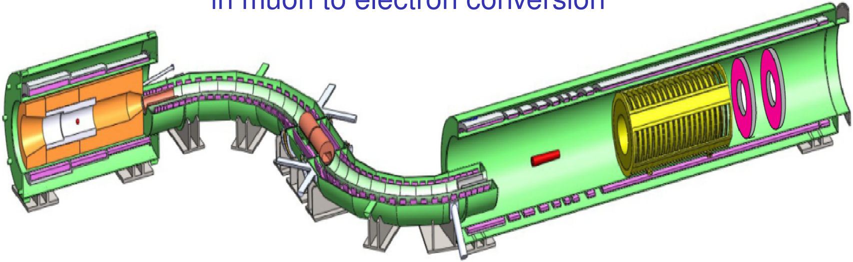
The Mu2e experiment

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



Andrei Gaponenko (Fermilab)
on behalf of the Mu2e Collaboration
http://mu2e.fnal.gov/collaboration.shtml

CLFV 2016

Mu2e collaboration

Over 200 scientists from 34 institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory University of California, Berkeley, University of California, Irvine, California Institute of Technology, City University of New York, Joint Institute for Nuclear Research, Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionali di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, INFN Genova, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce and Università del Salento, Lewis University, University of Louisville, Laboratori Nazionali di Frascati and Università Marconi Roma, University of Minnesota, Muons Inc., Northern Illinois University, Northwestern University, Novosibirsk State University/Budker Institute of Nuclear Physics, Institute for Nuclear Research, Moscow, INFN Pisa, Purdue University, Rice University, University of South Alabama, Sun Yat Sen University, University of Virginia, University of Washington, Yale University

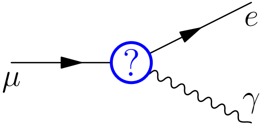
Outline

- What is muon to electron conversion
- Why search for it
- Mu2e approach to improving current best measurement
- Mu2e apparatus and performance
- Conclusion

Lepton flavor violation with muons

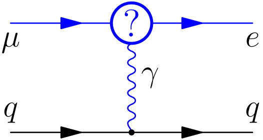
Options to conserve 4-momentum

Emit an on-shell photon



MEG talk by Cecilia

Recoil off a nucleus

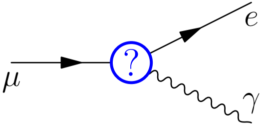


Muon to electron conversion

Lepton flavor violation with muons

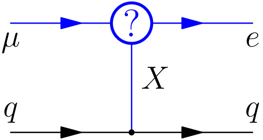
Options to conserve 4-momentum

Emit an on-shell photon



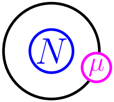
MEG talk by Cecilia

Recoil off a nucleus

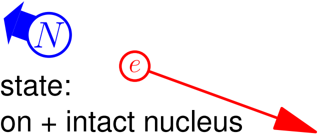


Muon to electron conversion

$\mu \longrightarrow e$ conversion:



Initial state:
muonic atom at rest



Final state:
electron + intact nucleus

- Kinematically allowed
- Violates lepton flavor conservation
- Signal is monoenergetic electron

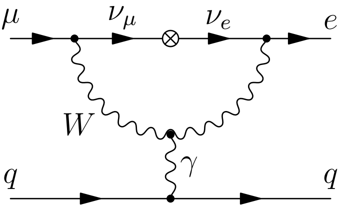
$$E_e = m_\mu - E_b - E_{\text{recoil}} \approx 104.97\ \text{MeV for Al}$$

- Conventional normalization to report results:

$$R_{\mu e} = \frac{\Gamma[\mu^- + N \rightarrow e^- + N]}{\Gamma[\mu^- + N \rightarrow \text{all captures}]}$$

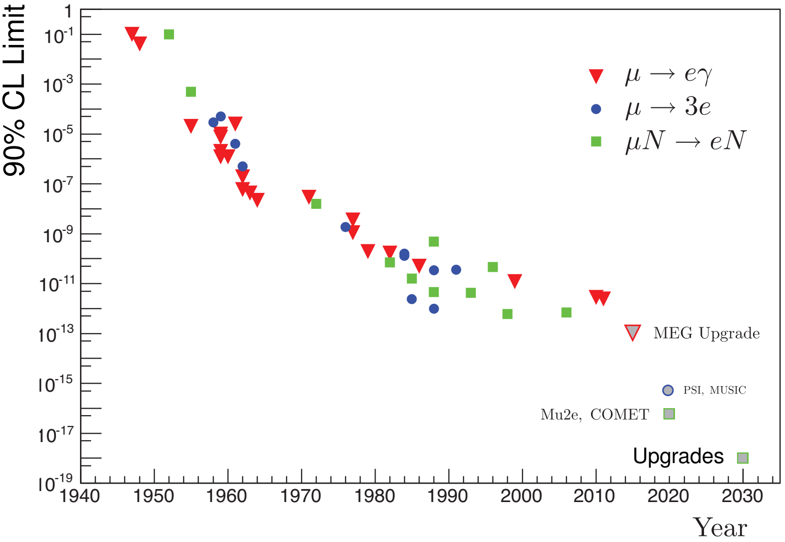
Expected rates

- 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

Past searches did not find anything. . .



R. H. Bernstein, P. S. Cooper

Phys.Rept.532(2013)27

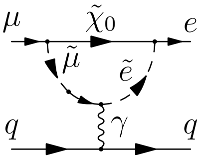
why is this still interesting?

Mu2e goals

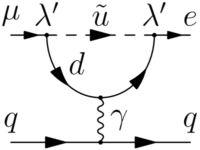
- Aim for a factor of 10 increase in the mass reach
  - Think Tevatron to LHC change
- Indirect search: must improve sensitivity by 10^4
  - Single event sensitivity goal 2.5×10^{-17}
- Leading New Physics models predict $\mu N \rightarrow eN$ signal in this range!

Mu2e can discover

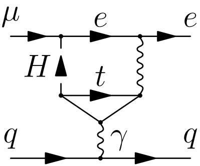
SUSY



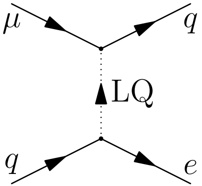
RPV SUSY



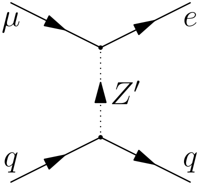
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

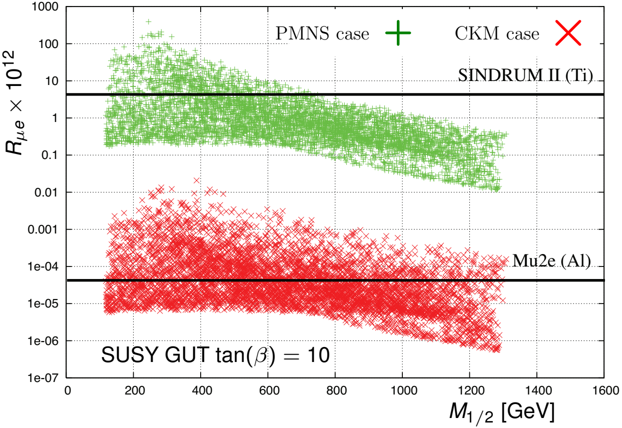
Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

$\mu N \to eN$ and the LHC

Scan of “LHC accessible” SUSY parameter space

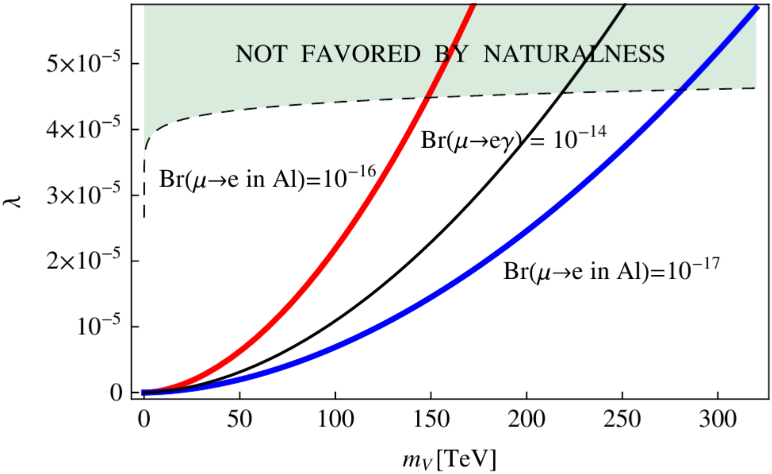


Calibbi, Faccia, Masiero, Vempati, *Phys.Rev.**D74** (2006) 116002*

Signal in Mu2e if LHC sees this SUSY. Or if it does not.

