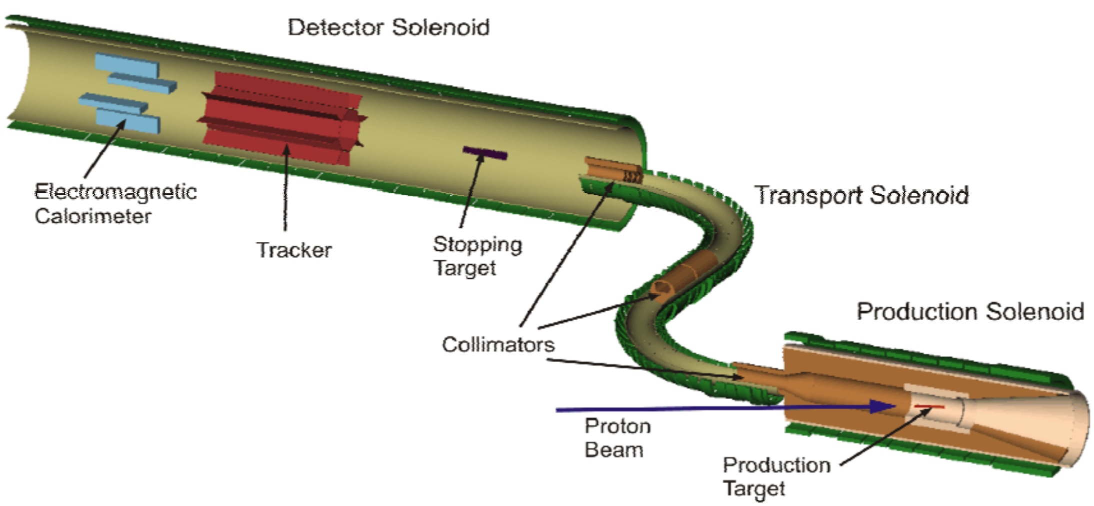
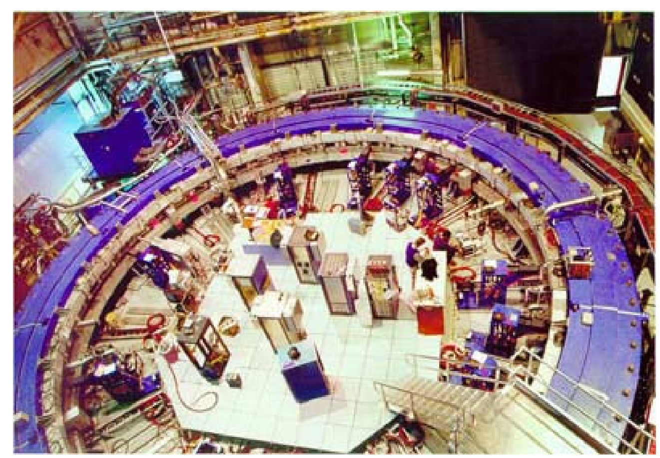
The Mu2e and g-2 Experiments

A precision window into physics beyond the standard model





Introduction

The world is poised for the LHC t

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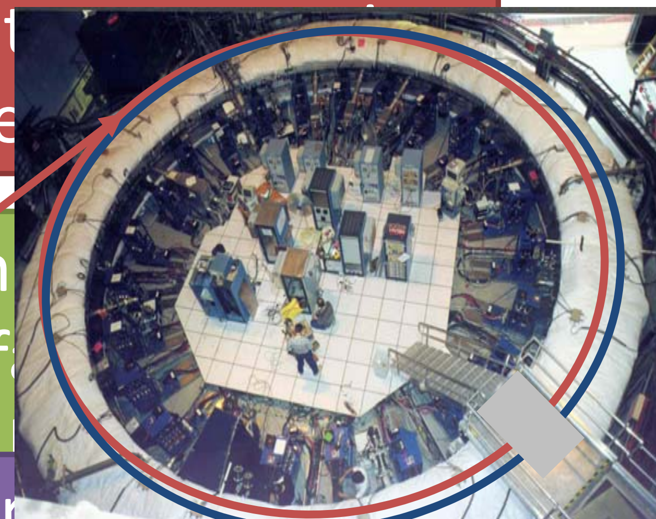
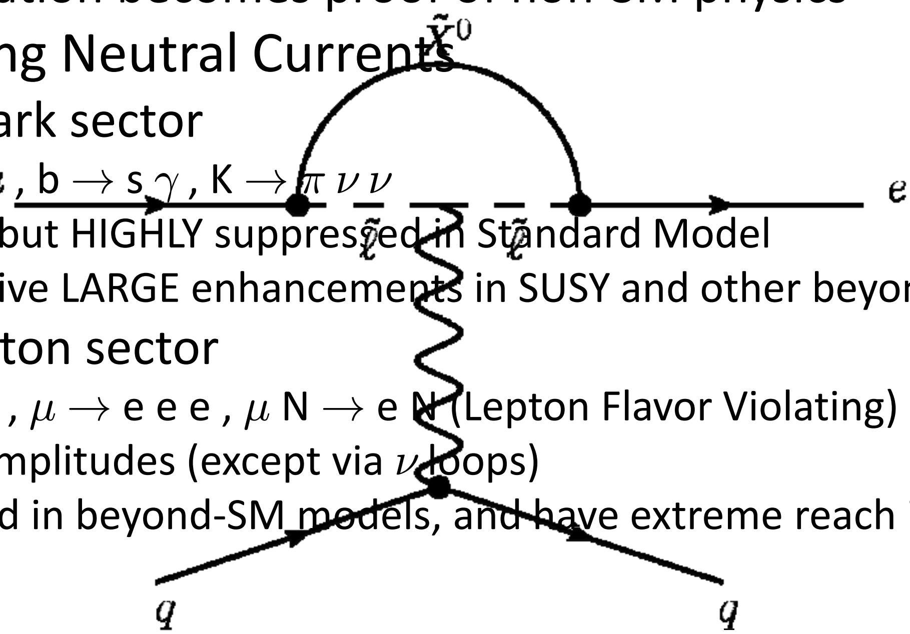


Two of these windows ar

Mu2e and **g-2** will probe new physics, new models and new energy scales through precision measurements and ultra rare searches

Why look for Ultra-Rare Processes?

