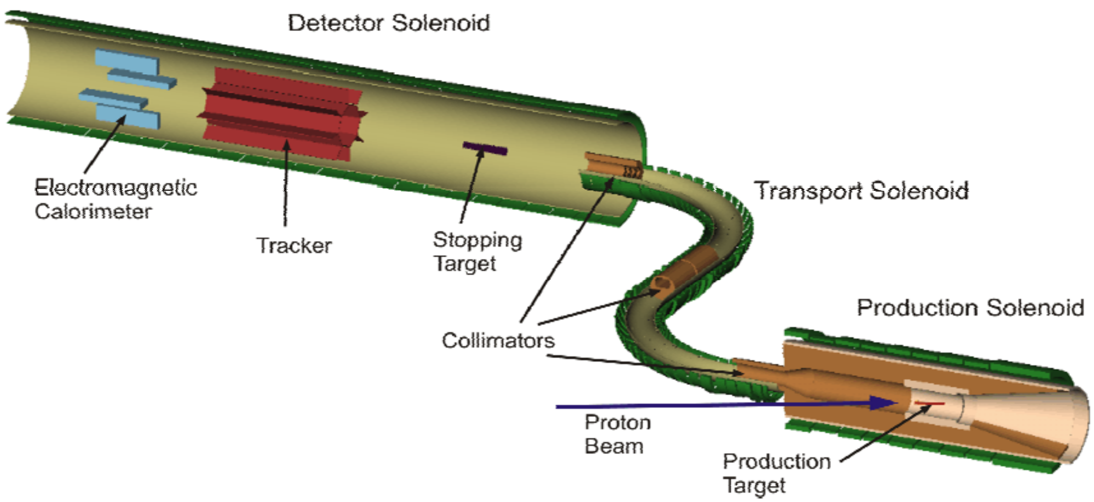
The Mu2e Experiment at FNAL

A precision window into physics beyond the standard model



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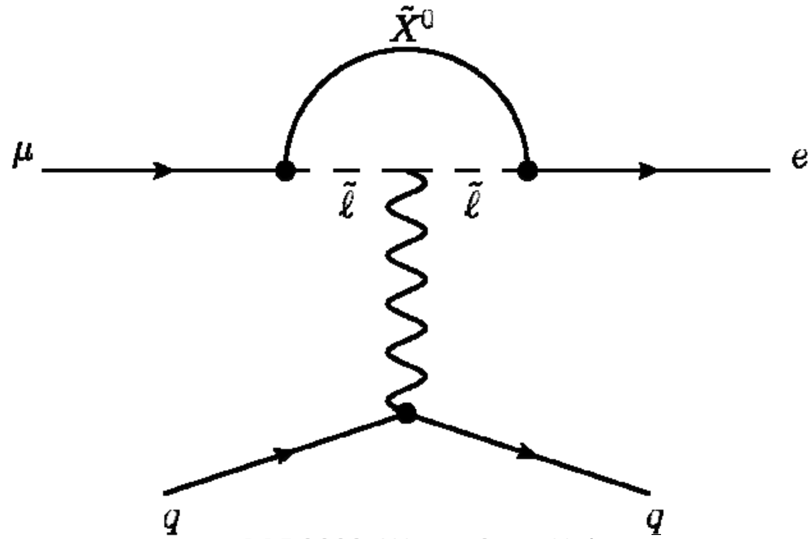
University of Virginia
For the Mu2e & g-2 Collaborations

DPF 2009, Detroit MI
Wayne State University

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



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- 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

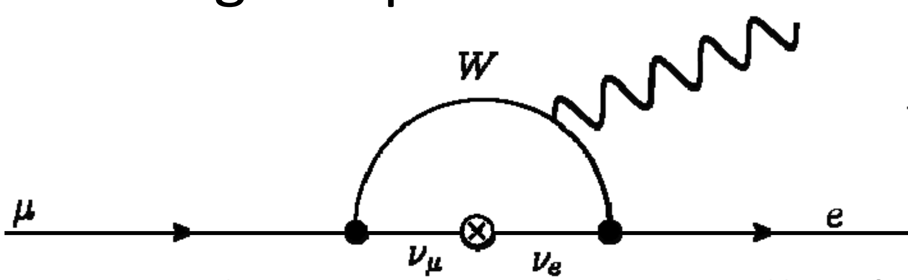
Lepton Mixing in the Standard Model

- 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:

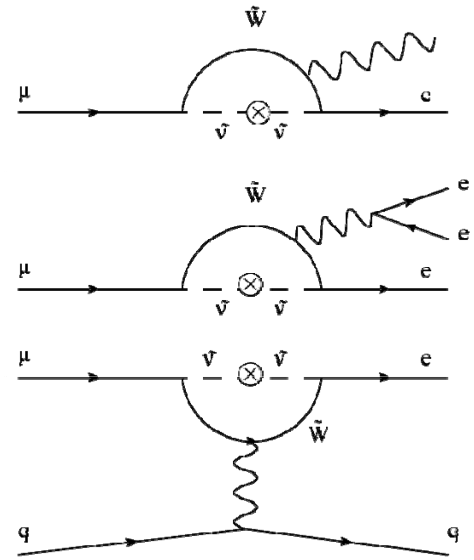
$$\mu^+ \rightarrow e^+\gamma$$
$$\mu^+ \rightarrow e^+e^+e^-$$
$$\mu^- N \rightarrow e^- N$$

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

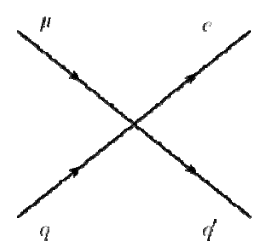
  $\approx$ 400 to 2 to 1

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

- New physics for these channels can come from loop level



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



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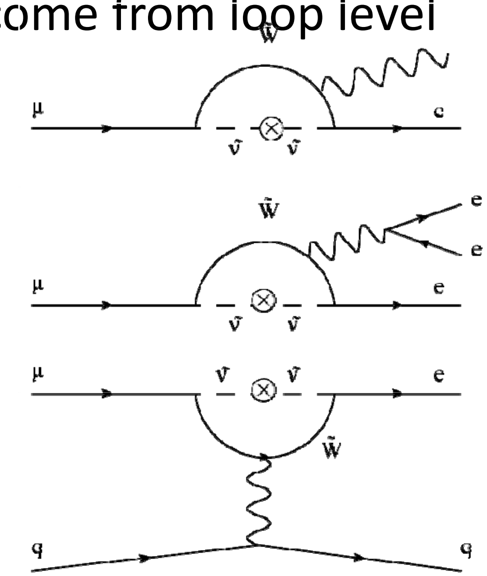

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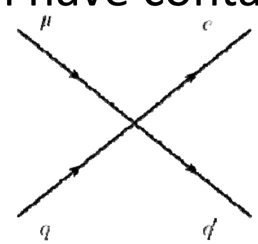


Note: $\mu \rightarrow e\gamma$ and $\mu \rightarrow$eee use a DC beam, and have *experimental* limitations (resolution, overlap, accidentals)

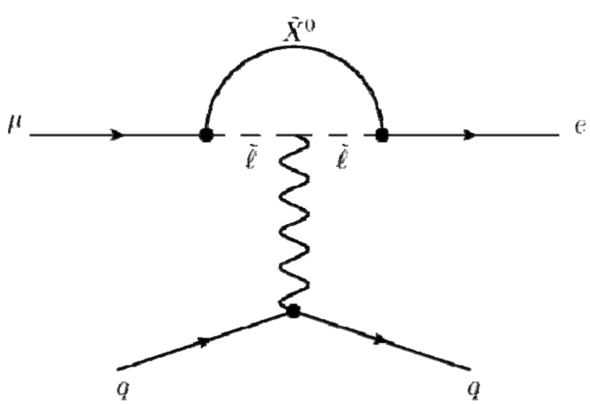
Ultimately Limits the measurement of:
Br($\mu \rightarrow$ e γ)$\sim 10^{-14}$

No such limits on μN$\rightarrow$eN channel

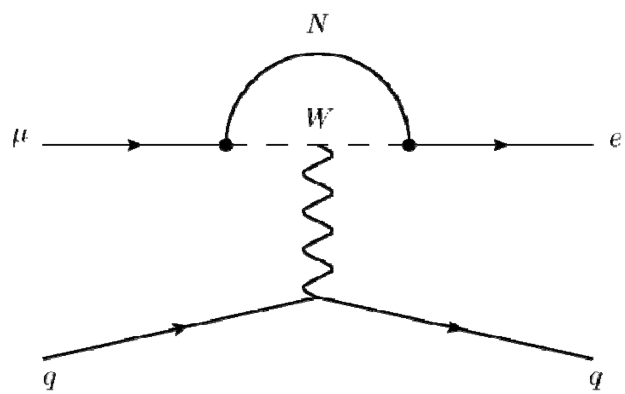
Beyond the Standard Model

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

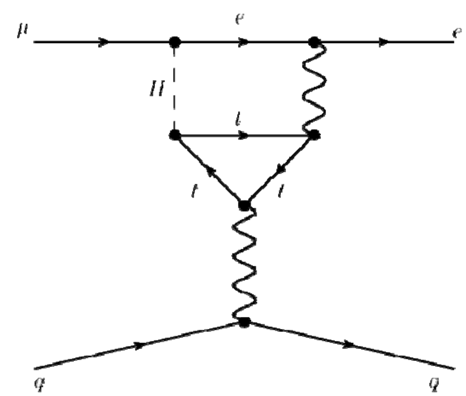
Loops



SUSY



Heavy Neutrinos



Second Higgs Doublet

Beyond the Standard Model

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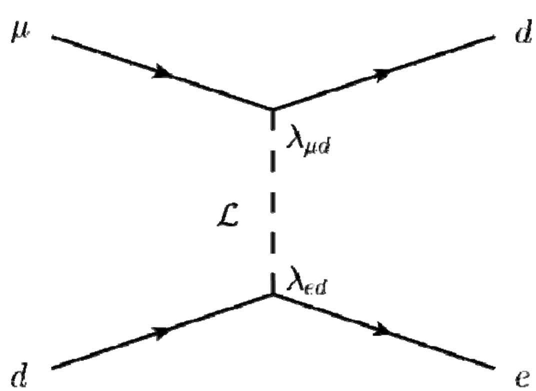
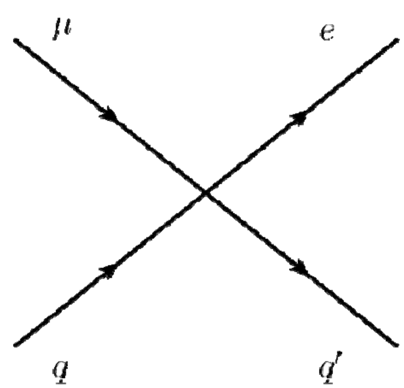
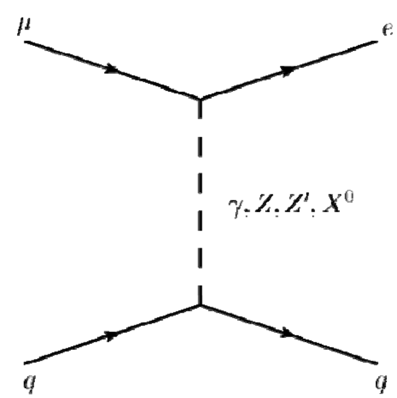
Contact Terms



Leptoquarks



Compositeness



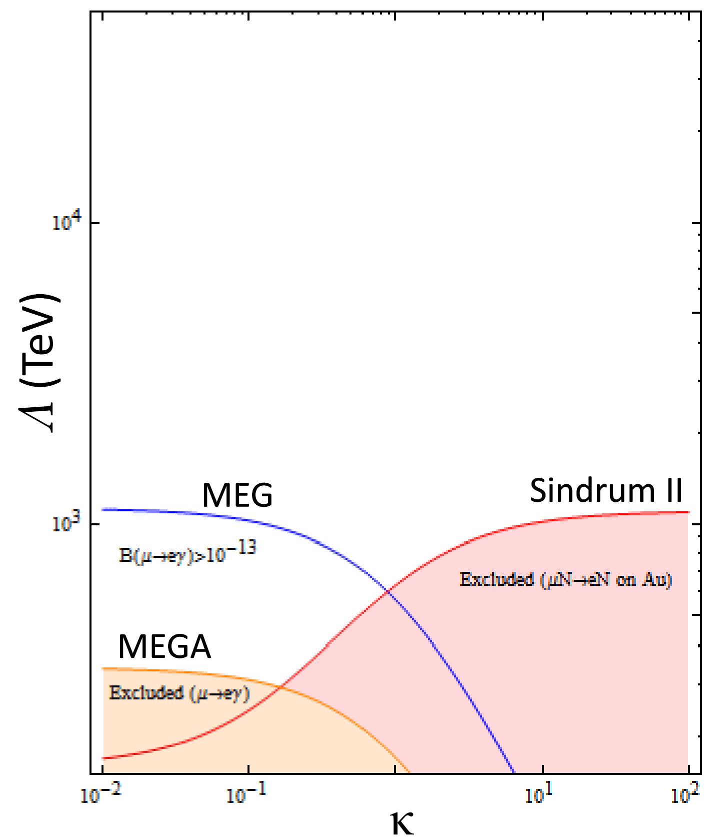
Anomalous Heavy Couplings

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 $\mu\rightarrow e\gamma$ measurements .
  - For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process



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Loops

Contact Interactions

Gives the same dipole structure as g-2

ensitivity into

s

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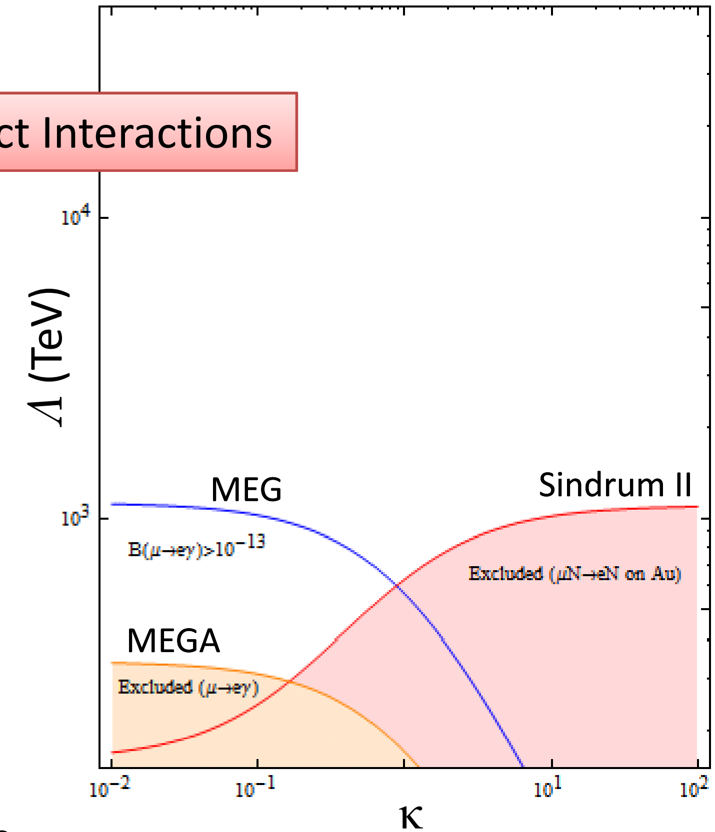

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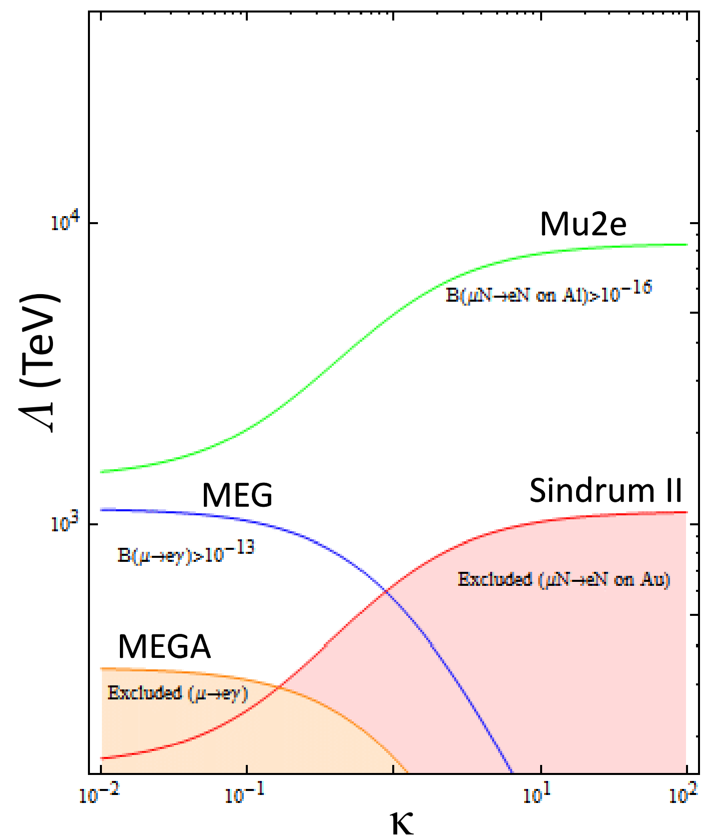

