Searching for Muon to electron conversion: The Mu2e experiment at Fermilab

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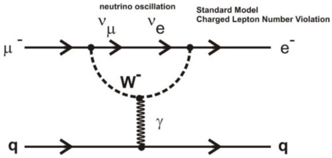
Mu2e: the basics

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

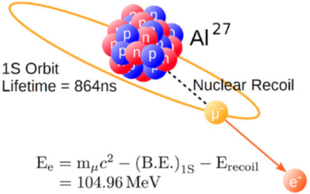
$$\mu^- N \rightarrow e^- N$$

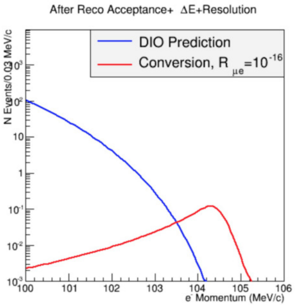
- This would violate **charged lepton flavor**, something that has never been seen before
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is $< 10^{-50}$)



- Mu2e goal is a 10^4 improvement! (previous limit 7×10^{-13} from SINDRUM II)

The Mu2e experiment at Fermilab





Measure the ratio of conversions to muon captures:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)}$$

- Signal of CLFV conversion is single monoenergetic electron
- Backgrounds:
  - Beam related: $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+ e^-$
  - Cosmic rays: $\mu^- \rightarrow e^- \nu_\mu \overline{\nu_e}$
  - Muon Decay in orbit: $\mu^- N \rightarrow e^- N \nu_\mu \overline{\nu_e}$

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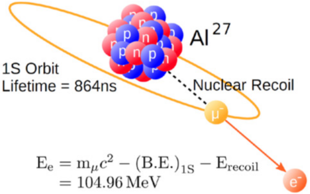

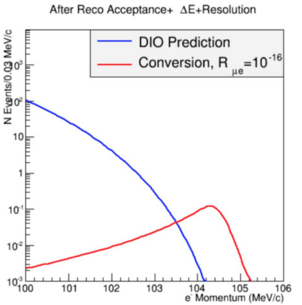

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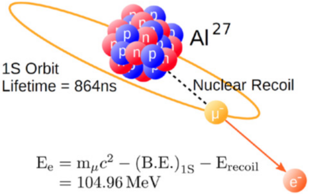

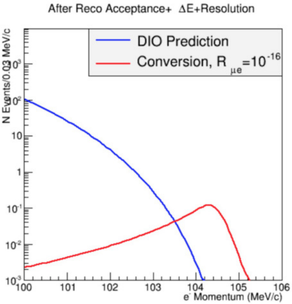

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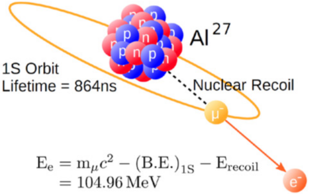

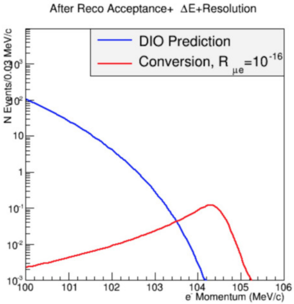

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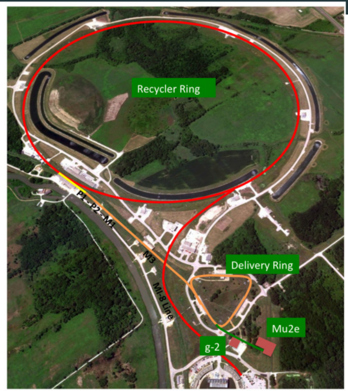
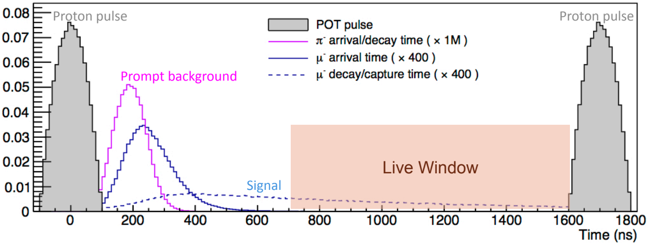
  - Muon Decay in orbit: $\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$ **(Momentum resolution)**

