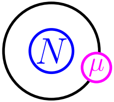
The Mu2e experiment

A search for charged lepton flavor violation in muon to electron conversion

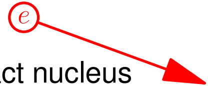
Andrei Gaponenko (Fermilab)
on behalf of the Mu2e Collaboration

BLV2019

$\mu \to e$ 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

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 change
- 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 $\mu N \to eN$ signal in this range!

Theory reviews:

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

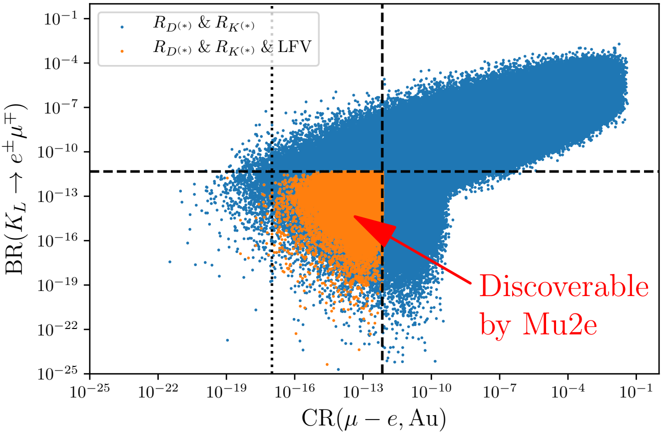
M. Raidal *et al.*, Eur.Phys.J. C57 (2008) 13–182

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

Fresh example—see the poster

Leptoquark explanation for the B anomalies.



C. Hati, J. Kriewald, J. Orloff, A.M. Teixeira, arXiv:1907.05511

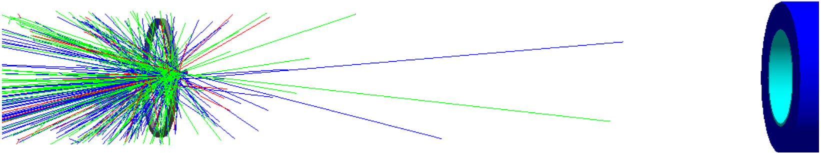
From SINDRUM II to Mu2e

- SINDRUM II:
  - $\mathcal{O}(10^7)$ muon stops per second
  - with $\mathcal{O}(1\ \text{MW})$ 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…

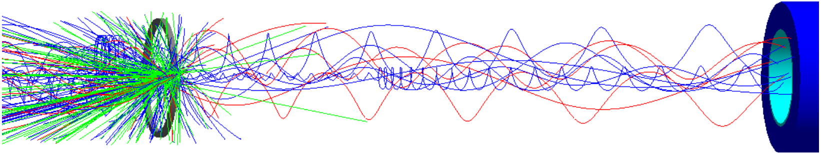
A more energy efficient way to get the rate

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

Instead of this



Do this



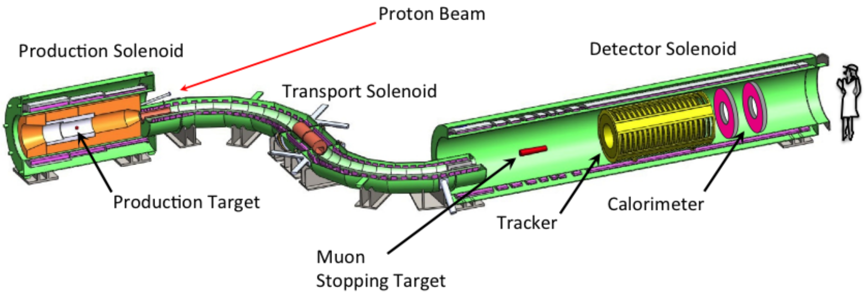
Solenoidal *B* field confines soft pions. Collect their muons.

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

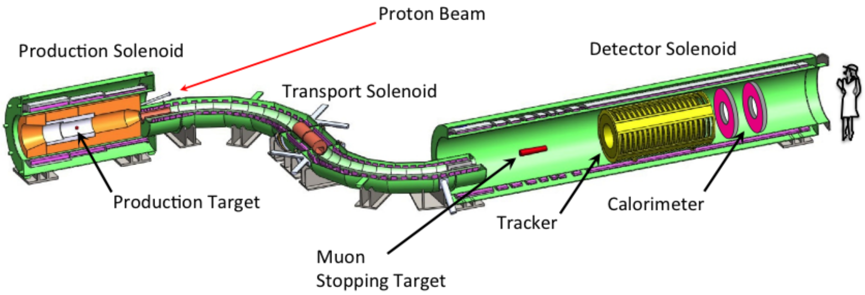
Mu2e setup



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
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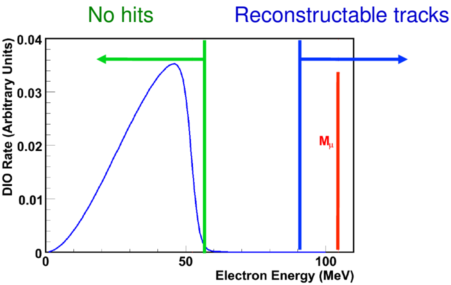
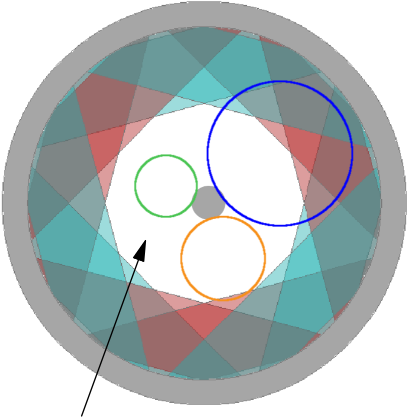
Not sh
Stoppi

