Using Muons to Probe for New Physics with the Muon (g-2) and Mu2e Experiments

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Fermilab

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Outline

- The Big Picture
- Muon experiment overview
- Muon (g-2) experiment
- Mu2e experiment
- Closing remarks

The Big Picture

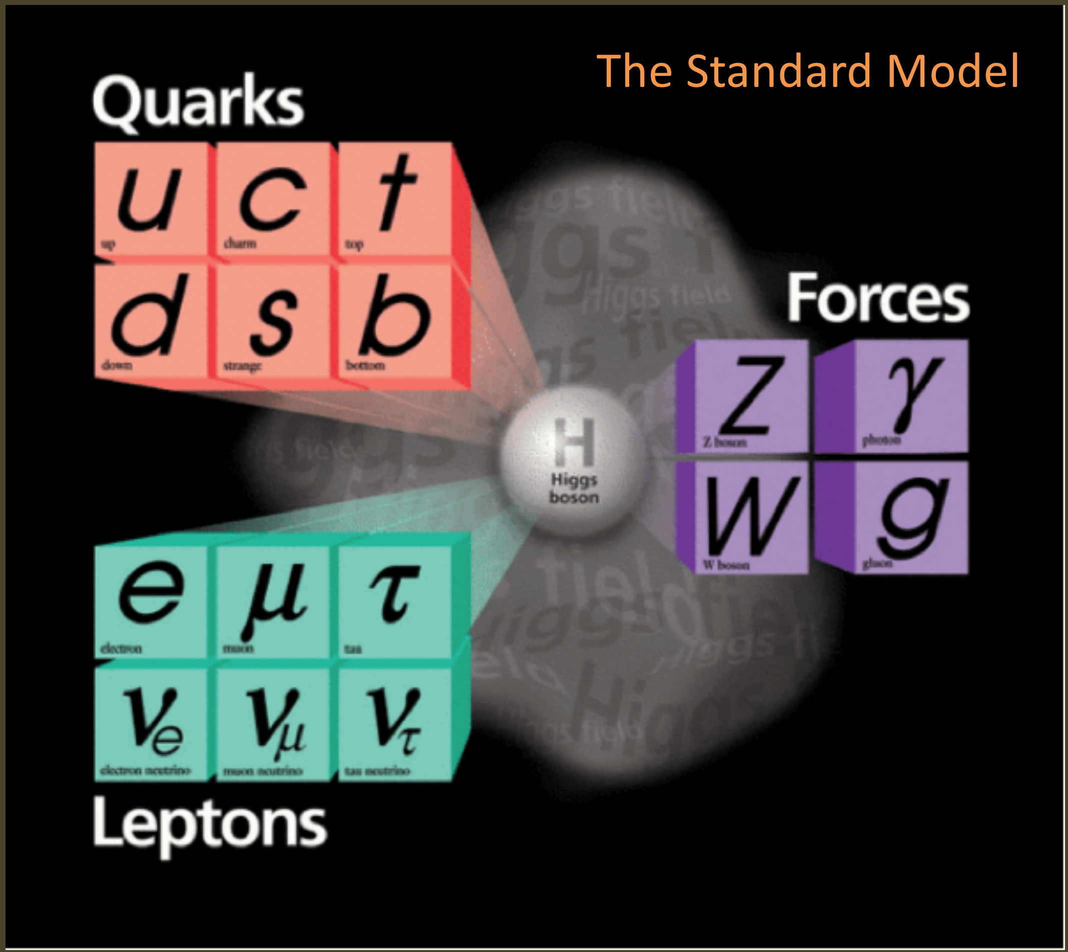
Basically HEP endeavors to accomplish two things:

1) Identify the fundamental constituents of nature
2) And describe the forces that govern their behavior

Our first guess…

earth, wind, fire, water

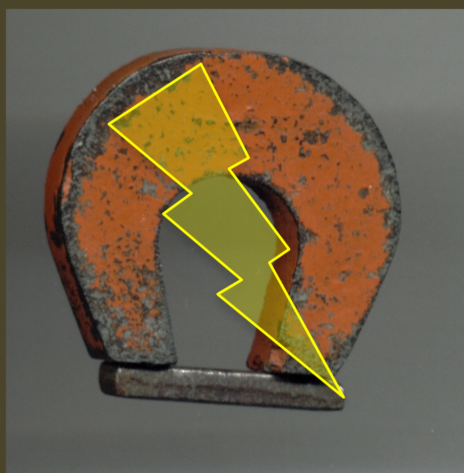
Current best guess…



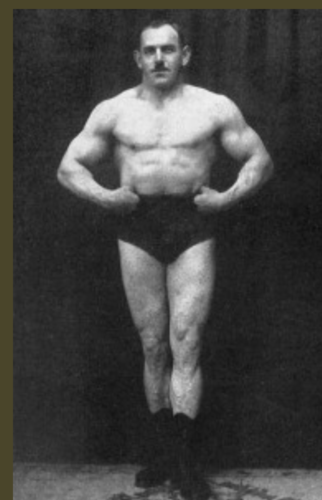
1) Fundamental constituents of all visible matter

Current best guess…

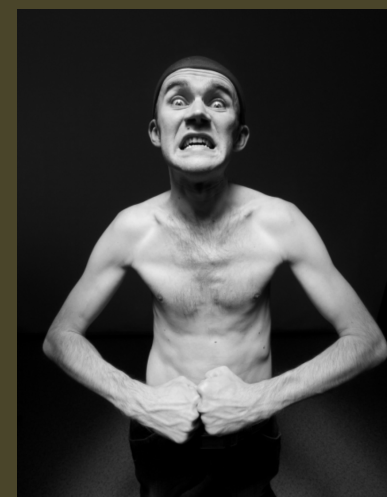
electromagnetic



strong



weak



2) The forces that govern their interactions

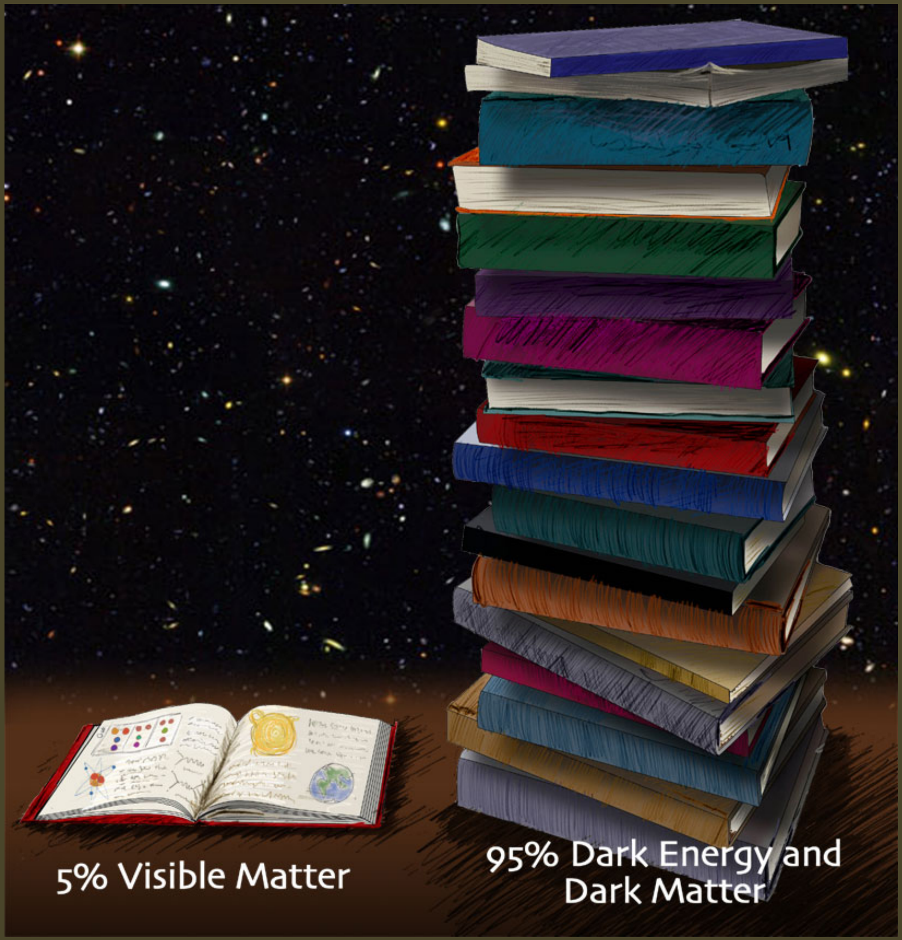
But there is a catch…

We know the SM to be incomplete

An (obvious) missing piece…

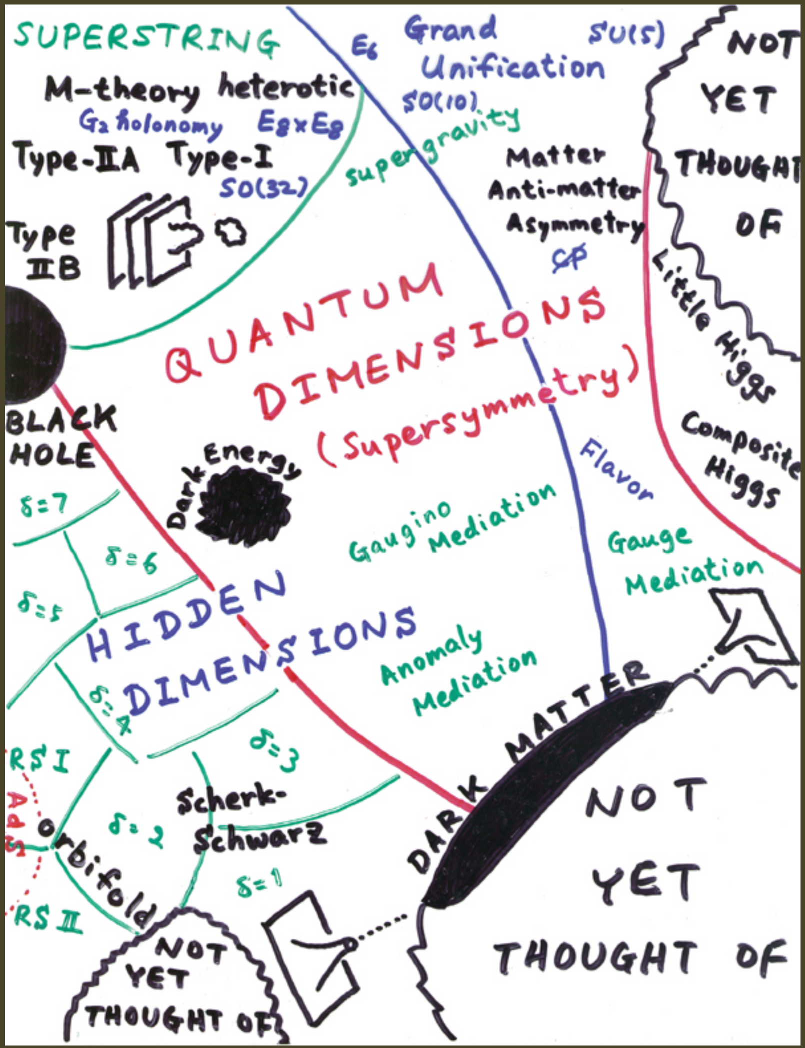
Gravitational force… fundamental to our being here, but too weak to affect particle dynamics in HEP experiments

There is a catch



Standard Model only describes 5% of Universe

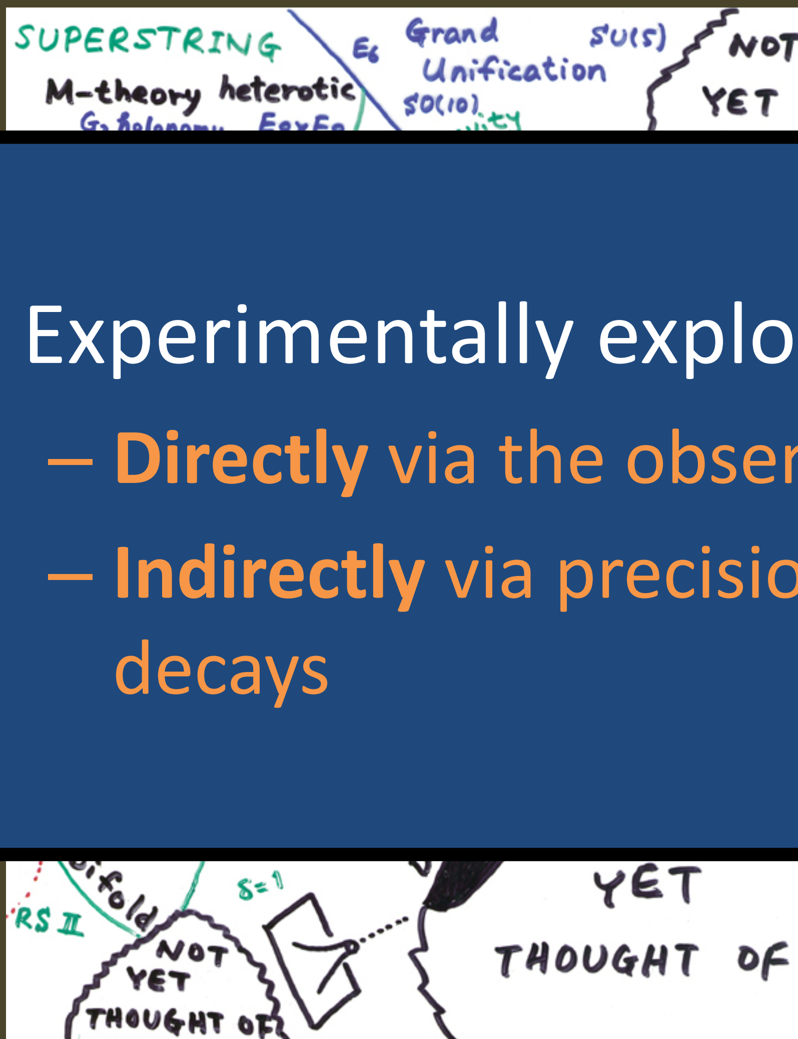
New Physics is required



We have lots of ideas of what a more complete theory might look like…

but we don't know which one (if any) is correct.

New Physics is required



We have lots of ideas of

- Experimentally explore for this NP
  - **Directly** via the observation of new particles
  - **Indirectly** via precision measurements and rare decays

one (if any) is correct.

The Power of Precision

- If measurements can obtain sufficient precision they become sensitive to quantum loop corrections (e.g. W mass)

$$\boxed{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}}$$

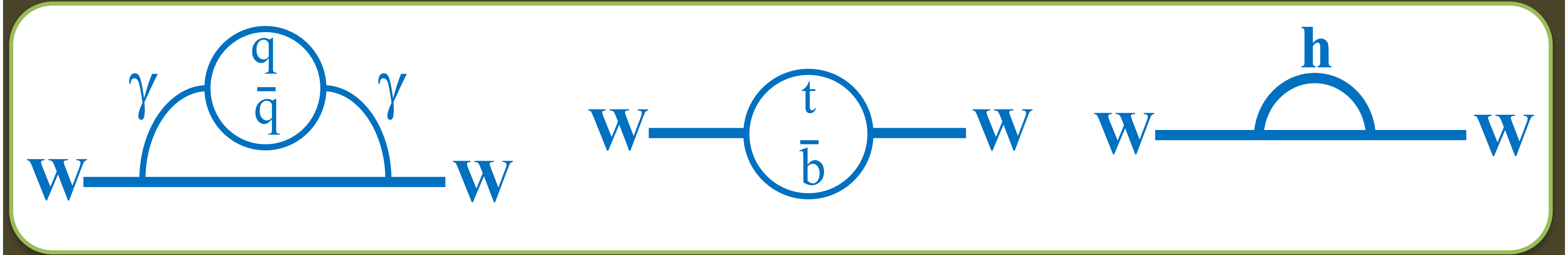
(the SM EWK theory starts from here)

The Power of Precision

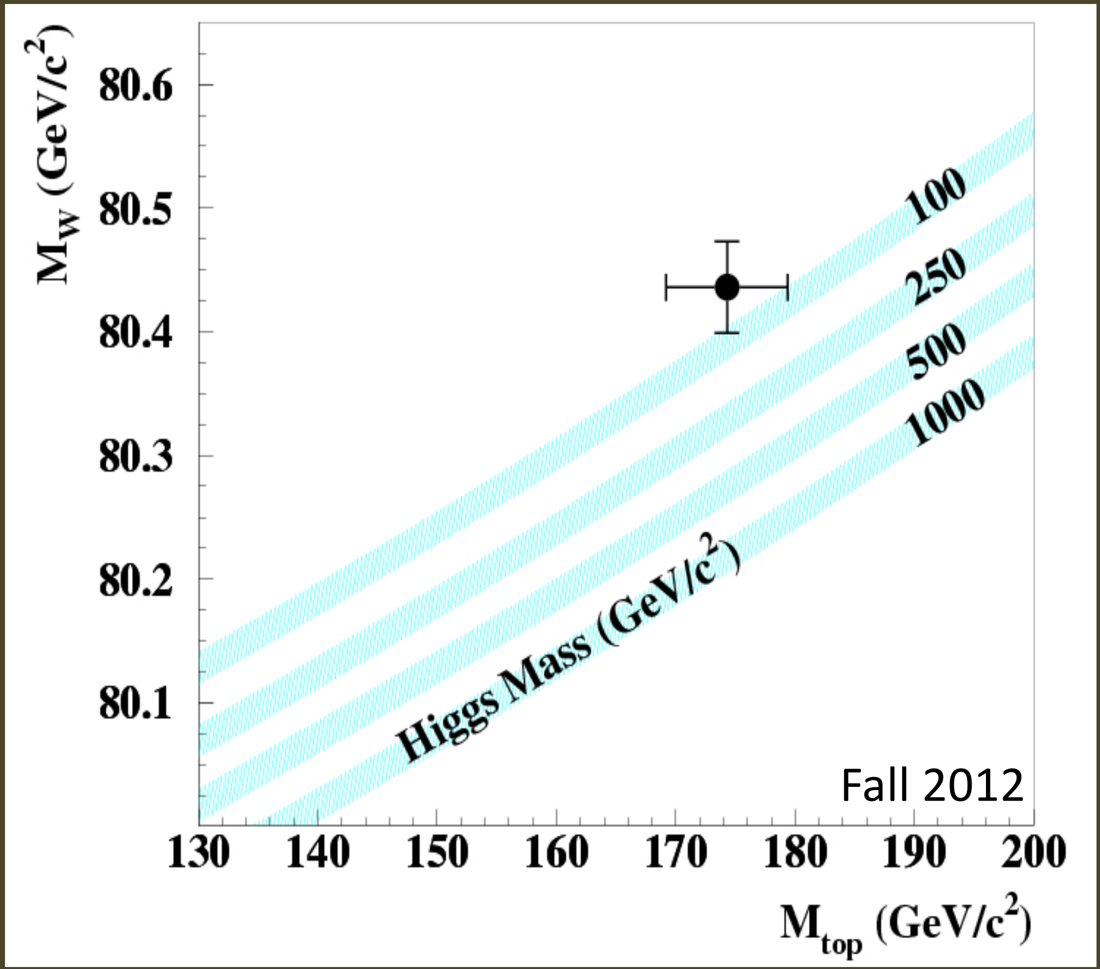
- If measurements can obtain sufficient precision they become sensitive to quantum loop corrections (e.g. W mass)

$$\boxed{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)}$$

(Δr accounts for quantum corrections from HVP, top quark, higgs boson)

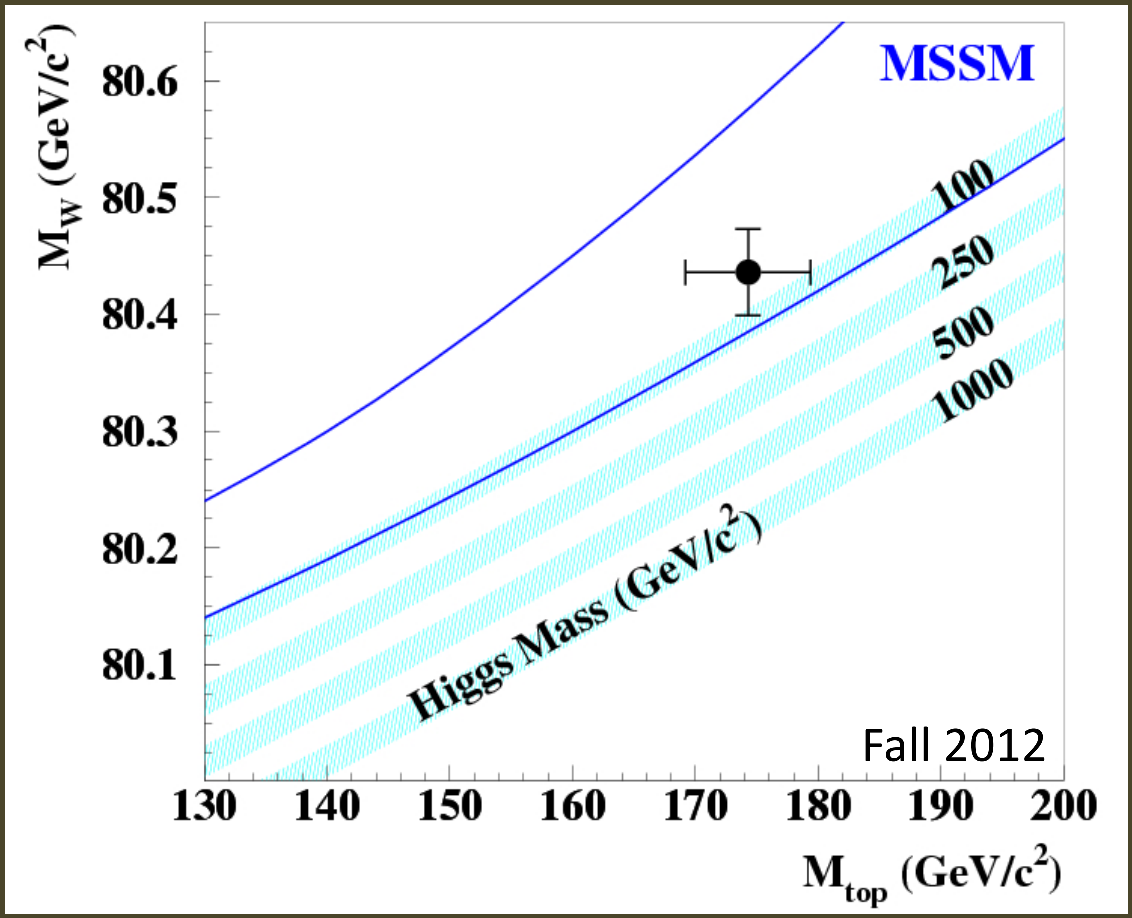


The Power of Precision



e.g. M_w, M_t measurements used to predict M_h

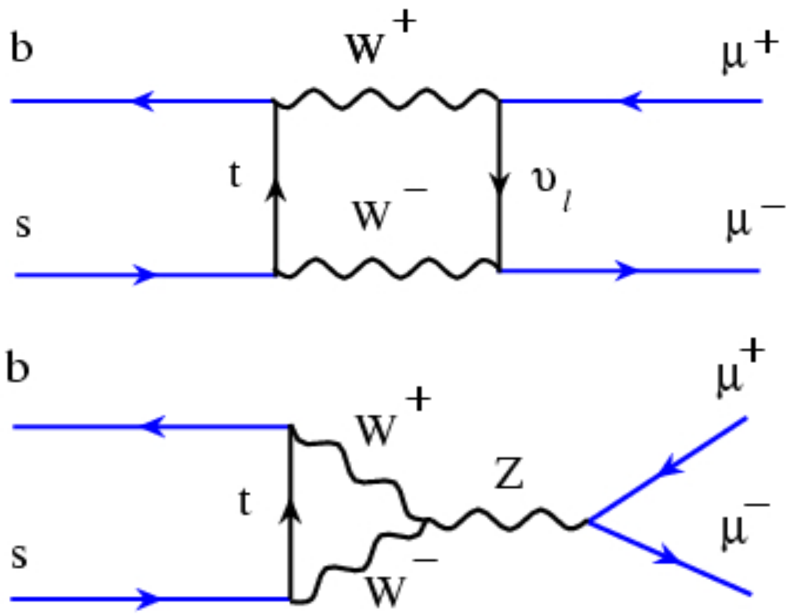
The Power of Precision



also sensitive to NP contributions

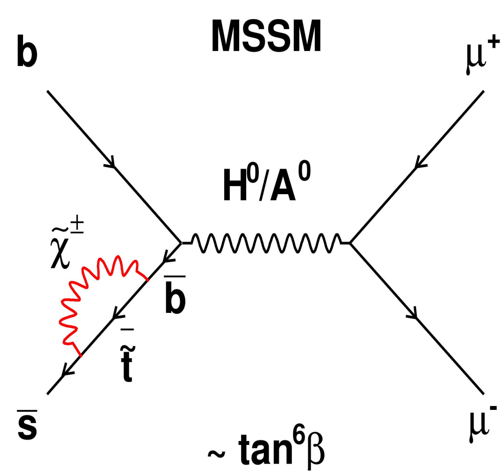
The Power of Rare Processes

- Processes that are suppressed in the SM offer enhanced NP sensitivity since NP contributions can affect observables at a level comparable to or >> SM (e.g. Flavor Changing Neutral Current decays)



$BF(B_s^0 \to \mu^+\mu^-)_{SM} \approx 3\times10^{-9}$

Significant NP enhancements possible



Using muons to advance the search for New Physics

- New facility to supply world's most intense muon beams
  - Muon (g-2) experiment (commissioning 2017)
  - Mu2e experiment (commissioning 2020)

Muon Campus Physics in one slide

- Muon (g-2)
  - Precision determination of $a_\mu = (g-2)/2$
  - If $[a_\mu(exp) - a_\mu(SM)] != 0$, signals NP contributions
  - nb. currently, $a_\mu(exp) > 3\sigma$ discrepant from $a_\mu(SM)$
- Mu2e
  - Search for a (extremely) rare FCNC decay
  - Observation signals NP contributions
  - nb. currently $R_{\mu e} < 7 \times 10^{-13}$ @ 90% CL

Muon Experiments

About the muon

The muon (μ) is a Charged Lepton

- Electric charge : -/+ 1
- Color charge : 0
- Spin : ½
- Mass : m_μ = 105 MeV/c^2 ~ 200 m_e
- Lifetime : $\tau_\mu = 2.2 \times 10^{-6}$ s
- Discovered 1936 by Anderson & Neddermeyer

Some important μ phenomenology

– Muons decay via a weak interaction:

$$\boxed{BF\left(\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu\right) \approx 100\%}$$

– Muons are penetrating:

$$\boxed{\left(\sigma_\mu/\sigma_e\right)_{Brem} \propto \left(m_e/m_\mu\right)^2 \approx 1/40{,}000}$$

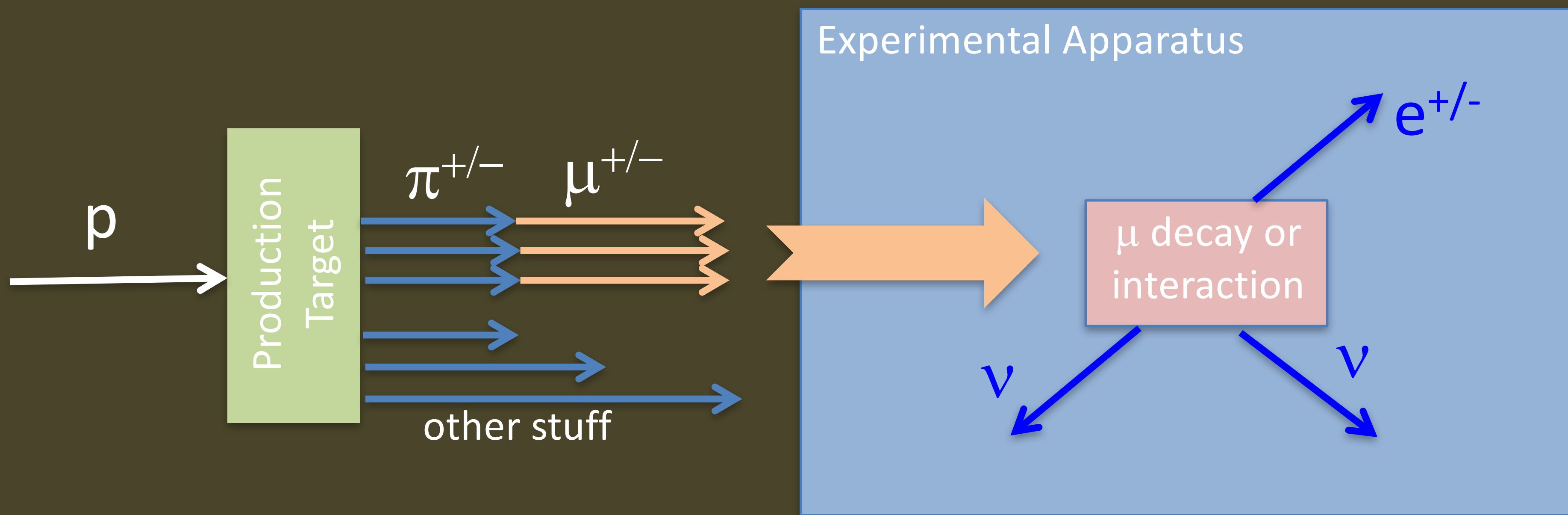
– Muons (μ^-) orbit atomic nuclei:

$$\boxed{\left(r_\mu/r_e\right)_{Bohr} \propto \left(m_e/m_\mu\right) \approx 1/200}$$

– Muons have an intrinsic magnetic moment:

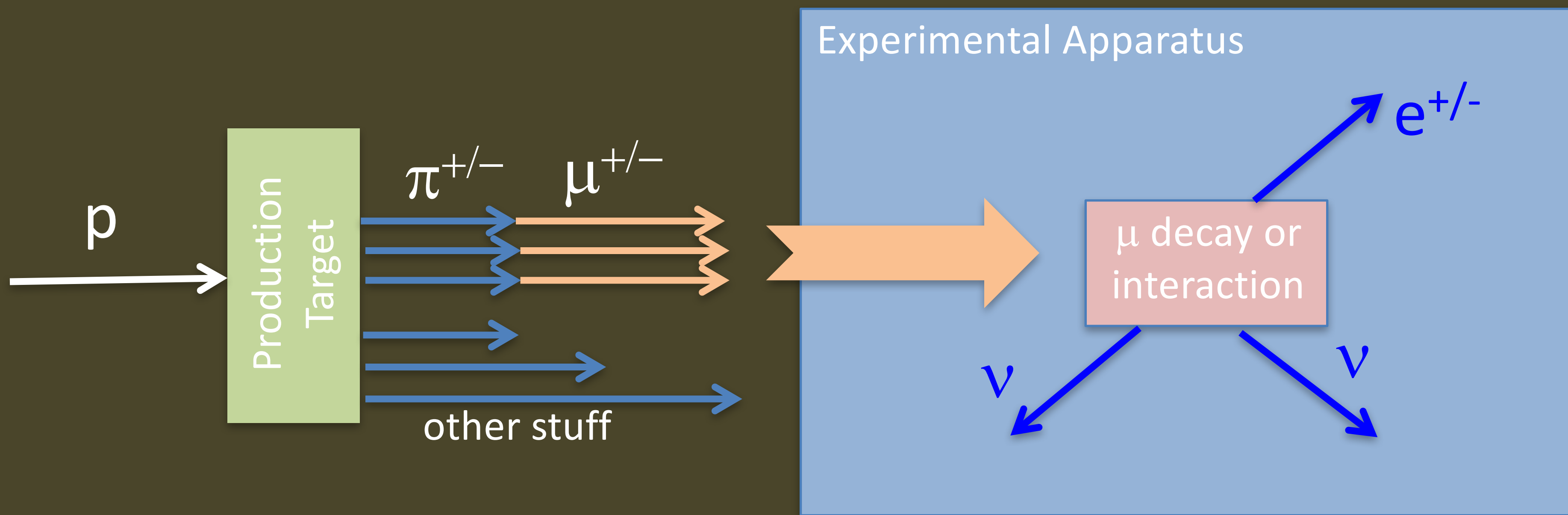
$$\boxed{\vec{\mu} = \frac{g}{2}\left(\frac{q\hbar}{2m_\mu}\right)}$$

Muon experiment cartoon



Both experiments use same basic principles

Muon experiment cartoon

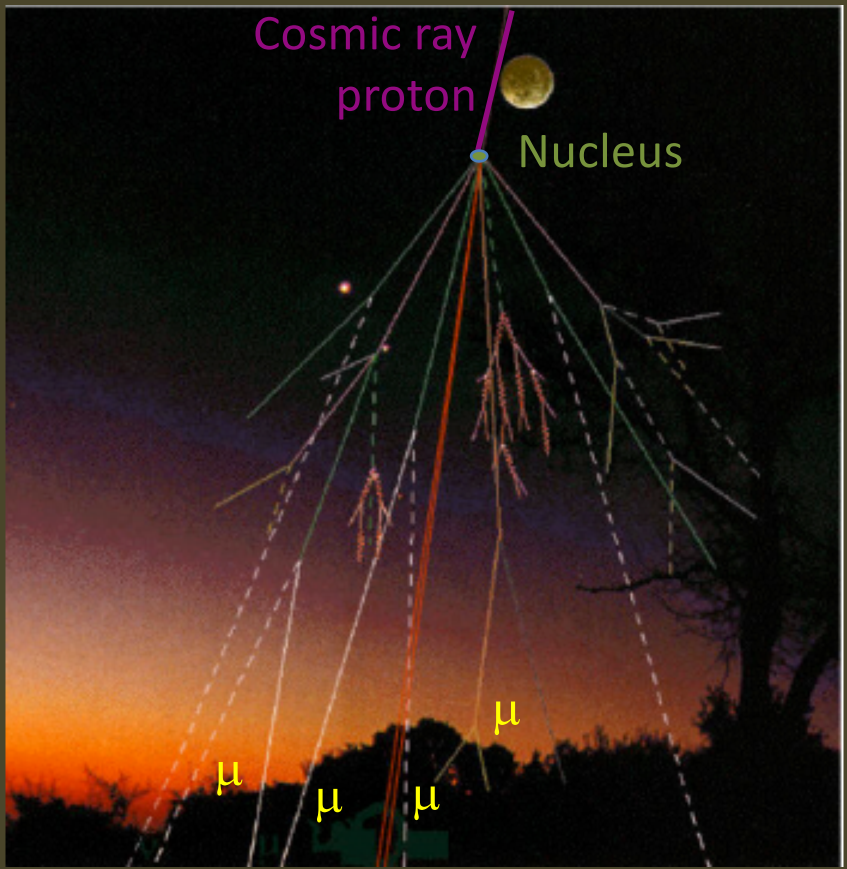


Require:

- High intensity, high purity μ source
- Using μ of appropriate momenta
- Custom apparatus to precisely measure particles consistent with having originated from μ decay

Cosmic ray muons

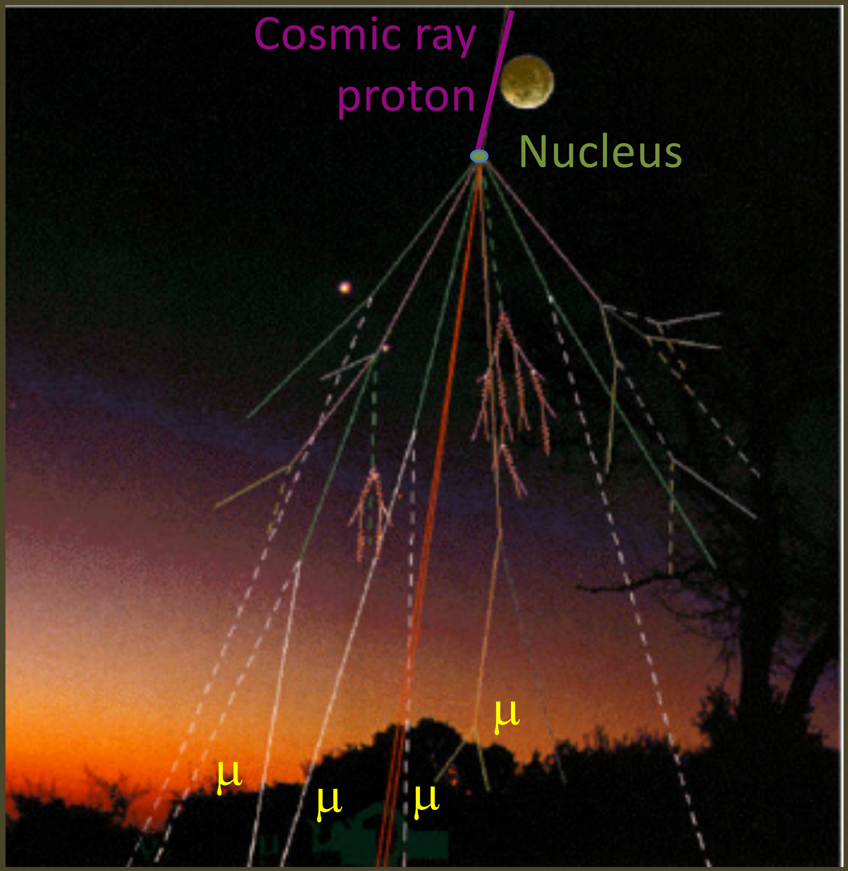
$p\,N \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu X$