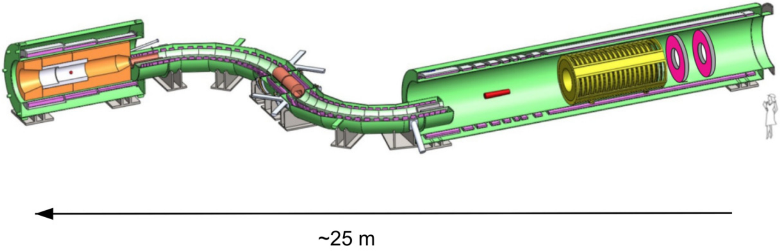
Mu2e Proton Beam



- 8 GeV 8 kW proton beam using protons from booster
- Resonantly extracted to get pulses of $4\text{x}10^7$ protons separated by 1.7 μs
- Runs simultaneously with NOVA
- Extinction factor (ratio of out-of-time protons to in-time protons) of $> 10^{-10}$

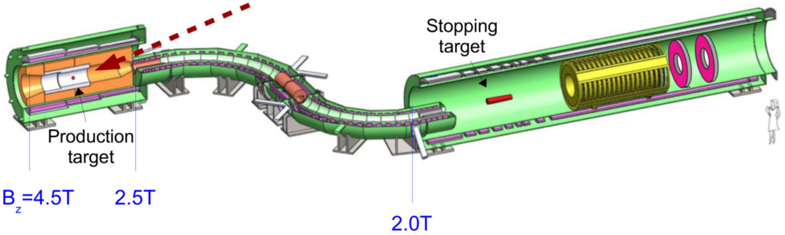


Mu2e experimental setup



- Consists of three superconducting solenoids:
  - Production Solenoid (PS)
  - Transport Solenoid (TS)
  - Detector Solenoid (DS)

Mu2e experimental setup



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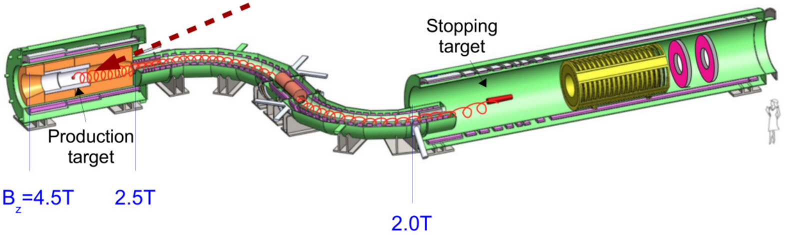

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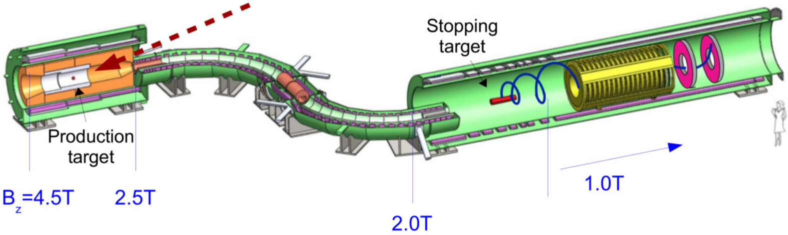

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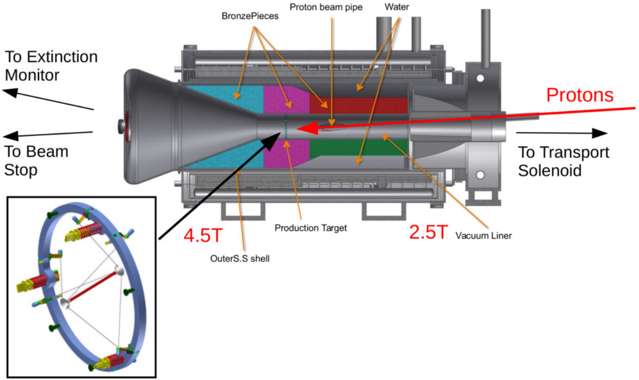
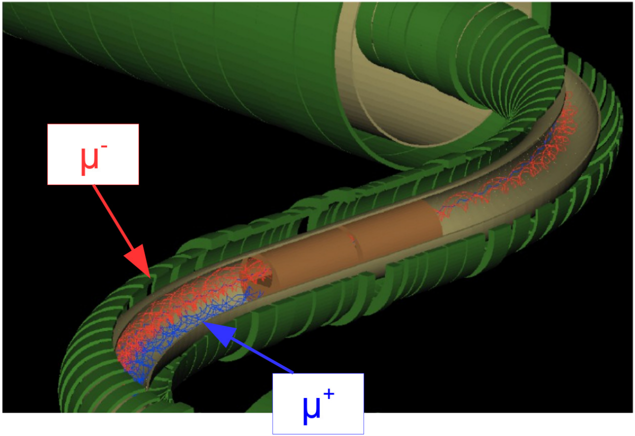
  - Detector Solenoid (DS)

