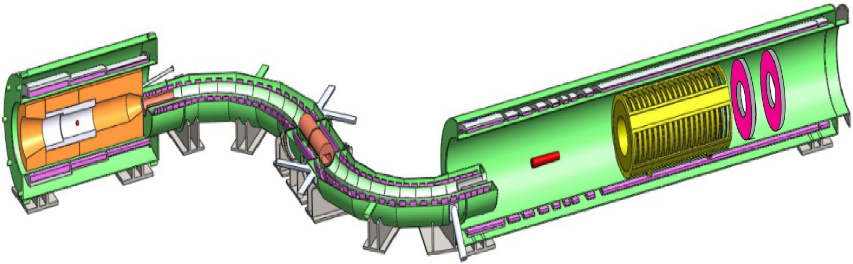
Precision muon physics 2

Charged lepton flavor violation



Andrei Gaponenko (Fermilab)

CTEQ 2018

First, catch up on flavor diagonal measurements: g-2

What's next?

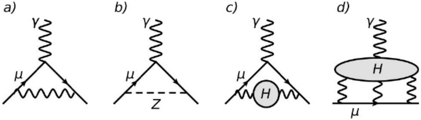
- The discrepancy

$$\Delta a_\mu = a_\mu^{\text{expt}} - a_\mu^{\text{SM}}$$
$$= (268 \pm 63(\text{expt}) \pm 43(\text{theory})) \times 10^{-11}$$

 is 3.5σ: large, but not conclusive [PDG 2018]
- Need to better understand the SM
- Need a better measurement

Need to better understand the SM

Theoretical status of a_μ

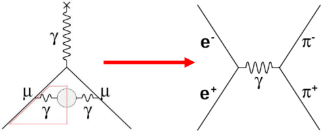


Source	Value (a_μ x 10^{-11})	Error
a) QED	116 584 718.95	0.08
b) EW	154	1
c) HVP	6850.6	43
d) HLBL	105	26

See Muon g-2 TDR and references therein

Summary	(a_μ x 10^{-11})
$a_\mu^{(EXP)}$	116 592 089(63)
$a_\mu^{(SM)}$	116 591 828(49)
$a_\mu^{(EXP)}$ - $a_\mu^{(SM)}$	261(80) → 3.3σ

- QED/EW uncertainties are tiny, e.g.
  - Recent calculation to 5th order in α contributes 5×10^{-11} to a_μ
  - Known Higgs mass reduces error on EW from 2 to 1×10^{-11}
- Error dominated by hadronic terms
  - HVP can be determined from e^+e^- → hadrons data
  - HLBL smaller overall error, but calculation model-dependent



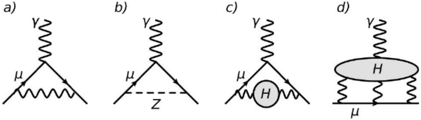
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Slide from Chris Polly

Need to better understand the SM

Theoretical status of a_μ



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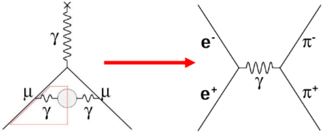

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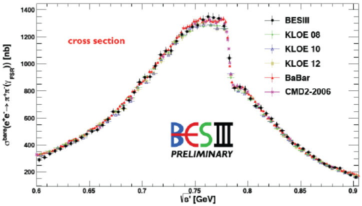
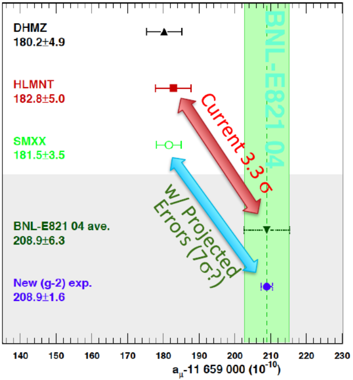
Need to better understand the SM

Theoretical status of a_μ

- New e^+e^- data for HVP continues to contribute
  - BESIII latest to map crucial 2π contributions
  - Multi-hadron final states from b-factories
  - CMD3 at VEPP2000
- Data driven approaches to HLBL
  - LE tagger at KLOE to measure $\gamma^*\gamma^*$ physics related to 70% of HLBL.
  - New data-driven evaluation of the pion-pole contribution spot on (Hoferichter et al. arXiv:1805.01471)
- Lattice progress looks very promising for both HVP and HLBL…see next talks…



http://arxiv.org/pdf/1311.2198v1.pdf



Projecting a factor of 2 reduction in theory error over course of experiment!

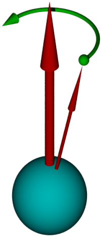
Slide from Chris Polly

How can we measure g?

- Spin precesses about external $\vec{B}$ field: the Larmor frequency

$$\vec{\omega}_S = -g_\mu \frac{q\vec{B}}{2m_\mu}$$

- Stop muons, measure B and ω_S?



T. P. Gorringe and D. W. Hertzog, Prog. Part. Nucl. Phys. **84**, 73 (2015) and PDG2018

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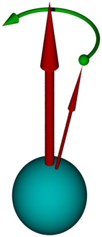

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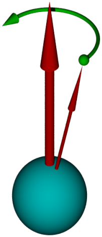

- Stop muons, measure B and ω_S?
- But the muon mass
  $m_\mu = 105.6583745 \pm 0.0000024$ MeV
  is known to “only” 23 ppb.
- Measure zero if you need precision!

T. P. Gorringe and D. W. Hertzog, Prog. Part. Nucl. Phys. **84**, 73 (2015) and PDG2018

How can we measure g continued?

- Instead of measuring $g \approx 2$ and looking for deviations, make Nature subtract the 2
- Then can look for quantum loop effects directly
- Precession of momentum vector direction in $\vec{B}$ field: the cyclotron frequency (all eqs are for $\vec{B} \cdot \vec{p} = 0$)

$$\vec{\omega}_c = -\frac{q\vec{B}}{m_\mu \gamma}$$

- For moving muons

$$\vec{\omega}_S = -g_\mu \frac{q\vec{B}}{2m_\mu} - (1-\gamma)\frac{q\vec{B}}{\gamma m_\mu}$$

- Then $\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{qB}{m_\mu} = -a_\mu \frac{q\vec{B}}{m_\mu}$

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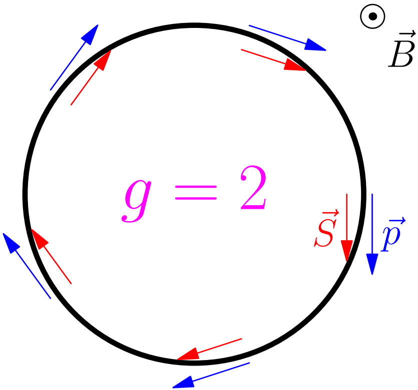
"Gee minus two" is the name of the experiment!

Experimental principle

- Observe the beat between two frequencies
- Remember "self analyzing" decay: determine spin direction by observing high energy Michel electrons
- Calorimeters along the ring: count electrons $E > E_{cut}$ vs time, or analyze deposited $E(t)$



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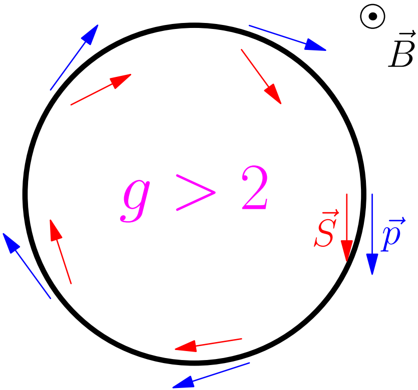

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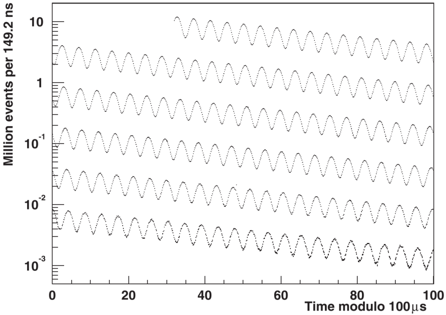
From E821 final report



Improving the measurement

- The BNL E821 measurement is statistically limited
- Need more muons to improve
- Fermilab can provide that

Newly constructed Muon Campus at Fermilab

Experimental complication

- Muons have non-zero momentum spread
- In uniform $\vec{B}$, they will drift along the field and hit the wall
- Accelerators use quadrupole magnets to focus beams
- g-2 needs uniform B to do the measurement

$\Rightarrow$ Use electrostatic quadrupoles for in-ring focusing

- Then

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

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"Magic momentum": $\gamma = 29.3$ (about 3.1 GeV/c muons)

$$R = 3.3\frac{p/\,\mathrm{GeV}}{B/\mathrm{Tesla}} \approx 7\ \mathrm{m}, \text{ for } 1.45\ \mathrm{T\ field}$$

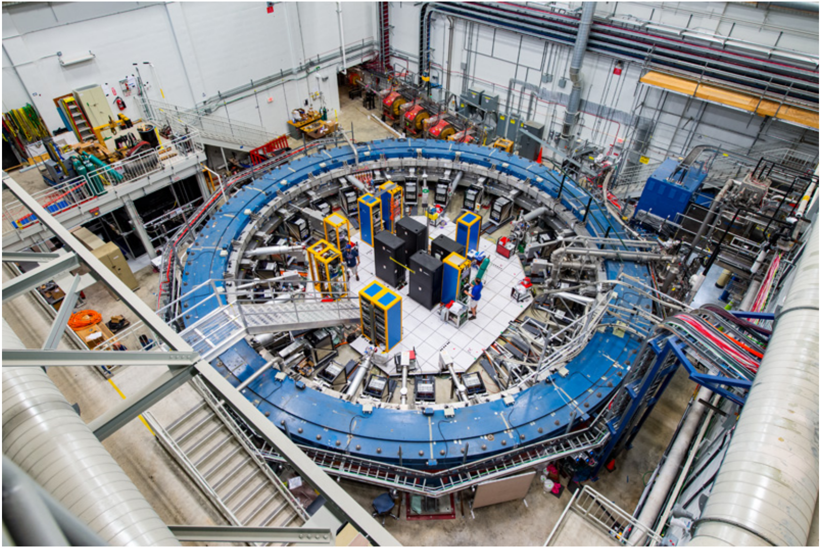
The magnet move

- \$20M and 2 years to construct new magnet from scratch
- Re-use the existing magnet for Fermilab g-2 to save time and money
- Steel yoke shipped BNL$\rightarrow$Fermilab by pieces
- Superconducting coils: $\approx$ 15 m diameter.
  - Can not be cut or unwound
  - Must not be flexed by more that 3 mm

Journey by barge

Traveling around Chicago

g-2 today



How does one *really* measure $g - 2$?

