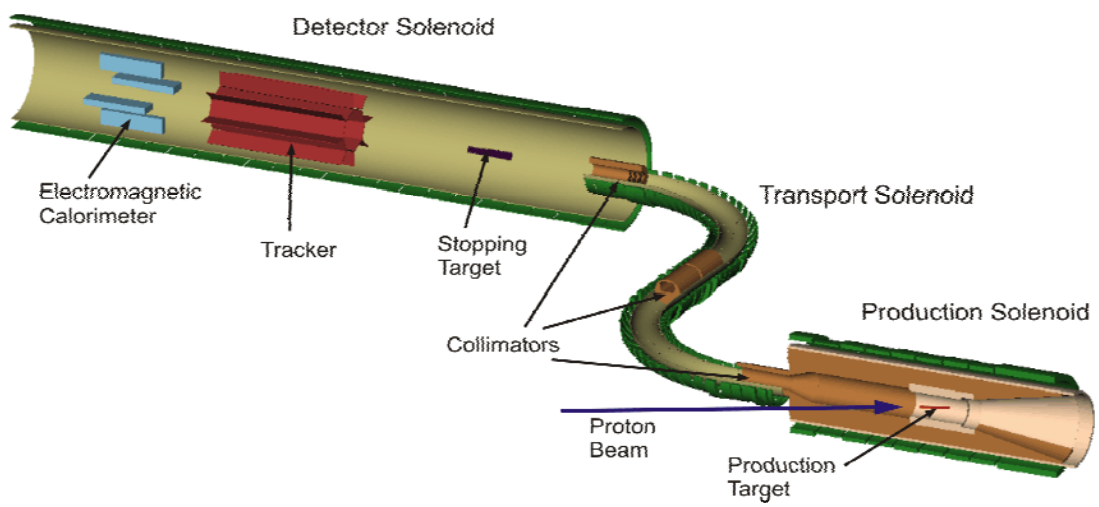
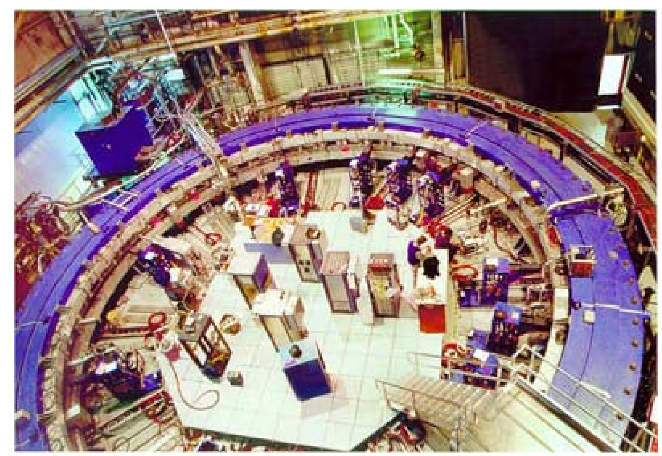
The Mu2e and Muon g-2 Experiments

Precision windows into physics beyond the standard model





Andrew Norman
University of Virginia
For the Mu2e & g-2 Collaborations

Introduction

The world is poised for the LHC to turn on give us direct access to physics at the Terascale....

But there are other windows into new physics that can reach far beyond the energies of the world's largest colliders

Two of these windows are here at Fermilab

Introduction

Mu2e and **g-2** will probe:

new physics,

new models

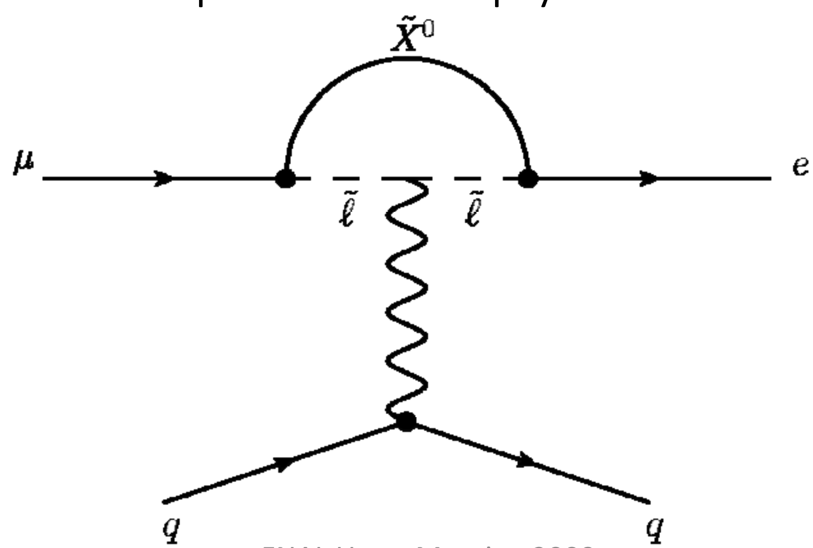
new energy scales

with ultra-rare searches

and precision measurements

Why Precision Measurements & Ultra-Rare Processes?

- We want to access physics beyond the standard model
  - This means access to High and Ultra-High Energy interactions
  - One way to get to these energies through loops
  - Getting at Loops means making precision measurements and looking for ultra-rare decays
- Ideally we start with processes that are forbidden or highly suppressed in the standard model
  - Any observation becomes proof of non-SM physics



Why Precision Measurements & Ultra-Rare Processes?

- We want to access physics beyond the standard model
  - This means access to High and Ultra-High Energy interactions
  - We get to these energies through loops
  - Getting at Loops means making precision measurements and looking for ultra-rare decays
- Ideally we start with processes that are forbidden or highly suppressed in the standard model
  - Any observation becomes proof of non-SM physics
- Flavor Changing Neutral Currents
  - FCNC in quark sector
    - $B_s \to \mu\,\mu$, $b \to s\,\gamma$, $K \to \pi\,\nu\,\nu$
    - Allowed but HIGHLY suppressed in Standard Model
    - Can receive LARGE enhancements in SUSY and other beyond-SM physics
  - FCNC in charged lepton sector
    - $\mu \to e\,\gamma$, $\mu \to e\,e\,e$, $\mu\,N \to e\,N$ (Lepton Flavor Violating)
    - No SM amplitudes (except via ν loops)
    - Permitted in beyond-SM models, and have extreme reach in energy

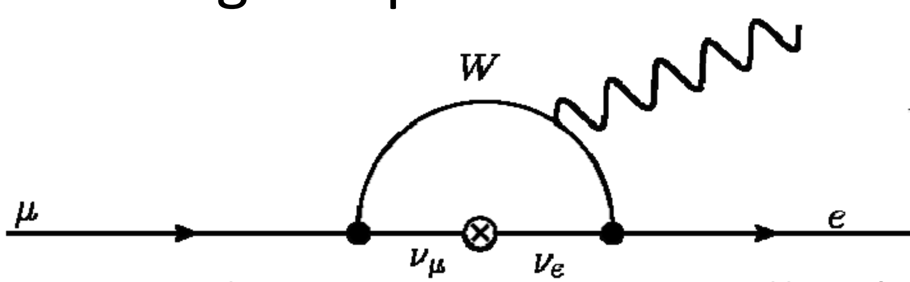
Lepton Mixing in the Standard Model

- We have three generations of leptons:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

No SM couplings between generation!

- In the standard model Lagrangian there is no coupling to mixing between generations
- But we have explicitly observed *neutrino oscillations*
- *Thus charged lepton flavor is* ***not*** *conserved.*
- Charged leptons must mix through neutrino loops



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W} \right|^2$$

$$\leq 10^{-54}$$

- But the mixing is so small, it's effectively forbidden

Charged Lepton Flavor Violation (CLFV) Processes with μ's

- There are three basic channels to search for μ-CLFV in:

$$\mu^+ \to e^+\gamma$$

$$\mu^+ \to e^+e^+e^-$$

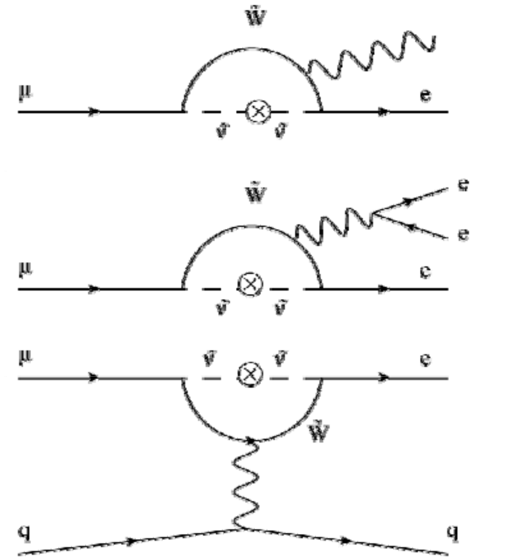
$$\mu^- N \to e^- N$$

- If loop like interactions dominate we expect a ratio of rates:

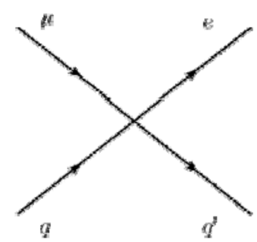
$\approx$ 400 to 2 to 1

- If contact terms dominate then μN$\to$eN can have rates 200 times that of $\mu\to$eγ

- New physics for these channels can come from loop level



- For μ N $\to$ e N and $\mu \to$ eee we also can have contact terms



Charged Lepton Flavor Violation (CLFV) Processes with μ's

- There are three basic channels to search for μ-CLFV in:

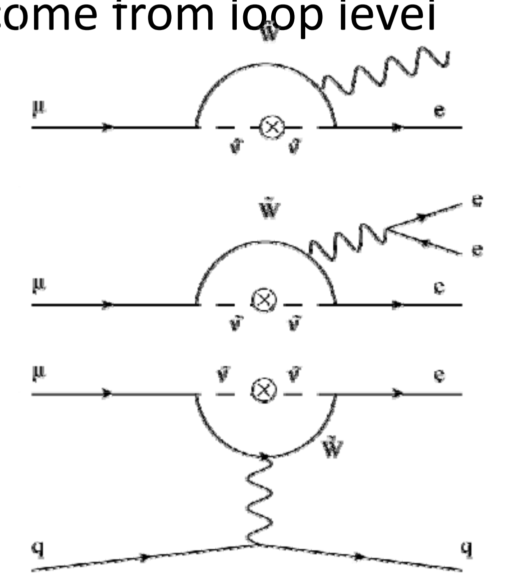
$$\mu^+ \to e^+\gamma$$
$$\mu^+ \to e^+e^+e^-$$
$$\mu^- N \to e^- N$$

Note: $\mu \to e\gamma$ and $\mu \to eee$ use a DC beam, and have *experimental* limitations (resolution, overlap, accidentals)

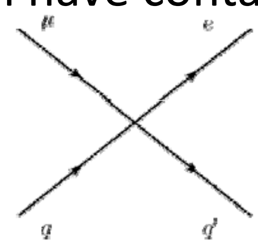
Ultimately Limits the measurement of:
Br($\mu \to e\,\gamma$)$\sim 10^{-14}$

No such limits on $\mu N \to eN$ channel

- New physics for these channels can come from loop level



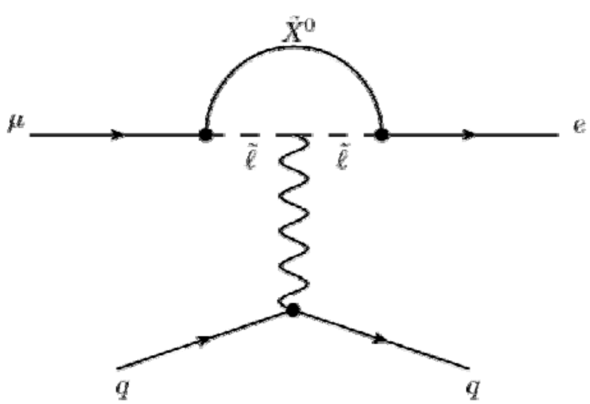
- For μ N $\to$ e N and $\mu \to$ eee we also can have contact terms



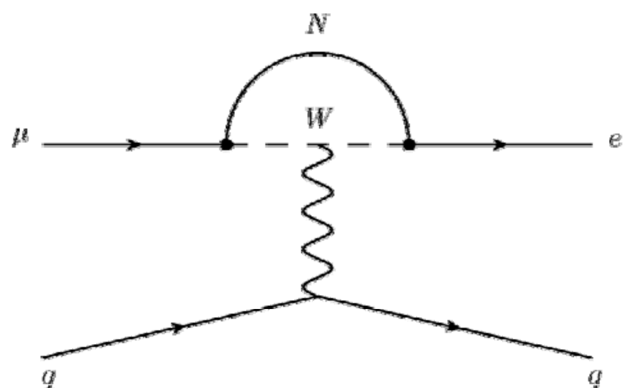
Beyond the Standard Model

- The CLFV process can manifest in the μN$\rightarrow$eN channel in many models with large branching fractions:

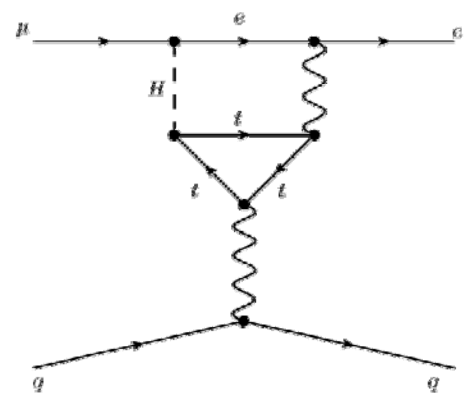
Loops



SUSY



Heavy Neutrinos

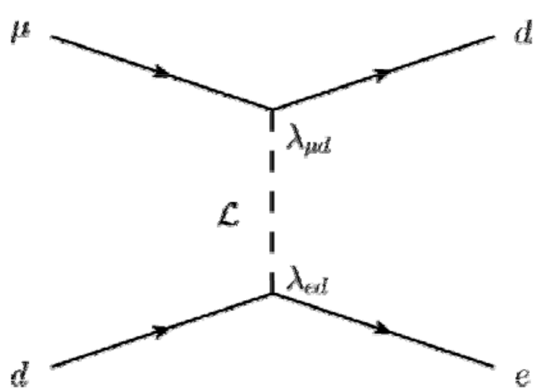


Second Higgs Doublet

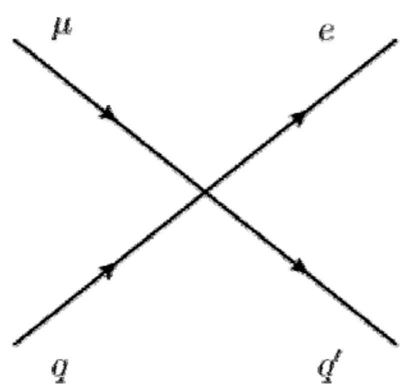
Beyond the Standard Model

- The CLFV process can manifest in the $\mu N \rightarrow eN$ channel in many models with large branching fractions:

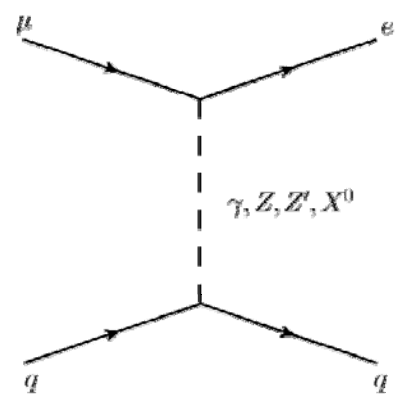
Contact Terms



Leptoquarks



Compositeness



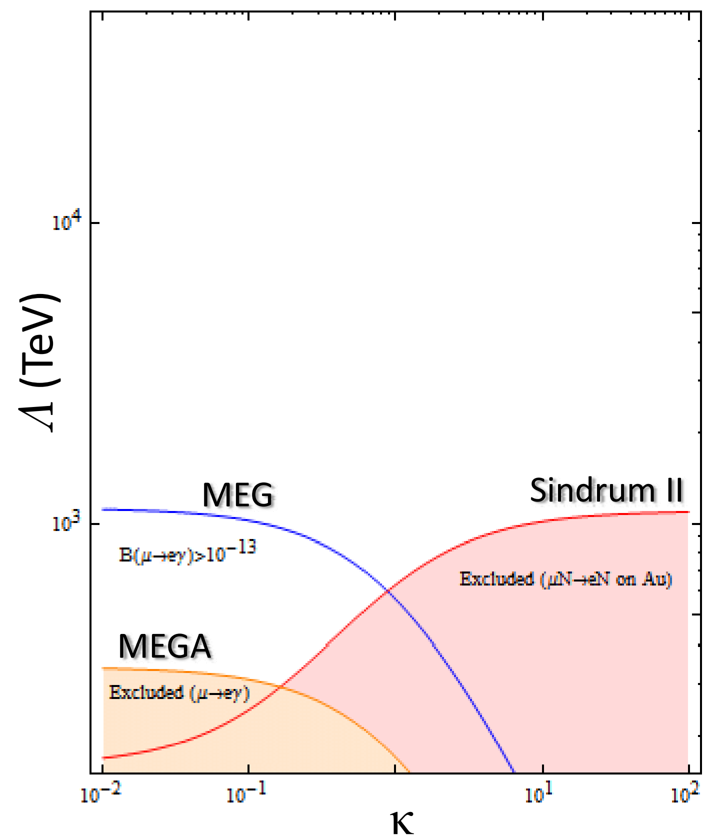
Anomalous Heavy Couplings

General CLFV Lagrangian

- Recharacterize these all these interactions together in a model independent framework:

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

  - Splits CLFV sensitivity into
    - Loop terms
    - Contact terms
  - Shows dipole, vector and scalar interactions
  - Allows us to parameterize the effective mass scale Λ in terms of the dominant interactions
  - The balance in effective reach shifts between favoring μN$\rightarrow$eN and $\mu\rightarrow$eγ measurements .
  - For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process



General CLFV Lagrangian

- Recharacterize these all these interactions together in a model independent framework:

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

Loops

Contact Interactions

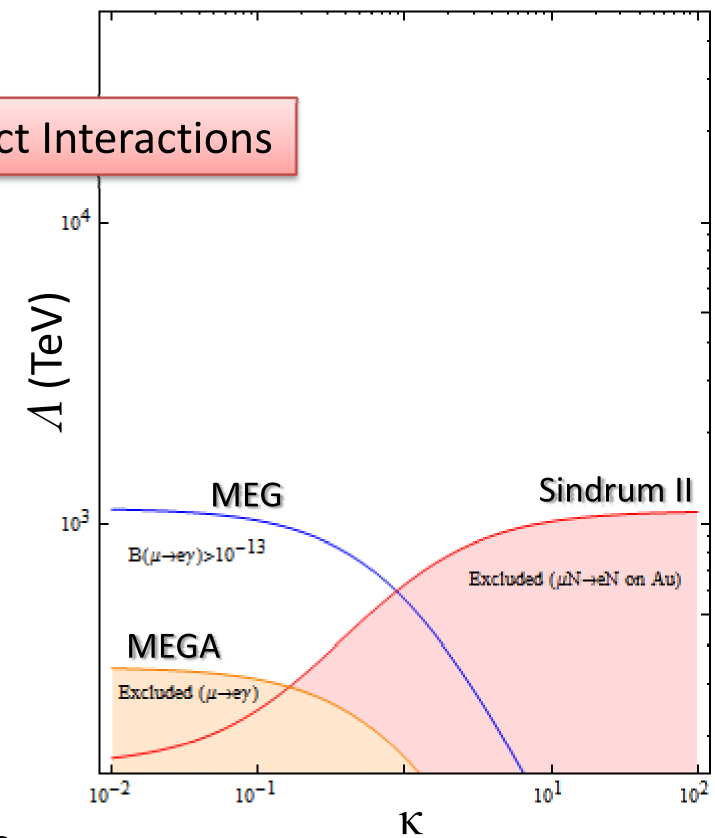
Gives the same dipole structure as g-2

ensitivity into

s

rms

- Shows dipole, vector and scalar interactions
- Allows us to parameterize the effective mass scale Λ in terms of the dominant interactions
- The balance in effective reach shifts between favoring μN→eN and $\mu\to e\gamma$ measurements .
- For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process

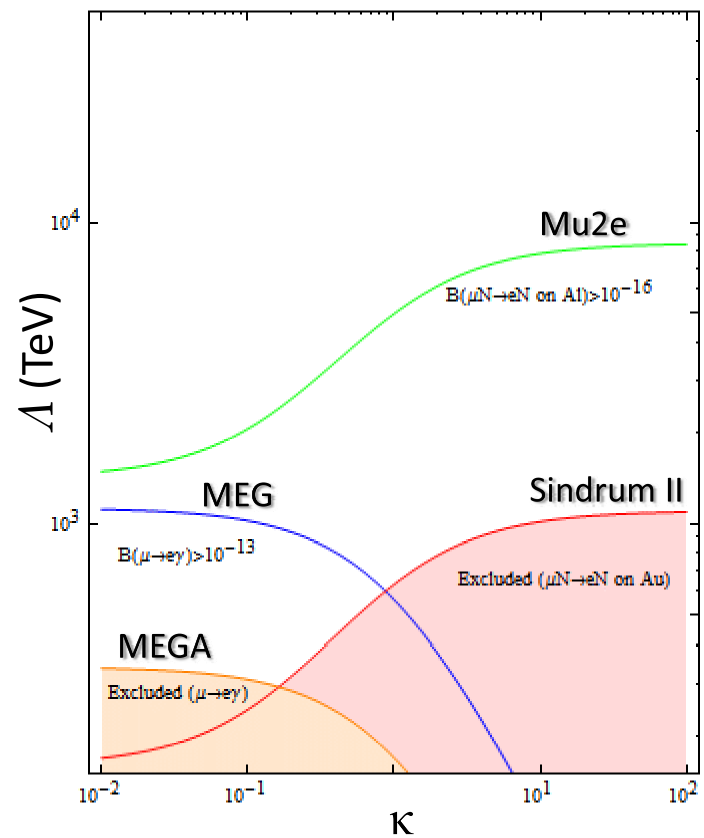


General CLFV Lagrangian

- Recharacterize these all these interactions together in a model independent framework:

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

  - Splits CLFV sensitivity into
    - Loop terms
    - Contact terms
  - Shows dipole, vector and scalar interactions
  - Allows us to parameterize the effective mass scale Λ in terms of the dominant interactions
  - The balance in effective reach shifts between favoring μN→eN and $\mu\rightarrow e\gamma$ measurements .
  - For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process

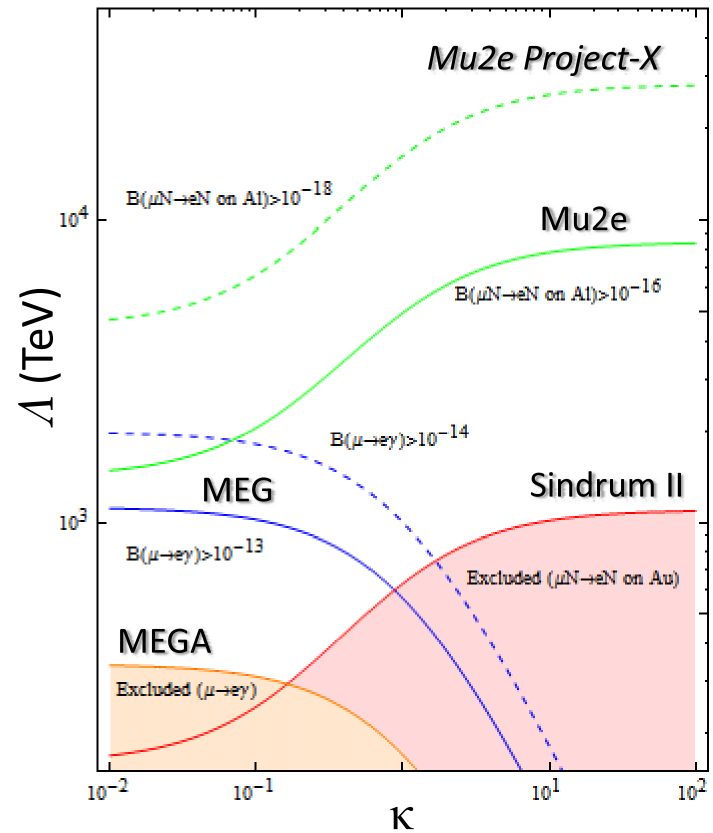


General CLFV Lagrangian

- Recharacterize these all these interactions together in a model independent framework:

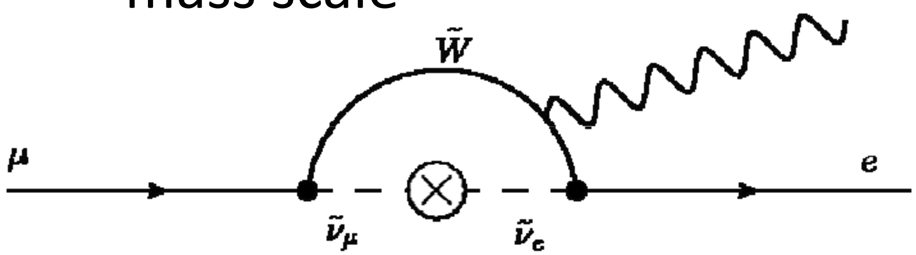
$$\mathcal{L}_{\mathcal{LFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

  - Splits CLFV sensitivity into
    - Loop terms
    - Contact terms
  - Shows dipole, vector and scalar interactions
  - Allows us to parameterize the effective mass scale Λ in terms of the dominant interactions
  - The balance in effective reach shifts between favoring μN$\rightarrow$eN and $\mu\rightarrow$eγ measurements .
  - For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process

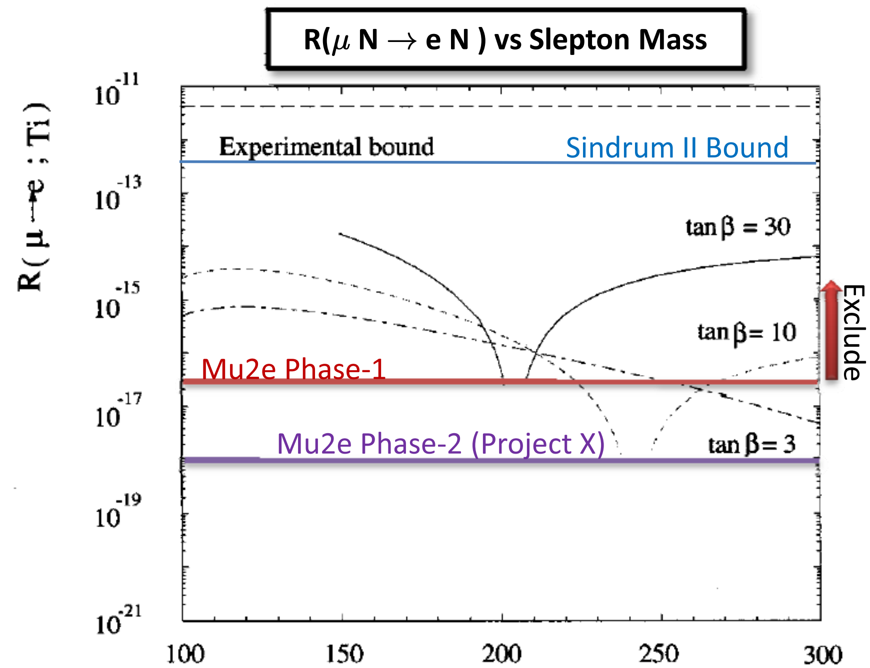


$\mu N \rightarrow eN$ Sensitivity to SUSY

- Rates are not small because they are set by the SUSY mass scale



- For low energy SUSY like we would see at the LHC:
  $Br(\mu\ N \rightarrow e\ N) \sim 10^{-15}$
- Makes $\mu N \rightarrow eN$ compelling, since for Mu2e this would mean observation of
  $\approx \mathcal{O}(40)$ events [0.5 bkg]



A 2×10^{-17} single event sensitivity,can exclude large portions of the available SUSY parameter spaces

Hisano et al. 1997

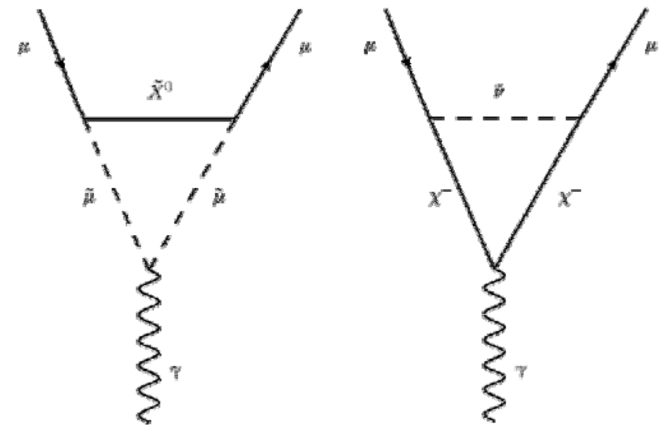
g-2 Sensitivity to SUSY

- SUSY contributes to a_μ= (g-2)/2:

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\text{GeV}}{M_{SUSY}}\right)^2 \tan\beta \; \text{sign}(\mu)$$

  - Gives direct access to tanβ and sign(μ)
  - g-2 result rules out large classes of models

- a_μ's sensitivity to SUSY is through the same loop interactions as CFLV channels

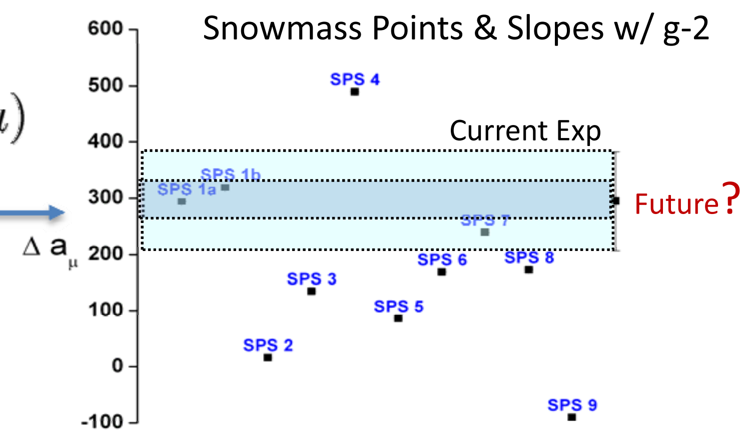


g-2 Sensitivity to SUSY

- SUSY contributes to a_μ= (g-2)/2:

$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\text{GeV}}{M_{SUSY}}\right)^2 \tan\beta \ \text{sign}(\mu)$$

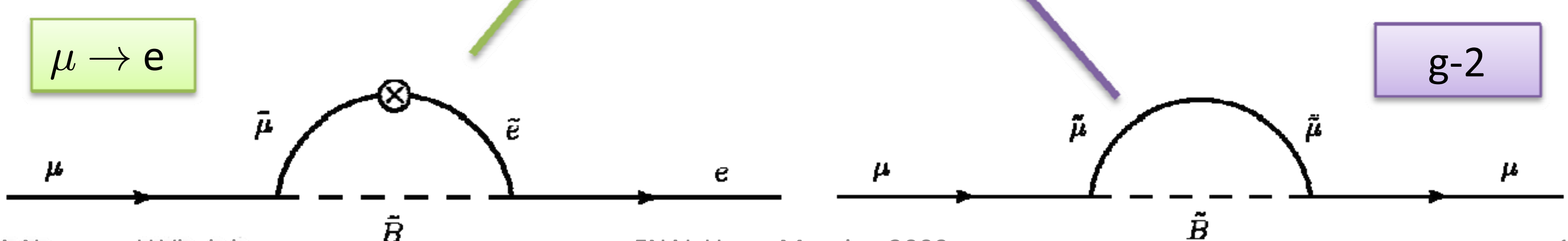
  - Gives direct access to tanβ and sign(μ)
  - g-2 result rules out large classes of models



- Gives us access to Slepton Mixing

Slepton Mixing Matrix

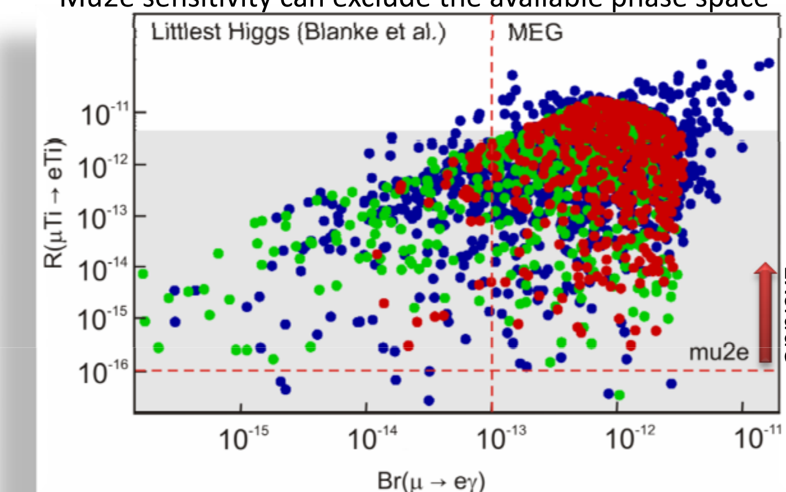
$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{e}\tilde{\mu}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

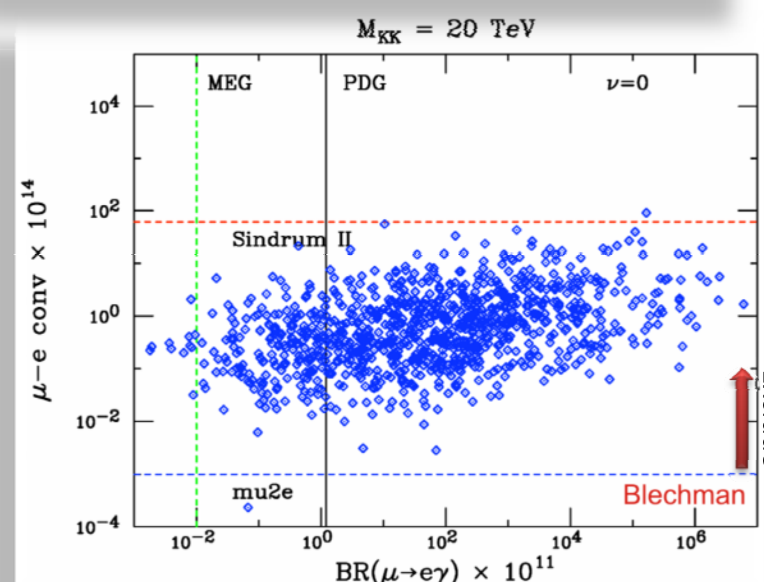


μN→eN, μ→eγ, g-2 Work Together

- Knowing μN→eN, μ→eγ allow us to exclude SUSY phase space
- Also knowing the g-2 results allows us to then over constrain SUSY models
- In some cases this permits us to make strong, testable predictions for our models in terms of Br(μ→eγ) & R(μN→eN)

Mu2e sensitivity can exclude the available phase space





MSSM/msugra/seesaw

Randall-Sundrum

$\mu N \to eN$, $\mu \to e\gamma$, g-2 Work Together

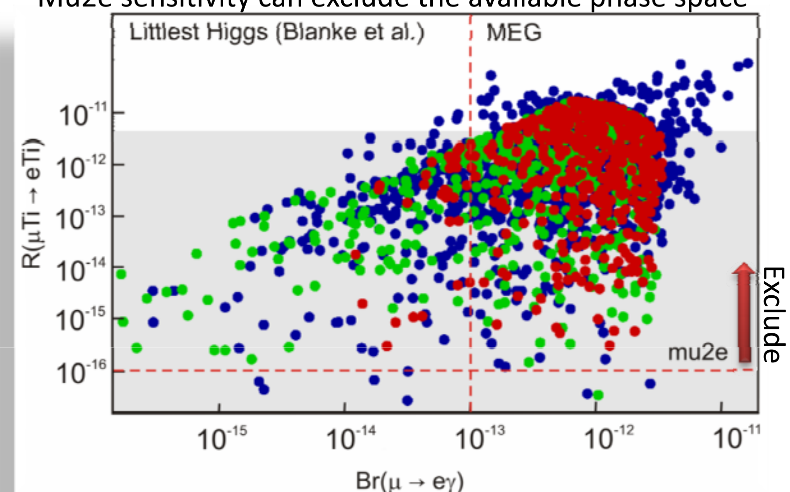
Example:

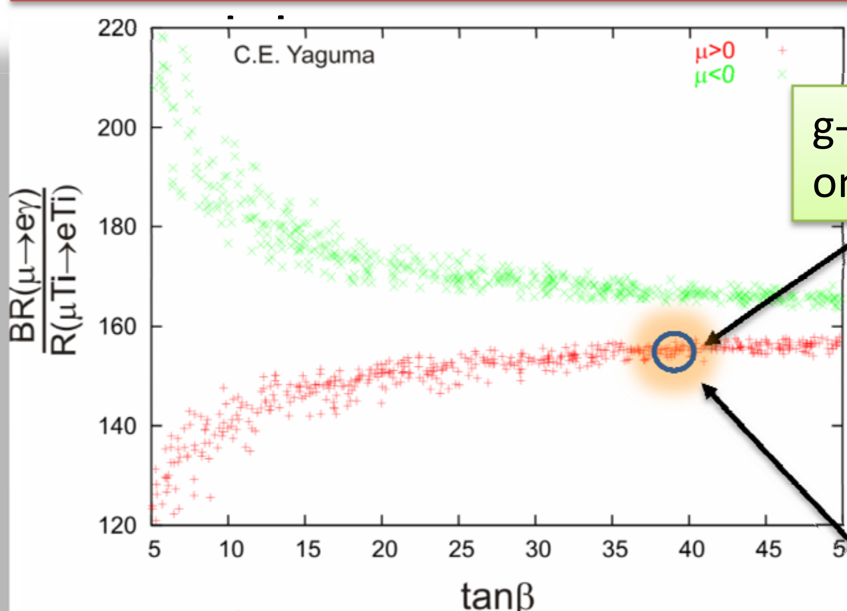
- From LHC we have the SUSY masses
- From g-2 we know tanβ
- From g-2 we know also know μ>0
- Combining these we get an a priori PREDICTION for:

$$\frac{Br(\mu \to e\gamma)}{R(\mu N \to eN)}$$

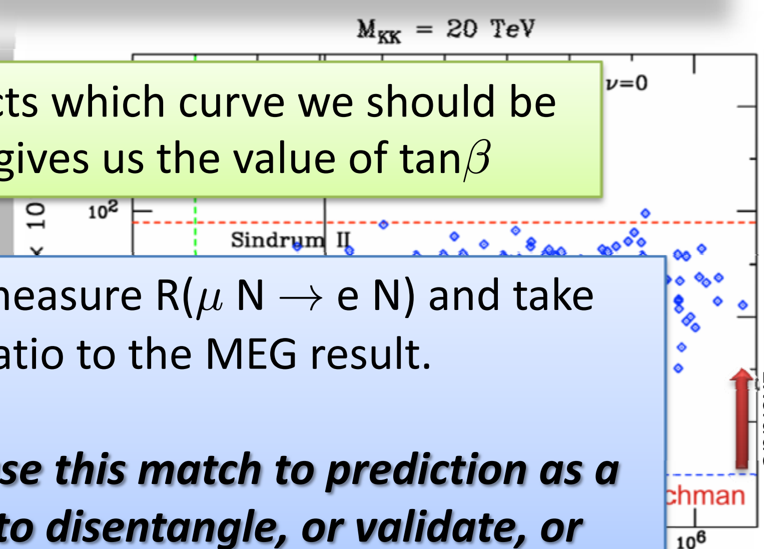
under MSSM/MSUGRA

Mu2e sensitivity can exclude the available phase space





MSSM/msugra/seesaw



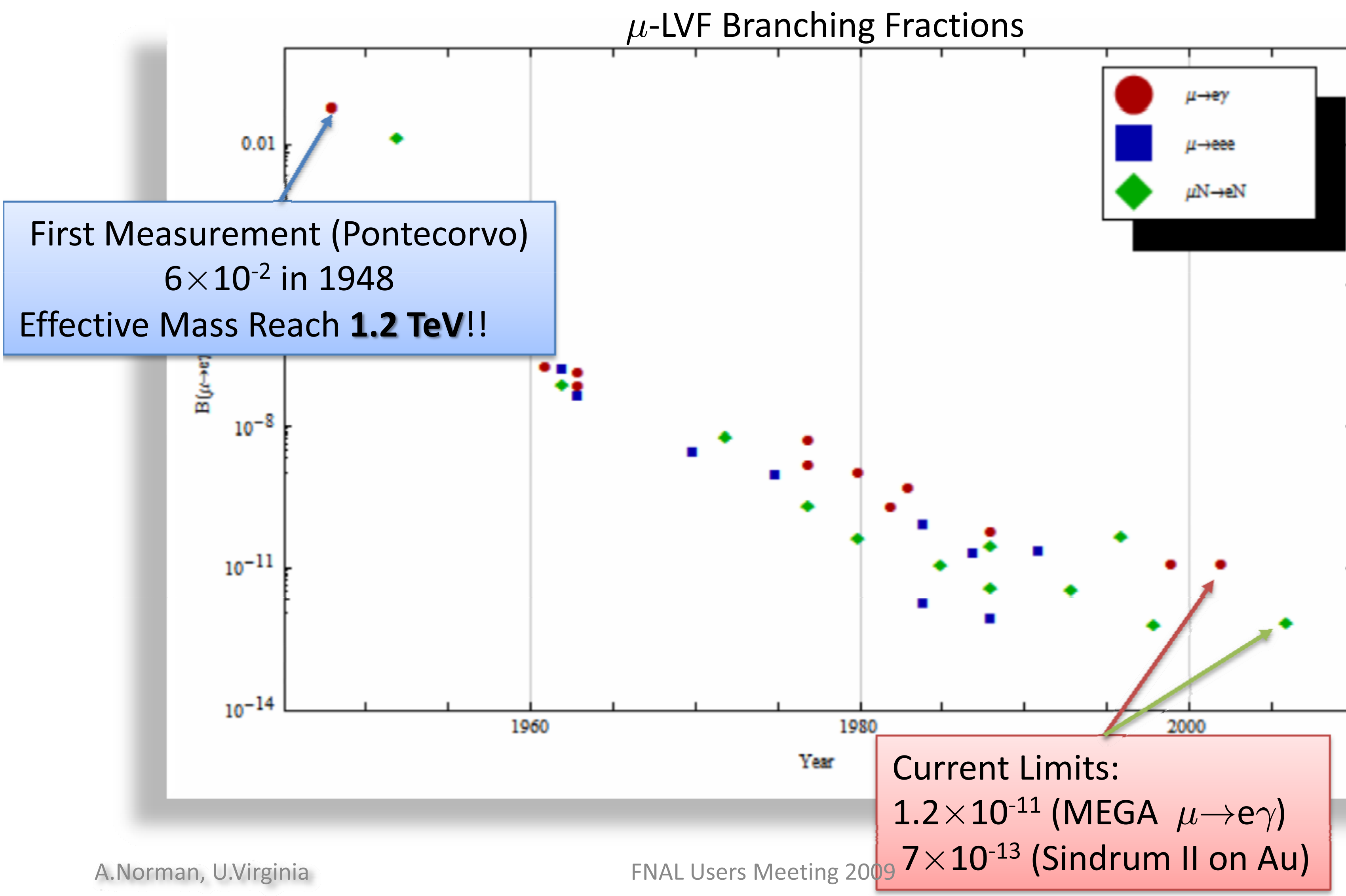
Randall-Sundrum

g-2 selects which curve we should be on, and gives us the value of tanβ

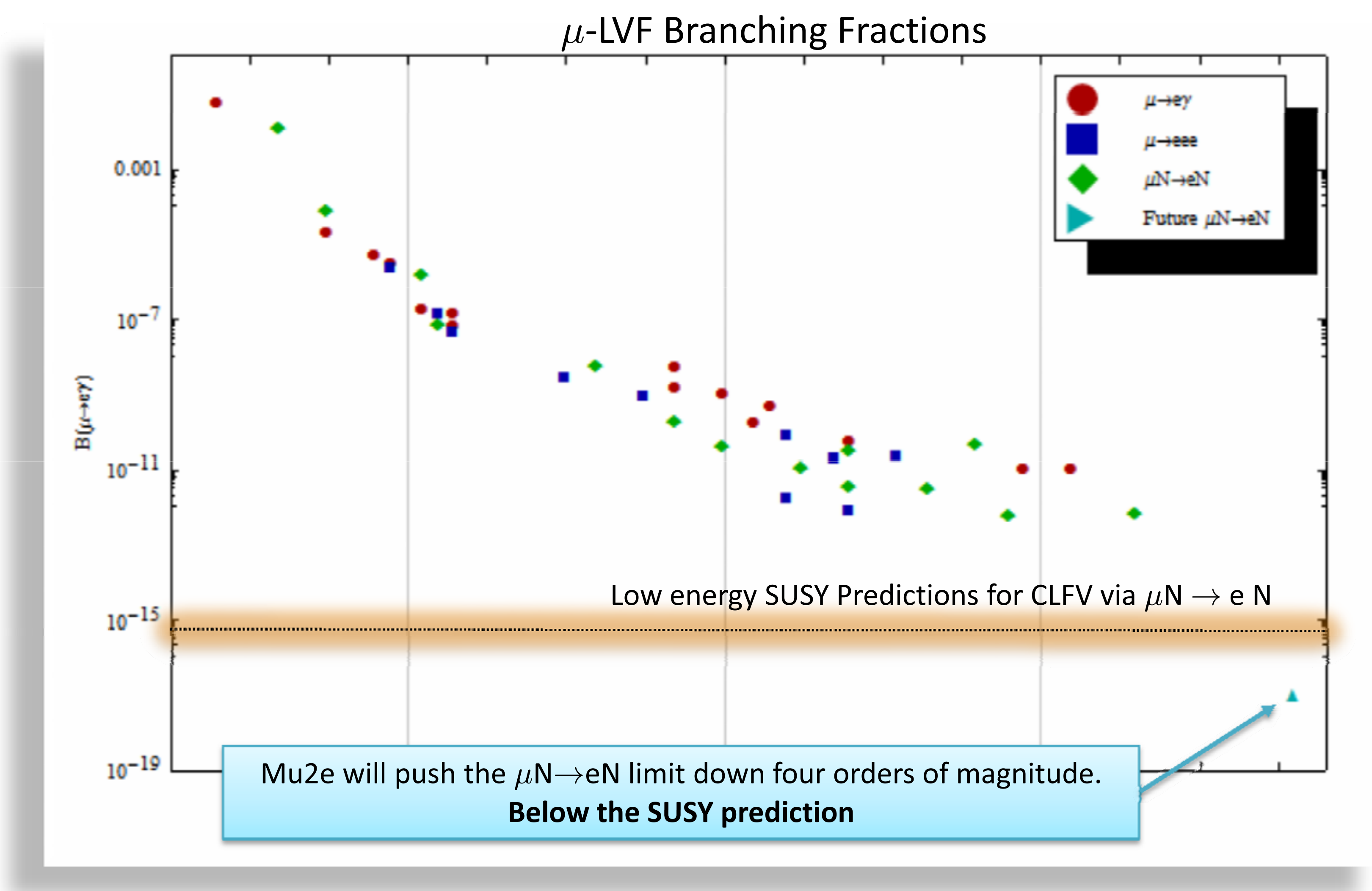
We measure R(μ N $\to$ e N) and take the ratio to the MEG result.

We use this match to prediction as a way to disentangle, or validate, or interpret manifestations of SUSY

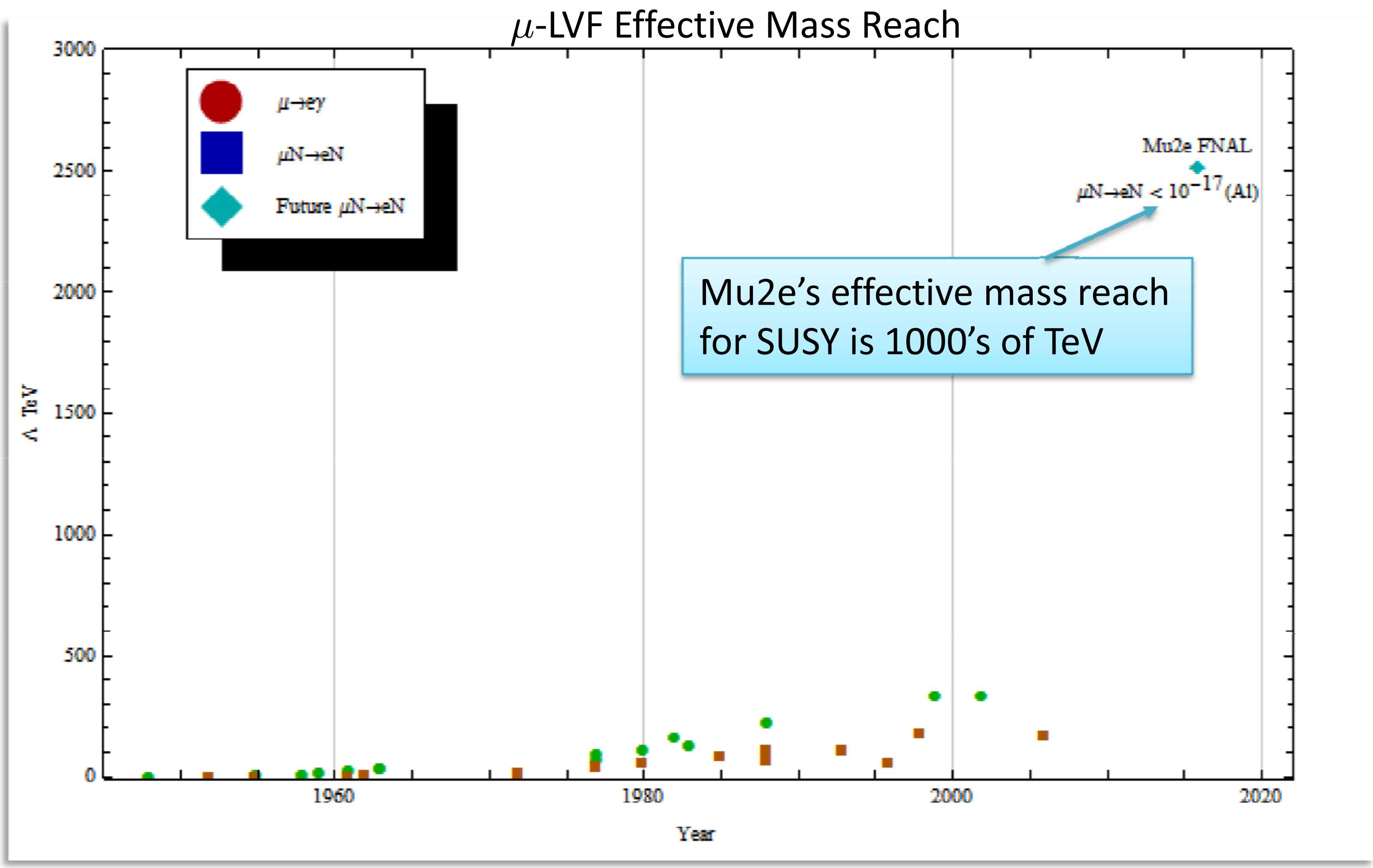
A Brief History of μ-cLFV

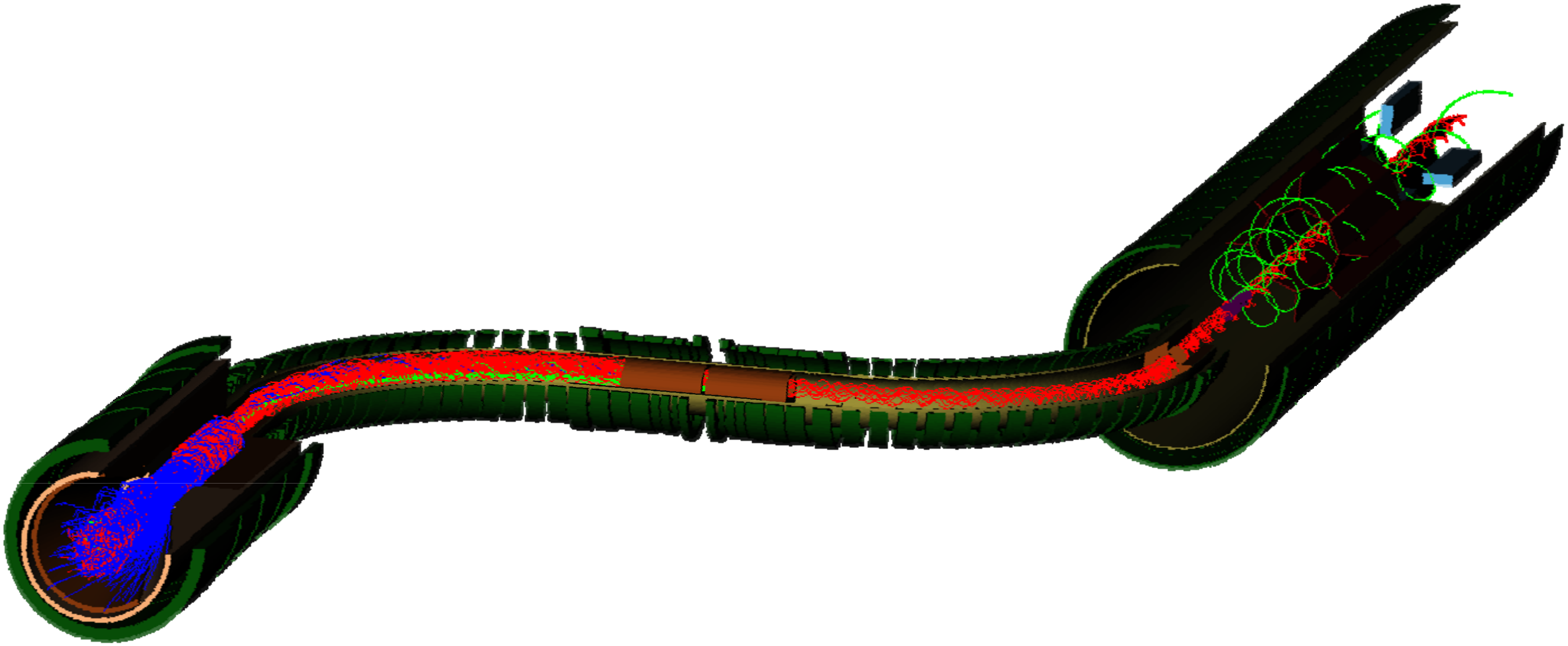


A Brief History of μ-cLFV



A Brief History of μ-cLFV





MU2E AT FNAL

The μN→eN measurement at Br(10^{-17}) (in a nutshell)

- Stop $\sim\mathcal{O}(5\times10^{10})$ μ^- per pulse on a target (Al, Ti, Au)
- Wait 700ns (to let prompt backgrounds clear)
- Look for the coherent conversion of a muon to a mono-energetic electron:

$$\begin{aligned} E_e &= M_\mu - N_{recoil} - (B.E.)^{1S}_\mu \\ &= 104.96 \text{ MeV (on } ^{27}\text{Al)} \end{aligned}$$

- Report the rate relative to nuclear capture

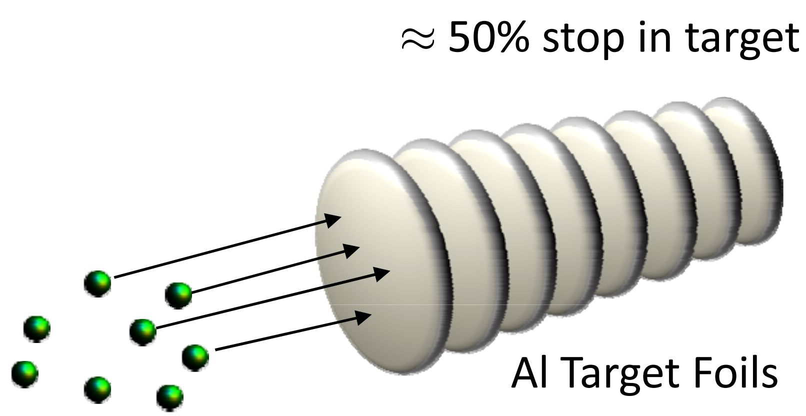
$$\mathcal{R} = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N(Z) \to \nu_\mu N(Z-1))}$$

- *If we see a signal, it's compelling evidence for physics beyond the standard model!*

μN→eN in Detail

Muonic Atom

- Start with a series of target foils
  - For Mu2E these are Al or Ti
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ 's
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius
    $\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z e^2} \approx 19.6 fm \ (for\ Al)$
  - Nuclear Size
    $R \approx 1.2 A^{1/3} fm = 3.6 fm \ (for Al)$
  - Provides large overlap in the muon's wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - **Decay in Orbit**: $\mu^- \rightarrow e^- \nu \bar{\nu}$

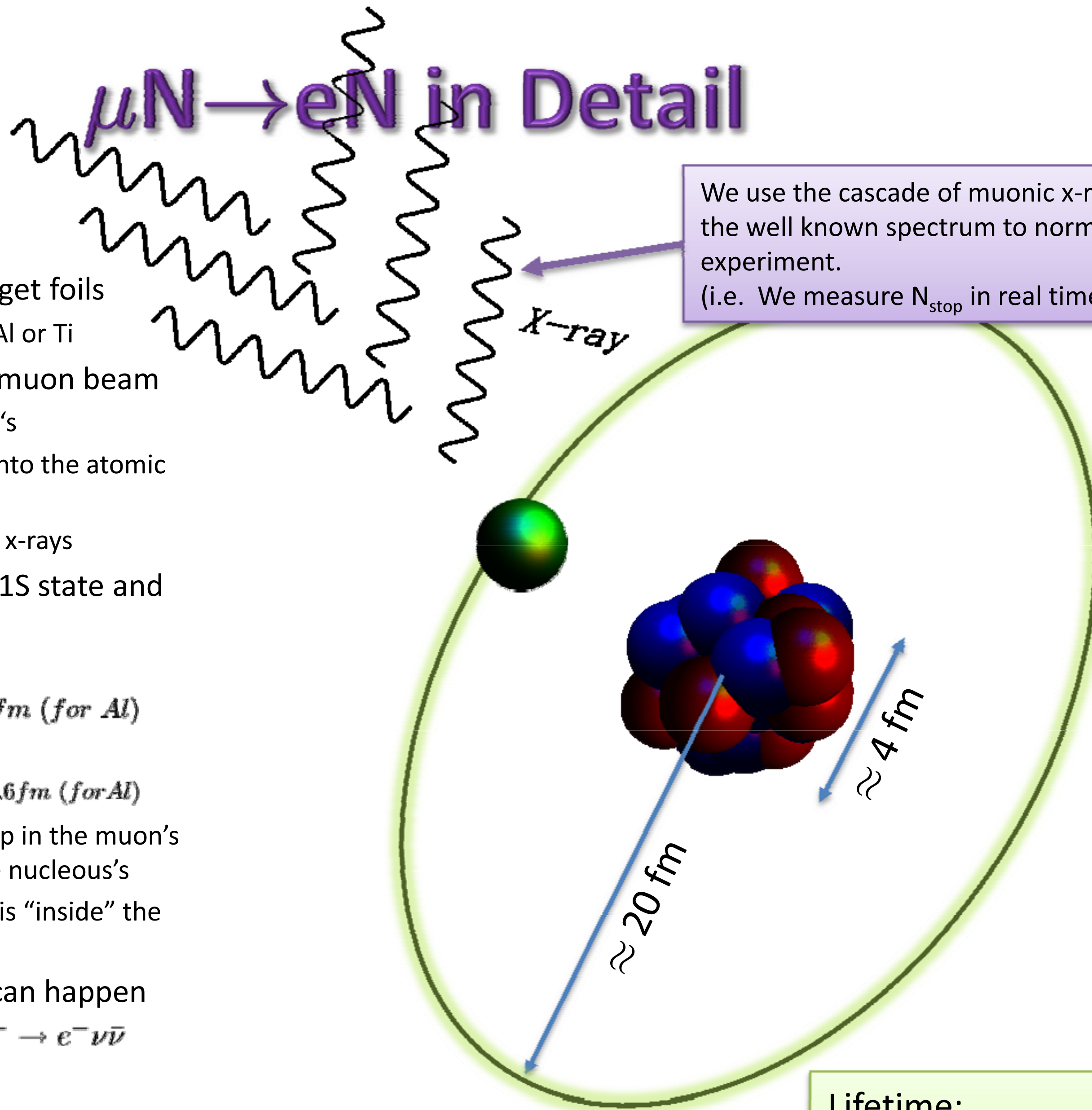


Target
200 µm, circular foils (^{27}Al)
Radius tapers from 10 cm to 6.5 cm
5cm spacing between foils

$\mu N \rightarrow eN$ in Detail

Muonic Atom

- Start with a series of target foils
  - For Mu2E these are Al or Ti
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ 's
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius
    $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu z e^2} \approx 19.6 fm\ (for\ Al)$
  - Nuclear Size
    $R \approx 1.2 A^{1/3} fm = 3.6 fm\ (for\ Al)$
  - Provides large overlap in the muon's wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - **Decay in Orbit**: $\mu^- \rightarrow e^- \nu \bar{\nu}$



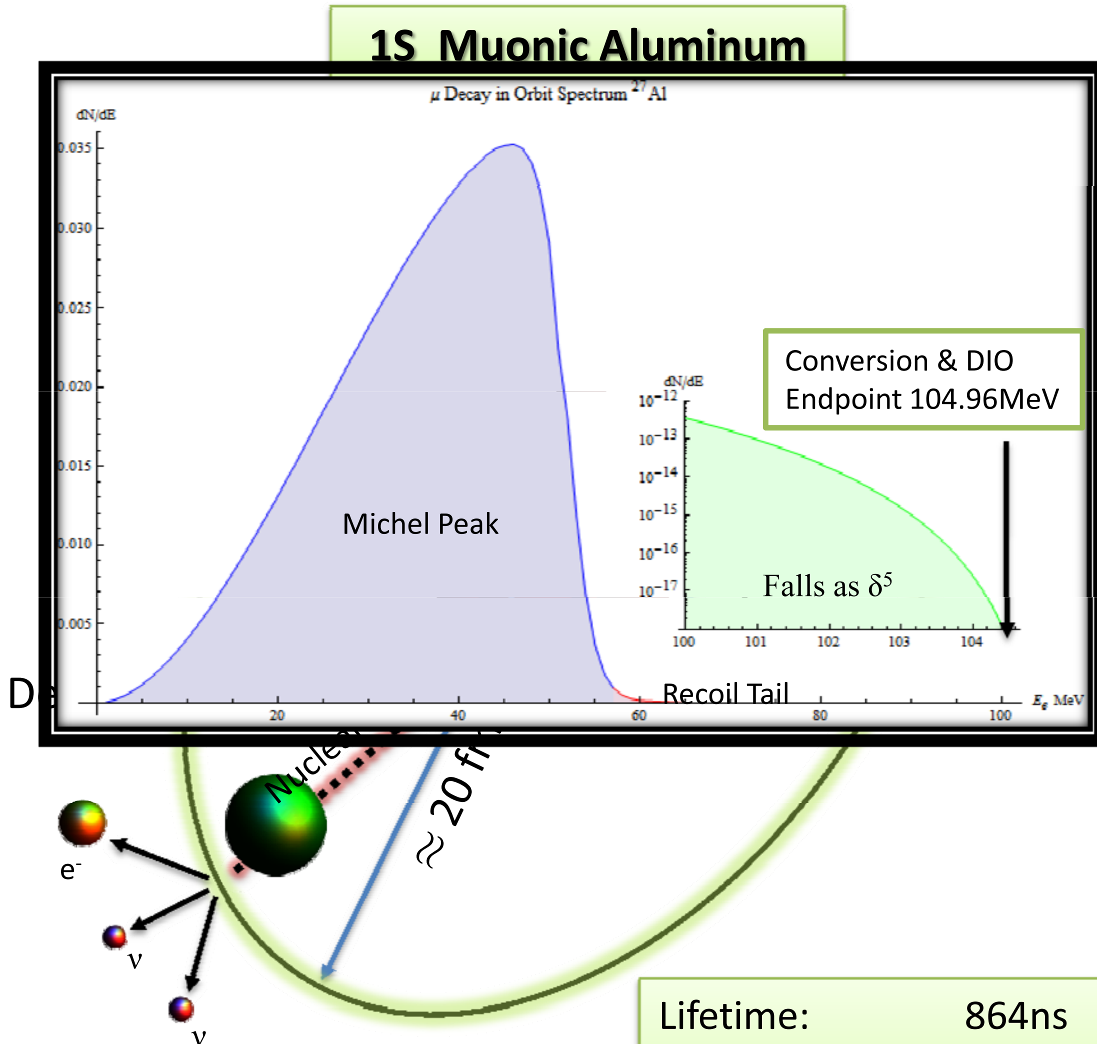
We use the cascade of muonic x-rays and the well known spectrum to normalize the experiment.
(i.e. We measure N_{stop} in real time)