- We want to access beyond standard model physics
  - This means access to High and Ultra-High Energy interactions
  - We get to these energies through loops, and this means rare effects
- 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
    - $B_s \to \mu \boldsymbol{\mu}$, $b \to s \gamma$, $K \to \pi \nu \nu$
    - Allowed but HIGHLY suppressed in Standard Model
    - Can receive LARGE enhancements in SUSY and other beyond-SM physics
  - FCNC in 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



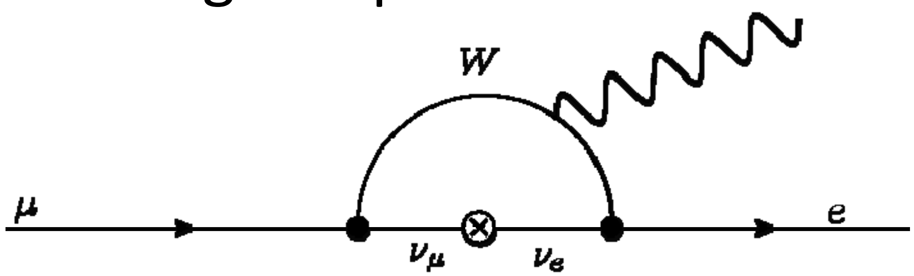
Lepton Mixing in the Standard Model

- 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 explicit mixing between generations
- But we have explicitly observed neutrino oscillations, and this means that leptons DO mix.
- Charged leptons must mix through neutrino loops



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

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

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

The Three LFV Processes

- There are three basic channels to search for cLFV in:

$$\mu^{\pm} \rightarrow e^{\pm}\gamma$$
$$\mu^{\pm} \rightarrow e^{\pm}e^{\pm}e^{\mp}$$
$$\mu^{-}N \rightarrow e^{-}N$$

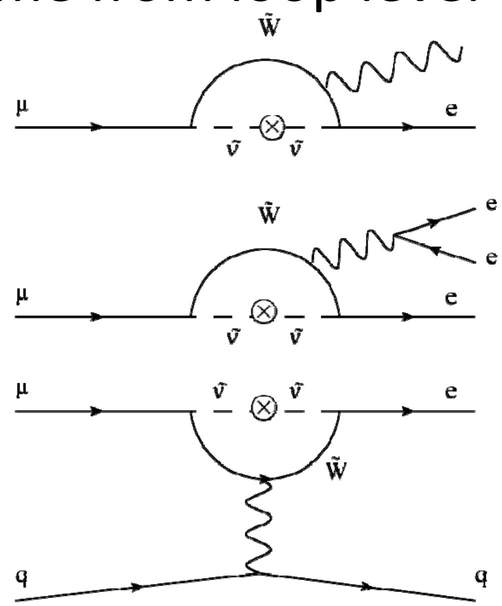
- Where if dipole like interactions dominate we expect a ratio of rates:

389 to 2.3 to 1

Note: $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ have experimental limitations from resolution and overlap with accidentals.

Limits the overall Br()$\sim 10^{-14}$

- New physics for all can come from loop level



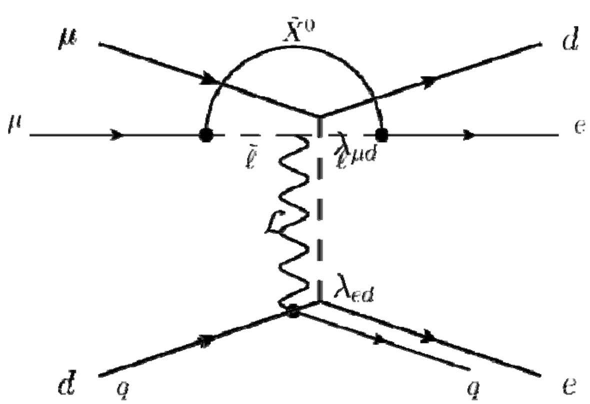
- For μ N $\rightarrow$ e N and $\mu \rightarrow$ eee we also have contact terms

Beyond the Standard Model

- The LFV process can manifest in the μN$\rightarrow$eN channel in many models:

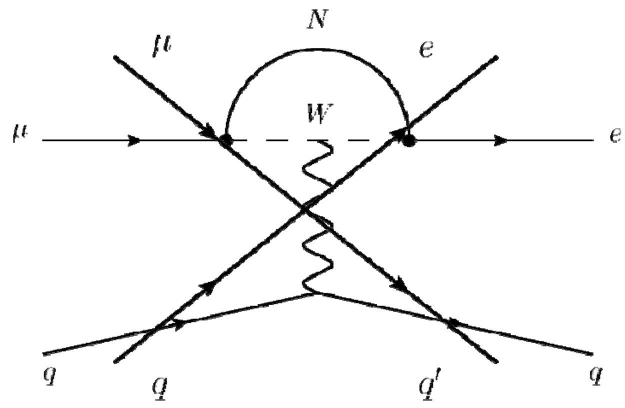
Contact Terms

Loops



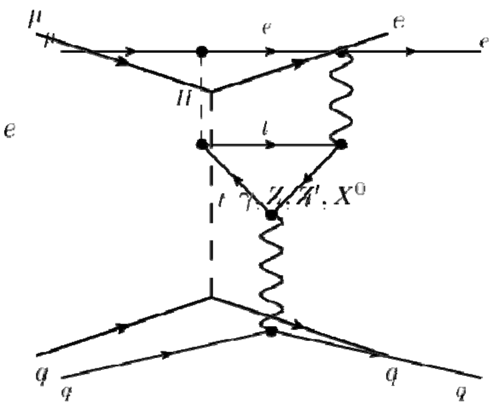
Leptoquarks

SUSY



Heavy Neutrinos

Compositeness



Second Higgs Doublet

Anomalous Heavy Couplings

General LFV Lagrangian

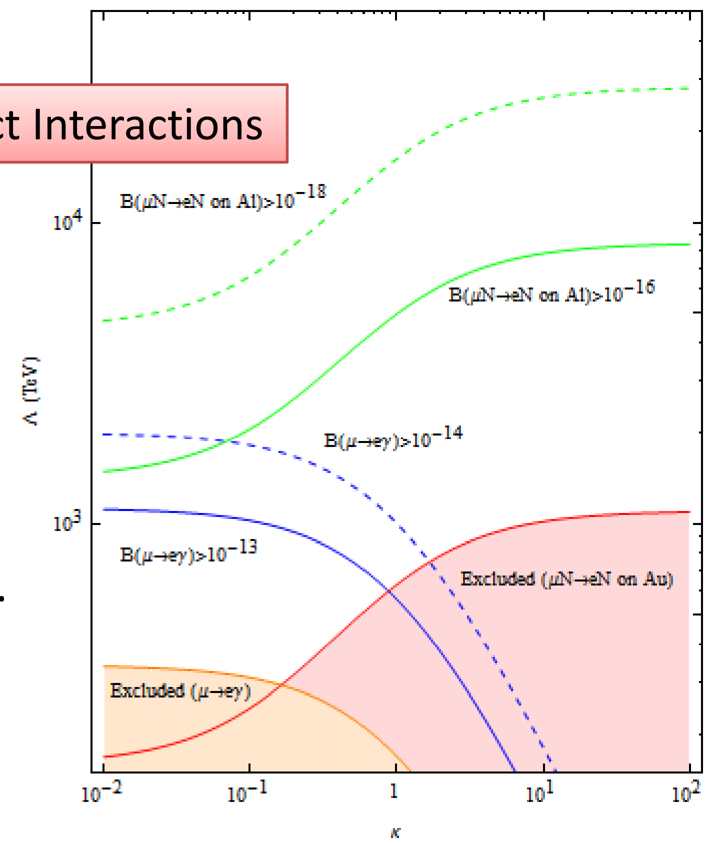
- Recharacterize as a model independent frame work:

Loops

Contact Interactions

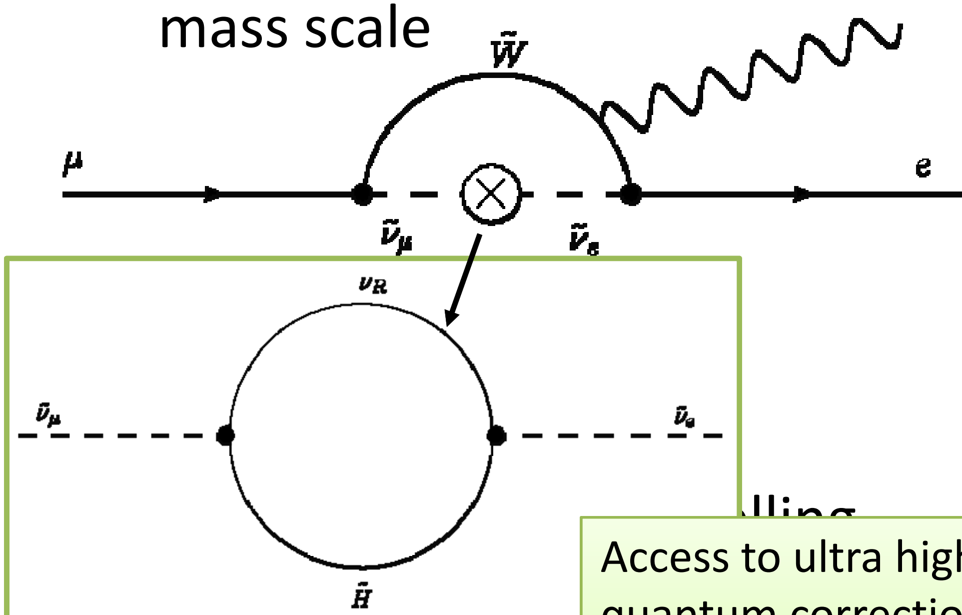
$$\mathcal{L}_{\mathcal{LFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2)}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

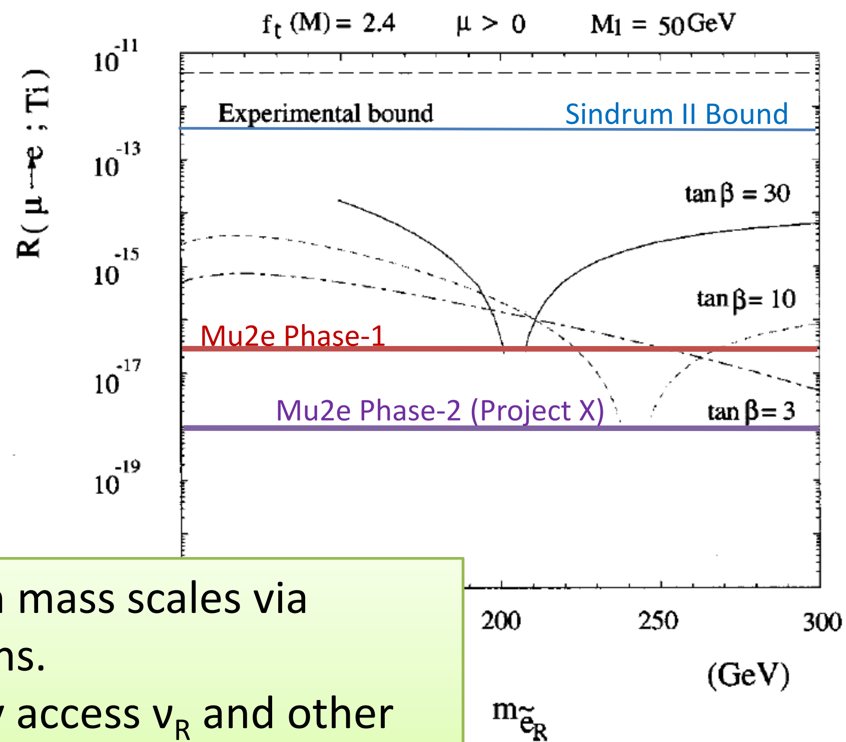
  - Splits LFV sensitivity into Loops terms and Contact terms
  - Allows us to look as the energy scale Λ in terms of the dominant interaction process
  - The balance in energy reach shifts between favoring μN$\rightarrow$eN and $\mu\rightarrow$eγ measurements .
  - For contact term dominated interaction (large κ) the energy the sensitivity in Λ reaches upwards of 10^4 TeV for the conversion process



Sensitivity to SUSY

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





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mean observatio

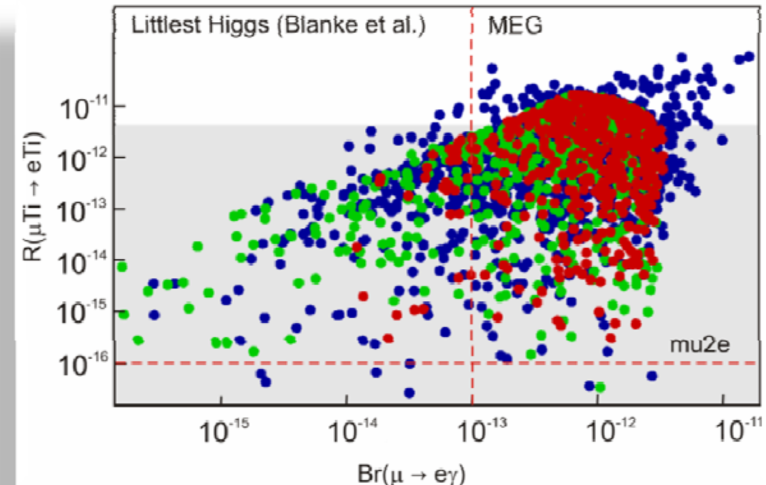
$\approx\mathcal{O}(40)$ ever

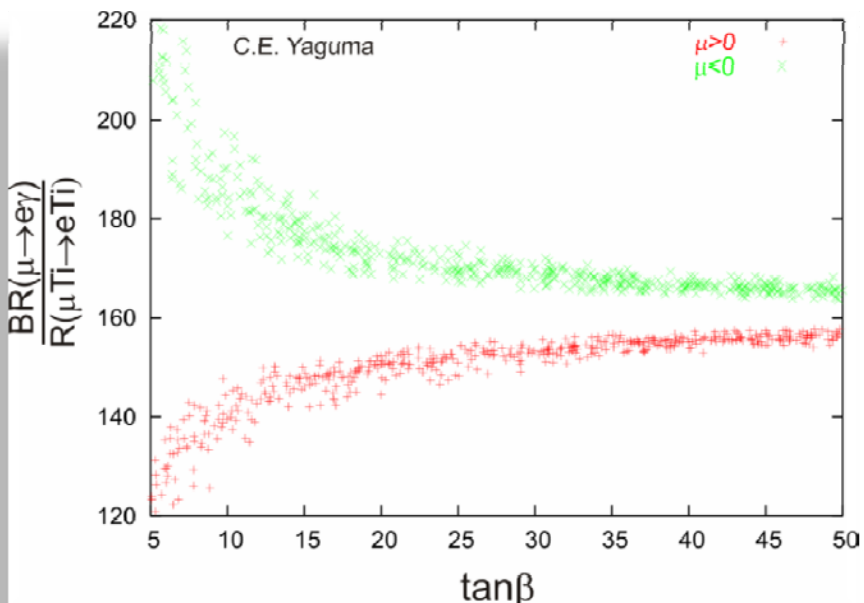
Access to ultra high mass scales via quantum corrections.
Can access possibly access ν_R and other processes at scales 10^{12}-10^{14} GeV/c^2