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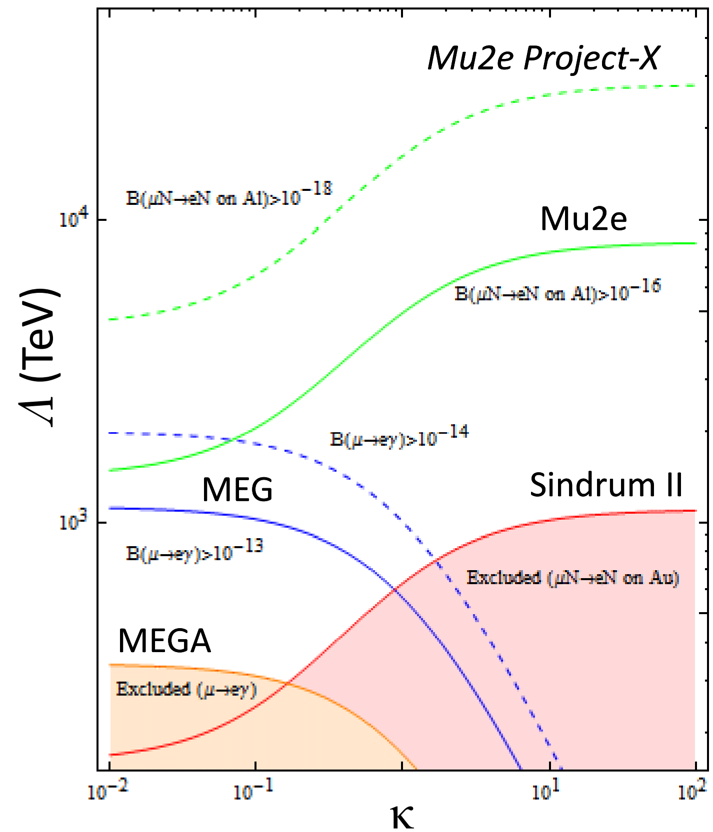
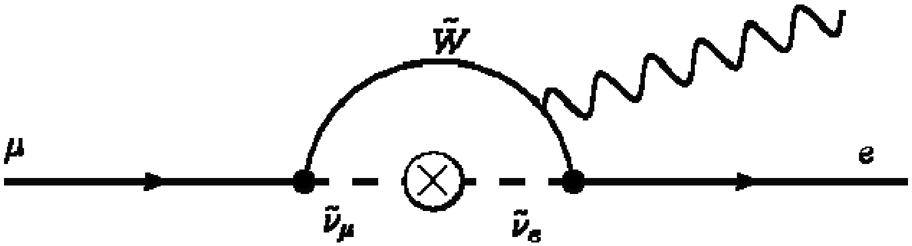
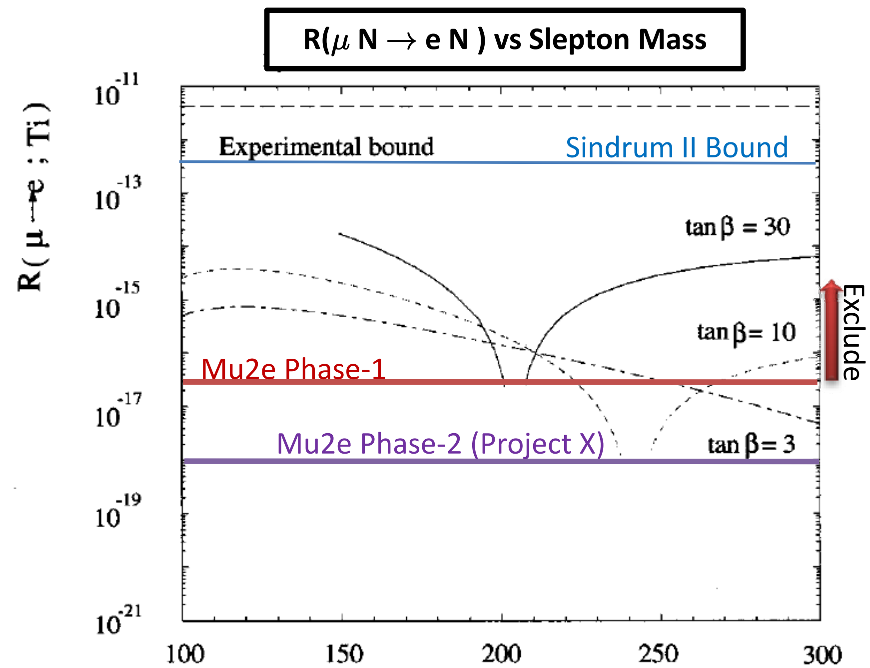


μN→eN Sensitivity to SUSY

- 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(μ N → e N) ~10^{-15}
- Makes μN→eN compelling, since for Mu2e this would mean observation of
  ≈$\mathcal{O}$(40) events [0.5 bkg]



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

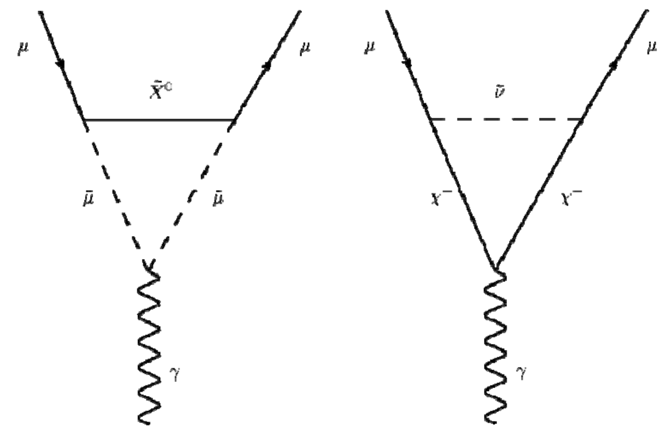
Hisano et al. 1997

g-2 Sensitivity to SUSY

- SUSY contributes to $a_\mu = (g-2)/2$:

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

  - Gives direct access to $\tan\beta$ 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



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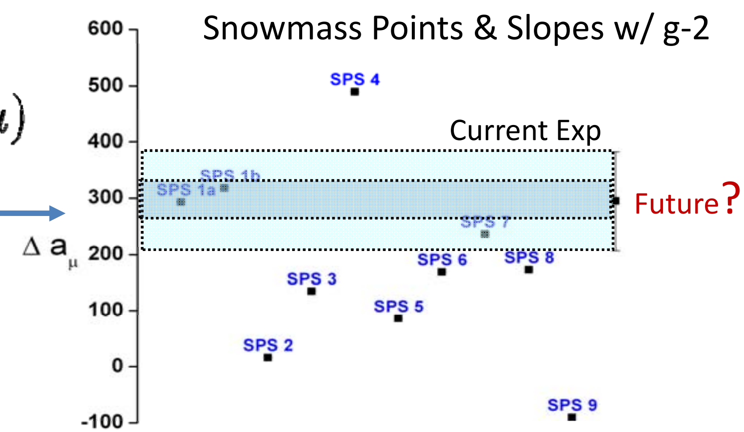
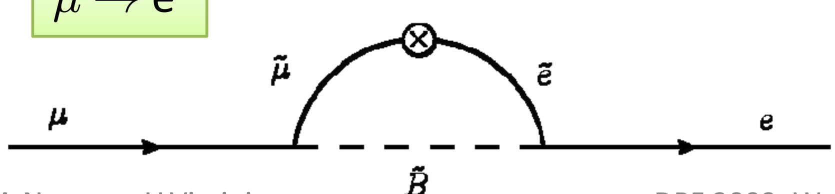


- Gives us access to Slepton Mixing

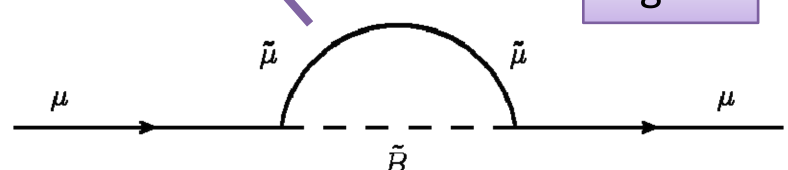
Slepton Mixing Matrix

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

$\mu \to$ e



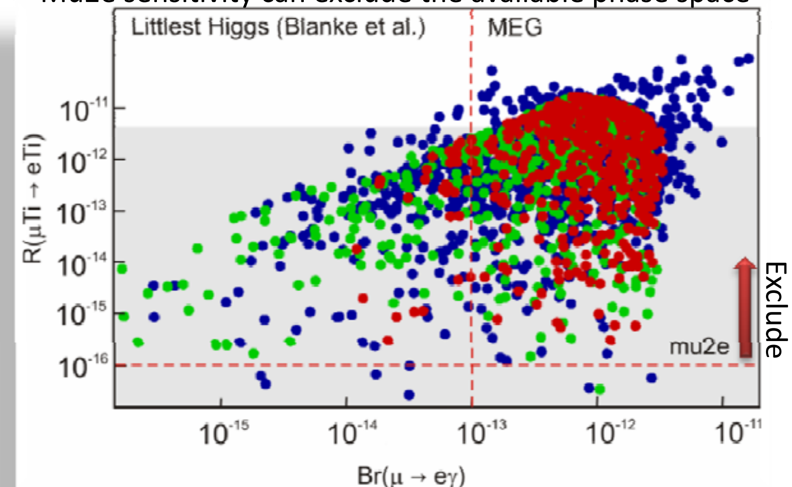
g-2

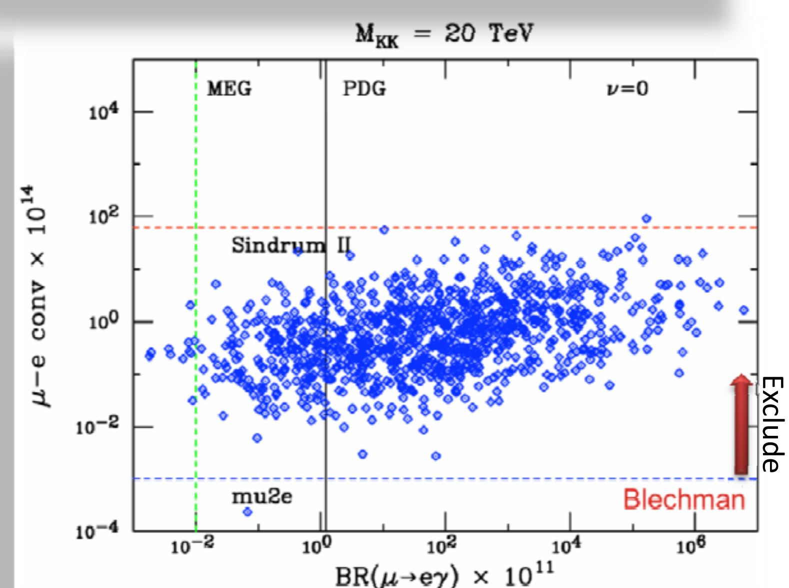


μN→eN, μ→eγ, g-2 Work Together

- 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

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

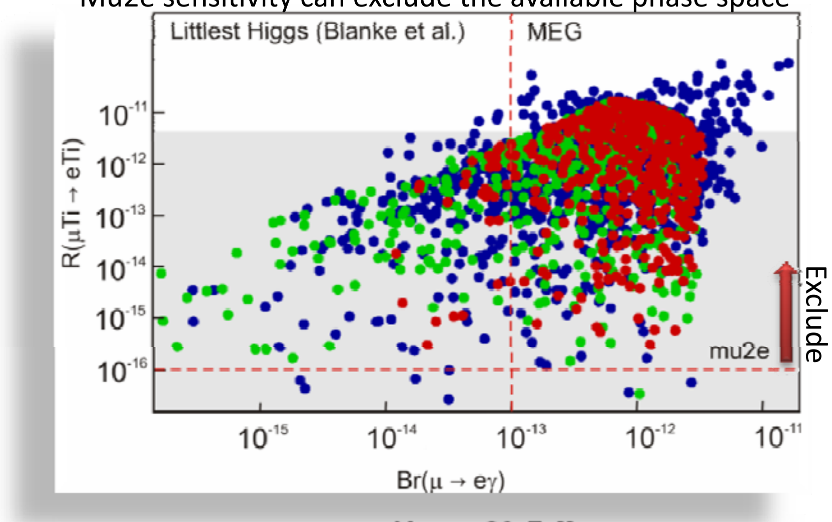
Example:

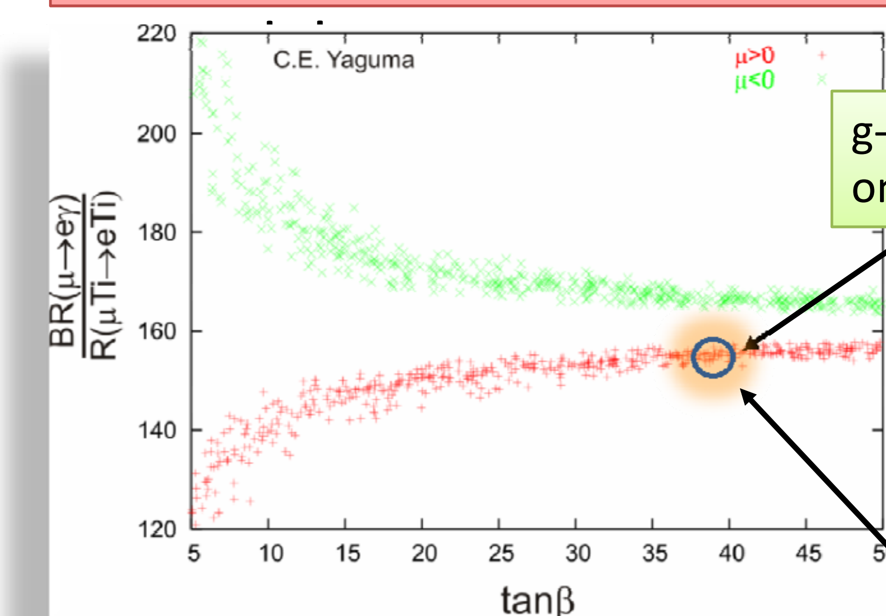
- From LHC we have the SUSY masses
- From g-2 we know tanβ
- From g-2 we know also know μ>0
- Combining these we get an a priori PREDICTION for:

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

under MSSM/MSUGRA

Mu2e sensitivity can exclude the available phase space





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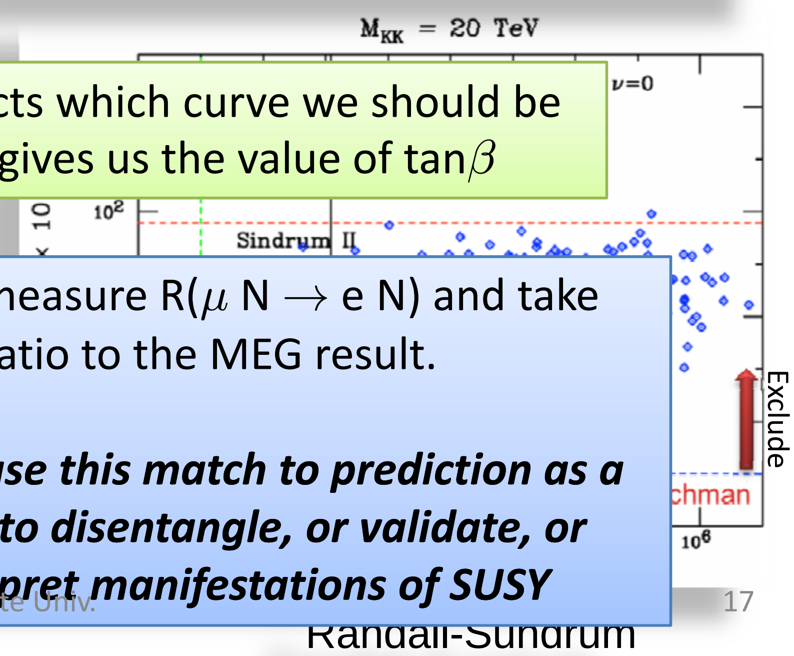


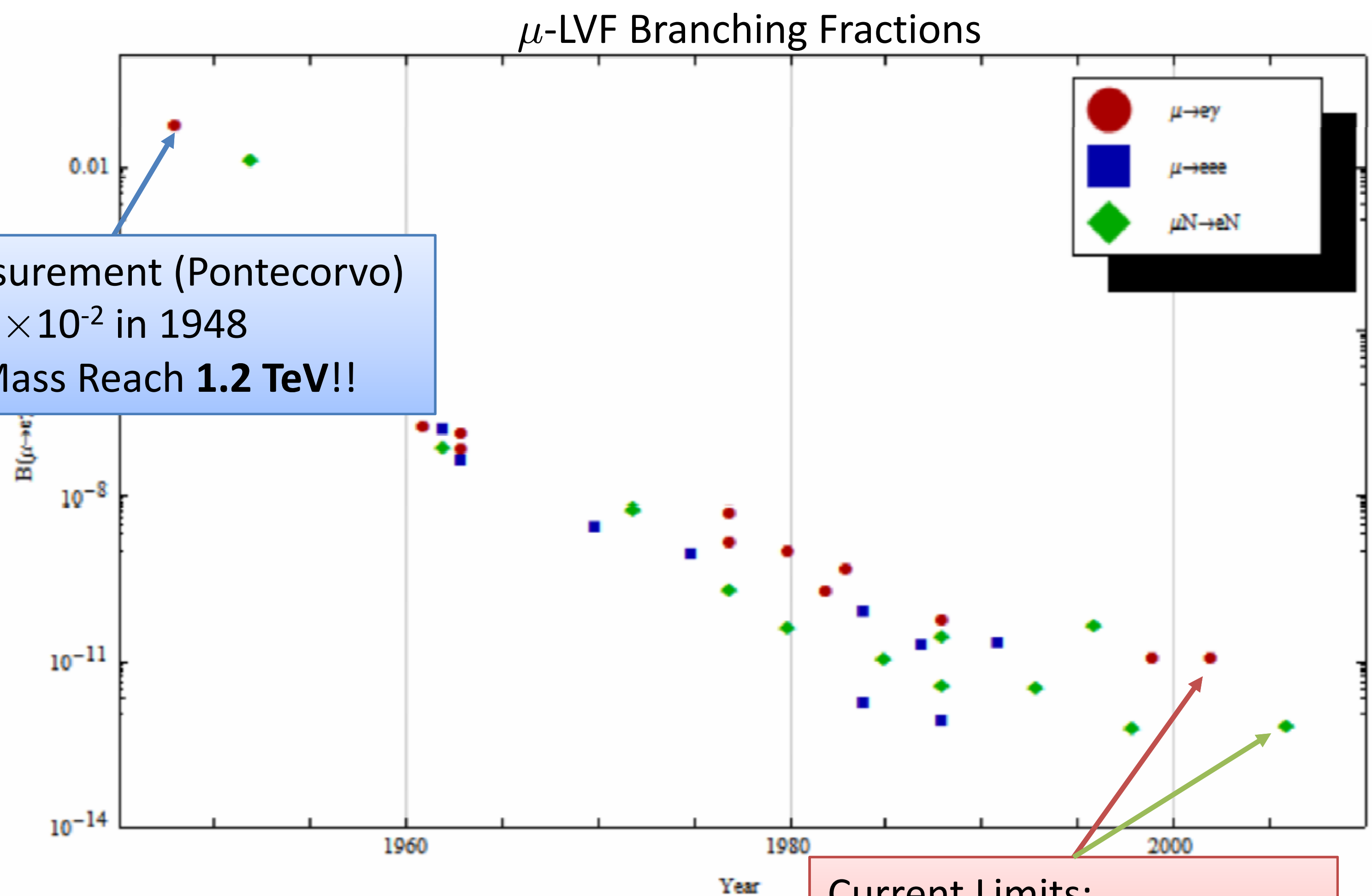
Randall-Sundrum

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

We measure R(μ N $\rightarrow$ 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