Production Target and Solenoid produce slow muon beam in the reverse direction of the proton beam

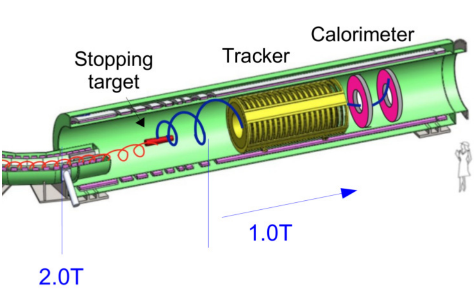


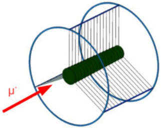
- Tungsten production target
- Magnetic mirror traps and redirects back to TS

Transport Solenoid sign selects charged particles



Detector solenoid directs electrons to detector elements

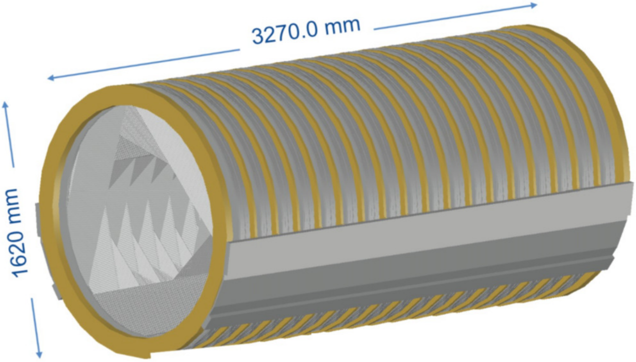


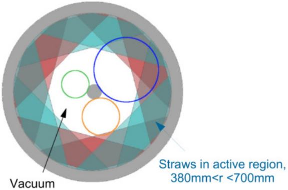


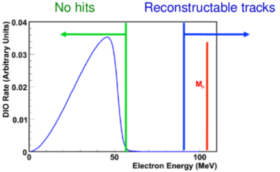
- Muons stopped on thin aluminum foils, again graded field for magnetic mirror
- Constant field in tracking volume
- High precision straw tracker in vacuum
- Electromagnetic calorimeter for PID

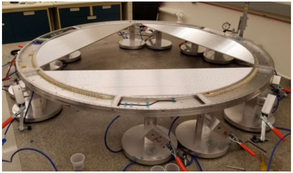
Straw Tracker Detector

- 18 stations, each containing 12x 120° panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than 200 keV/c



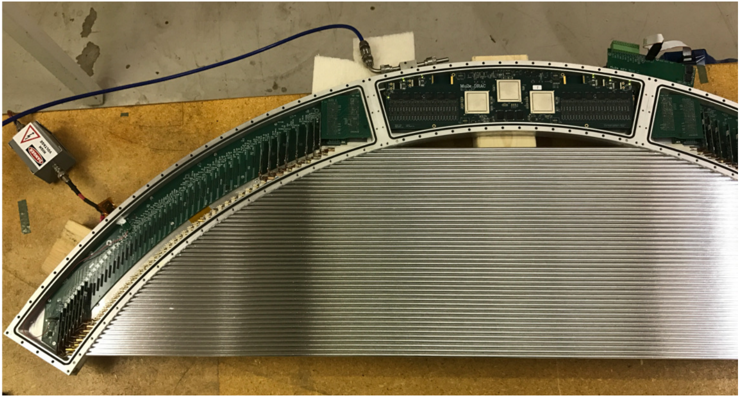




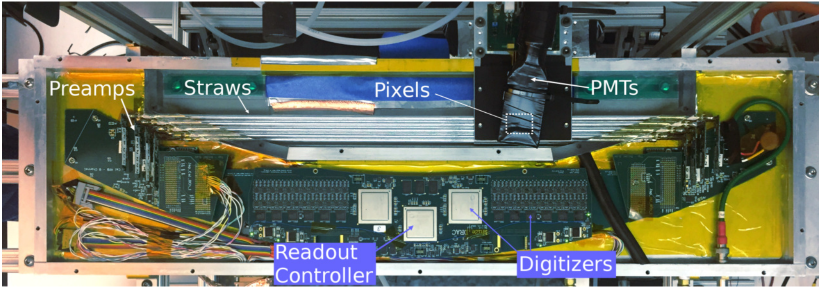


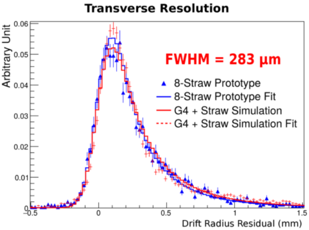
Straw Tracker Detector

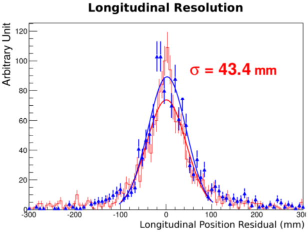
- ∼21,000 low mass straw tubes in vacuum
- 5 mm diameter, 15 μm thick mylar walls
- Measure transverse position to ∼200μm, longitudinal position along straw to ∼4cm
- Waveform digitized to reject proton hits