Hisano et al. 1997

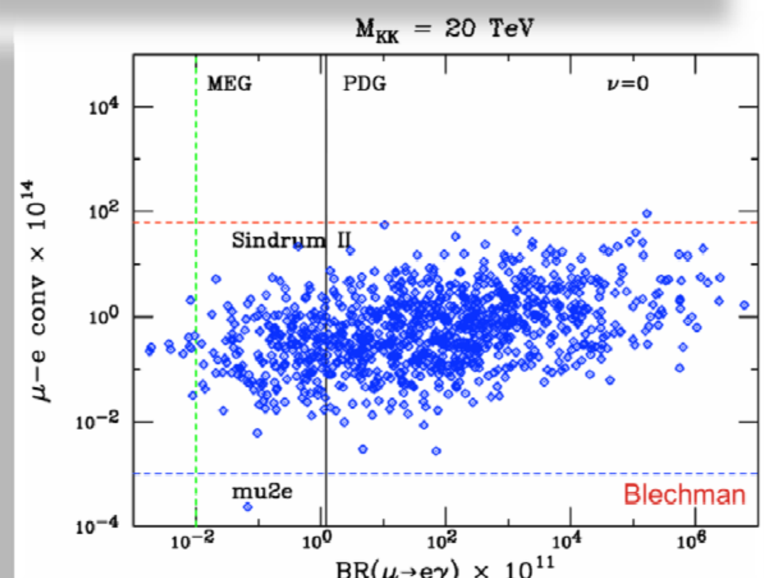
We Need Both $\mu N \rightarrow eN$ and $\mu \rightarrow e\gamma$

- Knowing both mu2e and mu2e gamma gives us knowledge about the structure of SUSY