Lifetime: 864ns
DIO Fraction: 39.3%
Capture Fraction: 60.7%

μN→eN in Detail

Muonic Atom

- Start with a series of target foils
  - For Mu2E these are Al or Ti
- Bring in the low energy muon beam
  - We stop ≈ 50% of μ 's
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius
    $\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z c^2} \approx 19.6 fm \ (for\ Al)$
  - Nuclear Size
    $R \approx 1.2 A^{1/3} fm = 3.6 fm \ (for Al)$
  - Provides large overlap in the muon's wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - **Decay in Orbit**: $\mu^- \rightarrow e^- \nu \bar{\nu}$

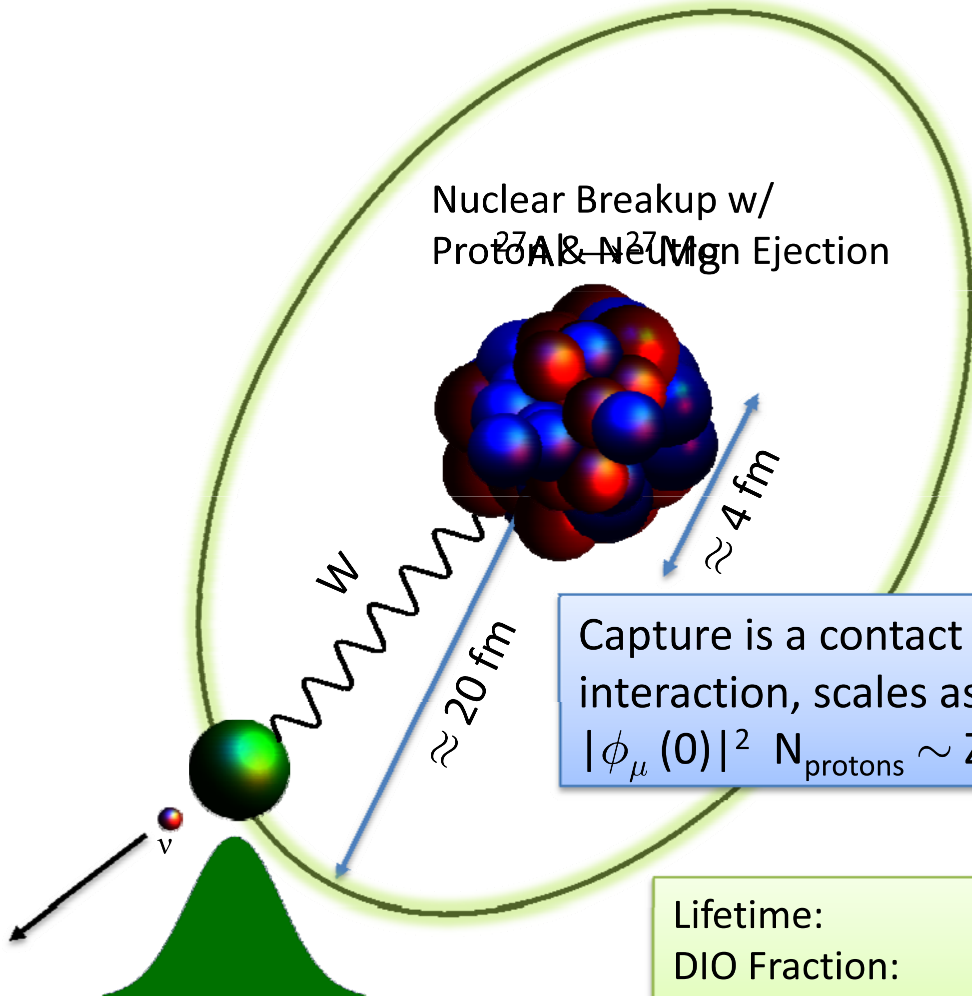


Lifetime: 864ns
DIO Fraction: 39.3%
Capture Fraction: 60.7%

Muonic Atom

- Start with a series of target foils
  - We stop $\approx$ 50% of μ 's
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ 's
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius
    $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu z e^2} \approx 19.6 fm\ (for\ Al)$
  - Nuclear Size
    $R \approx 1.2 A^{1/3} fm = 3.6 fm\ (for\ Al)$
  - Provides large overlap in the muon's wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \rightarrow e^- \nu \bar{\nu}$
  - **Nuclear Capture**: $\mu^- N(Z) \rightarrow \nu N(Z-1)$

Ordinary Muon Capture (OMC)



Capture is a contact like interaction, scales as:
$|\phi_\mu(0)|^2\ N_{protons} \sim Z^4$

Lifetime: 864ns
DIO Fraction: 39.3%
Capture Fraction: 60.7%

Muonic Atom

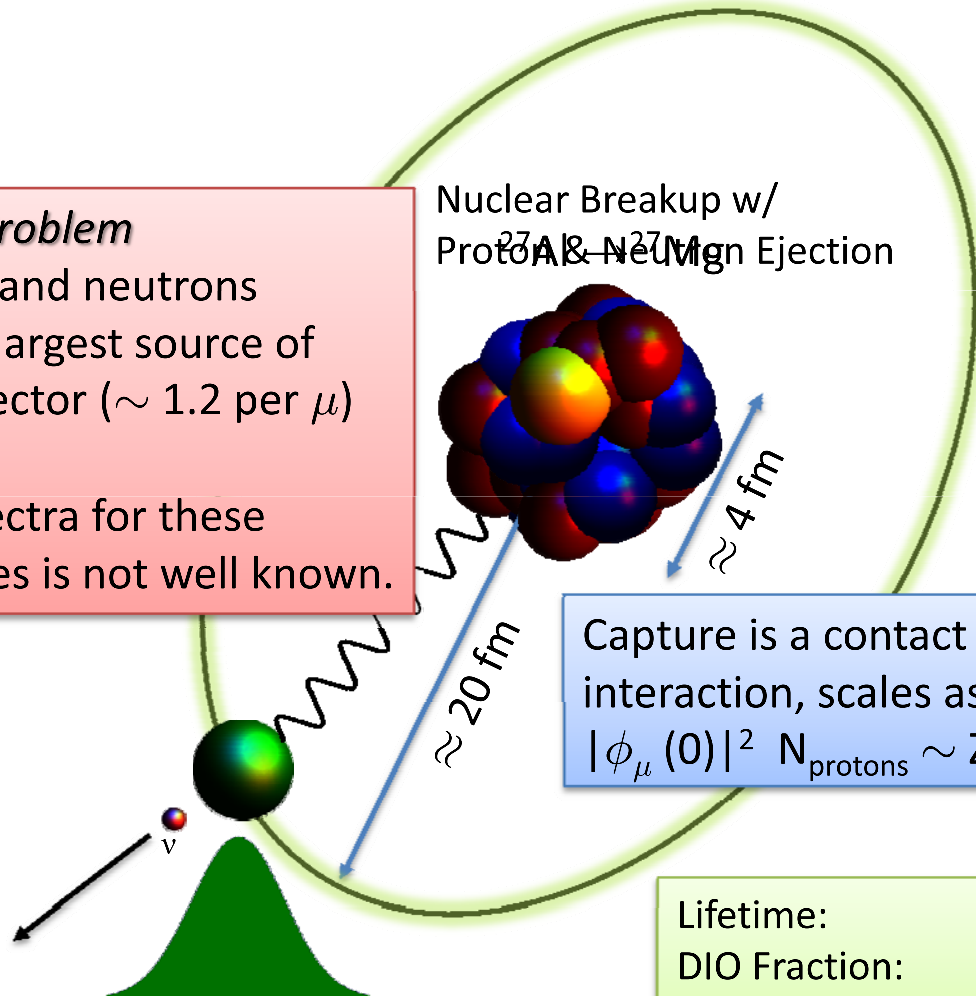
- Start with a series of target foils
  - We stop $\approx$ 50% of μ 's
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ 's
  - Stopped muons ... potential
  - As they do they ...
- Muons fall down to ... a captured in the orb...
  - Muonic Bohr Ra...
    $\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z e^2} \approx$ ...
  - Nuclear Size
    $R \approx 1.2 A^{1/3} f$...
  - Provides large overlap ... wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \to e^- \nu \bar{\nu}$
  - **Nuclear Capture**: $\mu^- N(Z) \to \nu N(Z-1)$

Problem

These protons and neutrons constitute the largest source of rate in the detector ($\sim$ 1.2 per μ)

The energy spectra for these ejected particles is not well known.

Ordinary Muon Capture (OMC)



Capture is a contact like interaction, scales as: $|\phi_\mu(0)|^2 \; N_{protons} \sim Z^4$

Lifetime:	864ns
DIO Fraction:	39.3%
Capture Fraction:	**60.7%**

Muonic Atom

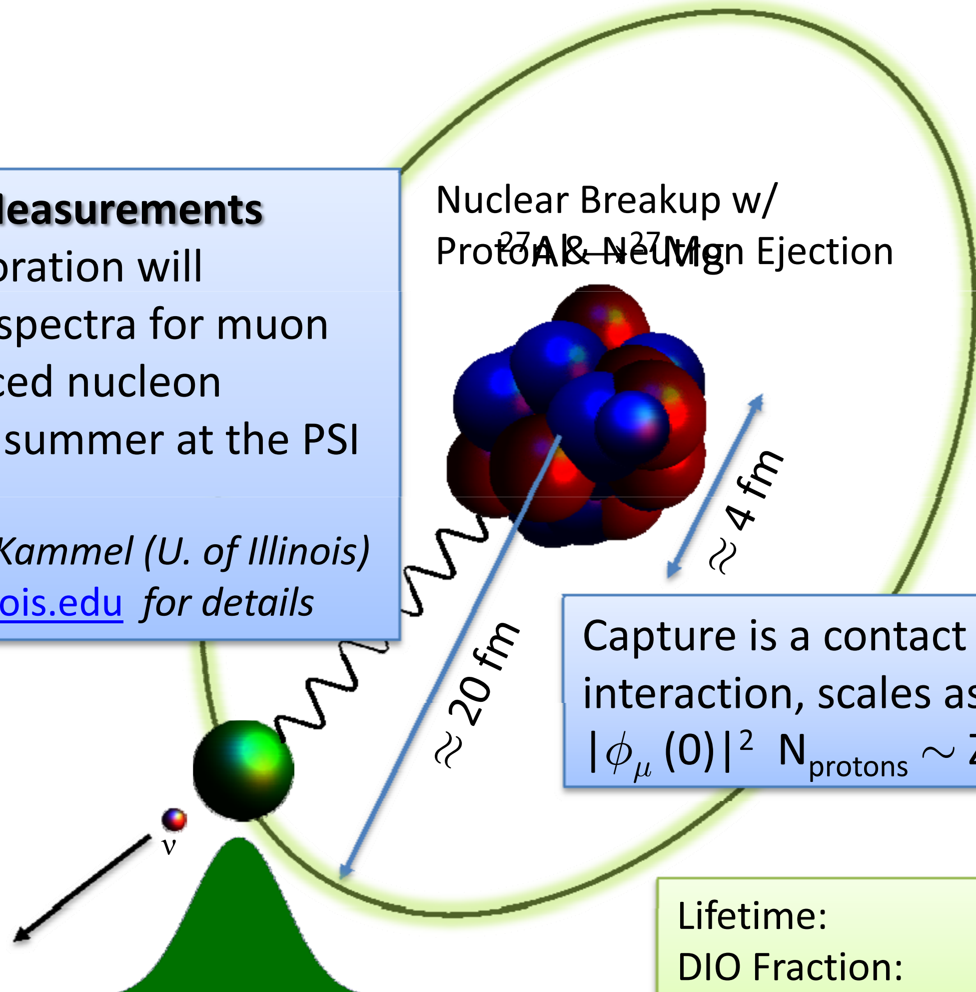
- Start with a series of target foils
  - We stop $\approx$ 50% of μ 's
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ 's
  - Stopped muons fa potential
  - As they do they er
- Muons fall down to th a captured in the orbit
  - Muonic Bohr Radi $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu z e^2} \approx 1$
  - Nuclear Size $R \approx 1.2 A^{1/3} fm$
  - Provides large ove wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \rightarrow e^- \nu \bar{\nu}$
  - **Nuclear Capture**: $\mu^- N(Z) \rightarrow \nu N(Z-1)$

2009 Measurements

Mu2E Collaboration will measure the spectra for muon capture induced nucleon emission this summer at the PSI test beam.

Contact: Peter Kammel (U. of Illinois) pkammel@illinois.edu *for details*

Ordinary Muon Capture (OMC)



Capture is a contact like interaction, scales as: $|\phi_\mu(0)|^2 \, N_{protons} \sim Z^4$

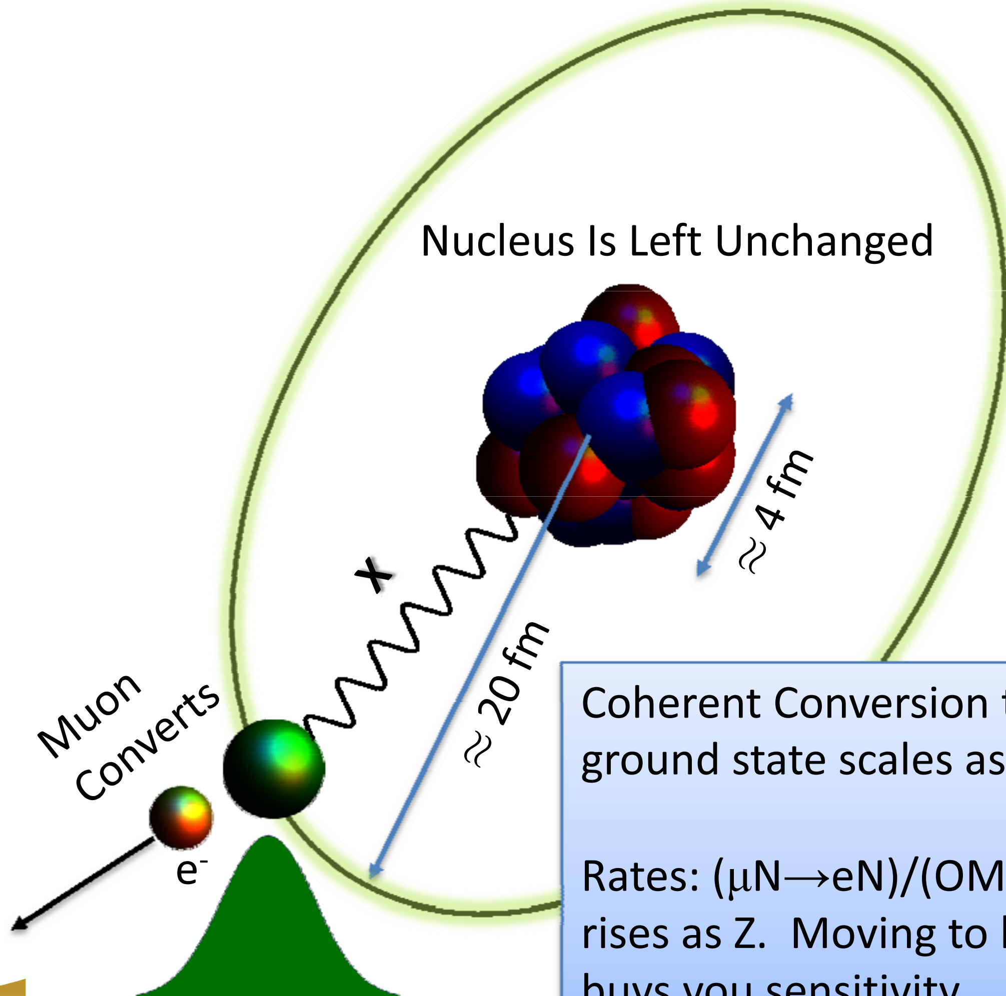
Lifetime:	864ns
DIO Fraction:	39.3%
Capture Fraction:	**60.7%**

Muonic Atom

- Start with a series of target foils
  - We stop $\approx$ 50% of μ ‘s
- Bring in the low energy muon beam
  - We stop $\approx$ 50% of μ ‘s
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius
    $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu z c^2} \approx 19.6 fm \ (for\ Al)$
  - Nuclear Size
    $R \approx 1.2 A^{1/3} fm = 3.6 fm \ (for Al)$
  - Provides large overlap in the muon’s wavefunction with the nucleus's
  - For Z > 25 the muon is “inside” the nucleus
- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \rightarrow e^- \nu \bar{\nu}$
  - Nuclear Capture: $\mu^- N^Z \rightarrow \nu N^{Z-1}$
  - **New Physics! i.e. μ N $\rightarrow$ e N**

$E_e \approx 105$ MeV

Coherent Conversion (μ→e)

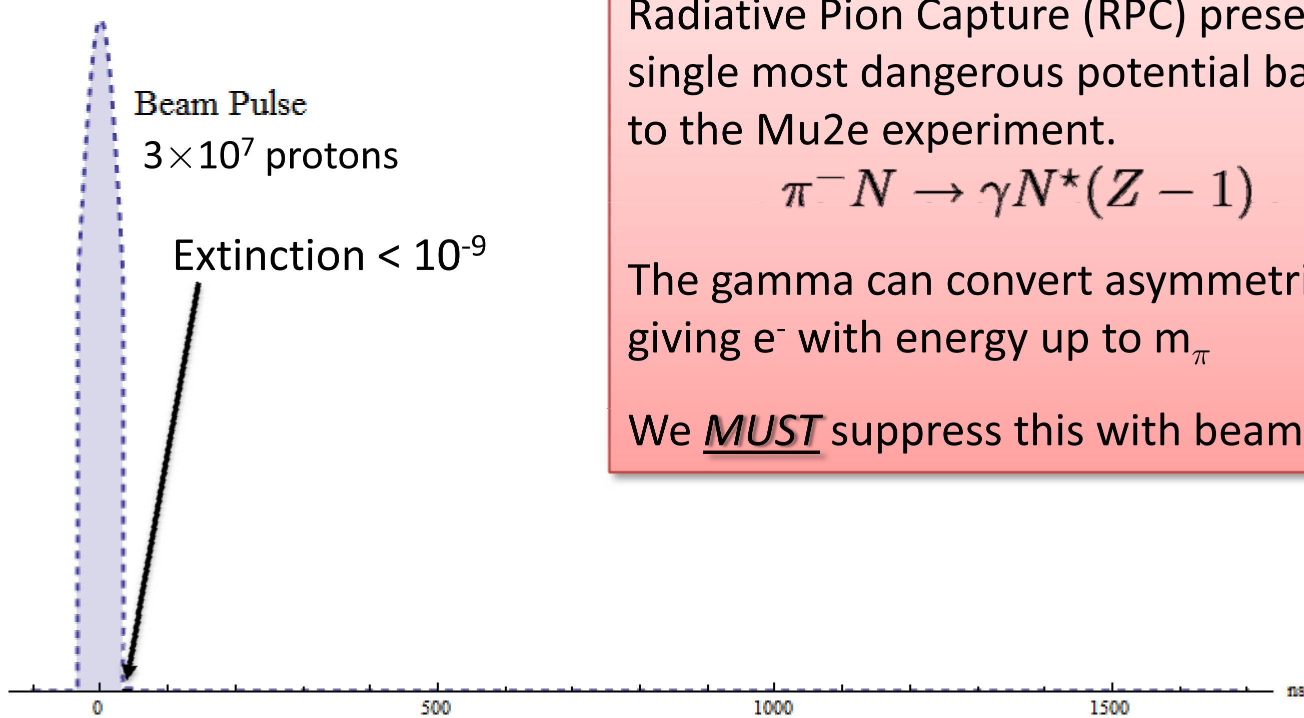


Coherent Conversion to the ground state scales as $\sim Z^5$.

Rates: (μN→eN)/(OMC) rises as Z. Moving to high Z buys you sensitivity

Beam Structure

- μ's are accompanied by "prompt" e, π, ….
- These cause real background
- Must limit our beam extinction, and detector live window



Prompt Backgrounds

Radiative Pion Capture (RPC) presents the single most dangerous potential background to the Mu2e experiment.