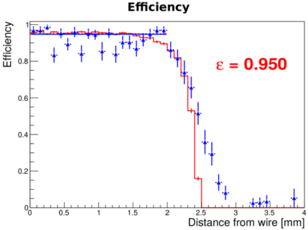


8 straw tracker prototype used to tune simulation and verify expected resolution

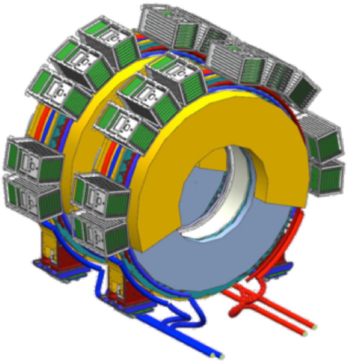


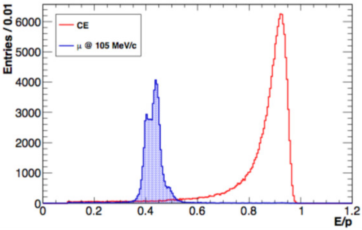






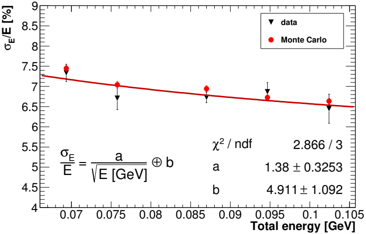
Calorimeter

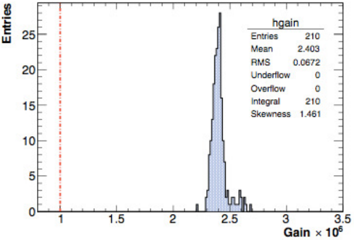


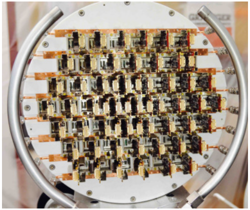


- Two annular disks separated by half a "wavelength" (70cm) of electron's helical path
  - Maximize probability to hit at least one disk
- Each disk contains 674 undoped CsI 34x34x200 mm^3 crystals read out by SiPMs
- 0.5 ns time, 5% energy, 1 cm position measurement independent of straw tracker
- Provides particle ID for track rejection
- Seed for tracking algorithm / trigger

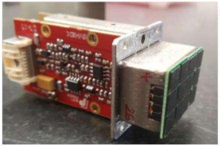
Calorimeter Prototypes





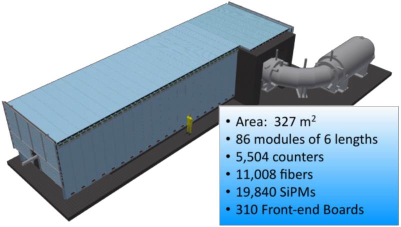


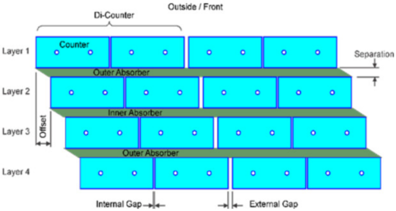
- Small 3x3 prototype tested in 80-120 MeV e^- beam
  - $\sigma_E \sim 6.5\%$ and $\sigma_t \sim 110$ps at 100 MeV
- Larger preproduction prototype (51 crystals, 102 SiPMs, 102 FEE boards)



Cosmic ray veto

- Expect cosmic rays to produce 1 conversion-like event per day
- 4 overlapping layers of scintillator, read out on both ends with SiPMs
  - Veto on 3-fold coincidence
- Covers entire DS, half of TS, better than 10^{-4} inefficiency