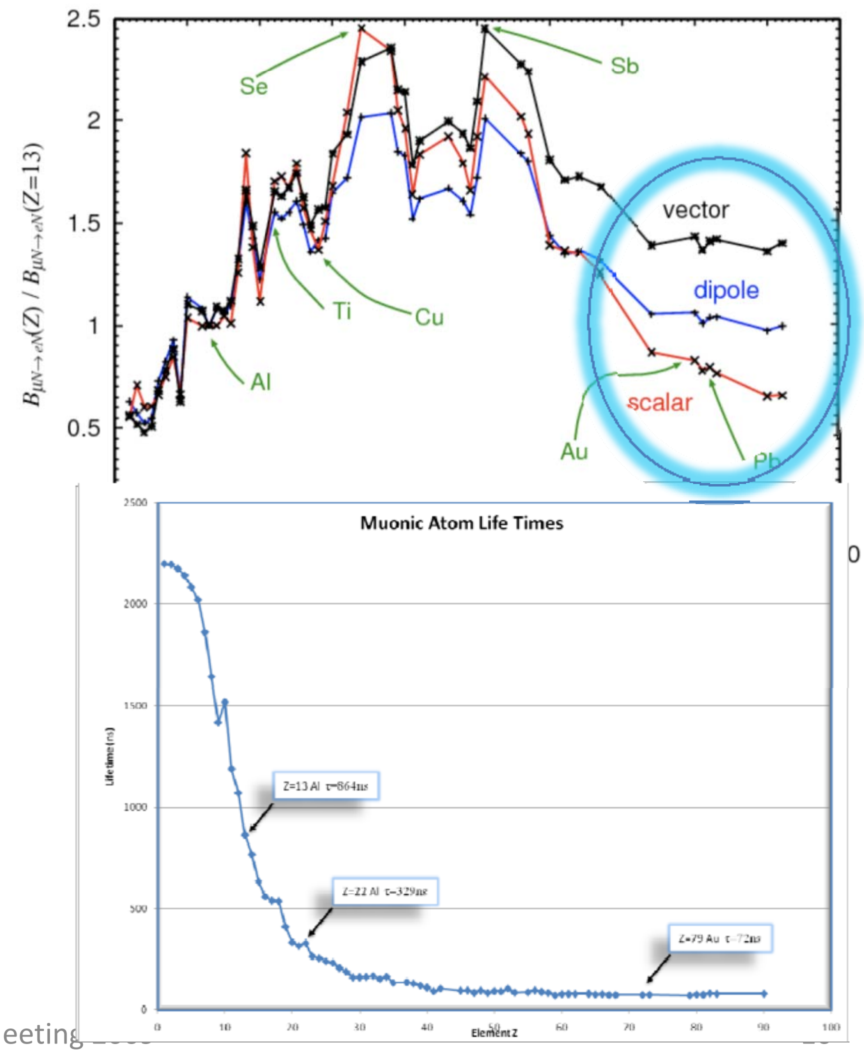
MSSM/msugra/seesaw



Randall-Sundrum

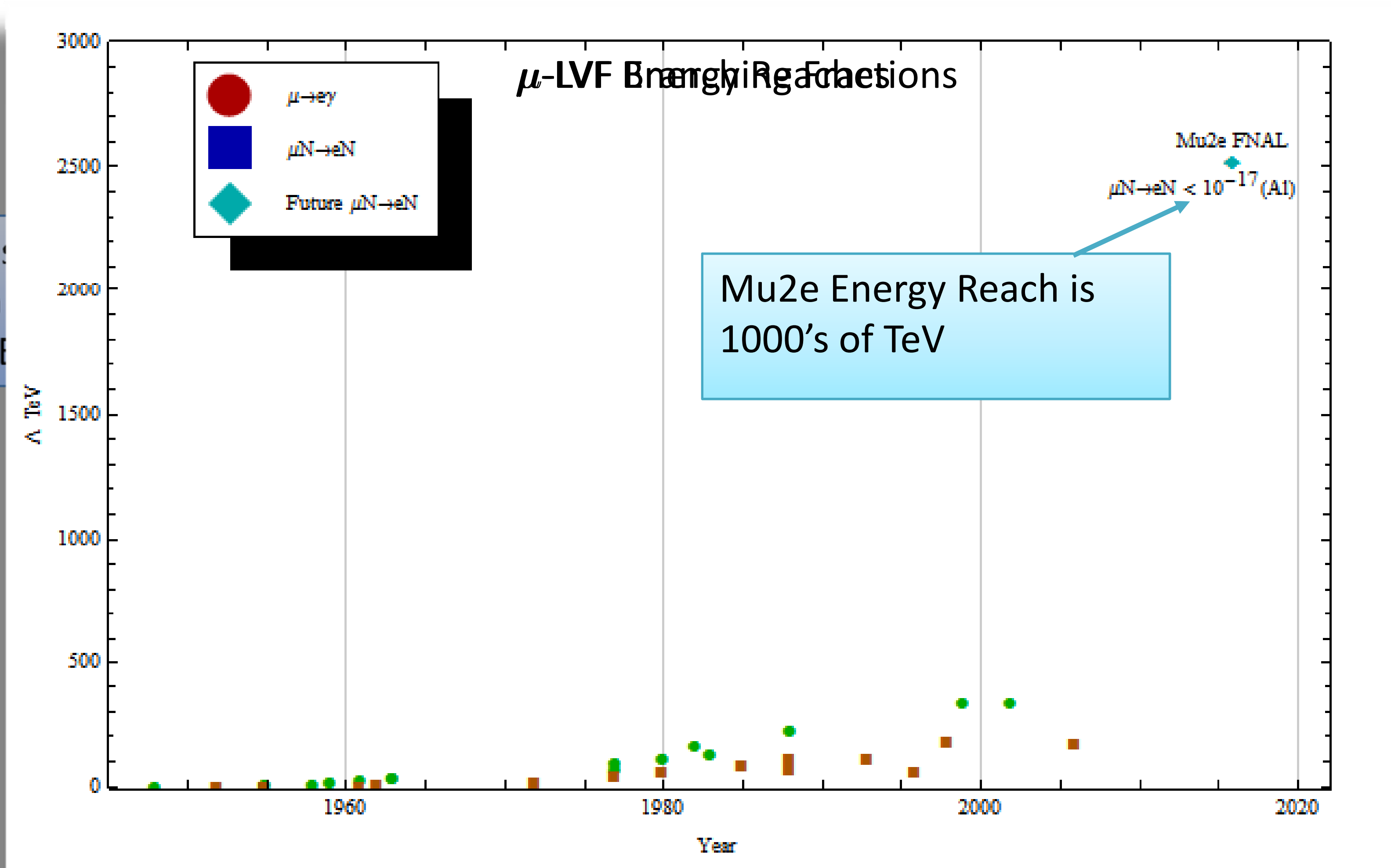
μN $\rightarrow$ eN & SUSY Models

- 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



A Brief History of μ-LFV

First Meas
6×10^{-2} in
Effective E



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

Part I

MU2E AT FNAL

The μN$\rightarrow$eN measurement (in a nutshell)

- Stop $\sim\mathcal{O}(10^{18})$ μ^- 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:

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

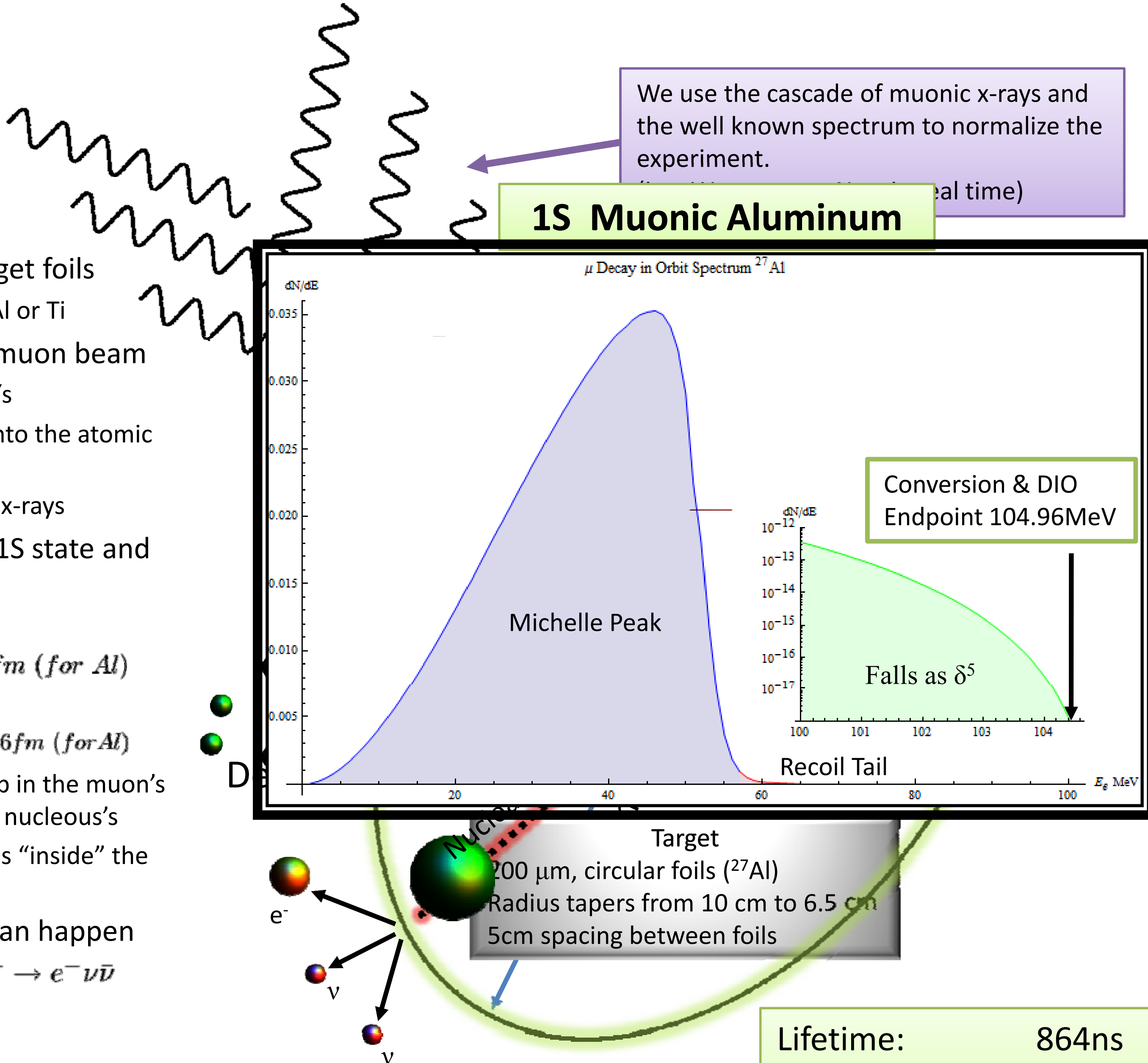
- Report the rate relative to nuclear capture

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

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

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**: $\mu^- \rightarrow e^- \nu \bar{\nu}$