- 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

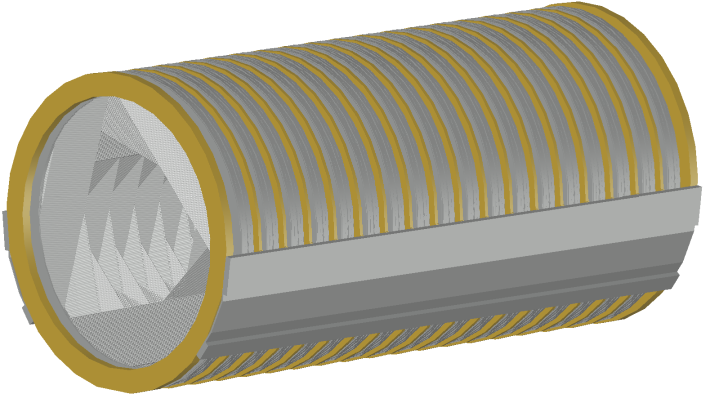




Vacuum: no scattering

Tracker

Precise momentum measurement

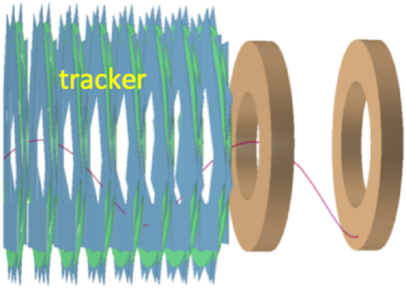


- About 3 m long in 1 T *B* field
- “Good” tracks make 1.5–2 turns
- Low mass straw tubes in vacuum

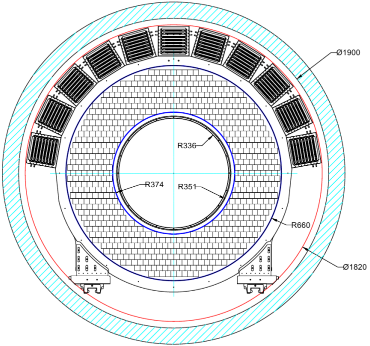
Calorimeter

Particle ID to suppress some backgrounds

Two disk geometry



CsI crystals, SiPM readout

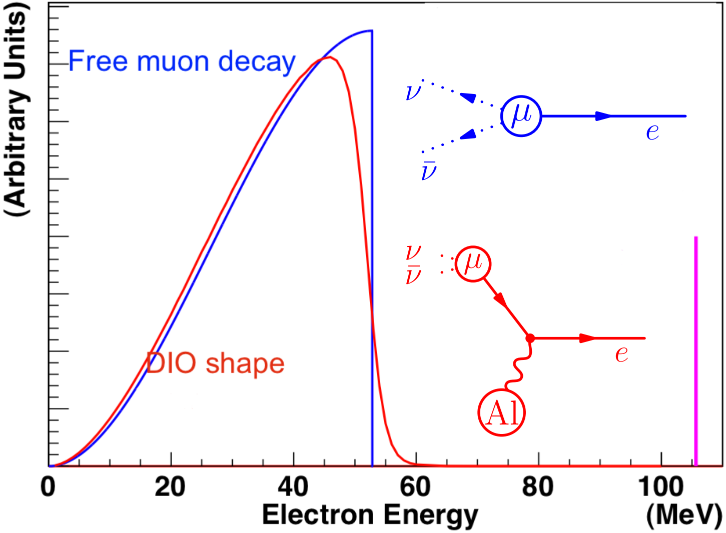


Also provides precise timing, alternate track seed.

Types of backgrounds

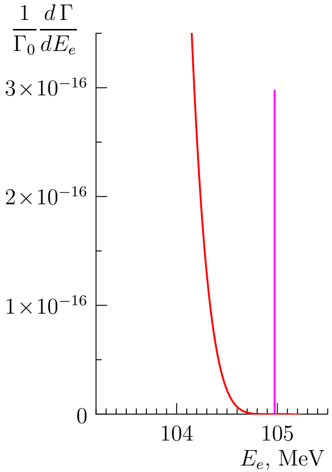
- Muon induced
  - Muon decay in orbit (DIO)
- Proton beam related
  - Radiative pion capture
  - Muon decay in flight
  - Pion decay in flight
  - Beam electrons
- Long transit through muon beamline
  - Antiprotons
- Cosmic rays

Decay electron spectra

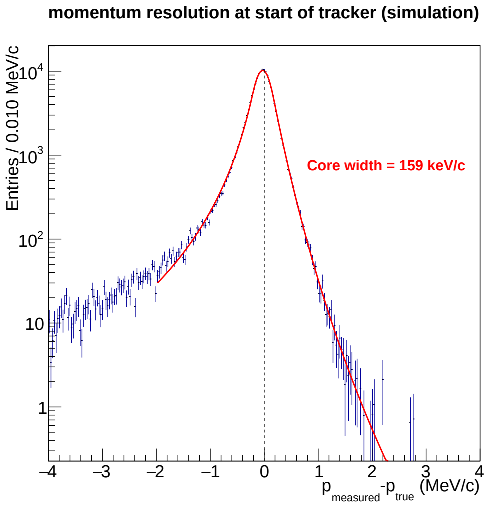


Decay in orbit

- 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!