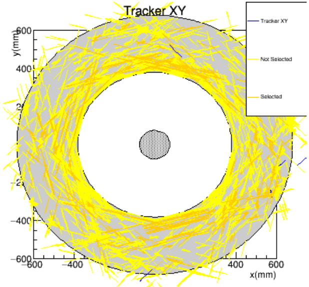


Expected backgrounds for 3 year run

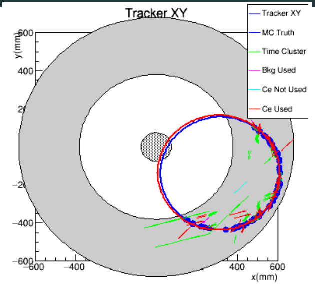
Process	Expected event yield
Cosmic ray muons	$0.21 \pm 0.02\text{(stat)} \pm 0.06\text{(syst)}$
DIO	$0.14 \pm 0.03\text{(stat)} \pm 0.11\text{(syst)}$
Antiprotons	$0.040 \pm 0.001\text{(stat)} \pm 0.020\text{(syst)}$
Pion capture	$0.021 \pm 0.001\text{(stat)} \pm 0.002\text{(syst)}$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13\text{(stat+syst)}$

- Fewer than $\sim$0.5 background events expected over entire run
- 3.6 x 10^{20} protons on target over 3 years $\rightarrow \sim 10^{18}$ stopped muons

Simulation and Reconstruction



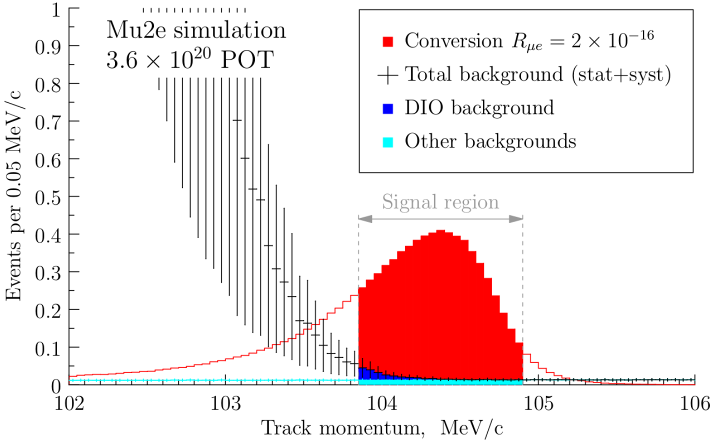
1 μs selection window after beam flash



Hits selected by track finder within $\pm$50 ns selection window around potential track

- Detailed Geant4 simulation of full detector
- Straw response tuned to data and detector prototype measurements
- Simulate from production target forward (including backgrounds)
- Kalman Filter track fit

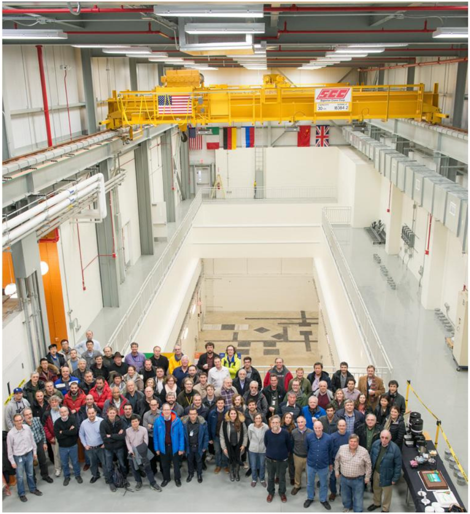
Sensitivity



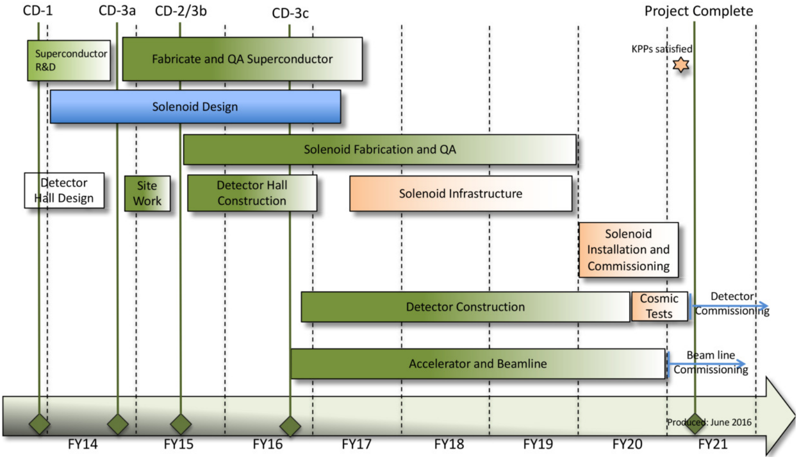
- Discovery reach (5σ): $R_{\mu e} \geq 2\text{x}10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8\text{x}10^{-17}$