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

Muonic Atom

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- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \to e^- \nu \bar{\nu}$
  - **Nuclear Capture**: $\mu^- N^Z \to \nu N^{Z-1}$

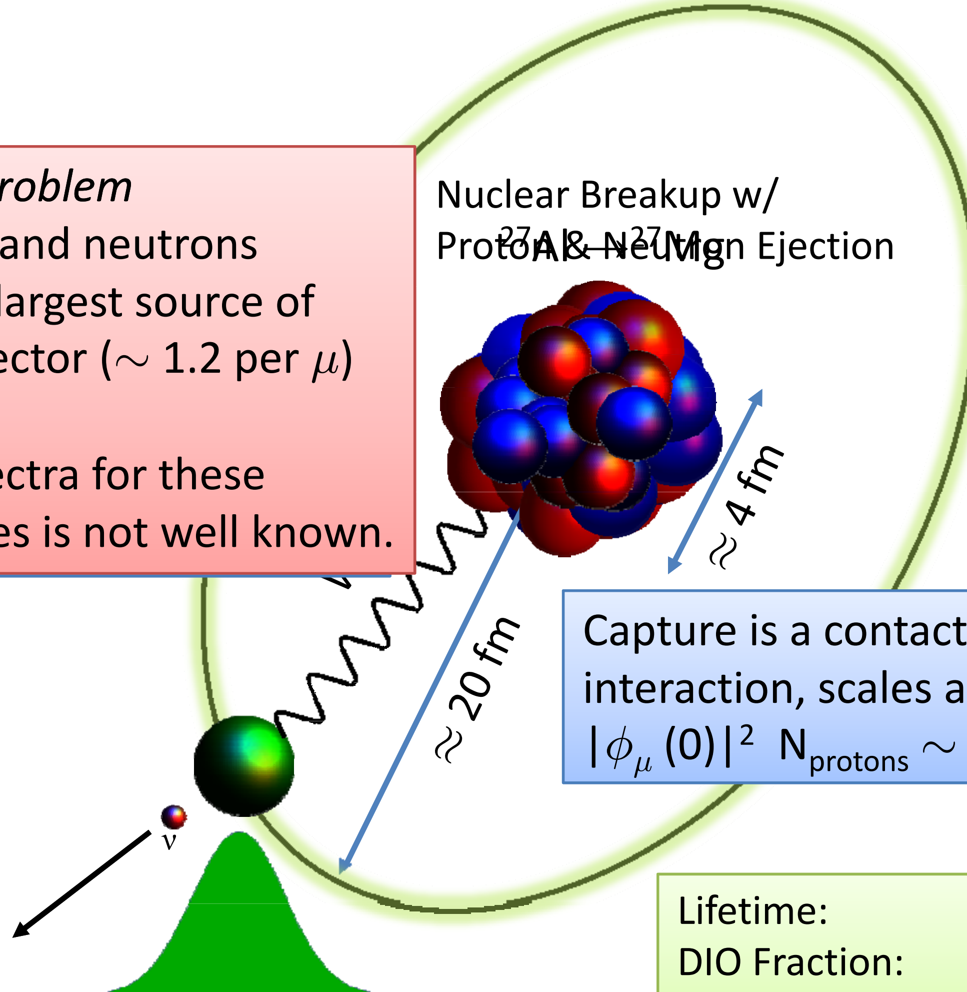
Problem

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)

Nuclear Breakup w/
Proton & Neutron Ejection



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
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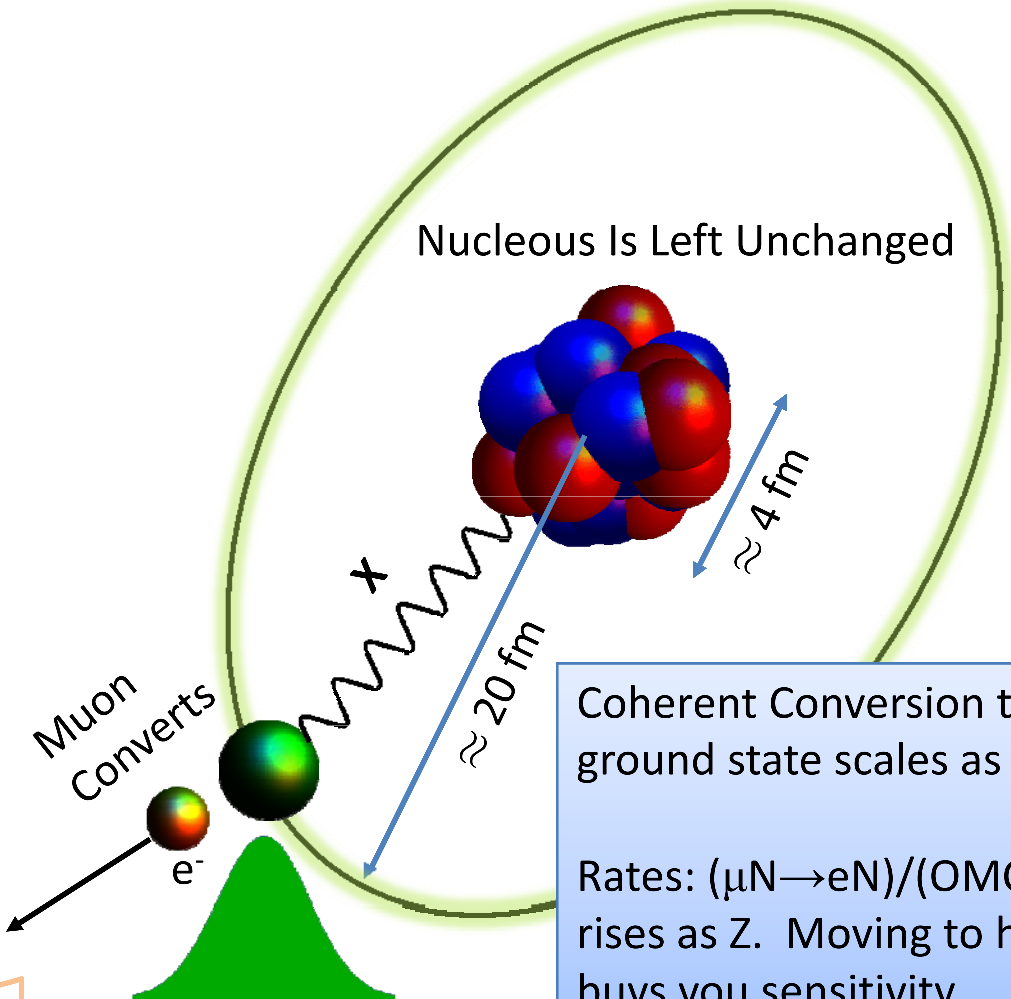
- Once captured 3 things can happen
  - Decay in Orbit: $\mu^- \rightarrow e^- \nu \bar{\nu}$
  - Nuclear Capture: $\mu^- N^Z \rightarrow \nu N^{Z-1}$
  - **New Physics! i.e. μ N → e N**