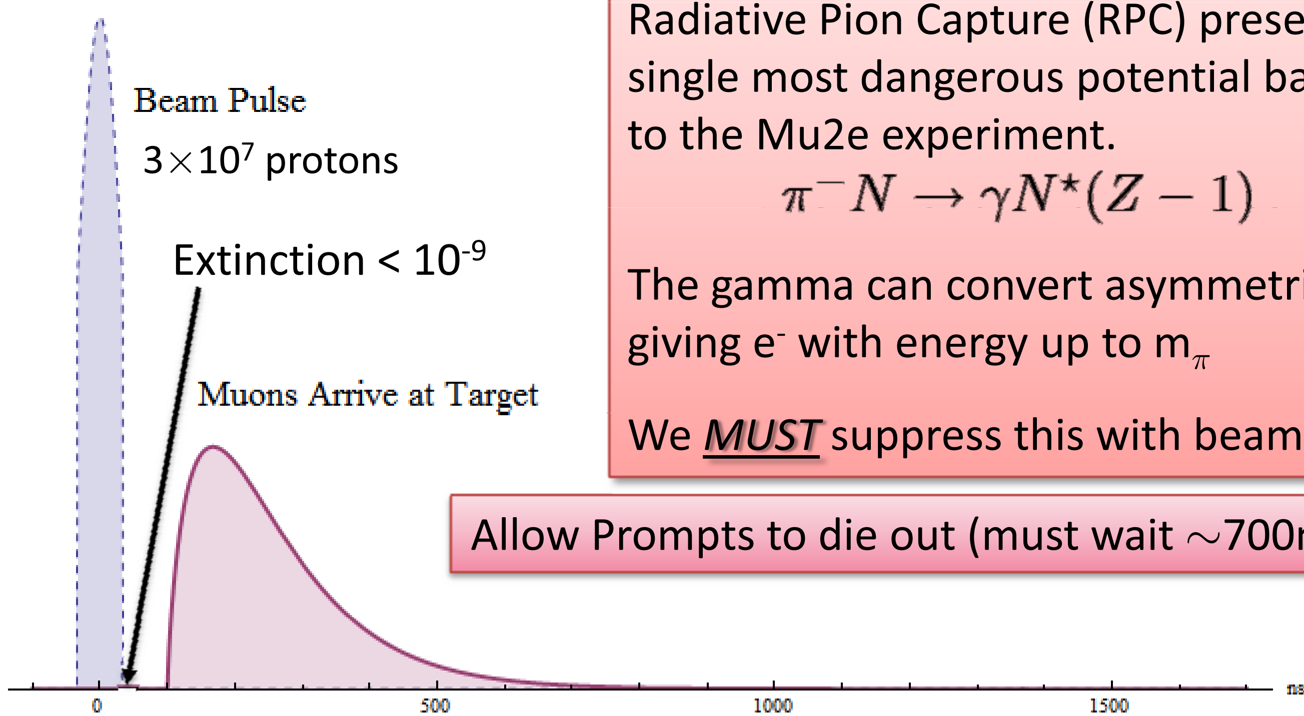
$$\pi^- N \rightarrow \gamma N^*(Z-1)$$

The gamma can convert asymmetrically giving e^- with energy up to m_π

We ***MUST*** suppress this with beam extinction

Beam Structure

- μ's are accompanied by "prompt" e, π, ….
- These cause real background
- Must limit our beam extinction, and detector live window



Prompt Backgrounds

Radiative Pion Capture (RPC) presents the single most dangerous potential background to the Mu2e experiment.

$$\pi^- N \rightarrow \gamma N^*(Z-1)$$

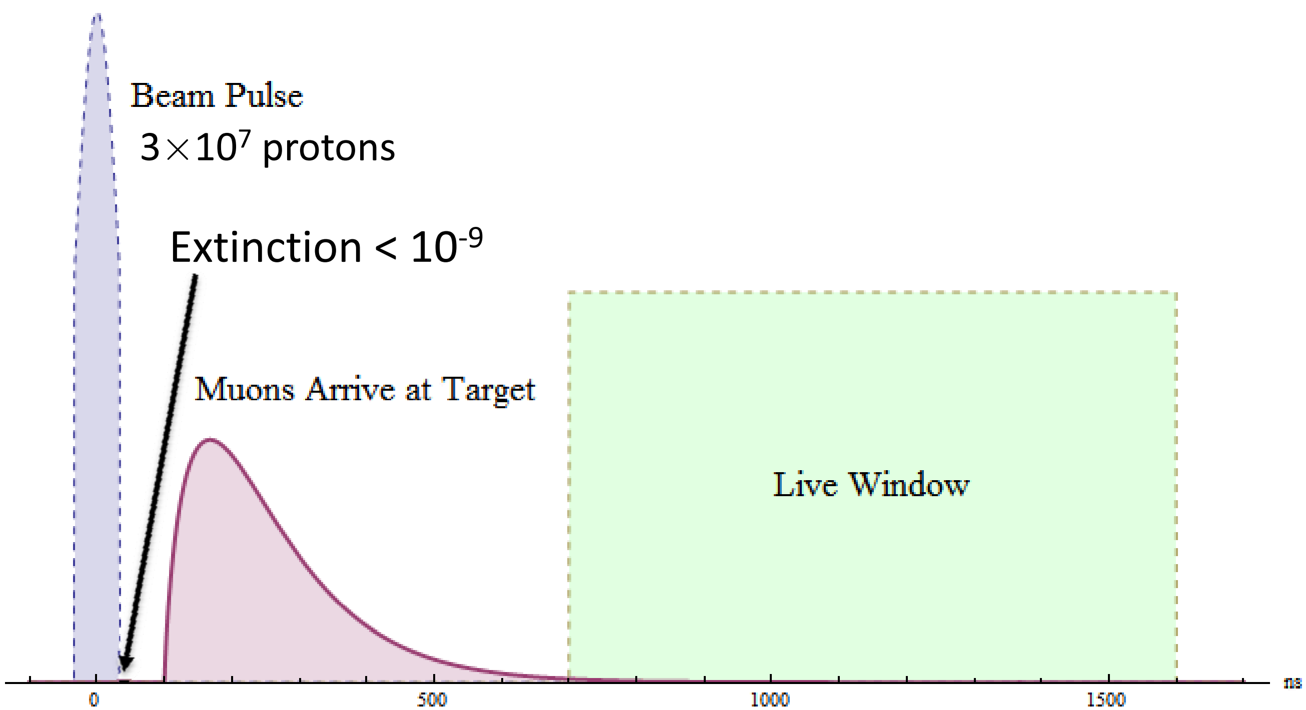
The gamma can convert asymmetrically giving e^- with energy up to m_π

We ***MUST*** suppress this with beam extinction

Allow Prompts to die out (must wait $\sim$700ns)

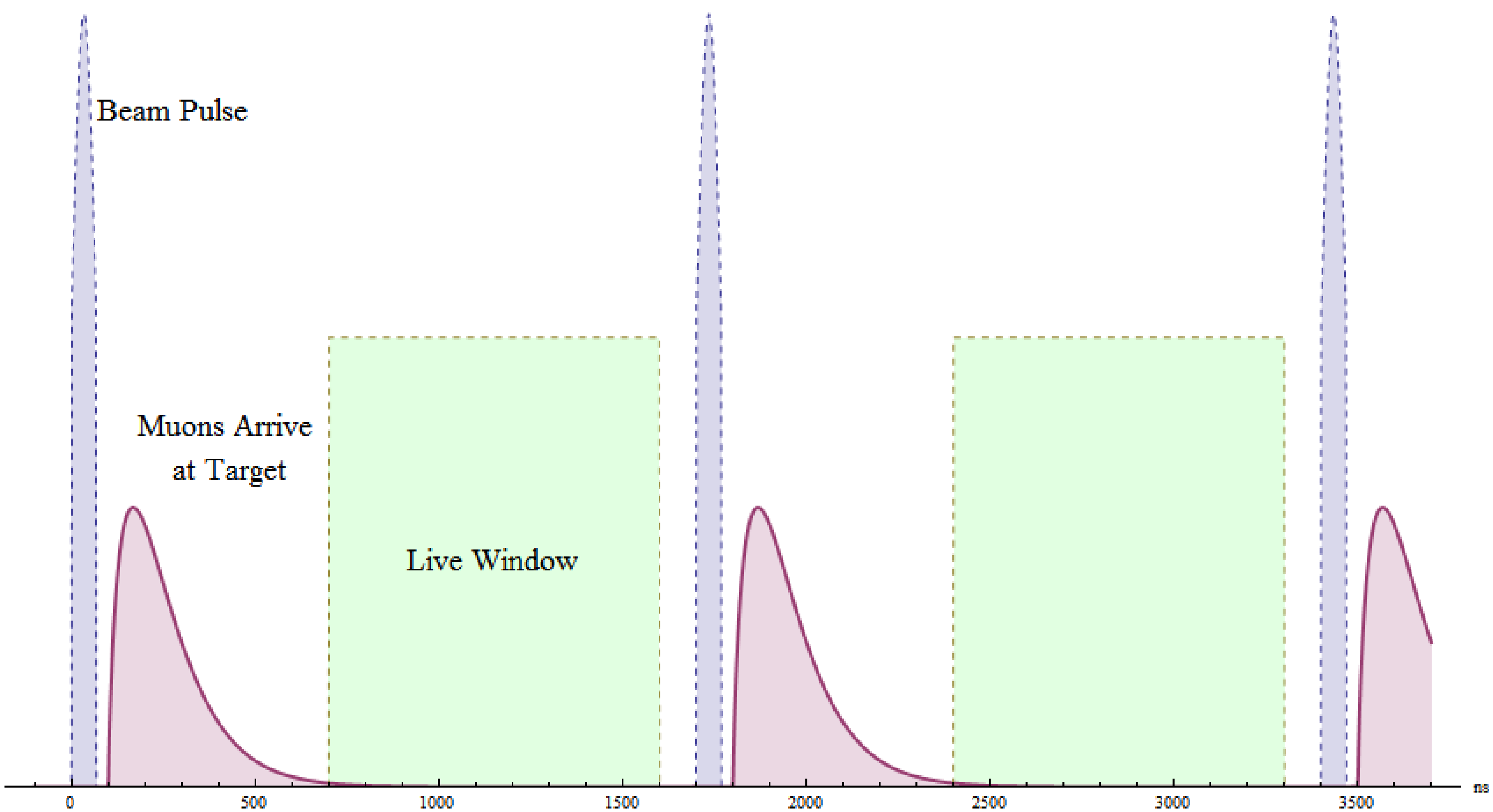
Beam Structure

- μ's are accompanied by "prompt" e, π, ….
- These cause real background
- Must limit our beam extinction, and detector live window



Beam Structure

- μ's are accompanied by "prompt" e, π, ...
- These cause real background
- Must limit our beam extinction, and detector live window



Total Backgrounds

- Largest Background
  - Decay in Orbit (DIO)
  - Rad π Capture (RPC)

- Limiting Backgrounds
  - Can limit prompt backgrounds w/ extinction
  - In particular, Rad π Cap. drives the extinction requirement
  - Current Background Estimates require 10^{-9} extinction
  - BNL AGS already has demonstrated extinction of 10^{-7} with out using all the available tools

Background	Evts (2×10^{-17})
μ Decay in Orbit (DIO) Tail	0.225
Radiative pion capture	0.072
Beam Electrons	0.036

Total Backgrounds

- Largest Background
  - Decay in Orbit (DIO)
  - Rad π Capture (RPC)
- Limiting Backgrounds
  - Can limit prompt backgrounds w/ extinction
  - In particular, Rad π Cap. drives the extinction requirement
  - Current Background Estimates require 10^{-9} extinction
  - BNL AGS already has demonstrated extinction of 10^{-7} with out using all the available tools

Background	Evts (2×10^{-17})
μ Decay in Orbit (DIO) Tail	0.225
μ Decay in flight w/ scatter	0.036
Beam Electrons	0.036
Cosmic Ray	0.016
μ Decay in flight (no scatter)	< 0.027
Anti-proton	0.006
Radiative μ capture	<0.002
Radiative π capture	0.072
π Decay in flight	<0.001
Pat. Recognition Errors	<0.002
Total	0.415

Total Backgrounds

- Largest Background
  - Decay in Orbit (DIO)
  - Rad π Capture (RPC)

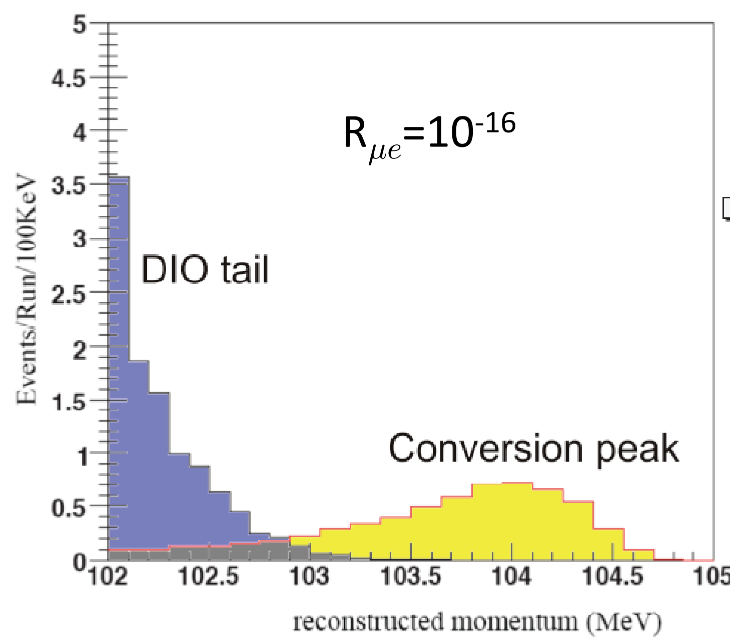
- Limiting Backgrounds
  - Can limit prompt backgrounds w/ extinction
  - In particular, Rad π Cap. drives the extinction requirement
  - Current Background Estimates require 10^{-9} extinction
  - BNL AGS already has demonstrated extinction of 10^{-7} with out using all the available tools

Background	Evts (2×10^{-17})
μ Decay in Orbit (DIO) Tail	0.225
μ Decay in flight w/ scatter	0.036
Beam Electrons	0.036
Cosmic Ray	0.016
μ Decay in flight (no scatter)	< 0.027
Anti-proton	0.006
Radiative μ capture	<0.002
Radiative π capture	0.072
π Decay in flight	<0.001
Pat. Recognition Errors	<0.002
Total	0.415

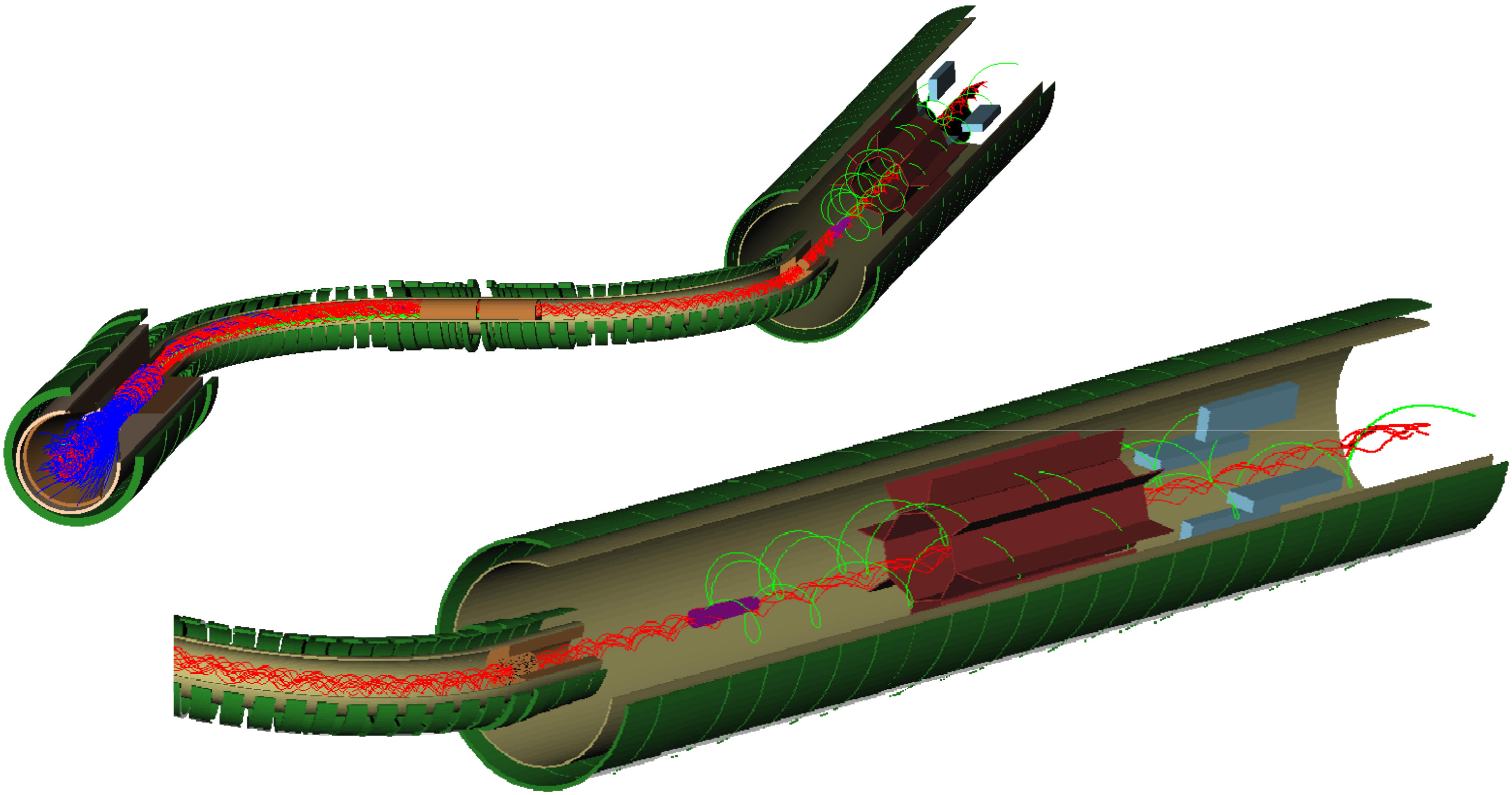
Signal to All Backgrounds

- Signal significance
  - If we assume SUSY accessible at the LHC:
    - Mu2e may see $\sim\mathcal{O}(40)$ events
    - On 0.5 event background
  - At $R_{\mu e}=10^{-16}$ (limit of sensitivity)
    - Mu2e sees $\sim$ 4 events
    - on 0.5 event background
  - This is a Strong Signature