- $\omega_a = a_\mu \frac{eB}{m}$
- ω_a can be fit from the "wiggle plot"
- B can be precisely measured with NMR probes: RF frequency ω_p of proton spin precession in the field

How does one *really* measure $g-2$?

FNAL Projected Errors:
140 ppb (total) =
100 (stat) ⊕ 100 (syst)

2017 CODATA

-0.001 519 270 380(5) [3 ppb] Hydrogen Maser

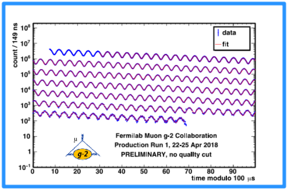
206.768 2826(46) [22 ppb] Muonium Hyperfine

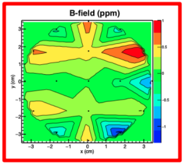
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$$\Downarrow$$

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





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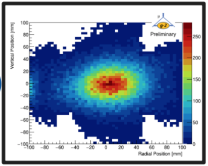


Improvements from BNL

ω_a — the "wiggle"

- Muon rate $\times 6$
- Hadronic flash removed
  - π decay
  - p removed by TOF before injection into $g-2$
- Granular calorimeters

B field map

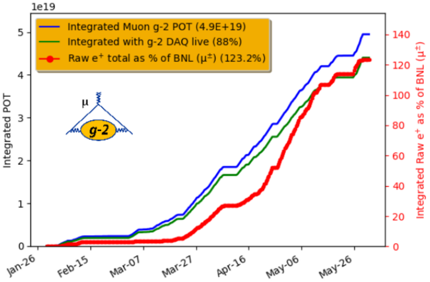
- A year of shimming: $\times 2$ improvement from BNL field uniformity
- Working on better absolute calibration of NMR probe

Muon distribution

- New tracking detectors a major improvement

Fermilab g-2 status

- After spending most of year finalizing commissioning, started physics production running in early April
- Have > 1.2 x BNL on tape
- Collecting a BNL-sized data sample every 6 weeks!
  - 5 weeks left in this run
- Aiming to publish results exceeding BNL precision by Summer 2019



1st publication (>1 x BNL statistics)	2nd publication (5-10 x BNL statistics)	3rd publication (>20 x BNL statistics)

CY18 → CY19 → CY20 → CY21

1st publication (>1 x BNL statistics) — CY19

2nd publication (5-10 x BNL statistics) — CY20

3rd publication (>20 x BNL statistics) — CY21

Another way to measure g-2

Instead of this

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

- Give up the electrostatic focusing: $E = 0$
- Need very cold muon beam for that to work
- But no need for "magic" => use a lower momentum $\Rightarrow$ smaller ring $\Rightarrow$ easier to control $\vec{B}$ uniformity and many other things
- This is JPARC g-2 proposal. New method with different systematics than BNL and Fermilab measurements.

The following slides are from Glen Marshall

Another way to measure g-2

Do this

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\cancel{\vec{\beta} \times \vec{E}}}{c}\right]$$

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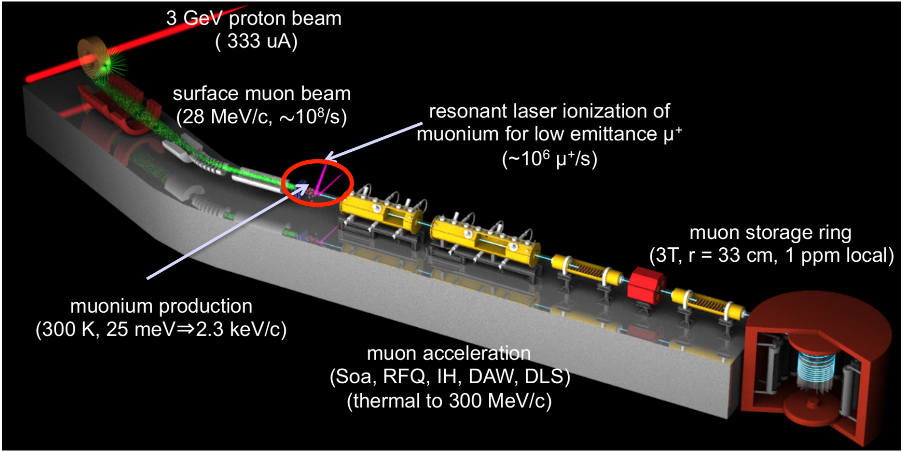
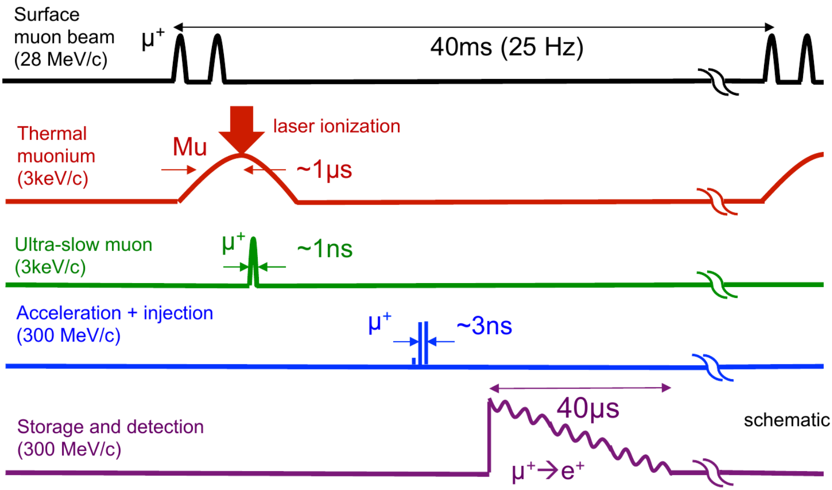
JPARC g-2


3 GeV proton beam
(333 uA)
surface muon beam
(28 MeV/c, ~10⁸/s)
resonant laser ionization of
muonium for low emittance μ⁺
(~10⁶ μ⁺/s)
muon storage ring
(3T, r = 33 cm, 1 ppm local)
muonium production
(300 K, 25 meV⇒2.3 keV/c)
muon acceleration
(Soa, RFQ, IH, DAW, DLS)
(thermal to 300 MeV/c)

Time sequence: μ production to decay



schematic by T. Mibe

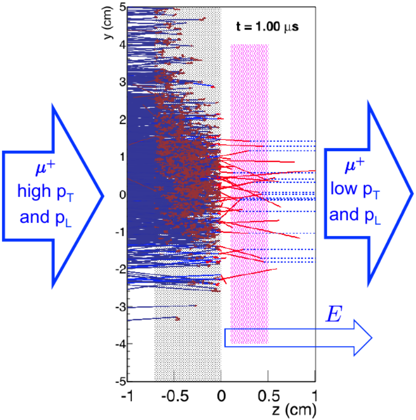
Getting cold muons

R&D at TRIUMF: S1249

- Thermalization of ~10^8 s^{-1} surface muons

	Surface beam	Thermal beam
E_k, MeV	3.4	0.03×10^{-6}
p, MeV/c	27	2.3×10^{-3}
Δp/p, rms	0.05	0.4
Δp, MeV/c	1.3	1×10^{-3}

- Thermal diffusion of Mu (μ^+e^-) into vacuum
  - decay length ~14 mm
  - TRIUMF experiment S1249
- Ionization
  - 1S→2P→unbound (122 nm,355 nm)
- Acceleration
  - E field, RFQ, linear structures
  - adds to p_z but not significantly to Δp



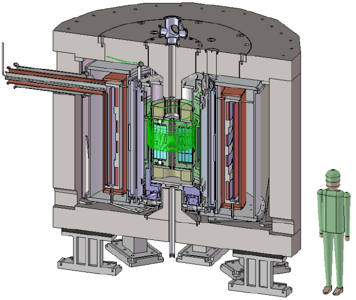
Muon injection and storage

Superconducting solenoid

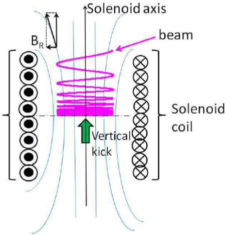
- cylindrical iron poles and yoke
- vertical B = 3 Tesla, <1ppm locally
- storage region r = 33.3±1.5 cm, h = ±5 cm
- tracking detector vanes inside storage region radius
- storage maintained by static weak focusing
  - n = 1.5 × 10^{-4}, $rB_r(z) = -n\, zB_z(r)$ in storage region

Spiral injection

- dipole-quadrupole transfer line from end of linac with downward deflection
- hole in upper yoke for beam entrance
  - permits entry, shields beam from field
- pulsed radial field on injection
  - reduces vertical momentum to match a trapped orbit



from K. Sasaki



from H. Iinuma

Charged lepton flavor violation

Sensitivity scaling of an experiment

Looking for some signal S, also get some background counts B. Both proportional to the data taking time: $S = s \times t$, $B = b \times t$.

Large B

- Statistical uncertainty $\propto \sqrt{S + B}$.
- Discoverable $s \propto t^{-1/2}$
- Need 100 times more data to improve $\times$ 10

$B \ll 1$

- For small B even $S = 1$ can be 5σ
- Discoverable $s \propto t^{-1}$
- Improve by $\times$ 10 with $\times$ 10 more data.

(s is always small, otherwise it would have been already discovered!)

Rare processes

SM-forbidden processes are powerful probes

- Irreducible SM background to NP contributions: 0
  - No theory ambiguity: non-zero signal is a discovery!
- Need to design experiments to have other backgrounds small (< 1 event)

$\Rightarrow$ A way to do sensitive searches for New Physics

A particular kind of forbidden: CLFV

- Brings us back to "Who ordered that?":
  - why are there flavors and generations?
- Before νSM: lepton flavor is conserved
  - No particular reason why
  - But we never saw $\mu \to e\gamma$ (or $Z \to e\mu$, or . . .)
  - An accidental symmetry of the SM
- There are quark transitions between generations (CKM), but not leptons?
- Now we know that neutrinos violate lepton flavor all the time! (There is mixing close to maximal!)
- Why not charged leptons?

