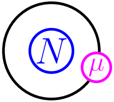
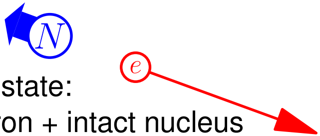
The Mu2e experiment

Andrei Gaponenko (Fermilab)
on behalf of the Mu2e Collaboration

$\mu \to e$ conversion:



Initial state:
muonic atom at rest



Final state:
electron + intact nucleus

Conventional normalization: $R_{\mu e} = \Gamma(\text{conversion})/\Gamma(\text{capture})$

Theoretical features

- νSM: $R_{\mu e} \sim 10^{-52}$: no theory uncertainty
- Sensitivity to broad range of BSM models

Plenary talk by S. Middleton

Experimental features

- Signal: electron at 104.97 MeV (Al)
- Single particle—scales well with μ rate

Extremely powerful probe of BSM

Mu2e goals

- Aim for a factor of 10 increase in the mass reach
  - Think Tevatron-to-LHC like advancement
- Best previous measurement (SINDRUM II, gold nucleus): $R_{\mu e} < 7 \times 10^{-13}$ 90% CL [Eur.Phys.J C47(2006)]
- Indirect search: must improve sensitivity by 10^4
  - Single event sensitivity goal 3×10^{-17}
- Many models predict $\mu N \rightarrow eN$ signal in this range!

Theory reviews:

Y. Kuno, Y. Okada, Rev.Mod.Phys. 73 (2001) 151–202

M. Raidal *et al.*, Eur.Phys.J. C57 (2008) 13–182

A. de Gouvêa, P. Vogel, Prog.Part.Nucl.Phys. 71 (2013) 75–92

L. Calibbi, G. Signorelli, Riv.Nuovo Cim. 41 (2018) no.2, 71–174

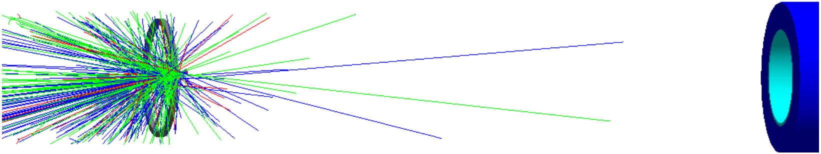
From SINDRUM II to Mu2e

- SINDRUM II:
  - $\mathcal{O}(10^7)$ muon stops per second
  - with $\mathcal{O}$(1 MW) proton beam
- Mu2e single event sensitivity goal 3×10^{-17}
- Need $\mathcal{O}(10^{18})$ muon stops
  - thousands years of data taking?
  - GW proton beam is not an option…

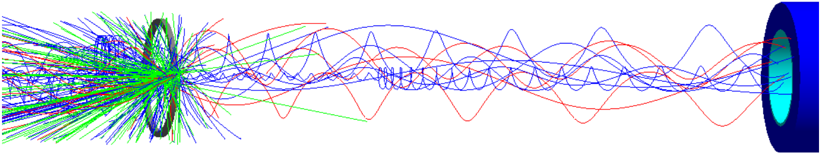
A more energy efficient way to get the rate

R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

Instead of this



Do this



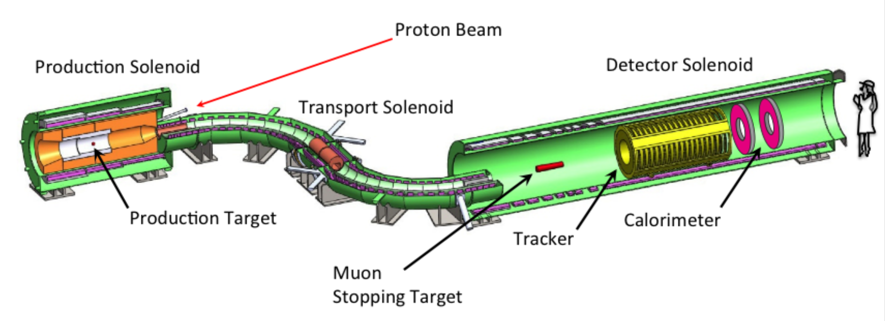
Solenoidal *B* field confines soft pions. Collect their muons.