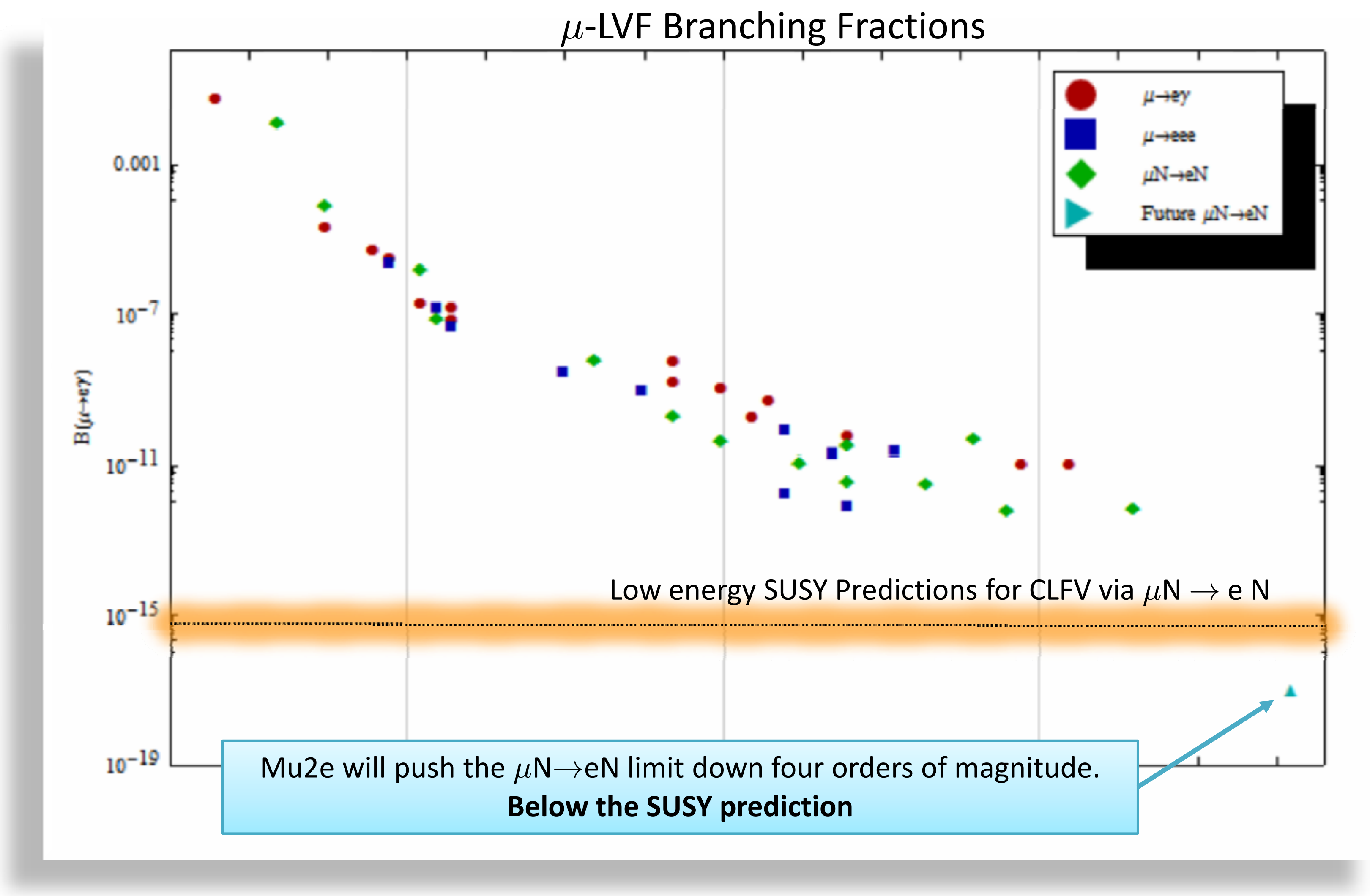
A Brief History of μ-cLFV



First Measurement (Pontecorvo)
6×10^{-2} in 1948
Effective Mass Reach **1.2 TeV**!!

Current Limits:
1.2×10^{-11} (MEGA $\mu\rightarrow e\gamma$)
7×10^{-13} (Sindrum II on Au)

A Brief History of μ-cLFV



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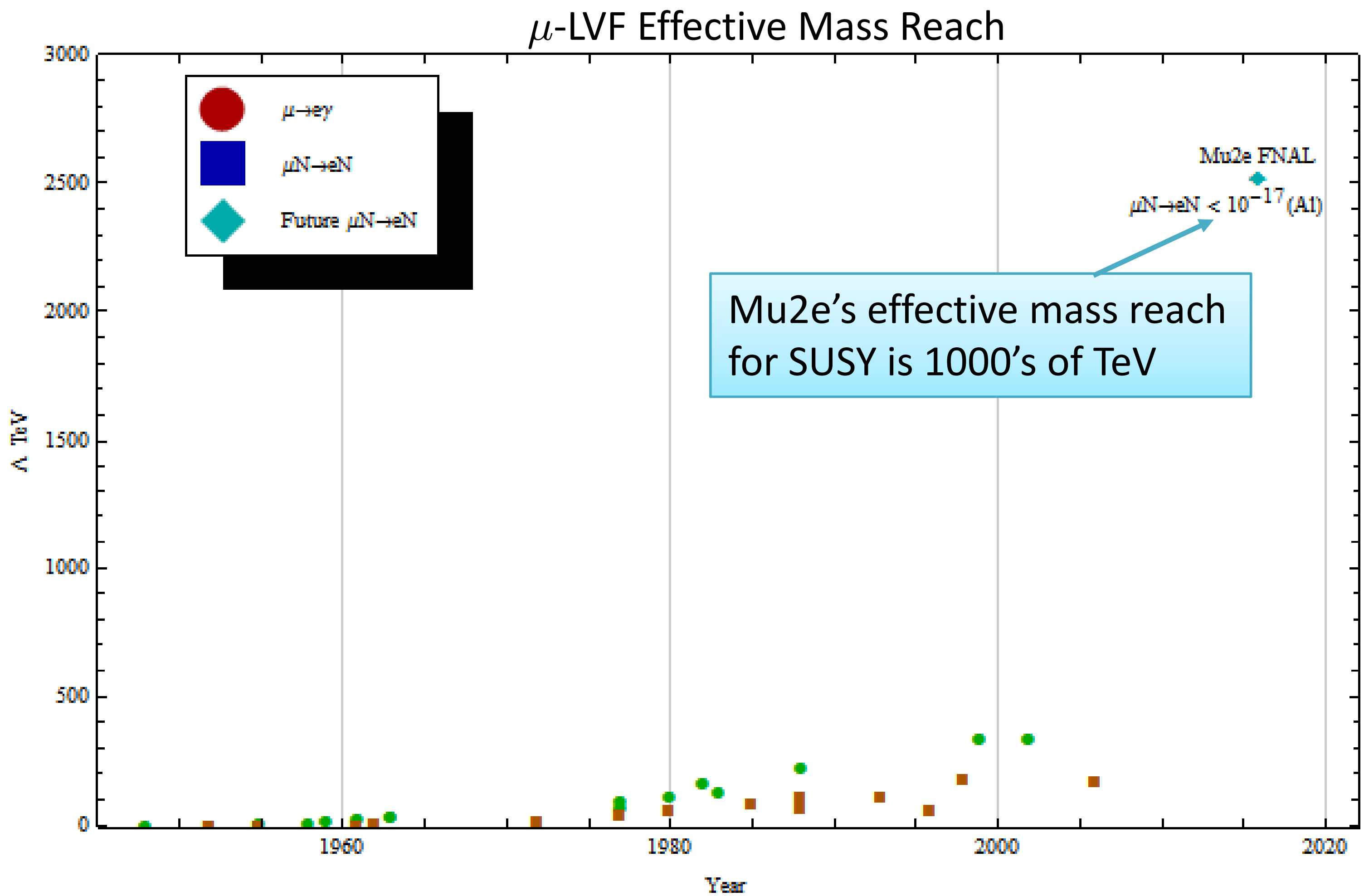
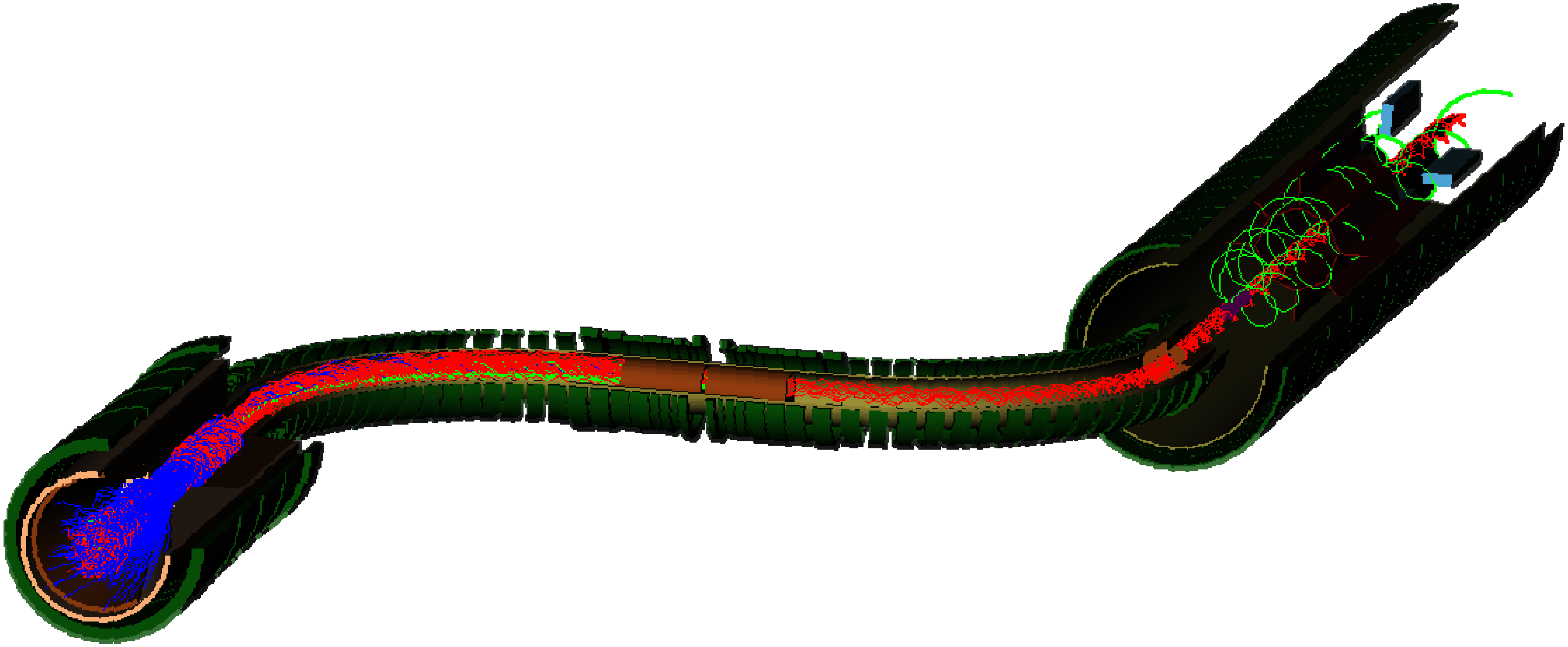




MU2E AT FNAL

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:

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

- Report the rate relative to nuclear capture

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

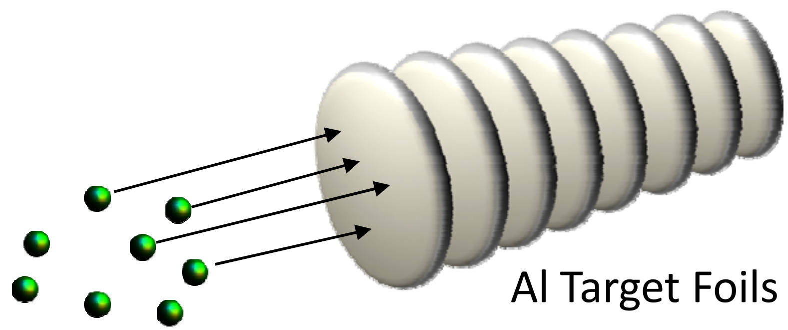
- *If we see a signal, it's compelling evidence for physics beyond the standard model!*

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
    $\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z c^2} \approx 19.6 fm\ (for\ Al)$
  - 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**: $\mu^- \rightarrow e^- \nu \bar{\nu}$

$\approx$ 50% stop in target



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

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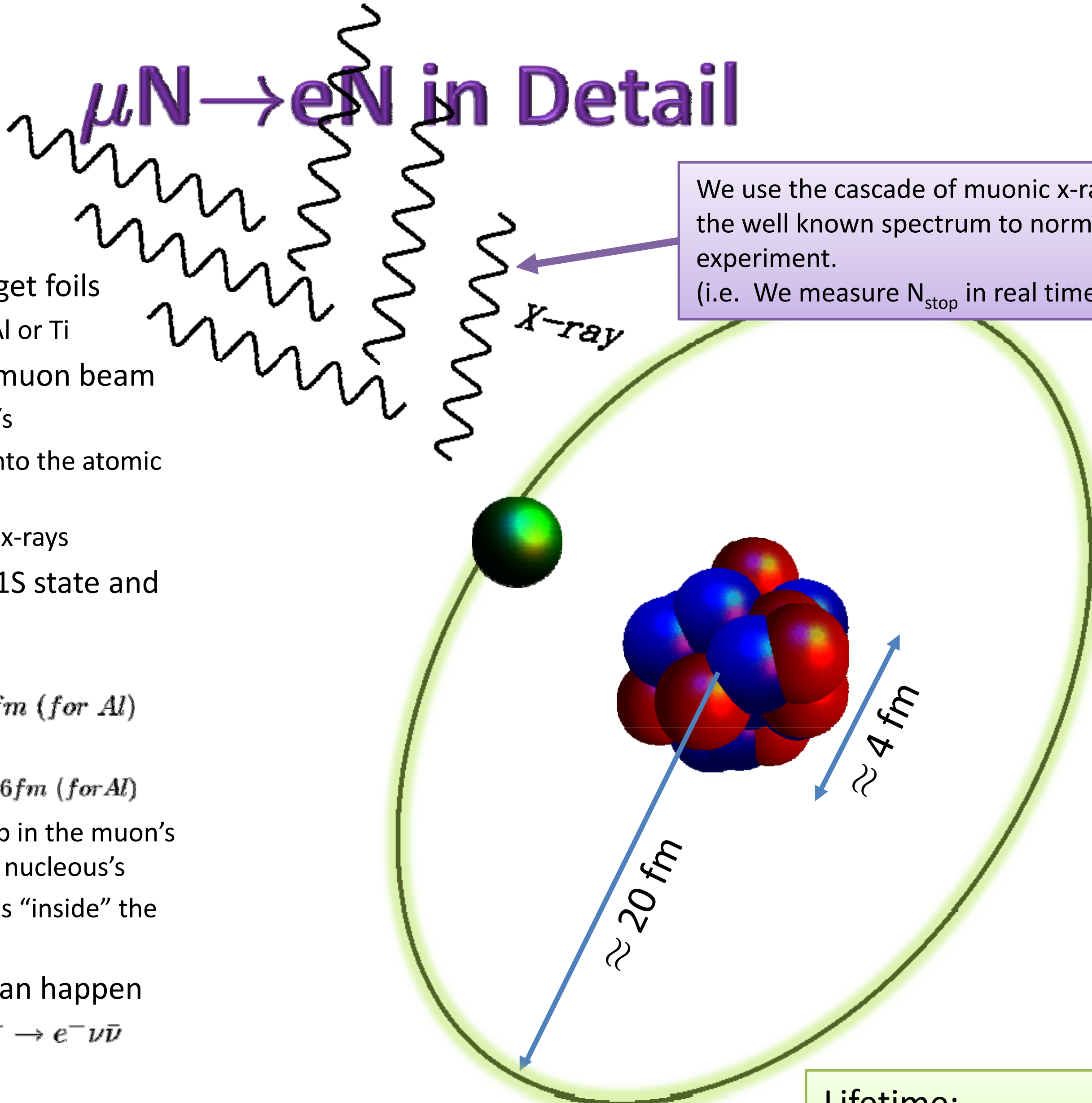
We use the cascade of muonic x-rays and the well known spectrum to normalize the experiment.
(i.e. We measure N_{stop} in real time)