Cosmic ray muons reach us here at a rate of ~ 1 / cm^2 / min

Making muons for experiments

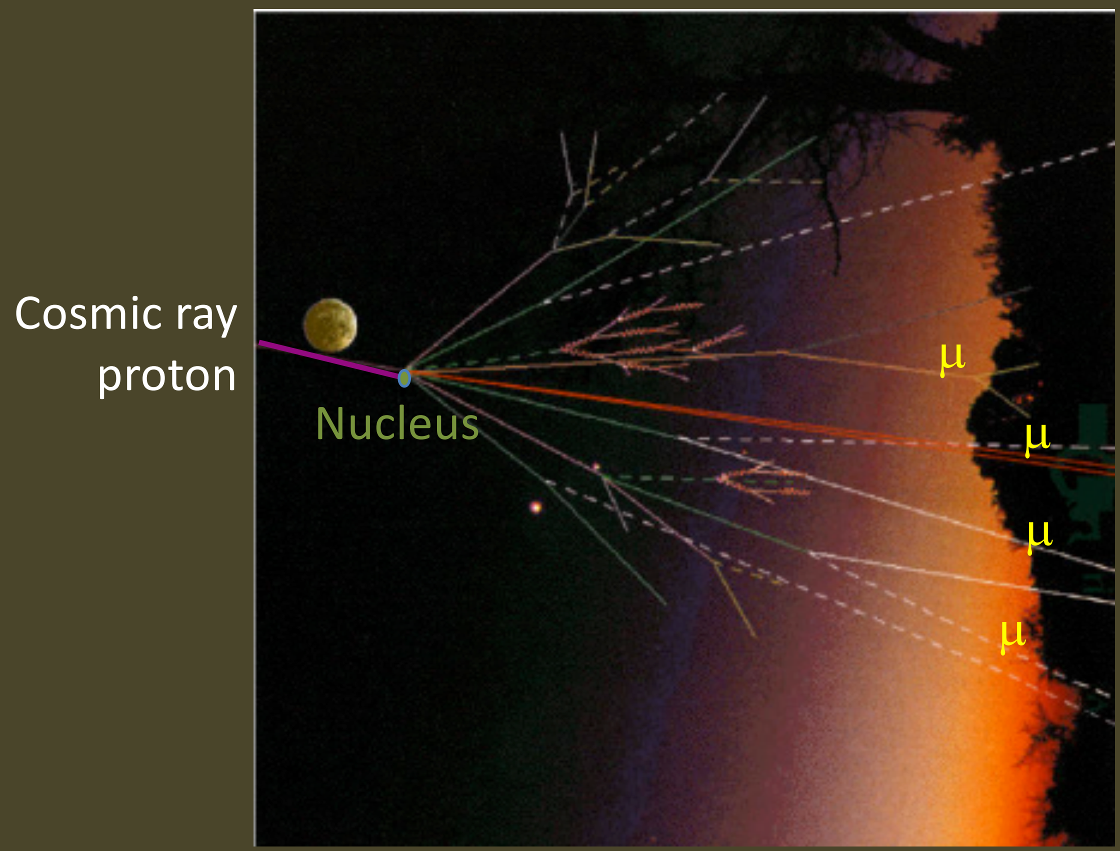
$$p\,N \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu X$$



Smash protons on nuclei, collect the debris (just like cosmic rays)

Making muons for experiments

$$p\,N \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu X$$

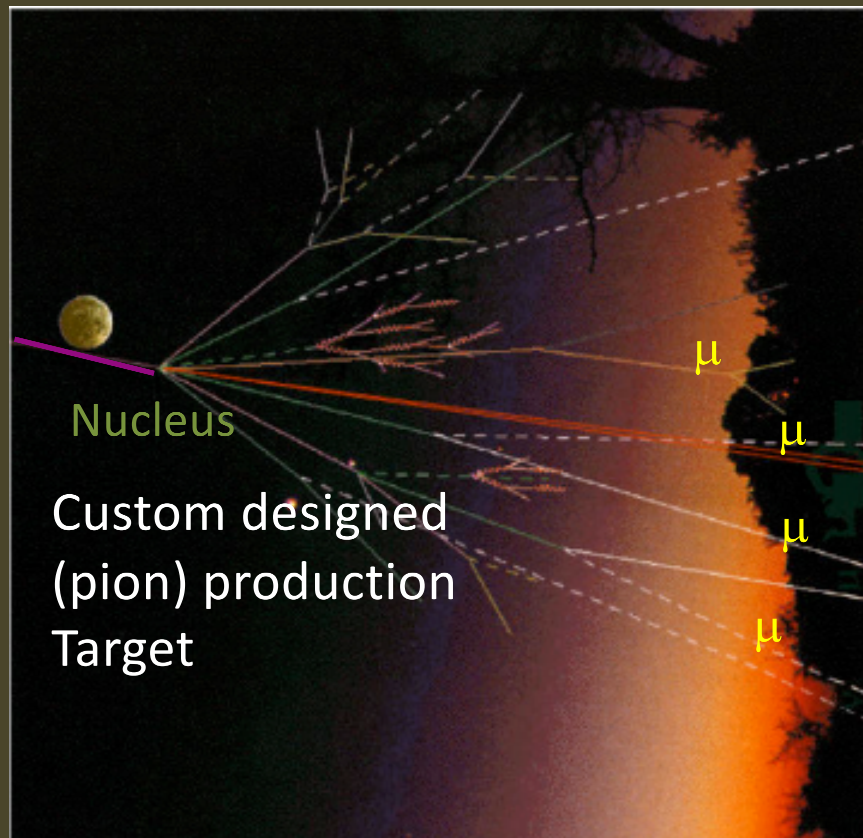


Smash protons on nuclei, collect the debris (just like cosmic rays)

Making muons for experiments

$$p\,N \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu X$$

Protons from Booster
- 8 GeV kinetic energy
- 99.4% speed of light
- 667,000,000 mph

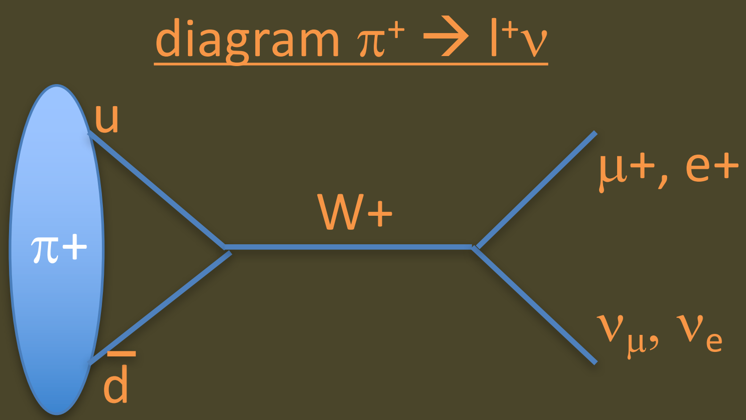


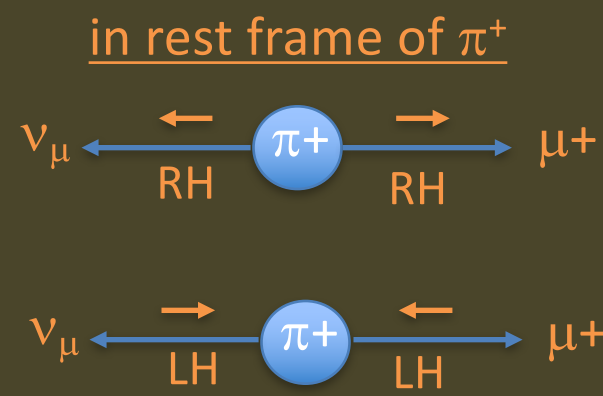
The debris eventually decays, often to μs

Use magnets to collect the μs

Smash protons on nuclei, collect the debris (just like cosmic rays)

Pion Decay





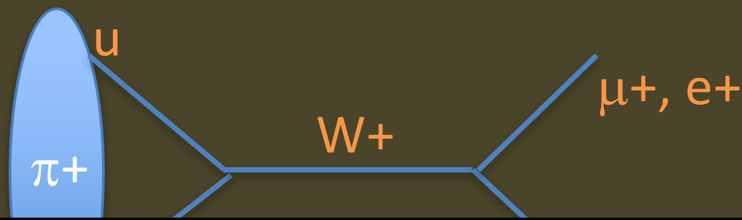
- For m_ν=0, no RH ν, ∴ since π is spin=0, lepton$^+$ is LH
- Fraction of LH lepton$^+$ ~m^2, so μ decays dominant

$$BF(\pi^+ \to e^+\nu_e)/BF(\pi^+ \to \mu^+\nu_\mu) \propto \left(\frac{m_e}{m_\mu}\right)^2 \approx 10^{-4}$$

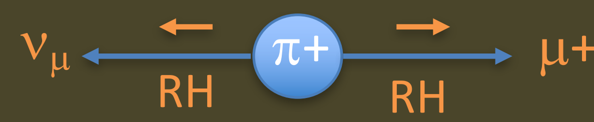
- In lab frame (for p_π ~500 MeV/c or larger),
  - forward boosted μ+ LH polarized with p_μ ~1.1 p_π
  - backward boosted μ+ RH polarized with p_μ ~0.6 p_π

Pion Decay

diagram $\pi^+ \rightarrow l^+\nu$



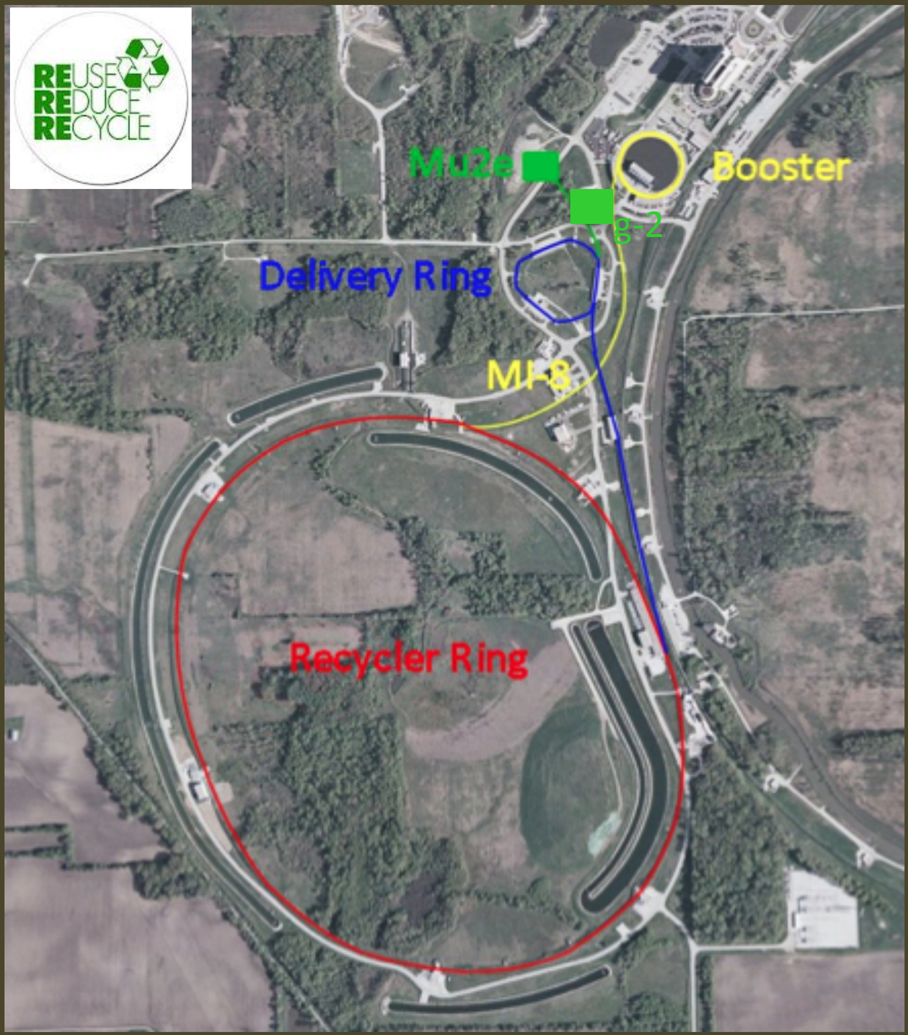
in rest frame of π^+



- Charge pion decays ~always produce a muon
- The muons are highly polarized
- The muon polarization is along $\vec{p}_\mu$
- Appropriately designed beam lines can achieve high purity (>99%) muon beams with polarization fractions of ~90%

  - forward boosted μ+ LH polarized with p_μ ~1.1 p_π
  - backward boosted μ+ RH polarized with p_μ ~0.6 p_π

Muon Campus Beam lines



- Begins with 8 GeV protons from the Booster.
- Commissioning with first beam began June 2017.
- Will be capable of delivering up to 10^{10} μ/s (x100 larger than current state-of-the-art).

Muon (g-2)

Muon (g-2) Collaboration

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Russia:

- Dubna
- Novosibirsk

England

- University College London
- Liverpool
- Oxford

Korea

- KAIST

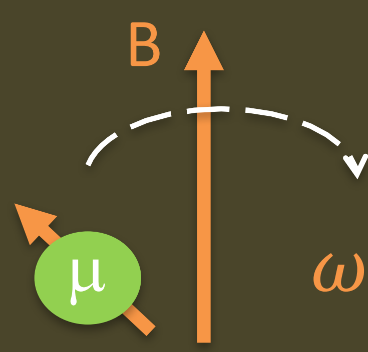
- About 150 members from 33 institutions

Muon magnetic moment

- For a spin ½ point particle:

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s} = g\left(\frac{e\hbar}{2m}\right)\left(\frac{1}{2}\right) = \frac{g\overrightarrow{\mu_B}}{2}$$

- In the presence of an external magnetic field, the particle will precess



$$\omega \sim \vec{\mu}\vec{B}$$

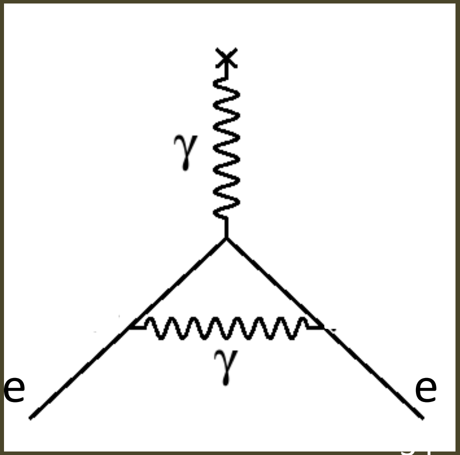
Muon magnetic moment

- Quantum corrections affect Lande' g factor

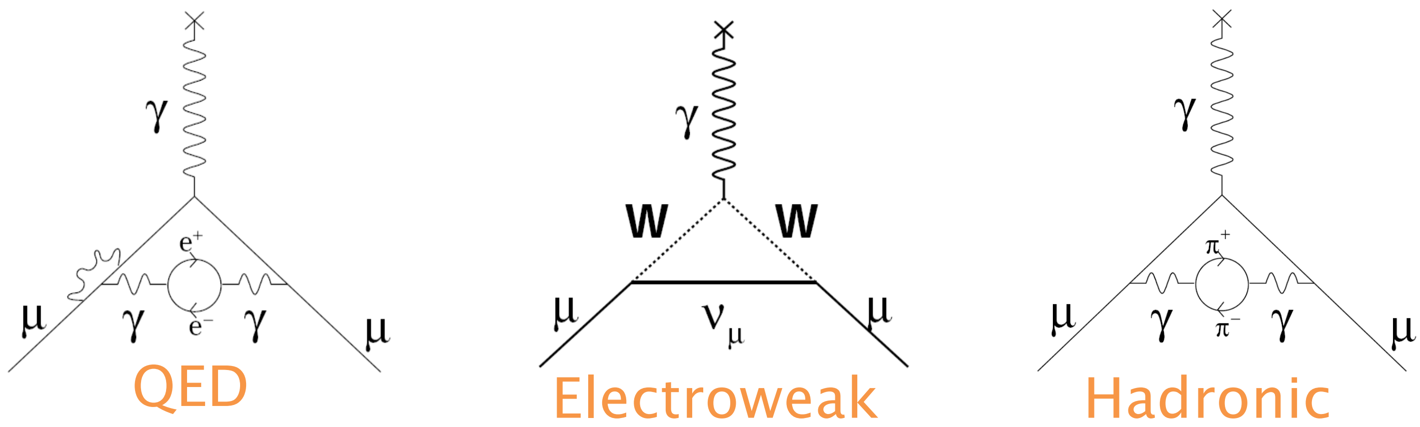
$$\vec{\mu} = \frac{g\overrightarrow{\mu_B}}{2} \rightarrow (1+a)\overrightarrow{\mu_B}$$

- "a" is the anomalous magnetic moment and accounts for quantum loop contributions

$$a = \frac{g-2}{2}$$



Other Contributions



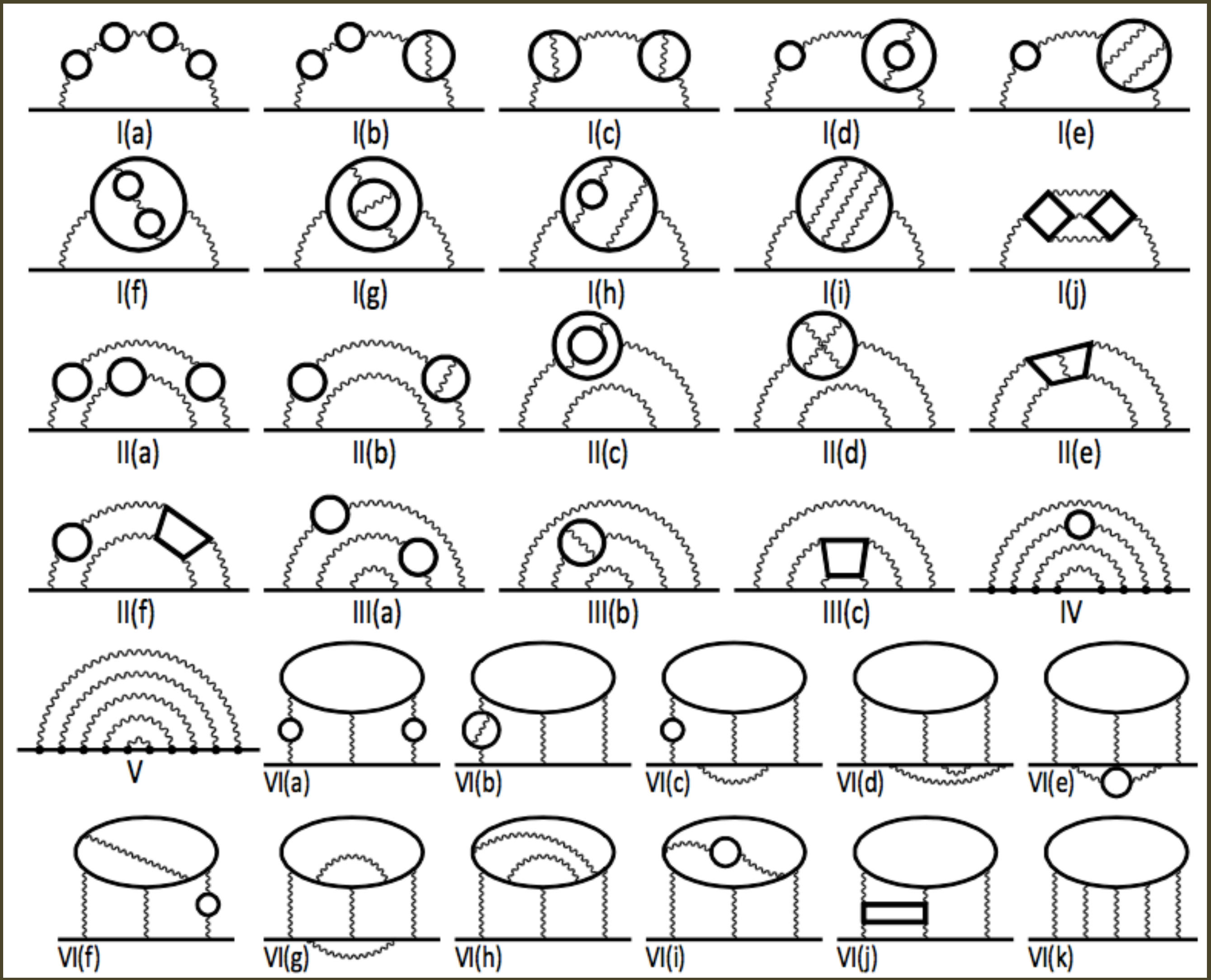
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP}$$

- Any standard model particle can contribute… BSM particles can too!

QED contributions

- Known to 5^{th} order in α_{em}

- (Aoyama, Hayakawa, Kinoshita, Nio, 2012)



State-of-the-Art

- Theory (0.42 ppm=parts per million):

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	-98.4 ± 0.7
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

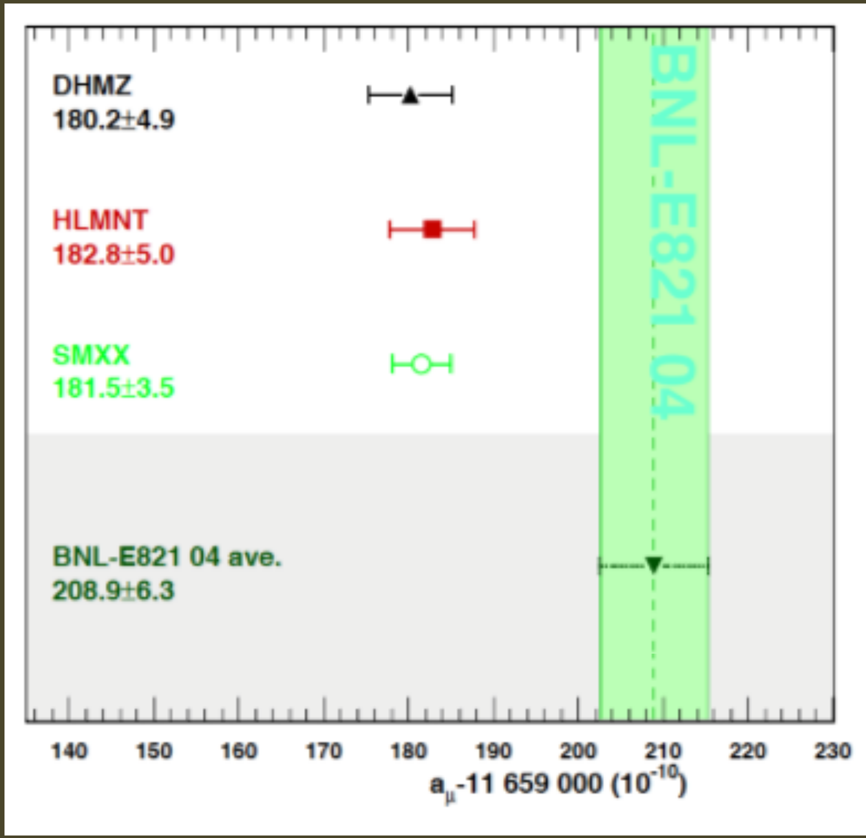
*Davier, et al.,Eur. Phys. J C (2011) 71 **Higiwara, et al., J. Phys. G38 (2011) 085003, + Glasgow Consensus, Prades, et al.

- Experiment (0.54 ppm, stats dominated):

a_μ(exp) = 116 592 089 (63) x 10^{-11} (0.54 ppm)

BNL E821 (2004)

State-of-the-Art

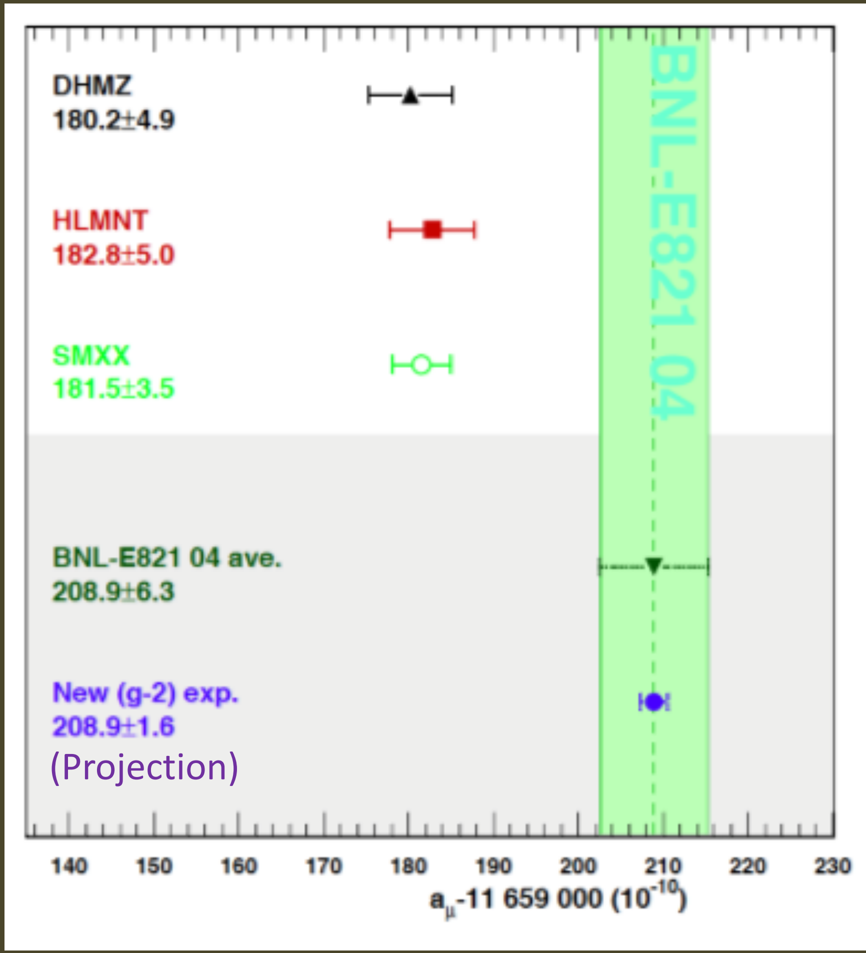


- Experiment and Theory are discrepant at >3σ
  - Need more information to resolve

Muon (g-2) Goal

- Reduce total experimental uncertainty by x4
  - Requires ~x20 the statistics
  - Must also reduce systematic uncertainty by ~x2
  - 0.54 ppm → 0.14 ppm
- Assuming central values remain unchanged, this alone would make the Exp-Theory discrepancy >5σ
  - Anticipated improvements in Theory uncertainty could bring the discrepancy to ~7σ
  - 0.42 ppm → 0.30 ppm (assuming same δ(HLBL))

State-of-the-Art



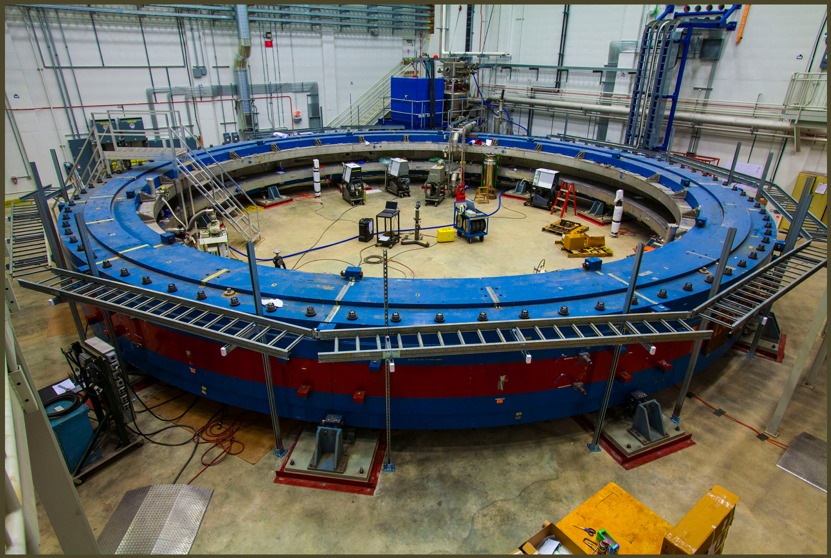
- Experiment and Theory are discrepant at $>3\sigma$
  – Fermilab Muon (g-2) will provide important insight

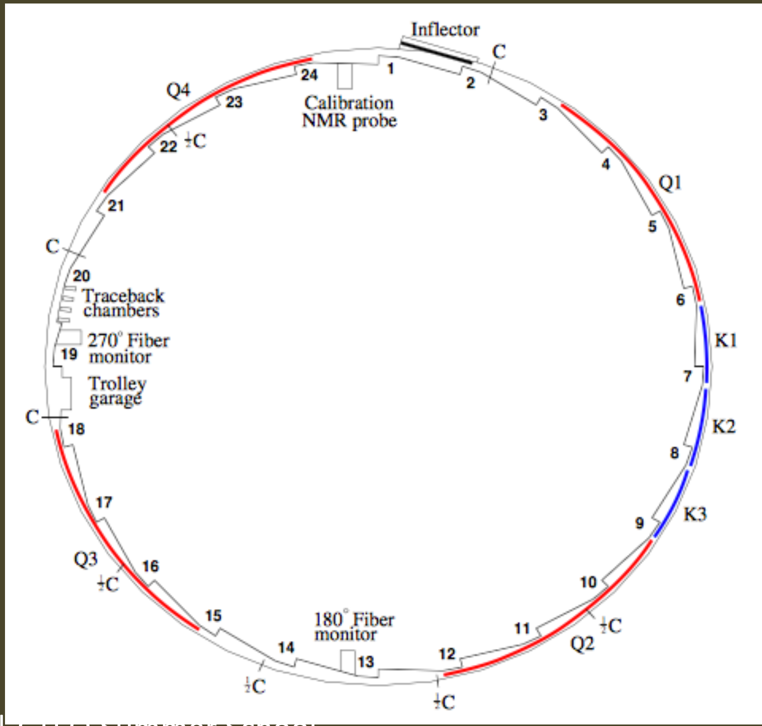
g-2 Experimental Technique

- Make, collect, and store polarized μ^+
  - $p\,N \rightarrow \pi^+ X \rightarrow \mu^+ \nu_\mu X$
  - Select μ^+ with p_μ = 3.09 GeV/c ("magic momentum")
  - Trap them in a storage ring with external B-field
- Measure arrival time and energy of e^+ from $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
  - Determine ω_a ("muon spin frequency")
- Precisely determine the B-field

g-2 Experimental Technique

- Collect pions of 3.11 GeV/c and their (forward) decay muons ($\mathcal{P}$ ~ 97%)
- Inject those muons into the g-2 storage ring





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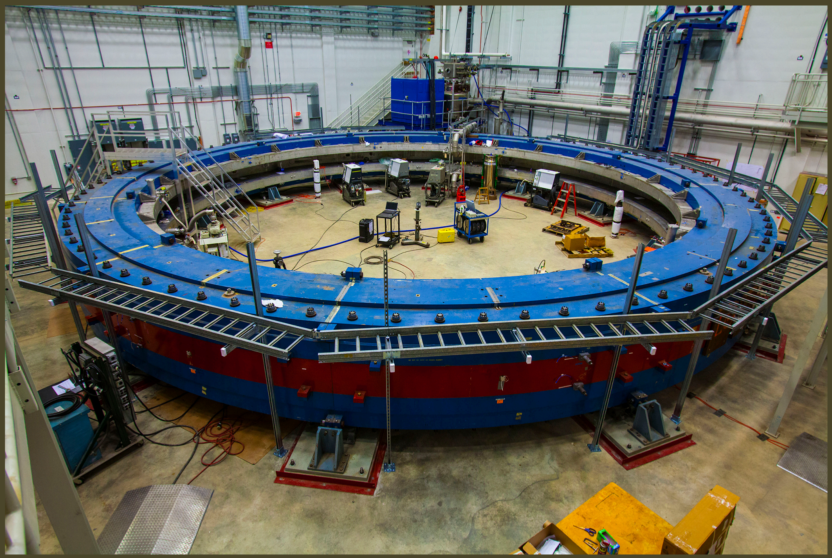
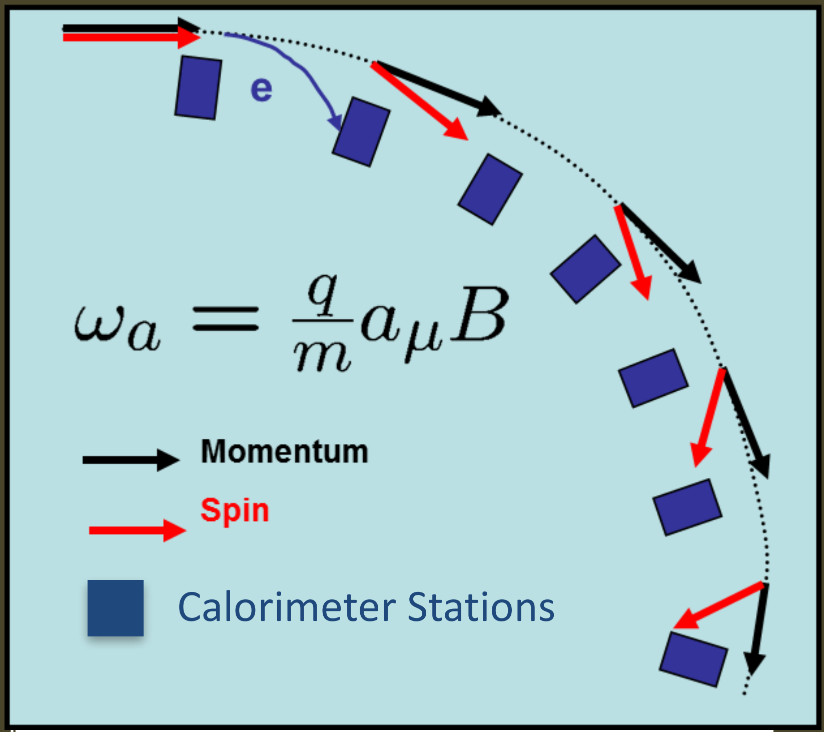
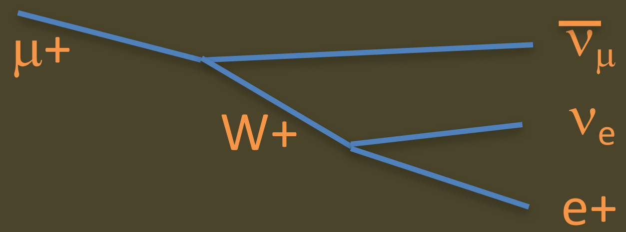


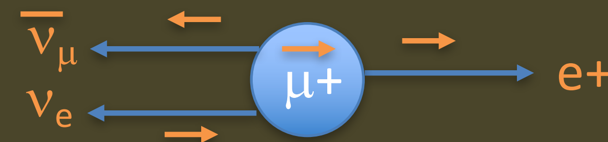


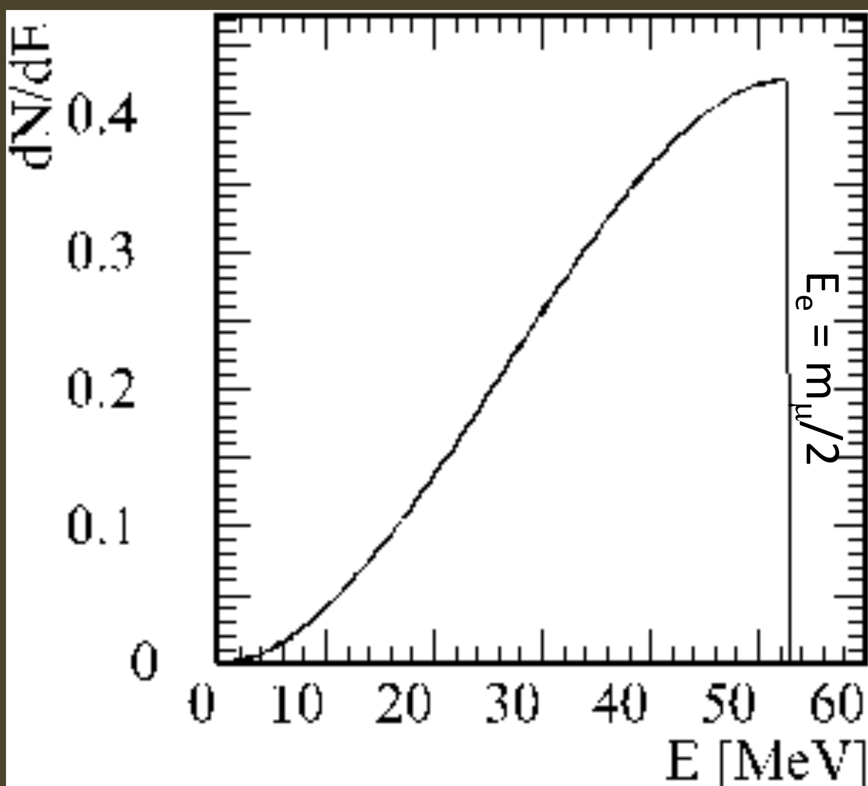
Muon Decay

diagram $\mu^+ \rightarrow e^+\nu$



in rest frame of μ^+



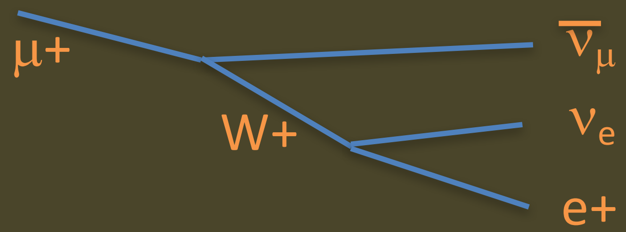


Energy spectrum of decay e (Michel spectrum)