Mu2e: $> 10^{10}$ μ^{-}/s from only 8 kW of protons!

The concept of the measurement

- Make muons
- Collect and stop them
- Wait for prompt backgrounds to decay
- Look for electrons at conversion energy

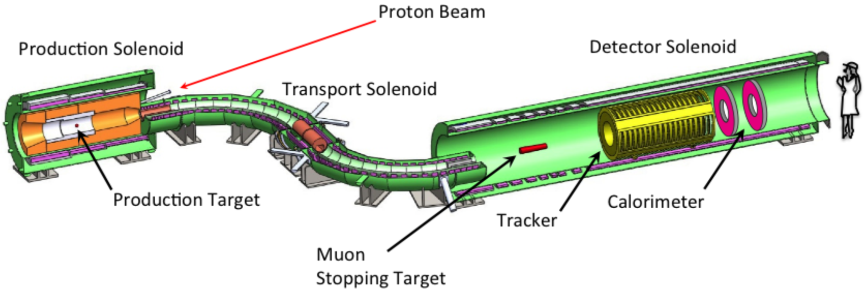
Mu2e setup



Muon beamline: B 4.5 $\longrightarrow$ 1 T, negative gradient
Tracker+calo region: uniform $B = 1$ T
Muon charge selection using a rotating collimator
Symmetric detectors: measure e^- and e^+

Not shown: Cosmic Ray Veto, beam Extinction Monitor, Stopping Target Monitor

Mu2e setup



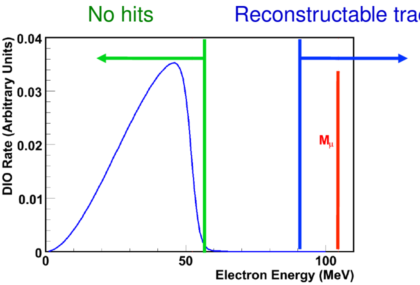
Muon beamline: B 4.5 $\longrightarrow$ 1 T, negative gradient
Tracker+calo region: uniform $B = 1$ T
Muon charge selection using a rotating collimator
Symmetric detectors: measure e^- and e^+

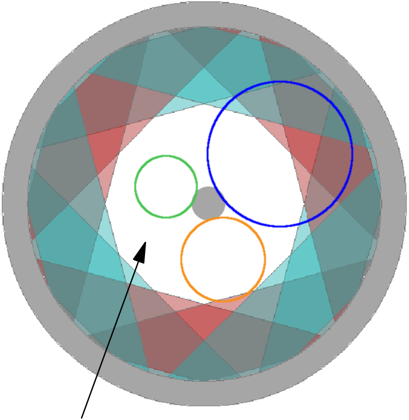
Not sho
Stoppi

- Measure pion background in data
- Search for $\Delta L = 2$ process $\mu^- N \to e^+ N'$

How to measure 3×10^{-17}

Be blind to most tracks: annular design

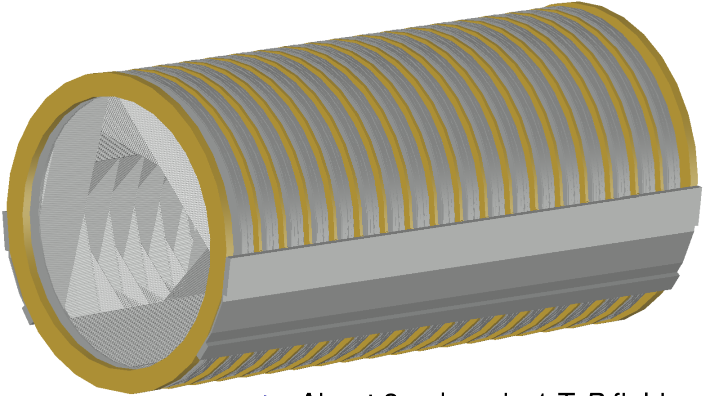




Vacuum: no scattering

Tracker

Precise momentum measurement

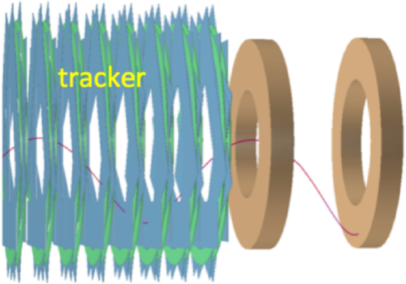


- About 3 m long in 1 T *B* field
- "Good" tracks make 1.5–2 turns
- Low mass straw tubes in vacuum