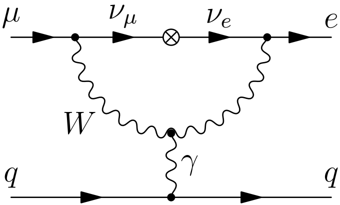
Expected rates (no NP)

SM

$R_{\mu e} = 0$

νSM

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



Observation of a CLFV process would be an unambiguous signal of New Physics

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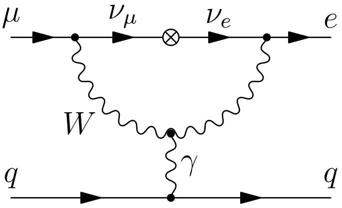

Observation of a CLFV process would be an
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Total amount of water on Earth 1.4×10^9 *km*^{3} *[water.usgs.gov]*
molar mass 18 g/mole, $N_A = 6 \times 10^{23}$ *mole*$^{-1}$
$\Rightarrow 7 \times 10^{46}$ *molecules of water, or*

10^{47} *available protons on Earth*

CLFV searches

$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016	[49]
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988	[50]
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}^{\dagger}$	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998	[51]
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}^{\dagger}$	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996	[52]
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}^{\dagger}$	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006	[54]
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^{*\,\dagger}$	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998	[53]
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999	[55]
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010	[56]
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010	[57]
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007	[58]
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007	[59]
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011	[60]
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011	[60]
$\pi^0 \to \mu e$	$< 3.6 \times 10^{-10}$	90%	KTeV	2008	[61]
$K^0_L \to \mu e$	$< 4.7 \times 10^{-12}$	90%	BNL E871	1998	[62]
$K^0_L \to \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$	90%	KTeV	2008	[61]
$K^+ \to \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$	90%	BNL E865	2005	[63]
$J/\psi \to \mu e$	$< 1.5 \times 10^{-7}$	90%	BESIII	2013	[64]
$J/\psi \to \tau e$	$< 8.3 \times 10^{-6}$	90%	BESII	2004	[65]
$J/\psi \to \tau\mu$	$< 2.0 \times 10^{-6}$	90%	BESII	2004	[65]
$B^0 \to \mu e$	$< 2.8 \times 10^{-9}$	90%	LHCb	2013	[68]
$B^0 \to \tau e$	$< 2.8 \times 10^{-5}$	90%	BaBar	2008	[69]
$B^0 \to \tau\mu$	$< 2.2 \times 10^{-5}$	90%	BaBar	2008	[69]
$B \to K\mu e^{\ddagger}$	$< 3.8 \times 10^{-8}$	90%	BaBar	2006	[66]
$B \to K^*\mu e^{\ddagger}$	$< 5.1 \times 10^{-7}$	90%	BaBar	2006	[66]
$B^+ \to K^+\tau\mu$	$< 4.8 \times 10^{-5}$	90%	BaBar	2012	[67]
$B^+ \to K^+\tau e$	$< 3.0 \times 10^{-5}$	90%	BaBar	2012	[67]
$B^0_s \to \mu e$	$< 1.1 \times 10^{-8}$	90%	LHCb	2013	[68]
$\Upsilon(1s) \to \tau\mu$	$< 6.0 \times 10^{-6}$	95%	CLEO	2008	[70]
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014	[71]
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995	[72]
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997	[73]
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016	[74]
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017	[75]
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017	[75]

The best limits are from muons!

L. Calibbi and G. Signorelli, arXiv:1709.00294

Broadest discovery sensitivity with muons!

Models →

Observables ↓

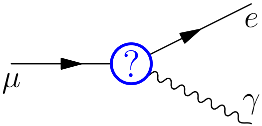
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\mathrm{CP}}(B \to X_s \gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^* \mu^+ \mu^-)$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

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

Lepton flavor violation with muons

$m_\mu \neq m_e$. Options to conserve 4-momentum

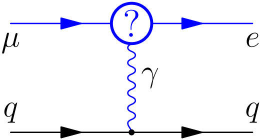
Emit a photon



$\mu \to e\gamma$ decay: MEG

(Another option: virtual $\gamma \to ee$, aka $\mu \to eee$)

Recoil off a nucleus



Muon to electron conversion: Mu2e

Lepton flavor violation with muons

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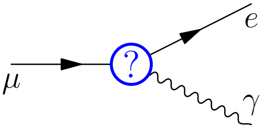

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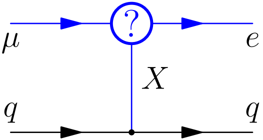
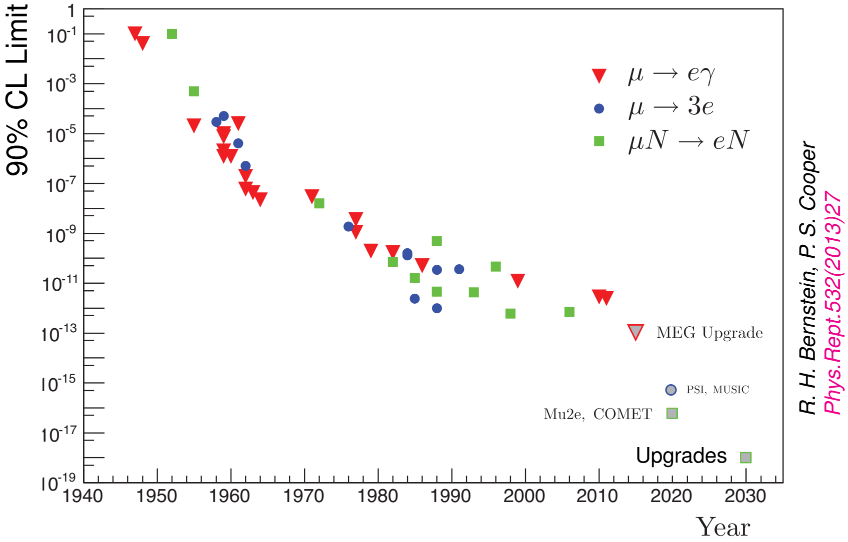


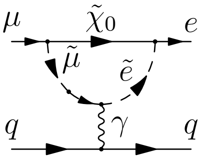
Muon to electron conversion: Mu2e

History of CLFV searches with muons

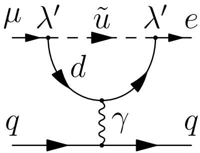


We can discover

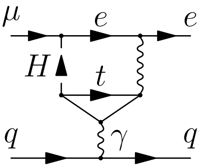
SUSY



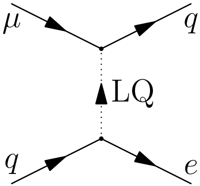
RPV SUSY



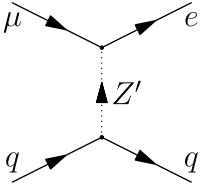
Second Higgs doublet



Leptoquarks



Z'/anomalous couplings



Extra dimensions, etc.

Theory reviews:

Y. Kuno, Y. Okada, 2001

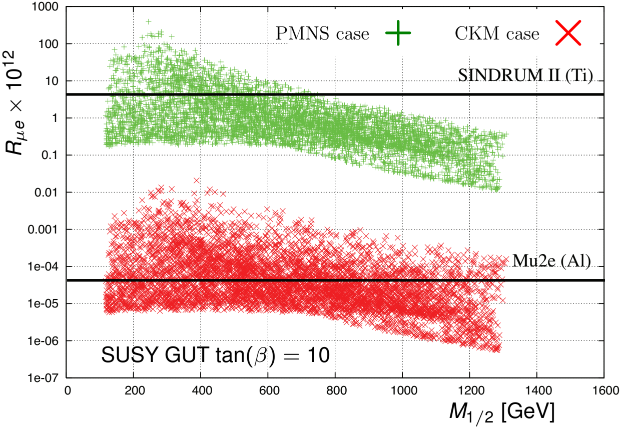
M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013

L. Calibbi and G. Signorelli, arXiv:1709.00294

$\mu N \to eN$ and the LHC

Scan of “LHC accessible” SUSY parameter space

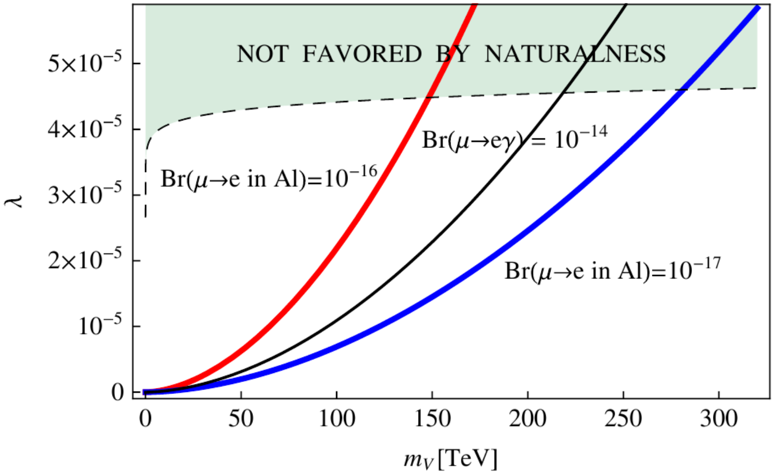


Calibbi, Faccia, Masiero, Vempati,
*Phys.Rev.**D74** (2006) 116002*

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

Muon CLFV mass scale reach example

Combination of couplings vs scalar leptoquark mass



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

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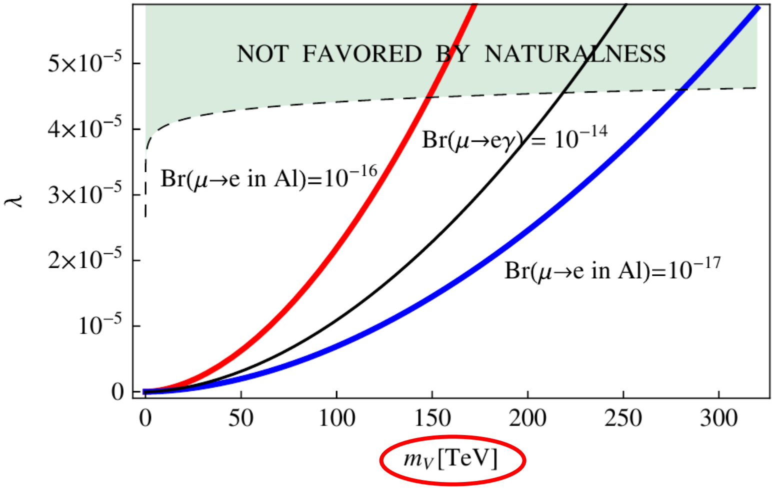