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

μN→eN in Detail

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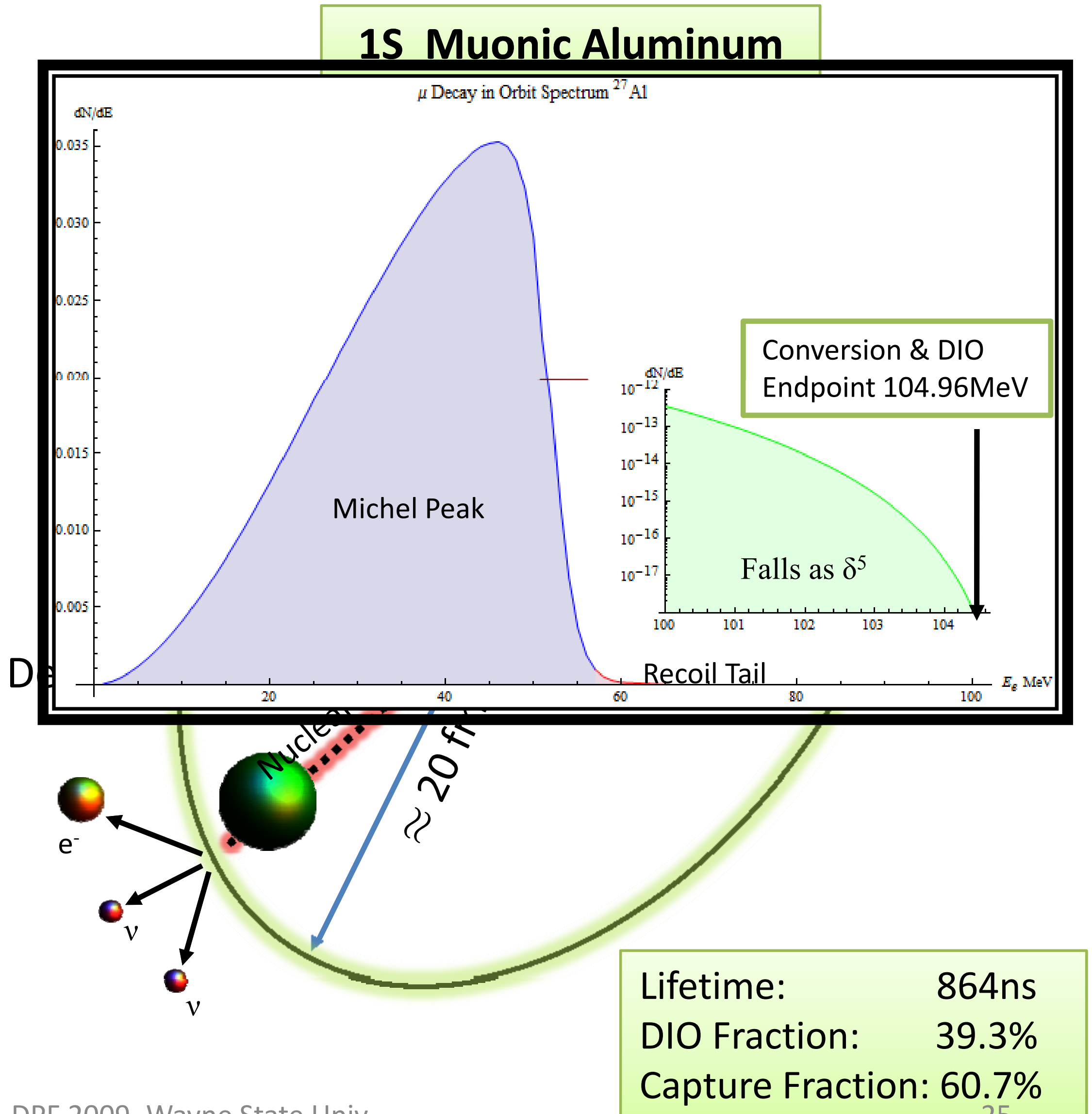

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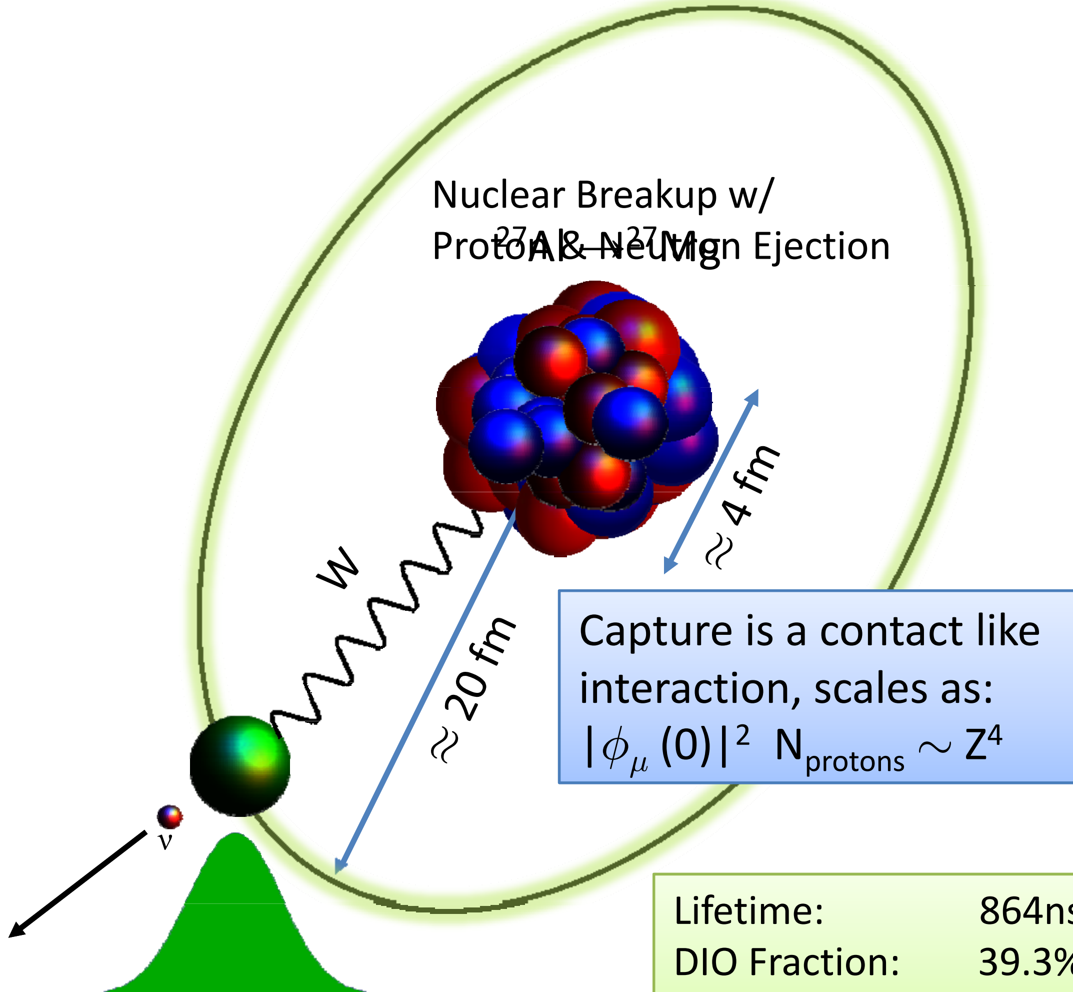
  - Decay in Orbit: $\mu^- \to e^- \nu \bar{\nu}$
  - **Nuclear Capture**: $\mu^- N(Z) \to \nu N(Z-1)$

Ordinary Muon Capture (OMC)



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
    $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu Z c^2} \approx$
  - Nuclear Size
    $R \approx 1.2A^{1/3} f$
  - Provides large 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 Captur**: $\mu^- N(Z) \to \nu N(Z-1)$

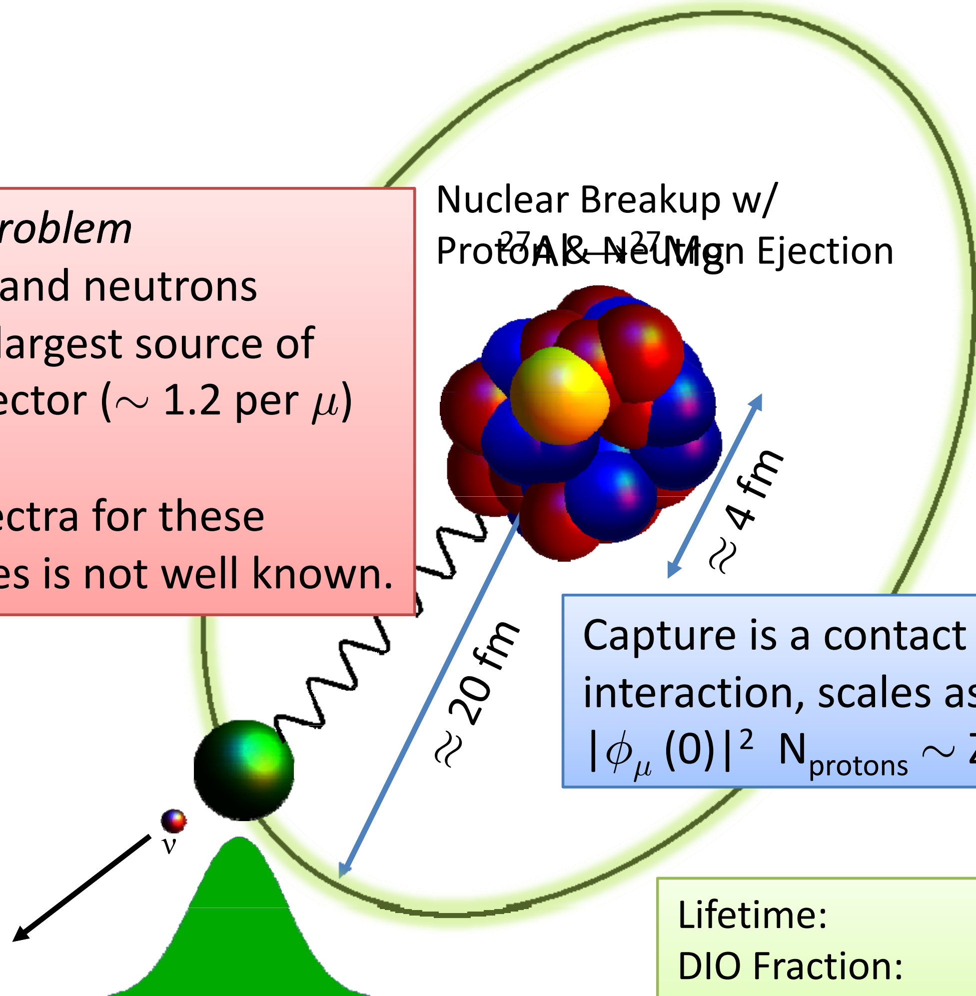
Ordinary Muon Capture (OMC)

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.

Nuclear Breakup w/
Proton & Neutron Ejection
$^{27}Al \to {}^{27}Mg$



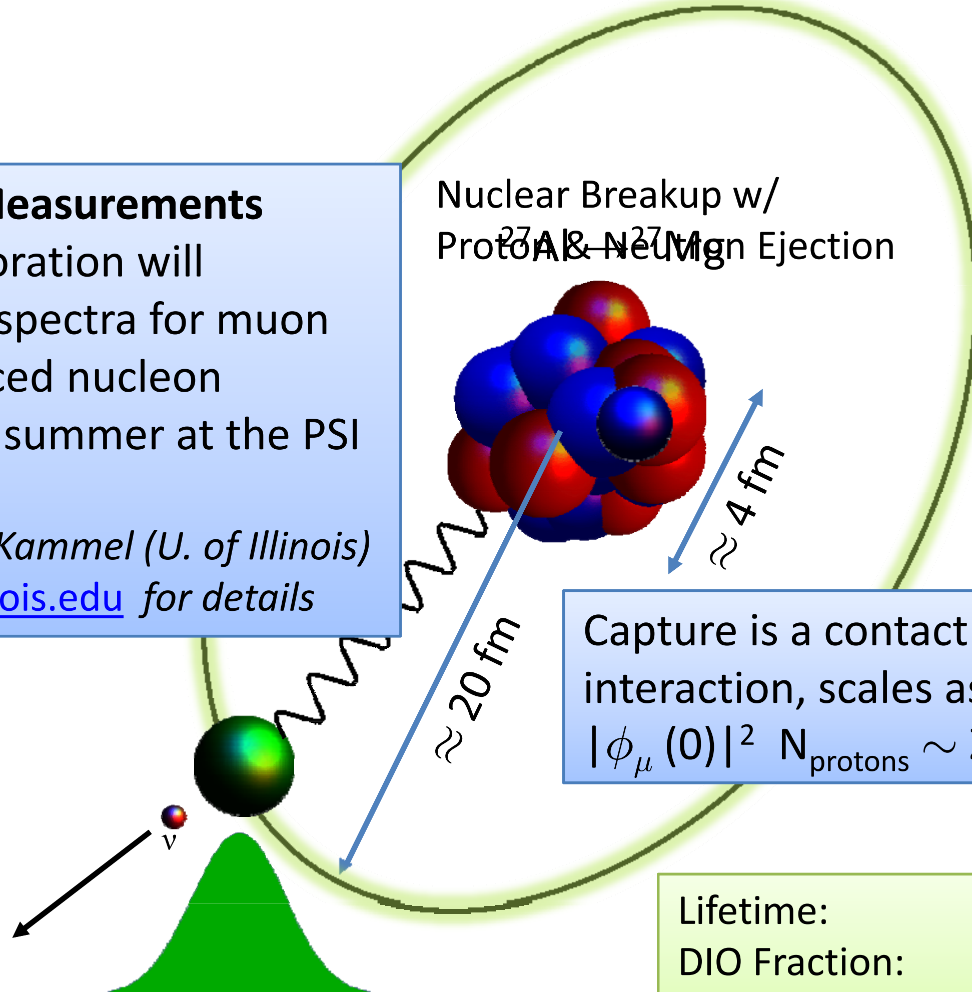
Capture is a contact like interaction, scales as:
$|\phi_\mu(0)|^2 \; N_{protons} \sim Z^4$

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

Muonic Atom

- Start with a series of target foils
  - We stop ≈ 50% of μ 's
- Bring in the low energy muon beam
  - We stop ≈ 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 $\langle r_\mu \rangle = \frac{n^2\hbar}{m_\mu z c^2} \approx 19$
  - 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**: $\mu^- N(Z) \rightarrow \nu N(Z-1)$

Ordinary Muon Capture (OMC)



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*

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

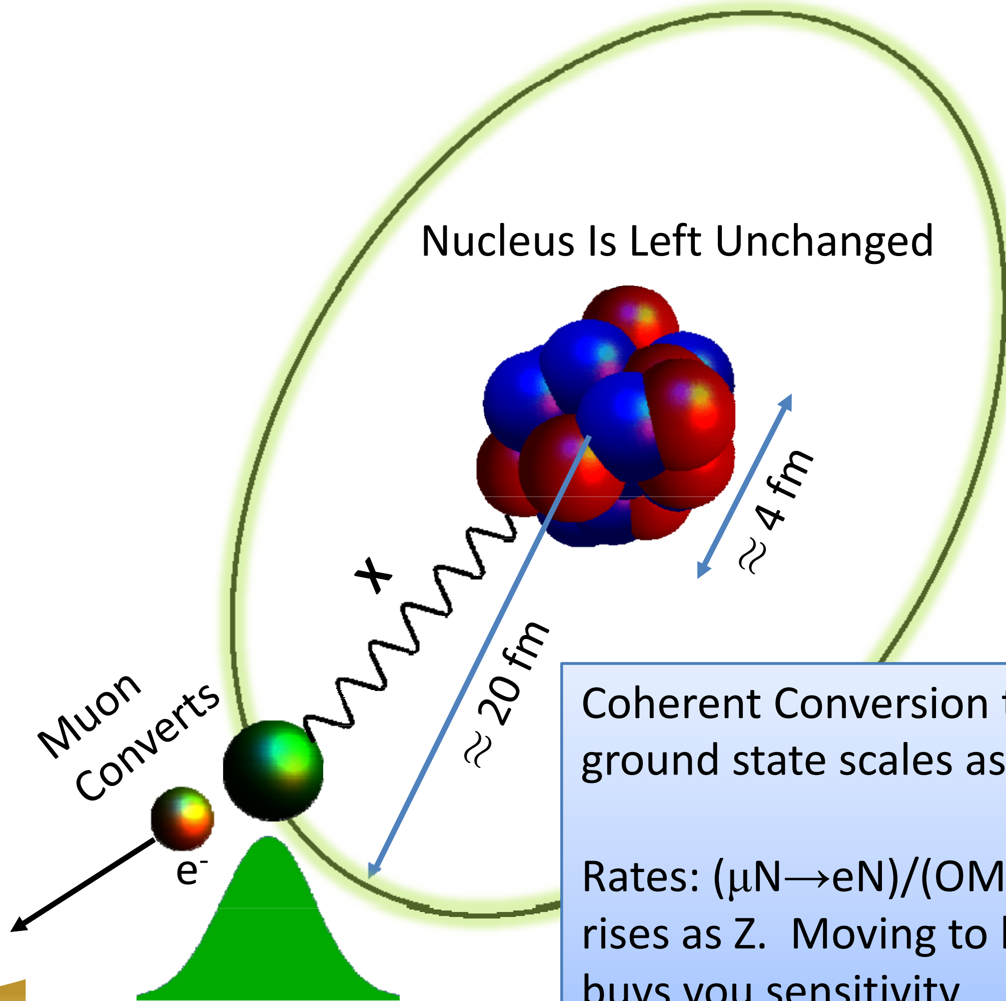
Lifetime:	864ns
DIO Fraction:	39.3%
Capture Fraction:	**60.7%**

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: $\mu^- \to e^- \nu \bar{\nu}$
  - Nuclear Capture: $\mu^- N^Z \to \nu N^{Z-1}$
  - **New Physics! i.e. μ N $\to$ e N**

$E_e \approx 105$ MeV

Coherent Conversion ($\mu \to$e)

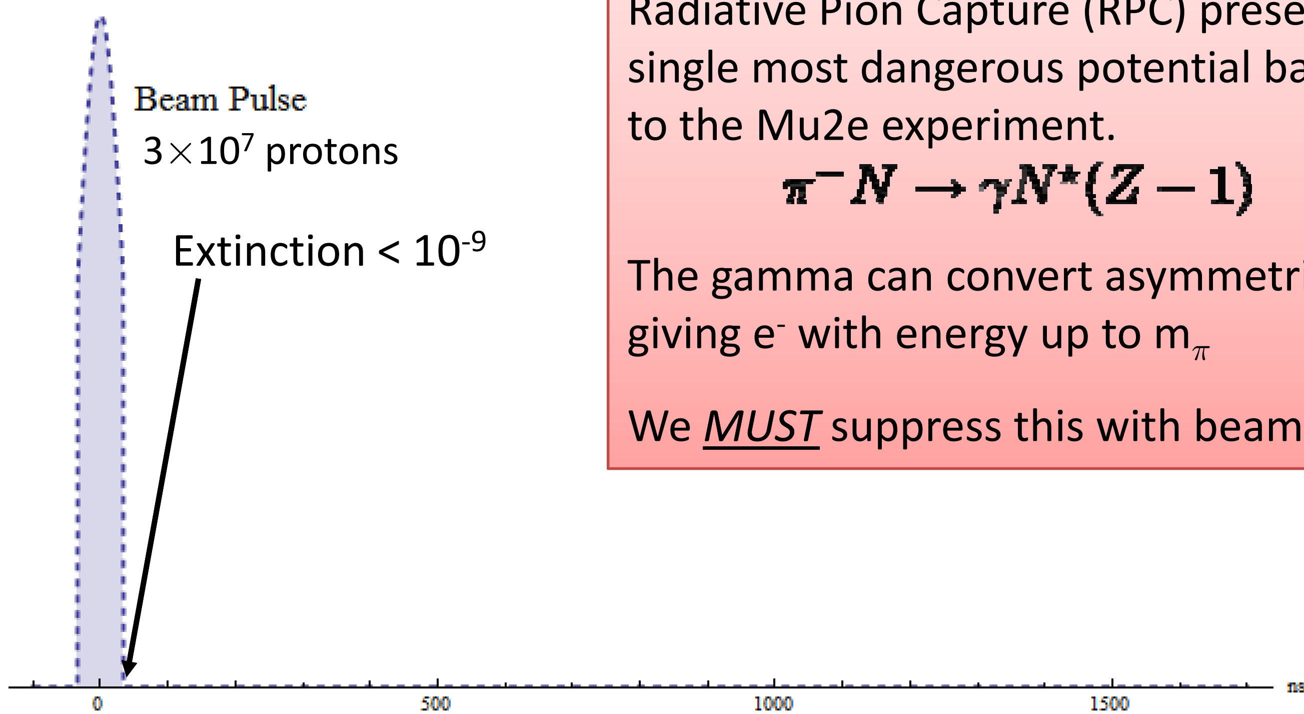


Coherent Conversion to the ground state scales as $\sim Z^5$.