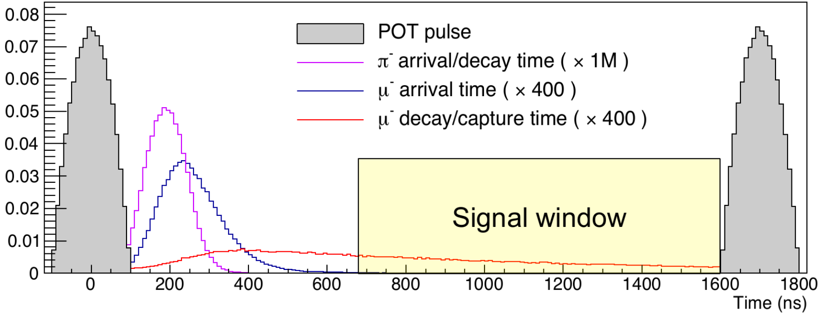
Tracker simulation tuned to prototype data



0.15% at 105 MeV/c

Beam related backgrounds

Mu2e time structure



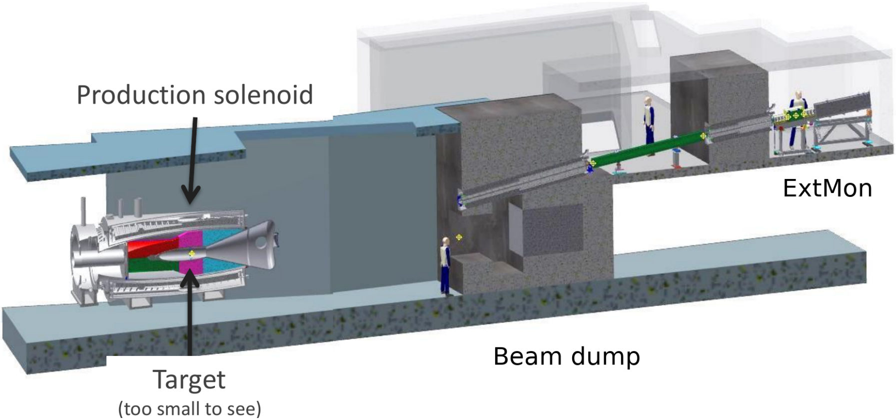
Proton pulse spacing $\approx 2 \times$ muonic Al lifetime $= 864$ ns

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

Need continuous monitoring of beam quality.

Mu2e beam extinction monitor

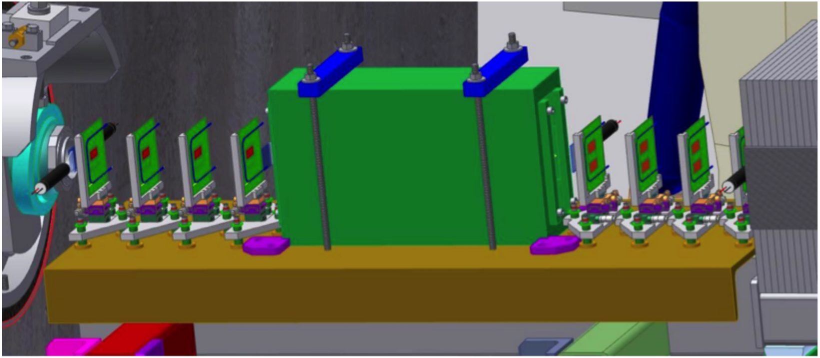
Observe charged secondaries from the production target, accumulate time profile



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

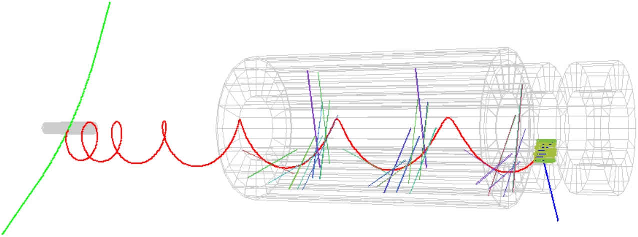
Extinction monitor detector

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



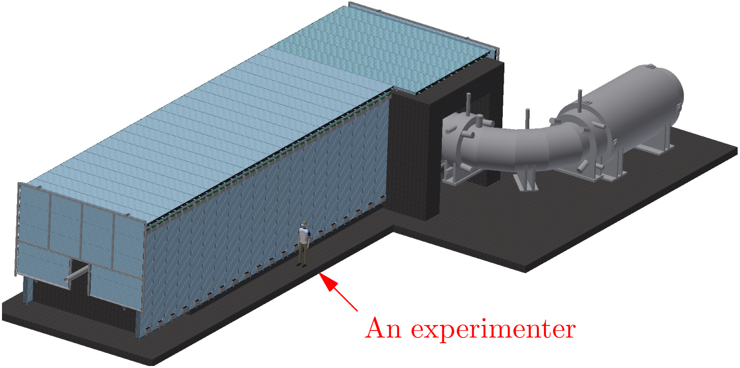
Cosmic background

- 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

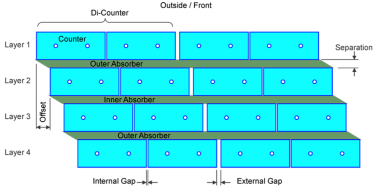


- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much coverage as possible

Cosmic Ray Veto



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



With statistics of 3.6×10^{20} POT

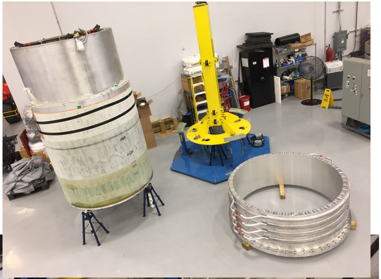
Process	Expected event yield
Cosmic ray muons	0.21 ± 0.06
DIO	0.14 ± 0.11
Antiprotons	0.04 ± 0.02
Pion capture	0.021 ± 0.002
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total background	0.41 ± 0.13(stat+syst)