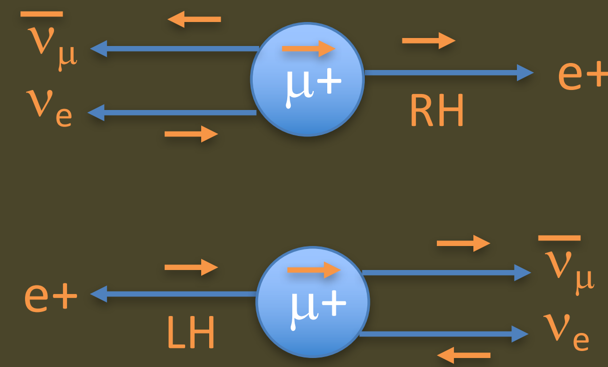
- There is a kinematic cut-off at $E_e = m_\mu/2$ for the decay electrons

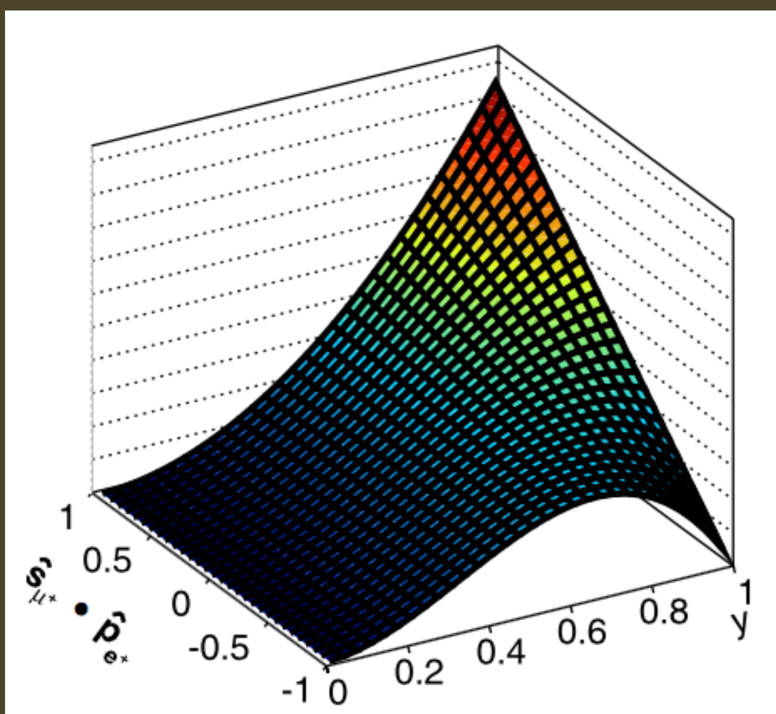
Muon Decay

<u>diagram $\mu^+ \rightarrow e^+\nu$</u>



<u>in rest frame of μ^+</u>





$y = E_e/E_e(\max)$; $E_e(\max) = m_\mu/2$

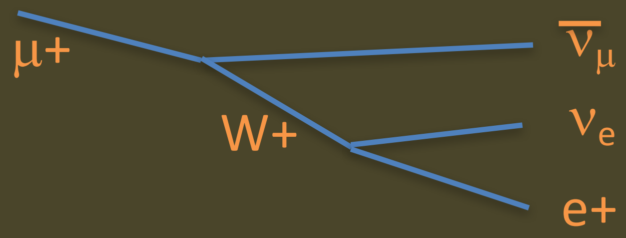
[T.P. Gorringe, D.W. Hertzog, Prog.Part.Nucl.Phys. 84 (2015) 73]

- For μ+: forward produced RH e+ preferred
- For μ- : backward produced LH e- preferred

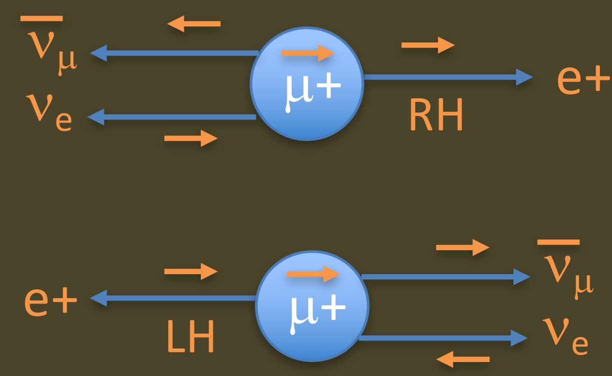
(nb. where "forward" is defined relative to the direction of muon spin)

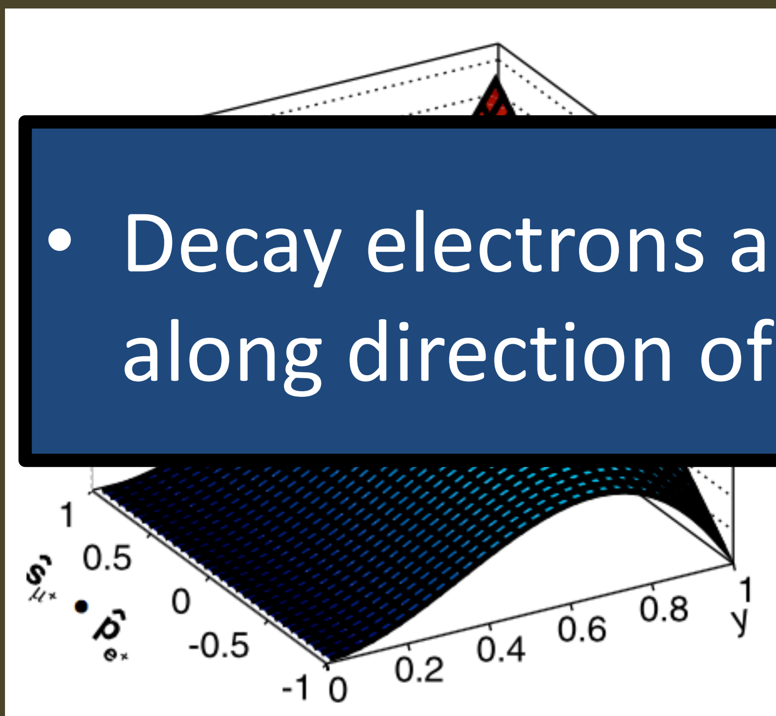
Muon Decay

diagram $\mu^+ \rightarrow e^+\nu$



in rest frame of μ^+





$y = E_e/E_e(max);\ E_e(max) = m_\mu/2$

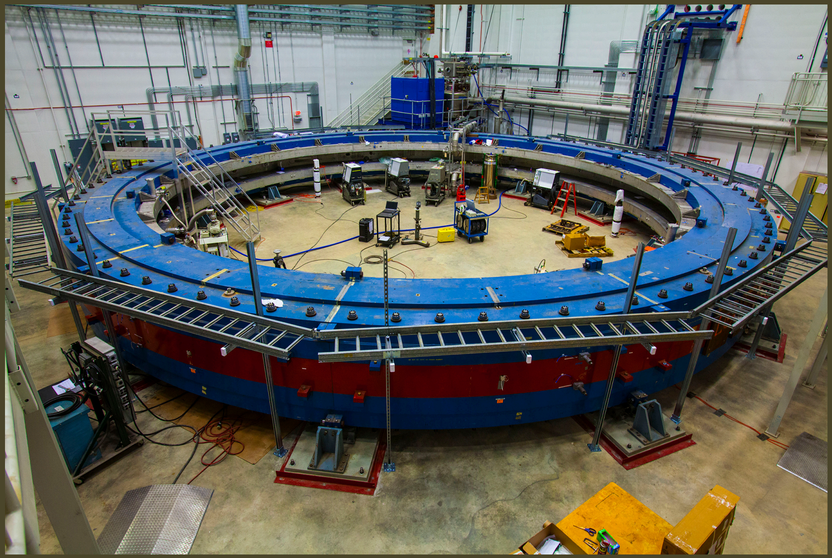
[T.P. Go … t.Nucl.Phys. 84 (2015) 73]

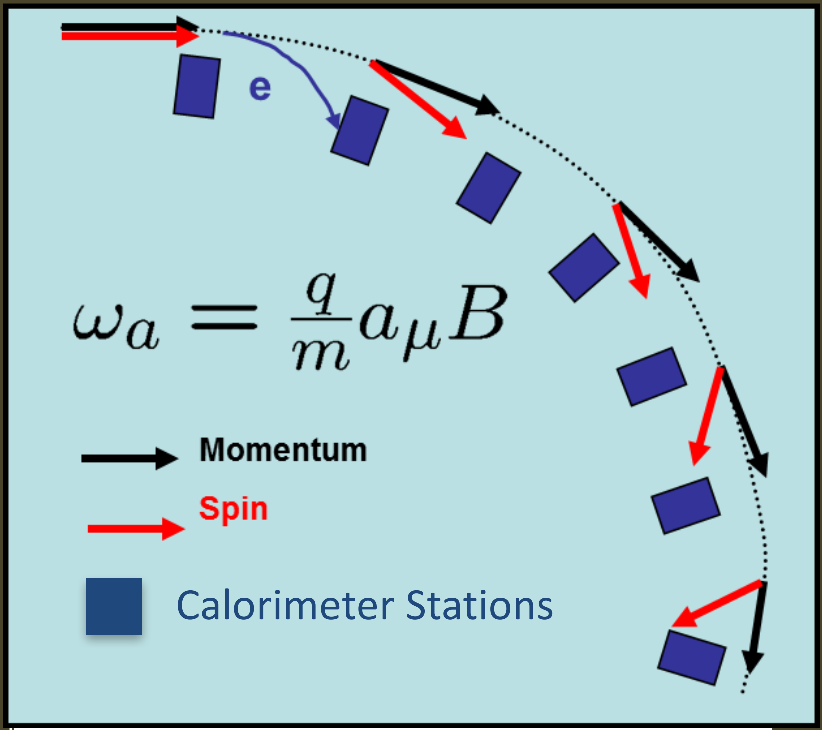
- Decay electrons are preferentially produced along direction of the muon spin

- For μ- : backward produced LH e- preferred

g-2 Experimental Technique

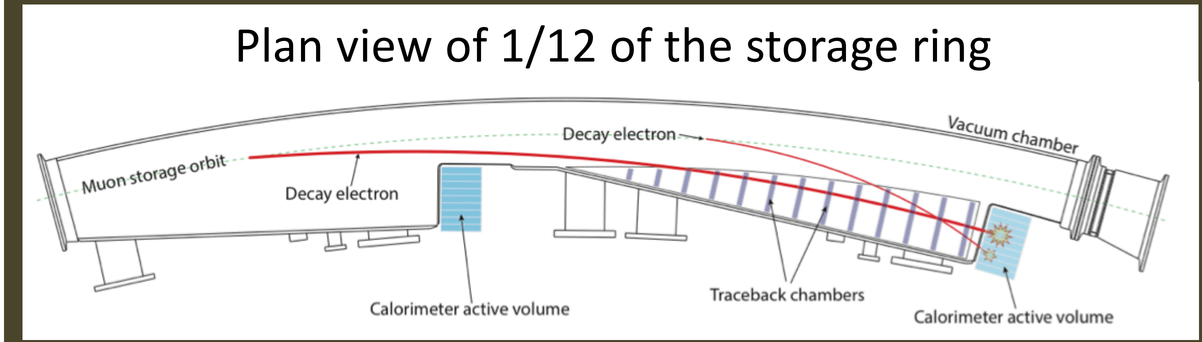
- Collect pions of 3.11 GeV/c and their (forward) decay muons ($\mathcal{P}$ ~ 97%)
- Inject those muons into the g-2 storage ring

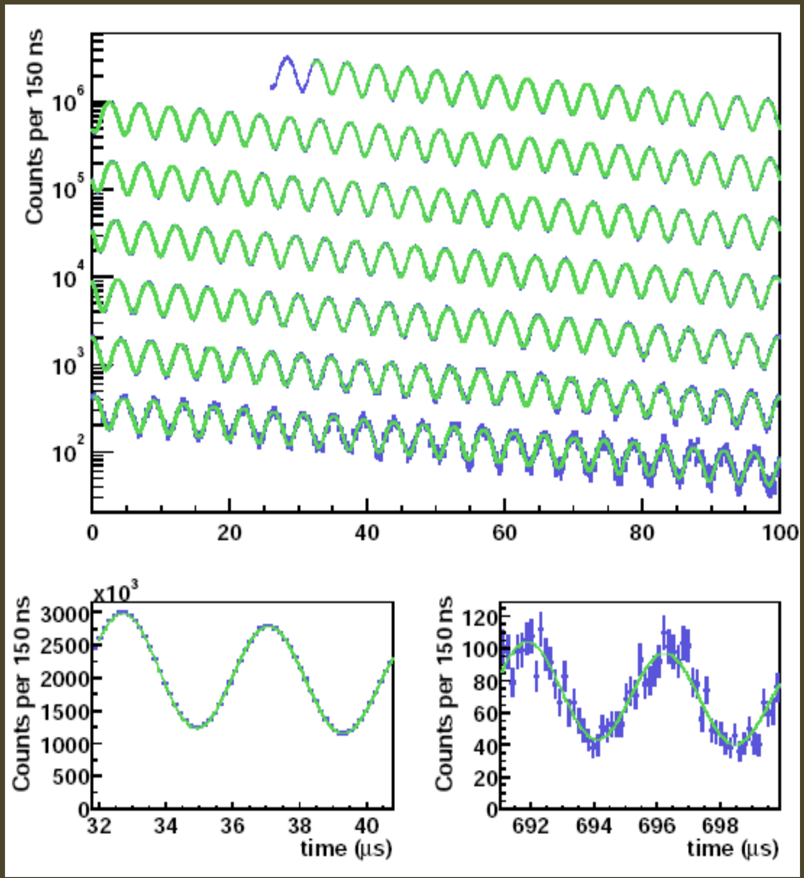




g-2 Experimental Technique

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

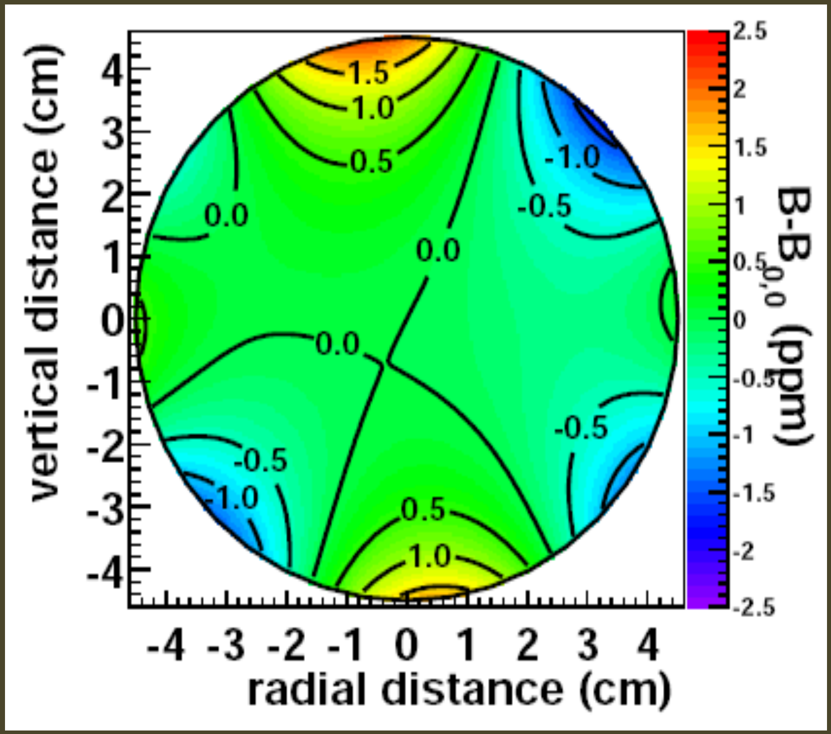


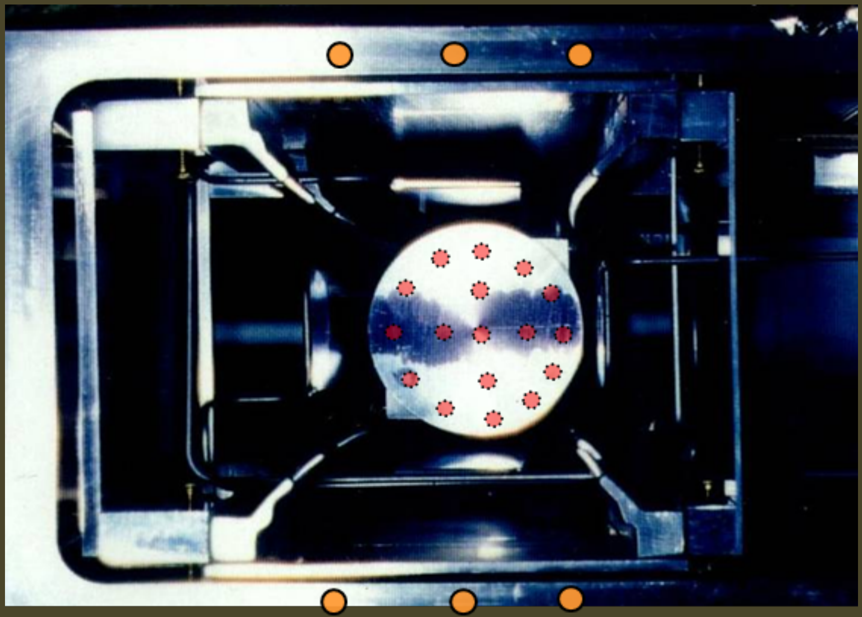


- The rate of e^+ at the inner radius of the storage rings varies with ω_a
- At the magic momentum the β x E term vanishes

g-2 Experimental Technique

- Shim storage ring magnet to achieve a very uniform dipole field





- Utilize high precision NMR probes to track field stability

Muon (g-2) Improvements

- Beam line offers many improvements
  - Pion collection, muon capture, momentum spread, longer decay channel, improved injection into the ring, reduced hadronic flash, improved rate capability
- Leverage experience from BNL experiment to build-in handles that ought allow a reduction in systematic uncertainties
  - Improved B-field uniformity and monitoring, improved monitoring of beam, improved rate capability

Muon (g-2) Improvements

systematics on ω_a

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

systematics on B

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70

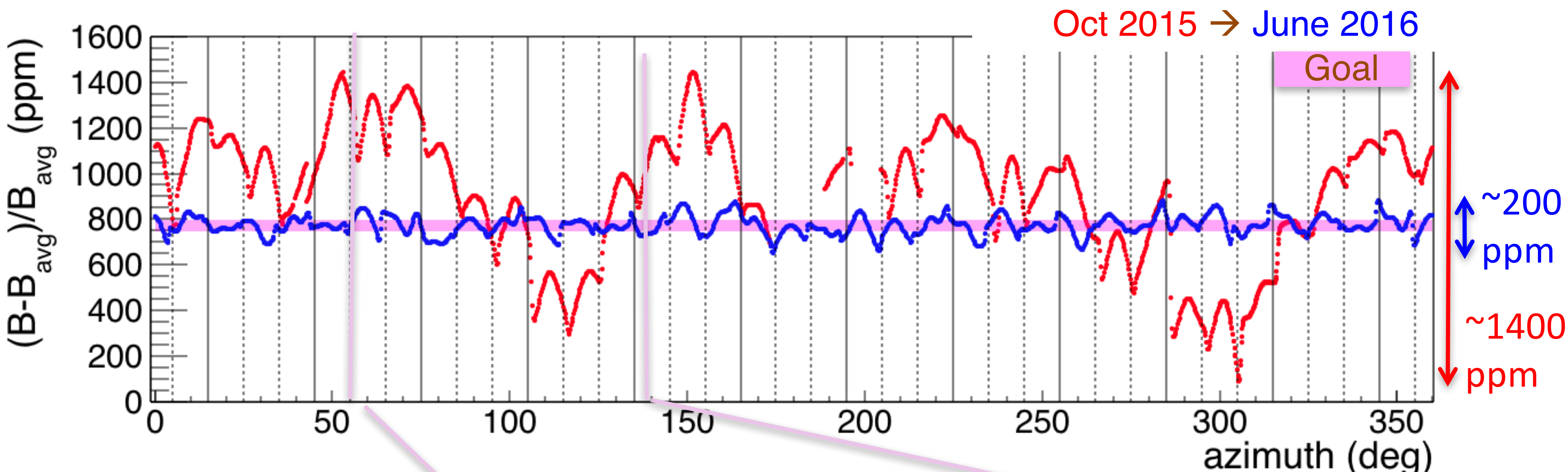
- Projected uncertainties for Muon (g-2) for full dataset:
  - Stat: 0.1 ppm Syst: 0.1 ppm Total: 0.14 ppm

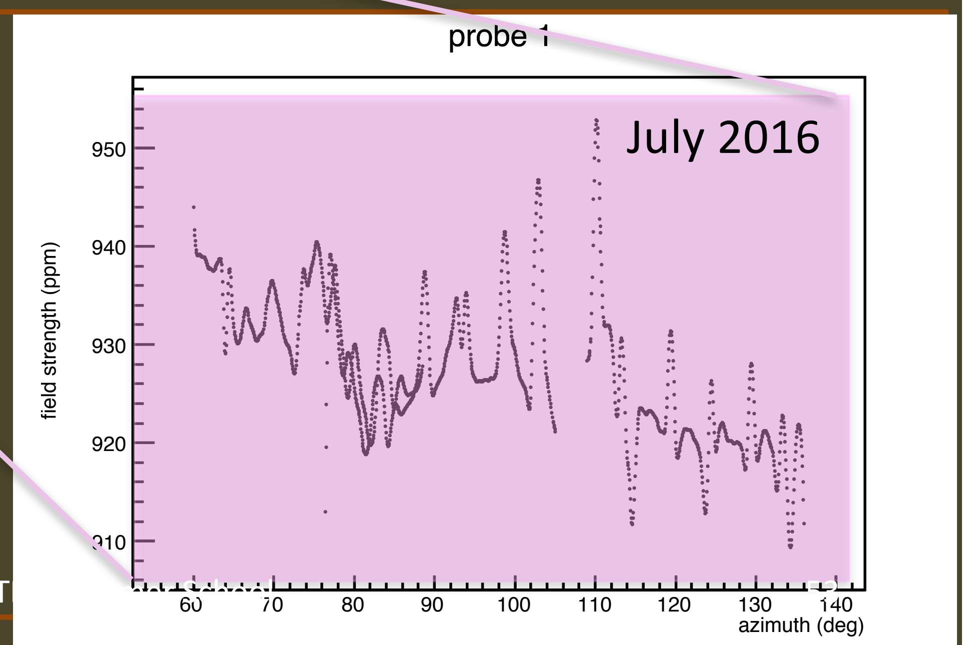
Muon (g-2) Progress

Storage ring arrived in 2014…

… shimming started in 2015

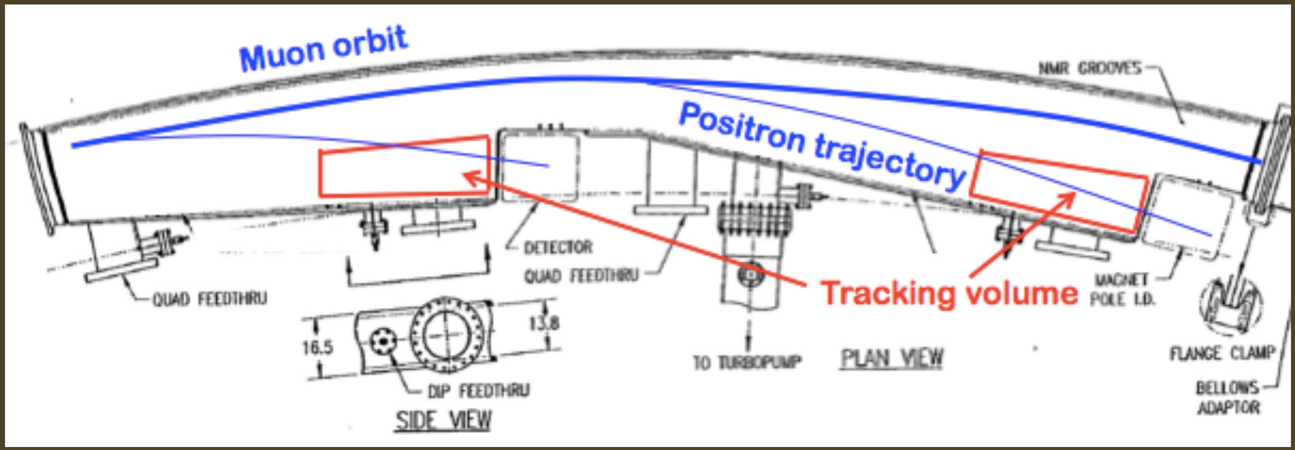
Muon (g-2) Progress





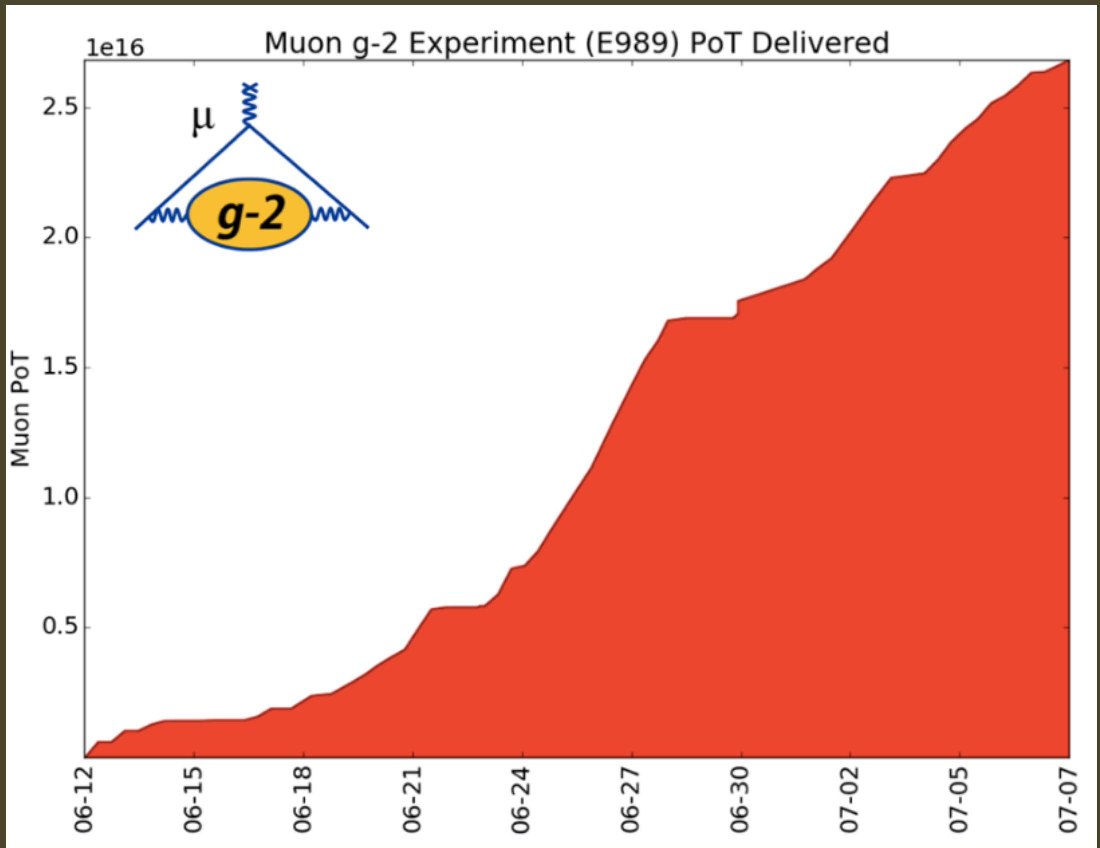
- Met initial shimming specifications in 2016

Muon (g-2) Progress



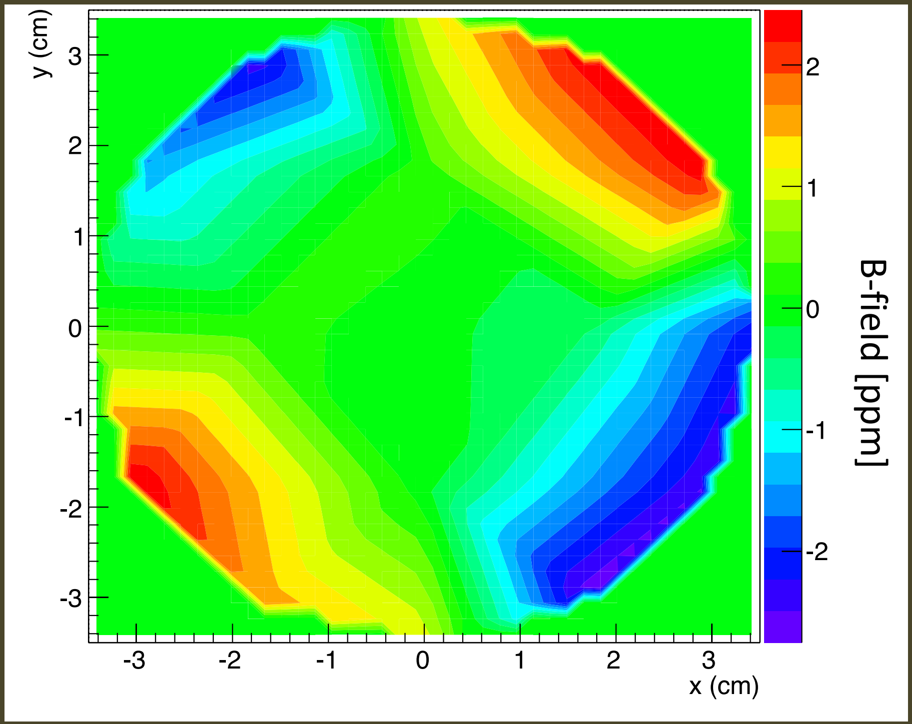
- Installed all calorimeter stations and 1 tracker station in spring 2017

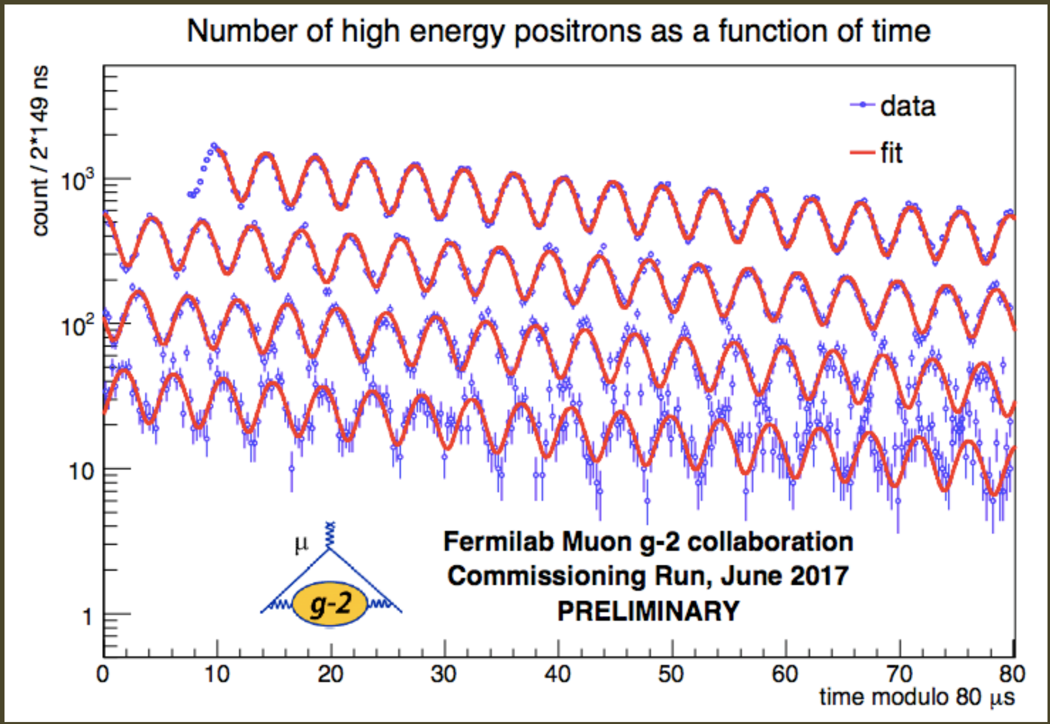
Muon (g-2) Commissioning Run



- June-July 2017
- Total of 2.7 x 10^{17} protons on target (POT)

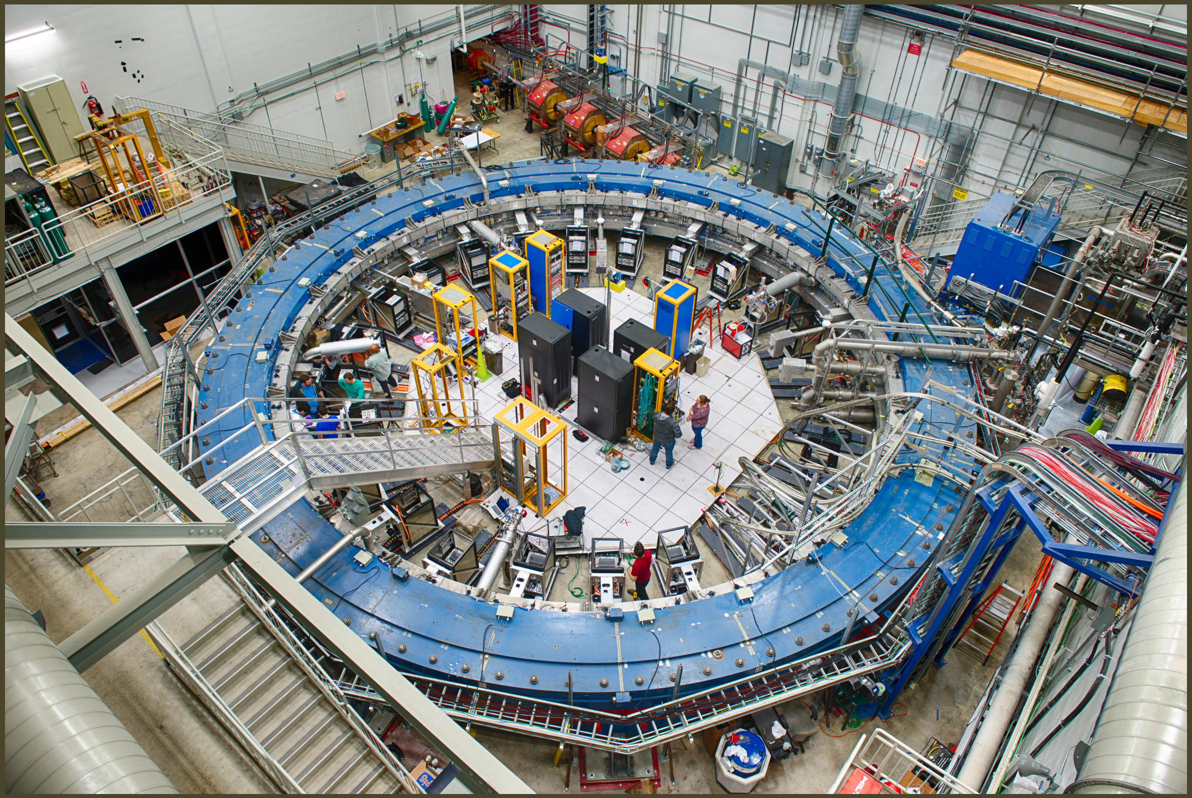
Muon (g-2) Commissioning Run





- Successful trolley runs to map B-field
  - Variation in B-field approaching desired level
- First (uncorrected) "wiggle plot" using calorimeter data
- Tracks reconstructed in tracker station