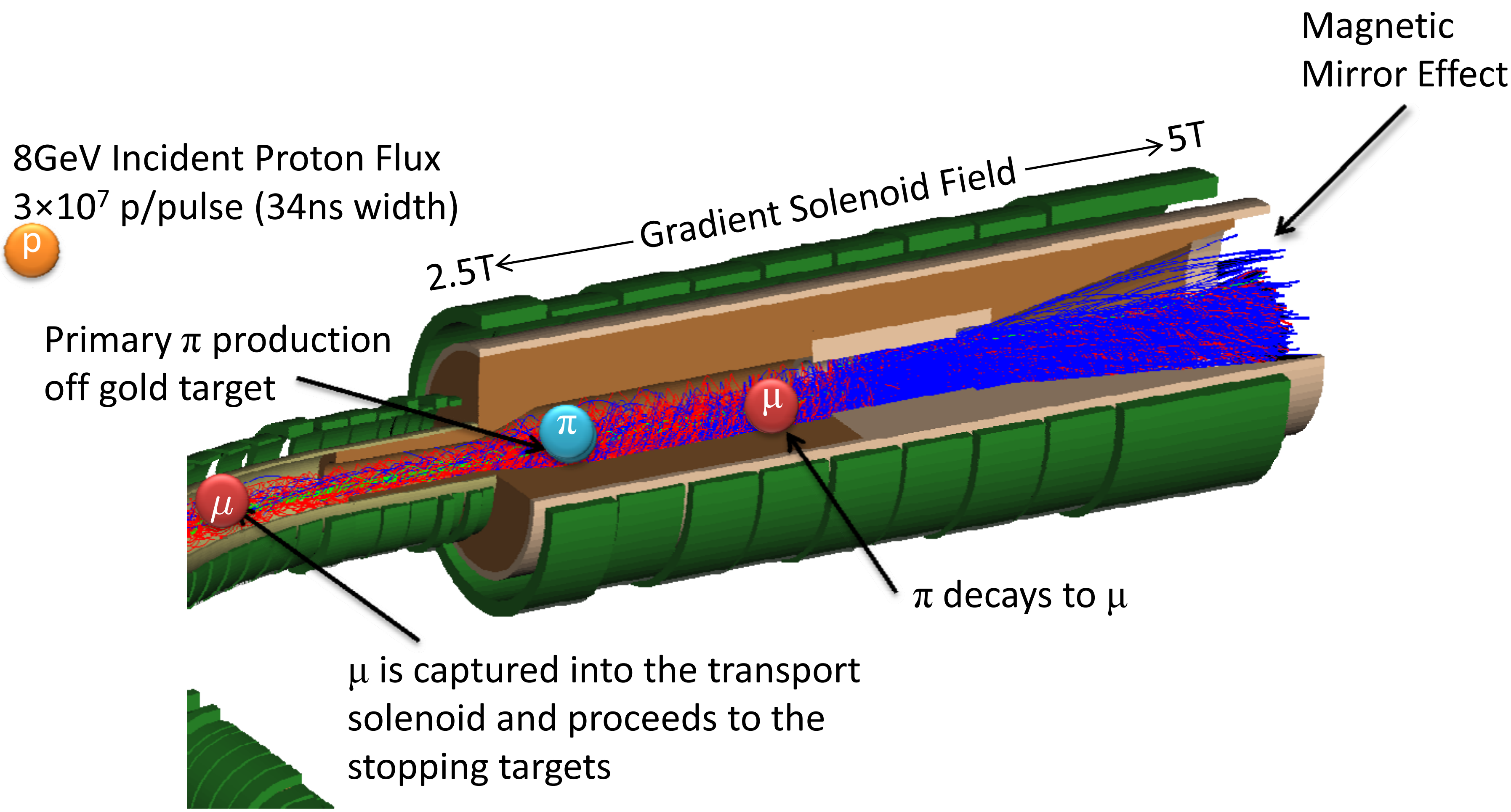
$$\frac{S}{\sqrt{B}} \sim 5.5$$



The Mu2e Detector in Detail

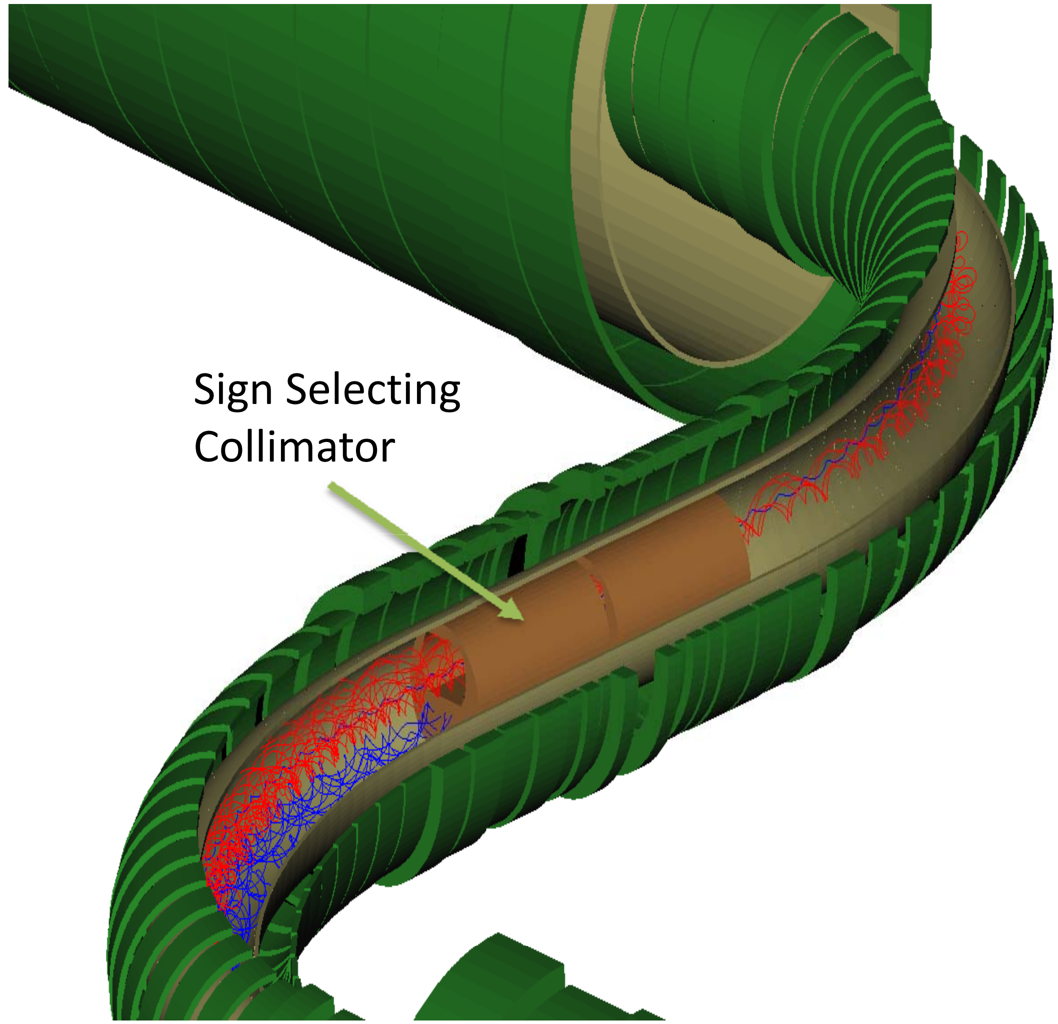


Production Solenoid

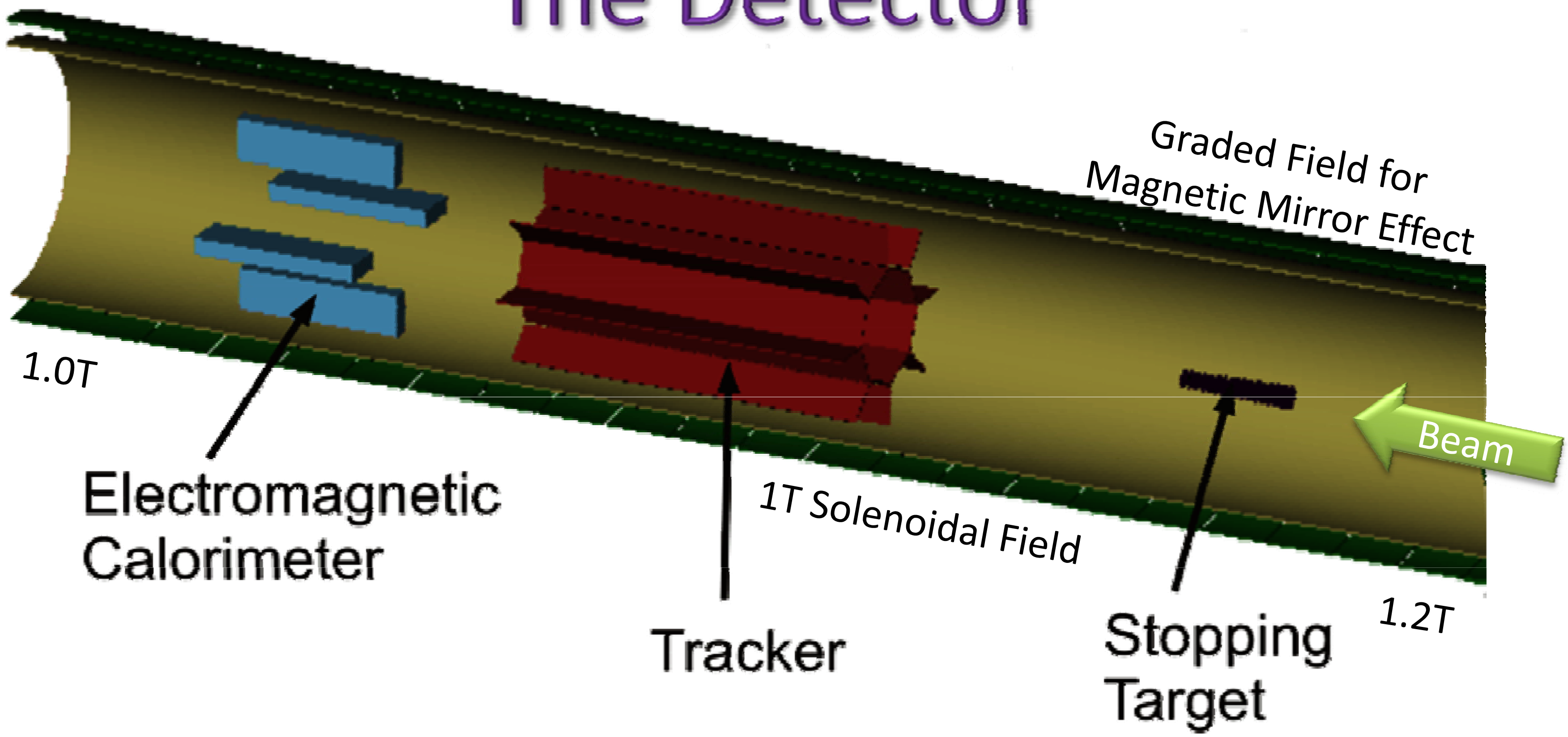


Transport Solenoid

- Designed to sign select the muon beam
  - Collimator blocks the positives after the first bend
  - Negatives are brought back on axis by the second bend



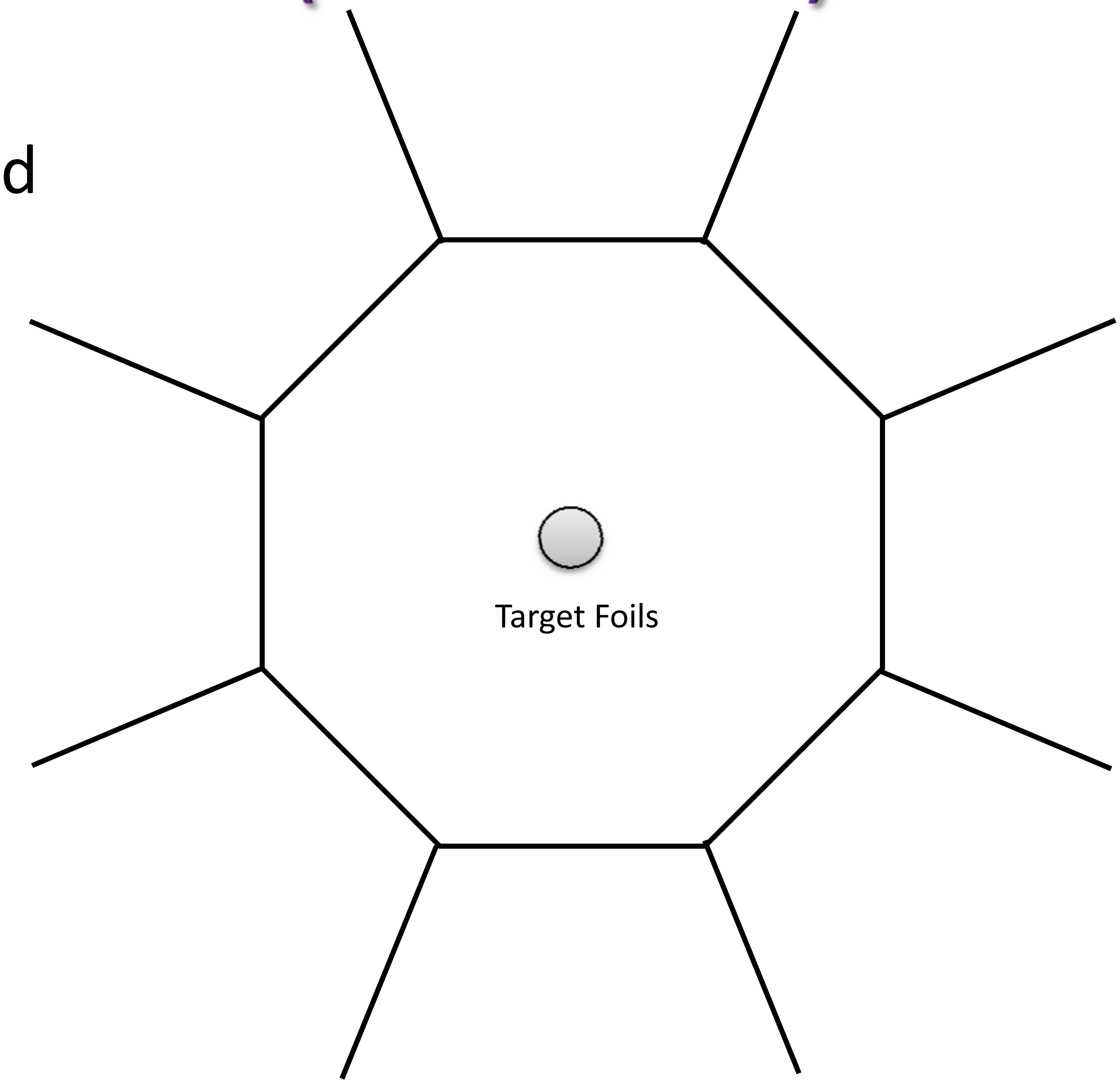
The Detector



- The detector is specifically design to look for the helical trajectories of 105 MeV electrons
- Each component is optimized to resolve signal from the *Decay in Orbit* Backgrounds

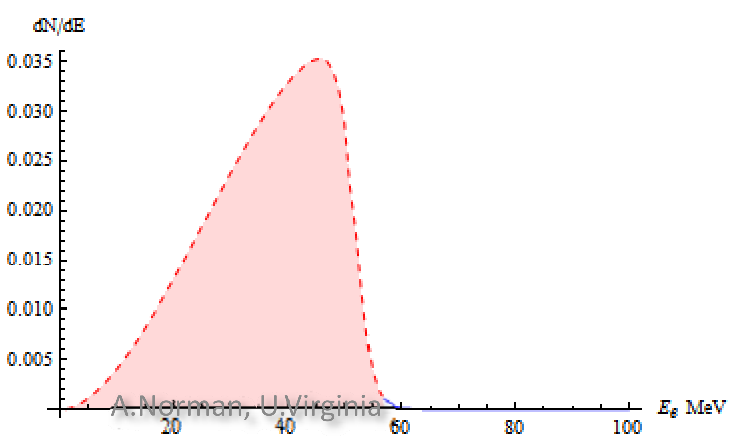
Straw Tracker (In Vacuum)

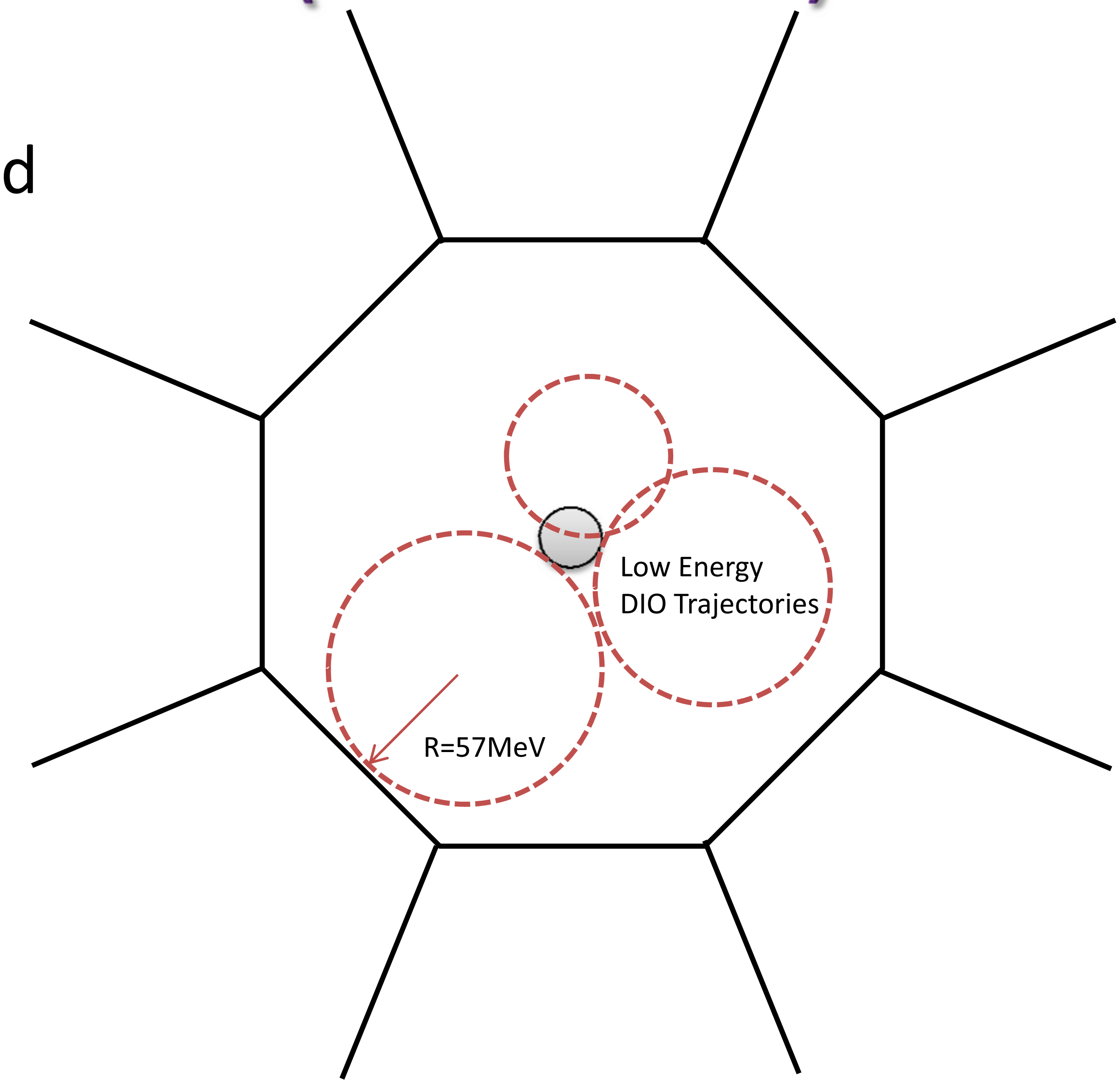
- Octagonal+Vanes geometry is optimized for reconstruction of 105MeV helical trajectories
- Extremely low mass
- Acceptance for DIO tracks < 10^{-13}



Straw Tracker (In Vacuum)

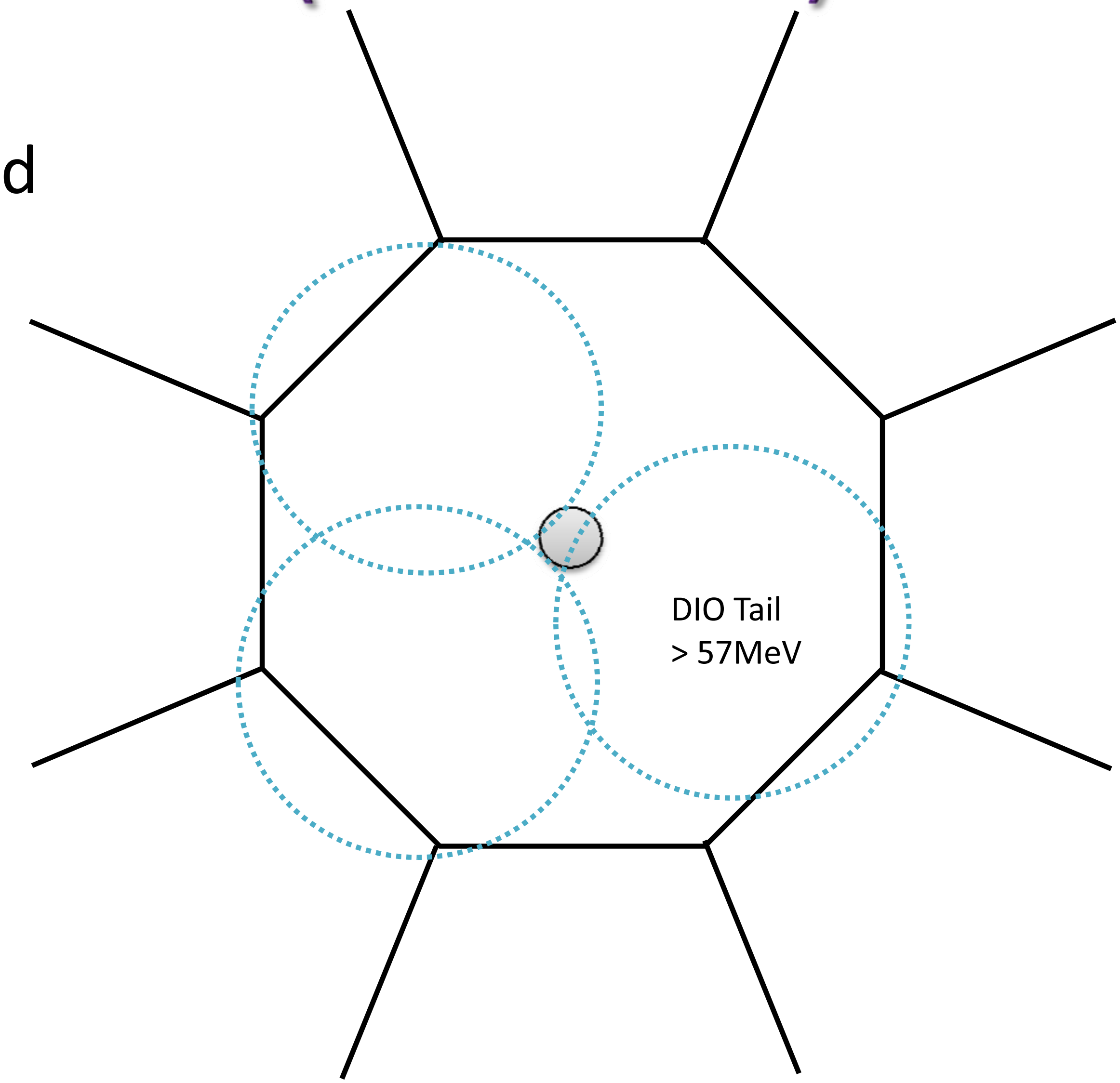
- Octagonal+Vanes geometry is optimized for reconstruction of 105MeV helical trajectories
- Extremely low mass