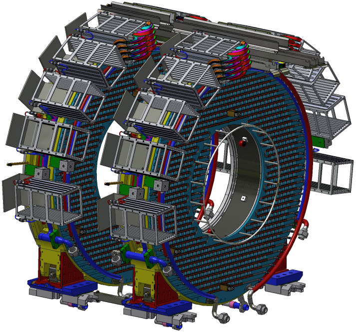
Calorimeter

Particle ID to suppress some backgrounds

Two disk geometry



CsI crystals, SiPM readout

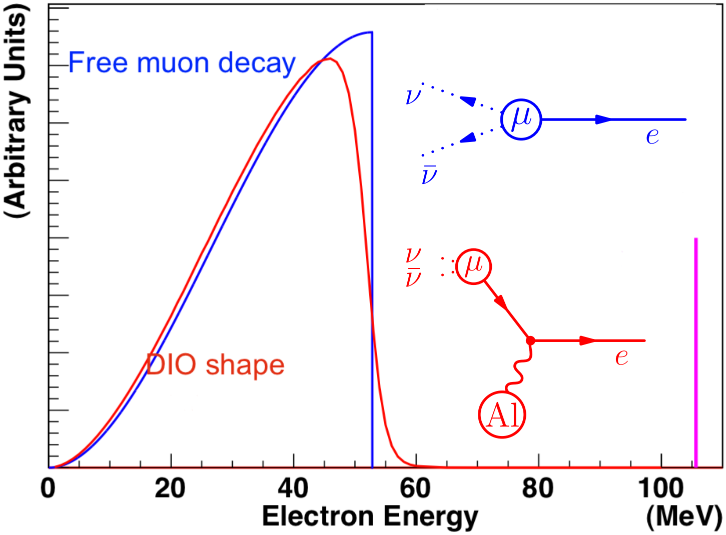


Also provides precise timing, alternate track seed.

Types of backgrounds

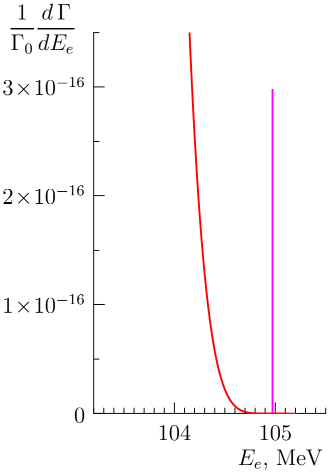
- Muon induced
  - Muon decay in orbit (DIO)
- Proton beam related
  - Radiative pion capture
  - Muon decay in flight
  - Pion decay in flight
  - Beam electrons
- Long transit through muon beamline
  - Antiprotons
- Cosmic rays

Decay electron spectra



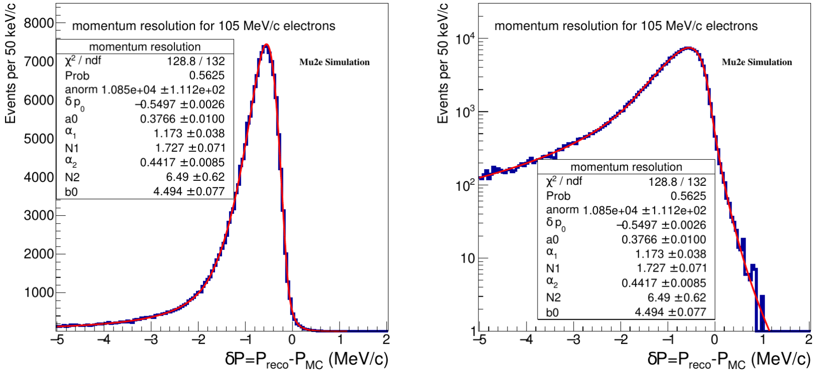
Decay in orbit

- Small, but steep tail
- Theory prediction: R. Szafron, A .Czarnecki, Phys. Rev. D**94**(2016)051301
- DIO electron differs from signal only by its momentum
- High tail of detector resolution pushes DIO “wall” into signal window
- Momentum resolution is critical!