Muon (g-2) Physics Running



- At full intensity expect to collect
  - A x2 BNL data set in 6 weeks
  - A x10 BNL data set by fall 2019
  - Full data set (x21 BNL) by fall 2020

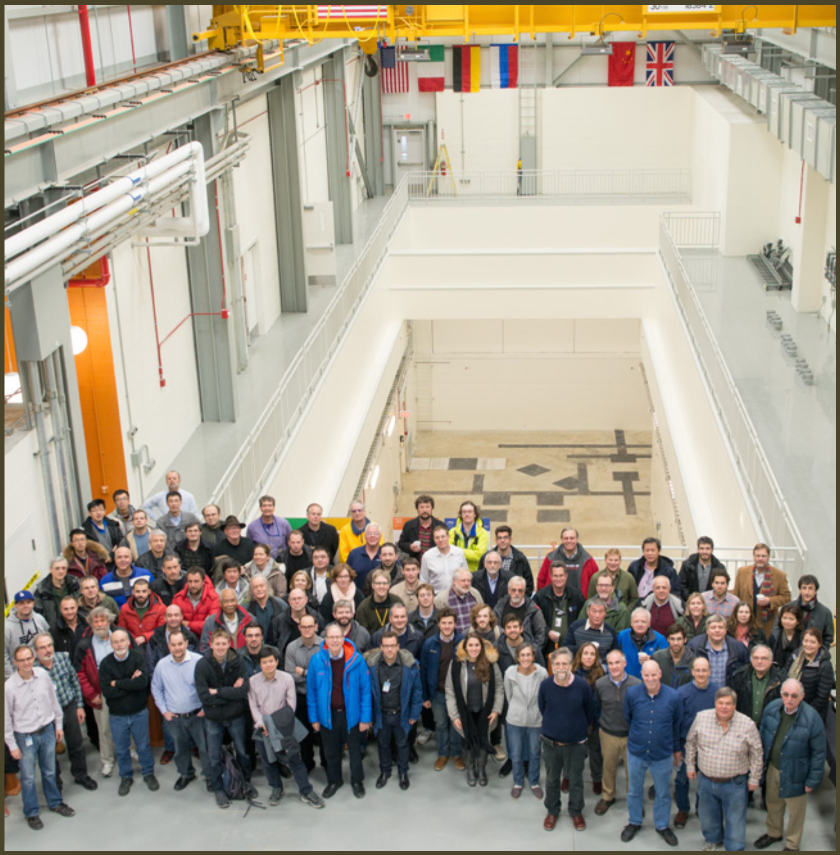
- Expect to begin physics data taking in fall

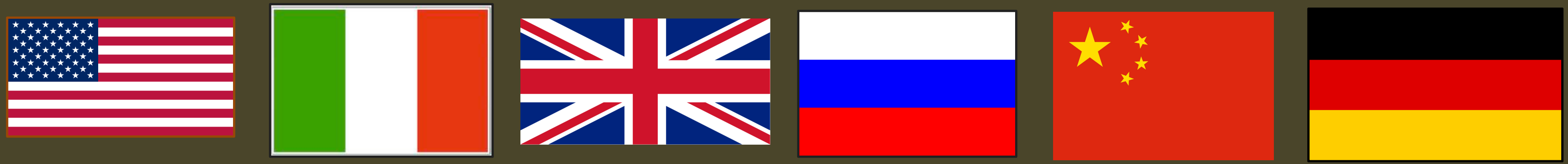
Mu2e

The Mu2e Collaboration

<u>Over 200 Scientists from 37 Institutions</u>

Argonne National Laboratory, Boston University, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, INFN Genova, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, INFN Pisa, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University





Mu2e Introduction

- What is Mu2e?
  - A search for Charged-Lepton Flavor Violation via

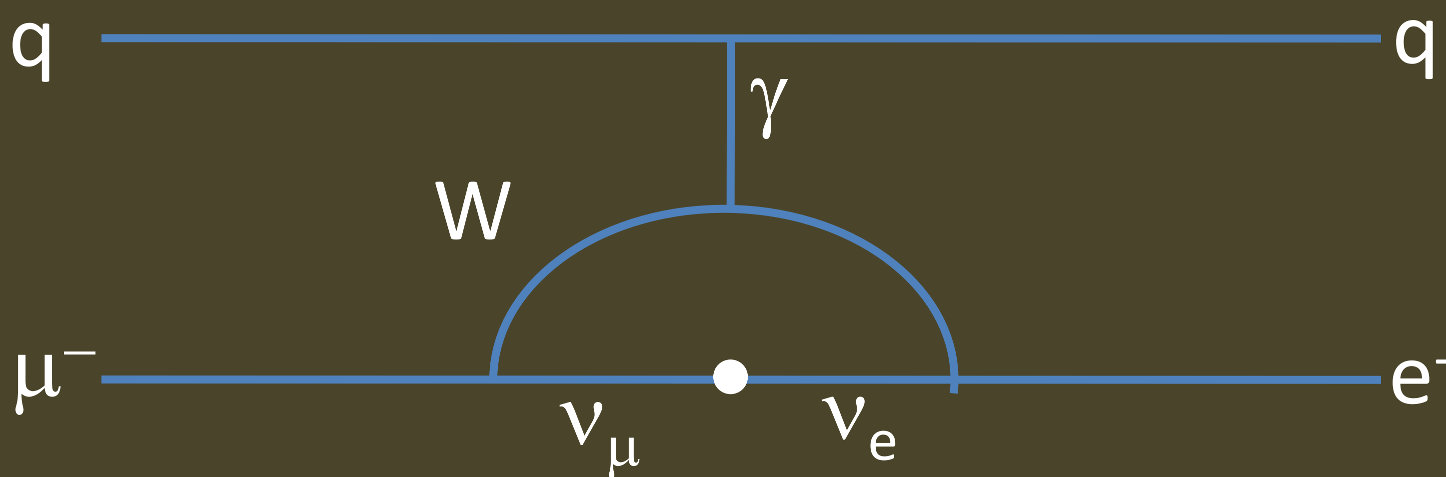
$$\mu^- N \rightarrow e^- N$$

  - Will use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than current world's best
  - Will have *discovery* sensitivity over broad swath of New Physics parameter space

Flavor Violation

- We've known for a long time that quarks mix → (Quark) Flavor Violation
  - Mixing strengths parameterized by CKM matrix
- In last 15 years we've come to know that neutrinos mix → Lepton Flavor Violation (LFV)
  - Mixing strengths parameterized by PMNS matrix
- Why not charged leptons?
  - Charged Lepton Flavor Violation (cLFV)

cLFV in the Standard Model



- Strictly speaking, forbidden in the SM
- Even in ν-SM, extremely suppressed
  (rate ~ $\Delta m_\nu^4 / M_W^4 < 10^{-50}$)
- However, most all NP models predict rates observable at next generation cLFV experiments

Some cLFV Processes

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

(current limits from the PDG)

- Most promising cLFV measurements use μ

cLFV Predictions

M.Blanke, A.J.Buras, B.Duling, S.Recksiegel, C.Tarantino

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\cdot 10^{-3}$	$\sim 6\cdot 10^{-3}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 0.1$
$\frac{Br(\tau^-\to e^-\mu^+\mu^-)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.02\ldots 0.04$
$\frac{Br(\tau^-\to \mu^-e^+e^-)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$\sim 1\cdot 10^{-2}$
$\frac{Br(\tau^-\to e^-e^+e^-)}{Br(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots 2.0$	~ 5	$0.3\ldots 0.5$
$\frac{Br(\tau^-\to \mu^-\mu^+\mu^-)}{Br(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots 1.6$	~ 0.2	$5\ldots 10$
$\frac{R(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$0.08\ldots 0.15$

Table 3: *Comparison of various ratios of branching ratios in the LHT model ($f = 1\,\mathrm{TeV}$) and in the MSSM without [92, 93] and with [96, 97] significant Higgs contributions.*

arXiv:0909.5454v2[hep-ph]

- Relative rates model dependent
- Measure several to pin-down theory details

cLFV Predictions

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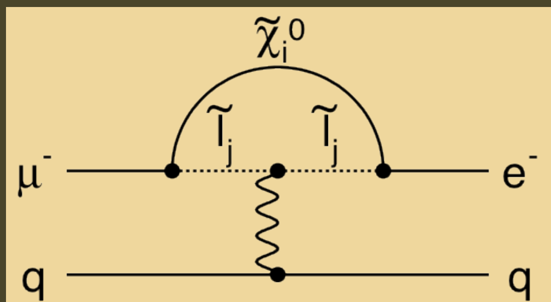
arXiv:0909.5454v2[hep-ph]

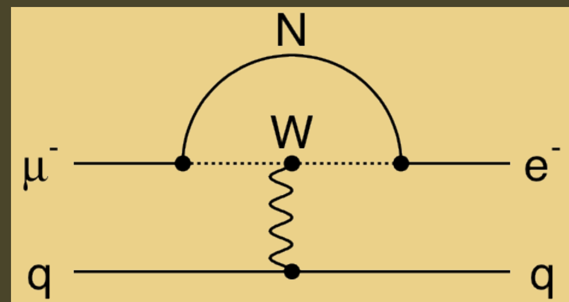
- Relative rates model dependent
- Measure several to pin-down theory details

New Physics Contributions to μN→eN

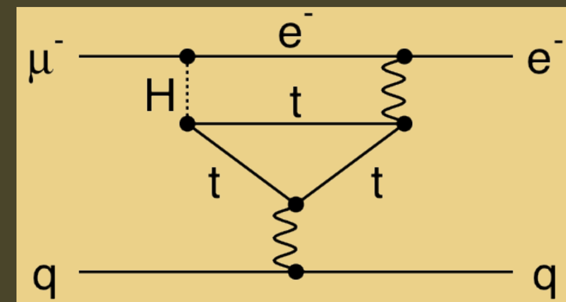
Loops



Supersymmetry

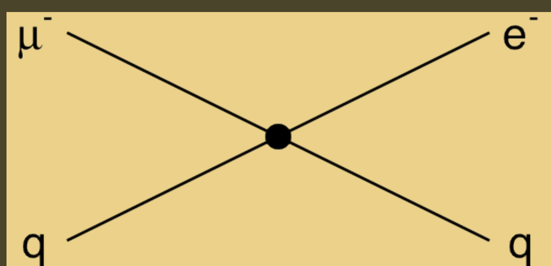


Heavy Neutrinos

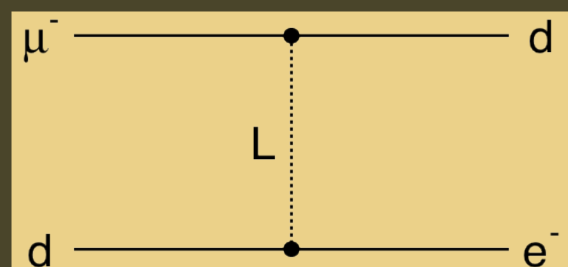


Two Higgs Doublets

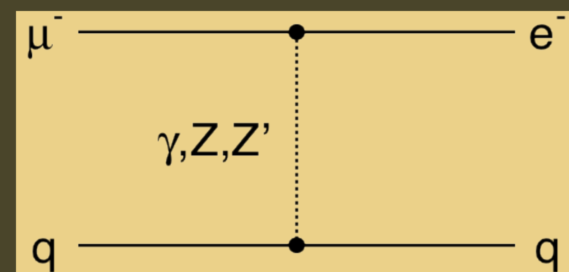
Contact Terms



Compositeness



Leptoquarks



New Heavy Bosons / Anomalous Couplings

μN→eN sensitive to wide array of New Physics models

Mu2e will probe effective NP mass scales up to 10,000 TeV/c^2

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

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

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

★★★ = Discovery Sensitivity

arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e Sensitivity

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

★★★ = Discovery Sensitivity

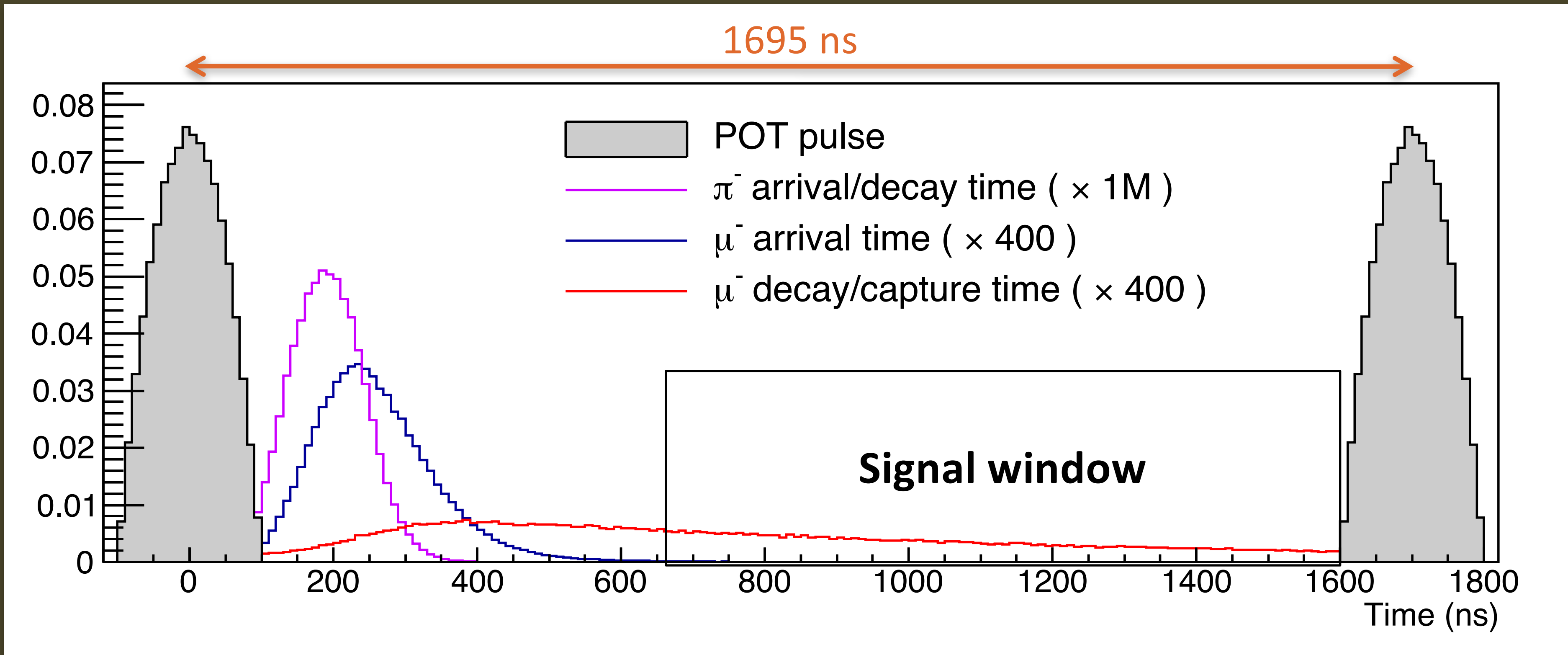
arXiv:0909.1333[hep-ph]

- Mu2e sensitive across the board

Mu2e Concept

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
  - Large τ_μ^N important for discriminating background
- Look for events consistent with $\mu N \rightarrow eN$

Mu2e Proton Beam



- Mu2e will use a pulsed proton beam and a delayed live gate to suppress prompt backgrounds

Mu2e Concept

- Generate a beam of low momentum muons (μ^-)
- Stop the muons in a target
  - Mu2e plans to use aluminum
  - Sensitivity goal requires ~10^{18} stopped muons
- The stopped muons are trapped in orbit around the nucleus
  - In orbit around aluminum: τ_μ^{Al} = 864 ns
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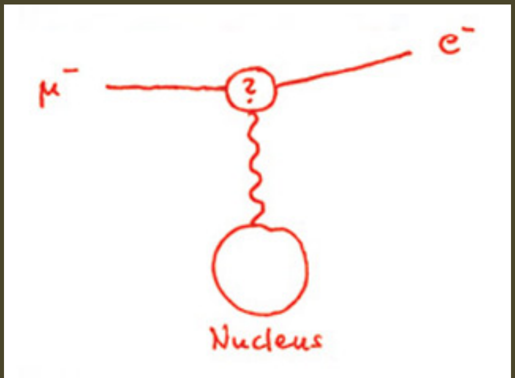
- Look for events consistent with $\mu N \rightarrow eN$

Mu2e Signal



- The process is a coherent one
  - The nucleus is kept intact
- Experimental signature is an electron and nothing else
  - Energy of electron: $E_e = m_\mu - E_{recoil} - E_{1S\text{-}B.E.}$
  - For aluminum: E_e=104.96 MeV
  - Important for discriminating background

Mu2e Sensitivity

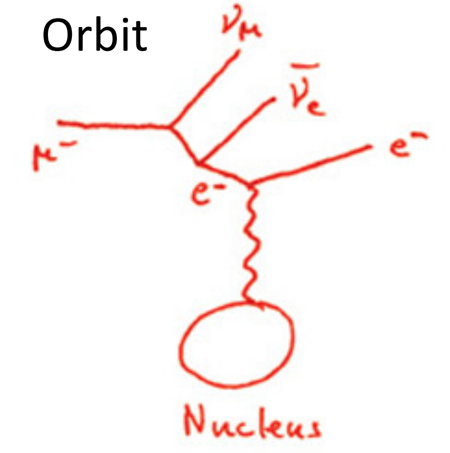
- Design goal: single-event-sensitivity of 2.4×10^{-17}
  - Requires about 10^{18} stopped muons
  - Requires about 10^{20} protons on target
  - Requires extreme suppression of backgrounds
- Expected limit: $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL
  - Factor 10^{4} improvement
- Discovery sensitivity: all $R_{\mu e} >$ few $\times 10^{-16}$
  - Covers broad range of new physics theories

Backgrounds

What happens once μ- stops?

- Begins orbiting nucleus and quickly cascades to ground state (emitting characteristic γ rays)
- Once in ground state it
  - Is captured on the nucleus (61% for Al)
    - $\mu^- N_Z \rightarrow \nu N^*_{Z-1}$ (ordinary capture)
    - $\mu^- N_Z \rightarrow \nu N^*_{Z-1} + \gamma$ (radiative capture; suppressed 10^{-5})
    - On average produces 2 γ, 1n, 0.1 p
  - Decays in orbit (39% for Al)
    - Nuclear recoil gives tail to E_e spectrum

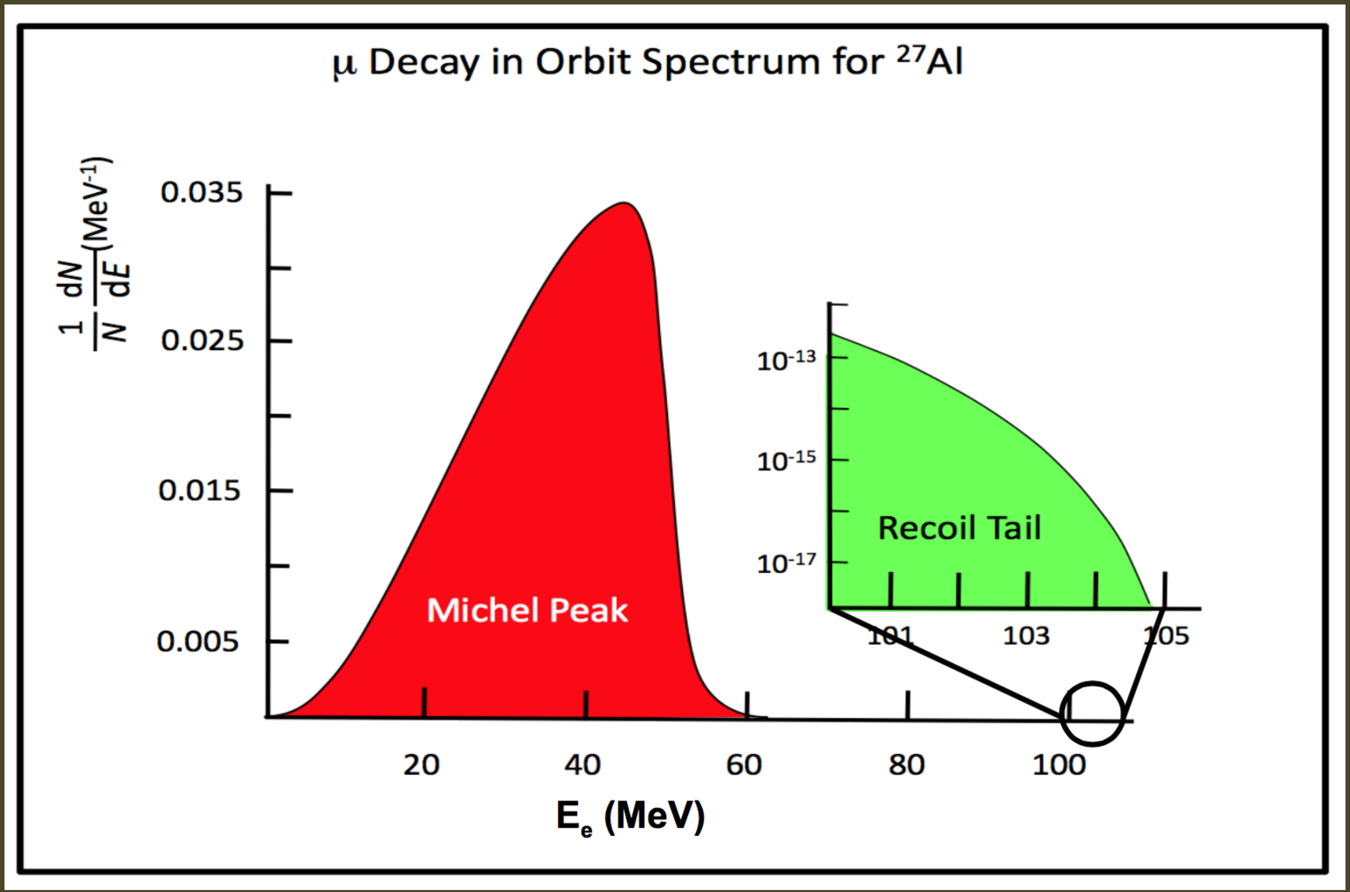
Decay in Orbit

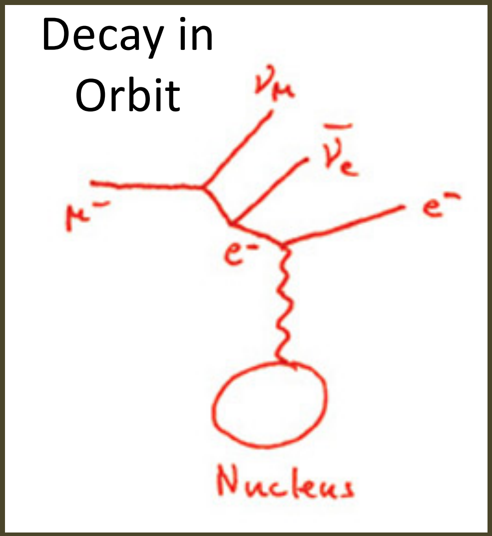


What happens once μ- stops?

– Decays in orbit (39% for Al)

- Nuclear recoil gives tail to E_e spectrum





Mu2e Backgrounds

- Intrinsic – scale with no. stopped muons
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)
- Late arriving – scale with no. late protons
  - Radiative pion capture (RPC)
  - μ and π decay-in-flight (DIF)
- Miscellaneous
  - Anti-proton induced
  - Cosmic-ray induced

Mu2e Backgrounds

Category	Source	Events
Intrinsic	μ Decay in Orbit	0.14
	Radiative μ Capture	<0.01
Late Arriving	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
	π Decay in Flight	<0.01
Miscellaneous	Anti-proton induced	0.04
	Cosmic muon induced	0.21
Total Background		0.41

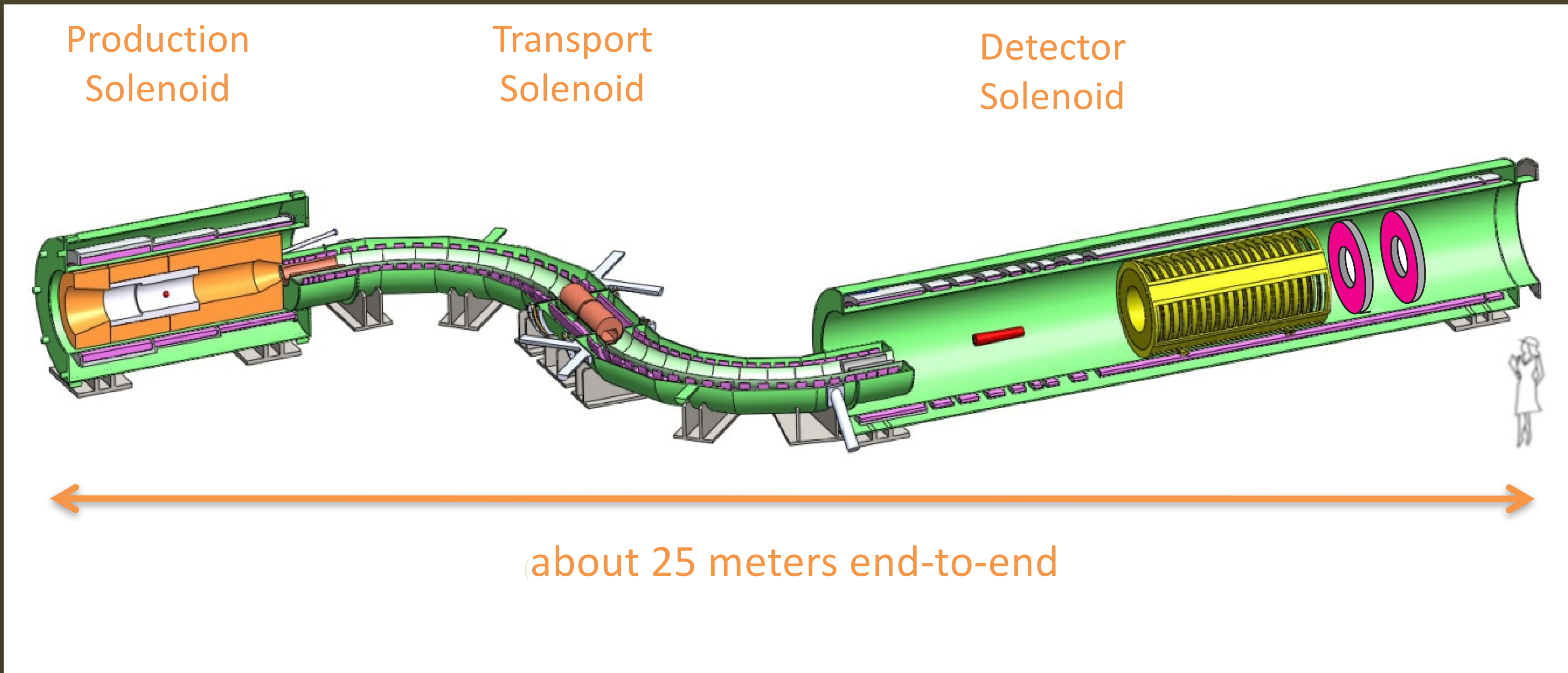
(assuming 6.8E17 stopped muons in 6E7 s of beam time)

- Designed to be nearly background free

Keys to Mu2e Success

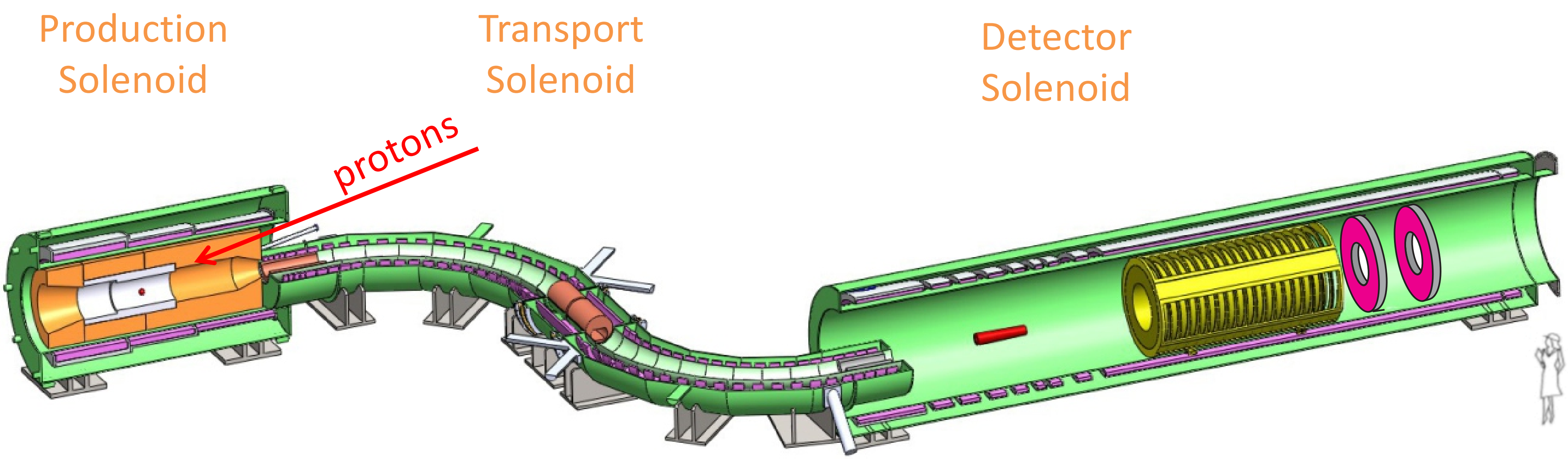
- Pulsed proton beam
  - Narrow proton pulses (< +/- 125 ns)
  - Very few out-of-time protons ($< 10^{-10}$)
- Avoid trapping particles… B-field requirements
  - Further mitigates beam-related backgrounds
- High cosmic ray veto efficiency (>99.99%)
- Excellent momentum resolution (<200 keV core)
- Thin anti-proton annihilation window(s)

Mu2e Experimental Apparatus



- Consists of 3 solenoid systems

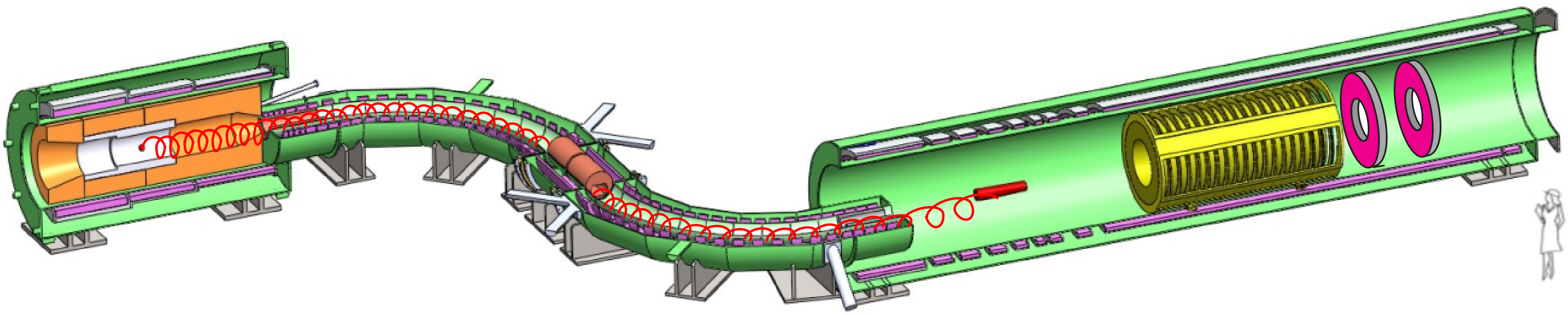
Mu2e Experimental Apparatus



Production Solenoid:
8 GeV protons interact with a tungsten target to produce μ- (from π- decay)

- Consists of 3 solenoid systems

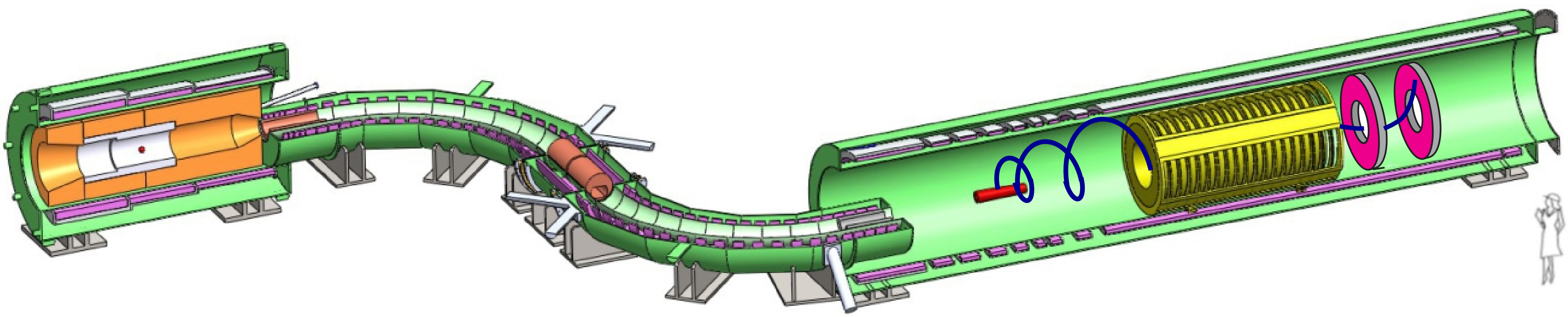
Mu2e Experimental Apparatus



Transport Solenoid:
Captures π- and subsequent μ-; momentum- and sign-selects beam

- Consists of 3 solenoid systems

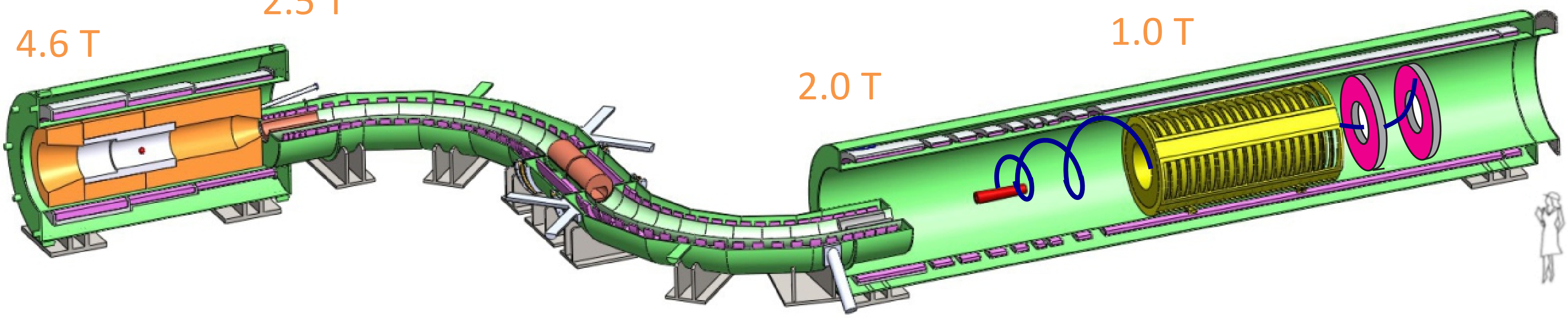
Mu2e Experimental Apparatus



Detector Solenoid:
Upstream – Al. stopping target, Downstream – tracker, calorimeter
(not shown – cosmic ray veto system, extinction monitor, target monitor)

- Consists of 3 solenoid systems

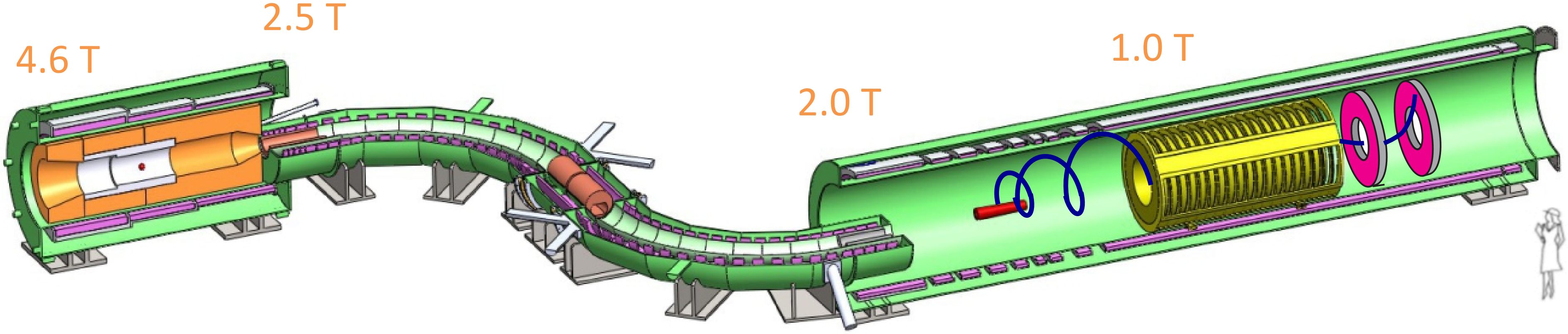
Mu2e Experimental Apparatus



Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

- Consists of 3 solenoid systems

Mu2e Experimental Apparatus



Graded fields important to suppress backgrounds, to increase muon yield, and to improve geometric acceptance for signal electrons

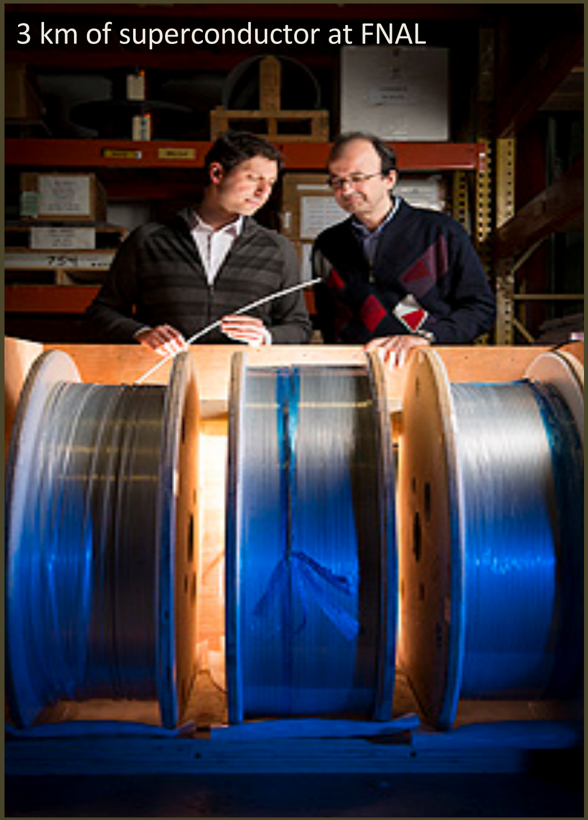
- Derived from MELC concept originated by Lobashev and Djilkibaev in 1989

Mu2e Solenoid Summary

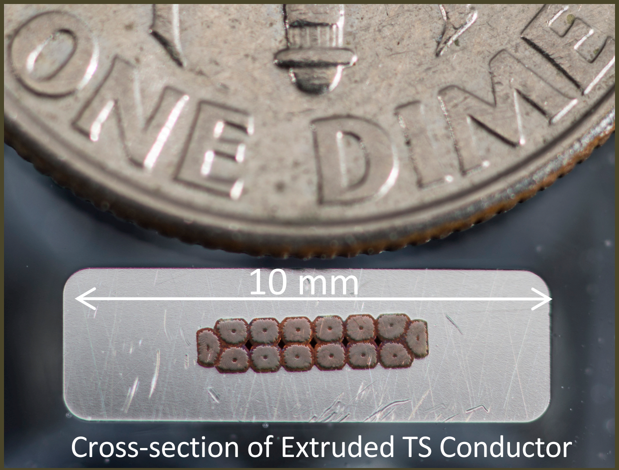
	PS	TS	DS
Length (m)	4	13	11
Diameter (m)	1.7	0.4	1.9
Field @ start (T)	4.6	2.5	2.0
Field @ end (T)	2.5	2.0	1.0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8

- PS, DS will be built by General Atomics
- TS will be built by ASG + Fermilab

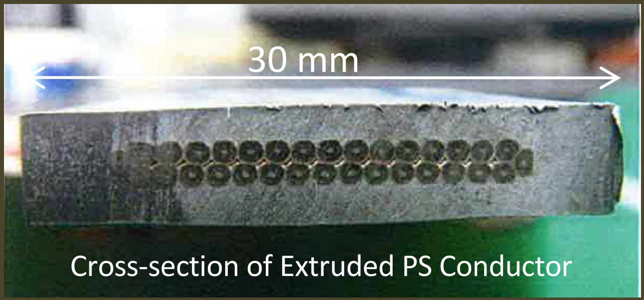
Mu2e (Super)Conductor



3 km of superconductor at FNAL



Cross-section of Extruded TS Conductor



Cross-section of Extruded PS Conductor

- Conductor production is well along
  - We have in hand enough conductor to fabricate all three solenoids
  - Still awaiting final assembly and delivery of some PS spare lengths

Mu2e Solenoid Summary


TS Coil Module prototype at Fermilab


TS coils at ASG in Italy

- Designs are finalized.
- TS fabrication has begun (31/52 coils wound).
- PS, DS fabrication has started commissioning with test coils.