5σ discoverable: median $R_{\mu e} = 2 \times 10^{-16}$
For no conversion 90% CL upper limit $R_{\mu e} < 8 \times 10^{-17}$

Mu2e status

Detector solenoid support installed

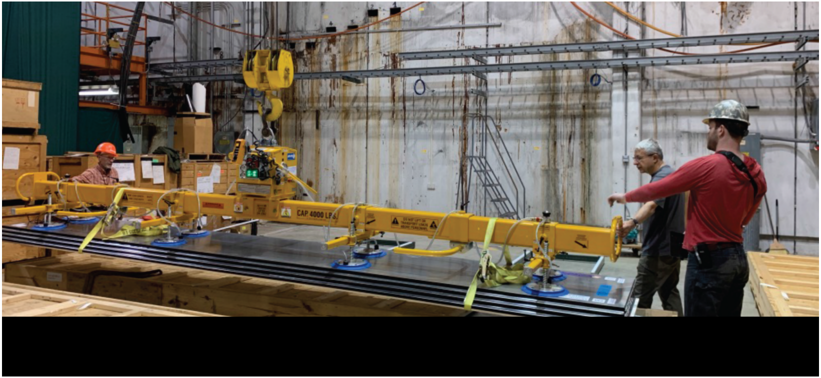
PS and DS production at vendor



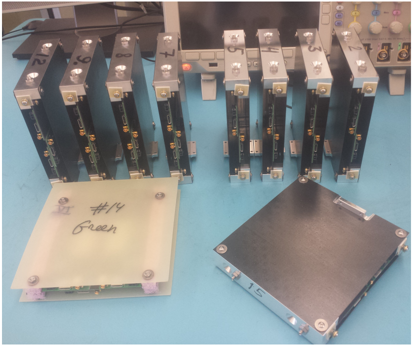
Transport solenoid at Fermilab

Tracker panel production

CRV



Extinction monitor

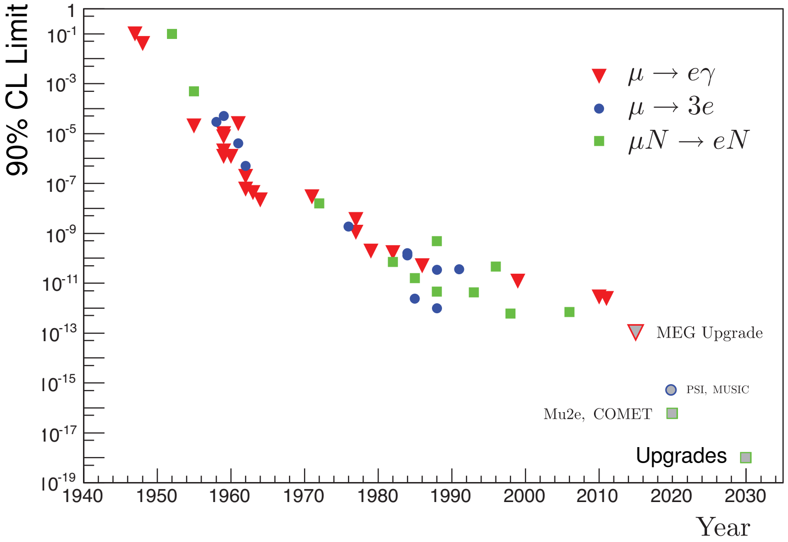


Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aims for $\times$ 10 mass scale reach improvement
  - 4 orders of magnitude advance on the conversion rate: $R_{\mu e} \approx 3 \times 10^{-17}$ single event sensitivity at $\approx$ 0.5 events background
- Mu2e is in intensive construction stage. Many things are done, many are still to do. We plan to
  - begin commissioning beam line (mid 2021)
  - begin commissioning detector (early 2022)
  - first physics data taking (early-mid 2023)
- 4-5 years of run time to collect our full data set. (Including calibrations, special runs, etc.)
- More information: `http://mu2e.fnal.gov`

Extra slides

History of muon CLFV searches. . .