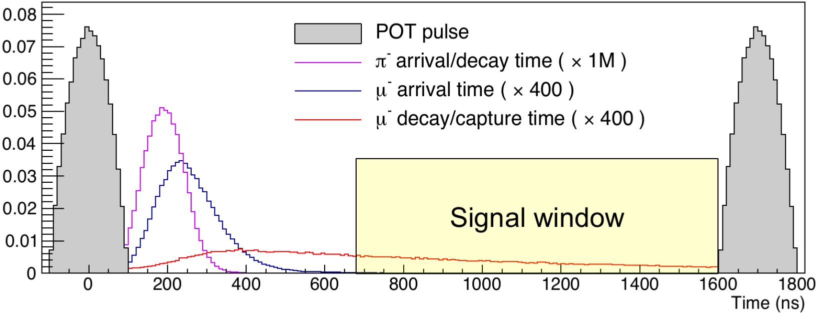
Tracker momentum resolution

Mu2e simulation*



Beam related backgrounds

Mu2e time structure



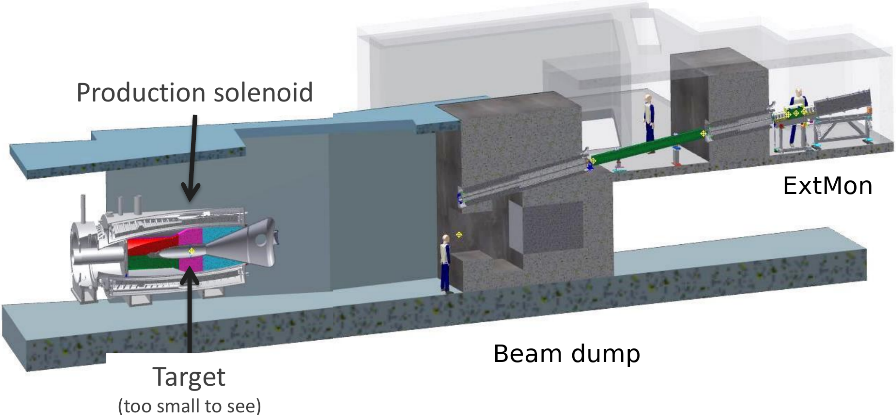
Proton pulse spacing $\approx 2 \times$ muonic Al lifetime $= 864$ ns

Beam extinction (fraction of protons between pulses):
Mu2e requires $\epsilon < 10^{-10}$

Need continuous monitoring of beam quality.

Mu2e beam extinction monitor

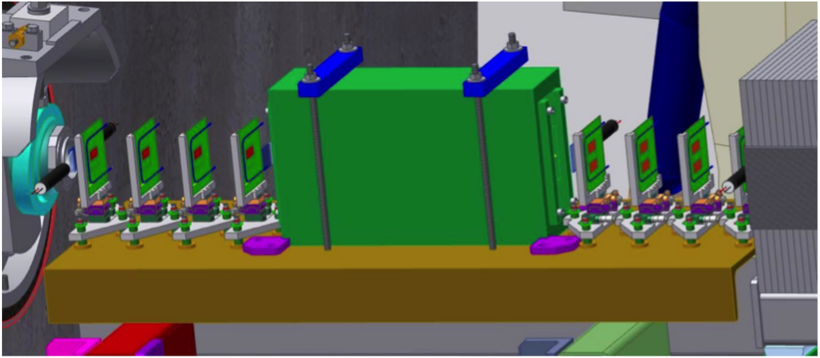
Observe charged secondaries from the production target, accumulate time profile



(The rest of Mu2e is off the slide to the left and away.)