$E_e \approx 105$ MeV

Coherent Conversion (μ→e)

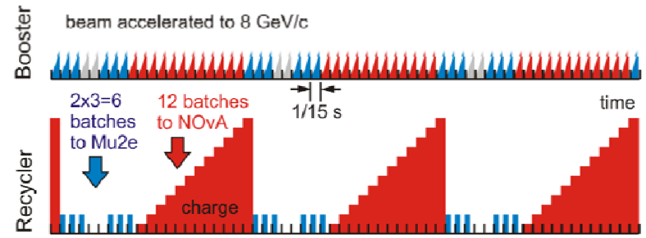


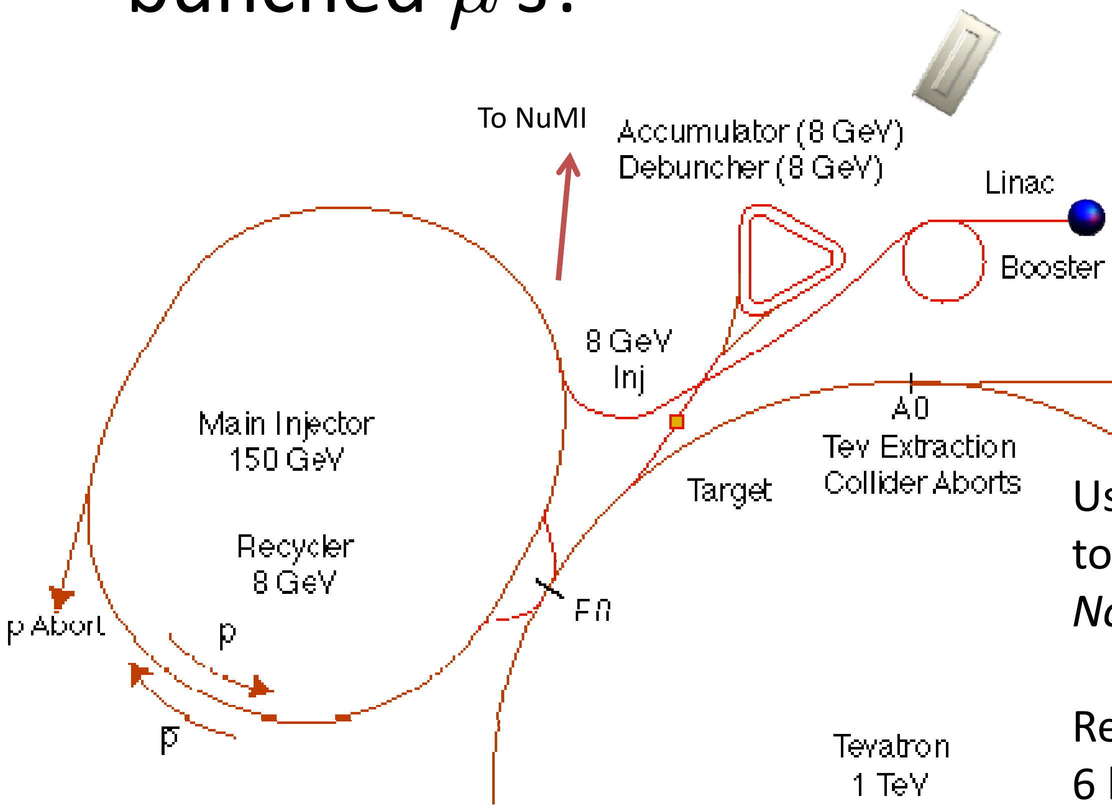
Coherent Conversion to the ground state scales as ~ Z^5.