Rates: (μN$\to$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

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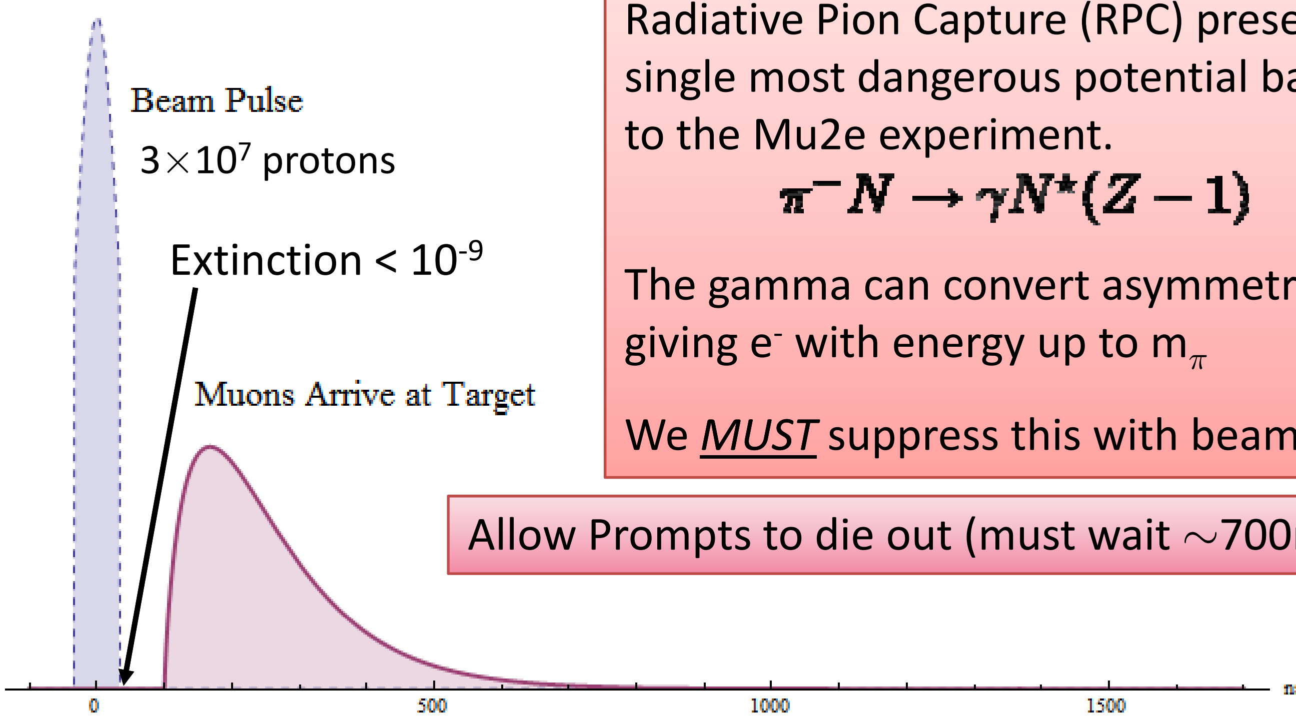


Prompt Backgrounds

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

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

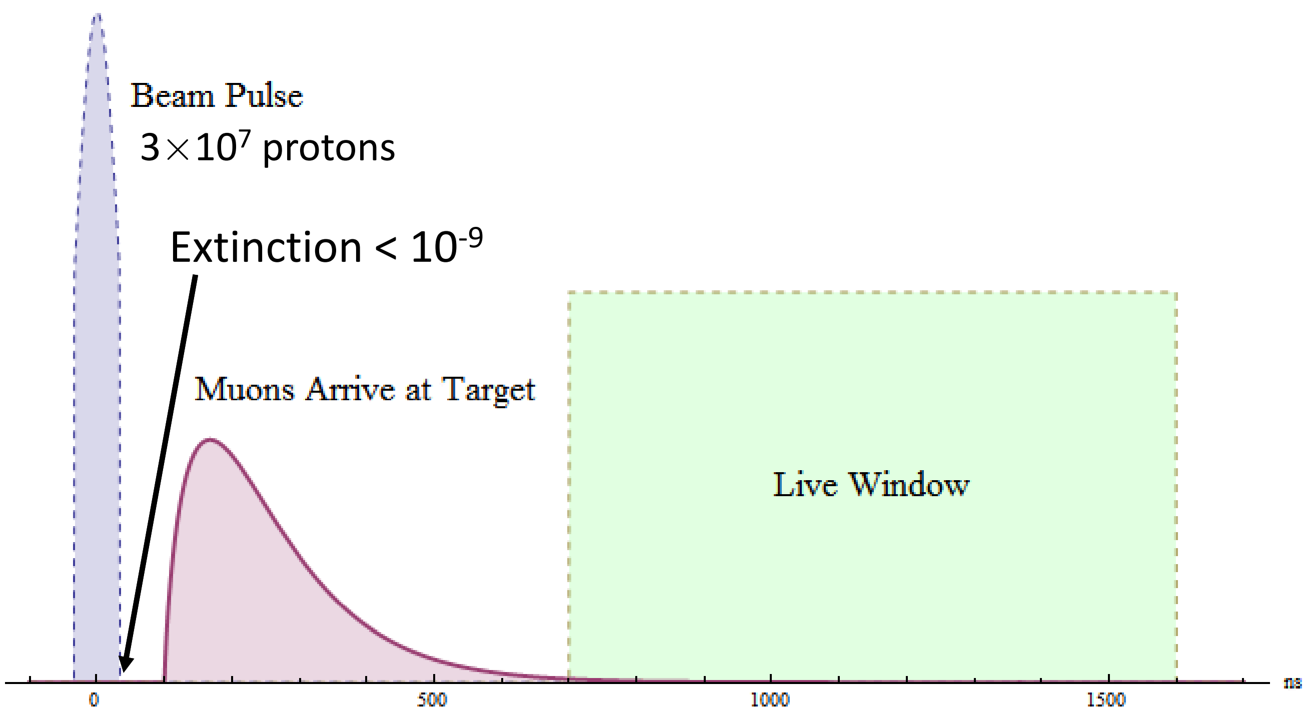
The gamma can convert asymmetrically giving e^- with energy up to m_π

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, ….
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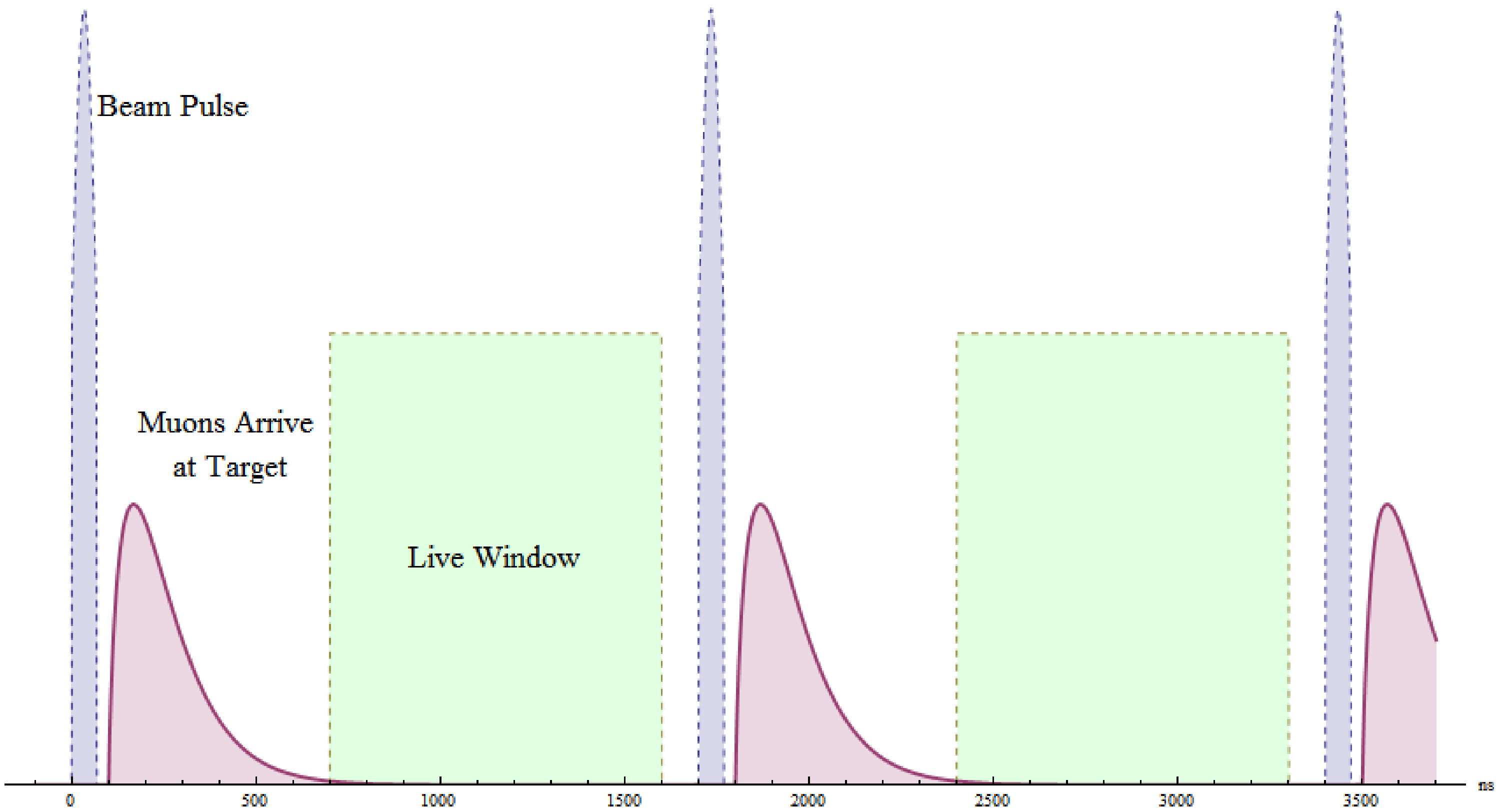

Total Backgrounds

- 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)
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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
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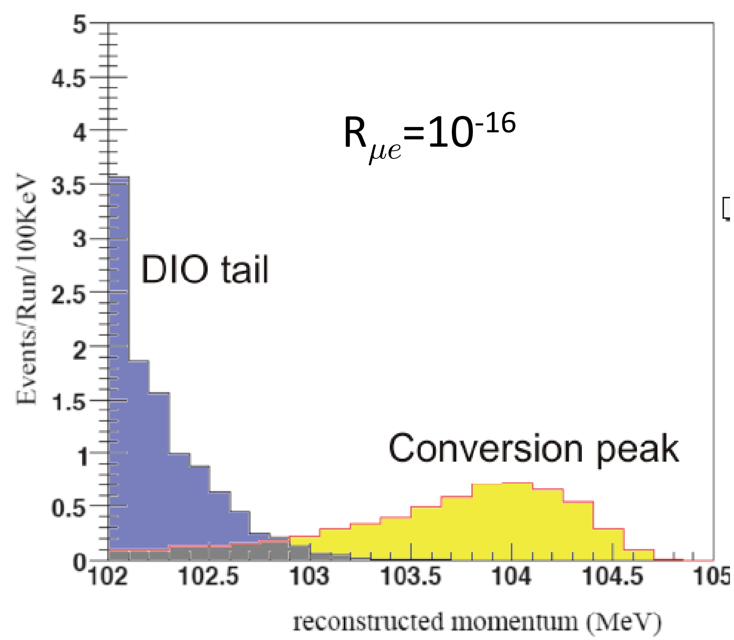
Radiative π capture	0.072
π Decay in flight	<0.001
Pat. Recognition Errors	<0.002
Total	0.415