Some Mu2e numbers

- Every 1 second Mu2e will
  - Send 7,000,000,000,000 protons to the Production Solenoid
  - Send 26,000,000,000 μs through the Transport Solenoid
  - Stop 13,000,000,000, μs in the Detector Solenoid
- By the time Mu2e is done…

Total number of stopped muons

1,000,000,000,000,000,000

Some Perspective

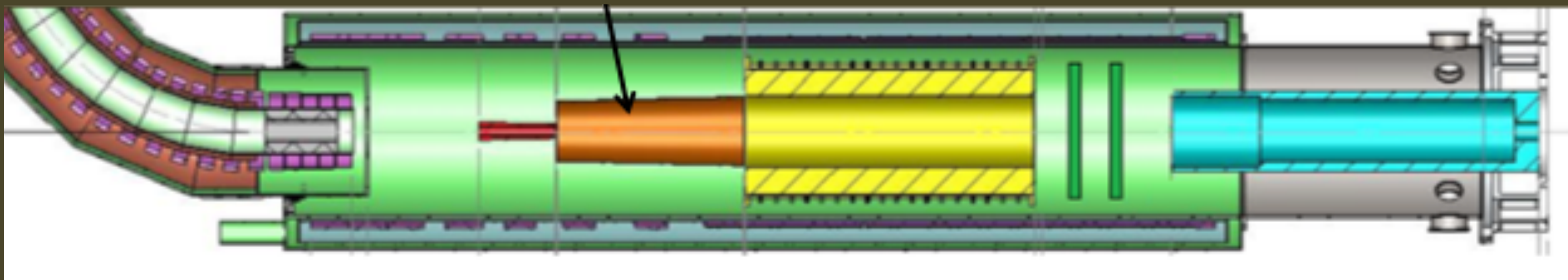
1,000,000,000,000,000,000

= number of stopped Mu2e muons

= number of grains of sand on earth's beaches

The Mu2e Detectors

The Mu2e Detector



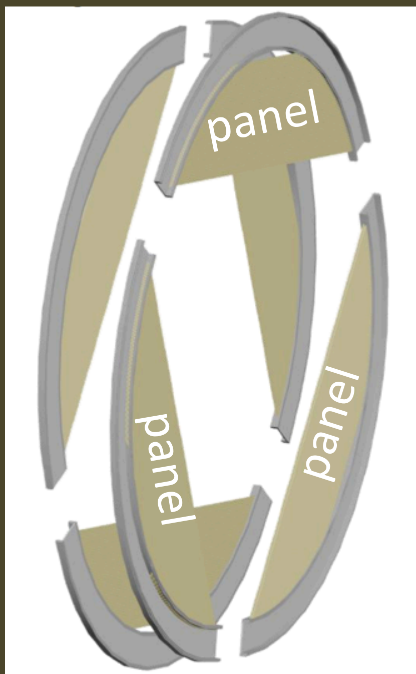
- I am going to focus on the principle elements:
  - Tracker, Calorimeter, Cosmic-Ray Veto

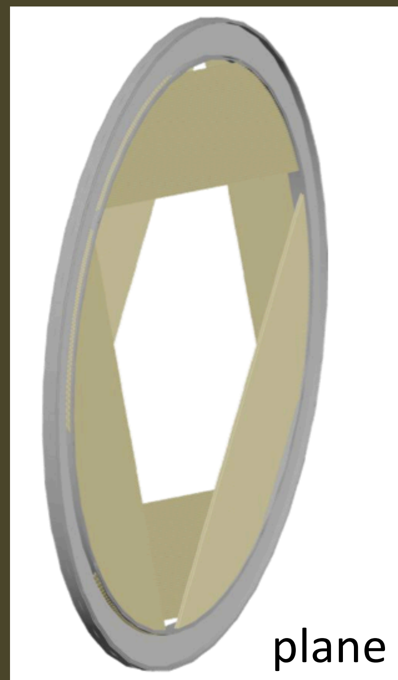
The Mu2e Tracker

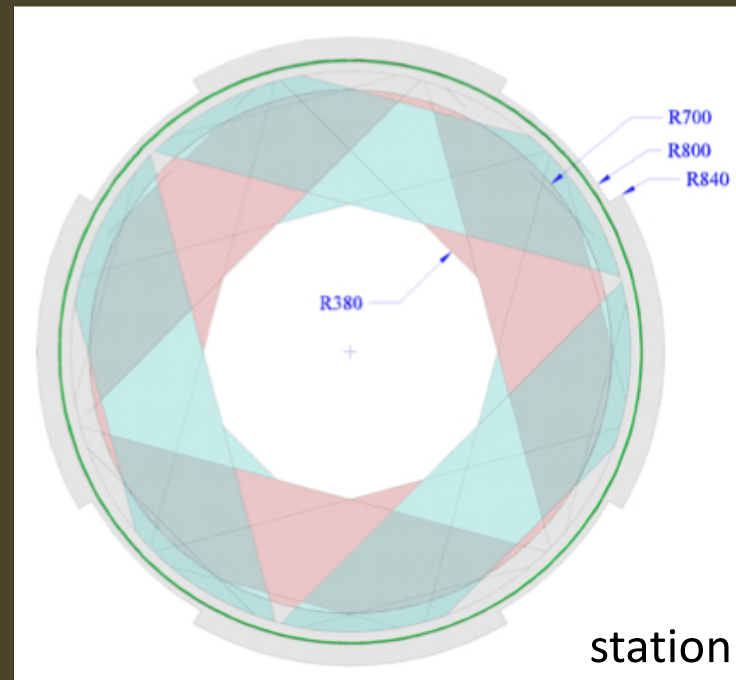
- Will employ straw technology
  - Low mass
  - Can reliably operate in vacuum
  - Robust against single-wire failures

- 5 mm diameter straw
- Spiral wound
- Walls: 12 μm Mylar + 3 μm epoxy + 200 Å Au + 500 Å Al
- 25 μm Au-plated W sense wire
- 33 – 117 cm in length
- 80/20 Ar/CO_2 with HV < 1500 V

The Mu2e Tracker

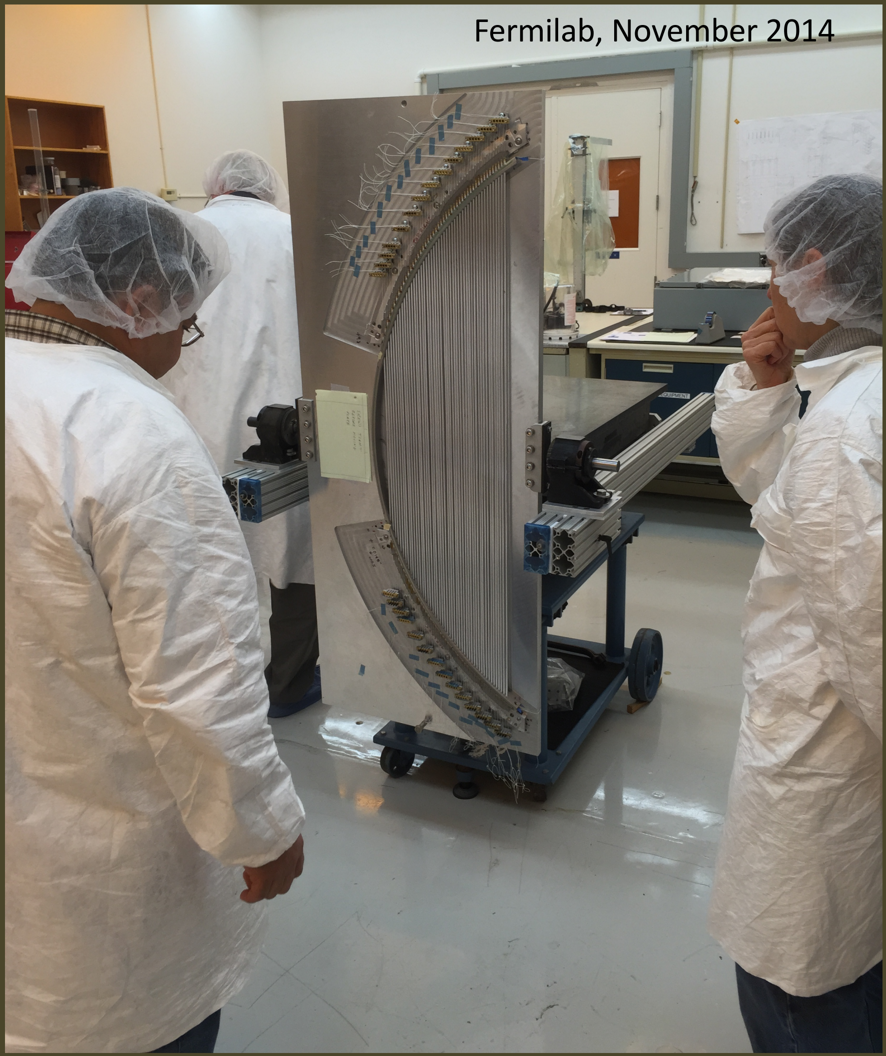






- Self-supporting "panel" consists of 100 straws
- 6 panels assembled to make a "plane"
- 2 planes assembled to make a "station"
- Rotation of panels and planes improves stereo information
- >20k straws total

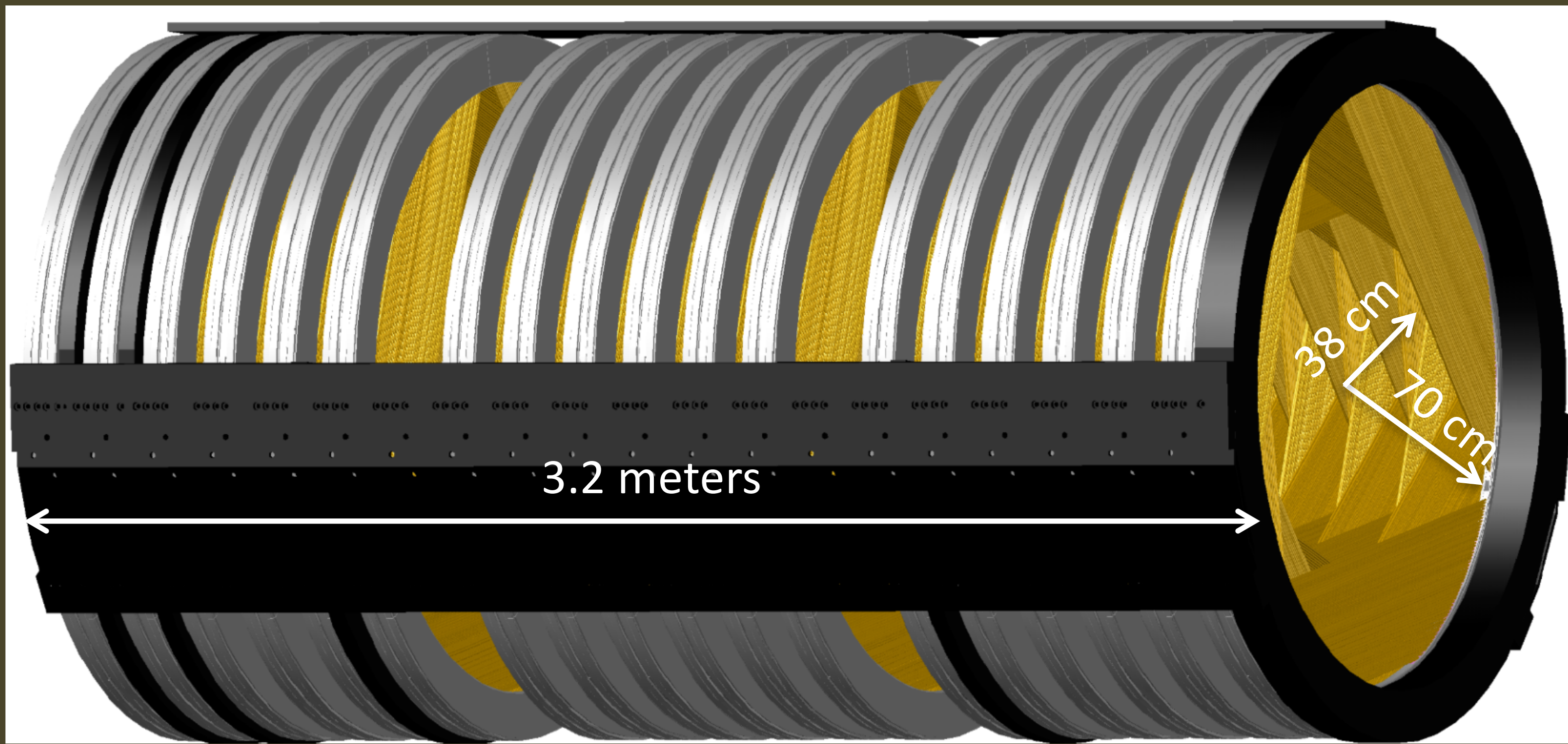
First Prototype Panel



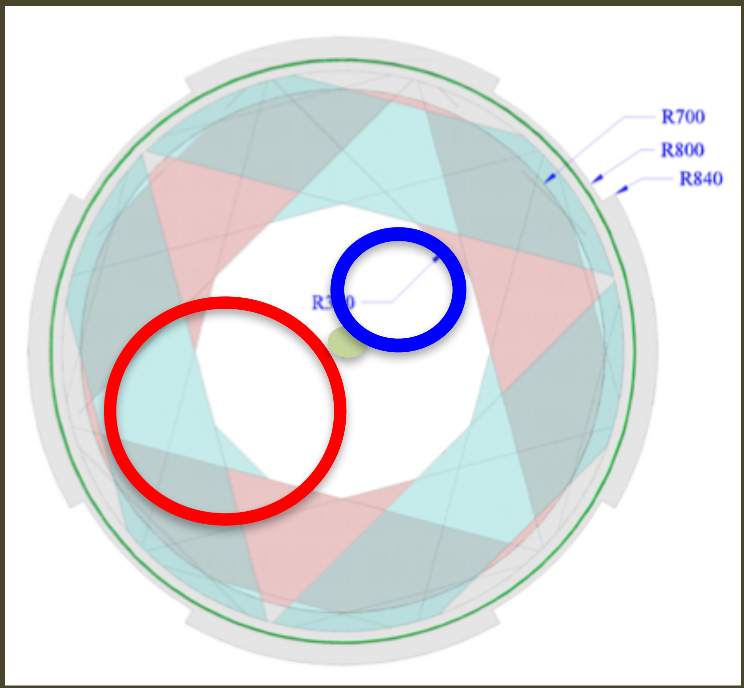
- Starting to test in vacuum

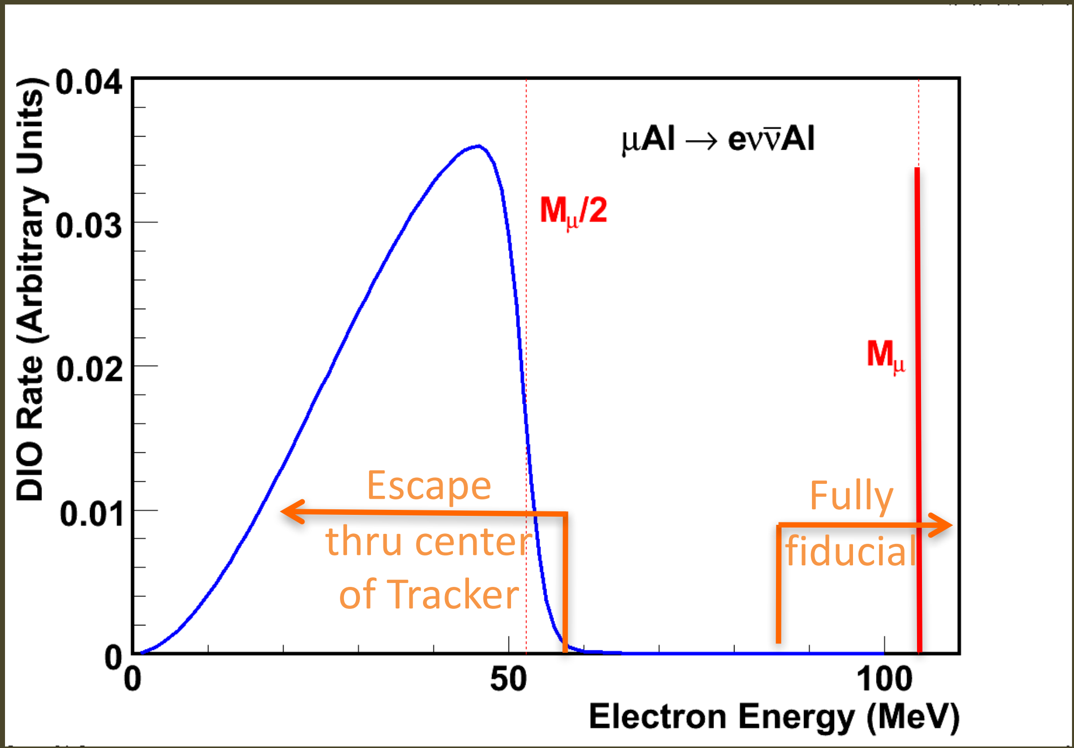
The Mu2e Tracker

- 18 “stations” with straws transverse to the beam
- Naturally moves readout and support to large radii, out of the active volume



The Mu2e Tracker





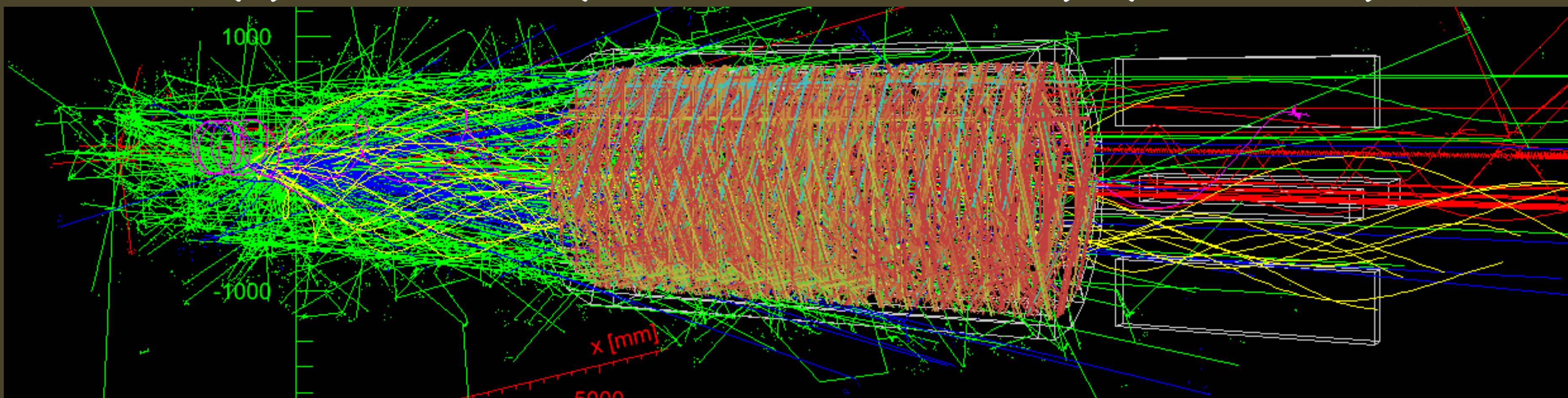
- Inner 38 cm is purposefully un-instrumented
  - – Blind to beam flash
  - – Blind to >99% of DIO spectrum

Mu2e Pattern Recognition

Stopping Target

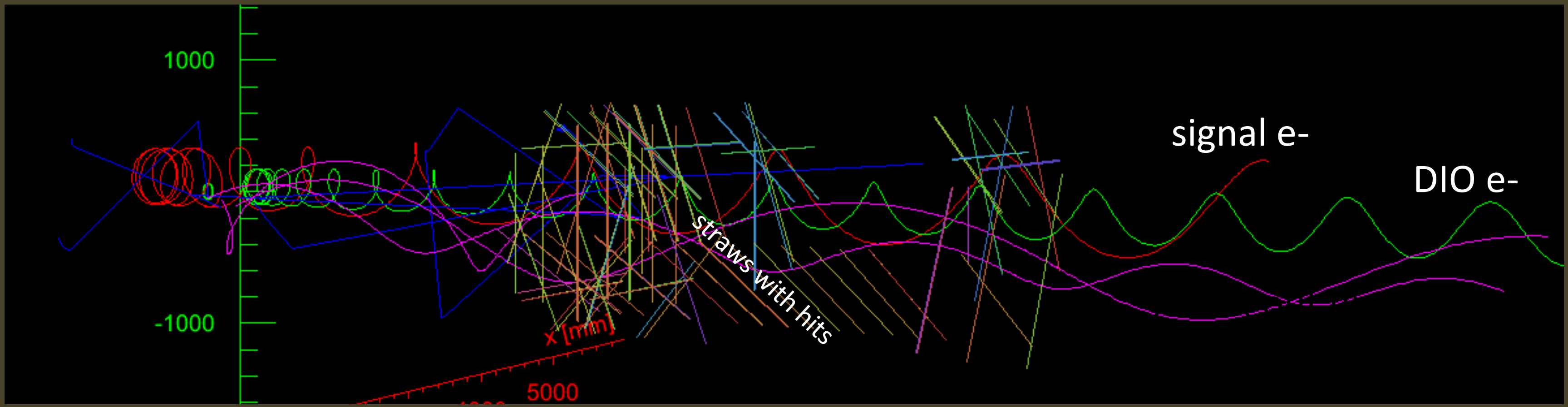
Straw Tracker

Crystal Calorimeter



- A signal electron, together with all the other "stuff" occurring simultaneously, integrated over 500-1695 ns window

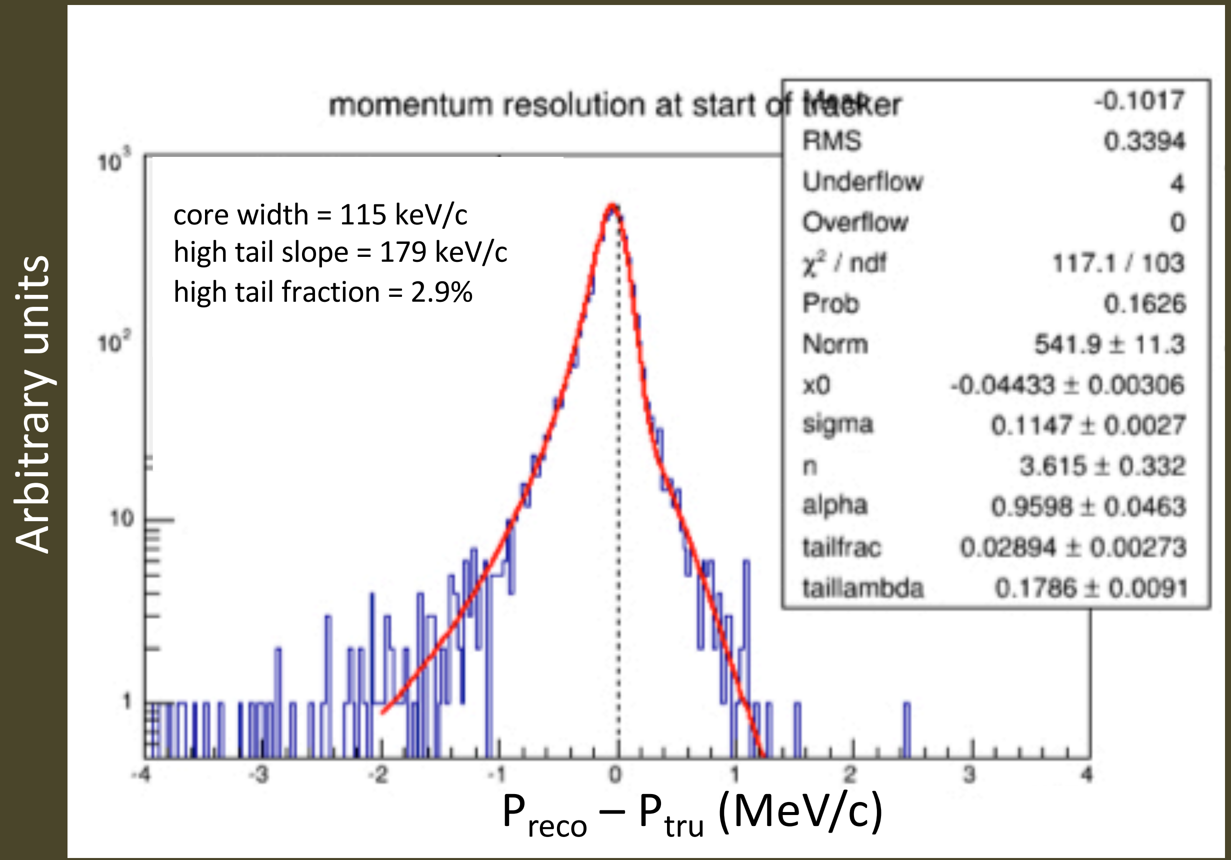
Mu2e Pattern Recognition



(particles with hits within +/-50 ns of signal electron t_{mean})

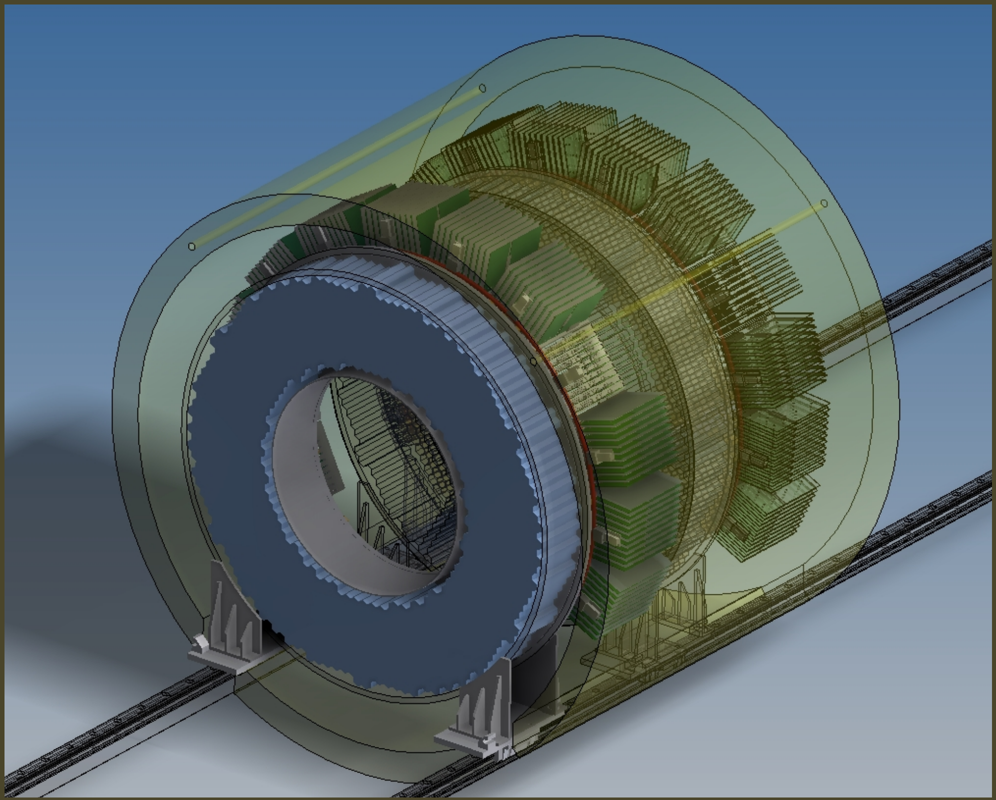
- We use timing information to look in +/- 50 ns windows – significant reduction in occupancy and significant simplification for Patt. Rec.