Mu2e mass scale reach example

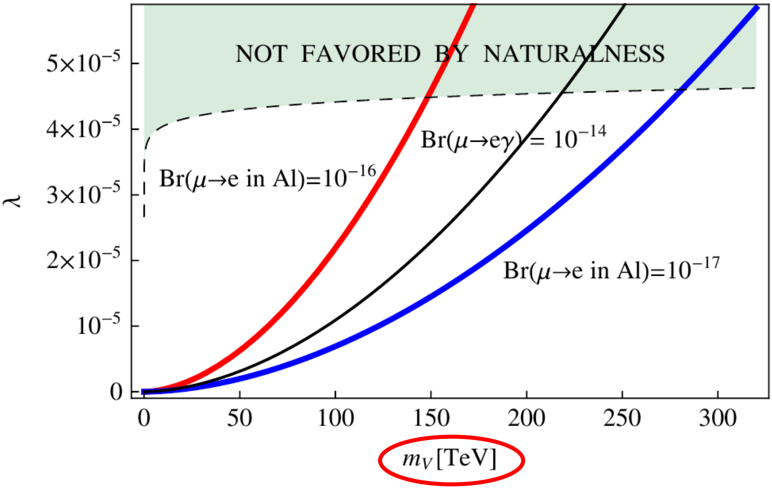
Combination of couplings vs scalar leptoquark mass



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

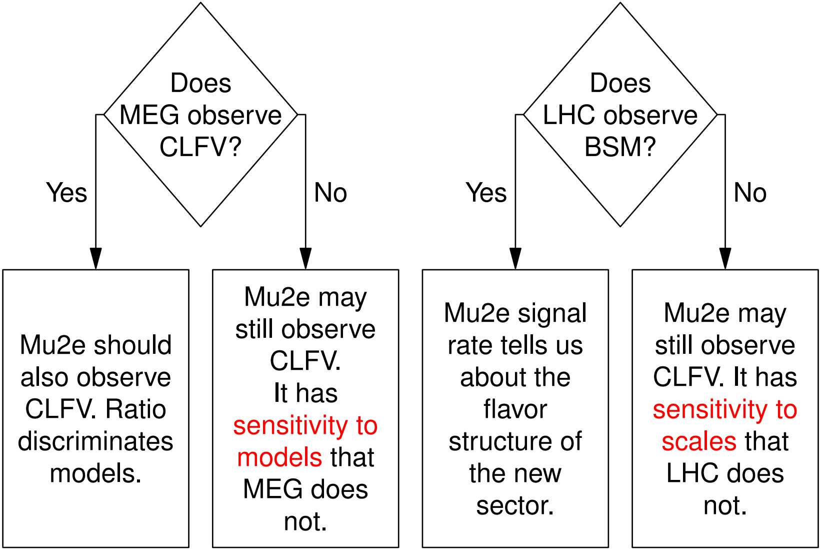
Mu2e mass scale reach example

Combination of couplings vs scalar leptoquark mass



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

Mu2e in different scenarios



Does MEG observe CLFV?

Yes

No

Mu2e should also observe CLFV. Ratio discriminates models.

Mu2e may still observe CLFV. It has sensitivity to models that MEG does not.

Does LHC observe BSM?

Yes

No

Mu2e signal rate tells us about the flavor structure of the new sector.

Mu2e may still observe CLFV. It has sensitivity to scales that LHC does not.

Outline

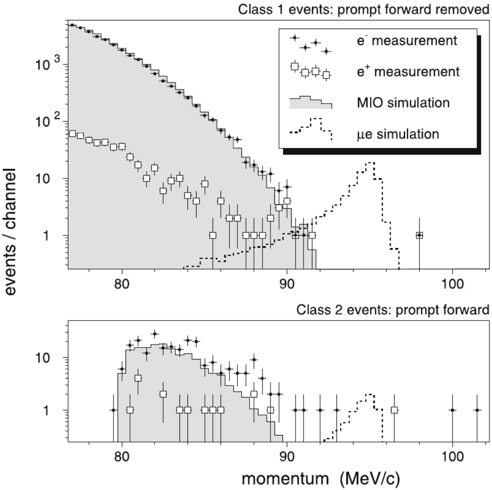
- What is muon to electron conversion
- Why search for it
- Mu2e approach to improving current best measurement
- Mu2e apparatus and performance
- Conclusion

Current best $\mu N \rightarrow eN$ 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
$S^{1}_{\mu e} = 2.5 \times 10^{-13}$



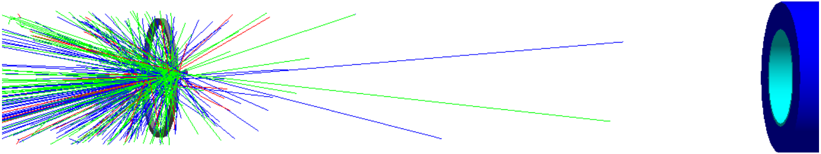
From SINDRUM II to Mu2e

- Mu2e single event sensitivity goal 2.5×10^{-17}
- Need $\mathcal{O}(10^{18})$ muon stops
- SINDRUM II: $\mathcal{O}(10^{7})$ muon stops per second
  - thousands years of data taking
- With PSI's 1.3 MW proton beam
  - GW proton beam is also not an option…

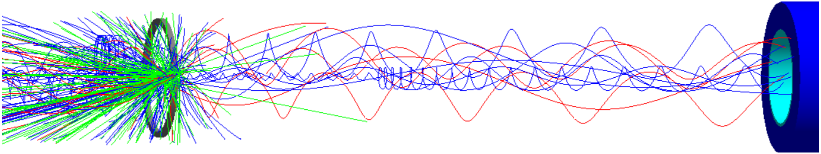
More energy efficient way to get the rate

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.

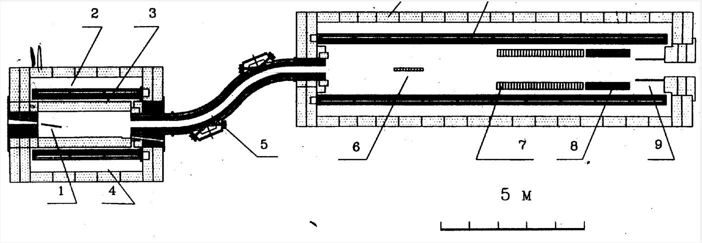
Mu2e: $> 10^{10}$ μ^-/s from only 8 kW of protons!

More energy efficient way to get the rate

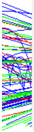
R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys **49**, 384 (1989)

Instead of this

1992 MELC experiment proposal



Dc

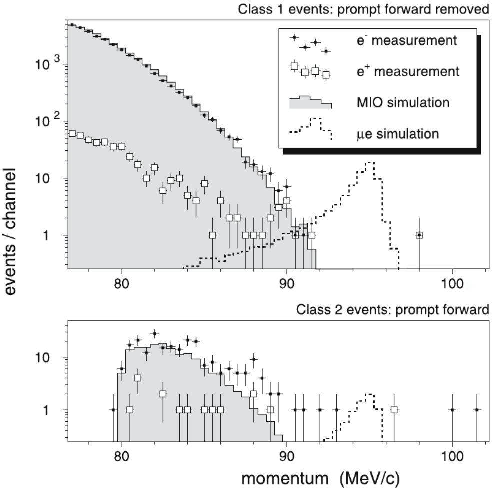


Solenoidal *B* field confines soft pions. Collect their muons.