J.M. Arnold, B. Fornal, M.B. Wise
Phys.Rev.**D88**(2013)035009

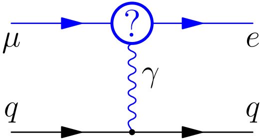
Effective theory

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

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

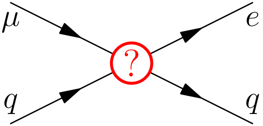
Λ: mass scale, κ: relative importance of contact term

Dipole: $\kappa = 0$



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

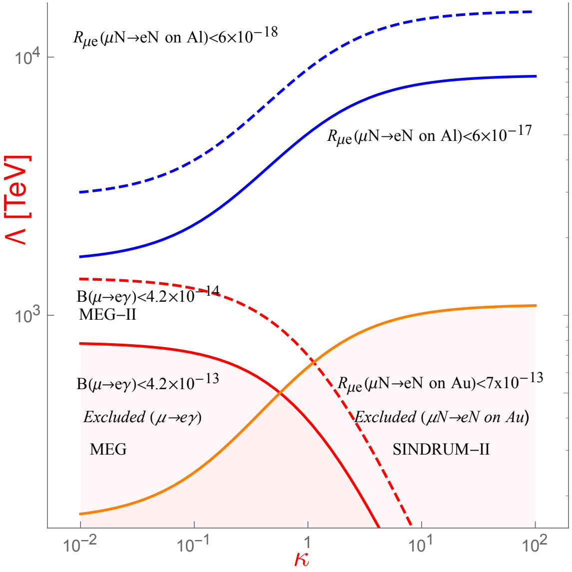
Contact: $\kappa = \infty$



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

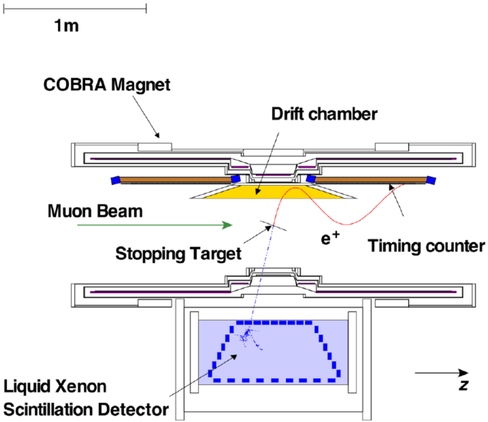
Relative rates of conversion and $\mu \to e\gamma$ are model dependent
Handle to discriminate New Physics models

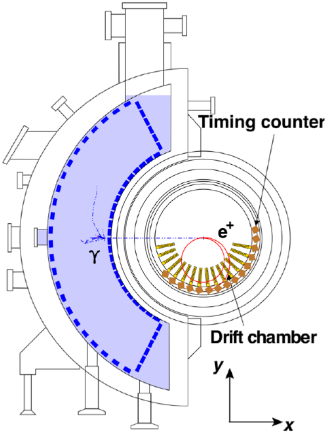
Muon CLFV physics reach



*Updated by R. Bernstein, D. Hitlin after A. de Gouvêa , P. Vogel Prog Part Nucl Phys **71**(2013)75*

MEG detector at PSI



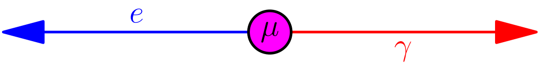


μ^+ stop rate $> 10^7$/s: $>$ 20 muons sit in the target at any time

Lesson learned: COBRA magnet, not simple solenoid

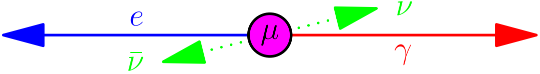
$\mu \to e\gamma$

Signal

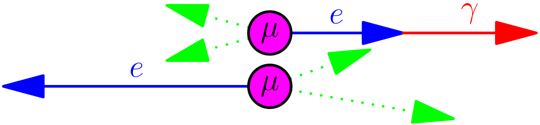


Back to back e and γ,
in time

Backgrounds

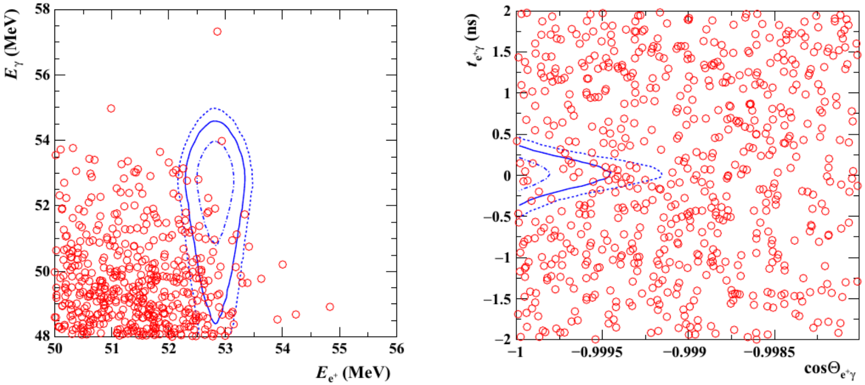


Correlated:
$\mu \to e\gamma\nu\bar{\nu}$



Accidental:
e from one μ, γ from another

MEG results



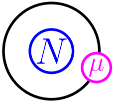
MEG final result

$Br(\mu^+ \to e^+\gamma) < 4.3 \times 10^{-13}$, 90% CL [Eur.Phys.J.C (2016) 76:434]

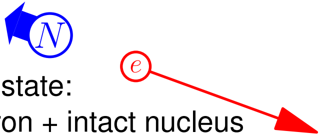
Upgrades are in progress

MEG-II aims to get another order of magnitude

$\mu \to e$ conversion:



Initial state:
muonic atom at rest



Final state:
electron + intact nucleus

- 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:

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

Experimental considerations

$\mu \to e\gamma$, $\mu \to eee$

- signal is combination of final state particles
- $N_{sig} \propto$ (muons/s)
- $N_{bg} \propto$ (muons/s)$^{2 \text{ or } 3}$
- Accidental coincidences limit usable μ rate
- Want continuous μ^+ beam

$\mu N \to eN$

- signal is single track
- $N_{sig} \propto$ (muons/s)
- $N_{bg} \propto$ (muons/s)
- Can take more muons/second
- Want pulsed μ^- beam

Mu2e goals

- Current best $\mu \to e$ conversion limit:
  $R_{\mu e} < 7 \times 10^{-13}$ [SINDRUM-II, 2006]
- Mu2e: aims 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 3×10^{-17}
- Many New Physics models predict $\mu N \to eN$ signal in this range!

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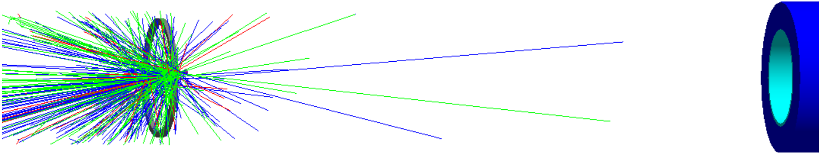
- Mu2e needs $\mathcal{O}(10^{18})$ muon stops
- SINDRUM II: $\mathcal{O}(10^7)$ muon stops per second
  - thousands of years of Mu2e data taking if same rate
- With PSI's 1.3 MW proton beam
  - GW proton beam is also not an option...

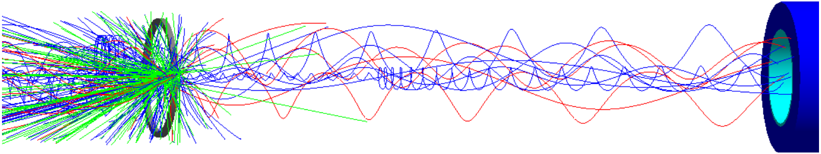
More energy efficient way to get the rate

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!

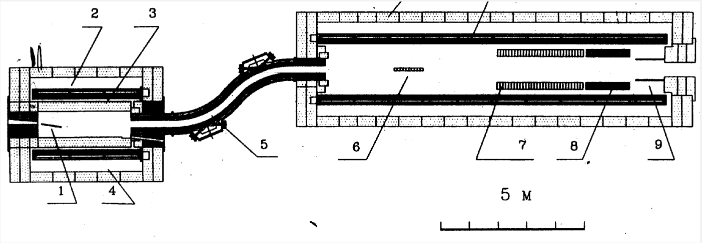
More energy efficient way to get the rate

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

Instead of this

Dc

1992 MELC experiment proposal



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

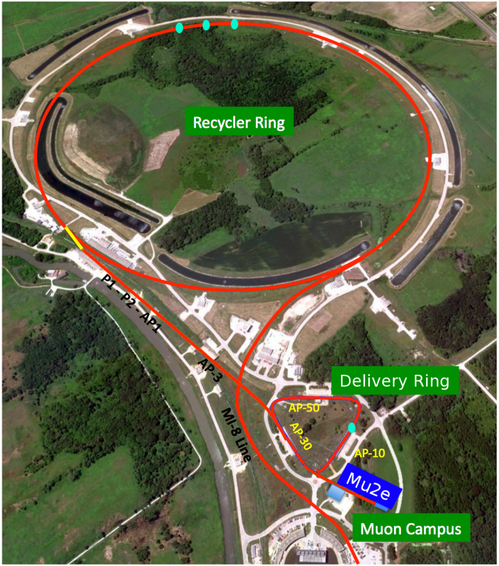
SINDRUM II

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

Mu2e

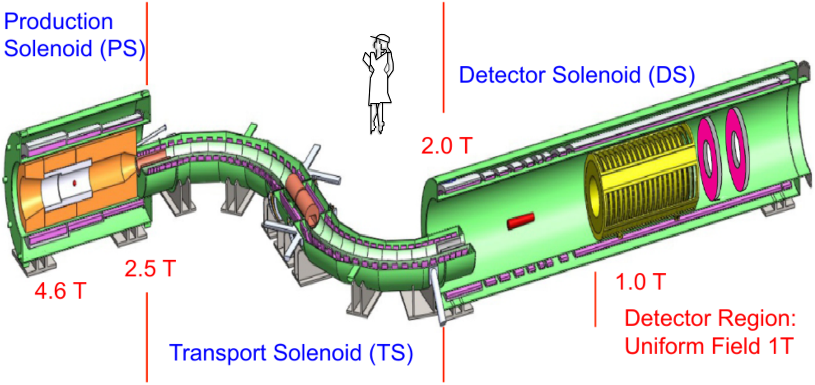
- Make muons
- Collect and stop them
- Wait for prompt backgrounds to decay
- Look for electrons at conversion energy