Mu2e Spectrometer Performance



- Performance well within physics requirements

Mu2e Calorimeter



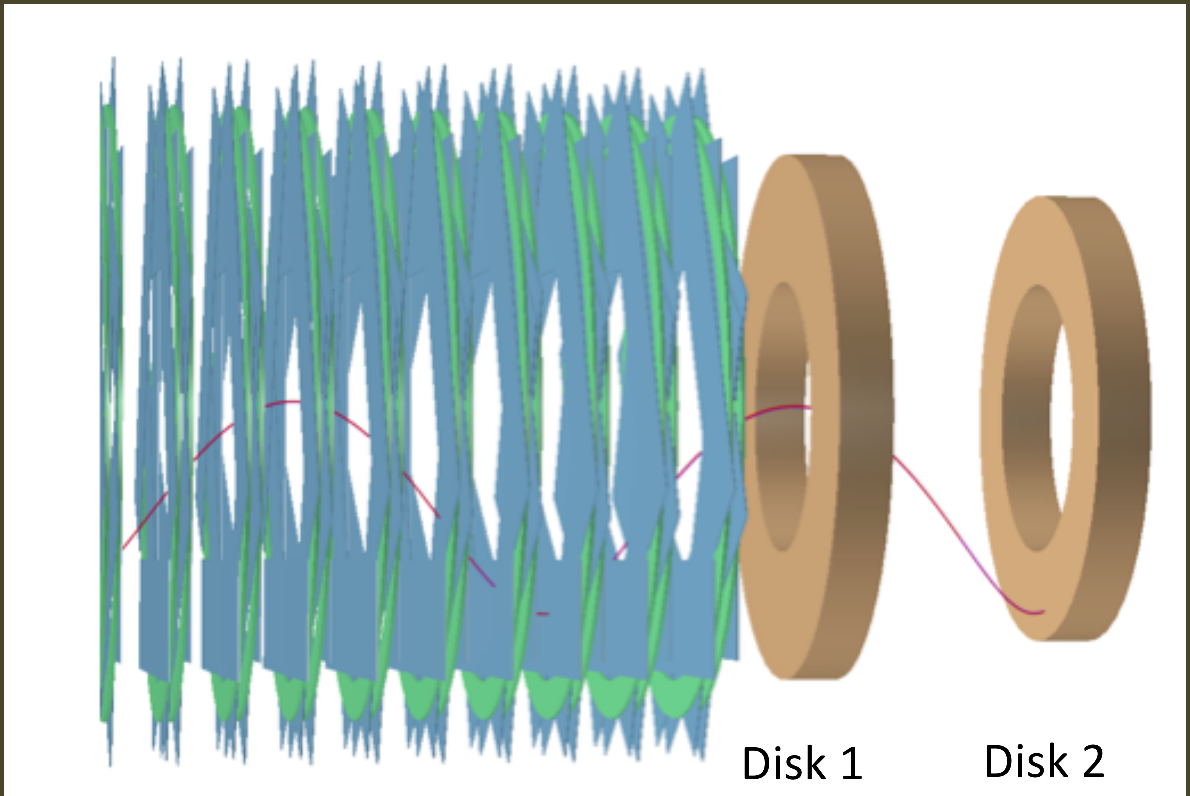
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing and energy resolution

Mu2e Calorimeter

- Baseline design : Cesium Iodine (CsI)
  - Radiation hard, fast, non-hygroscopic

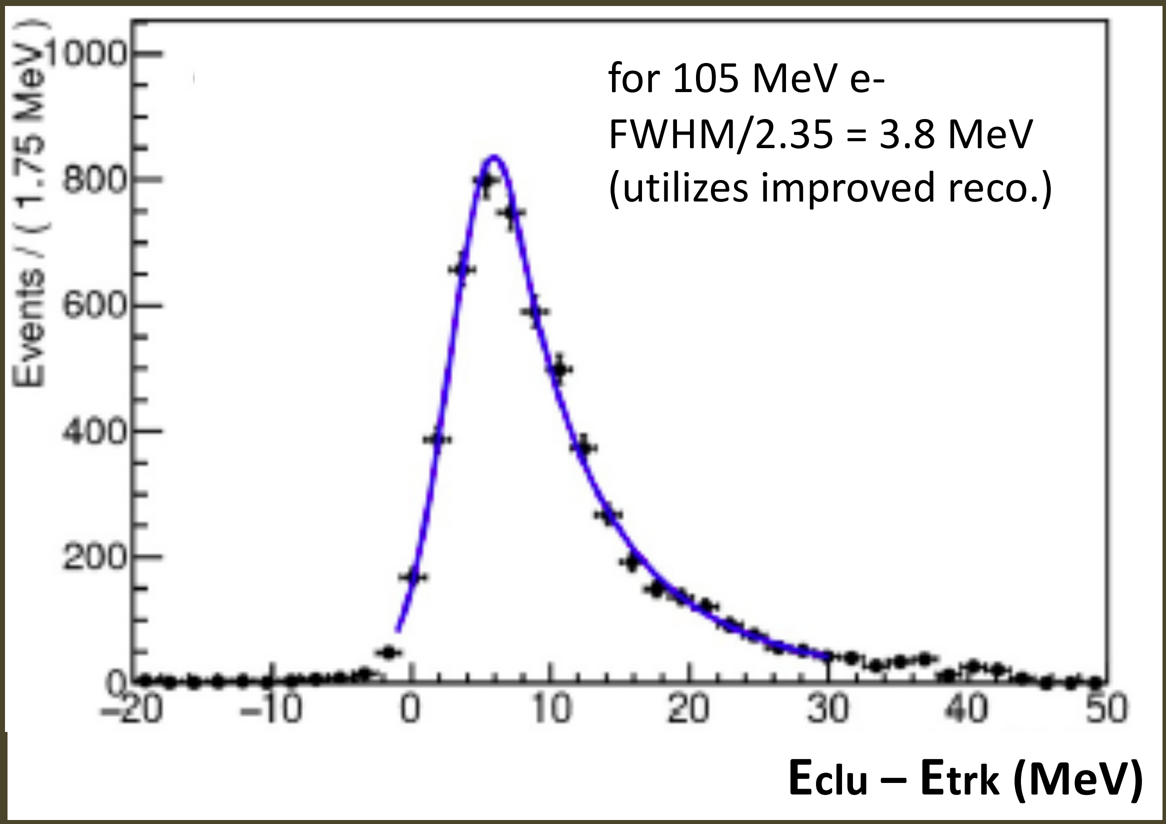
	CsI
Density (g/cm3)	4.51
Radiation length (cm)	1.86
Moliere Radius (cm)	3.57
Interaction length (cm)	39.3
dE/dX (MeV/cm)	5.56
Refractive index	1.95
Peak luminescence (nm)	310
Decay time (ns)	26
Light yield (rel. to NaI)	3.6%
Variation with temperature	-1.4% / deg-C

Mu2e Calorimeter



- Will employ 2 disks (radius = 37-66 cm)
- ~1400 crystals with square cross-section
  - ~3 cm diameter, ~20 cm long (10 X_0)
- Two photo-sensors/crystal on back (SiPMs)

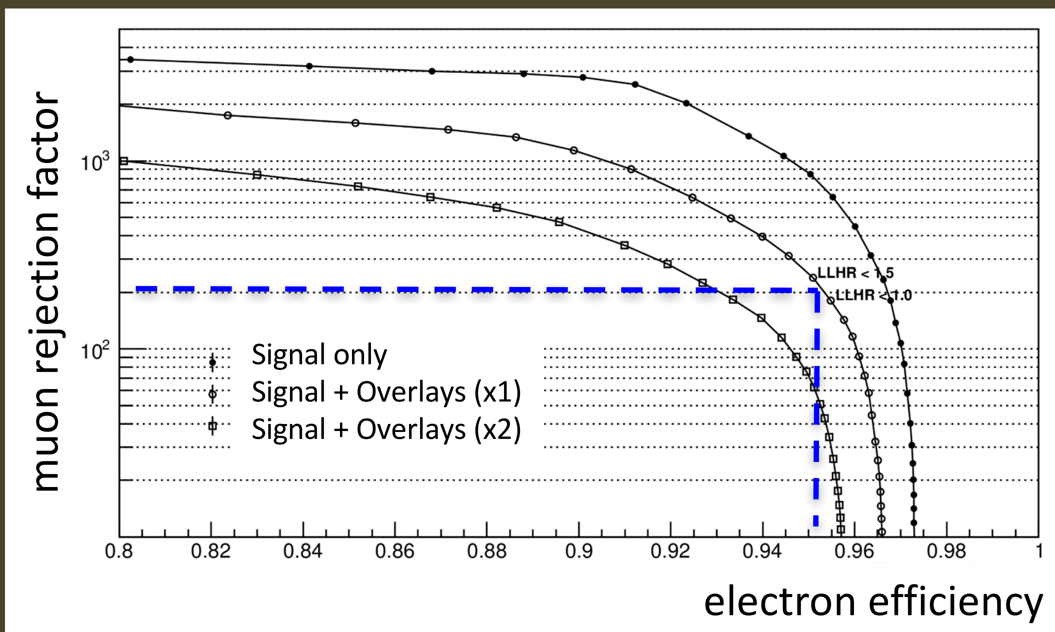
Mu2e Calorimeter

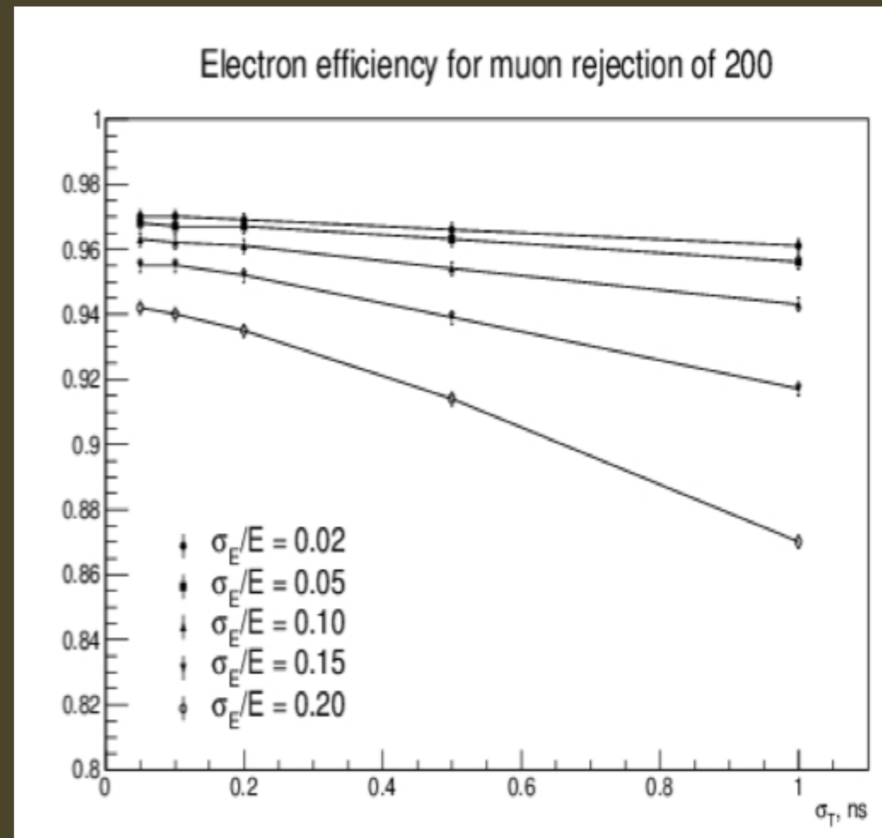


- With 60 ns integration, expect to achieve an energy resolution ~5% for 105 MeV electrons
  - Performance a weak function of rate in relevant range

Calorimeter Particle ID

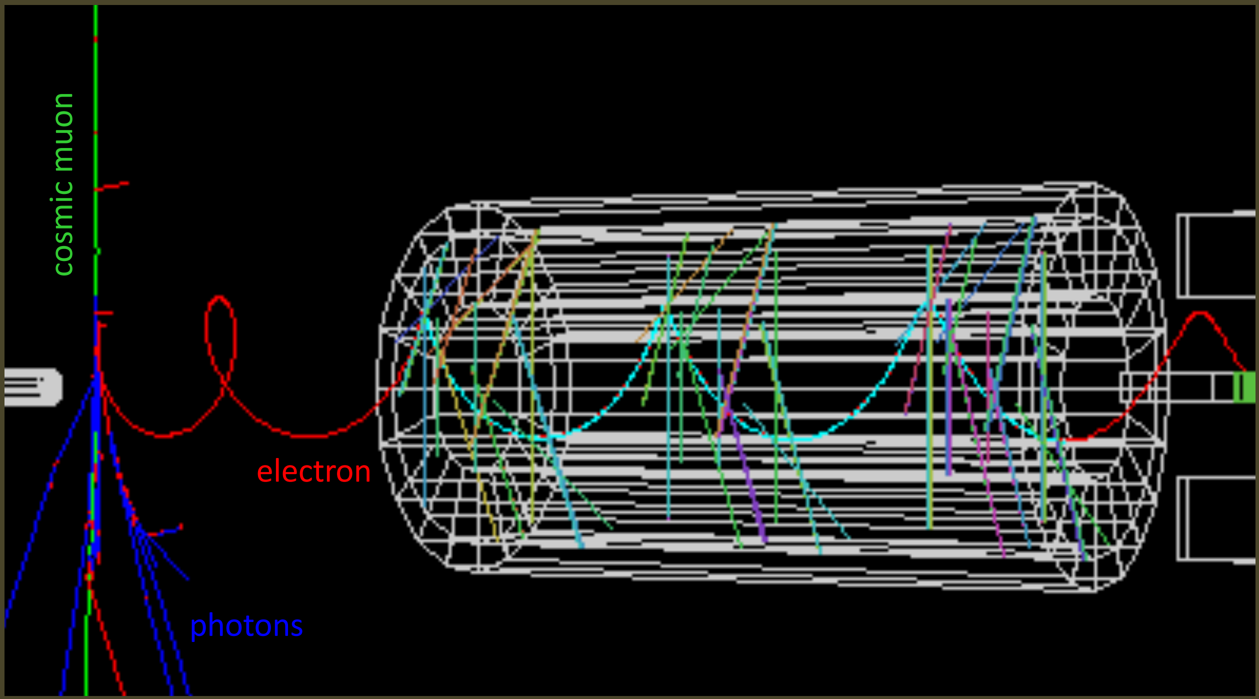
Muon rejection vs Electron efficiency





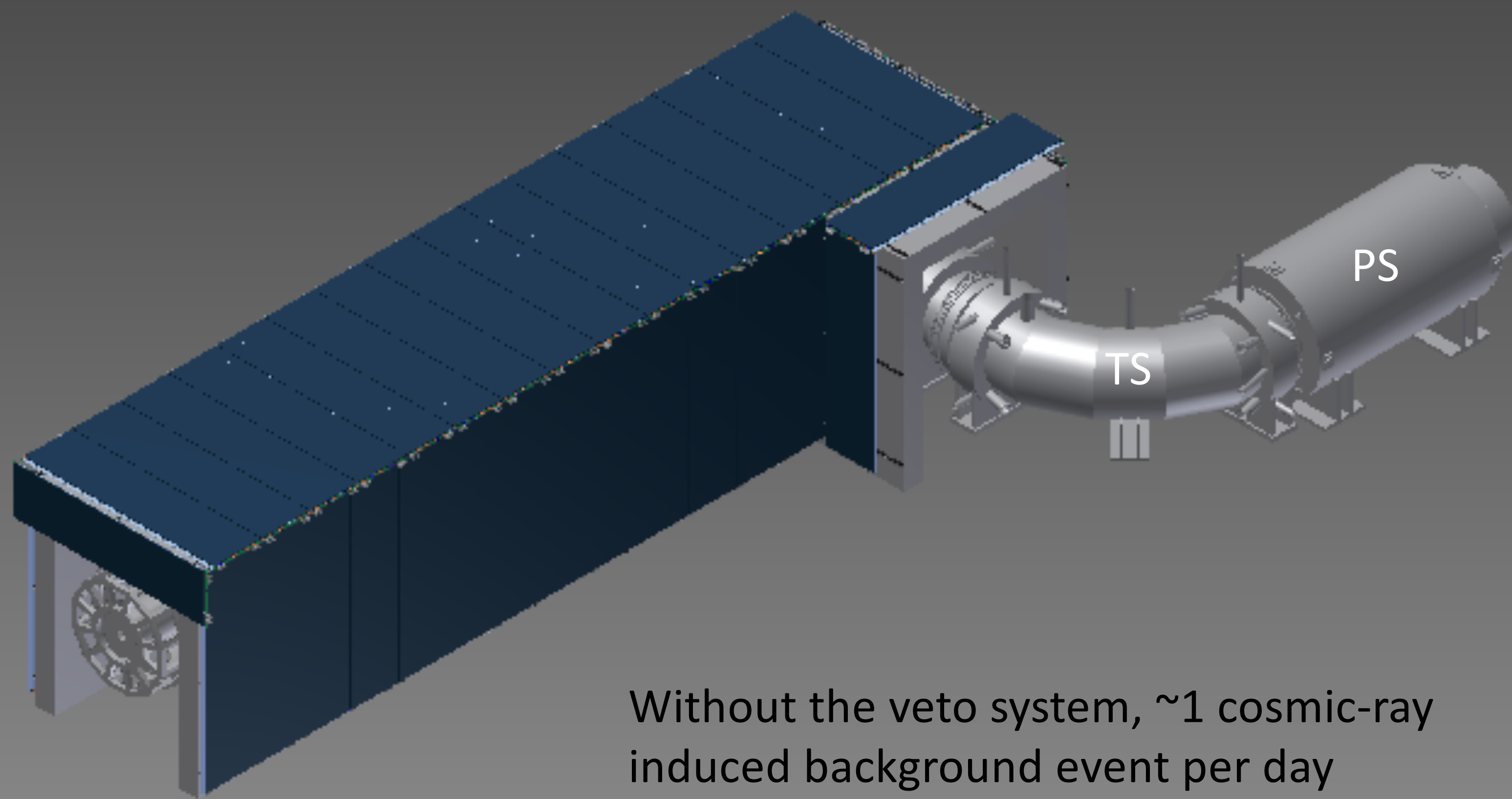
- Combine TOF and E/P information in LLR
  - 95% electron efficiency for muon rejection x200

Mu2e Cosmic-Ray Veto



- Cosmic μ can generate background events via decay, scattering, or material interactions

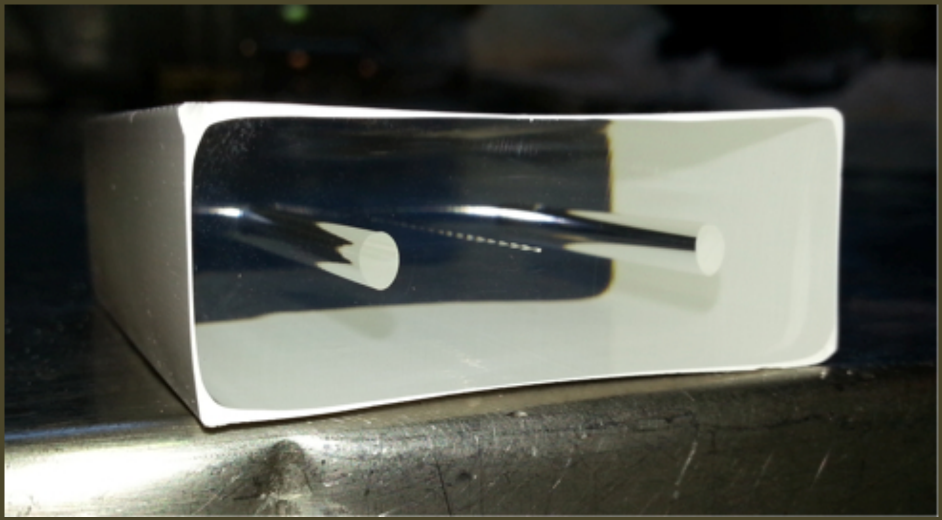
Mu2e Cosmic-Ray Veto

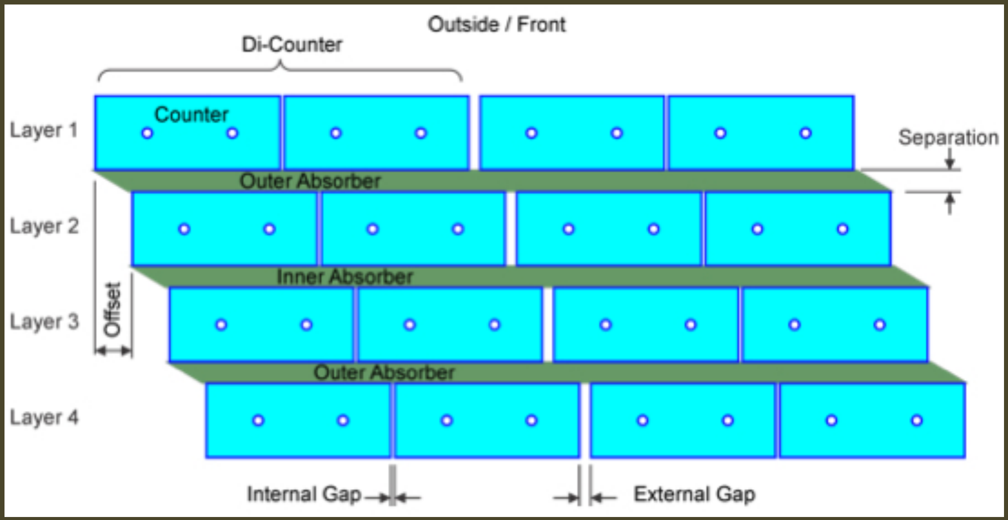


Without the veto system, ~1 cosmic-ray induced background event per day

- Veto system covers entire DS and half TS

Mu2e Cosmic-Ray Veto





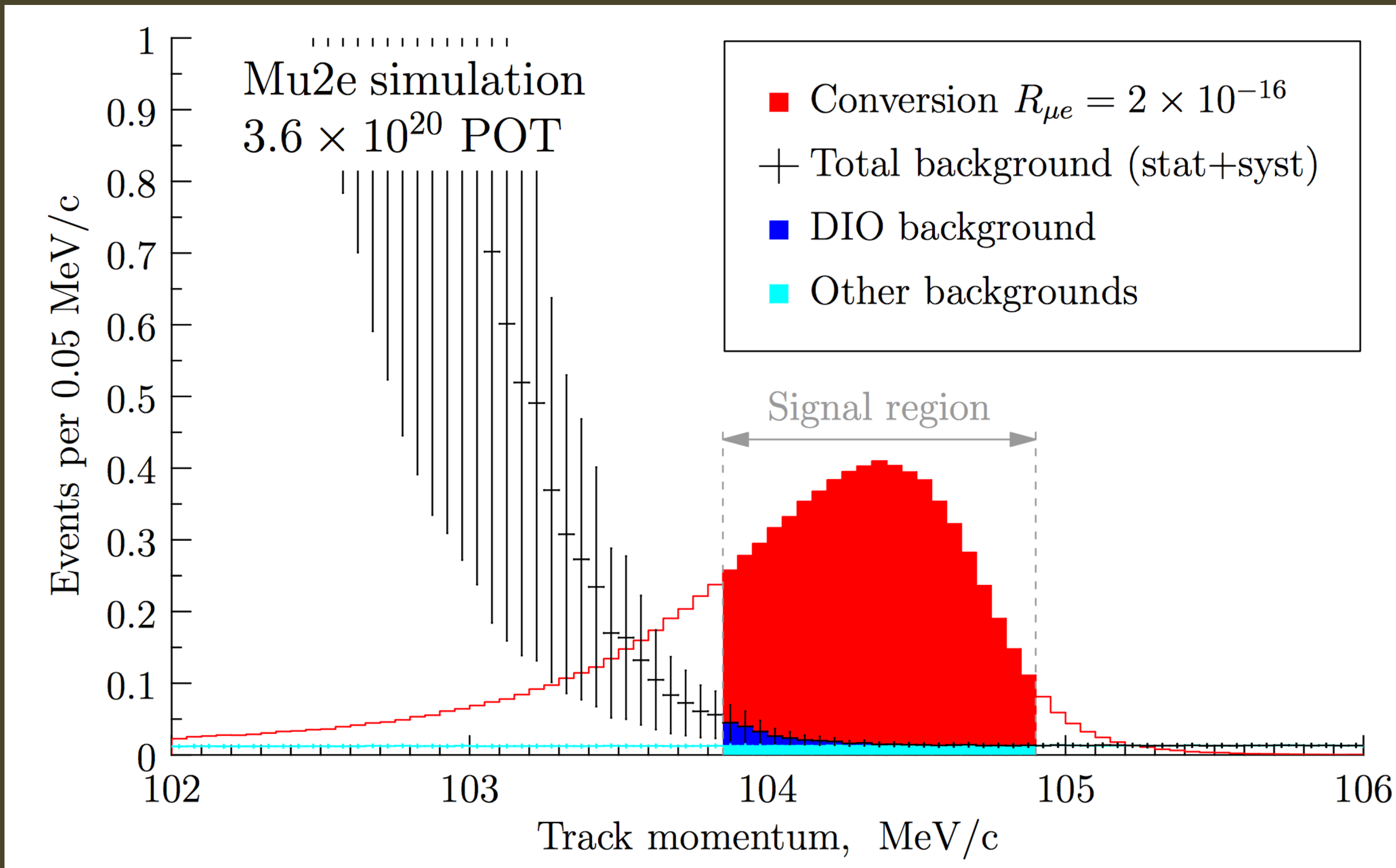
- Will use 4 overlapping layers of scintillator
  - Each bar is 5 x 2 x ~450 cm^3
  - 2 WLS fibers / bar
  - Read-out both ends of each fiber with SiPM
  - Have achieved ε > 99.4% (per layer) in test beam

Mu2e Schedule

- Full scale solenoid construction started
- Full scale detector construction starts in 2018
- Solenoid and detector installation in 2020
- Initial commissioning in 2021
- First physics running in 2022

- At full intensity
  - Reach Sindrum-II sensitivity in 100 min
  - x10 in 17 hours running
  - x100 in 7 days running
  - x10000 in 700 days running

After full data set (projection)



- Discovery sensitivity for all $R_{\mu \to e} > 2 \times 10^{-16}$!

Concluding remarks

Summary

- Fermilab's Muon Campus is being built to host two world class experiments – Muon (g-2) and Mu2e
- Muon (g-2) will reuse the BNL storage ring and a significantly improved beam line at FNAL to improve the uncertainty on a_μ by x4
  - Will provide >5σ sensitivity to NP contributions assuming central values unchanged
  - Probes NP at effective mass scales of a few TeV
  - Commissioning with beam has begun!
- Mu2e will utilize a novel system of solenoids and a pulsed proton beam to search for cLFV with a sensitivity x10^4 improvement
  - Will provide discovery sensitivity to broad range of NP models
  - Probes effective NP mass scales up to 10^4 TeV/c^2
  - Commissioning with beam begins in 2020 (4-5y run time)
- These experiments will provide incisive probes of BSM physics

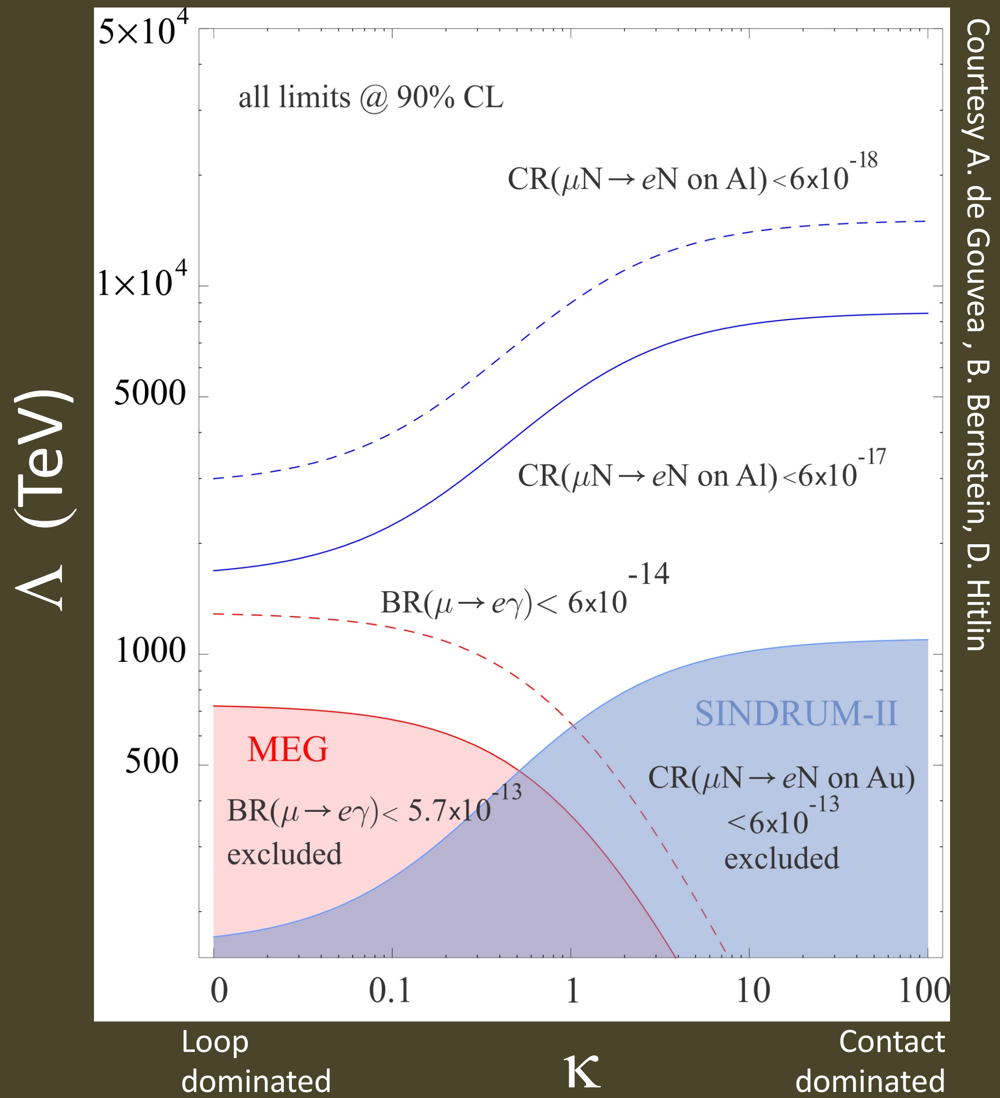
Interested in learning more?

- Technical Design Report
  - http://arXiv.org/abs/1501.05241 (Mu2e)
  - http://arXiv.org/abs/1501.06858 (g-2)

- Experiment web site
  - http://mu2e.fnal.gov
  - http://muon-g-2.fnal.gov

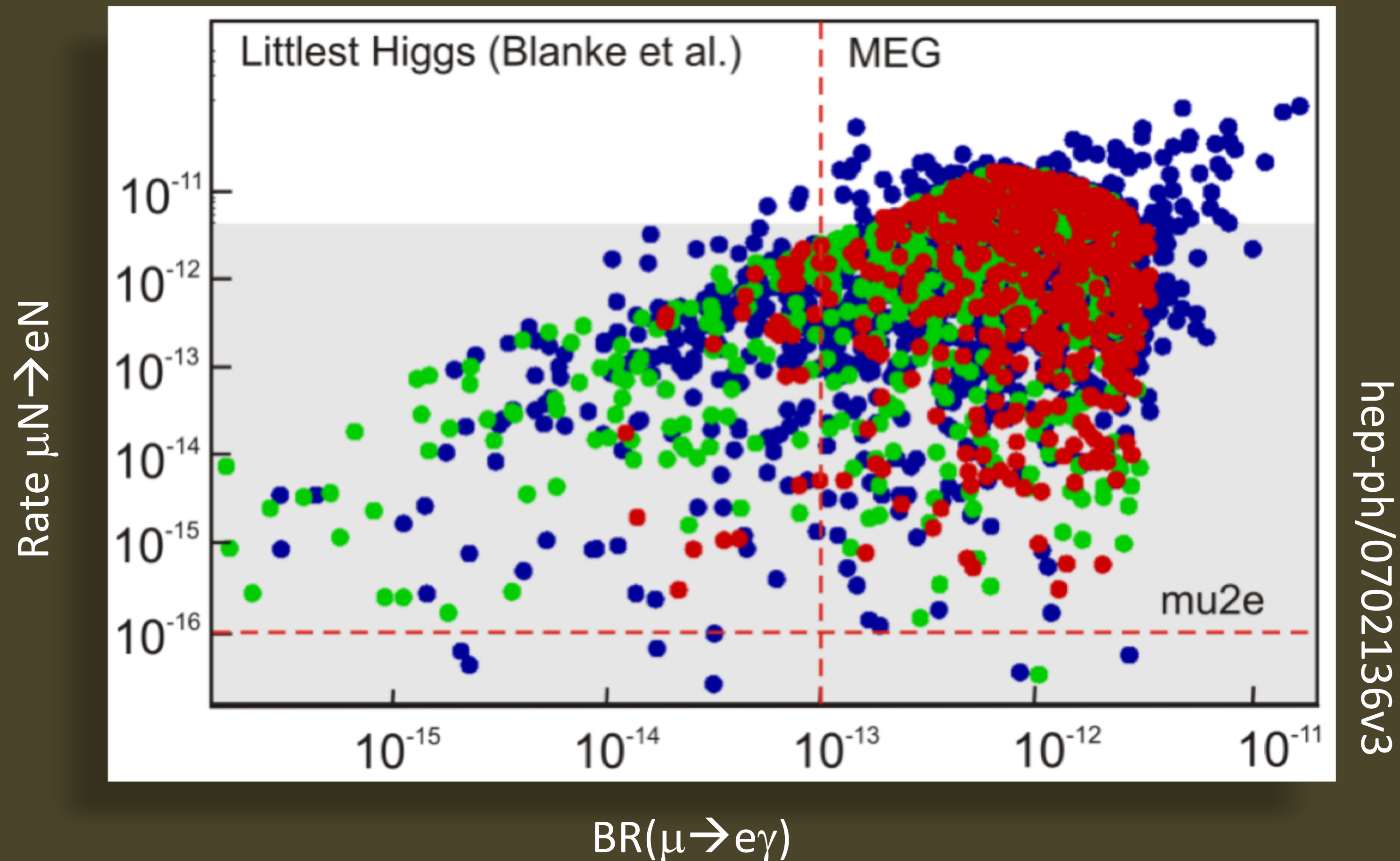
Additional Slides

Mu2e Sensitivty



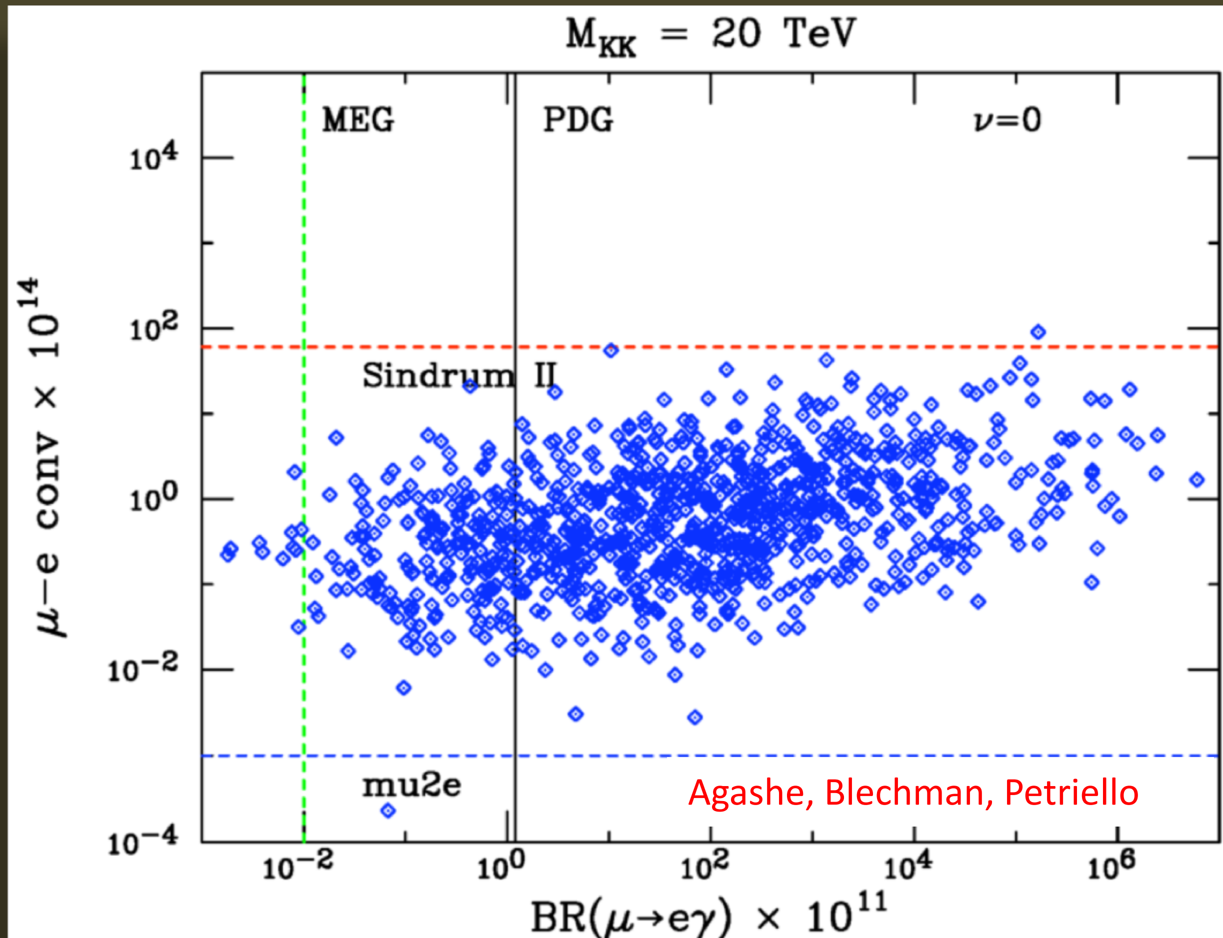
- Mu2e provides world-class sensitivity in all scenarios

Mu2e Sensitivity



- Mu2e will cover the entire space

Mu2e Sensitivity

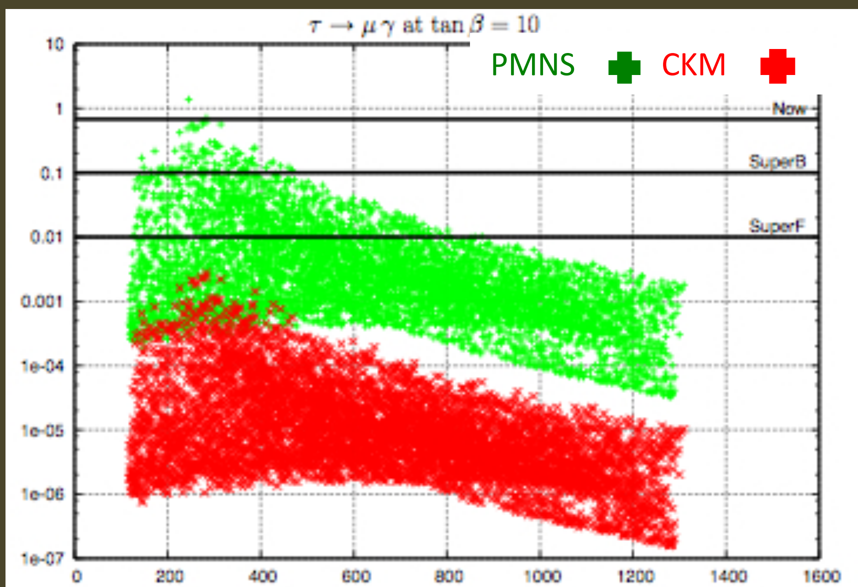


hep-ph/0606021v2

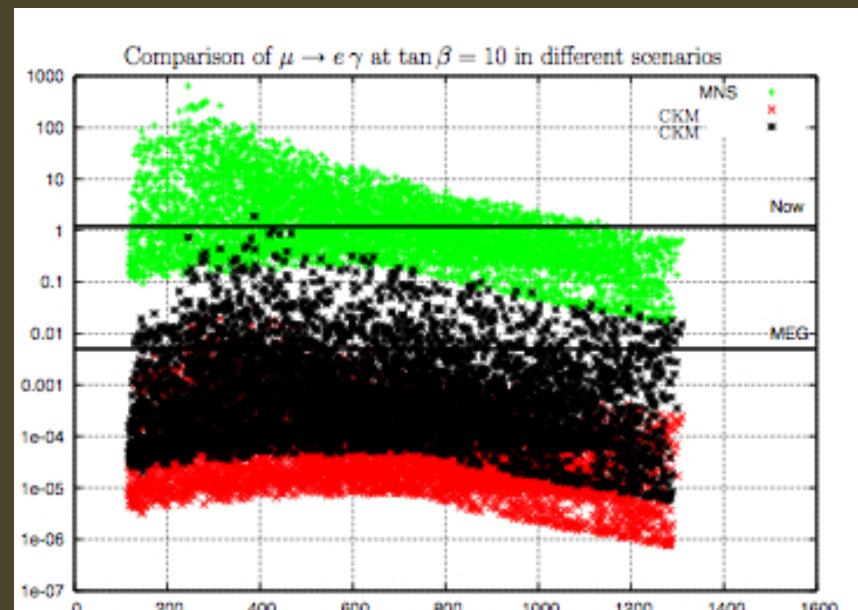
- Mu2e, MEG will each cover entire space