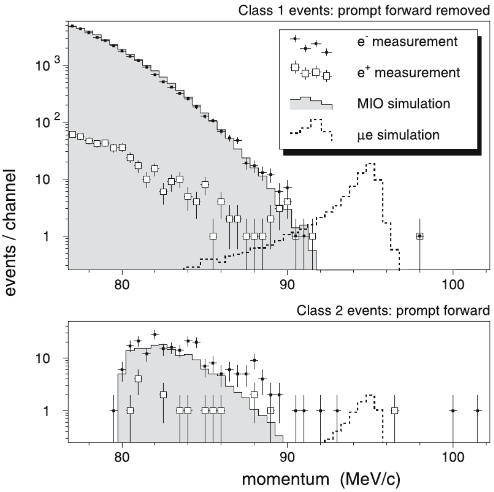
R. H. Bernstein, P. S. Cooper
Phys.Rept.532(2013)27

Current best $\mu N \to eN$ limit

SINDRUM II experiment at PSI

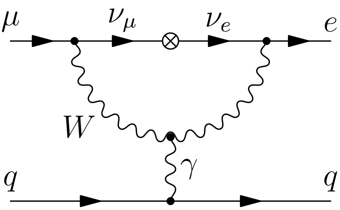
Conversion on gold:
$R_{\mu e} < 7 \times 10^{-13}$ 90% CL
[Eur.Phys.J C47(2006)]

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



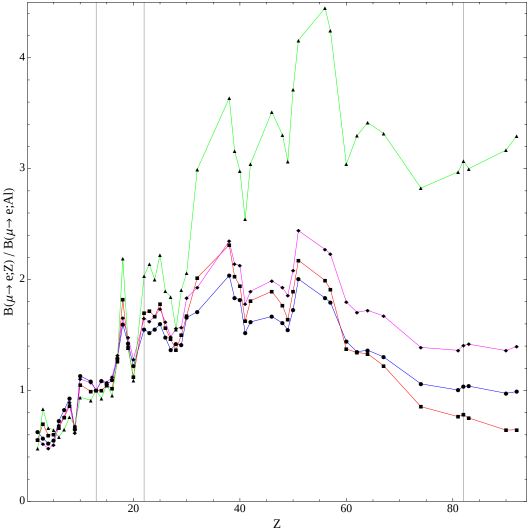
Expected rates

- 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

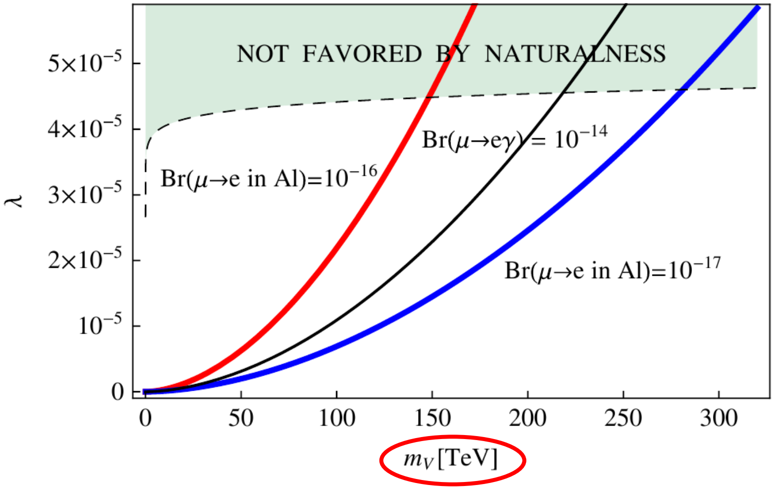
Target Z dependence



V. Cirigliano et al., Phys. Rev. D **80**, *013002 (2009)*

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 ↓

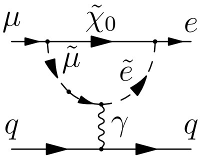
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s \gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^* \mu^+ \mu^-)$	★	★	★	★	★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

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

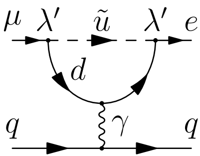
$\mu \to e$: broad discovery sensitivity!

Mu2e can discover

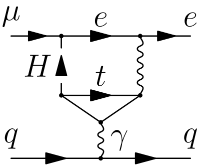
SUSY



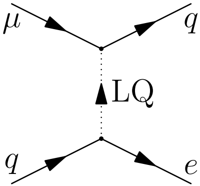
RPV SUSY



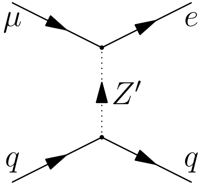
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

L. Calibbi, G. Signorelli, 2018

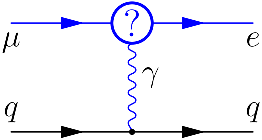
Effective theory

Parametrization: $\mathcal{L}_{CLFV} =$

$$\frac{m_\mu}{(1+\kappa)\,\Lambda^2}\,\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\,\Lambda^2}\,\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

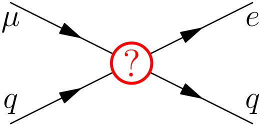
Λ: mass scale, κ: relative importance of contact term

