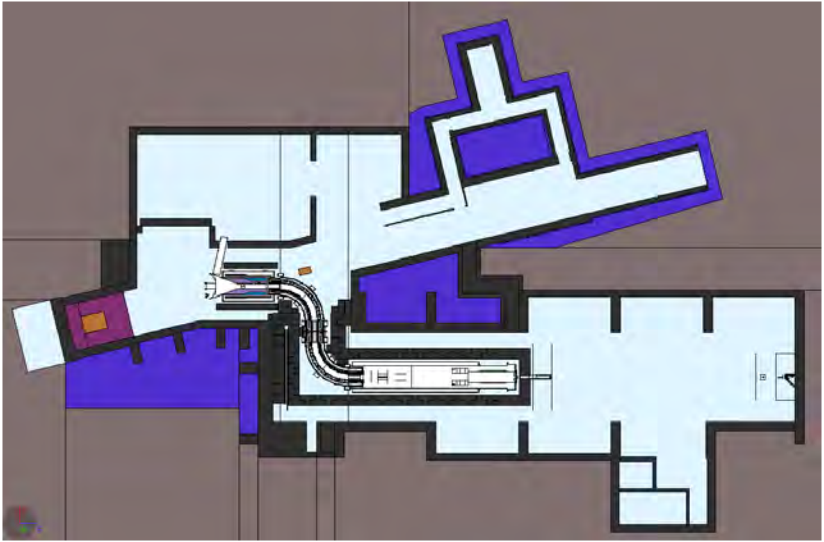




Paper in preparation!

HZDR contributions: FLUKA Simulations

(Most of) **Mu2e** offline simulation geometry has been ported to **FLUKA** (www.fluka.eu).

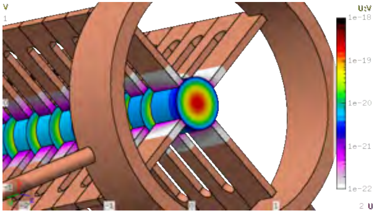


HZDR contributions: FLUKA Simulations

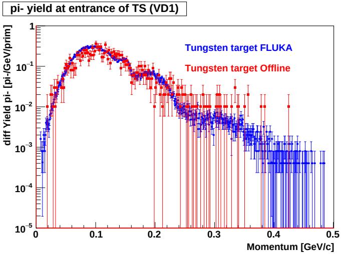
(Most of) **Mu2e** offline simulation geometry has been ported to **FLUKA** (www.fluka.eu).

This allowed e.g. for Production Target radiation hardness simulations (a), comparison of yield spectra (b) or first attempts to global shielding studies (c).

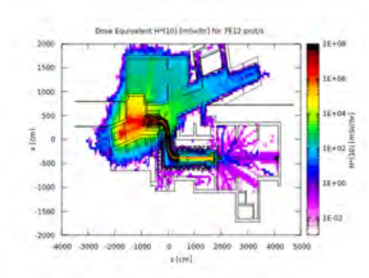
(a)



(b)



(c)



Work is ongoing...

The current Mu2e timeline and running plans

The **Mu2e** timeline is defined by

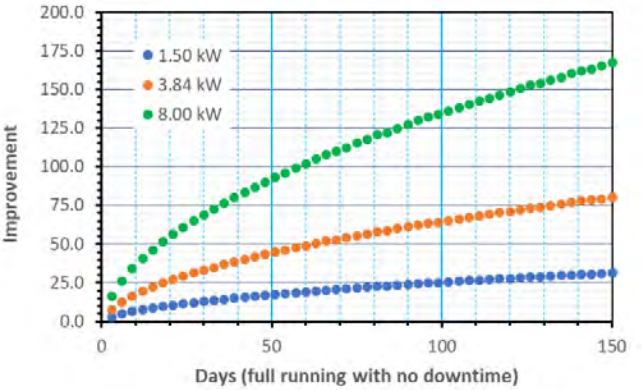
- Detector Solenoid delivery to FNAL and its commissioning
  - **DS** expected to arrive at FNAL March 2026
- The long shutdown at FNAL for the **PIP-II** upgrade
  - January 2028

Mu2e will begin running in 2027, collecting data until the long shutdown at FNAL, then run for two more years after the shutdown.
To take advantage of the available time before the shutdown, **Mu2e** will run in a reduced operating mode:

- Run 1 will only use CRV coverage above the detector
  - Full CRV cannot be installed until **DS** is installed and tested
- Reduced proton beam intensity (one booster batch instead of two)

Even with a reduced beam intensity from 8 kW to 4 kW and half of the CRV, **Mu2e** will reach a sensitivity for muon-to-electron conversion about a factor of 50 better than the current value of the **SINDRUM-II** experiment.

The current Mu2e timeline and running plans



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Summary & Conclusions

- 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)
- **MU2E** construction of magnets and detectors is well underway
- Integrated cosmic ray measurements with the calorimeter and CRV will begin at the end of this year, and include the tracker in these runs in early 2026
- **HZDR** contributions:
  - beamtimes at the **ELBE** Center for High-Power Radiation Sources for radiation hardness testing of crystals and electronics as well as detector tests for the Stopping Target Monitor
  - **FLUKA** simulations to cross check simulation results obtained with **GEANT4** and **MARS**
- **Mu2e** will begin with a reduced configuration Run 1 before the long shutdown at **FNAL** and then run with the full apparatus in Run 2 after the shutdown
- While in Run 1 an improvement on the the limit on muon $\rightarrow$ electron conversion of about a factor 50 is expected, with its full data set **Mu2e** will either unambiguously discover **CLFV** or push the limit on muon $\rightarrow$ electron conversion by four orders of magnitude