Mu2e Sensitivity

BR(τ→μγ) / 10^{-7}



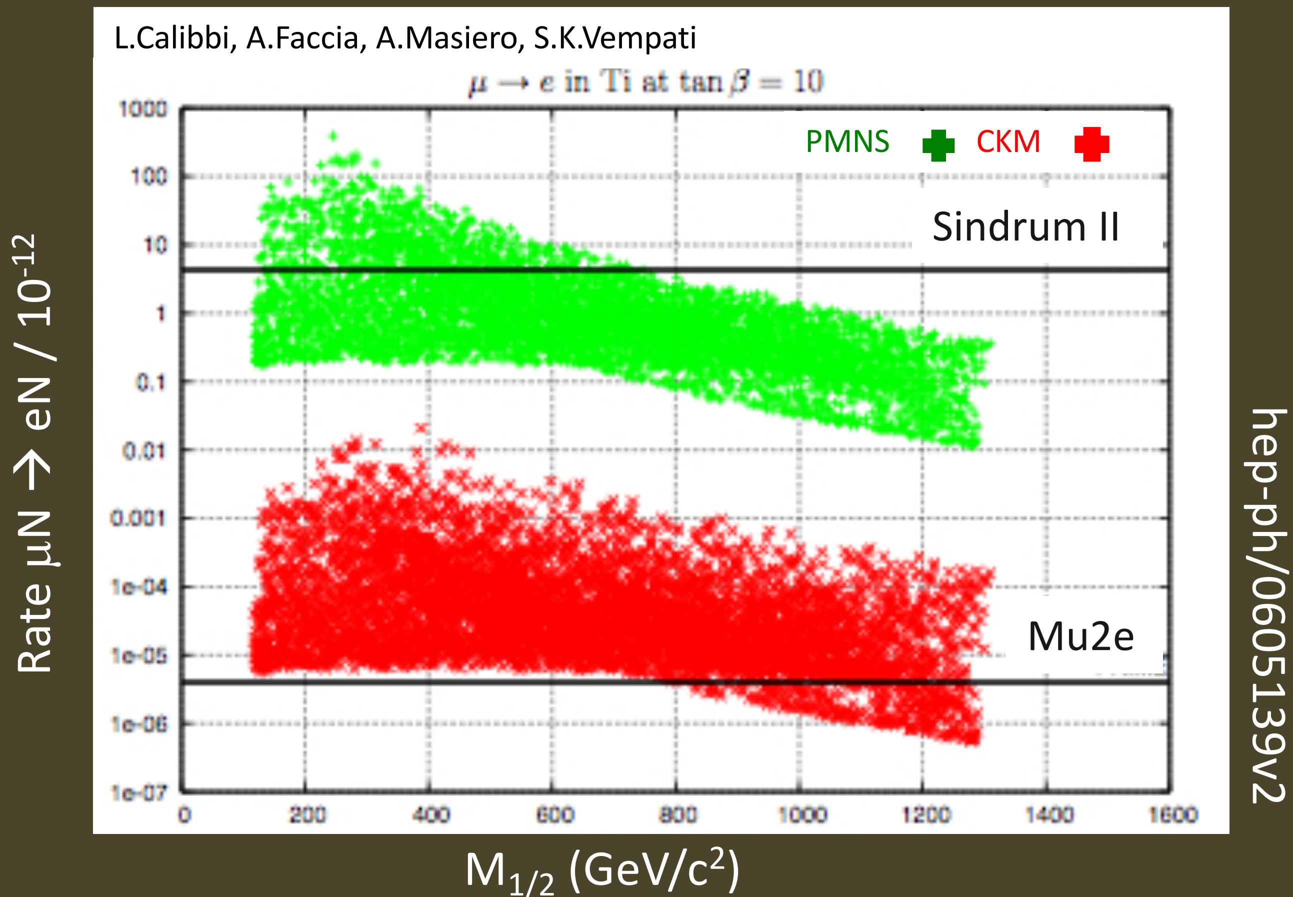
BR(μ→eγ) / 10^{-11}



$M_{1/2}$ (GeV/c^2)

- μ→eγ, τ→μγ will begin to probe this space

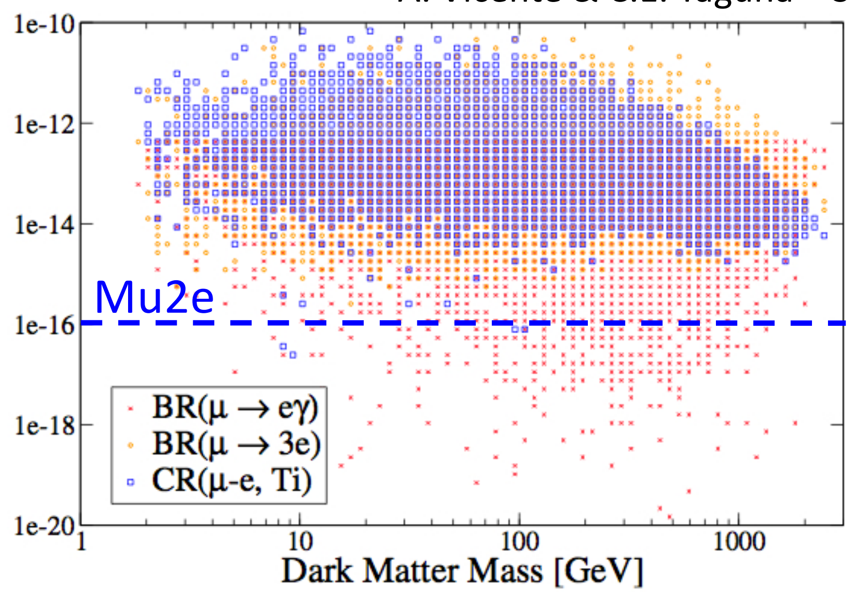
Mu2e Sensitivity

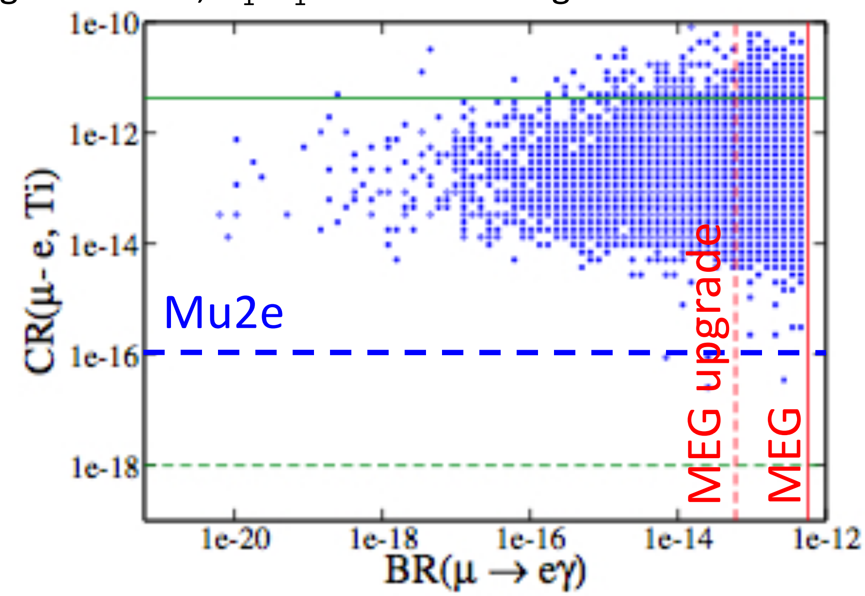


- Mu2e will cover (almost) entire space

Mu2e Sensitivity

A. Vicente & C.E. Yaguna – Scotogenic model, N_1-N_1 annihilation region





arXiv: 1412.2545 [hep-ph]

- Mu2e will explore a significant fraction of the parameter space

Mu2e Sensitivity

TABLE XII: LFV rates for points **SPS 1a** and **SPS 1b** in the CKM case and in the $U_{e3} = 0$ PMNS case. The processes that are within reach of the future experiments (MEG, SuperKEKB) have been highlighted in boldface. Those within reach of post–LHC era planned/discussed experiments (PRISM/PRIME, Super Flavour factory) highlighted in italics.

	SPS 1a		**SPS 1b**		**SPS 2**		**SPS 3**		Future
Process	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	CKM	$U_{e3}=0$	Sensitivity
$\mathrm{BR}(\mu \to e\,\gamma)$	$\mathbf{3.2 \cdot 10^{-14}}$	$\mathbf{3.8 \cdot 10^{-13}}$	$\mathbf{4.0 \cdot 10^{-13}}$	$\mathbf{1.2 \cdot 10^{-12}}$	$1.3 \cdot 10^{-15}$	$8.6 \cdot 10^{-15}$	$1.4 \cdot 10^{-15}$	$1.2 \cdot 10^{-14}$	$\mathcal{O}(10^{-14})$
$\mathrm{BR}(\mu \to e\,e\,e\,)$	$2.3 \cdot 10^{-16}$	$2.7 \cdot 10^{-15}$	$2.9 \cdot 10^{-16}$	$8.6 \cdot 10^{-15}$	$9.4 \cdot 10^{-18}$	$6.2 \cdot 10^{-17}$	$1.0 \cdot 10^{-17}$	$8.9 \cdot 10^{-17}$	$\mathcal{O}(10^{-14})$
$\mathrm{CR}(\mu \to e \text{ in Ti})$	$\mathit{2.0 \cdot 10^{-15}}$	$\mathit{2.4 \cdot 10^{-14}}$	$\mathit{2.6 \cdot 10^{-15}}$	$\mathit{7.6 \cdot 10^{-14}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{6.7 \cdot 10^{-16}}$	$\mathit{1.0 \cdot 10^{-16}}$	$\mathit{8.4 \cdot 10^{-16}}$	$\mathcal{O}(10^{-18})$
$\mathrm{BR}(\tau \to e\,\gamma)$	$2.3 \cdot 10^{-12}$	$6.0 \cdot 10^{-13}$	$3.5 \cdot 10^{-12}$	$1.7 \cdot 10^{-12}$	$1.4 \cdot 10^{-13}$	$4.8 \cdot 10^{-15}$	$1.2 \cdot 10^{-13}$	$4.1 \cdot 10^{-14}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to e\,e\,e)$	$2.7 \cdot 10^{-14}$	$7.1 \cdot 10^{-15}$	$4.2 \cdot 10^{-14}$	$2.0 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$5.7 \cdot 10^{-17}$	$1.5 \cdot 10^{-15}$	$4.9 \cdot 10^{-16}$	$\mathcal{O}(10^{-8})$
$\mathrm{BR}(\tau \to \mu\,\gamma)$	$5.0 \cdot 10^{-11}$	$\mathbf{1.1 \cdot 10^{-8}}$	$7.3 \cdot 10^{-11}$	$\mathbf{1.3 \cdot 10^{-8}}$	$2.9 \cdot 10^{-12}$	$\mathit{7.8 \cdot 10^{-10}}$	$2.7 \cdot 10^{-12}$	$\mathit{6.0 \cdot 10^{-10}}$	$\mathcal{O}(10^{-9})$
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	$1.6 \cdot 10^{-13}$	$3.4 \cdot 10^{-11}$	$2.2 \cdot 10^{-13}$	$3.9 \cdot 10^{-11}$	$8.9 \cdot 10^{-15}$	$2.4 \cdot 10^{-12}$	$8.7 \cdot 10^{-15}$	$1.9 \cdot 10^{-12}$	$\mathcal{O}(10^{-8})$

- These are SuSy benchmark points for which LHC has discovery sensitivity
- Some of these will be observable by MEG/SuprB
- All of these will be observable by Mu2e

The Mu2e Beamlines

The Mu2e Proton Beam

Quantity	Value	Units
MI-RR Cycle Time	1400.0	msec
Number of Spills per MI-RR Cycle	8	
Spill Duration	43.12	msec
Reset (Beam Off) Time Between Spills	5	msec
Number of Pulses per Spill	25.4k	
Pulse Spacing	1695	ns
Protons on Target (POT) Per Pulse	39×10^6	POT
Instantaneous Rate	24×10^{12}	POT/s
Average Rate	6×10^{12}	POT/s
Duty Factor	25%	
Proton Beam Energy	8	GeV

- Mu2e will use 8kW of 8 GeV proton beam

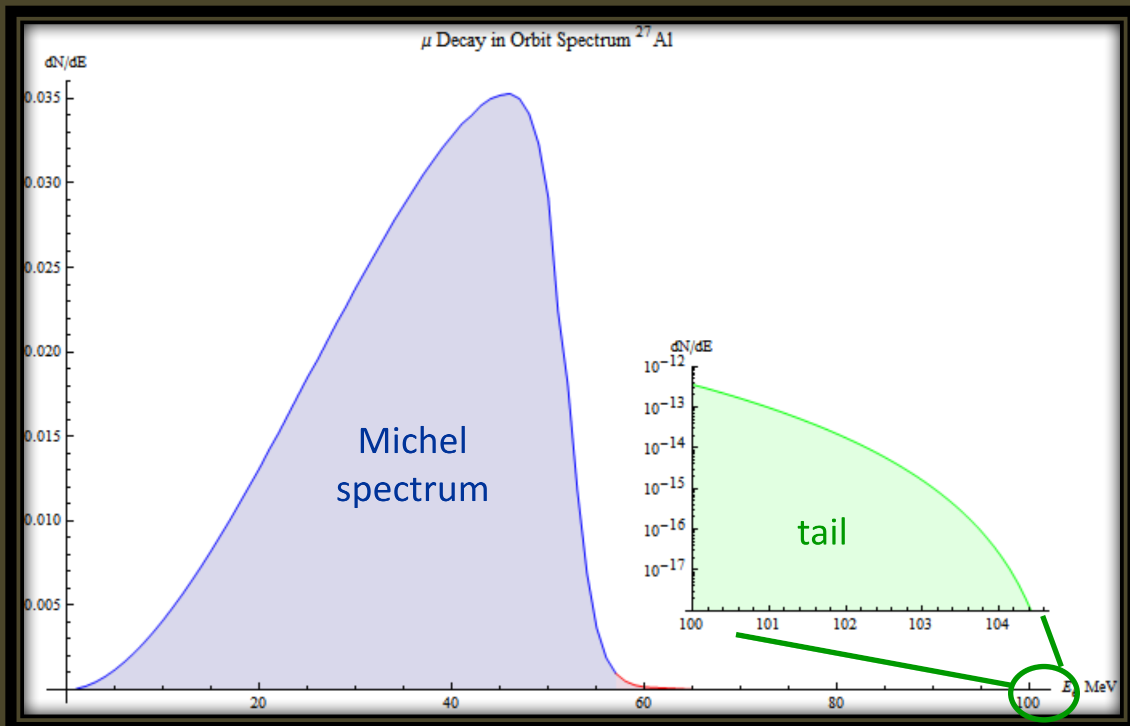
Mitigating out-of-time protons

- The RF structure of the Recycler provides some “intrinsic” extinction:
  - Extinction (Intrinsic) = few 10^{-5}
- A custom-made AC dipole placed just upstream of the production target provides additional “external” extinction:
  - Extinction (AC dipole) = 10^{-6} – 10^{-7}
- Together they provide a total extinction:
  - Extinction (Total) = few 10^{-11} – 10^{-12}

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

1) Decay in orbit (DIO): $\mu^- N \to e^- \nu_\mu \nu_e N$
   - For Al. DIO fraction is 39%
   - Electron spectrum has tail out to 104.96 MeV
   - Accounts for ~35% of total background



Electron energy in MeV

Mu2e Intrinsic Backgrounds

Once trapped in orbit, muons will:

2) Capture on the nucleus:
   - For Al. capture fraction is 61%
   - Ordinary μ Capture
     - $\mu^{-}N_{Z} \text{-->} \nu N^{*}_{Z\text{-}1}$
     - Used for normalization
   - Radiative μ capture
     - $\mu^{-}N_{Z} \text{-->} \nu N^{*}_{Z\text{-}1} + \gamma$
     - (# Radiative / # Ordinary) ~ 1 / 100,000
     - E_{γ} kinematic end-point ~102 MeV
     - Asymmetric γ -->$e^{+}e^{-}$ pair production can yield a background electron

Mu2e Late Arriving Backgrounds

- Backgrounds arising from all the other interactions which occur at the production target
  - Overwhelmingly produce a prompt background when compared to $\tau_{\mu}^{Al} = 864$ ns
  - Eliminated by defining a signal timing window starting 700 ns after the initial proton pulse
  - Must eliminate out-of-time ("late") protons, which would otherwise generate these backgrounds in time with the signal window

out-of-time protons / in-time protons $< 10^{-10}$

Mu2e Late Arriving Backgrounds

- Contributions from
  - Radiative π Capture
    - $\pi^{-}N_{Z}$ --> $N^{*}{}_{Z\text{-}1} + \gamma$
    - For Al. RπC fraction: 2%
    - E_{γ} extends out to ~m_{π}
    - Asymmetric γ ––> $e^{+}e^{-}$ pair production can yield background electron
  - Beam electrons
    - Originating from upstream π^{-} and π^{0} decays
    - Electrons scatter in stopping target to get into detector acceptance
  - Muon and pion Decay-in-Flight
- Taken together these backgrounds account for ~10% of the total background and scale *linearly* with the number of out-of-time protons

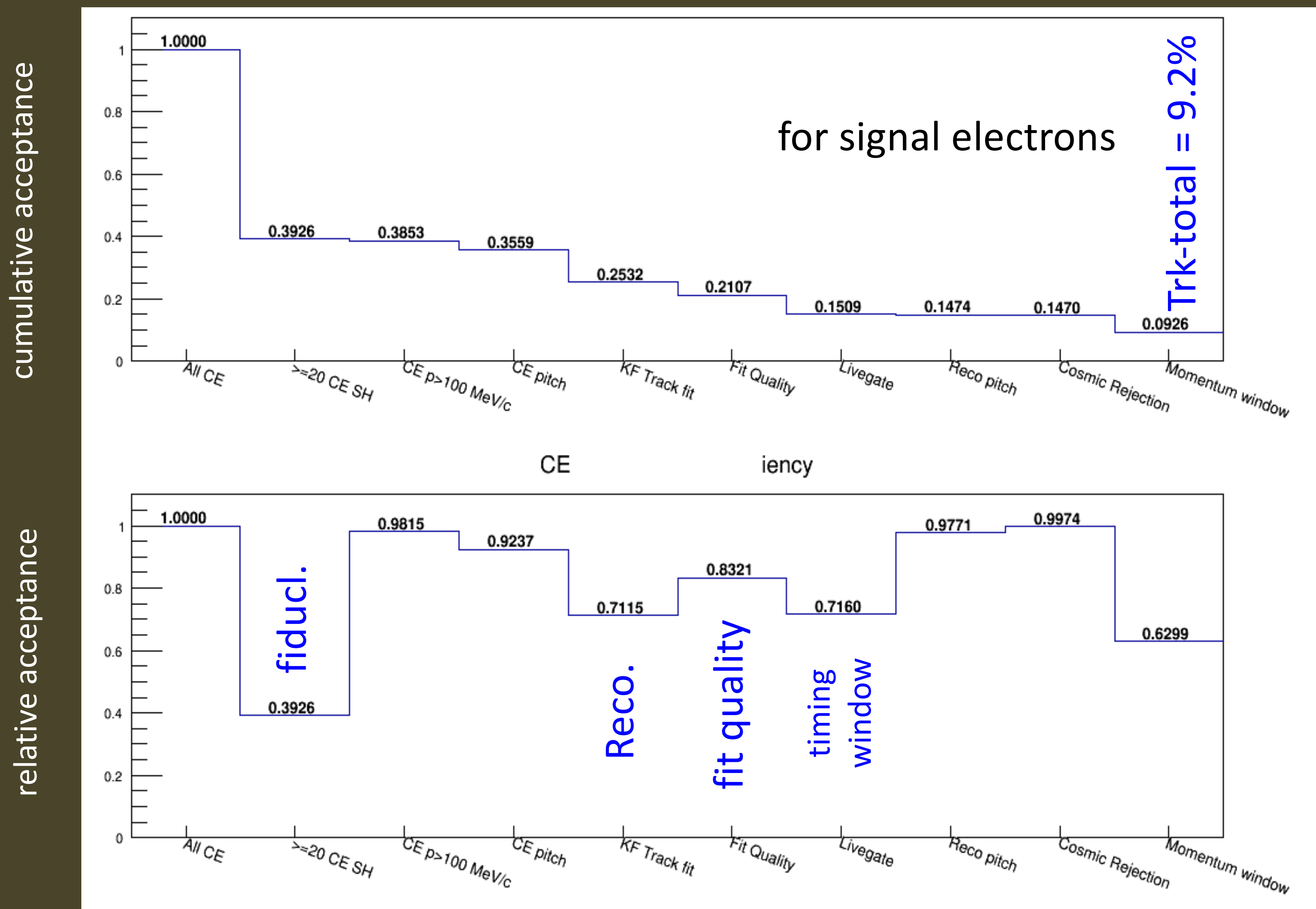
Mu2e Miscellaneous Backgrounds

- Several additional miscellaneous sources can contribute background - most importantly:
  - Anti-protons
    - Proton beam is just above pbar production threshold
    - These low momentum pbars wander until they annihilate
    - A thin mylar window in beamline absorbs most if them
    - Annihilations produce high multiplicity final states e.g. π^- can undergo RπC to yield a background electron
  - Cosmic rays
    - Suppressed by passive and active shielding
    - μ DIF or interactions in the detector material can give an e^- or γ that yield a background electron
    - Background listed assumes veto efficiency of 99.99%

Mu2e Track Reconstruction

- Straw-hit rates
  - From beam flash (0-300 ns): ~1000 kHz/cm^2
    - Need to survive this, but won't collect data
  - Later, near live window (>500 ns)
    - Peak ~ 20 kHz/cm^2 (inner straws)
    - Average ~ 10 kHz/cm^2 (over all straws)

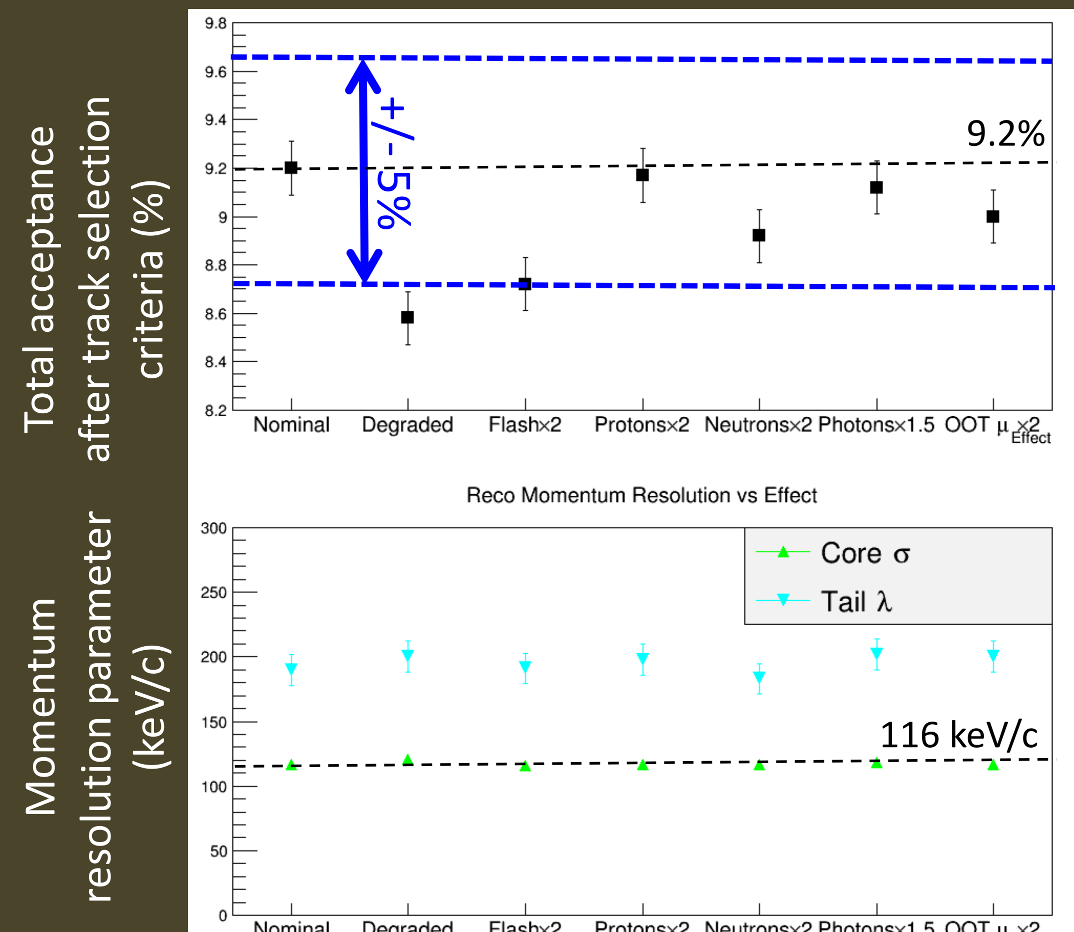
Track Reconstruction and Selection



Inefficiency dominated by geometric acceptance

After calorimeter PID and CRV deadtime, Total = 8.5%

Mu2e Performance



Variations in accidental hit rate

- Robust against increases in rate

Mu2e Selection Requirements

Parameter	Requirement
Track quality and background rejection criteria	
Kalman Fit Status	Successful Fit
Number of active hits	$N_{active} \geq 25$
Fit consistency	$\chi 2$ consistency > 2×10^{-3}
Estimated reconstructed momentum uncertainty	$\sigma_p < 250$ keV/c
Estimated track t_0 uncertainty	$\sigma_t < 0.9$ nsec
Track t_0 (livegate)	700 ns < t_0 < 1695 ns
Polar angle range (pitch)	$45° < \theta < 60°$
Minimum track transverse radius	-80 mm < d_0 < 105 mm
Maximum track transverse radius	450 mm < $d_0 + 2/\omega$ < 680 mm
Track momentum	103.75 < p < 105.0 MeV/c
Calorimeter matching and particle identification criteria	
Track match to a calorimeter cluster	$E_{cluster} > 10$ MeV $\chi 2$ (track-calo match) < 100
Ratio of cluster energy to track momentum	E/P < 1.15
Difference in track t_0 to calorimeter t_0	$\Delta t = \lvert t_{track} - t_{calo} \rvert < 3$ ns from peak
Particle identification	$\log(L(e)/L(\mu)) < 1.5$

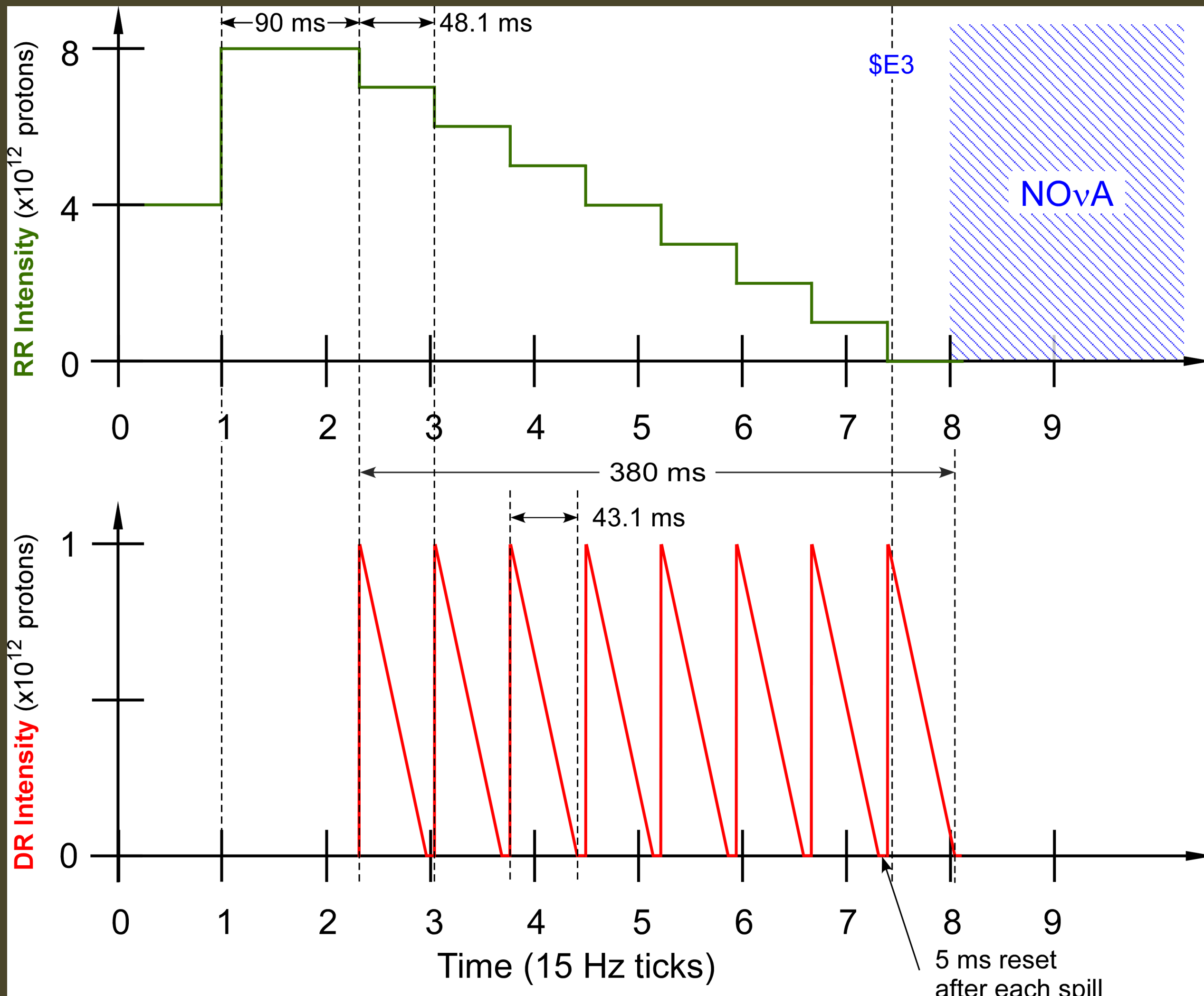
- Full set of selection criteria employed to estimate backgrounds and sensitivity reported in TDR (Summer 2014)

Mu2e Systematic Uncertainties

Effect	Uncertainty in DIO background yield	Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)
MC Statistics	±0.02	±0.07
Theoretical Uncertainty	±0.04	-
Tracker Acceptance	±0.002	±0.03
Reconstruction Efficiency	±0.01	±0.15
Momentum Scale	+0.09, -0.06	±0.07
μ-bunch Intensity Variation	±0.007	±0.1
Beam Flash Uncertainty	±0.011	±0.17
μ-capture Proton Uncertainty	±0.01	±0.016
μ-capture Neutron Uncertainty	±0.006	±0.093
μ-capture Photon Uncertainty	±0.002	±0.028
Out-Of-Target μ Stops	±0.004	±0.055
Degraded Tracker	-0.013	+0.191
Total (in quadrature)	+0.10, -0.08	+0.35, -0.29

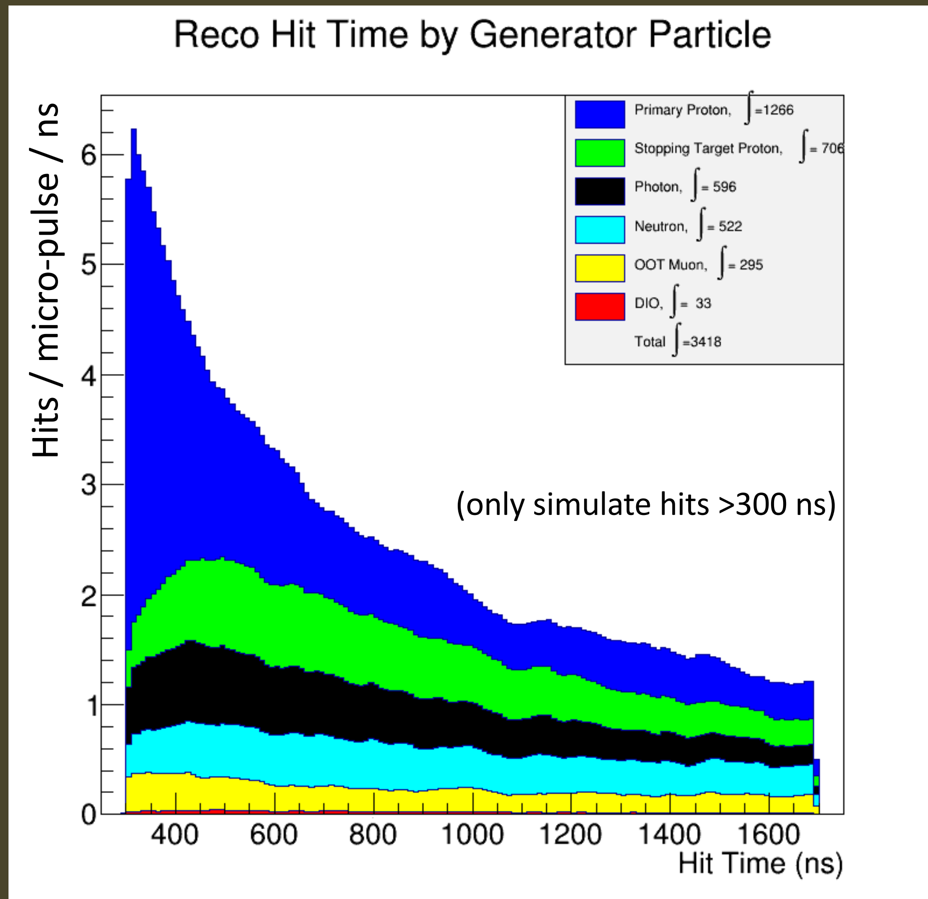
- Evaluated for all background sources

Mu2e Proton Timing



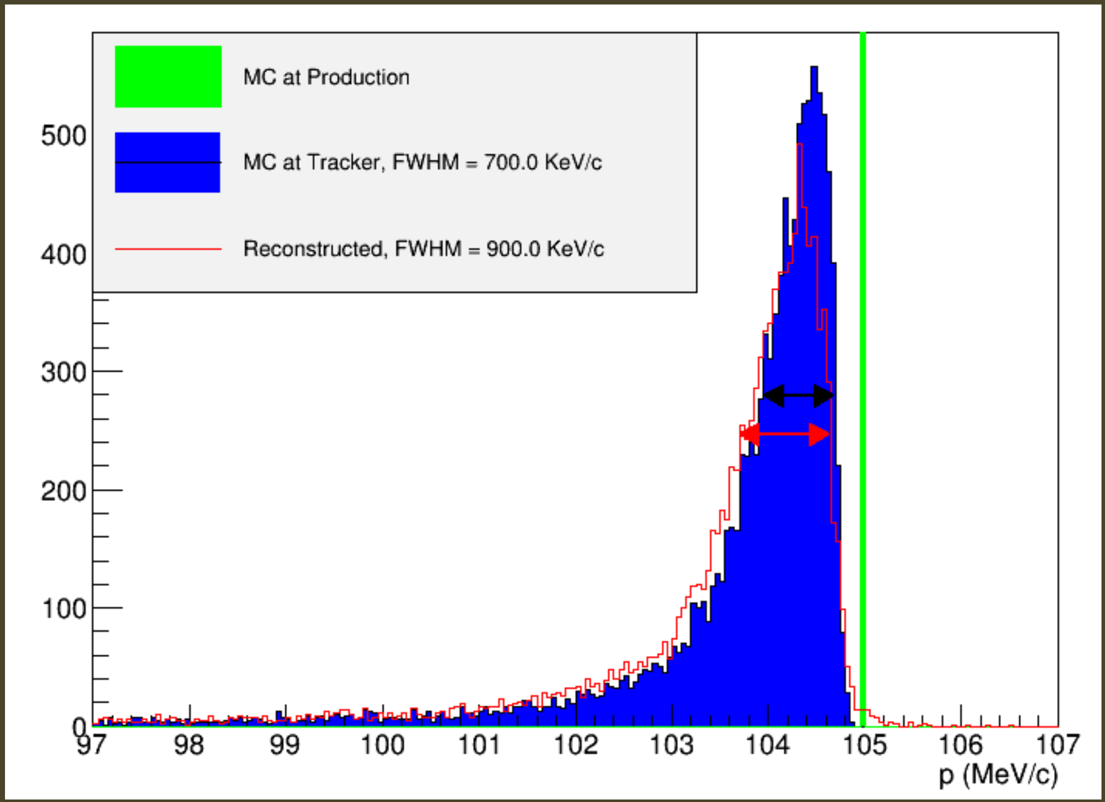
- Mu2e will run simultaneously with NOvA, BNB, etc.