Dipole: $\kappa = 0$



Often gives large $Br(\mu \to e\gamma)$

Contact: $\kappa = \infty$

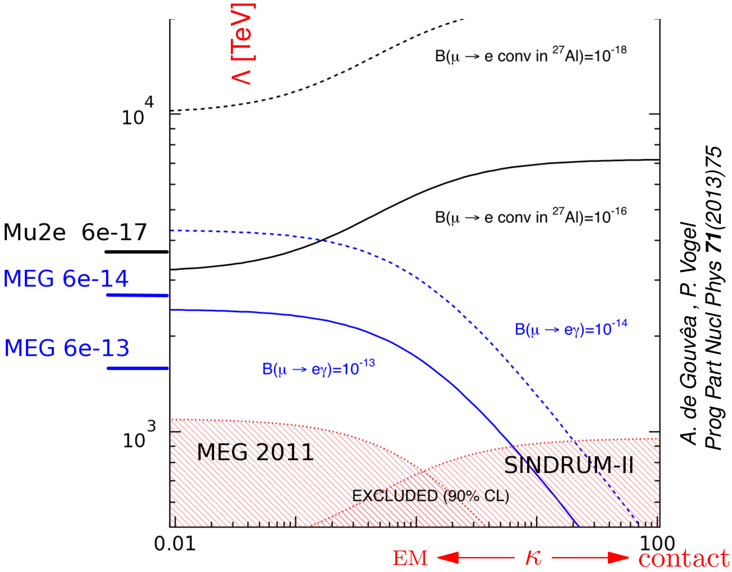


May be no $\mu \to e\gamma$ signal

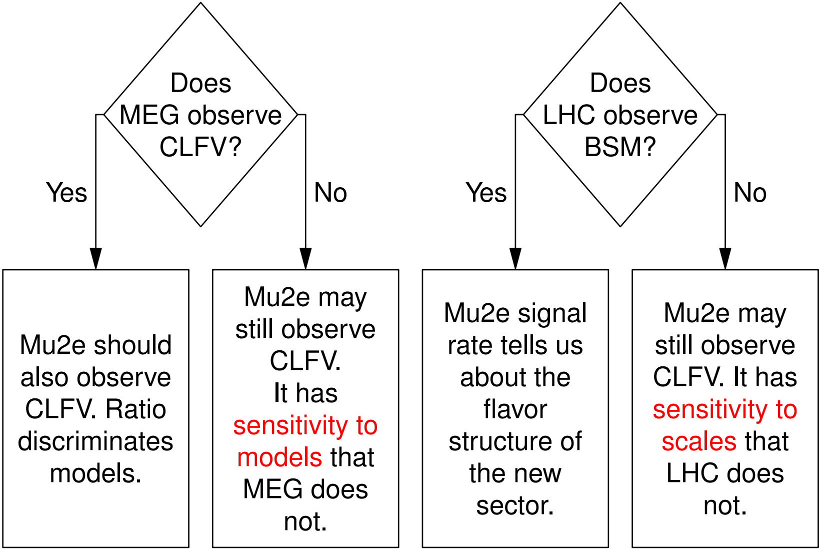
Relative rates of conversion and $\mu \to e\gamma$ are model dependent

Handle to discriminate New Physics models

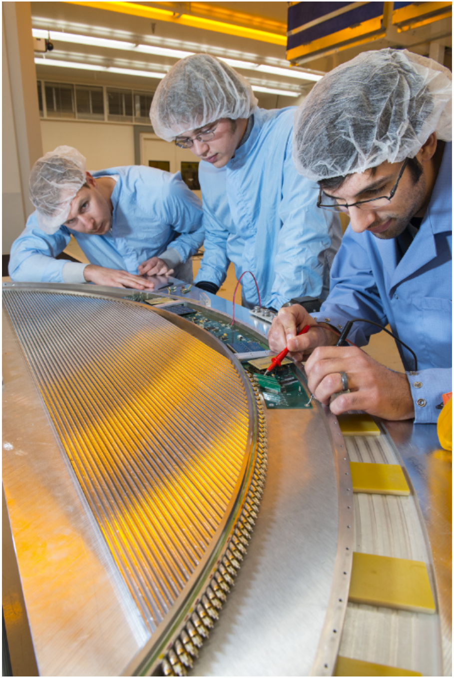
Muon LVF physics reach



Mu2e in different scenarios



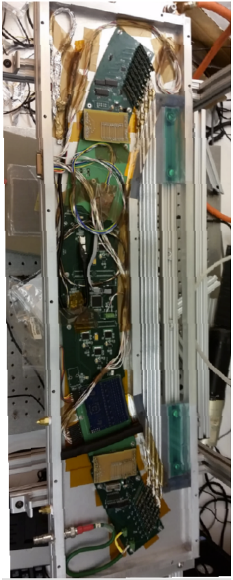
Work on prototype tracker panel



Understanding the tracker

First principle hit simulation

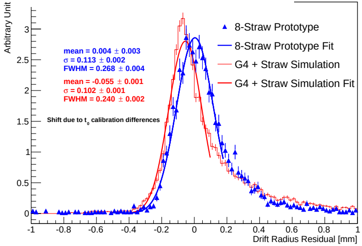
- Gas cluster formation
- Drift
- Avalanche amplification
- Signal propagation along the wire
- Analog and digital electronics response
  - Saturation, deadtime, cross-talk, bandwidth, electronics noise…
- Detector-like output hits
- Resolution and efficiency are emergent effects



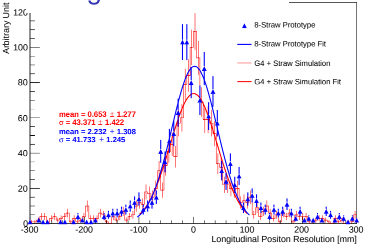
Functional 8-straw prototype

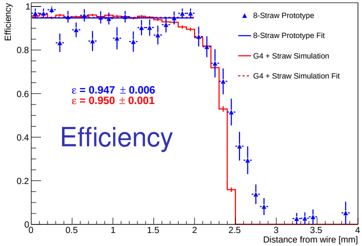
Tracker *hit* simulation vs prototype

Transverse resolution



Along wire resolution

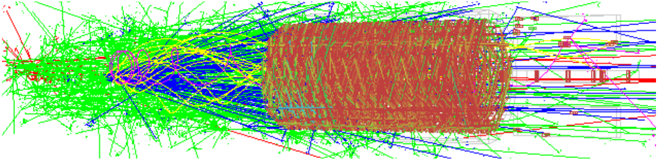




Compare PROTOTYPE measurements to SIMULATION

Mu2e *event* simulation (pile-up)