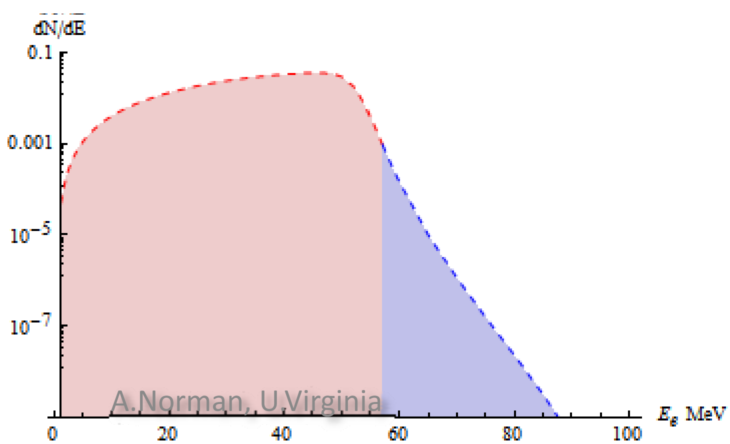




Straw Tracker (In Vacuum)

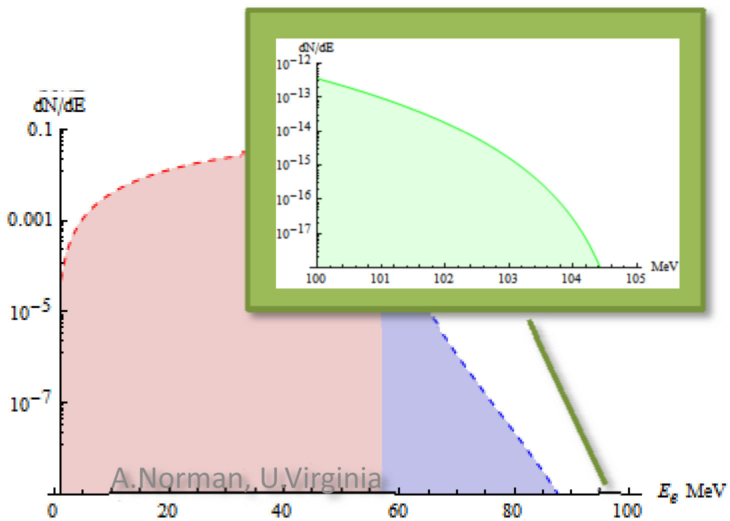
- Octagonal+Vanes geometry is optimized for reconstruction of 105MeV helical trajectories
- Extremely low mass

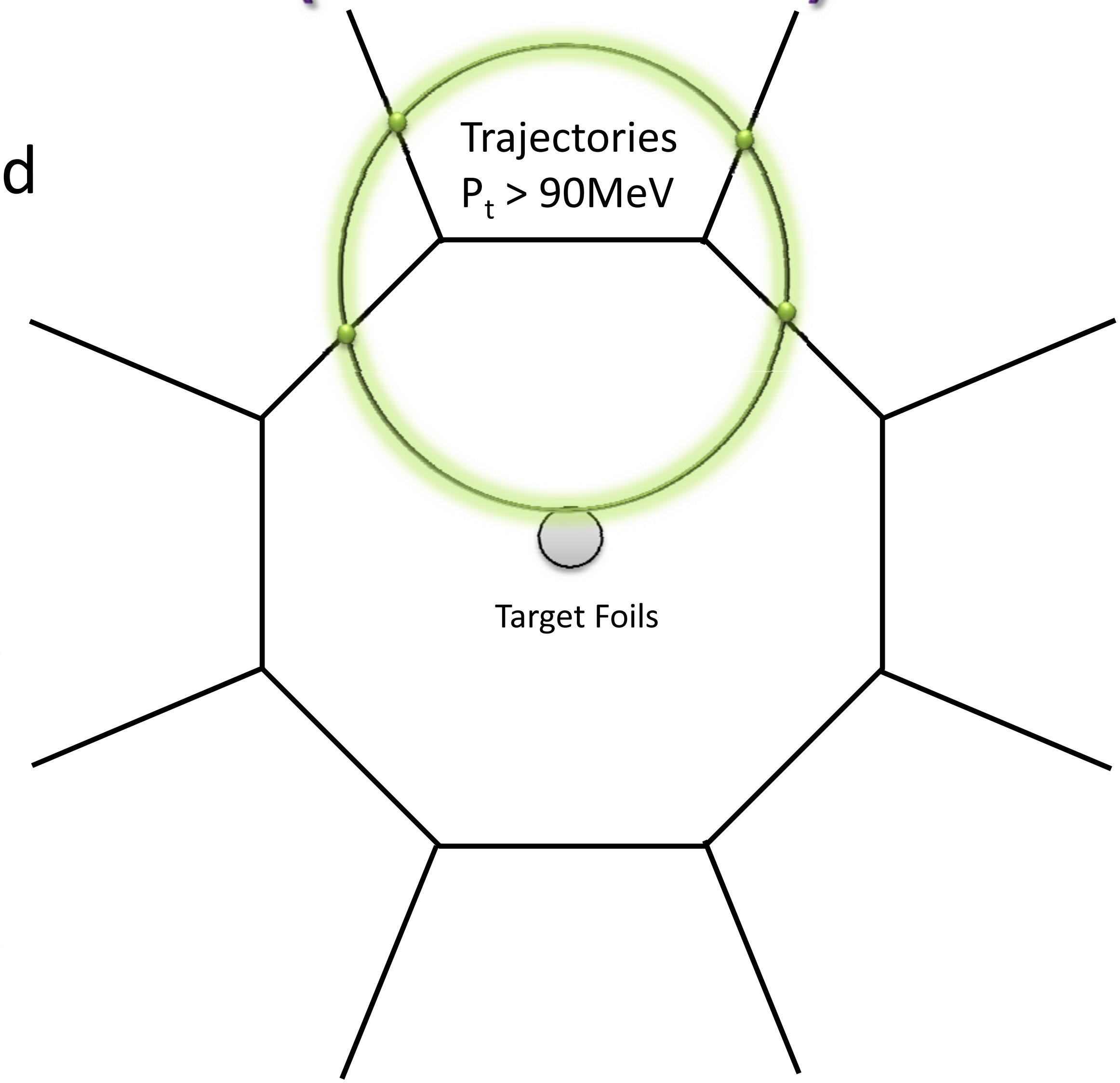




Straw Tracker (In Vacuum)

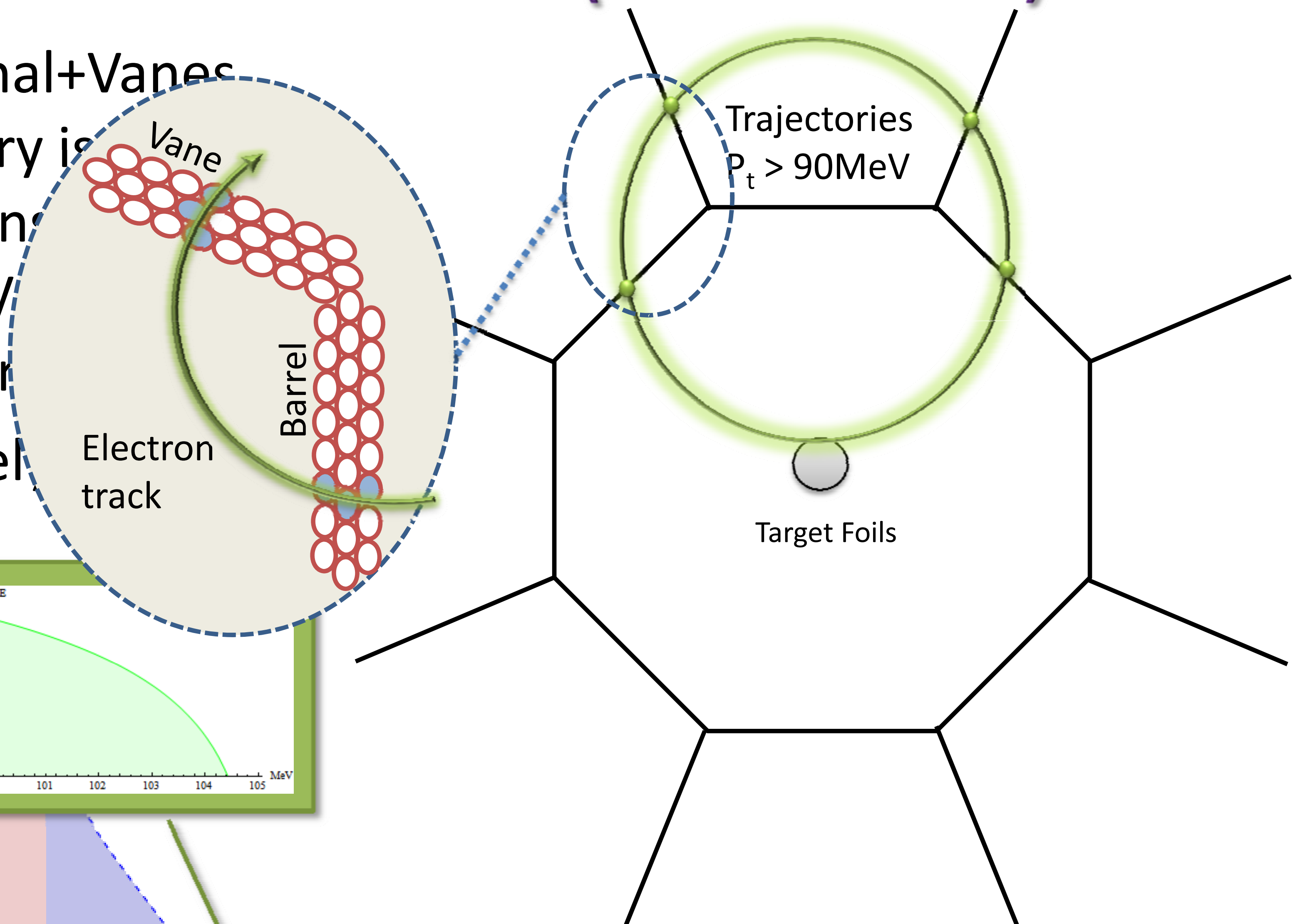
- Octagonal+Vanes geometry is optimized for reconstruction of 105MeV helical trajectories
- Extremely low mass

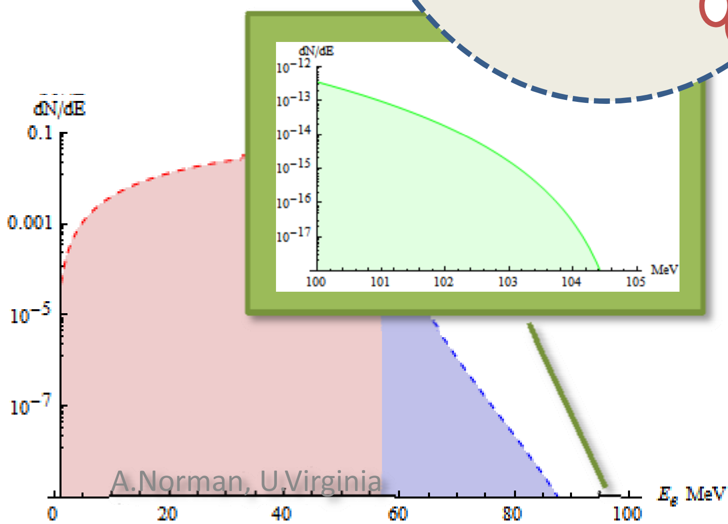




Straw Tracker (In Vacuum)

- Octagonal+Vanes geometry is for recon 105MeV trajector
- Extremel

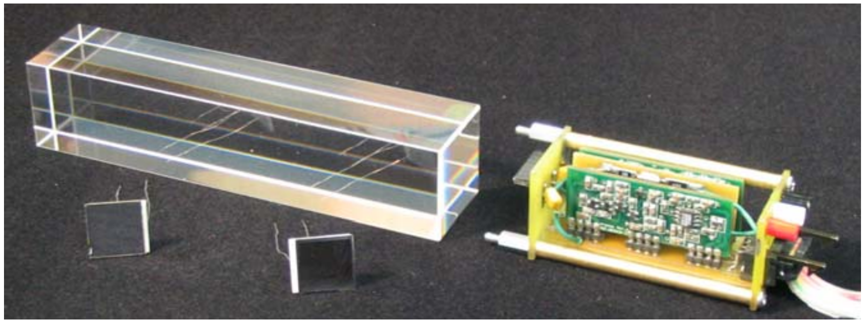


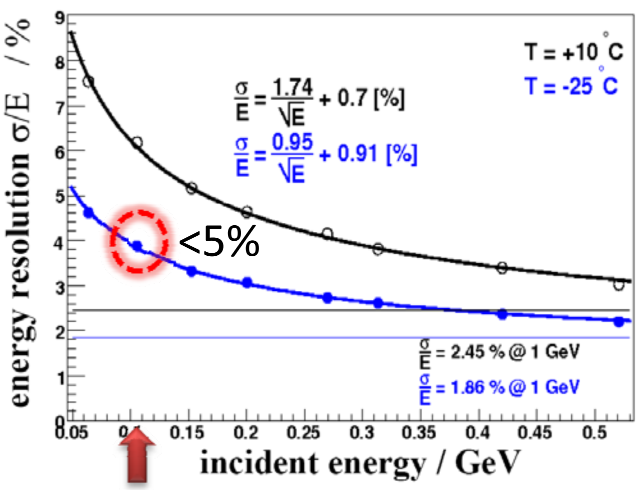


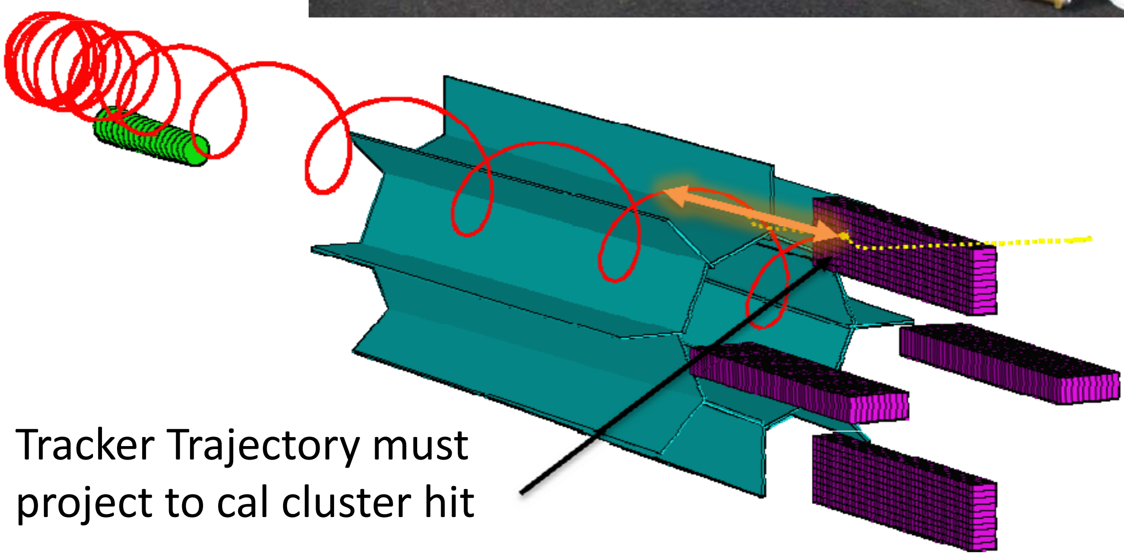
Crystal Calorimeter

Original Design:

- 5% energy measure for trigger decision (1kHz rate)
- Timing edge for event reconstruction
- Spatial match to tracker trajectory
- Low acceptance to Michel Peak

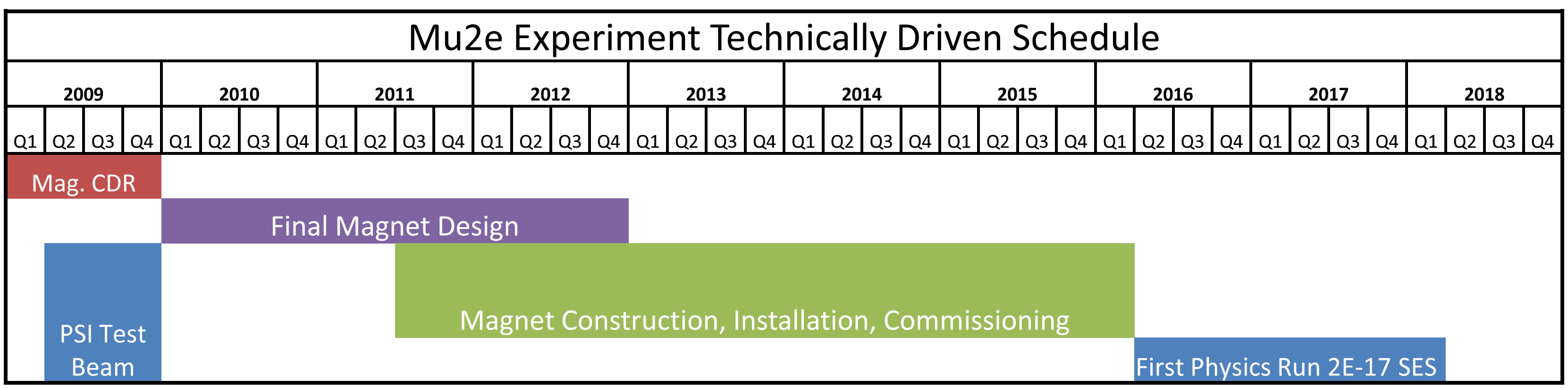






Cost and Schedule

- Total Project Cost Est. $200M (fully loaded, escalated, appropriate contingencies)
- Received Stage-1 Approval and DOE's CD-0 anticipated shortly
- Technically Driven Schedule (wholly magnet driven) results in 2016 start of data taking
- Opportunities for Significant R&D, Test Beam, and Auxiliary Measurement work for students and university groups



G-2 AT FNAL

Intro & Theory

- Remember that we can express the muon's magnetic moment

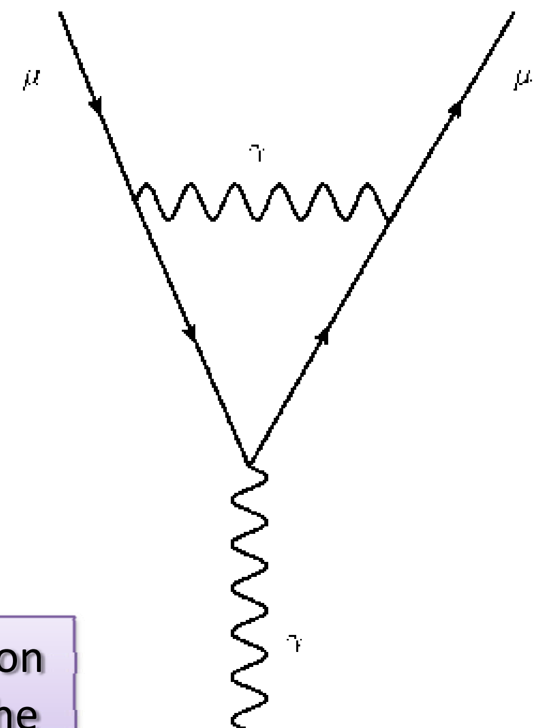
$$\mu = g_\mu \left(\frac{e}{2m_\mu} \right) \mathbf{S}$$

- Gives us the standard QED prediction:

$$g = 2 + \frac{\alpha}{2\pi} + \cdots$$

- The deviation of g from 2
  is the *anomalous magnetic moment*:

$$a_\mu = \frac{g-2}{2}$$



The purpose of g-2 is to measure with extreme precision the anomalous magnetic moment and compare it to the corrections that arise in the SM and Beyond SM physics

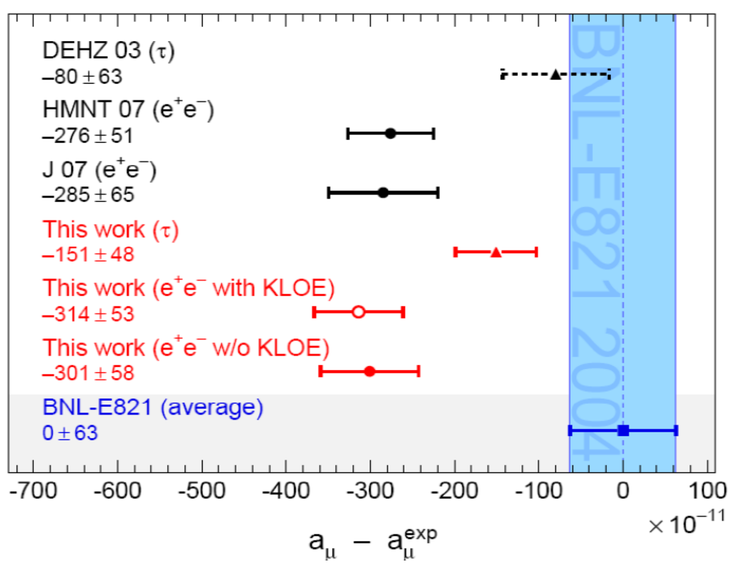
Current g-2 Numbers & Theory

BNL E821 a_μ

Experiment: 0.54 ppm (0.46 stat, 0.31 syst.)
Theory: 0.48 ppm

$$\Delta a_\mu(\text{expt.} - \text{theory}) = 314 \pm 82 \times 10^{-11}$$

Lopez Castro (Photon '09)
With Belle, KLOE & new IB corrections



Points of Reference

SUSY (SPS1A)