Construction

Construction



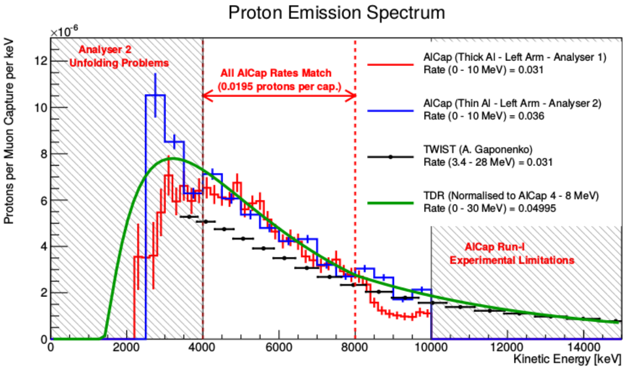
Schedule



CD-1
CD-3a
CD-2/3b
CD-3c
Project Complete
Superconductor R&D
Fabricate and QA Superconductor
KPPs satisfied
Solenoid Design
Solenoid Fabrication and QA
Detector Hall Design
Site Work
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Construction
Cosmic Tests
Detector Commissioning
Accelerator and Beamline
Beam line Commissioning
Produced: June 2016
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

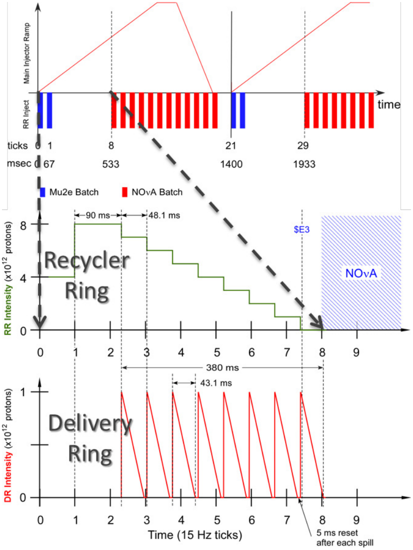
Backup

AlCap



- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al

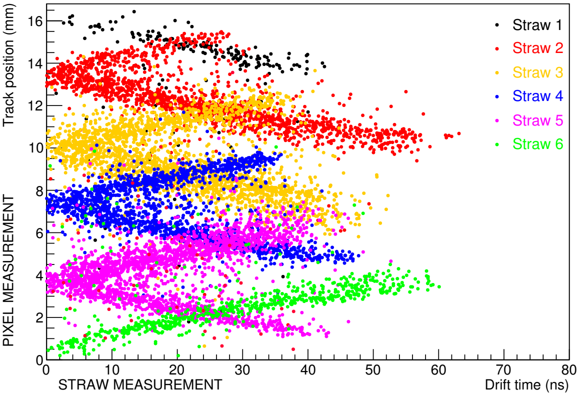
Beam structure



Beam requirements

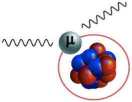
	Parameter	Design Value	Requirement	Unit
	Total protons on target	4.7×10^{20}	$\geq 4.7\times10^{20}$	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
	Maximum variation in pulse separation	< 1	10	nsec
	Spill duration	43.1	> 20	msec
	Beamline Transmission Window	230	< 250	nsec
	Transmission Window Jitter (rms)	< 5	<10	nsec
	Out-of-time extinction factor	1.6×10^{-12}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.9×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
	Target rms beam divergence	0.5	< 4.0	mrad

Tracker prototype



Stopping Target Monitor measures capture rate

- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement



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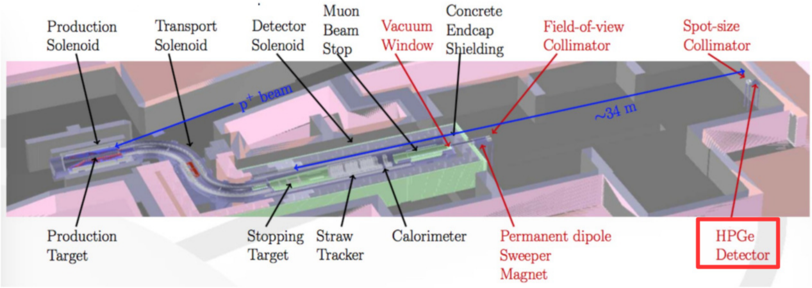
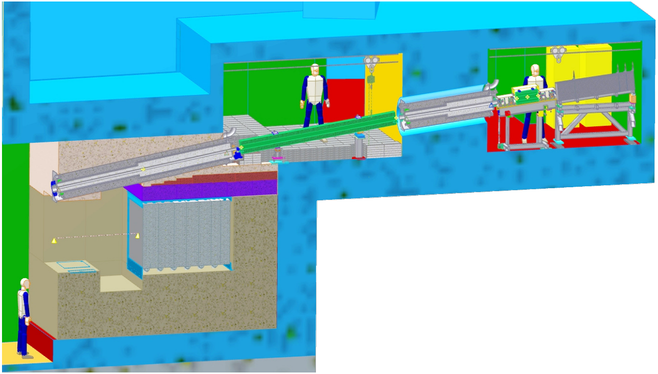