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

From SINDRUM II to Mu2e: backgrounds

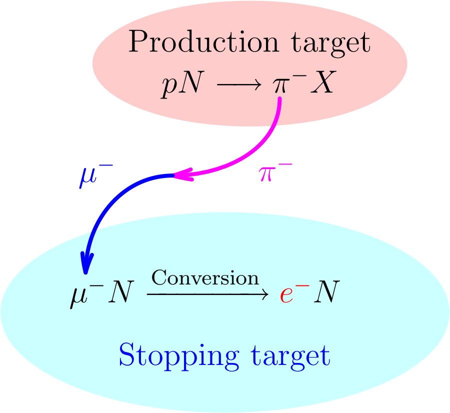
- $\mathcal{O}(1)$ background events in SINDRUM
- Likely caused by pions or cosmic rays
- $\Longrightarrow$ $\mathcal{O}(10^4)$ in Mu2e without improvements



Backgrounds

Focus on pions for now

- Secondary beam starts with π^-
- The intent is to produce μ^- rate



Production target

$pN \longrightarrow \pi^- X$

μ^-

π^-

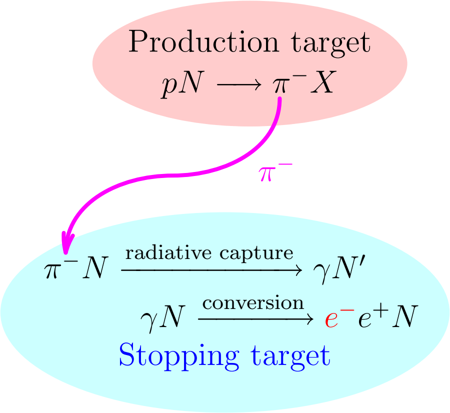
$\mu^- N \xrightarrow{\text{Conversion}} e^- N$

Stopping target

Backgrounds

Focus on pions for now

- Secondary beam starts with π^-
- The intent is to produce μ^- rate
- Non-decayed pions can create electrons with conversion signal momentum
- This background is charge symmetric—if we see e^+ there is a problem



Production target

$$pN \longrightarrow \pi^- X$$

π^-

$$\pi^- N \xrightarrow{\text{radiative capture}} \gamma N'$$

$$\gamma N \xrightarrow{\text{conversion}} e^- e^+ N$$

Stopping target

The concept of the measurement

SINDRUM II

- Make muons
- Collect and stop them
- Look for electrons at conversion eneregy

Mu2e

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

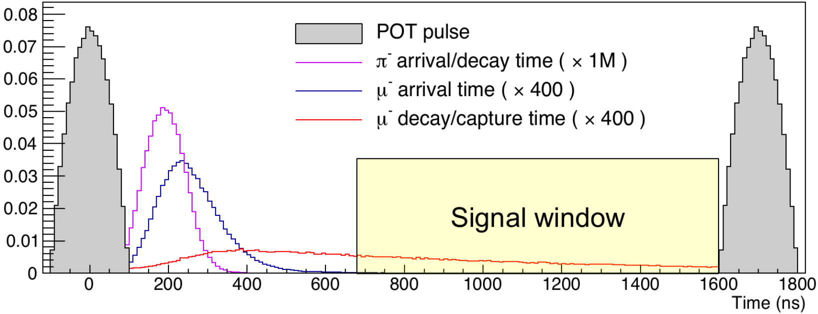
π lifetime is 26 ns

PSI beam pulses: 19.75 ns

Mu2e beam pulses: 1695 ns
Muonic Al lifetime: 864 ns

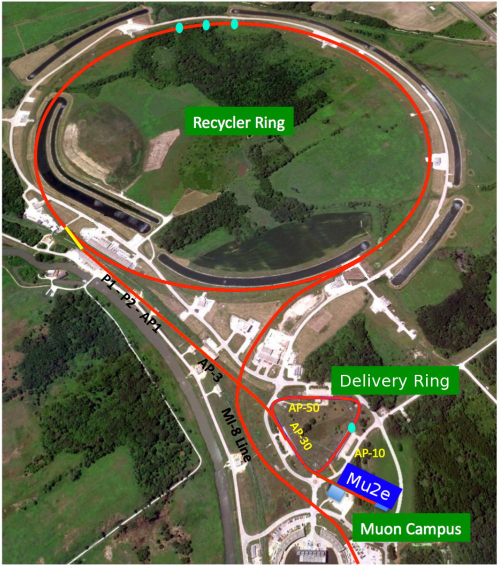
Mu2e also has to to improve on other backgrounds (cosmic, decay in orbit. . .)

Mu2e beam time structure



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

Mu2e beam delivery

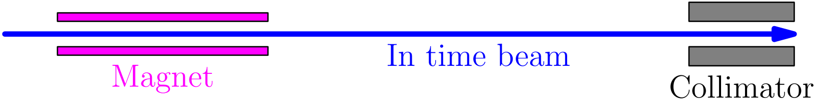


- A single beam bunch in the delivery ring at a time
- Revolution period is 1695 ns
- Resonant extractions “peels” a fraction of the bunch each turn
- Extracted beam: $\epsilon \approx 2 \times 10^{-5}$

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

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

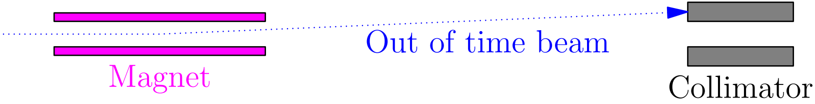
Deflect out of time beam with extinction magnets



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

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

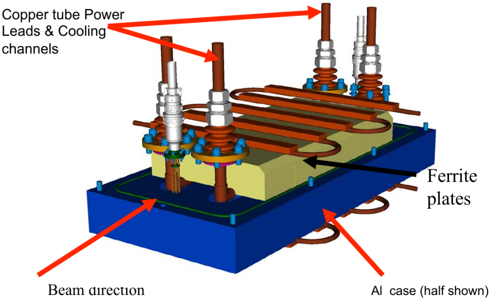
Deflect out of time beam with extinction magnets



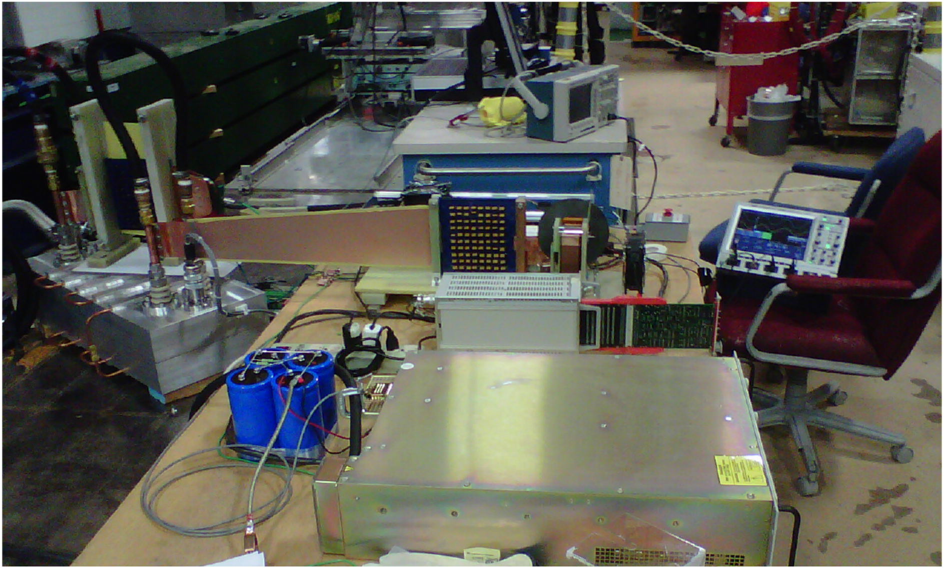
Achieving the extinction

- 0.6 MHz beam pulses
- Use resonant dipoles
- Optimized waveform and collimators

- 99.5% in-time transmission
- 5×10^{-8} extinction factor
- Final $\epsilon = 1.1 \times 10^{-12}$