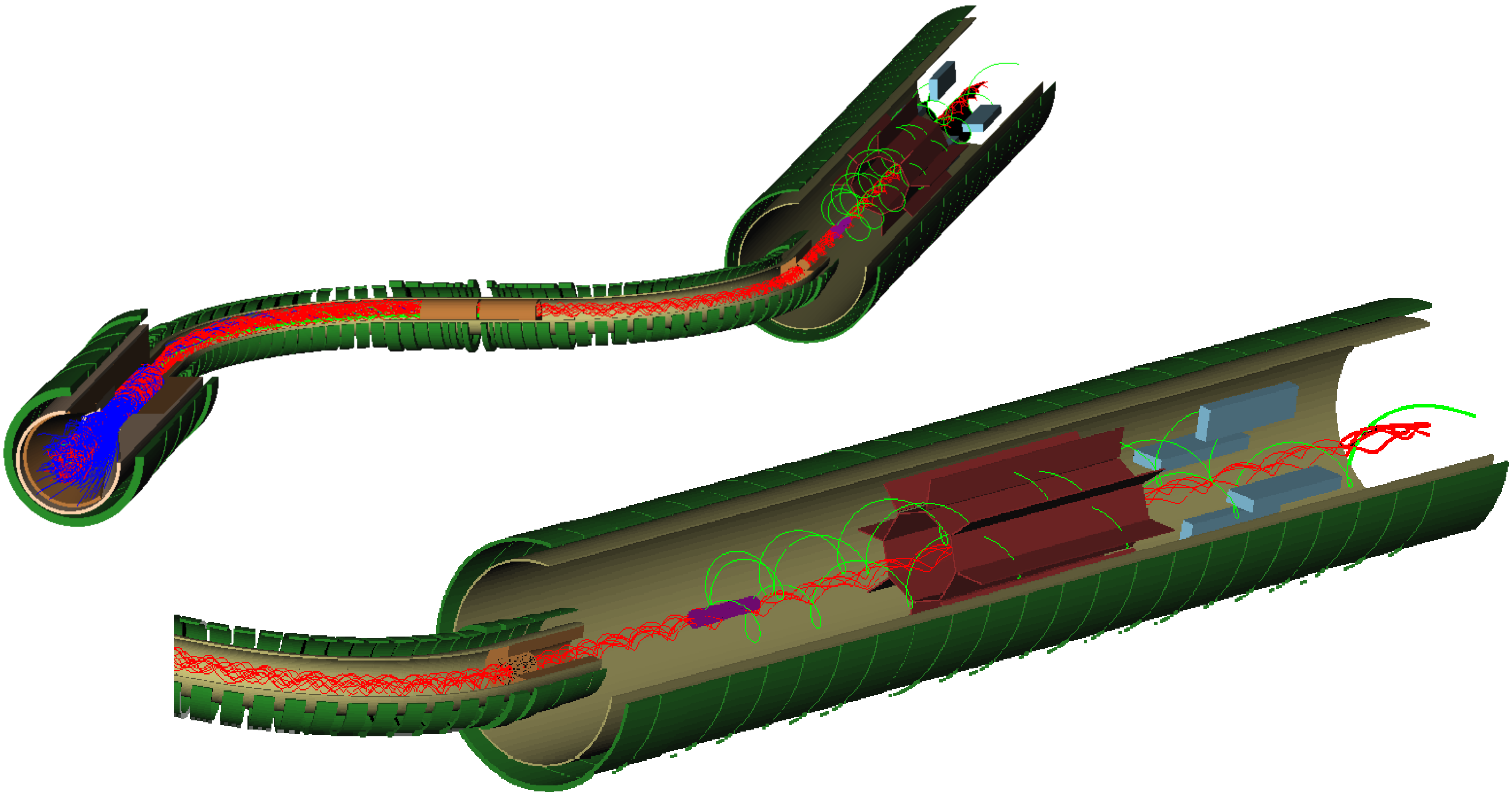
Signal to All Backgrounds

- 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

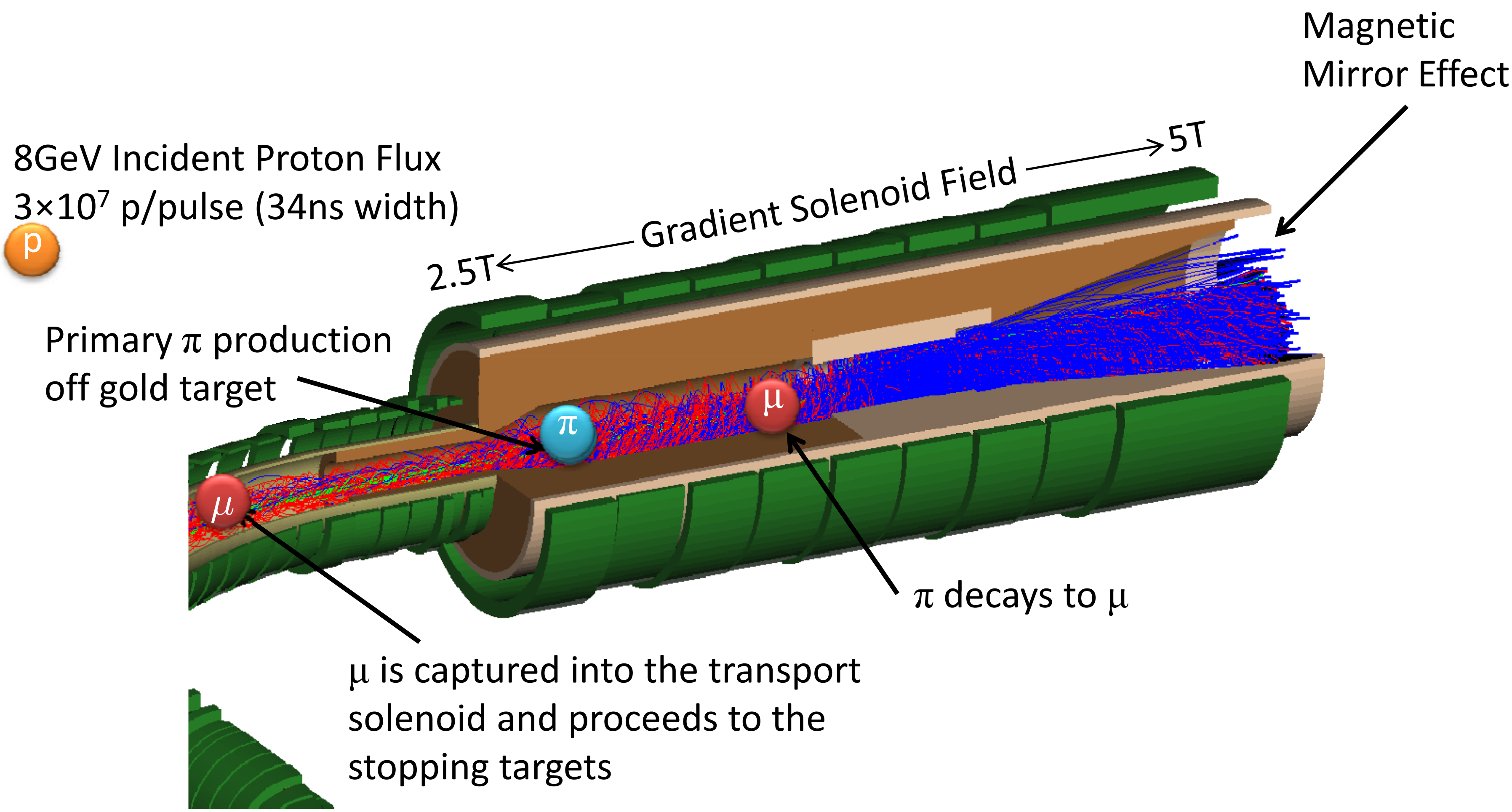
$$\frac{S}{\sqrt{B}} \sim 5.5$$



The Mu2e Detector in Detail

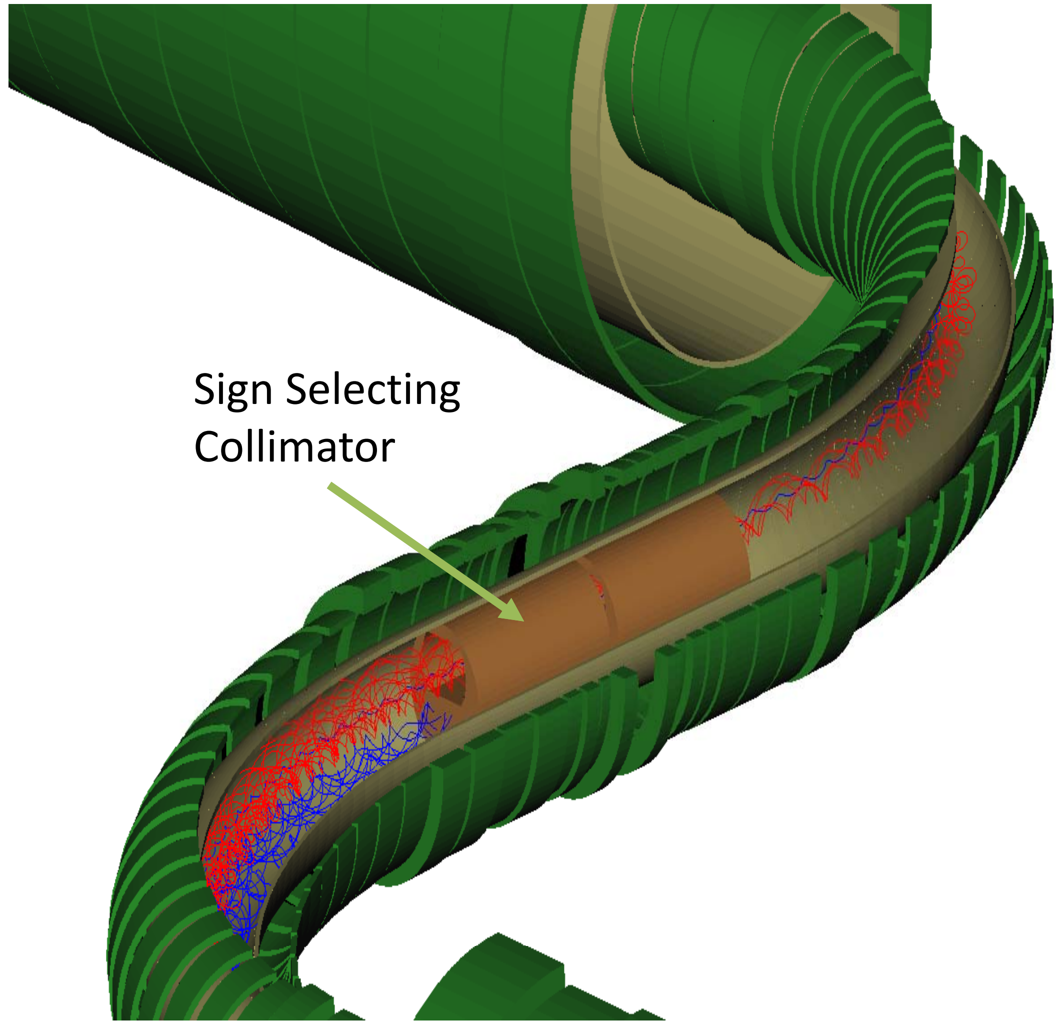


Production Solenoid

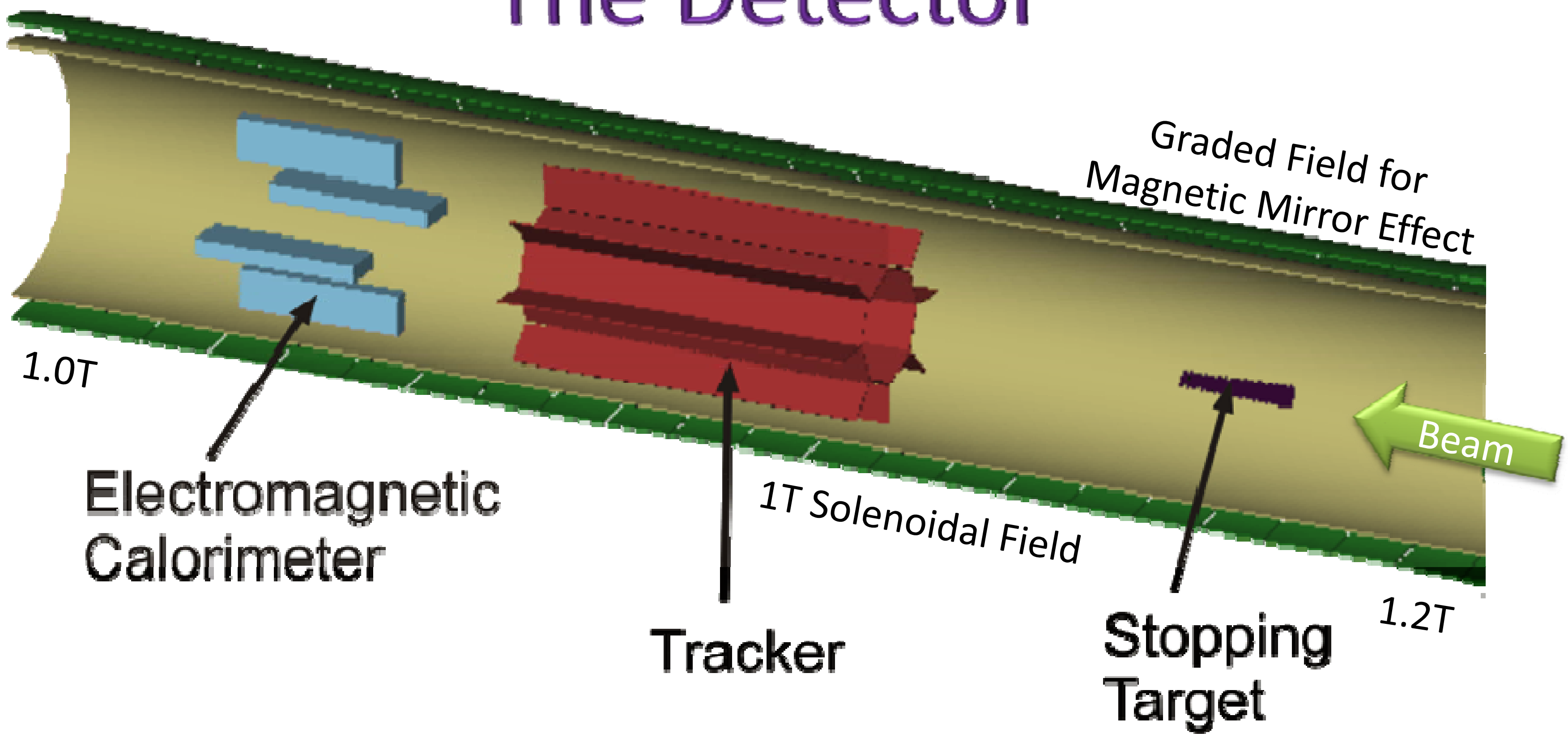


Transport Solenoid

- 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



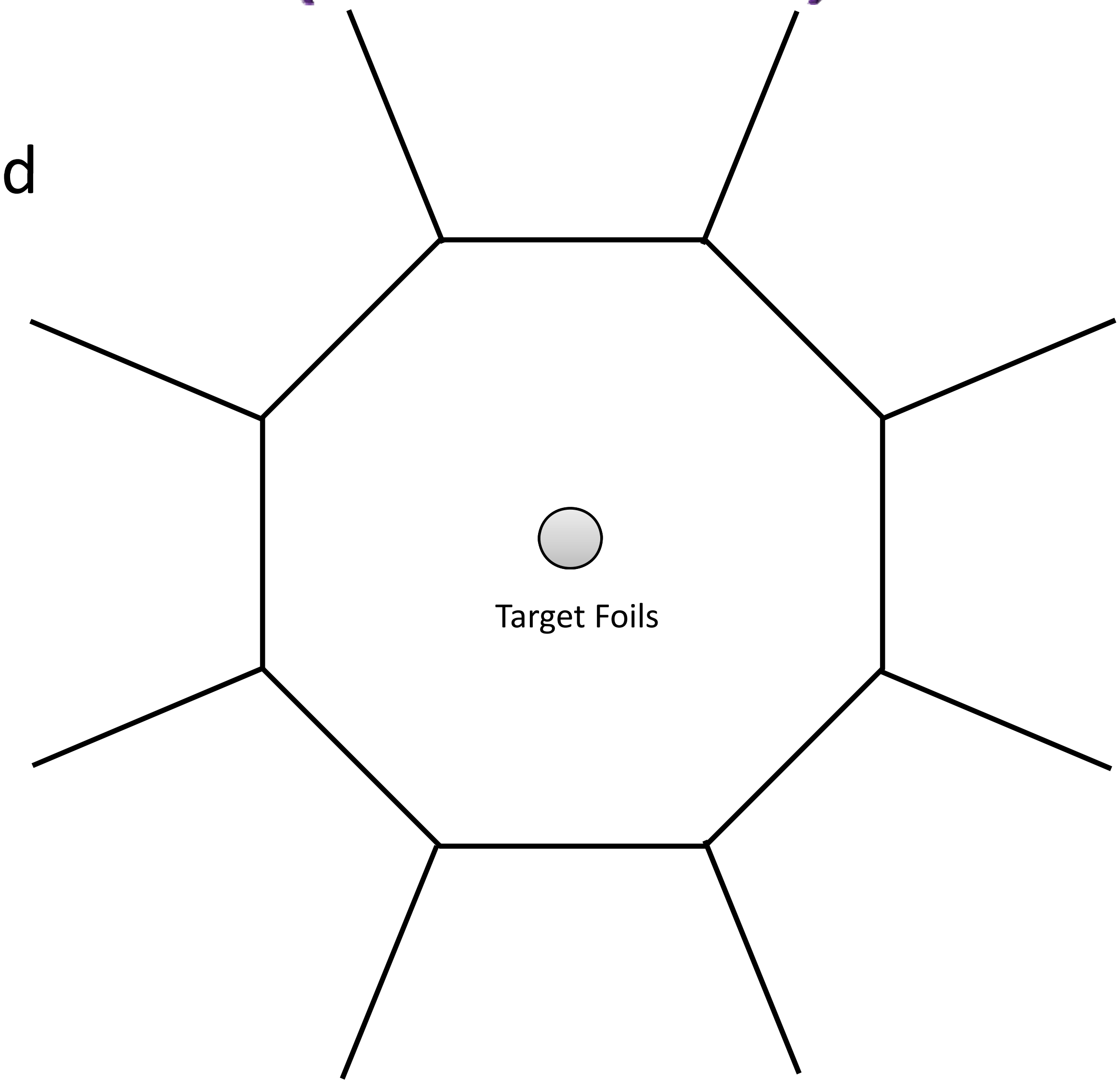
The Detector



- 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}



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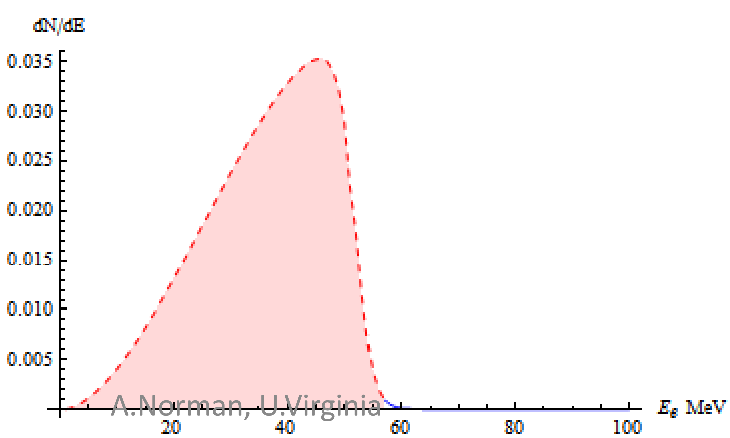