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
  $\Rightarrow$ beam pulse every 1695 ns
- Mu2e can run simultaneously with Fermilab neutrino experiments

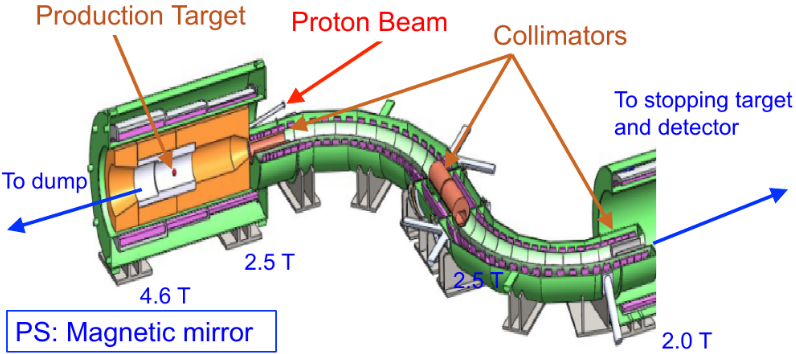
Overview of Mu2e setup



Graded B for most of length

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

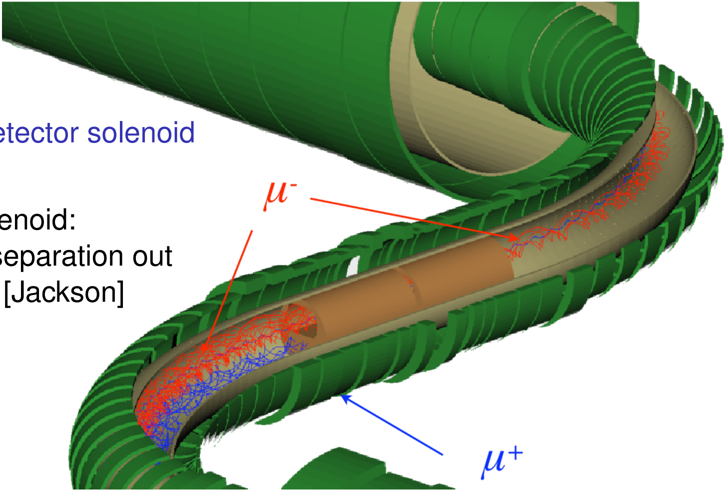
Muon production and delivery



PS: Magnetic mirror

TS: negative gradient and
charge selection at central collimator

Charge selection



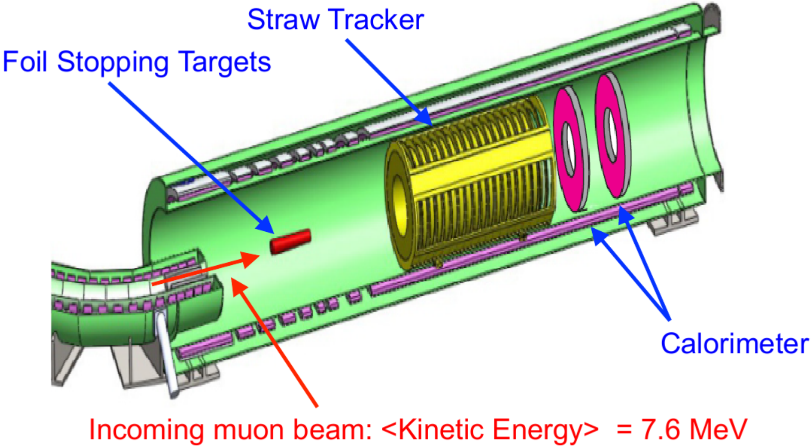
Detector solenoid

Bent solenoid:
charge separation out of plane [Jackson]

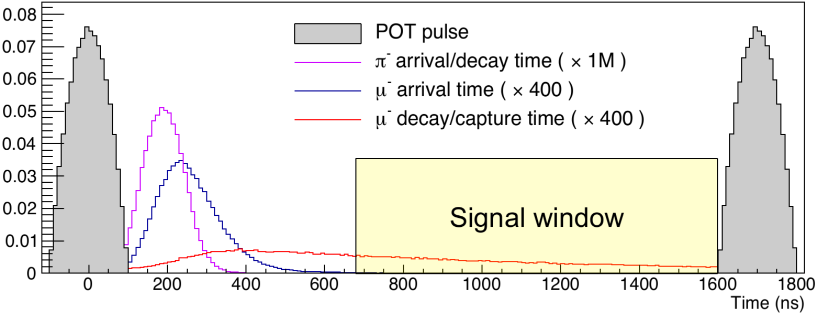
Production solenoid

Stopping target and detectors

Symmetric: measure e^- and e^+!



Mu2e beam time structure

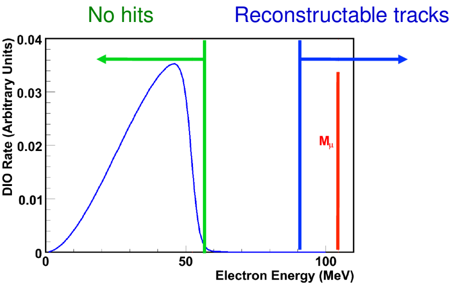


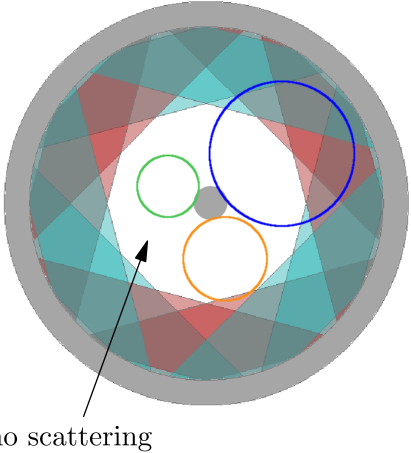
$\mathcal{O}(10^5)$ stopped muons in target at any time: muonic aluminum

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

How to measure 2.5×10^{-17}

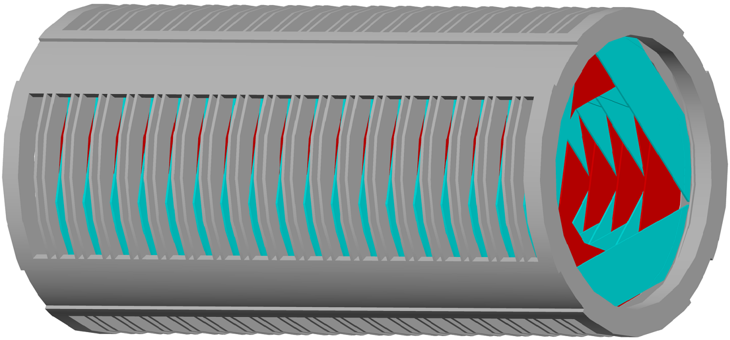
Be blind to most tracks: annular design





Tracker

Precise momentum measurement



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

Tracker

Precise momentum measurement

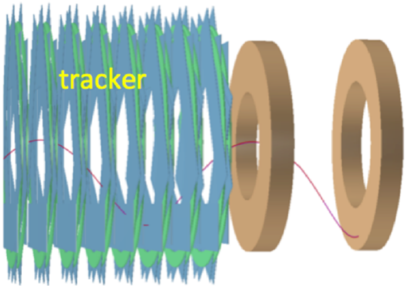
Straw tubes in vacuum, 15 μm walls

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

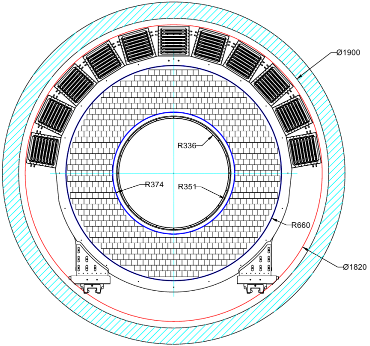
Calorimeter

Particle ID to suppress some backgrounds

Two disk geometry

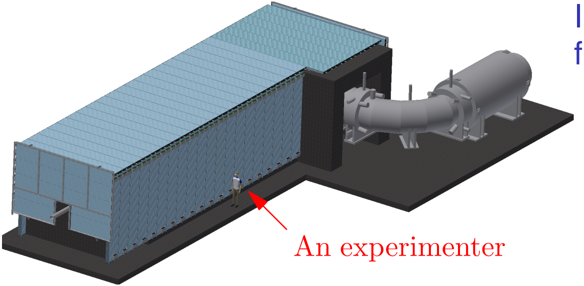


CsI crystals



Also provides precise timing, alternate track seed.