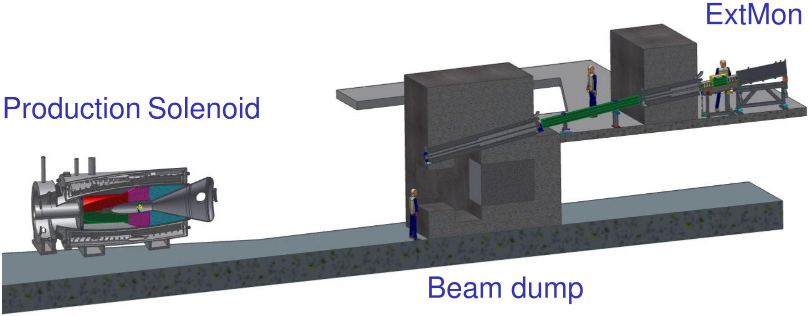


Testing extinction dipoles



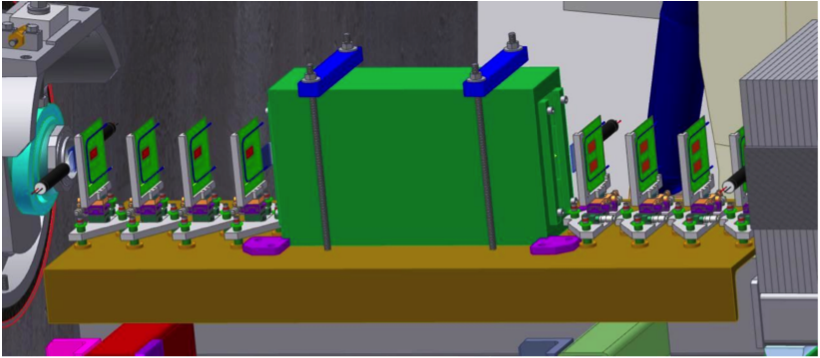
Monitoring beam extinction

- Must measure extinction directly to prove conversion signal
- Approach
  - observe charged secondaries from production target
  - Accumulate time profile of the beam
- Continuous monitoring with 10^{-10} sensitivity

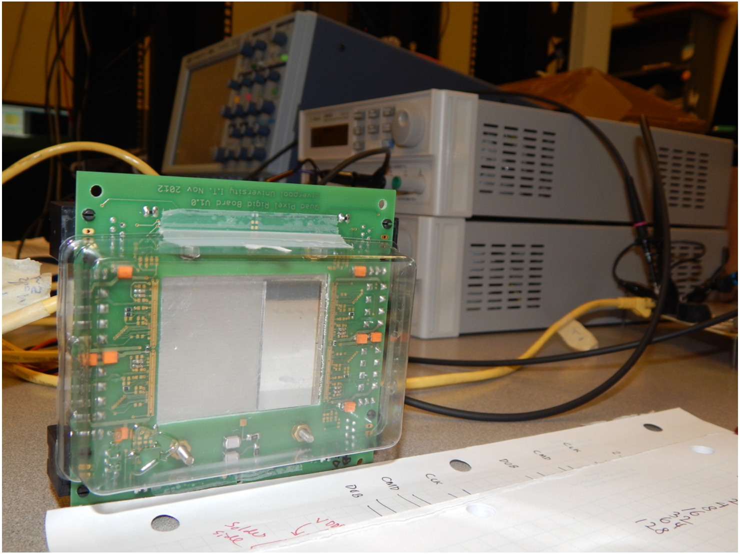


Extinction monitor

- Permanent magnet spectrometer
- Based on ATLAS silicon pixel chips
- Simulations show excellent performance, negligible background



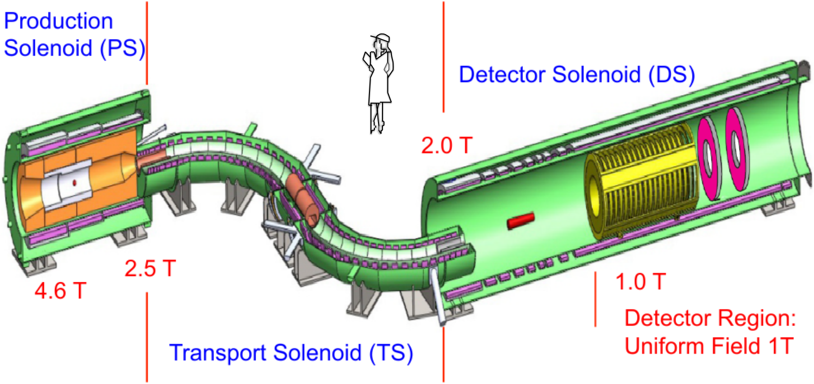
ExtMon: Pixel readout test



Outline

- What is muon to electron conversion
- Why search for it
- Mu2e approach to improving current best measurement
- Mu2e apparatus and performance
- Conclusion

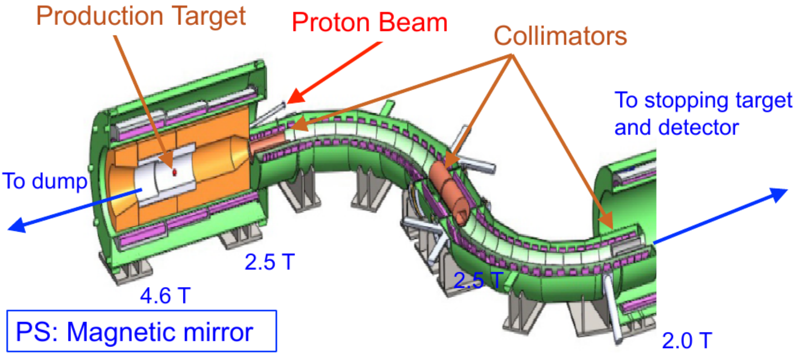
Overview of Mu2e setup



Graded B for most of length

Not shown: Cosmic Ray Veto, ExtMon, Stopping Target Monitor

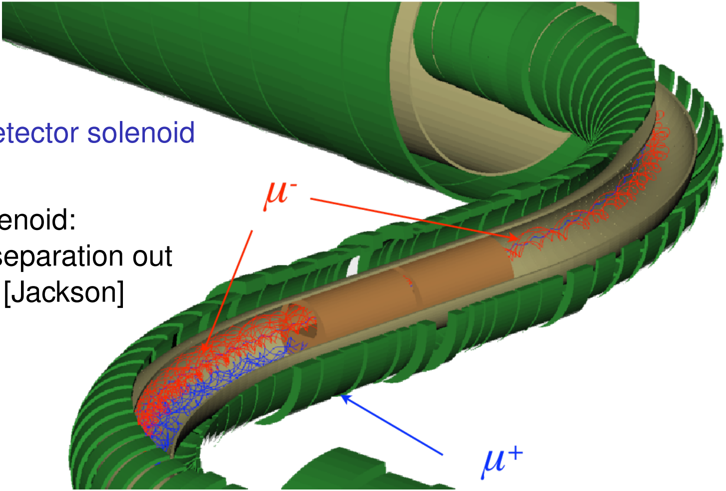
Muon production and delivery



PS: Magnetic mirror

TS: negative gradient and
charge selection at central collimator

Charge selection



Detector solenoid

Bent solenoid:
charge separation out
of plane [Jackson]

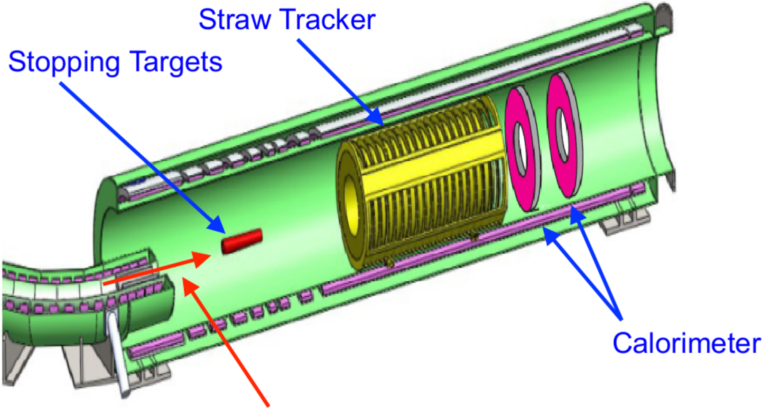
μ^-

μ^+

Production solenoid

Stopping target and detectors

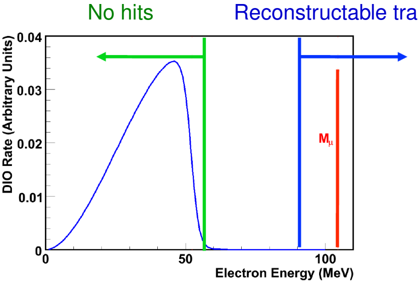
Symmetric: measure e^- and e^+!