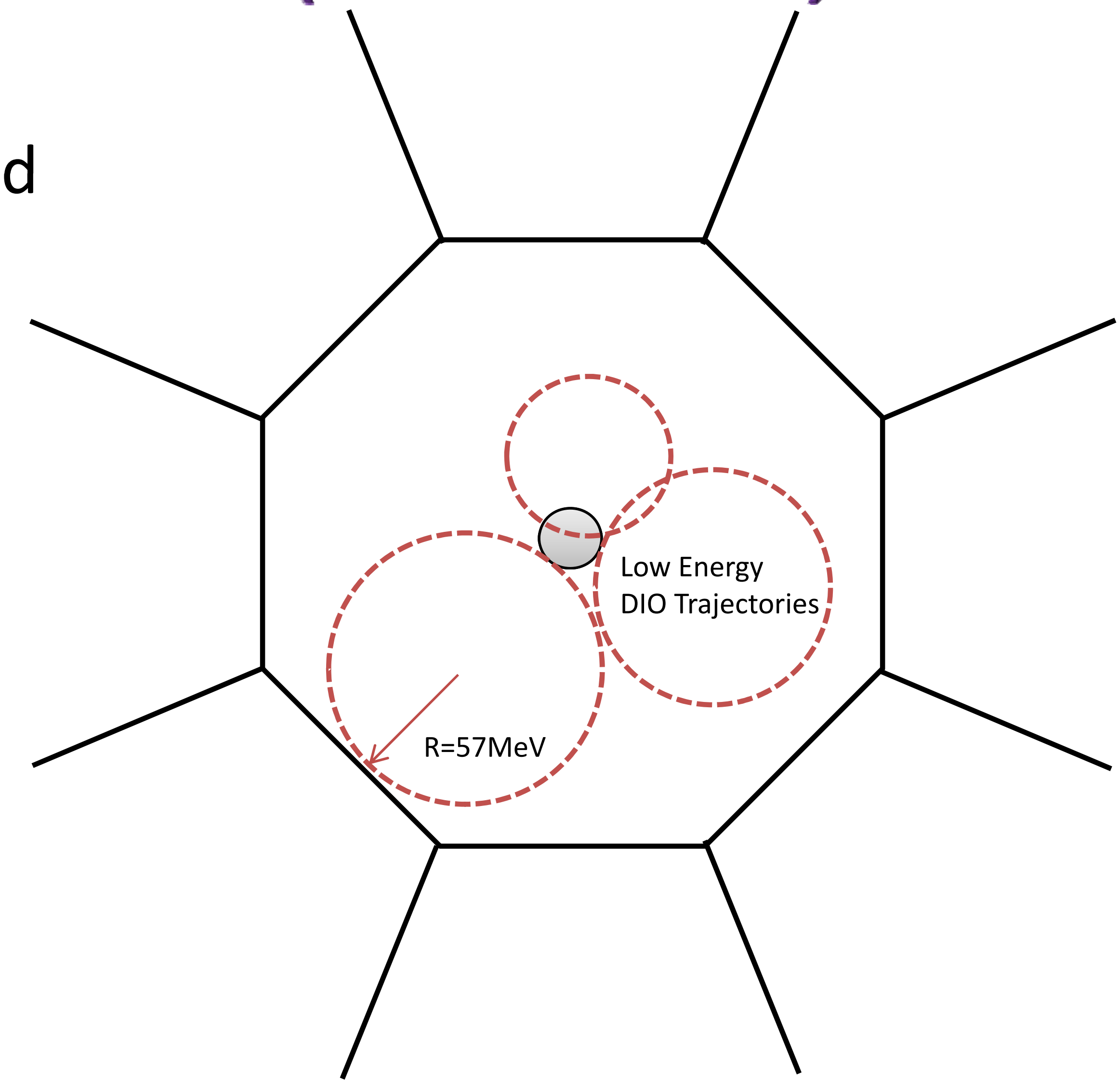

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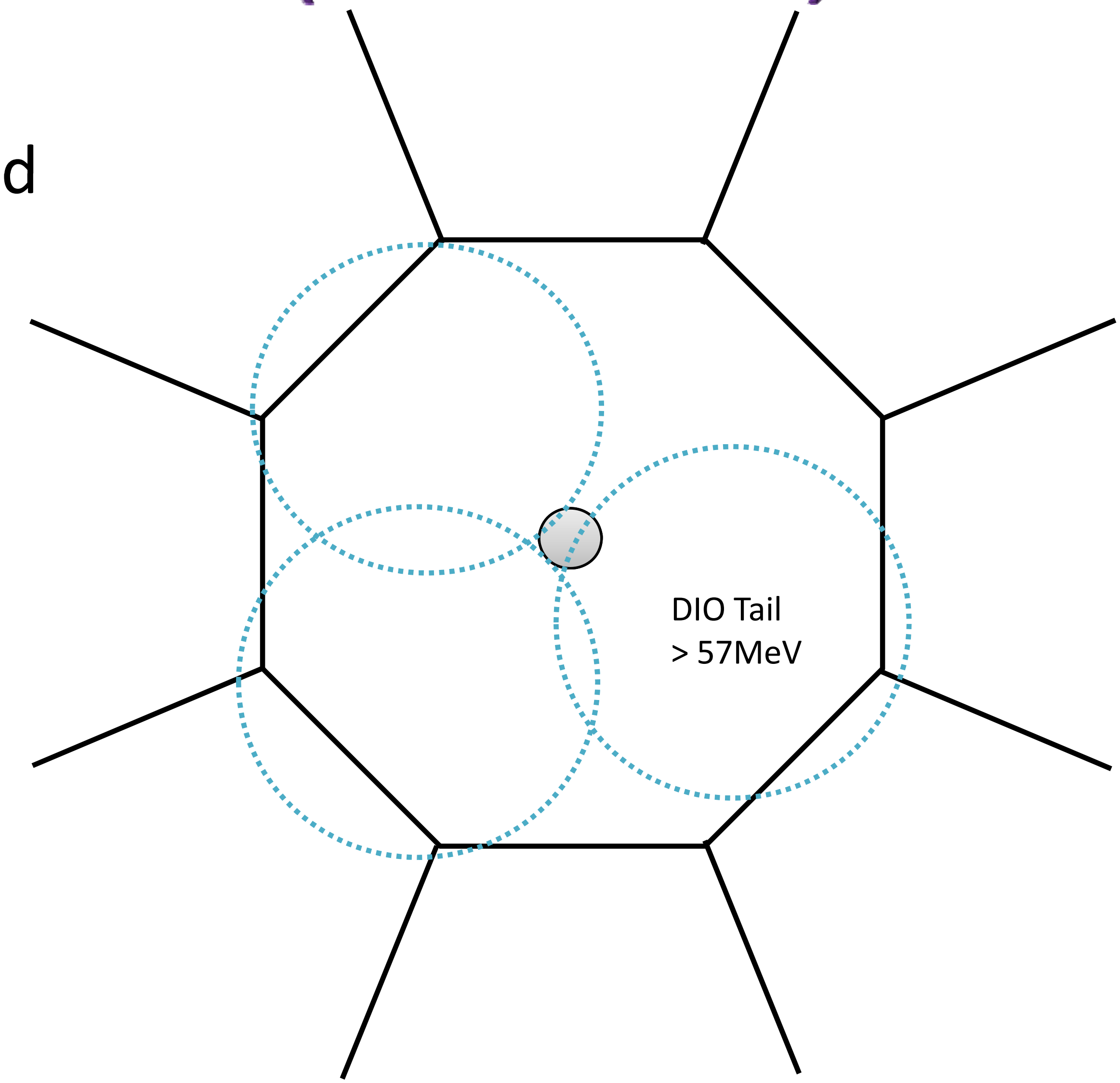

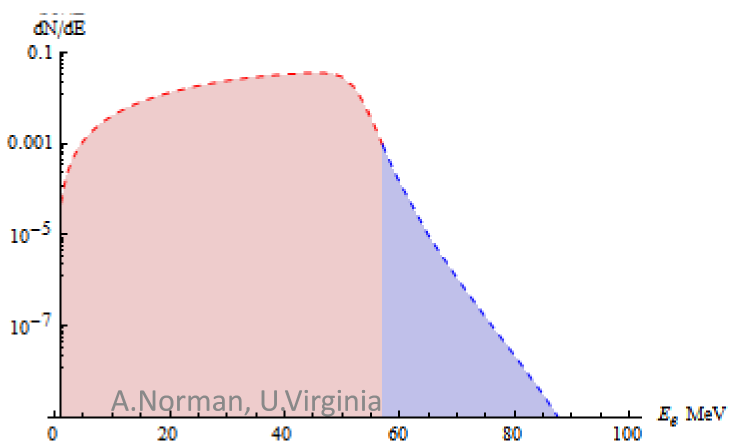

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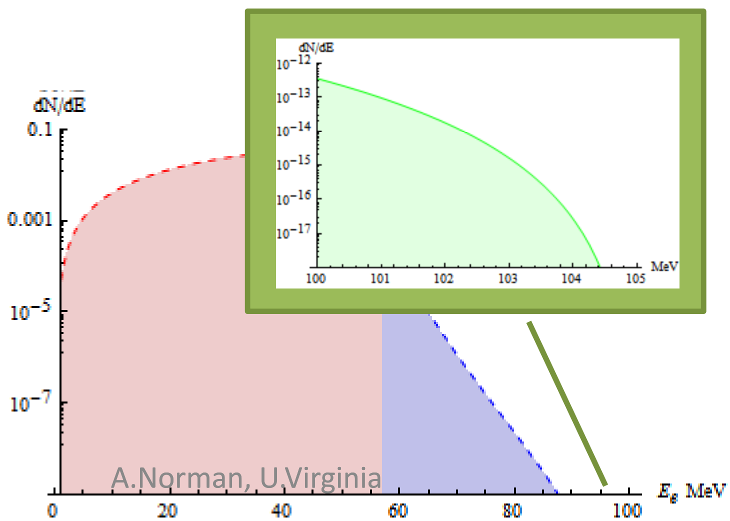
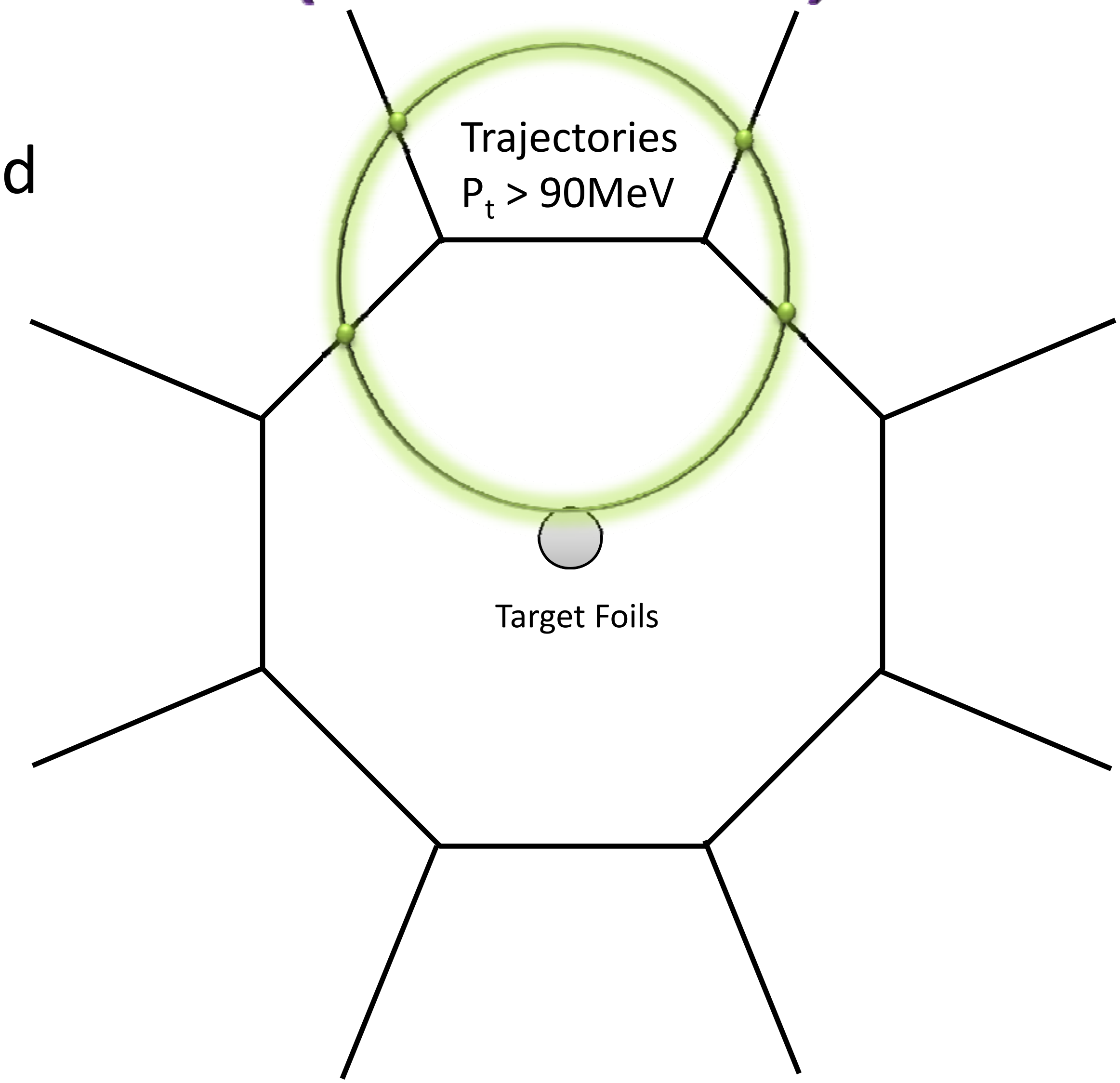
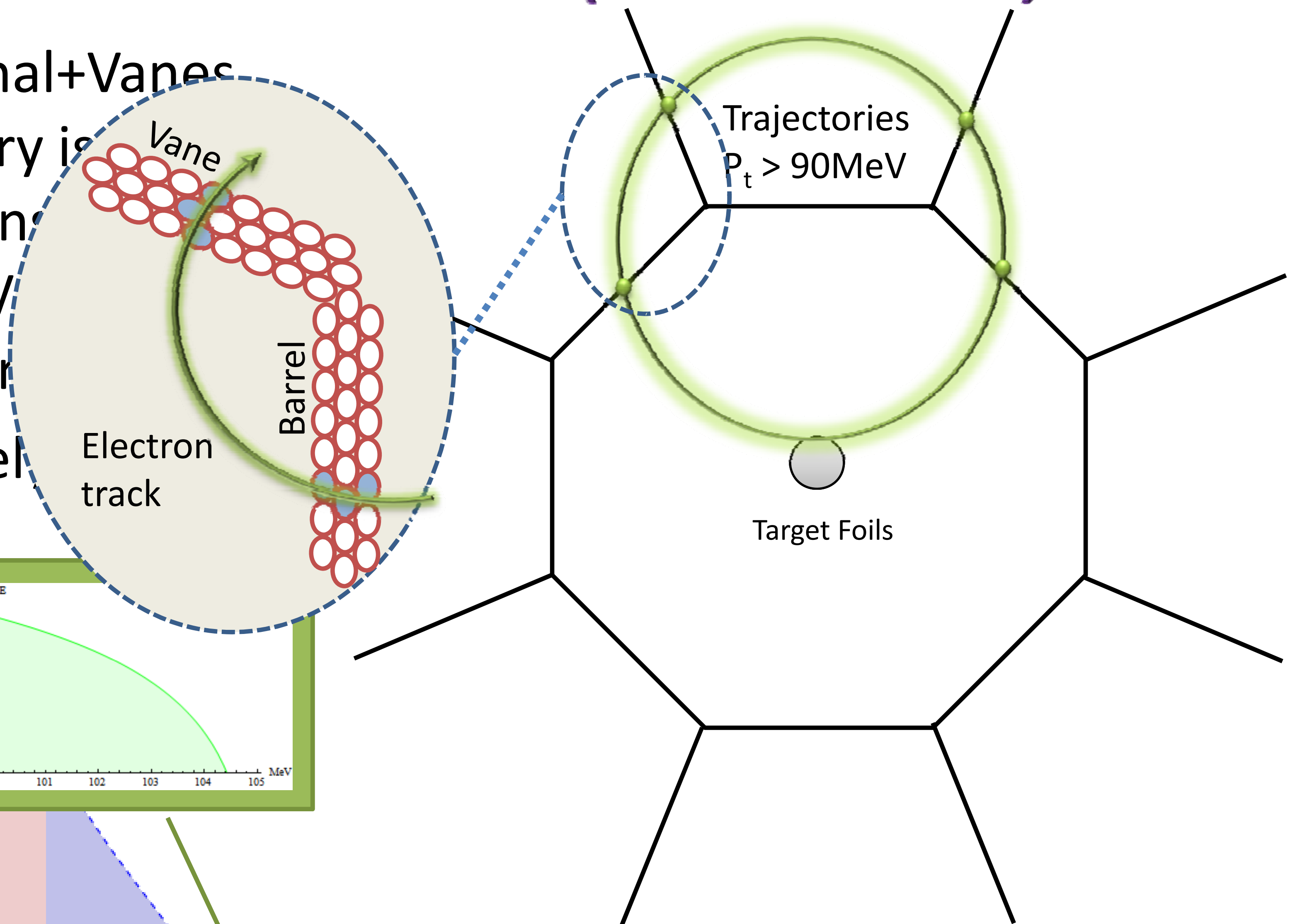
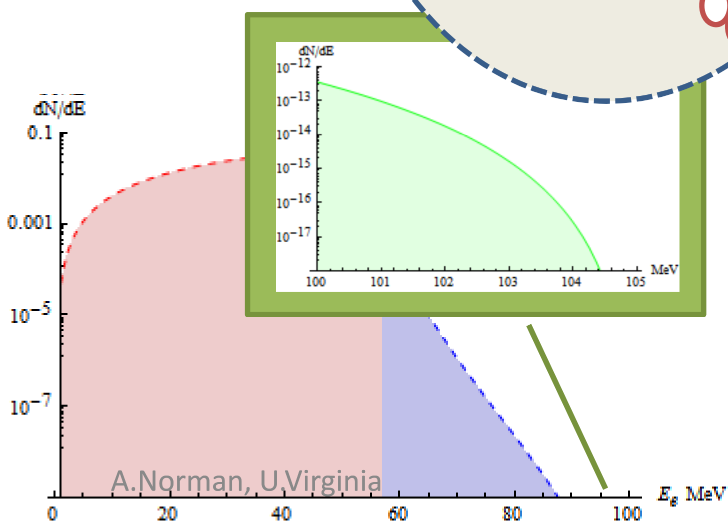




Straw Tracker (In Vacuum)