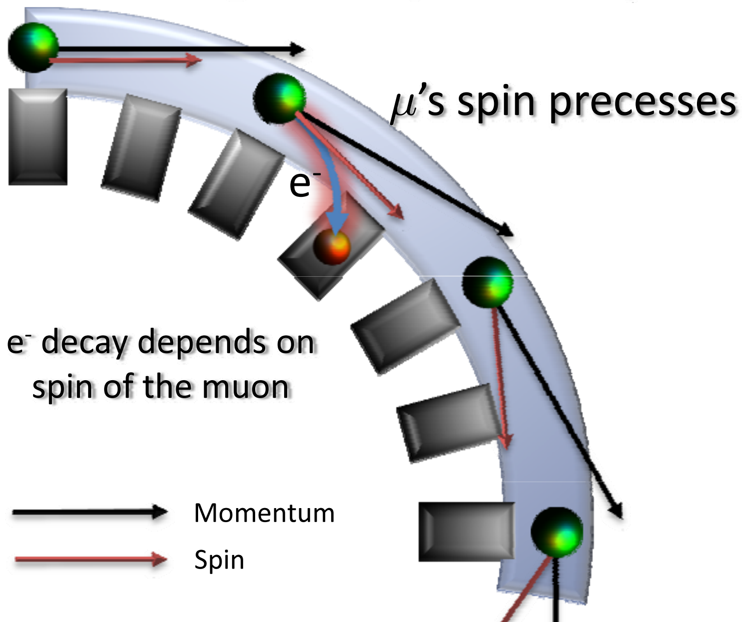
$$\Delta a_\mu^{MSSM} = 298 \times 10^{-11}$$

Extra Dimensions

$$\Delta a_\mu^{UED} \approx -13 \times 10^{-11}$$

The g-2 Measurement

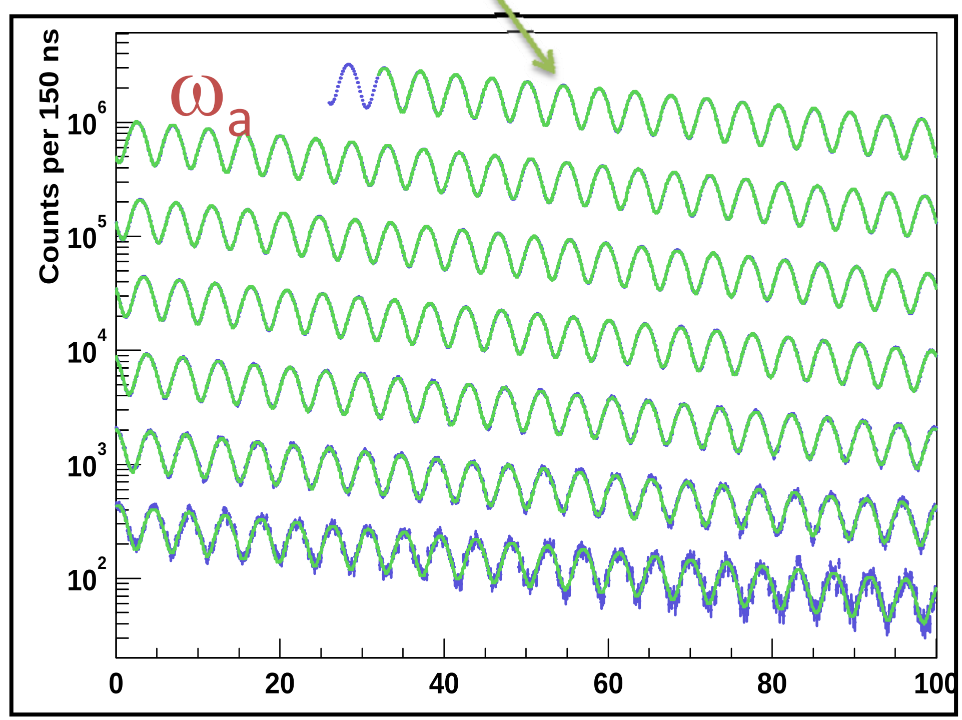
Inject 100% longitudinally Polarized μ's



$$\omega_a = \omega_{spin} - \omega_{cyclotron}$$
$$\omega_a = a_\mu \frac{q}{m} B$$

This method requires extremely precise knowledge of the B field

The muon is self analyzing, from the decay distribution of elections
The precession frequency is directly obtained from the electron rates in the detectors



g-2 Goals

- Collect 21$\times$ the current BNL data set
- Statistical & Systematic Error each 0.1ppm
- Achieve 4$\times$ the precision of the current a_μ
- Would result in the current deviation from theory moving from 3.8$\sigma \rightarrow$ 7σ significance (including theory error)

- Possible at FNAL because we can have:
  - More μ's
  - Less background

Conclusions

- In an era where, we are poised to see our first direct evidence of physics beyond the standard model:
- We must pay special attention to precision measurements
- Mu2e and g-2 have the ability, not only guide us as we begin to interpret and understand signs of new physics,
  But they naturally combine to:
  - Make elegant predictions
  - Probe large parameter spaces
  - and access physics beyond the Terascale

- Consider the possibilities and join us!
  - Mu2e: http://www-mu2e.fnal.gov
  - g-2: Lee Roberts (roberts@bu.edu) and
    Dave Hertzog (hertzog@illinois.edu)

BACKUP SLIDES

Mu2e Collaboration

Boston University
J.Miller, R.Carey, K.Lynch, B. L.Roberts

Brookhaven National Laboratory
P.Yamin, W.Marciano, Y.Semertzidis

University of California, Berkeley
Y.Kolomensky

University of Calivornia, Irvine
W.Molzon

City University of New York
J.Popp

Fermi National Accelerator Laboratory
C.Ankenbrandt, R.Bernstein, D.Bogert, S.Brice, D.Broemmelsiek, R.Coleman, D.DeJongh, S.Geer, D.Glenzinski, D.Johnson, R.Kutschke, M.Lamm, P.Limon, M.Martens, S.Nagaitsev, D.Neuffer, M.Popovic, E.Prebys, R.Ray, V.Rusu, P.Shanahan, M.Syphers, H.White,B.Tschirhart, K.Yonehara,C.Yoshikawa

Idaho State University
K.Keeter, E.Tatar

University of Illinois, Urbana-Champaign
P.Kammel, G.Gollin, P.Debevec, D.Hertzog

Institute for Nuclear Research, Moscow, Russia
V.Lobashev

University of Massachusetts, Amherst
K.Kumar, D.Kawall

Muons, Inc.
T.Roberts, R.Abrams, M.Cummings R.Johnson, S.Kahn, S.Korenev, R.Sah

Northwestern University
A.De Gouvea

Instituto Nazionale di Fisica Nucleare Pisa, Universita Di Pisa, Pisa, Italy
L.Ristori, R.Carosi, F.Cervelli, T.Lomtadze, M.Incagli, F.Scuri, C.Vannini

Rice University
M.Corcoran

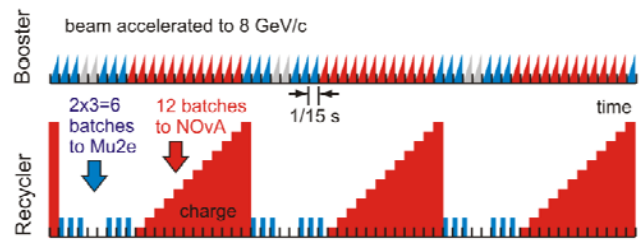
Syracuse University
P.Souder, R.Holmes

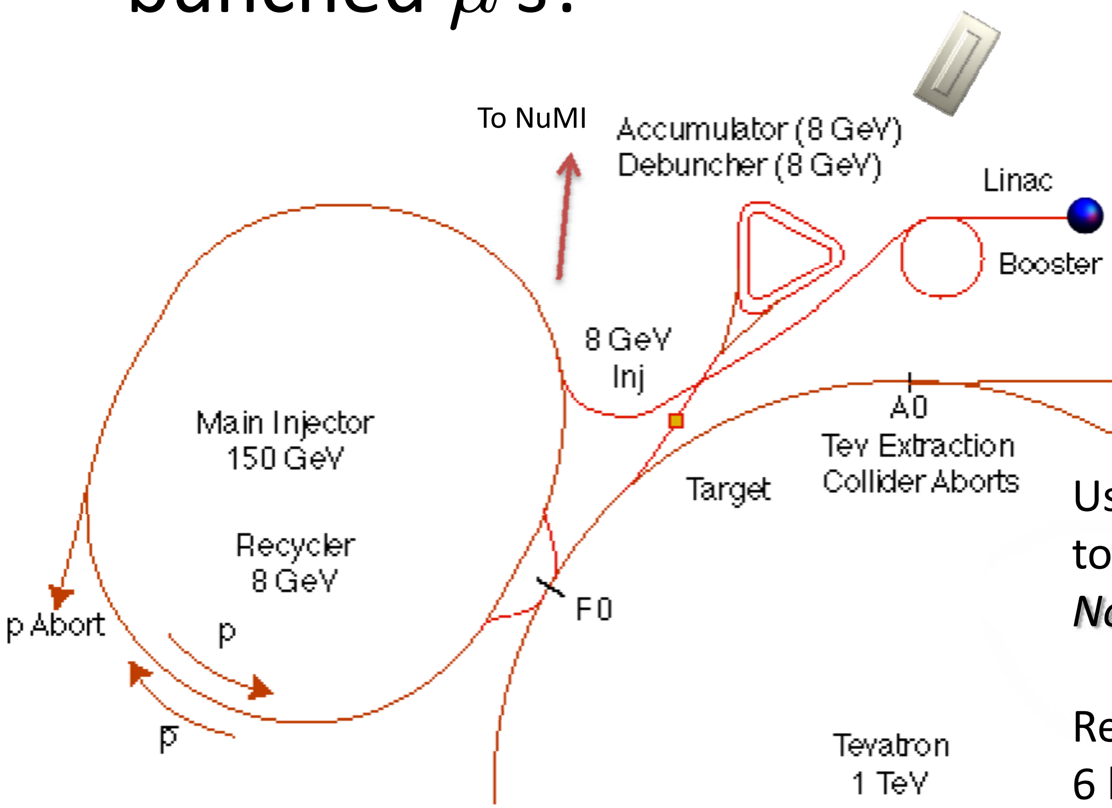
University of Virginia
E.C.Dukes, M.Bychkov, E.Frlez, R.Hirosky, A.Norman, K.Paschke, D.Pocanic

College of William and Mary
J.Kane

Mu2E & NOvA/NuMI

- How do we deliver $\mathcal{O}(10^{18})$ bunched μ's?





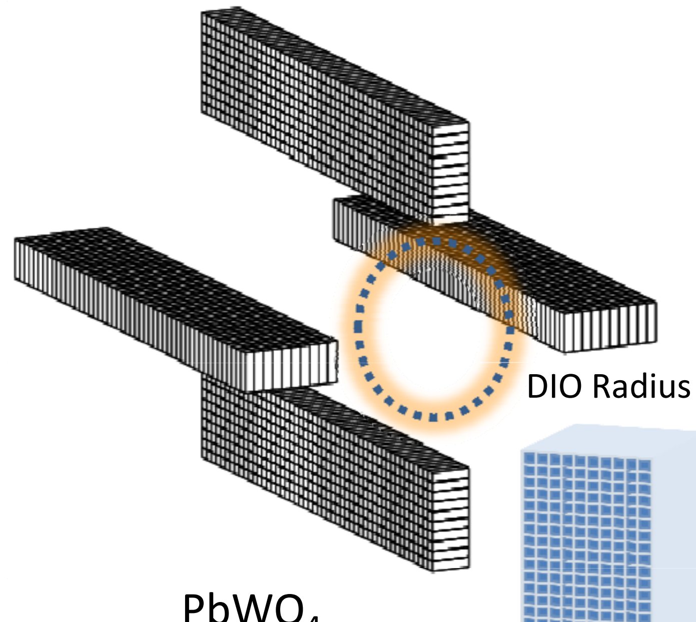
Use NuMI cycles in the Main injector to slow spill to Mu2e.
No Impact on NOvA

Results in:
6 batches x 4×10^{12} /1.33 s x 2×10^{7} s/yr
= 3.6×10^{20} protons/yr

Crystal Calorimeter

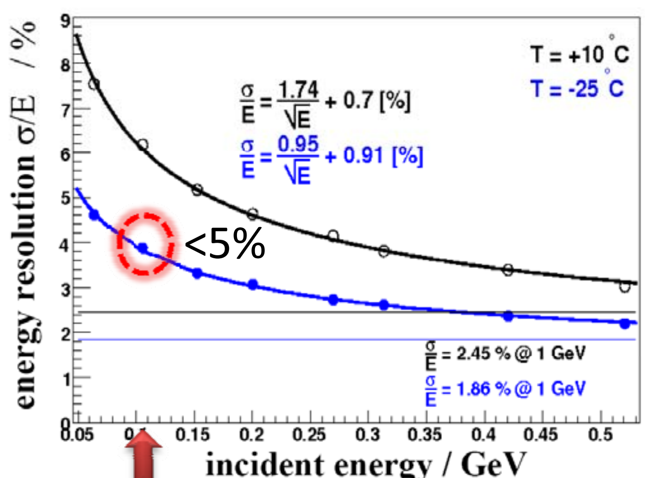
Original Design:

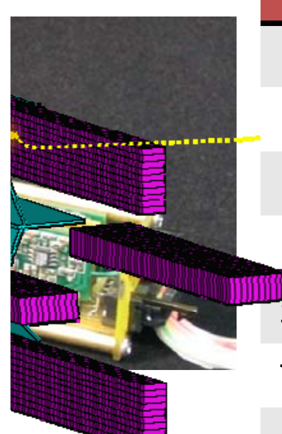
- 5% energy measure for trigger decision (1Hz rate)
- Timing edge for event reconstruction
- Spatial match to tracker trajectory
- Immune to DIO rates



PbWO$_4$

Tracker project



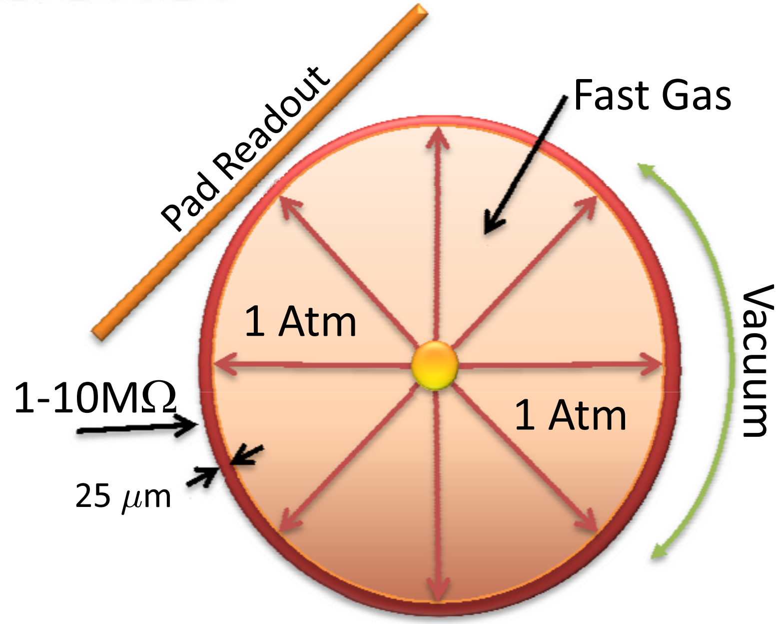


Calorimeter Properties	
Resolution	5%
Material	PbWO$_4$
Readout	Dual APD
Blocks	500 per fin, 4 fins
Segmentation	$30\times30\times120mm^3$
Trigger Rate	1kHz
Light yield	20-30p.e./MeV

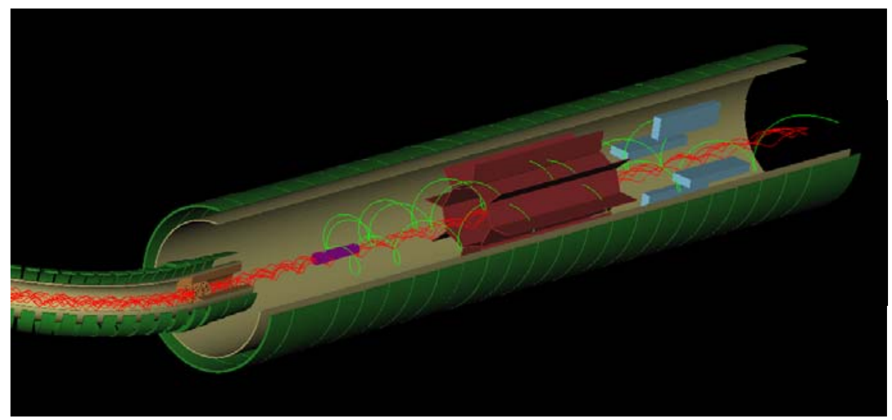
13.6X_0

Straw Tracker

- Longitudinal Tracker Features:
  - 2800 straw tubes in vacuum
  - Utilize 17,000 pad readouts
  - 50% Geometric acceptance to signal ($90° \pm 30°$)
  - Intrinsic resolution 200keV
  - Virtually Immune to DIO

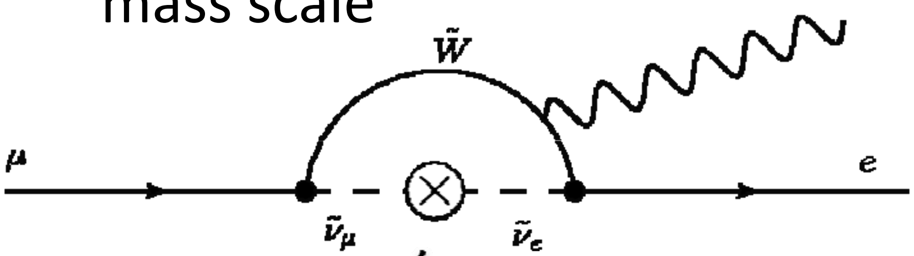


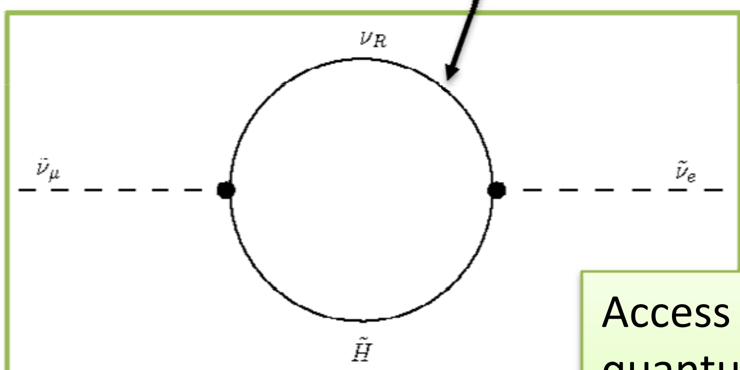
Diameter Swell > 1%



Sensitivity to SUSY

- Rates are not small because they are set by the SUSY mass scale





d see

.5

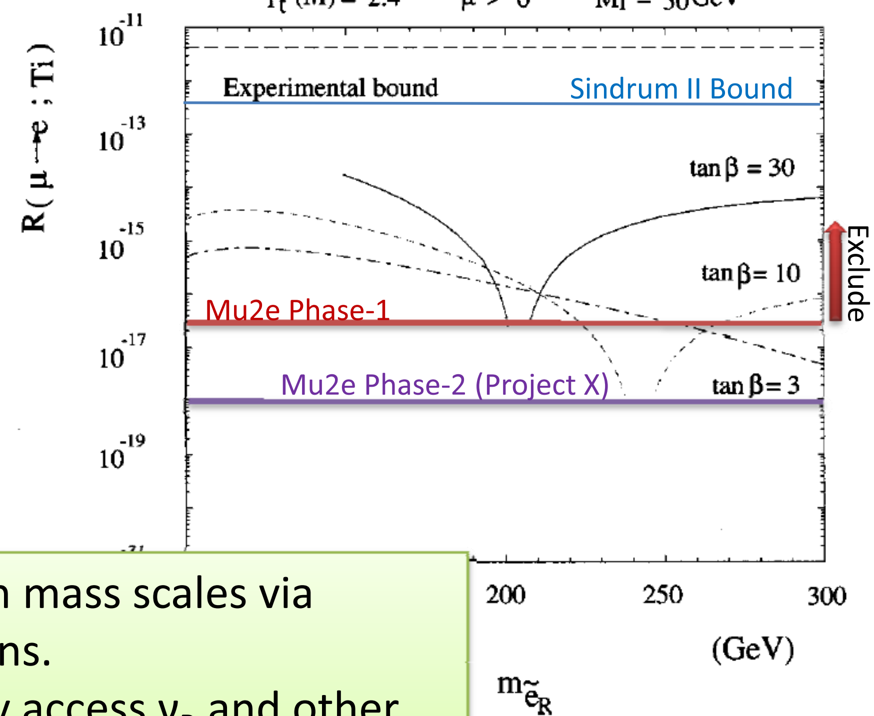
lling,

mean observatio

$\approx\mathcal{O}(40)$ even

Access to ultra high mass scales via quantum corrections.
Can access possibly access ν_R and other processes at scales 10^{12}-10^{14} GeV/c^2

Mu2e can exclude over the full range of slepton mass



Hisano et al. 1997

$\mu N \rightarrow eN$ & SUSY Models

- Assuming we see a signal:
  - By changing target, we gain sensitivity to the scalar, vector or dipole nature of the