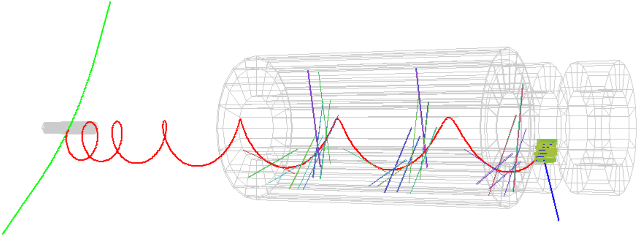
Extinction monitor detector

- Permanent magnet pixel spectrometer
- Based on ATLAS IBL silicon pixel chips



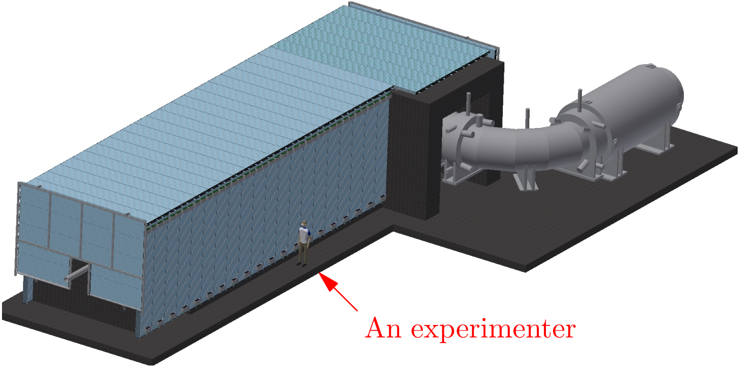
Cosmic background

- A cosmic muon track can look like a 105 MeV/c electron track
- A cosmic muon can decay, or knock out an electron from detector material

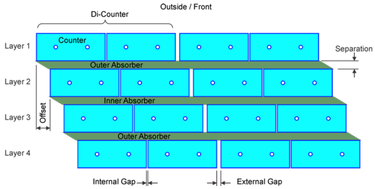


- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much coverage as possible

Cosmic Ray Veto



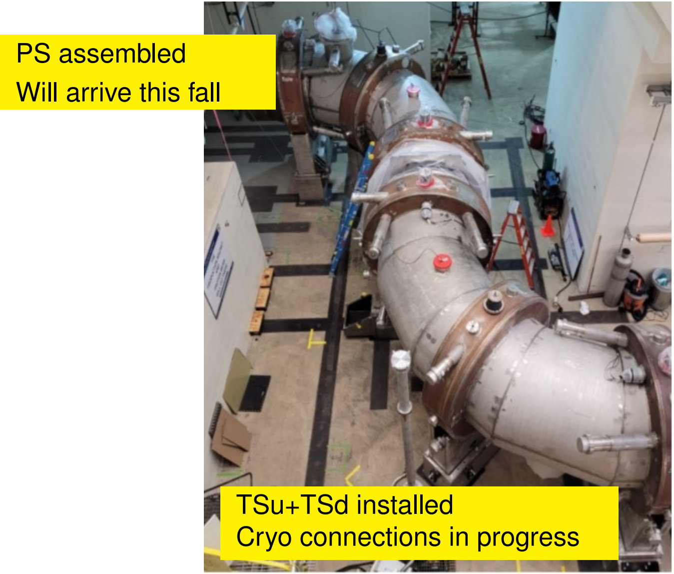
- Four layers of scintillator counters with aluminum absorbers
- SiPM readout
- Veto will be applied offline