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

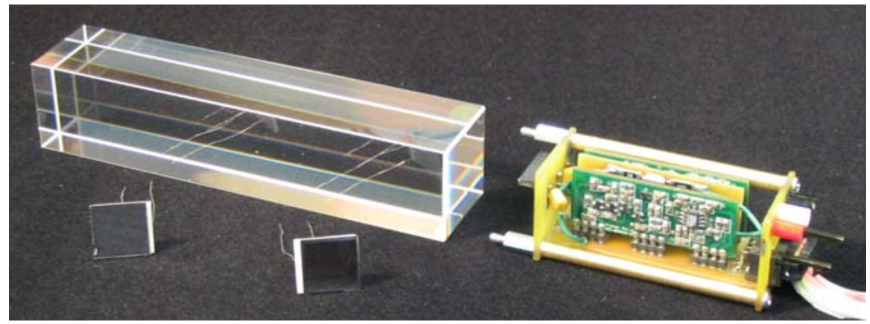


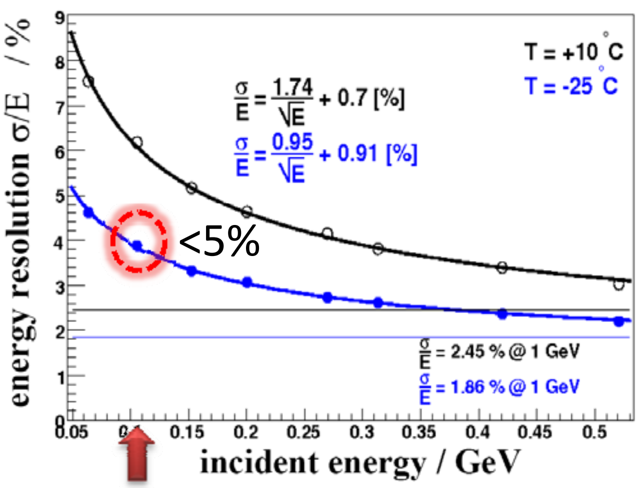


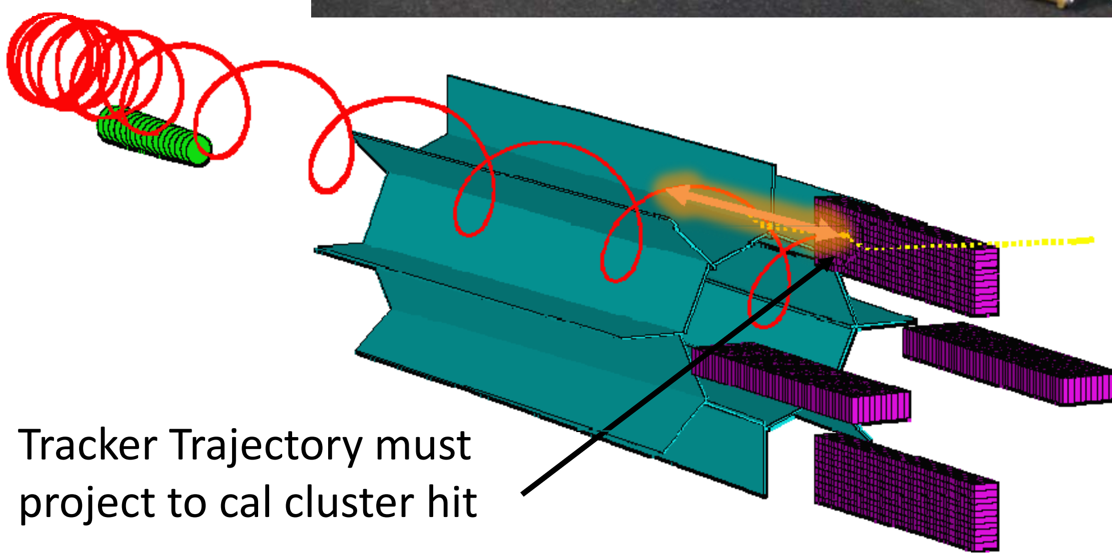
Crystal Calorimeter

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

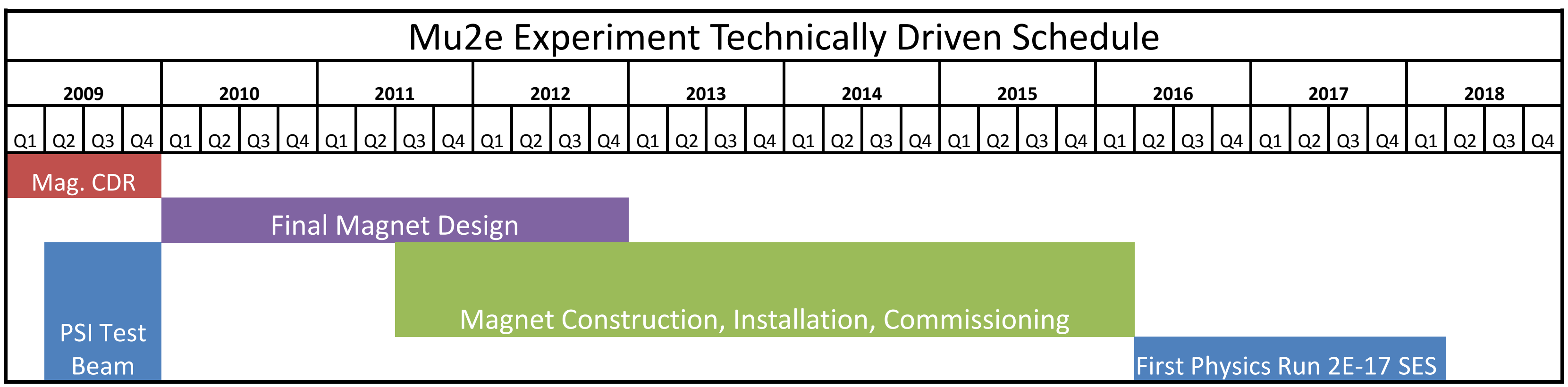






Cost and Schedule

- 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



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
- Charge Lepton Flavor Violation experiments 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
  - Spokesperson Contacts:
    - Robert Bernstein (rhbob@FNAL.gov)
    - James Miller (miller@buphy.bu.edu)

BACKUP SLIDES

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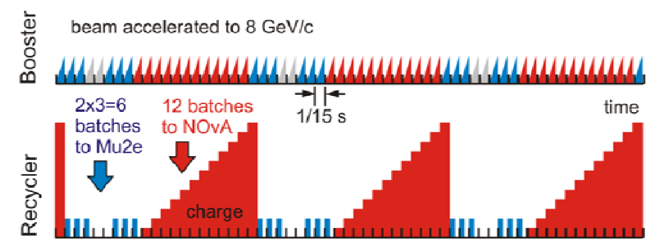
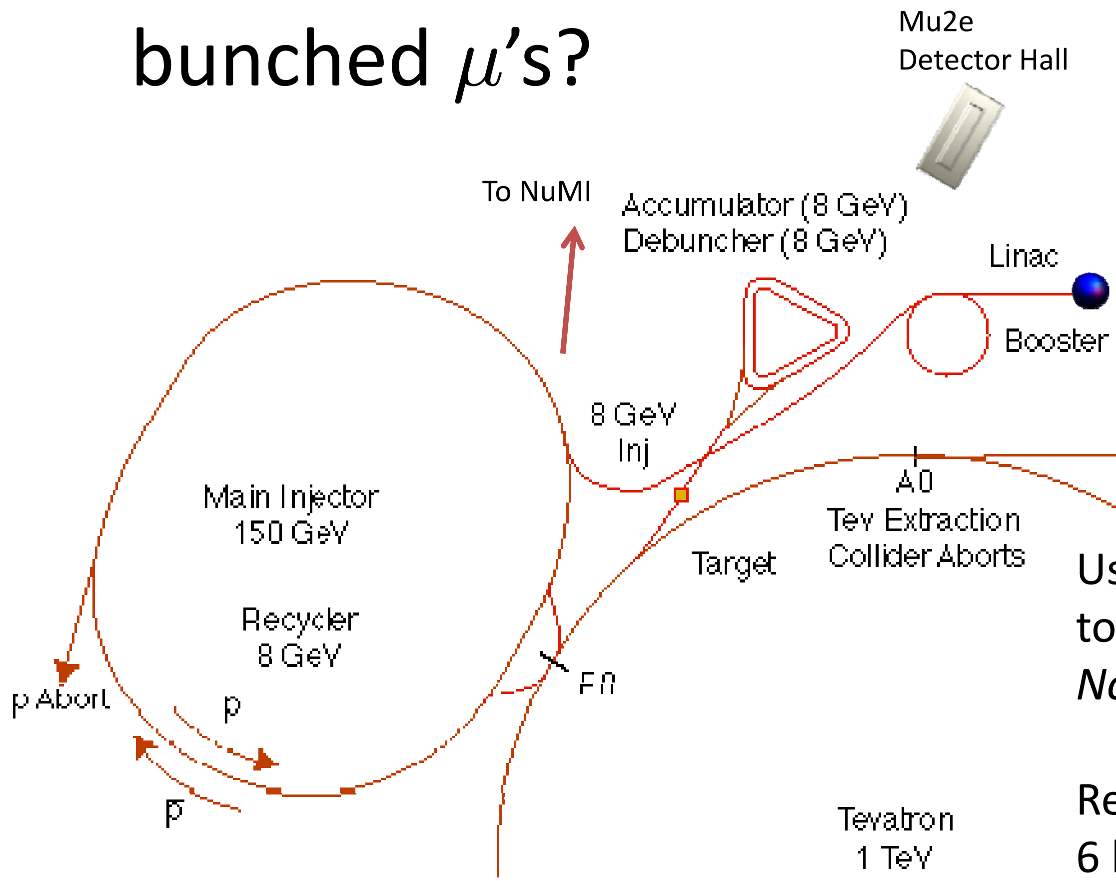
College of William and Mary
J.Kane

Mu2E & NOvA/NuMI

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





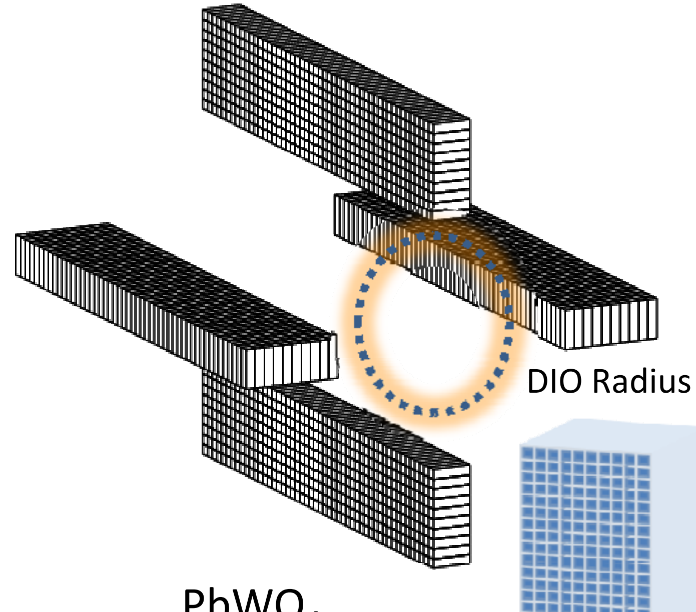
Use NuMI cycles in the Main injector to slow spill to Mu2e.
No Impact on NOvA

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

Crystal Calorimeter

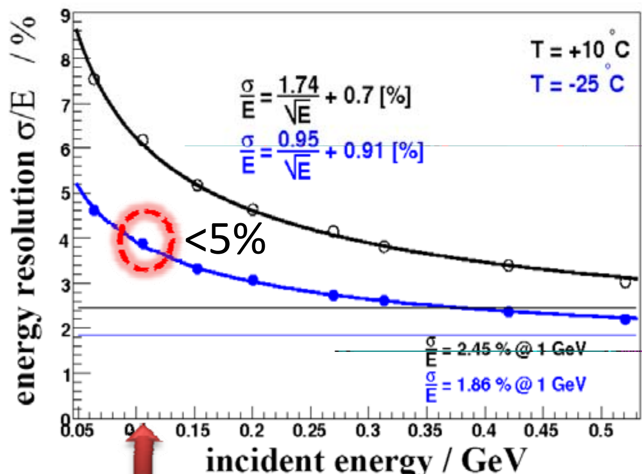
Original Design:

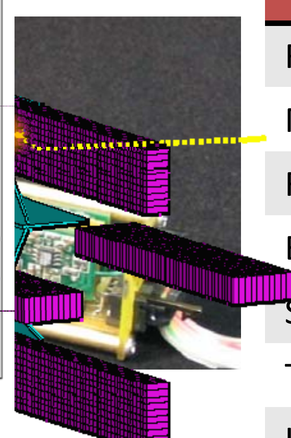
- 5% energy measure for trigger decision (1Hz rate)
- Timing edge for event reconstruction
- Spatial match to tracker trajectory
- Immune to DIO rates



PbWO$_4$

Tracker project



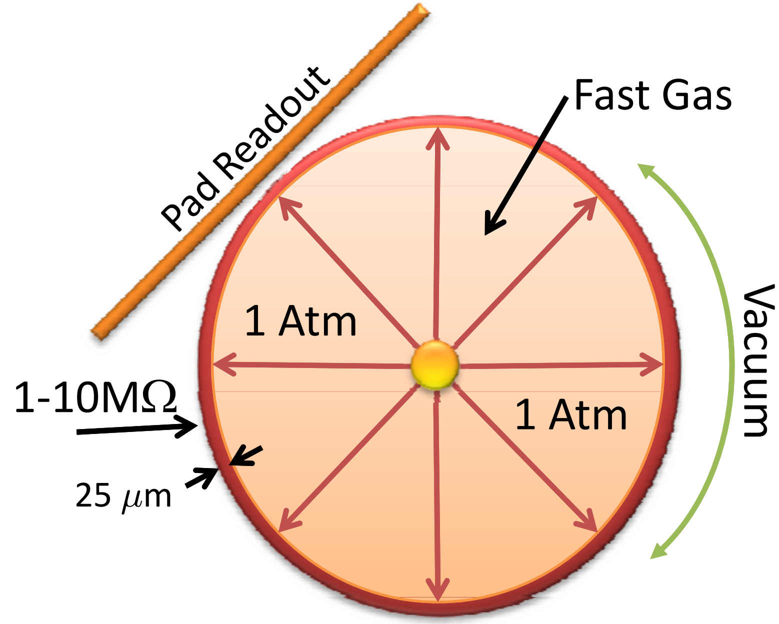


Calorimeter Properties	
Resolution	5%
Material	PbWO$_4$
Readout	Dual APD
Blocks	500 per fin, 4 fins
Segmentation	$30 \times 30 \times 120 mm^3$
Trigger Rate	1kHz
Light yield	20-30p.e./MeV

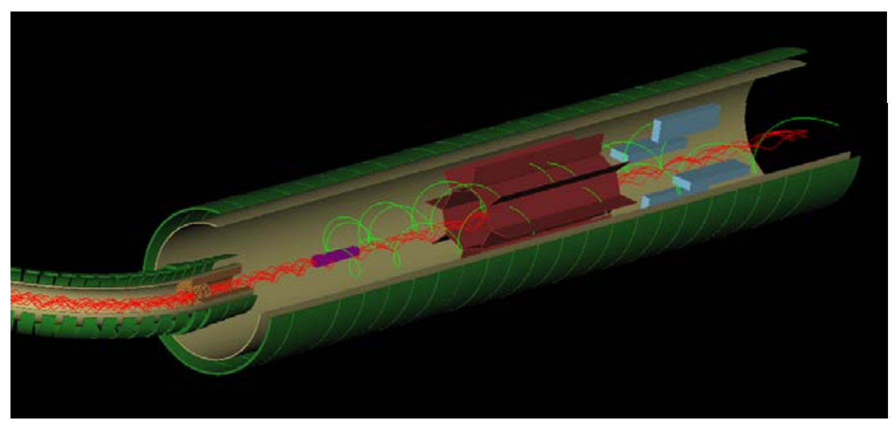
13.6X_0

Straw Tracker

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

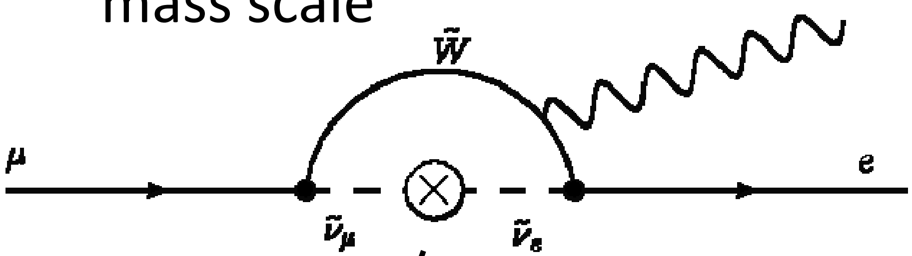


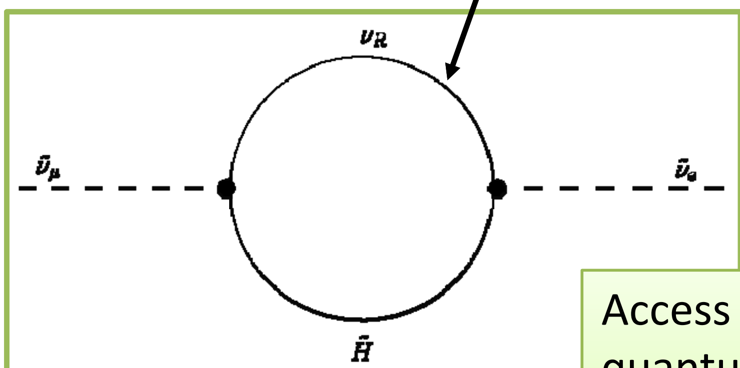
Diameter Swell > 1%



Sensitivity to SUSY

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





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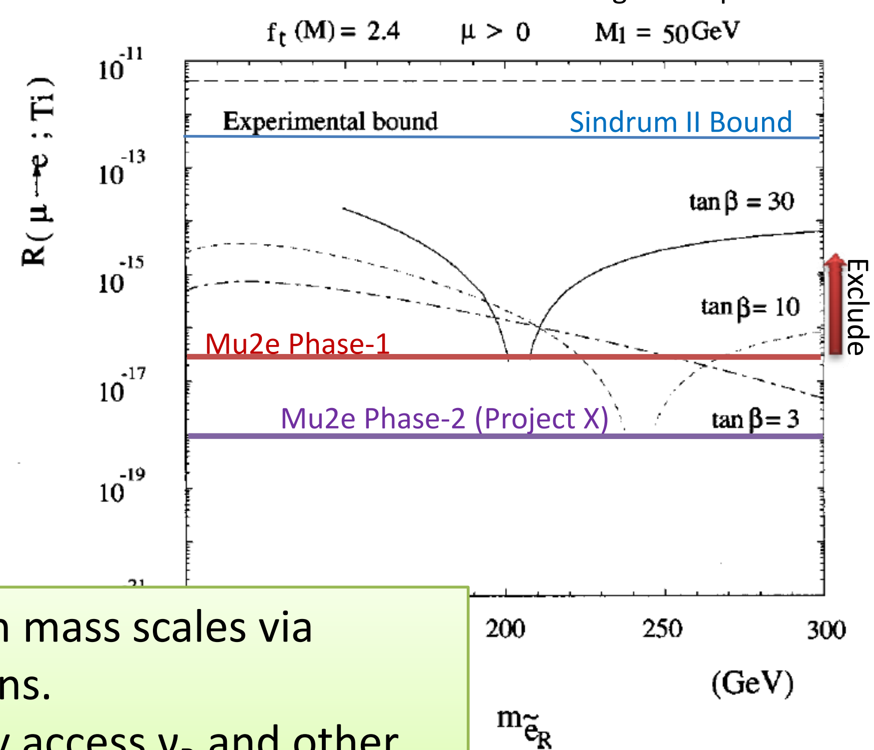
$\approx\mathcal{O}(40)$ even

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

μN $\rightarrow$ eN & SUSY Models

- Assuming we see a signal:
  - By changing target, we gain sensitivity to the scalar, vector or dipole nature of the interaction
  - Need to go to high Z
  - Hard because τ small for large Z (τ_{Au} =72ns)
  - But DIO backgrounds are suppressed and Conversion/OMC ratio scales as Z
- This is a unique feature of the μN $\rightarrow$eN measurements