- Hit digitization is validated
- Beam pulse: 39M $\pm$ 50% protons
- Combine charge depositions and digitize

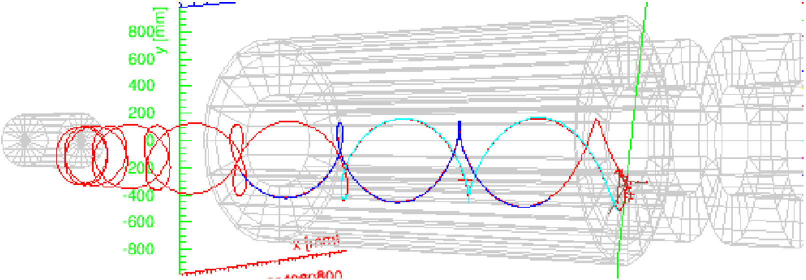


Particles and hits in 500–1695 ns time window

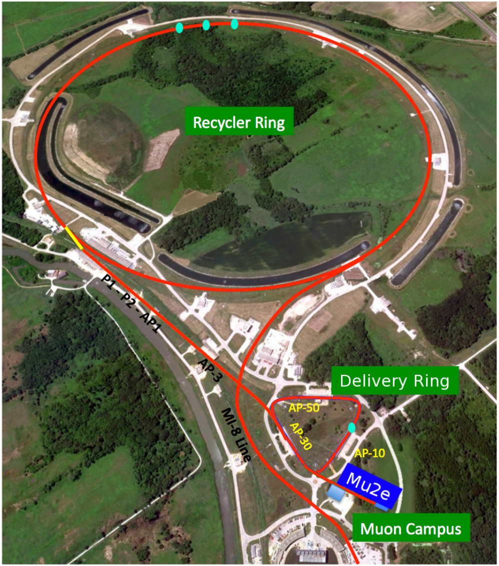
- Find and fit conversion tracks in mock data

Tracker energy loss calibration

Double-pass cosmic rays



Mu2e beam delivery

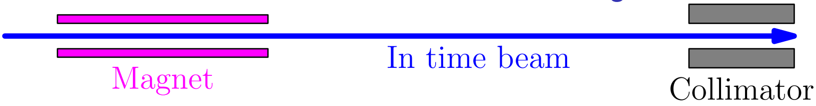


- A single beam bunch in the delivery ring at a time
- Revolution period is 1695 ns
- Resonant extractions "peels" a fraction of the bunch each turn
- Extracted beam: $\epsilon \approx 2 \times 10^{-5}$

How to get $\epsilon = 10^{-10}$

Start with $\epsilon = 2 \times 10^{-5}$ from the delivery ring

Deflect out of time beam with extinction magnets



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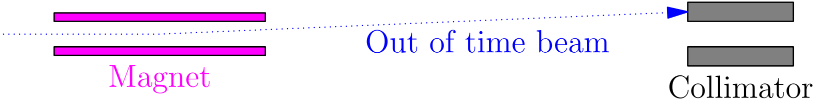
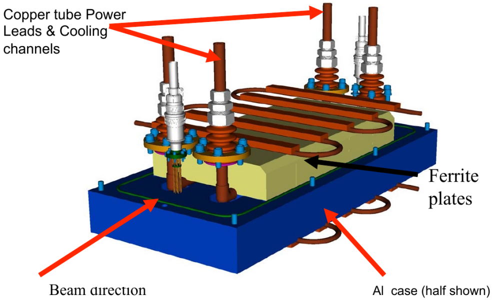
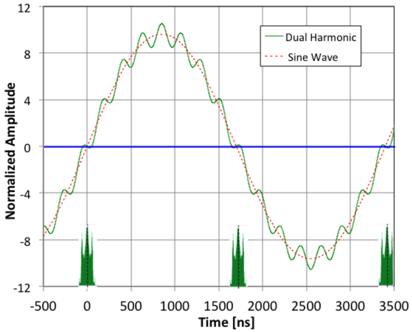


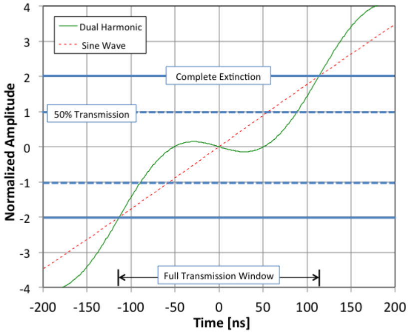
Achieving the extinction

- 0.6 MHz beam pulses
- Use resonant dipoles
- Optimized waveform and collimators
- 99.5% in-time transmission
- 5×10^{-8} extinction factor
- Final $\epsilon = 1.1 \times 10^{-12}$