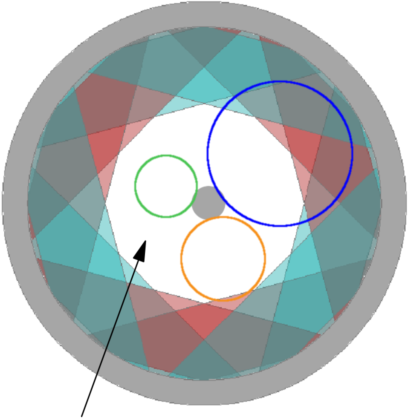


Incoming muon beam: <Kinetic Energy> = 7.6 MeV

How to measure 2.5×10^{-17}

Be blind to most tracks: annular design

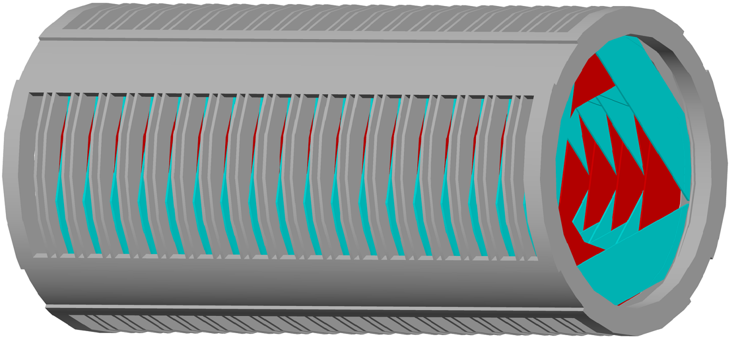




Vacuum: no scattering

Tracker

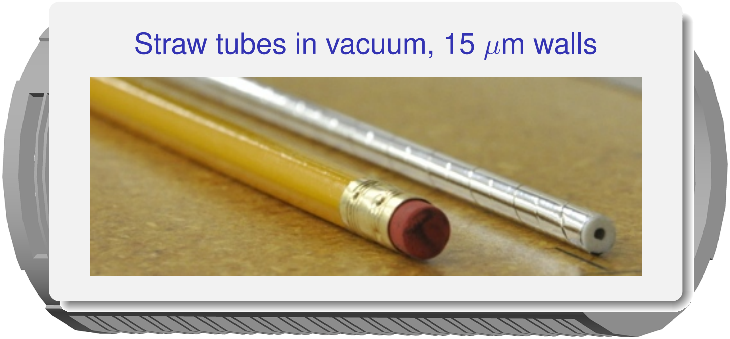
Precise momentum measurement



- about 3 m long
- 1 T *B* field
- “Good” tracks make 1.5–2 turns

Tracker

Precise momentum measurement



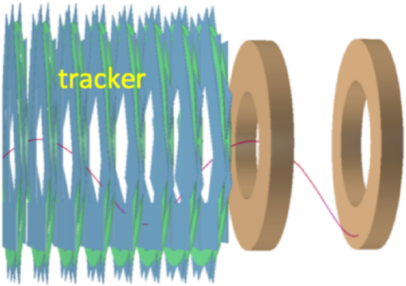
Straw tubes in vacuum, 15 μm walls

- about 3 m long
- 1 T B field
- "Good" tracks make 1.5–2 turns

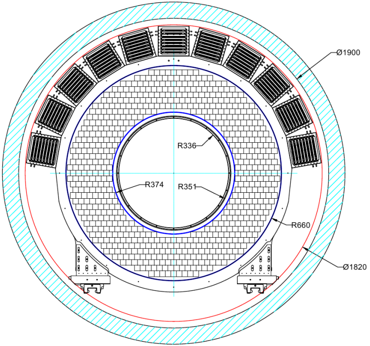
Calorimeter

Particle ID to suppress some backgrounds

Two disk geometry



CsI crystals

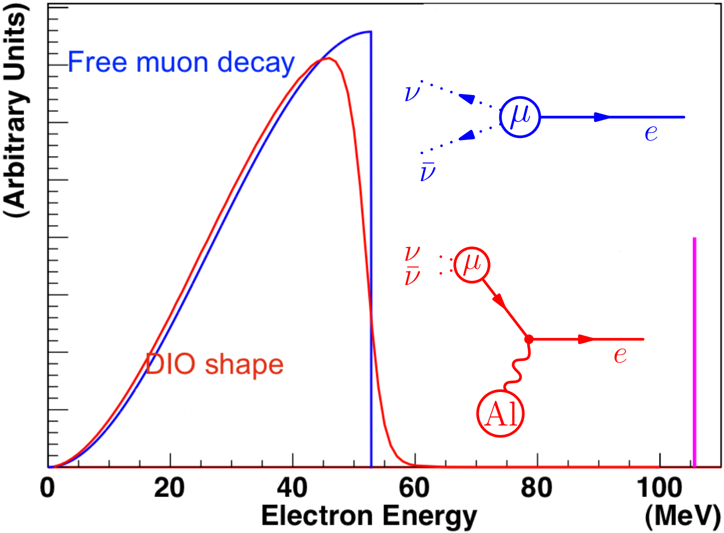


Also provides precise timing, alternate track seed.

Types of backgrounds

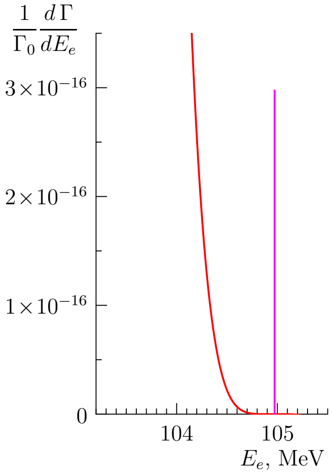
- Muon induced
    - Muon decay in orbit (DIO)
- Protons arriving out of time
    - Radiative pion capture
    - Muon decay in flight
    - Pion decay in flight
    - Beam electrons
- Long transit through muon beamline
    - *Antiprotons*
- Cosmic rays

Decay electron spectra



Decay in orbit

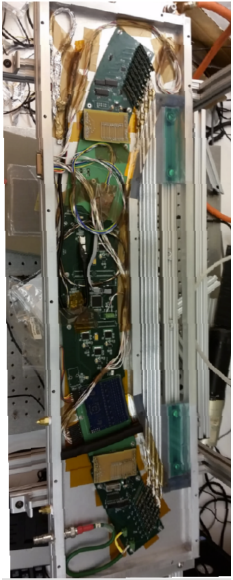
- Theory prediction: see R. Szafron's talk, and R. Szafron, A .Czarnecki, Phys. Lett. B **753**, 61 (2016)
- Small, but steep tail
- DIO electron differs from signal only by its momentum
- High tail of detector resolution pushes DIO "wall" into signal window
- Must understand resolution in detail!