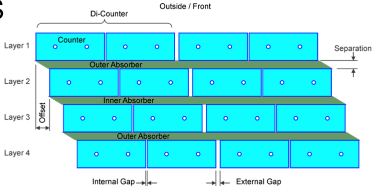
Cosmic Ray Veto



Intense radiation field

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

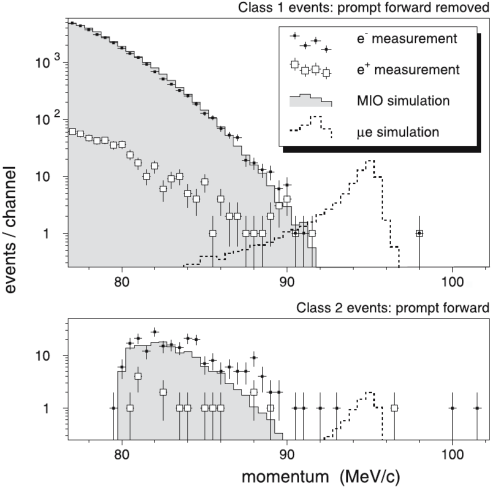
- Optimized counter and shielding design using massive G4 and MARS simulations
- Four layers of scintillator counters
- Aluminum absorbers
- Veto will be applied offline



The SINDRUM II result

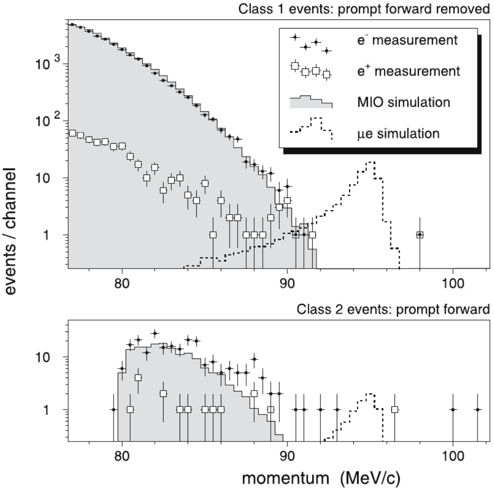
Conversion on gold:
$R_{\mu e} < 7 \times 10^{-13}$ 90% CL
[Eur.Phys.J C47(2006)]

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



From SINDRUM II to Mu2e: backgrounds

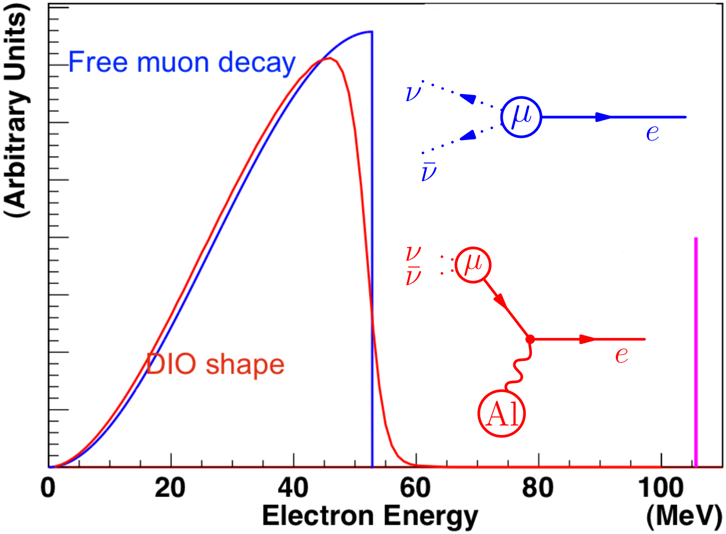
- $\mathcal{O}(1)$ background events in SINDRUM
- Likely caused by pions or cosmic rays
- $\Longrightarrow$ $\mathcal{O}(10^4)$ in Mu2e without improvements



Types of backgrounds

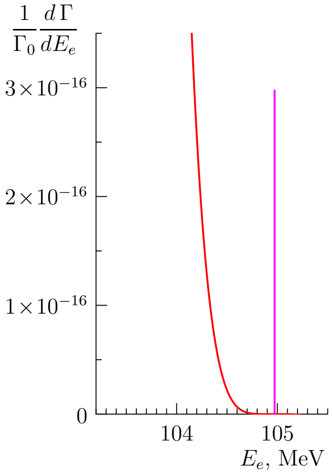
- Muon induced
  - Muon decay in orbit (DIO)
- Protons arriving out of time
  - Radiative pion capture
  - Muon decay in flight
  - Pion decay in flight
  - Beam electrons
- Long transit through muon beamline
  - *Antiprotons*
- Cosmic rays

Decay electron spectra



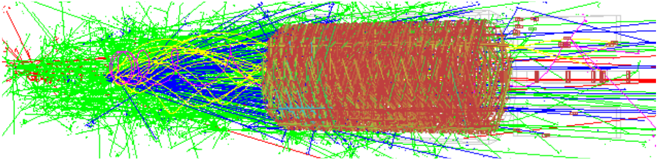
Decay in orbit

- Theory prediction: 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!



Mu2e event simulation

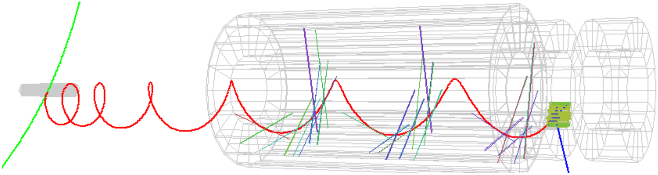
- Typical beam pulse of 39 M protons: tracker+calo see
  - 3.5 k daughters of stopped muons
  - 74 k “beam flash” particles (most before live window)
  - the numbers include pile-up from previous pulses
- Detailed G4 model: straws, supports, services, B-field, …
- Model beam intensity fluctuations from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



Particles and hits in 500–1695 ns time window

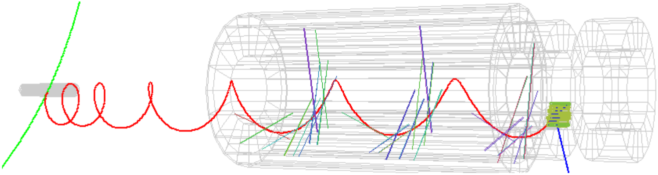
Mu2e can find and fit conversion electrons in this environment!

Cosmic background



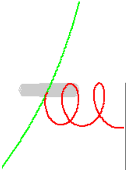
- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much CRV coverage as possible

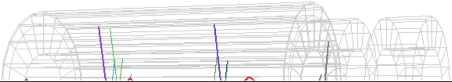
Cosmic background



- 1 event per day without counter-measures
- Vetoing cosmic muons is crucial
- Aim for as much CRV coverage as possible
- Some cosmic muons sneak through the beamline hole, scatter in material then go along curved *B* field to the detector.

Cosmic background



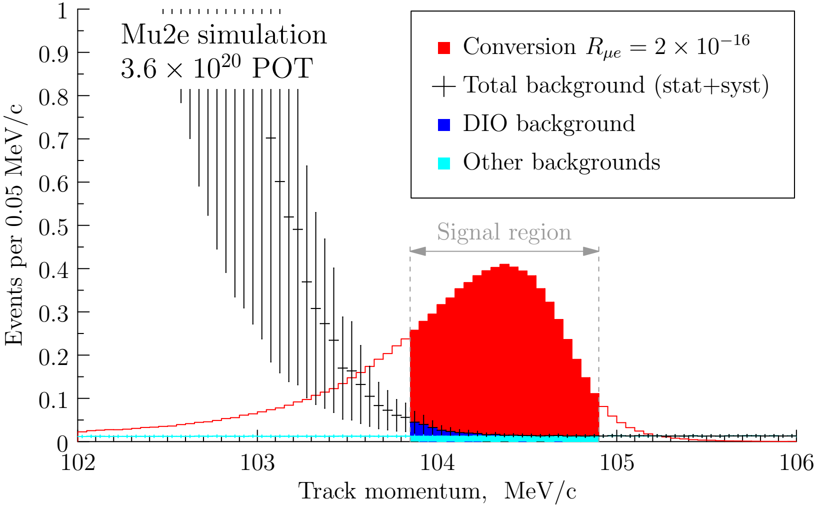


- 1 event per
- Vetoing cos
- Aim for as r
- Some cosm scatter in m detector.

Probability of...	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

Mu2e backgrounds, and signal discoverable at 5σ

Expected background: 0.41 $\pm$ 0.13 (stat+syst) events



Summary

- Muons have taught us a lot
- A unique “clean” probe for New Physics today
- Can open windows that may be closed to colliders
- Active field: groups at Fermilab (g-2, Mu2e), JPARC (g-2, COMET, DeeMe), PSI (MEG-II, Mu3e), TRIUMF (ultracold muons R&D), ...
- Potential Nobel class results from g-2 and muon CLFV in the next few years

Mu2e is hiring! Several Mu2e institutions are looking for postdocs.

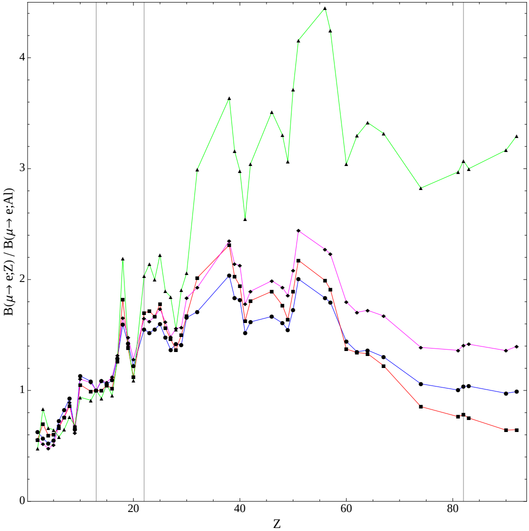
Thanks!