Mu2e status

Solenoids

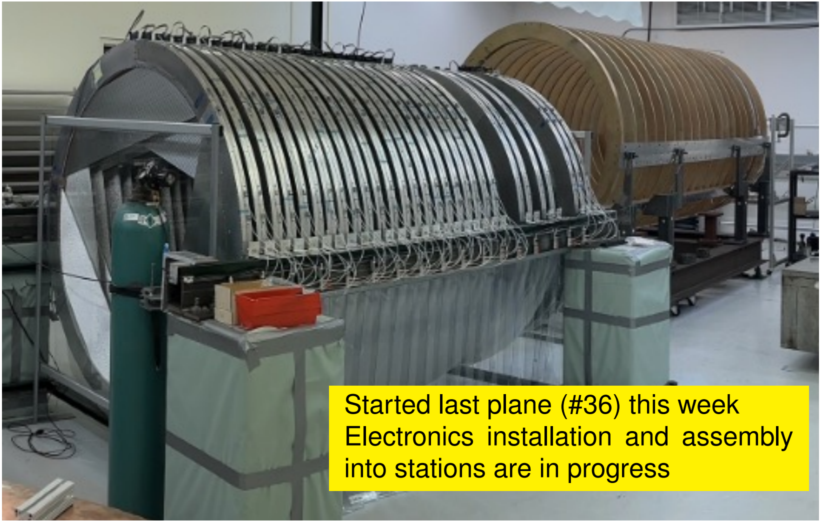
Solenoids


PS assembled
Will arrive this fall
TSu+TSd installed
Cryo connections in progress

Solenoids

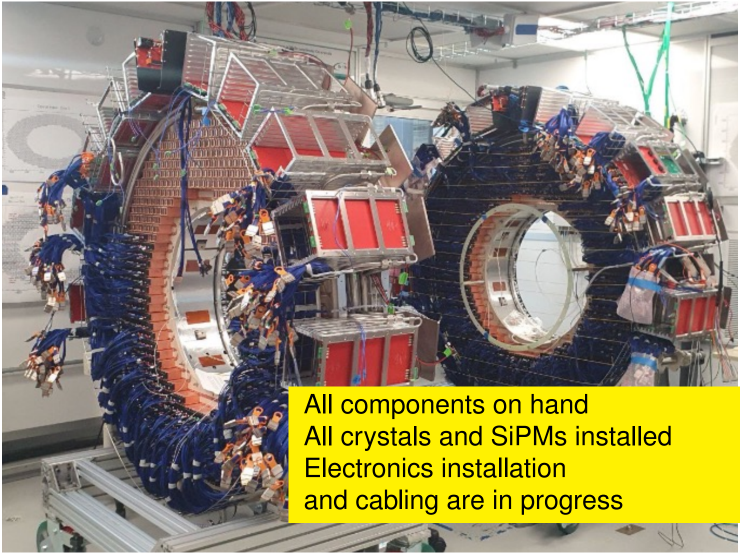

PS assembled
Will arrive this fall
DS cold mass ready
Arrival summer 2025
TSu+TSd installed
Cryo connections in progress

Tracker



Started last plane (#36) this week
Electronics installation and assembly into stations are in progress

Calorimeter



All components on hand
All crystals and SiPMs installed
Electronics installation
and cabling are in progress

Progress across all Mu2e areas

- All CRV module produced
- All Extinction Monitor planes produced
- Demonstrated readout from a part of each subdetector
- DAQ integration “global run” tests started this spring (subsets of channels)
- Started tests of proton beam slow extraction with final+prototype septum
- …

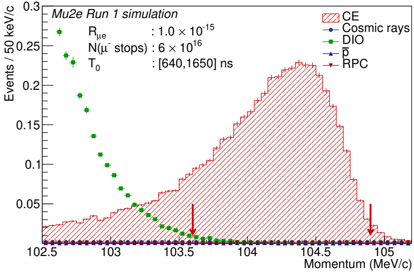
Mu2e schedule

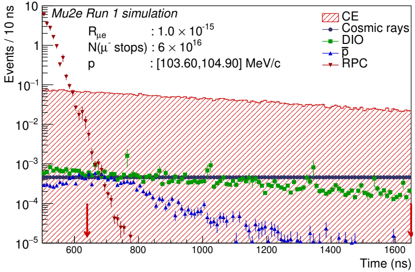
- Start cosmic ray commissioning of tracker, calorimeter, and part of CRV in Mu2e Hall in spring 2025. The detectors will be outside of the solenoid bore.
- Work on solenoid commissioning proceeds in parallel
- When solenoids are ready:
  - move tracker and calorimeter inside
  - commission in vacuum and with B field
  - keep taking cosmic ray data while finishing installation and waiting for beam
- Take Run I physics data with beam in 2027
- Resume after Fermilab Accelerator Long Shutdown that starts in 2028

Run I backgrounds and discovery reach

- Run I goal is $\times$ 1000 improvement over SINDRUM-II
- Expect single event sensitivity $R_{\mu e} = 2.4 \times 10^{-16}$ at ≈ 0.1 events background
- 5σ discovery for $R_{\mu e} = 1.5 \times 10^{-15}$ with 5 events
- or 90% CL limit of 6.2×10^{-16}