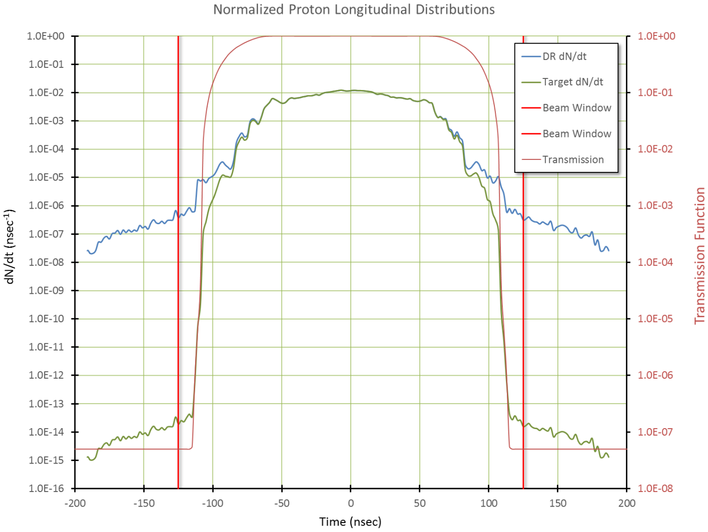


External extinction waveform

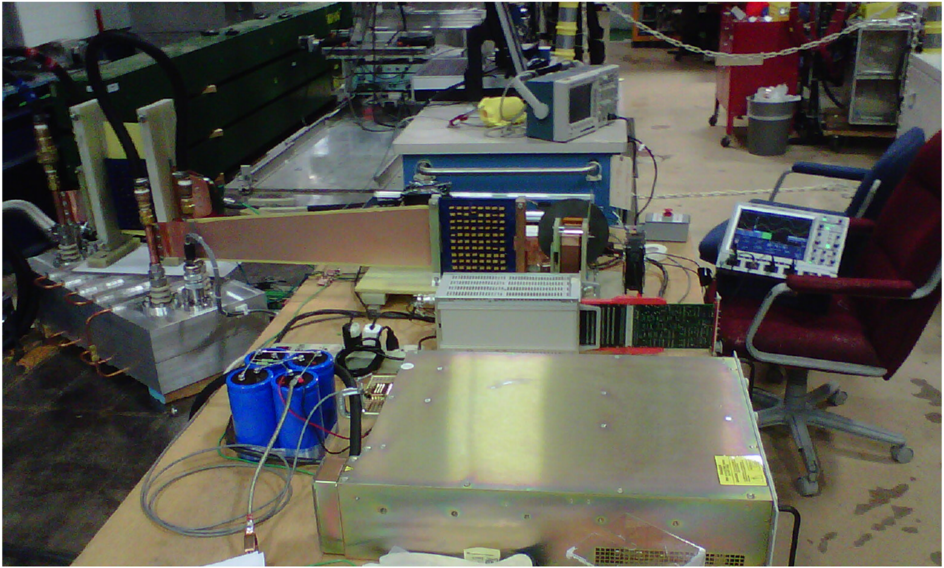




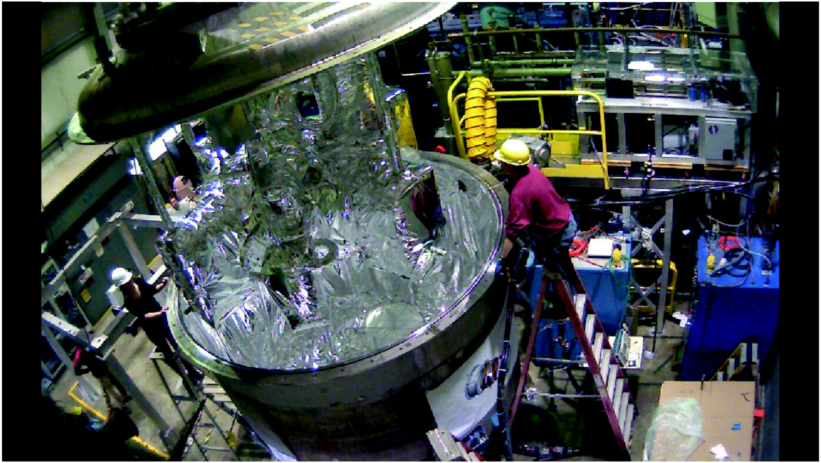
External extinction result



Testing extinction dipoles

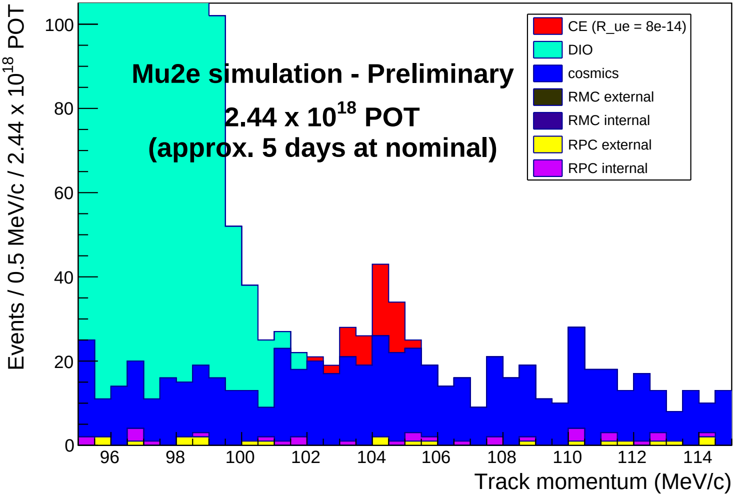


Cold test of a TS module



MCD2018

Triggered reconstructed tracks with cut on track quality



MCD2018

Triggered reconstructed tracks with cuts on track quality, geometry, PID, CRV, timing