A lot of material here was borrowed from, or inspired by

- Bob Bernstein
- Jason Bono
- Glen Marshall
- Brendan Kiburg
- Chris Polly

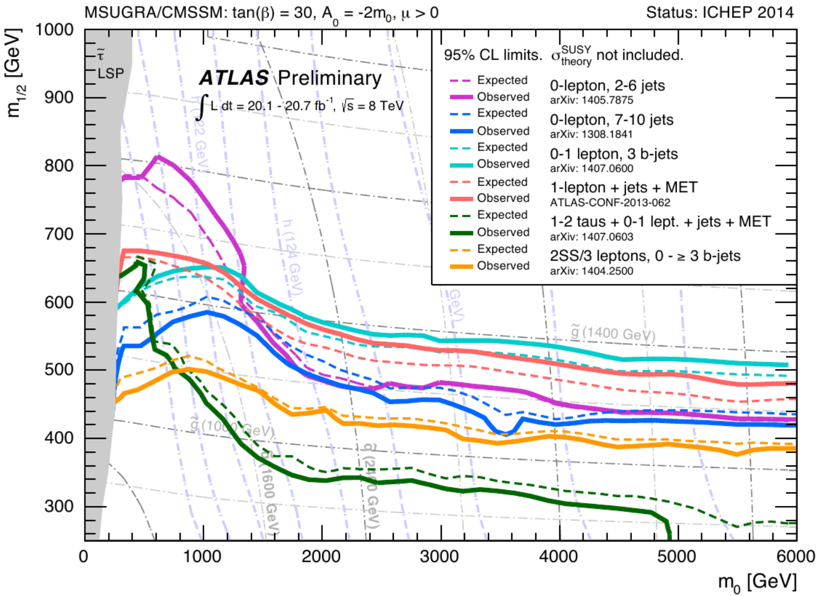
Extra slides

Target Z dependence

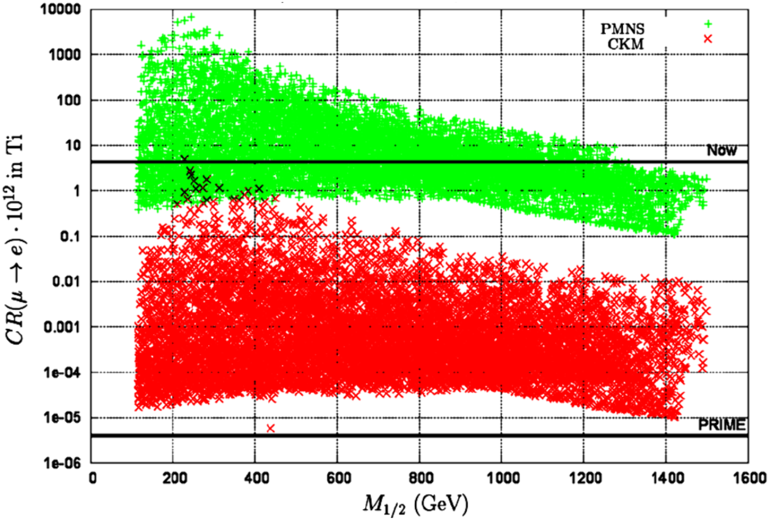


V. Cirigliano et al., Phys. Rev. D ***80****, 013002 (2009)*

ATLAS SUSY exclusion

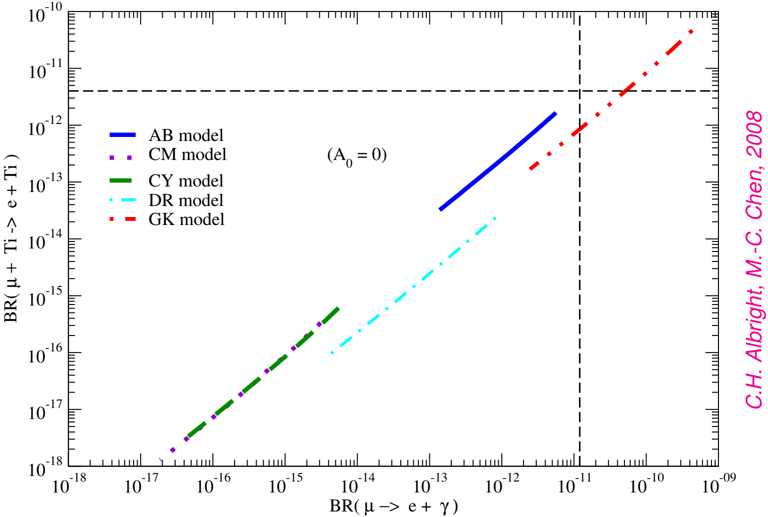


LHC SUSY scan for $\tan\beta = 40$

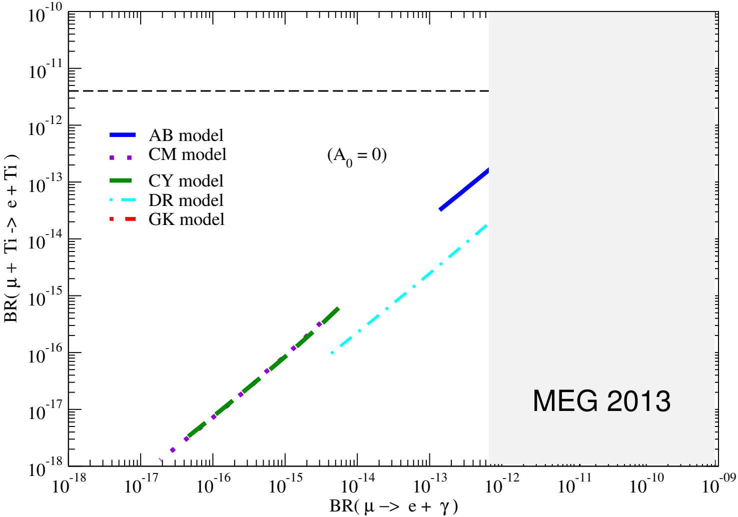


*Calibbi, Faccia, Masiero, Vempati, Phys.Rev.**D74** (2006) 116002*

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

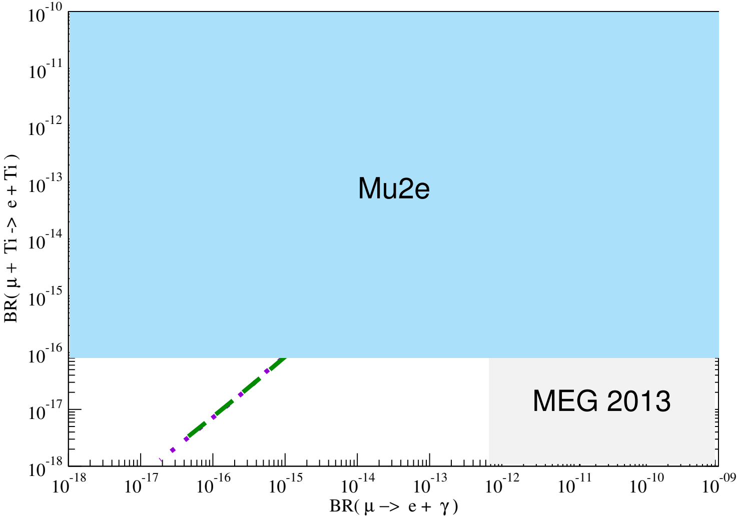


Mu2e and $\mu \to e\gamma$: SO(10) SUSY GUT



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

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



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

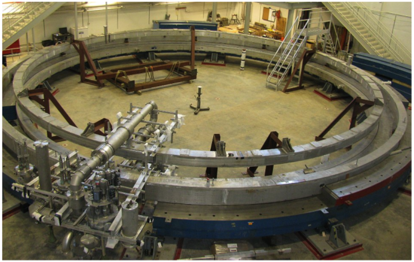
Leaving BNL

A tight spot

OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics
Fermilab
2473
2473

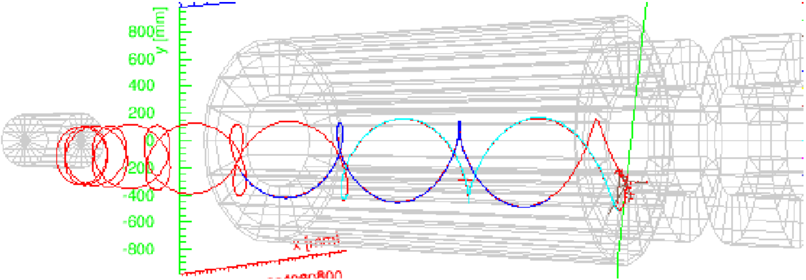
Arrival to Fermilab (July 2013)

Moved into the place (summer 2014)

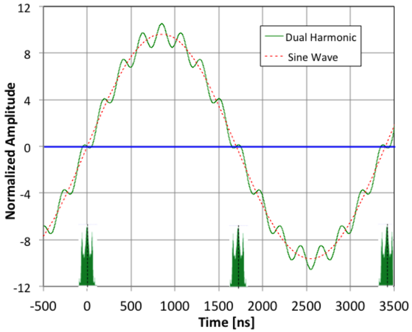


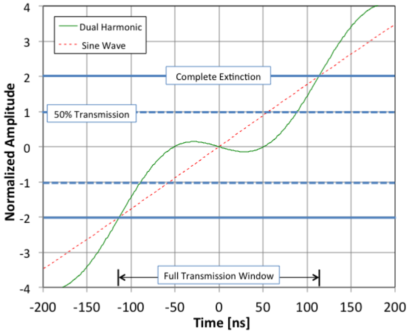
Tracker energy loss calibration

Double-pass cosmic rays

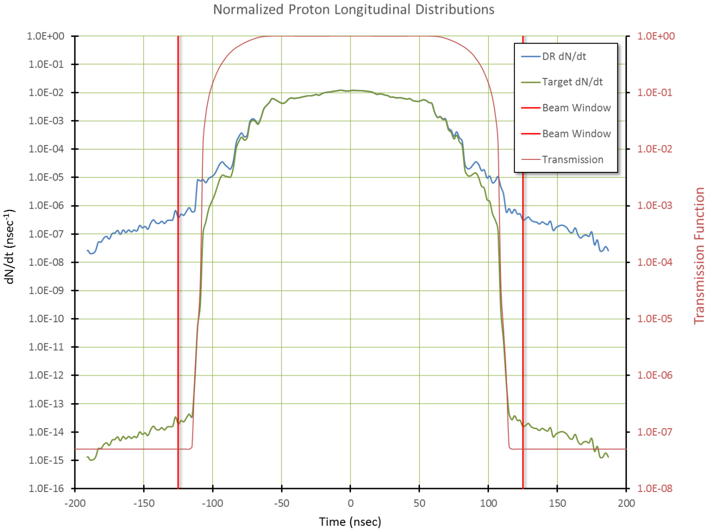


External extinction waveform





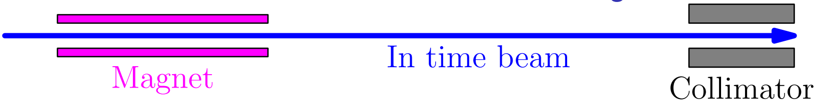
External extinction result



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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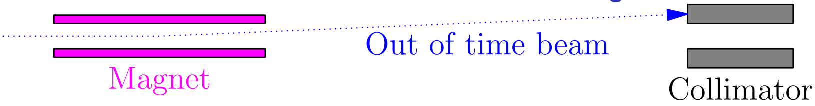
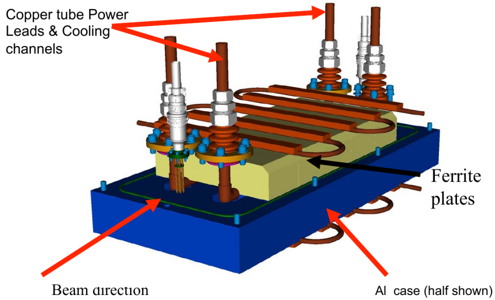