Universe **2023**, 9, 54





Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aim for $\times$ 10 mass scale reach improvement (4 orders of magnitude advance on the conversion rate with full dataset)
- Mu2e is completing detector and solenoid construction and entering the installation stage. On track to
  - Start cosmic commissioning in spring 2025
  - Take a year of physics data in 2027 (Run I)
- Expect 3 orders of magnitude improvement from Run I: $R_{\mu e} = 2.4 \times 10^{-16}$ single event sensitivity at ≈ 0.1 events background

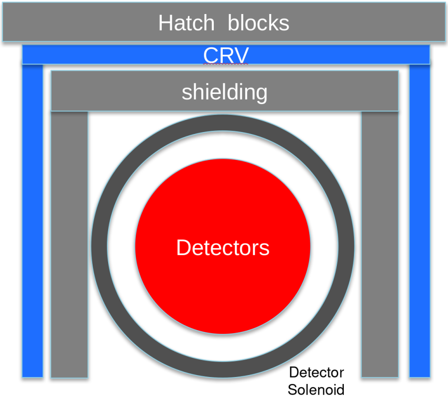
Extra slides

Mu2e Run I backgrounds

Universe **2023**, 9, 54

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	$0.046 \pm 0.010\ (\mathrm{stat}) \pm 0.009\ (\mathrm{syst})$
DIO	$0.038 \pm 0.002\ (\mathrm{stat})\ ^{+0.025}_{-0.015}\ (\mathrm{syst})$
Antiprotons	$0.010 \pm 0.003\ (\mathrm{stat})\ \pm 0.010\ (\mathrm{syst})$
RPC in-time	$0.010 \pm 0.002\ (\mathrm{stat})\ ^{+0.001}_{-0.003}\ (\mathrm{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\mathrm{stat})\ ^{+0.1}_{-0.3}\ (\mathrm{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

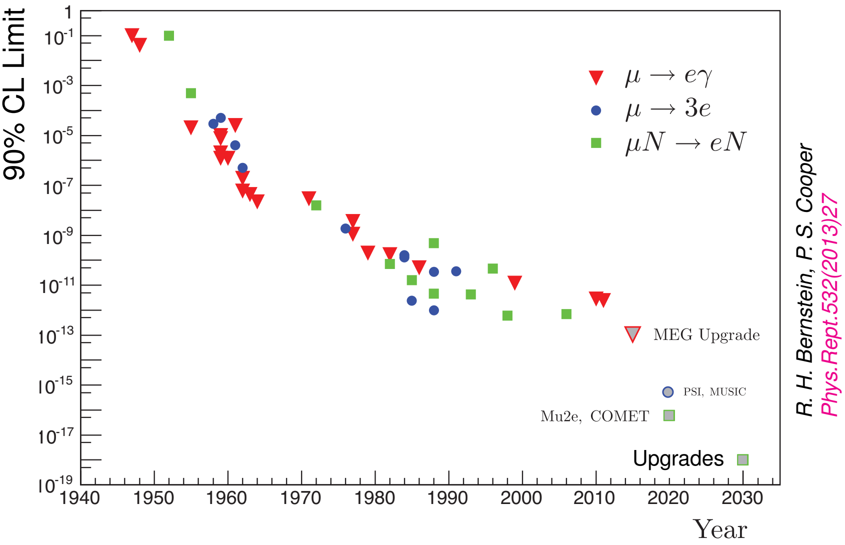
Items on the critical path to first physics