Extinction Monitor located downstream of production target



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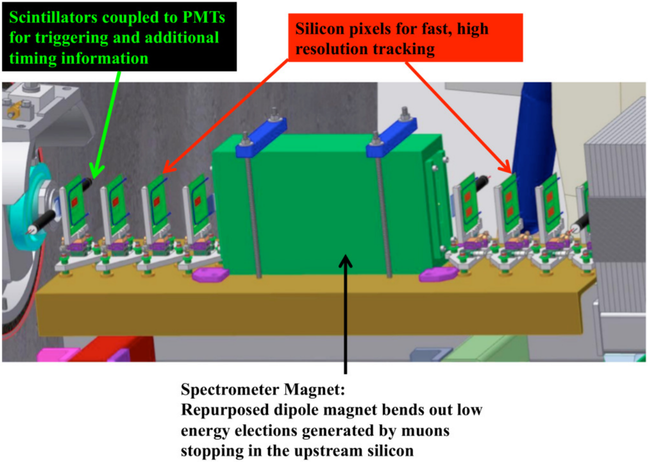
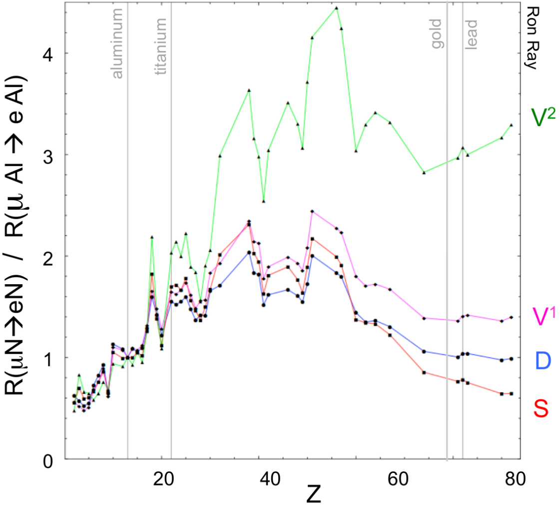


Types of CLFV measurements

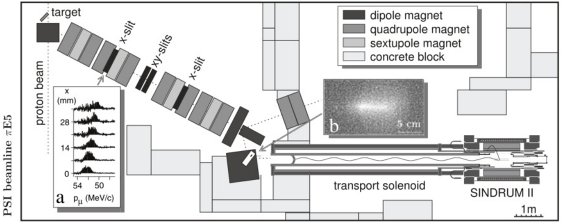
Process	Current Limit	Next Generation exp.
$\tau \to \mu\eta$	BR $<$ 6.5 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \to \mu\gamma$	BR $<$ 6.8 E-8	
$\tau \to \mu\mu\mu$	BR $<$ 3.2 E-8	
$\tau \to$ eee	BR $<$ 3.6 E-8	
$K_L \to e\mu$	BR $<$ 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR $<$ 1.3 E-11	
$B^0 \to e\mu$	BR $<$ 7.8 E-8	
$B^+ \to K^+ e\mu$	BR $<$ 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR $<$ 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR $<$ 1.0 E-12	10^{-16} (PSI)
$\mu^- N \to e^- N$	$R_{\mu e} <$ 7.0 E-13	10^{-17} (Mu2e, COMET)

Determining model with CLFV

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)