Understanding the tracker

First principle hit simulation

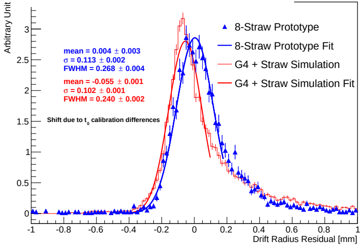
- Gas cluster formation
- Drift
- Avalanche amplification
- Signal propagation along the wire
- Analog and digital electronics response
  - Saturation, deadtime, cross-talk, bandwidth, electronics noise…
- Detector-like output hits
- Resolution and efficiency are emergent effects



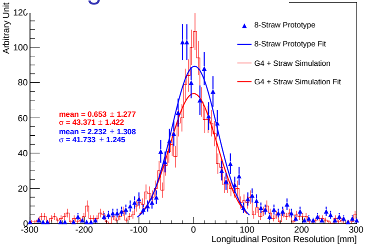
Functional 8-straw prototype

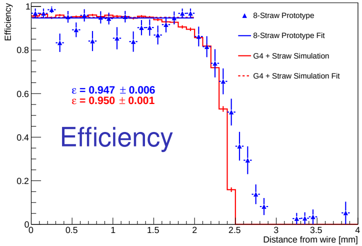
Tracker hits: simulation vs prototype

Transverse resolution



Along wire resolution

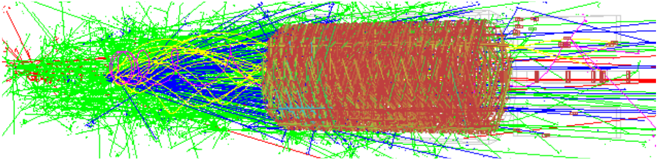




Compare PROTOTYPE measurements to SIMULATION

Mu2e event simulation

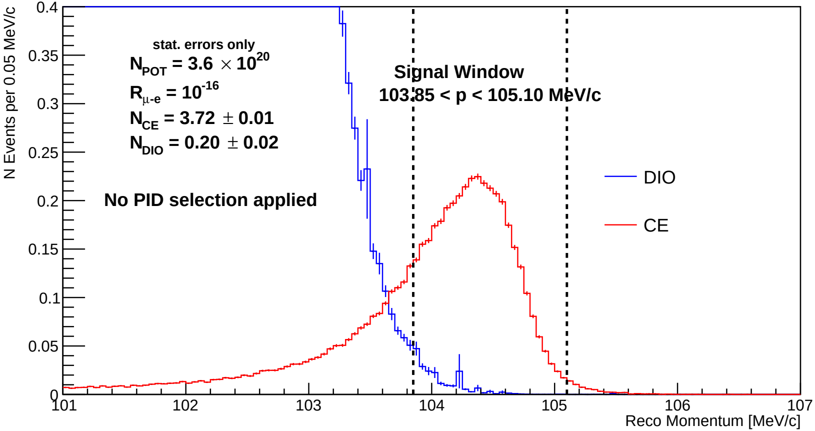
- Typical beam pulse of 39 M protons: tracker+calo see
    - 3.5 k daughters of stopped muons
    - 74 k “beam flash” particles (most before live window)
    - the numbers include pile-up from previous pulses
- Detailed G4 model: straws, supports, services, *B*-field, . . .
- Model beam intensity fluctuations from slow extraction



Particles and hits in 500–1695 ns time window

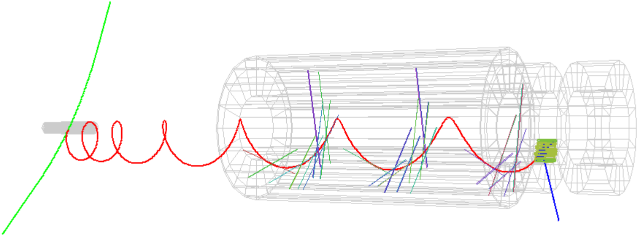
Mu2e can find and fit conversion electrons in this environment!

Separation of signal and DIO background



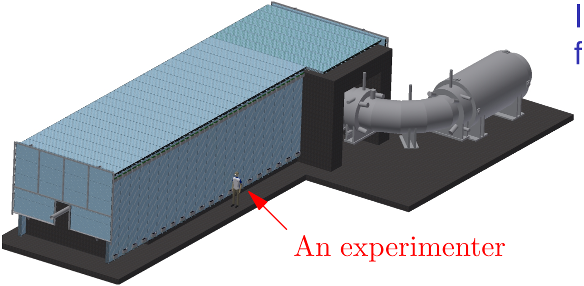
Cosmic background introduction

- 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

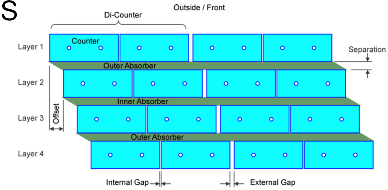


An experimenter

Intense radiation field

- proton target
- $\mathcal{O}(10^{10})$ muon captures per second: *n*, γ, ...
- false vetoes (dead time)

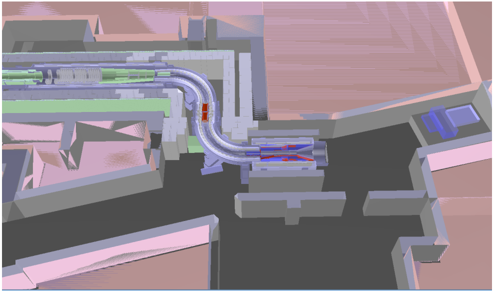
- Optimized counter and shielding design using massive G4 and MARS simulations
- Four layers of scintillator counters
- Aluminum absorbers
- Veto will be applied offline



Cosmic background simulations

Detailed GEANT4 model

- Detectors
- Mechanical supports, services
- Individual shielding blocks
- Civil infrastructure
- Dirt overburden, . . .



Simulation statistics

0.5×10^{12} events, $4 \times$ livetime (1 livetime = 3 year run)

4 additional samples targeting areas that lack CRV coverage: $> 255 \times$ livetime each

Summary of backgrounds

“Blessed” numbers from earlier sims—arXiv:1501.05241

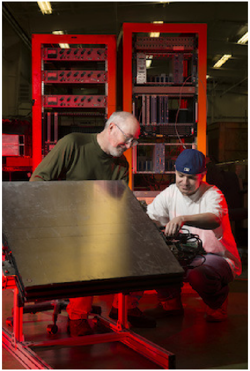
3 years of 1.2×10^{20} protons/year (8 kW beam power)

Category	Background	Expected events
Intrinsic	Muon decay in orbit	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late arriving	Pion capture	0.023 ± 0.006
	Muon decay in flight	< 0.003
	Pion decay in flight	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic rays	0.082 ± 0.018
Total		0.36 ± 0.10

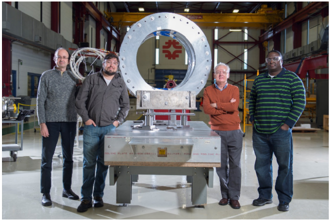
Assuming 10^{-10} beam extinction, 10^{-4} CRV inefficiency, and PID muon rejection of 200.

More Mu2e prototypes. . .