Component	Notes
Detector solenoid	Delivered, installed, cooled and powered
Inner detectors	Inserted into solenoid
External shielding	installation
Final focus	installation
Cosmic ray veto	Construct supports, install
Hatch blocks	Install
Accelerator readiness rev.	Before completion of hatch blocks
Beam to experiment	Soon after completion of hatch blocks

slide by B. Casey

History of muon CLFV searches…

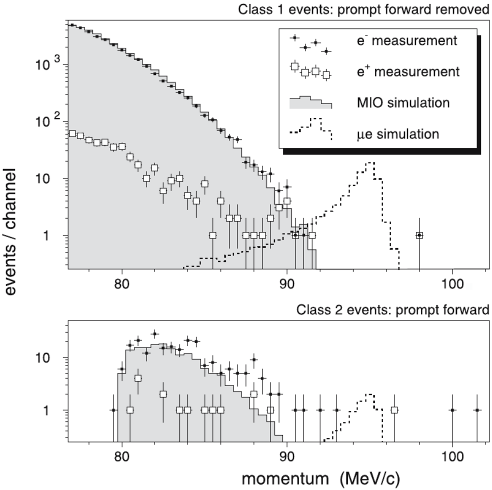


Current best $\mu N \to eN$ limit

SINDRUM II experiment at PSI

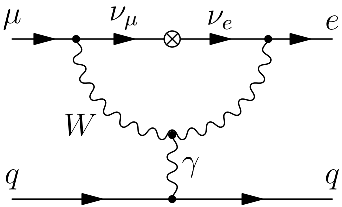
Conversion on gold:
$R_{\mu e} < 7 \times 10^{-13}$ 90% CL
[Eur.Phys.J C47(2006)]

Single event sensitivity
$S^1_{\mu e} = 2.5 \times 10^{-13}$



Expected rates

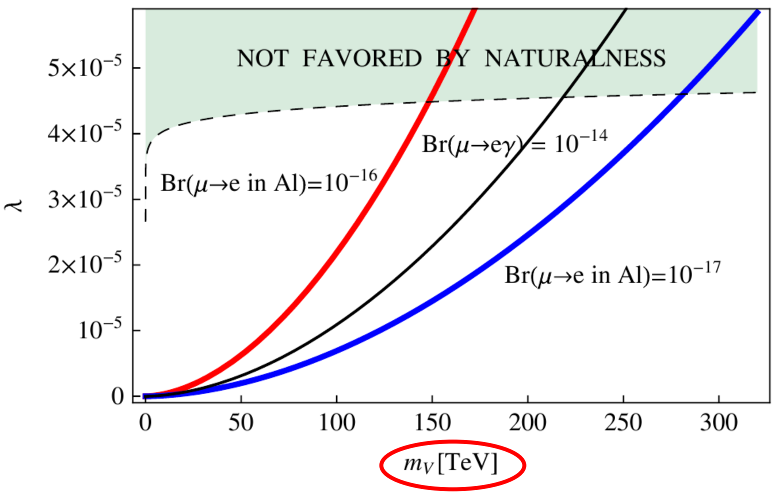
- SM: $R_{\mu e} = 0$
- νSM:
  $R_{\mu e} \propto (\Delta m_\nu^2 / M_W^2)^2 \approx 10^{-52}$



- Observation of $\mu \to e$ conversion would be an unambiguous signal of New Physics

Mu2e mass scale reach example

Combination of couplings vs scalar leptoquark mass



J.M. Arnold, B. Fornal, M.B. Wise
*Phys.Rev.**D88**(2013)035009*

The breadth of the physics reach

"Flavor physics DNA matrix":

Models →

↓ Observables

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

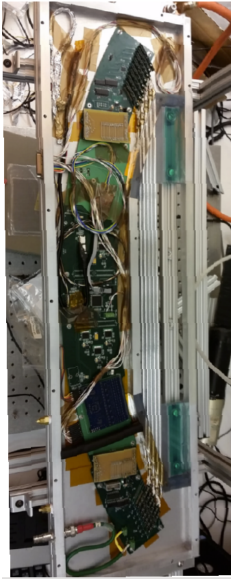
Altmannshofer, Buras, Gori, Paradisi, Straub
Nucl. Phys. B **830**, *17 (2010)*

$\mu \to e$: broad discovery sensitivity!

Understanding the tracker

First principle hit simulation

- Gas cluster formation
- Drift
- Avalanche amplification
- Signal propagation along the wire
- Analog and digital electronics response
  - Saturation, deadtime, cross-talk, bandwidth, electronics noise...
- Detector-like output hits
- Resolution and efficiency are emergent effects



Functional 8-straw prototype

Tracker energy loss calibration

Double-pass cosmic rays