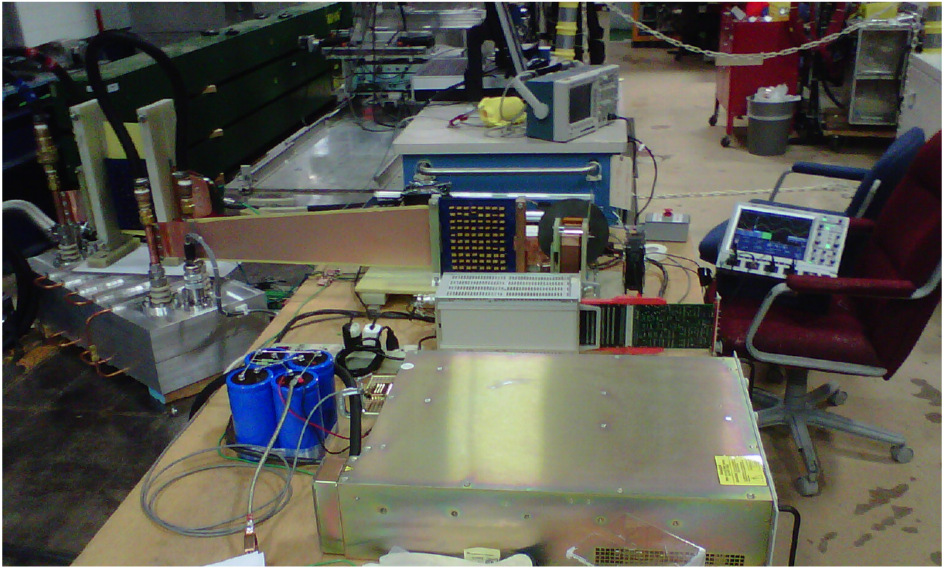
Achieving the extinction

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

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

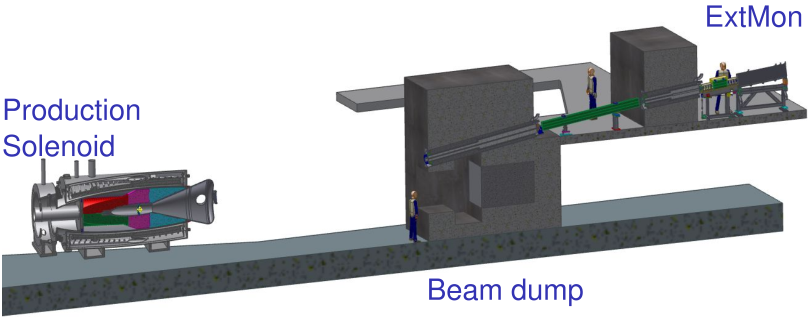


Testing extinction dipoles



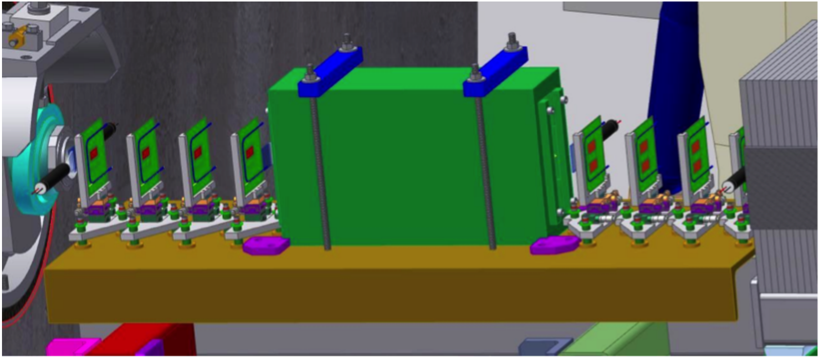
Monitoring beam extinction

- 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

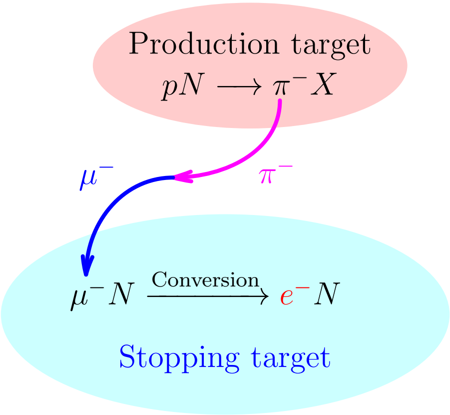
- Permanent magnet spectrometer
- Based on ATLAS silicon pixel chips
- Simulations show excellent performance, negligible background



Backgrounds

Focus on pions for now

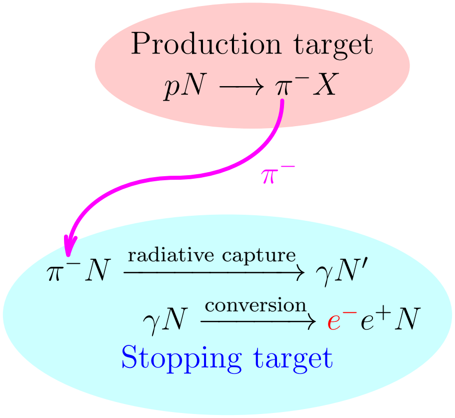
- Secondary beam starts with π^-
- The intent is to produce μ^- rate



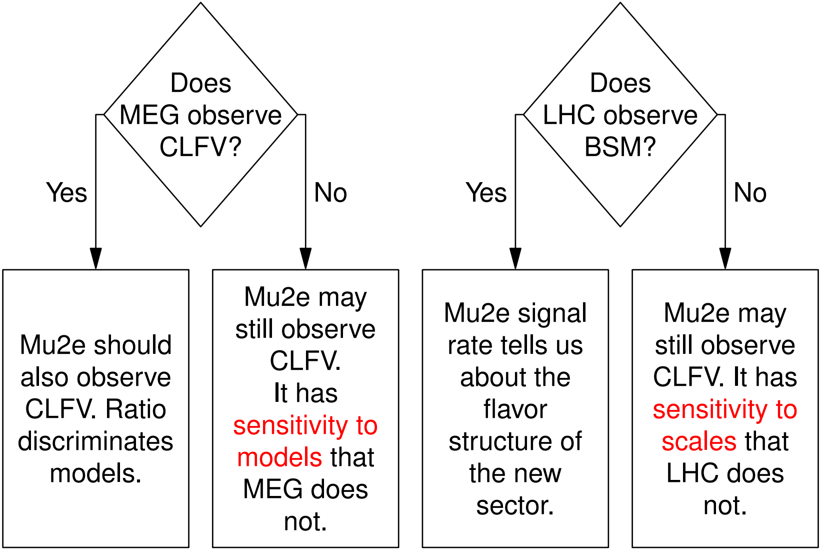
Backgrounds

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



Mu2e in different scenarios



Mu2e backgrounds for 3.6×10^{20} livetime POT

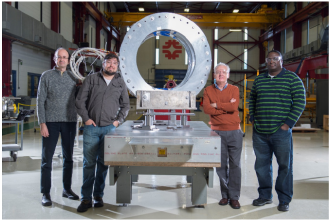
Single event sensitivity $(3.01 \pm 0.03(\text{stat}) \pm 0.41(\text{syst})) \times 10^{-17}$

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	$0.41 \pm 0.13(\text{stat+syst})$

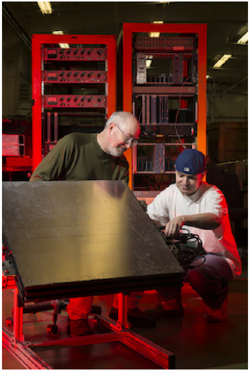
The pion capture and beam electron lines assume a 10^{-10} beam extinction.

More Mu2e prototypes. . .

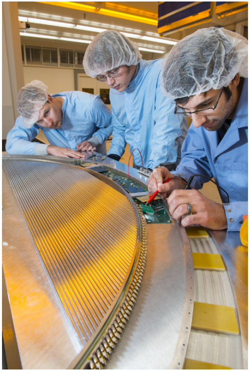
Transport solenoid



CRV



Tracker

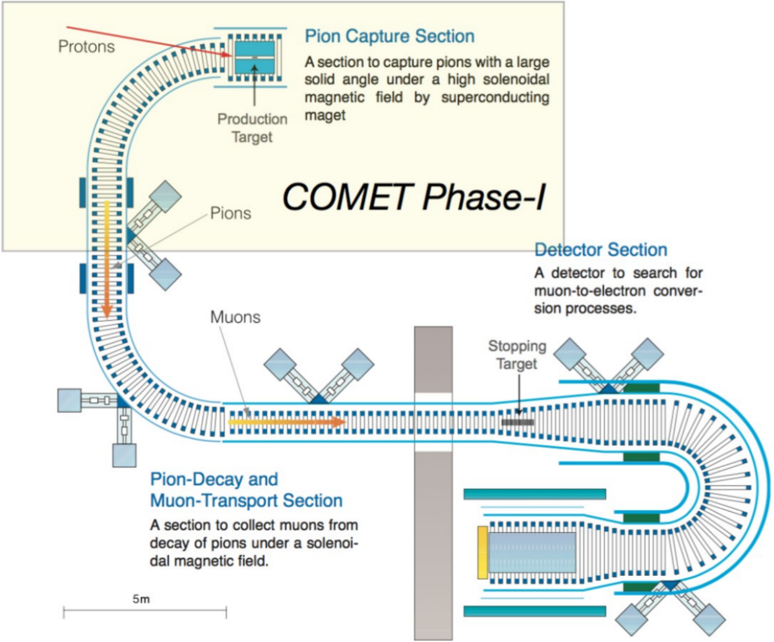


Calorimeter

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


Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
COMET Phase-I
Pions
Detector Section
A detector to search for muon-to-electron conversion processes.
Muons
Stopping Target
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.
5m