CRV

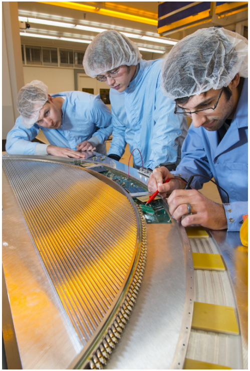


Transport solenoid

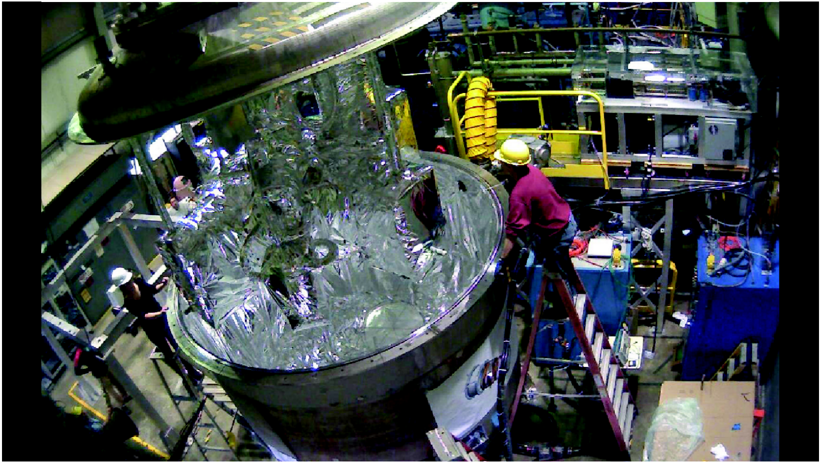


Calorimeter

Tracker



Cold test of a TS module



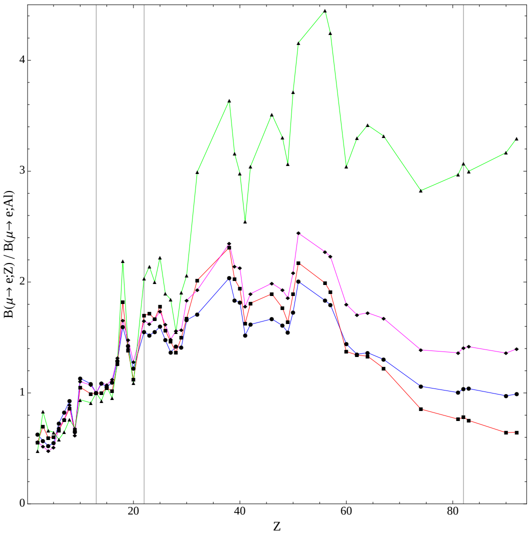
Civil construction

Conclusion

- Mu2e will test the physics of flavor and generations.
- Excellent physics potential
  - Aim for 4 orders of magnitude improvement:
    $R_{\mu e} \approx 2.5 \times 10^{-17}$ single event sensitivity
    at ≈ 0.5 events background
  - Mass scale reach far beyond direct production at colliders
    - $\times$ 10 improvement over current $\mu N \rightarrow eN$ measurement
- Building construction is almost finished
- Detectors are in advanced prototyping stage
- Solenoids are on schedule for data taking in 2021
- Mu2e had a successful CD-3 review last week. CD-3 gives the Project authority to construct the entire detector. The Project is fully funded.
- More information: `http://mu2e.fnal.gov`

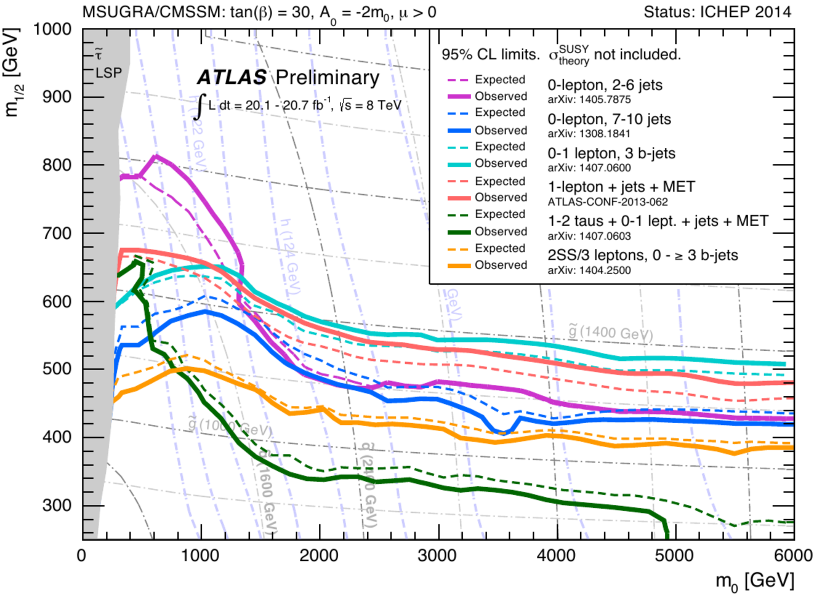
Extra slides

Target Z dependence

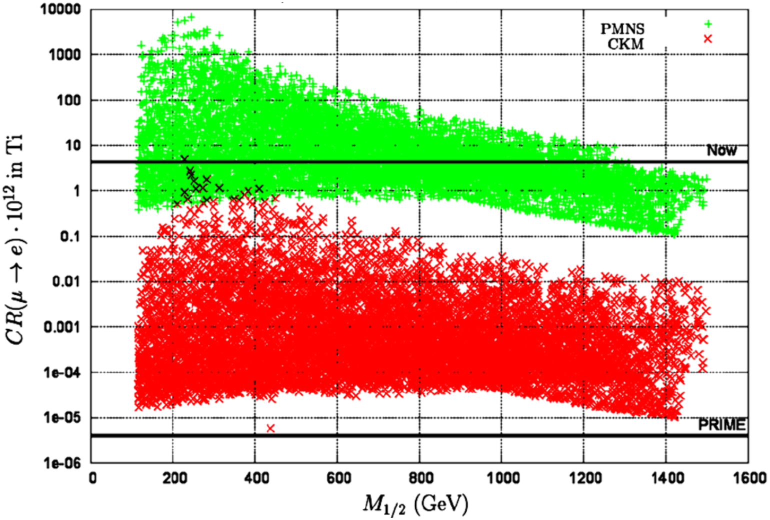


V. Cirigliano et al., Phys. Rev. D ***80****, 013002 (2009)*

ATLAS SUSY exclusion

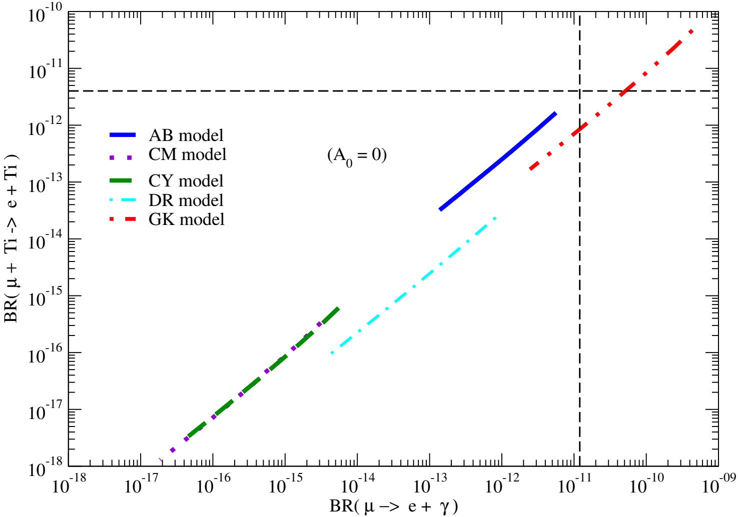


LHC SUSY scan for tan $\beta = 40$



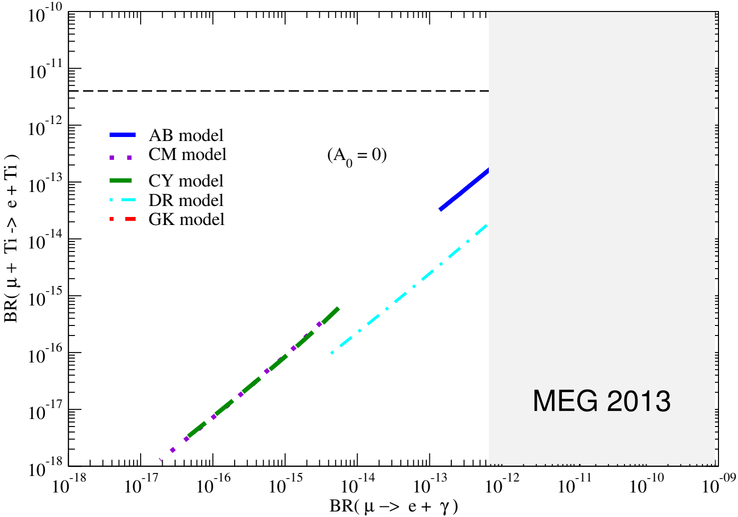
Calibbi, Faccia, Masiero, Vempati,
*Phys.Rev.**D74** (2006) 116002*

Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



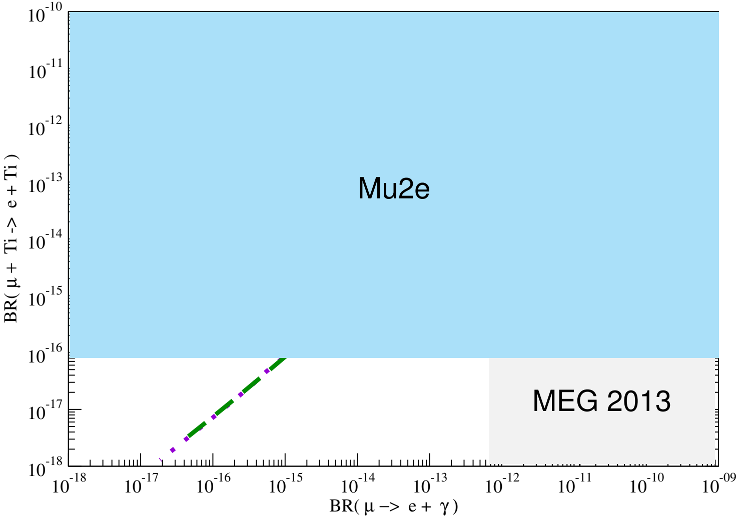
C.H. Albright, M.-C. Chen, 2008

Mu2e and $\mu \rightarrow e\gamma$: SO(10) SUSY GUT



C.H. Albright, M.-C. Chen, 2008

Mu2e and $\mu \rightarrow e\gamma$: SO(10) SUSY GUT



C.H. Albright, M.-C. Chen, 2008

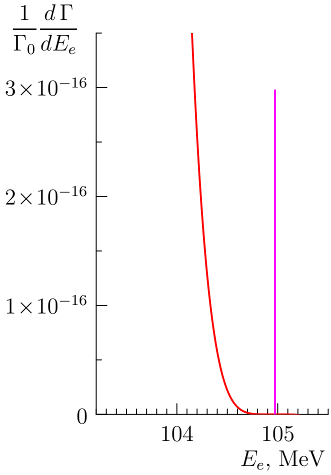
Decay in orbit

- Latest spectrum computation: Czarnecki, Tormo, Marciano (2011)
- End point expansion

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e} = B\left(E_\mu - E_e - \frac{E_e^2}{2m_N}\right)^5$$

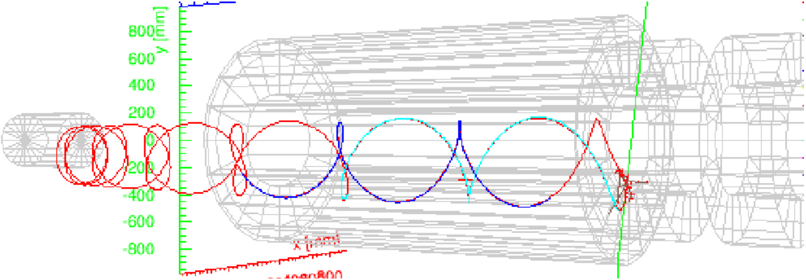
— small but steep tail!

- DIO electron differs from signal only by its *p*
- Momentum resolution is important!
  - Especially the high side tail: pushes DIOs into the signal region



Tracker energy loss calibration

Double-pass cosmic rays



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!

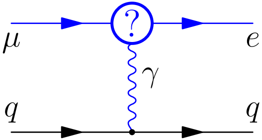
Effective theory

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

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

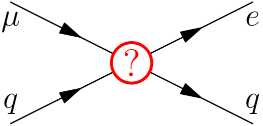
Λ: mass scale, κ: relative importance of contact term

Dipole: $\kappa = 0$



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

Contact: $\kappa = \infty$

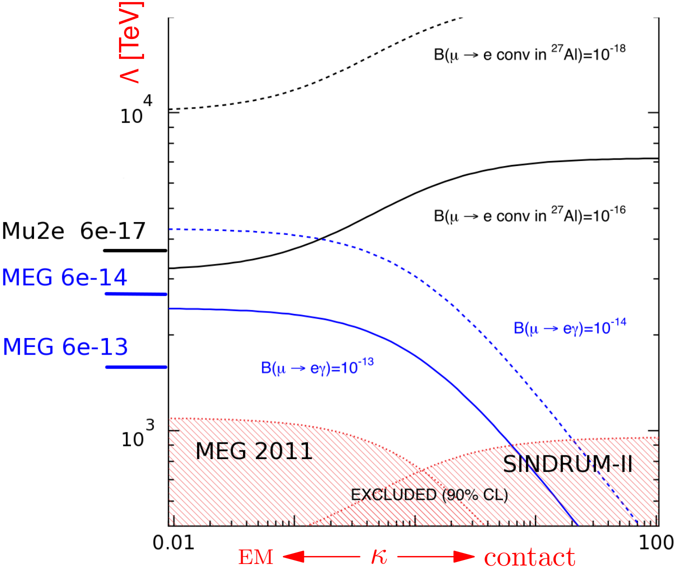


May be no $\mu \to e\gamma$ signal

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

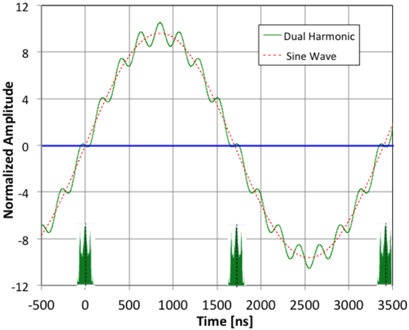
Handle to discriminate New Physics models

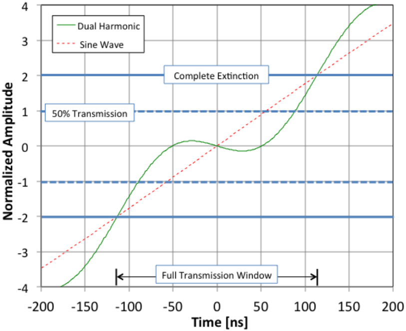
Muon LVF physics reach



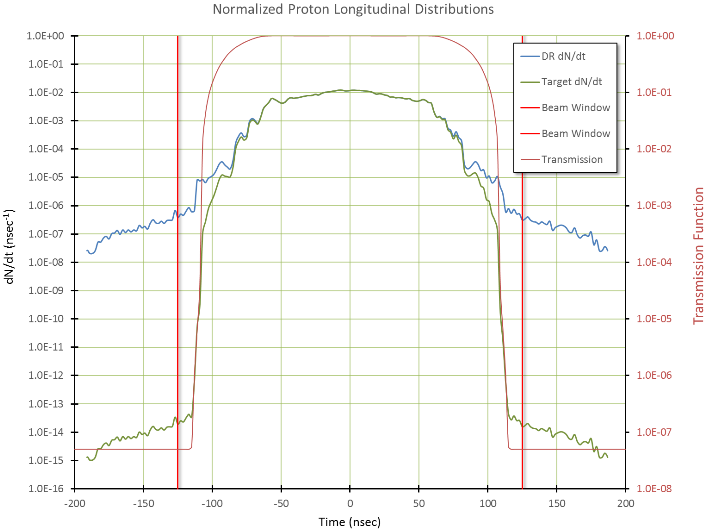
A. de Gouvêa , P. Vogel
Prog Part Nucl Phys ***71***(2013)75

External extinction waveform





External extinction result



Mu2e posters at this conference

- Boi, Steven *Impact from Beam Induced Radiation Backgrounds on the Cosmic Ray Veto Detector at the Mu2e Experiment*
- Bono, Jason *The Mu2e Tracker*
- Edmonds, Andrew *An 8-Straw Prototype Tracker for Mu2e*
- Ehrlich, Ralf *Cosmic Ray Background in the Mu2e Cosmic Ray Veto*
- Frank, Martin *Mu2e Cosmic Ray Veto Test Beam Results*
- Jenkins, Merrill *The Mu2e Cosmic Ray Veto*
- Kargiantoulakis, Manolis *Front-End Electronics for the Mu2e Tracker*
- Oksuzian, Yuri *Wavelength-Shifting Fiber Performance for the Mu2e Cosmic Ray Veto*
- Palladino, Anthony *Normalization System for the Mu2e Experiment; The Stopping-Target Monitor*
- Sarra, Ivano *New Tests with the New Large Area SiPMs for the Mu2e Calorimeter*
- Shrestha, Shruti *Electronics for the Cosmic Ray Veto*
- Uzunyan, Sergey *Radiation Damage Tests of Silicon Photo-Multipliers (SiPMs) for the Cosmic Ray Veto System of the Mu2e Experiment*