Mu2e Tracker Occupancy



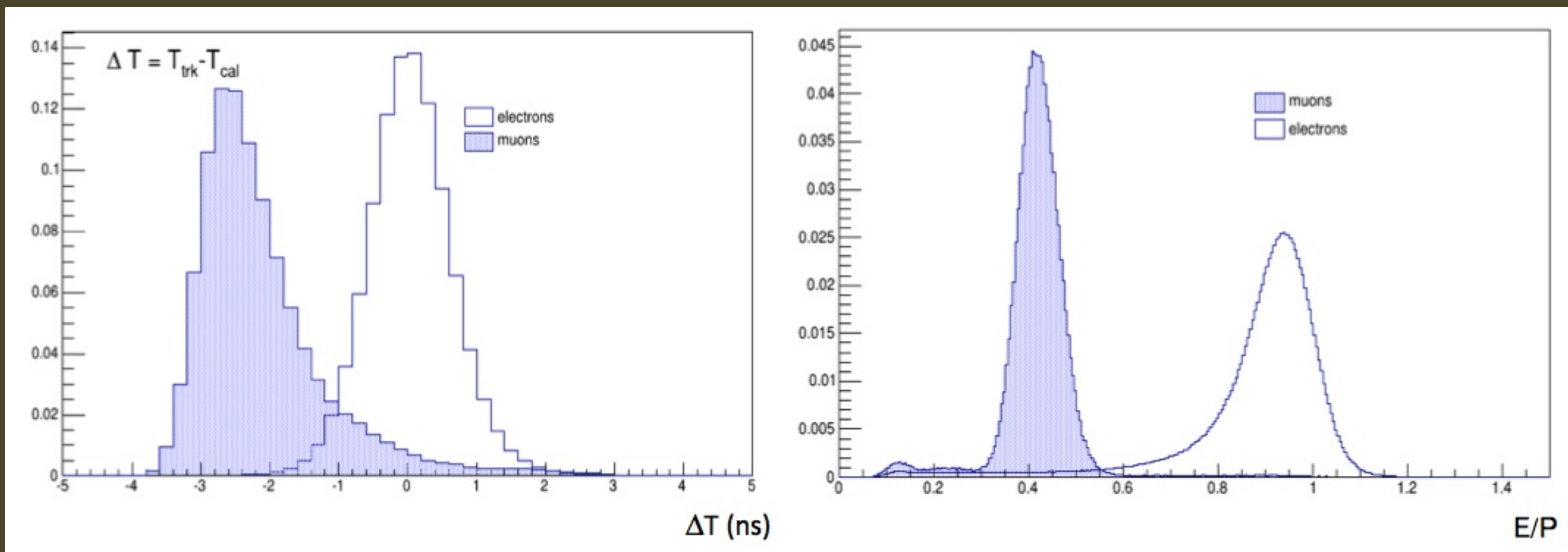
- Accidental occupancy from beam flash, μ capture products, out-of-target μ stops, etc.

Mu2e Signal Momentum Spectrum



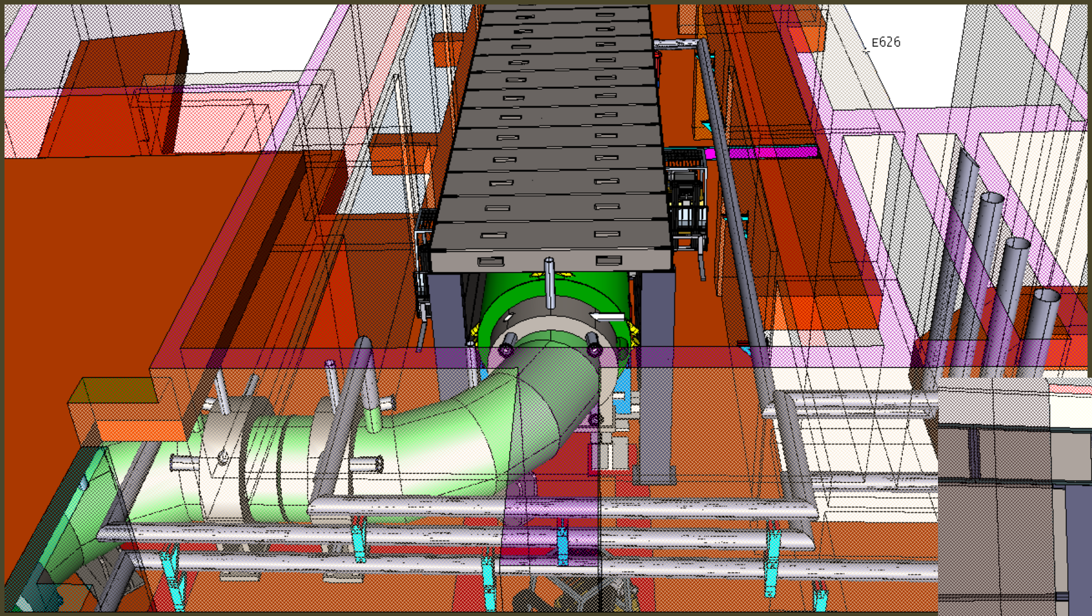
- Smearing dominated by interactions in stopping target and in (neutron/proton) absorbers upstream of tracker

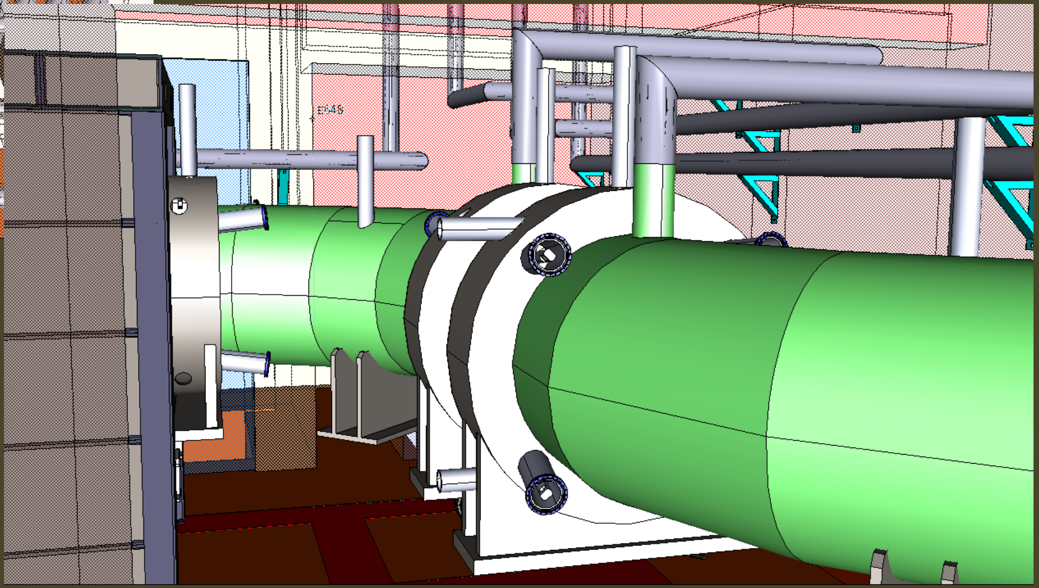
Mu2e Calorimeter Particle ID



- Electrons and muons well separated

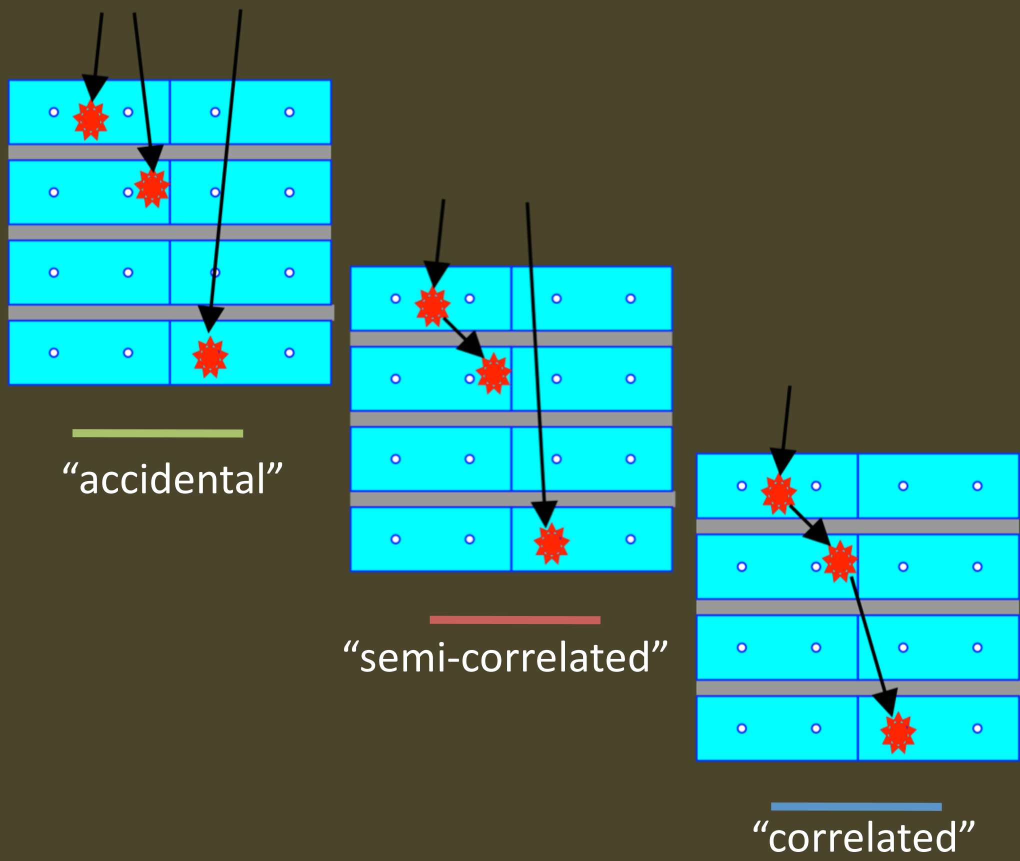
Details, details, details

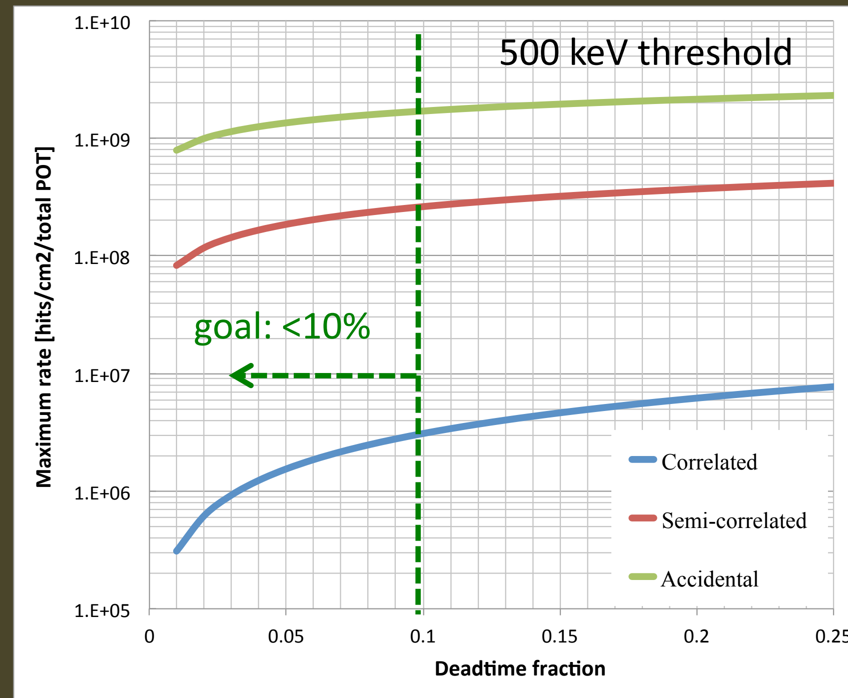




- Working to identify and resolve interface issues

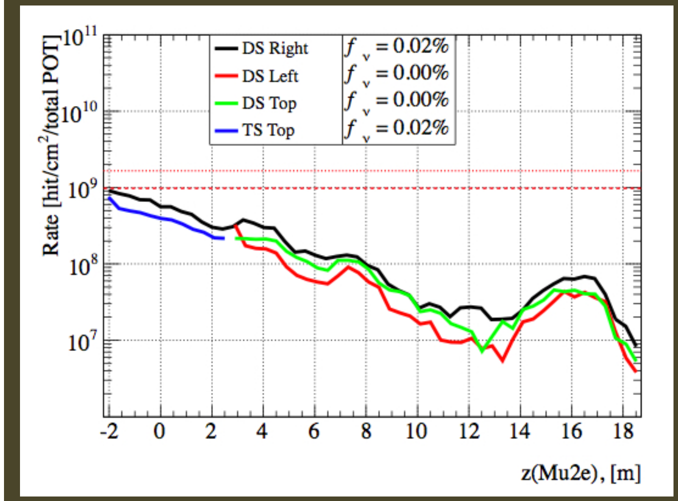
Mu2e False vetoes in CRV

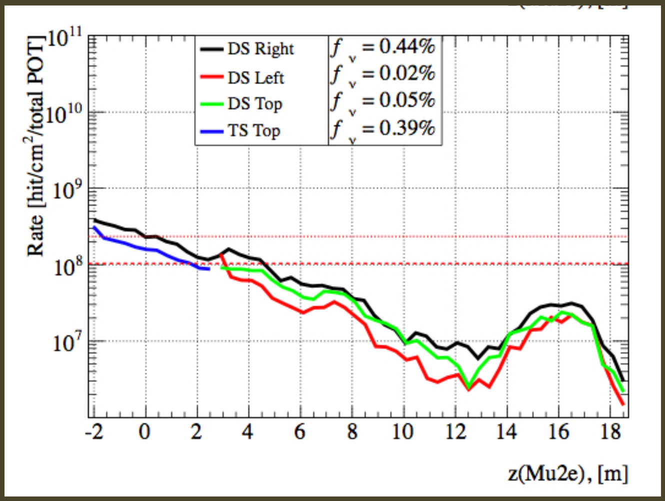


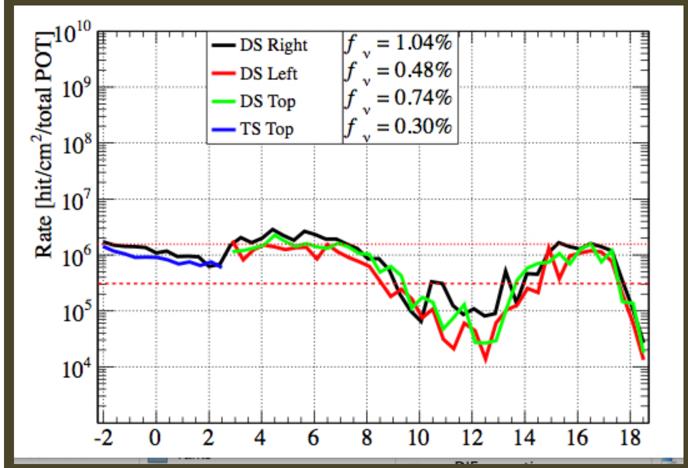


- We need to understand contributions from accidentals and correlated-accidentals
  - For neutrons and photons as a function of time, energy, timing resolution, and read-out threshold

Mu2e Estimated dead time from CRV vetos – dominated by n/γ background



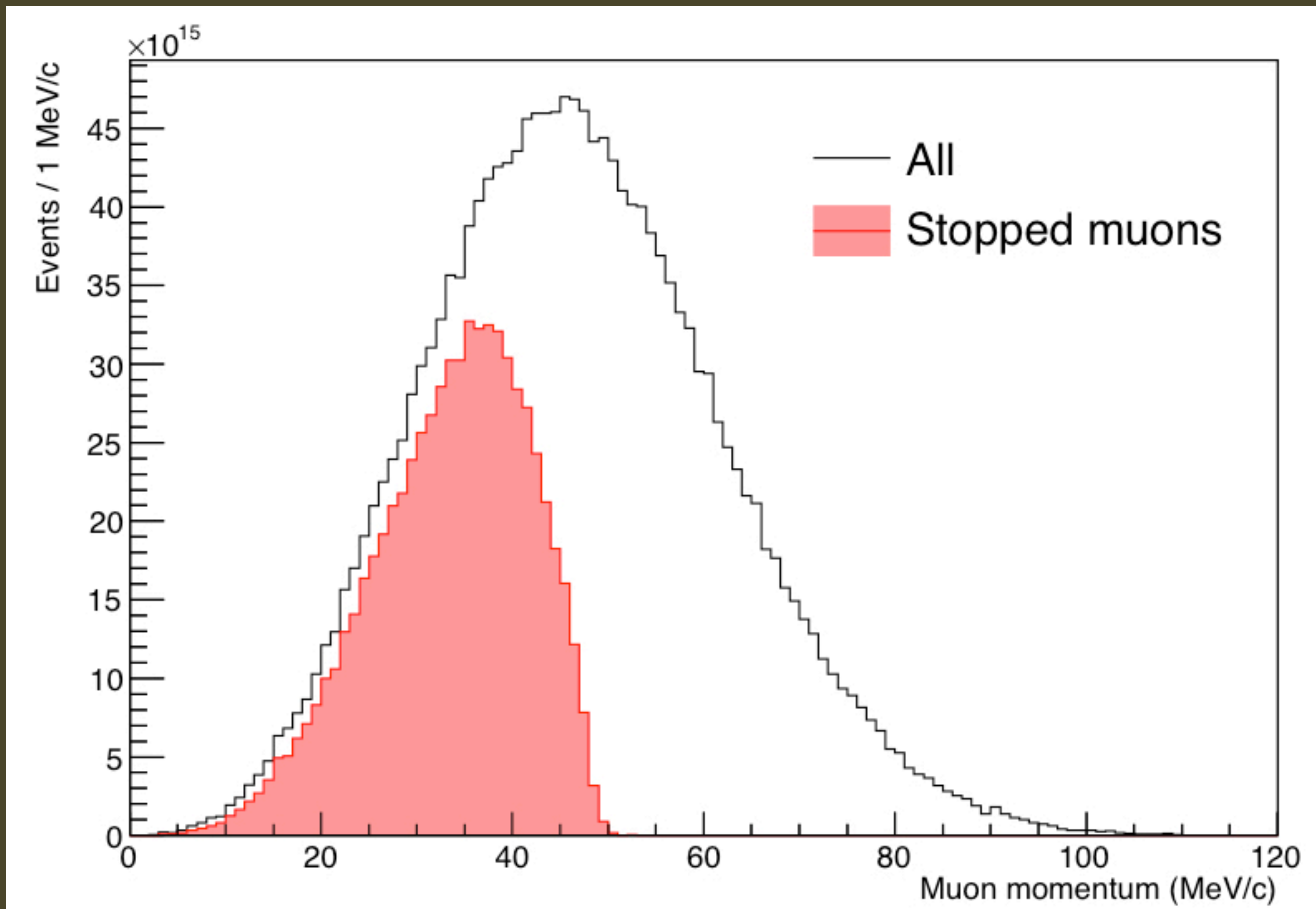




accidental semi-correlated correlated

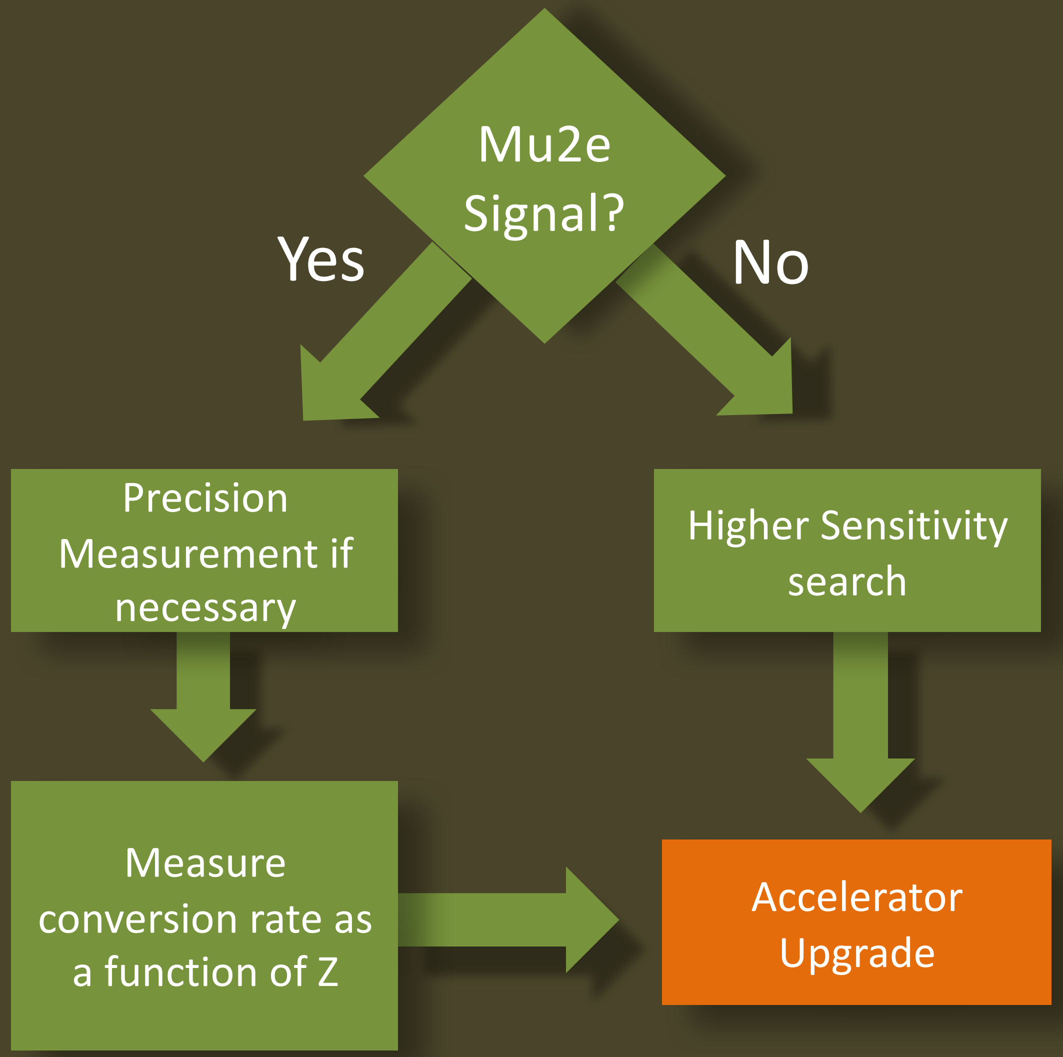
- Total dead time from neutron/photon “noise” = 5%
  - For 500 keV readout threshold
  - Increasing to 1 MeV reduces to 2%
  - Cross-check with a separate physics generator (MARS) yields dead time within 50%

Mu2e Muon momentum distribution



- The muons that stop are low momentum

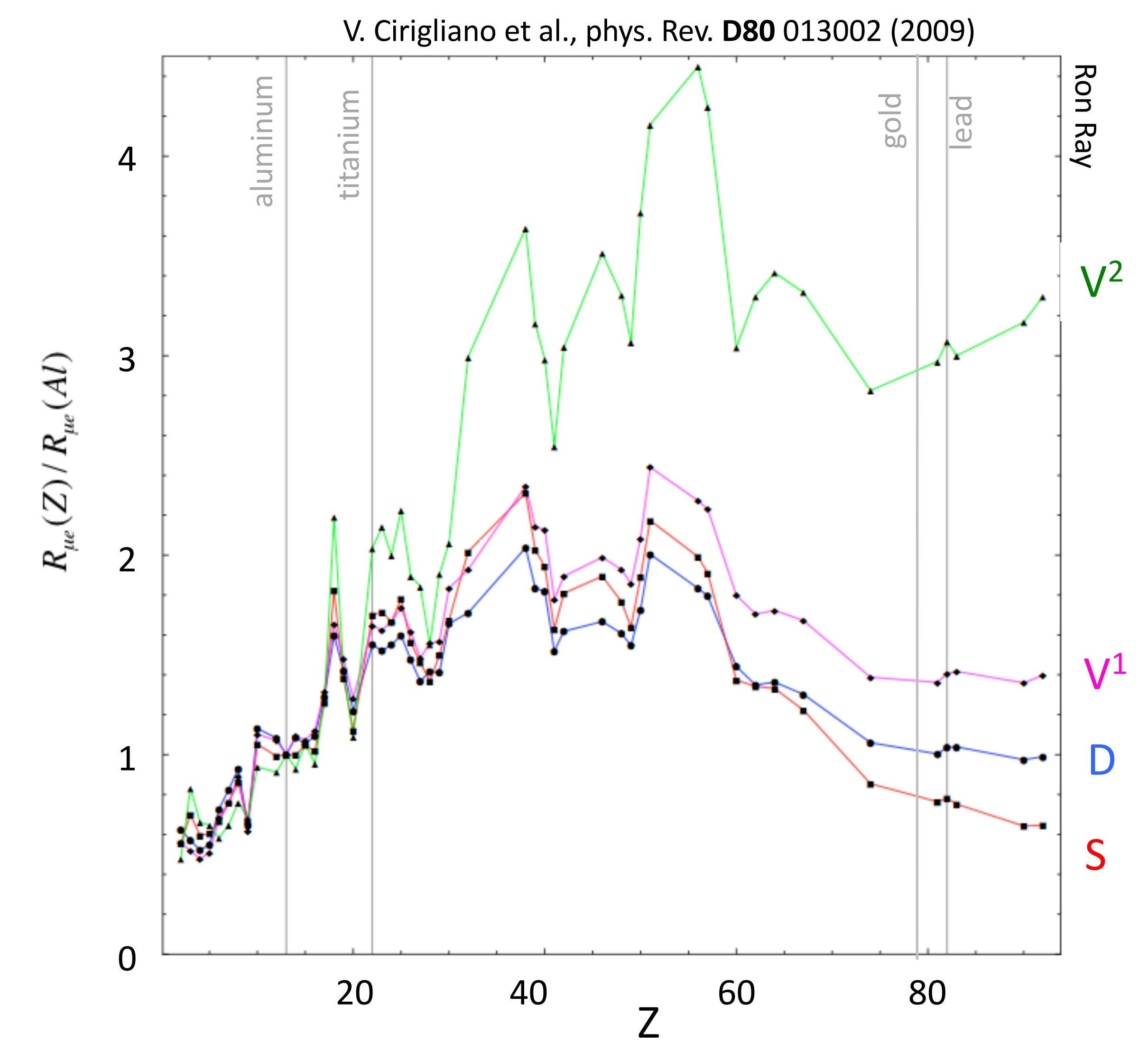
What next?



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator
  - Snowmass white paper, arXiv:1307.1168

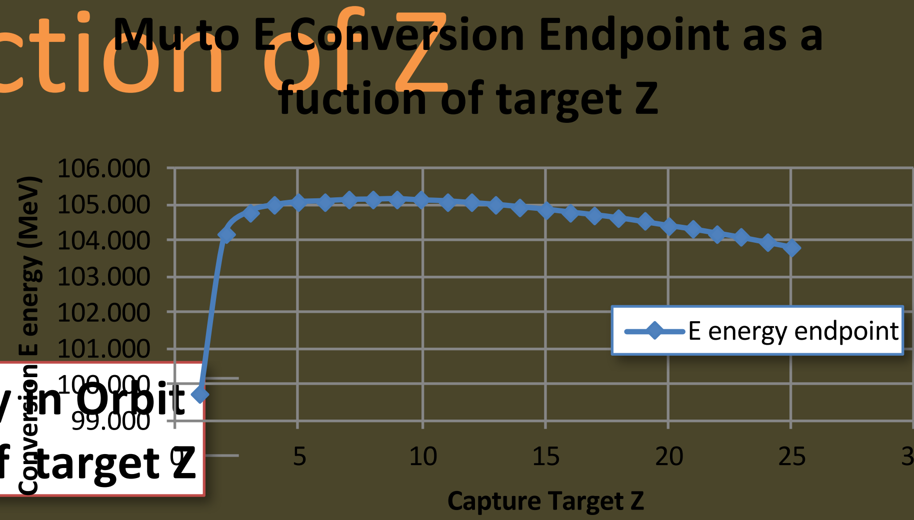
μN→eN vs stopping-target Z

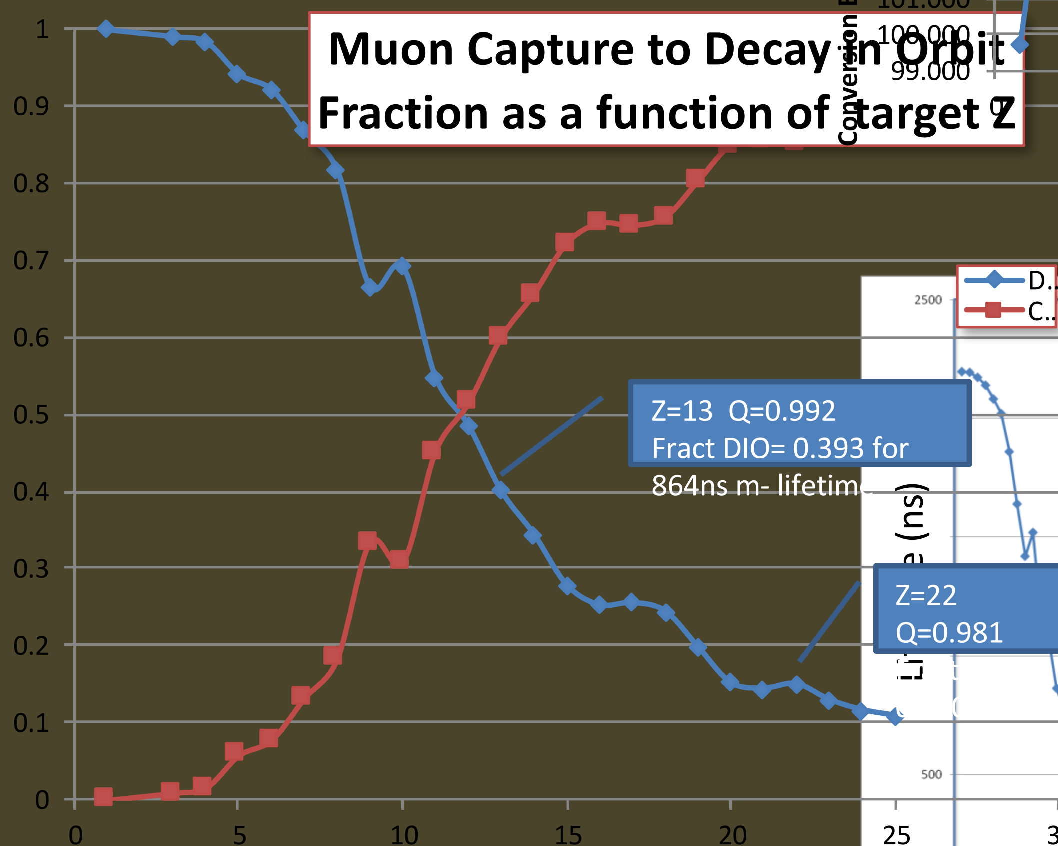
- By measuring the ratio of rates using different stopping targets Mu2e can unveil underlying new-physics mechanism

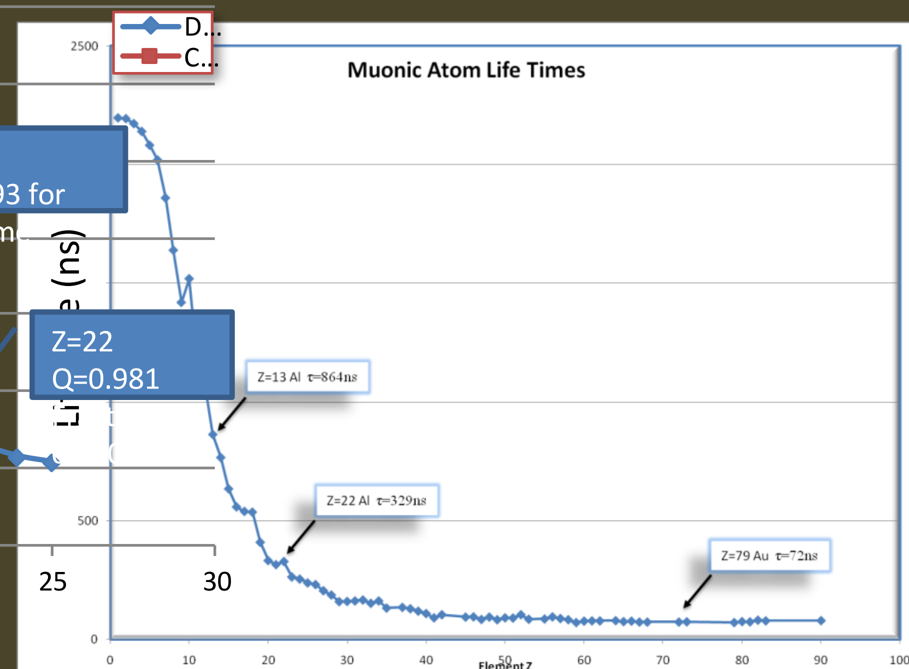


As a function of Z

- Things change



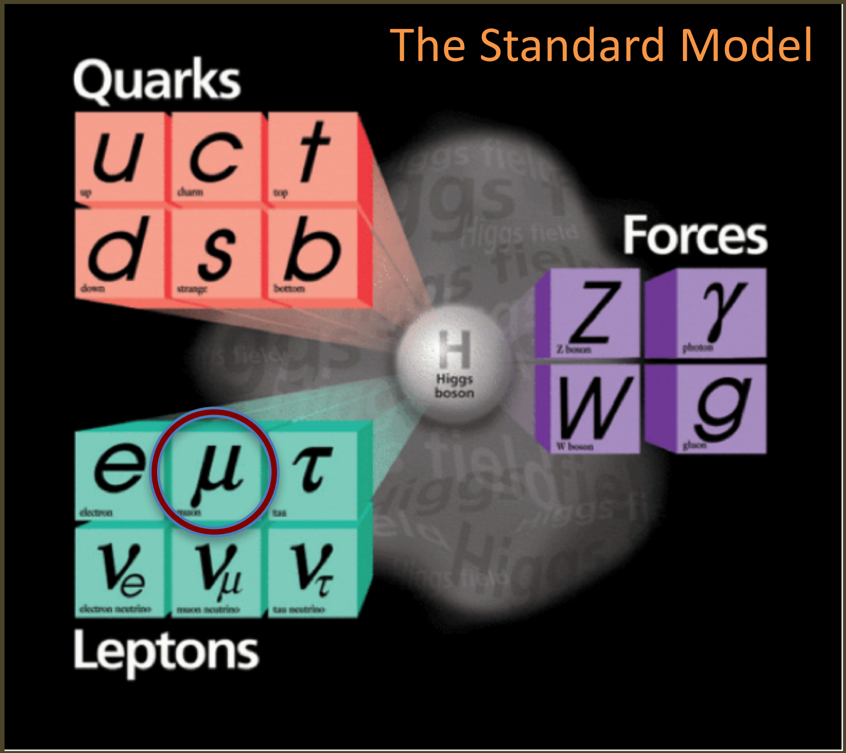




Muons as probes for new physics

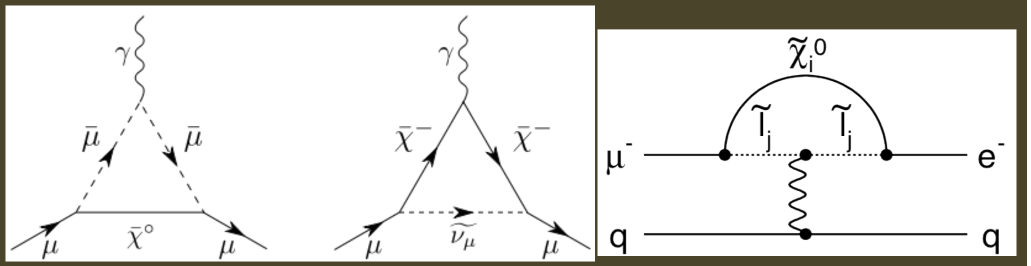
Muons offer important experimental advantages

- Easy to produce BR($\pi^\pm \to \mu^\pm \nu$) > 99%
- Clean final state BR($\mu^\pm \to e^\pm \nu\nu$) > 99%
- Don't get ensnared by the strong force
- Relatively long life time 2.2 μs
- Relatively heavy $(m_\mu/m_e)^2 = 40000$



Fermilab muon program uses muons to advance the search for NP

- Muon g-2 experiment (data 2017)
- Mu2e experiment (data 2020)
- Future possibilities for other muon-based experiments, e.g. muon EDM, other cLFV channels



Windows into new physics…