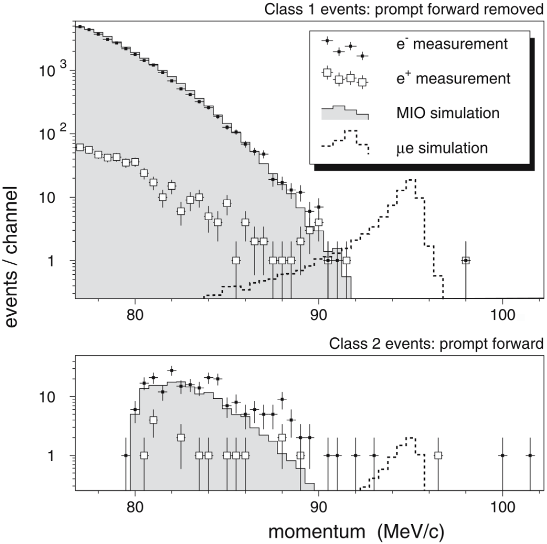


Previous experiments: SINDRUM II

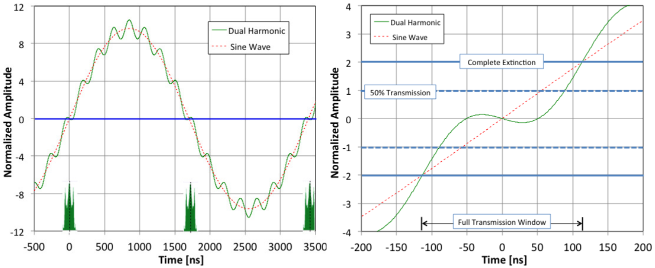


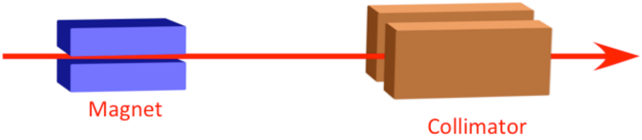
- Beam backgrounds reduced by degrader
  - Pions have half the range in CH_2 compared to muons
- Limit: 7×10^{-13} (90% confidence) on Au

Previous experiments: SINDRUM II



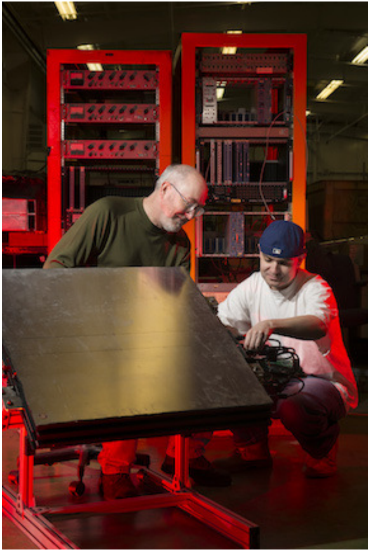
Achieving required beam extinction





- Beam from delivery ring starts with 10^{-4} extinction
- 2 AC dipoles coupled with collimators expected to bring extinction to 10^{-12}

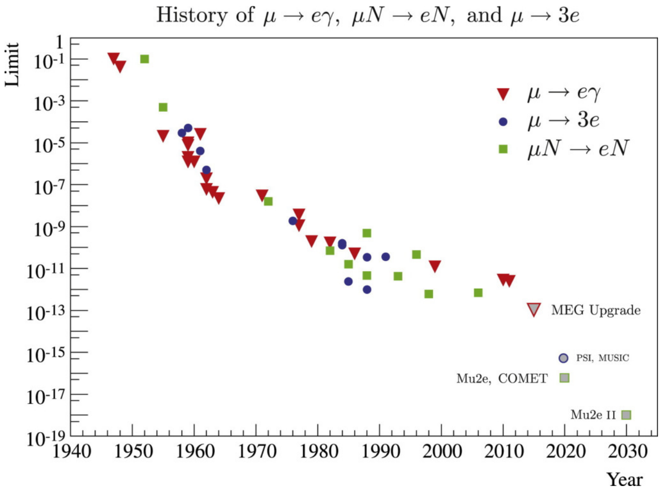
More prototypes



Cosmic ray veto

TS prototype module

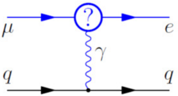
History

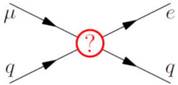


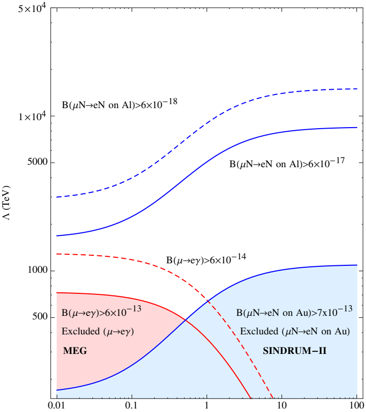
History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$
Limit
1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
Year
$\mu \to e\gamma$
$\mu \to 3e$
$\mu N \to eN$
MEG Upgrade
PSI, MUSIC
Mu2e, COMET
Mu2e II

CLFV Effective Lagrangian

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L \left(\sum_{q=u,d}\overline{q_L}\gamma^\mu q_L\right)$$







Bernstein, de Gouvea$^\kappa$

- loop: $\kappa \ll 1$, μN$\rightarrow$ eN and $\mu \rightarrow e\gamma$
- contact: $\kappa \gg 1$, μN$\rightarrow$ eN only
- Complementary to LHC: can probe mass scales up to 10^4 TeV