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

Mu2E & NOνA/NuMI

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



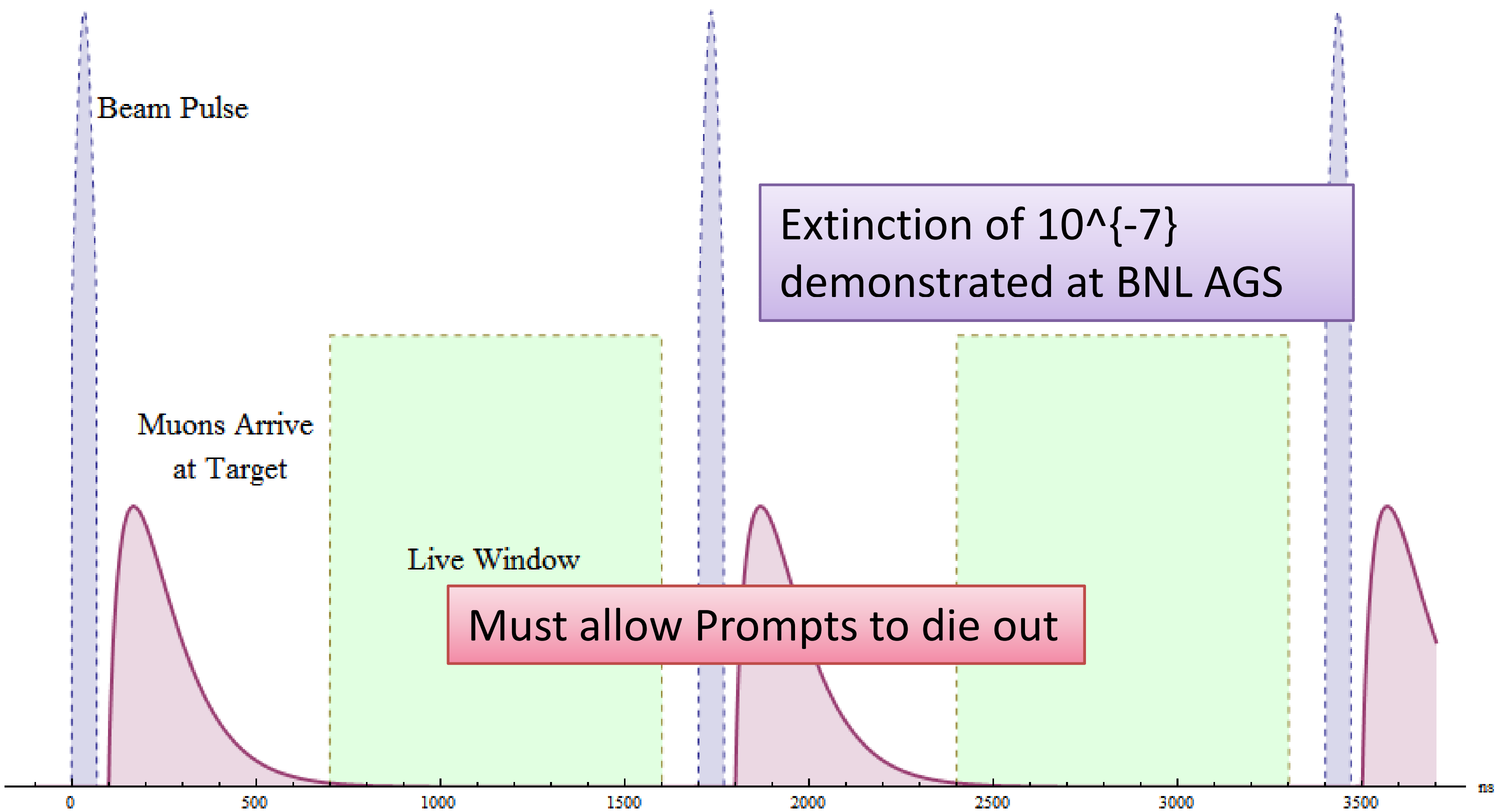


Use NuMI cycles in the Main injector to slow spill to Mu2e.
No Impact on NOvA

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

Beam Structure

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



Backgrounds

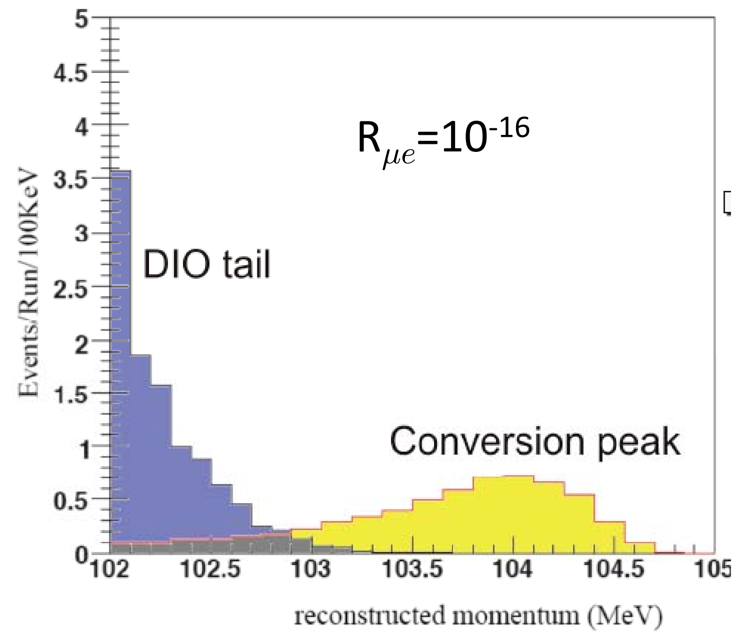
- DIO, RMC, RPC
- Dominant Backgrounds
  - Prompt backgrounds drive the extinction
  - In particular, Rad π Cap. drives the extinction requirement
  - Estimates are for an extinction of 10^{-9}
  - Monte Carlo limited on estimates

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	0.001
π Decay in flight	<0.001
Pat. Recognition Errors	<0.002
Total	0.415

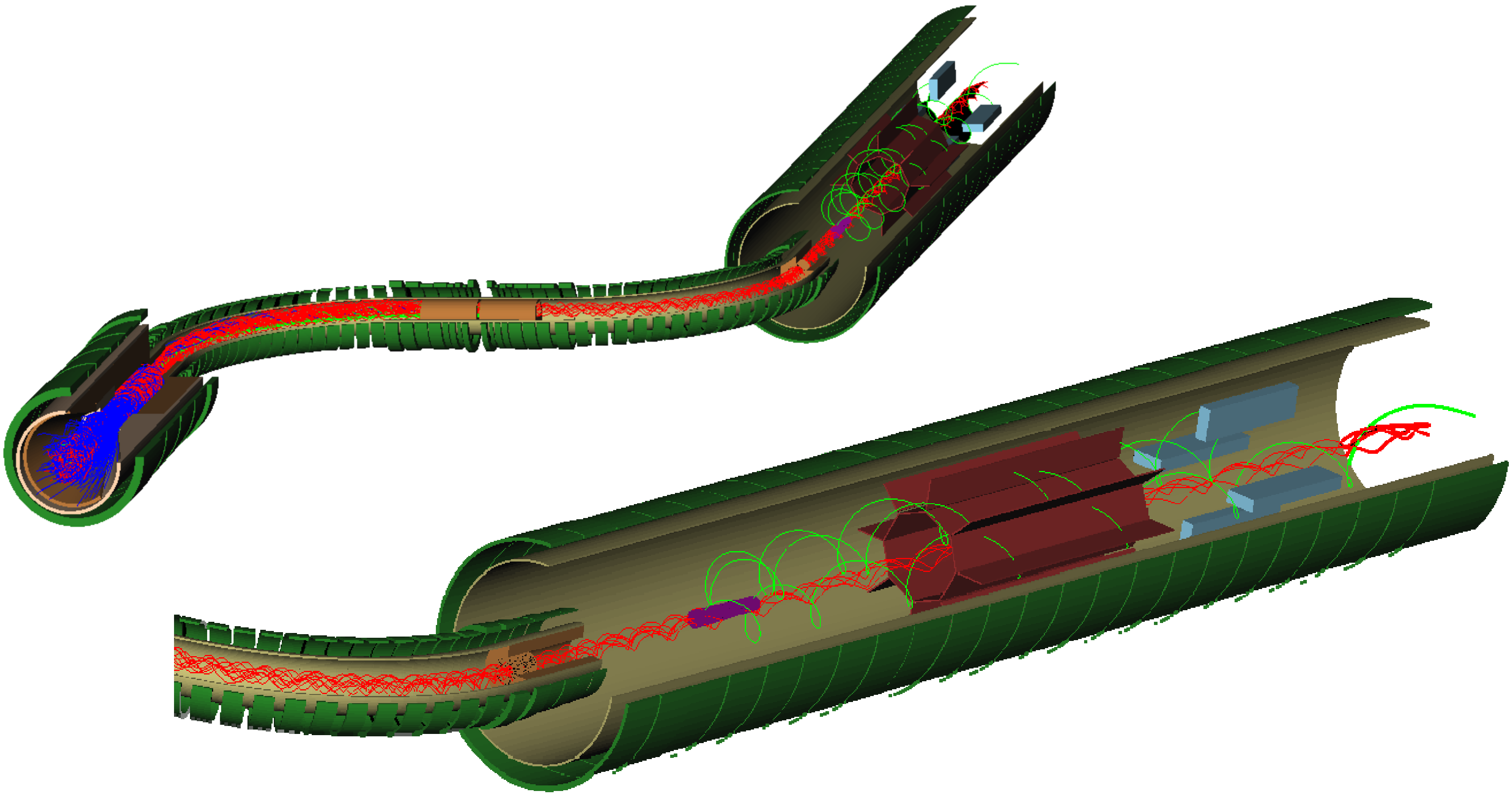
Signal to All Backgrounds

- Signal significance
  - If we assume SUSY like the LHC will see:
    - Mu2E will see $\sim\mathcal{O}(40)$ events
    - On 0.5 event background
  - Even at 10^{-15}
    - Mu2E sees $\sim$ 5 events
    - on 0.5 event background
  - This is a Strong Signature

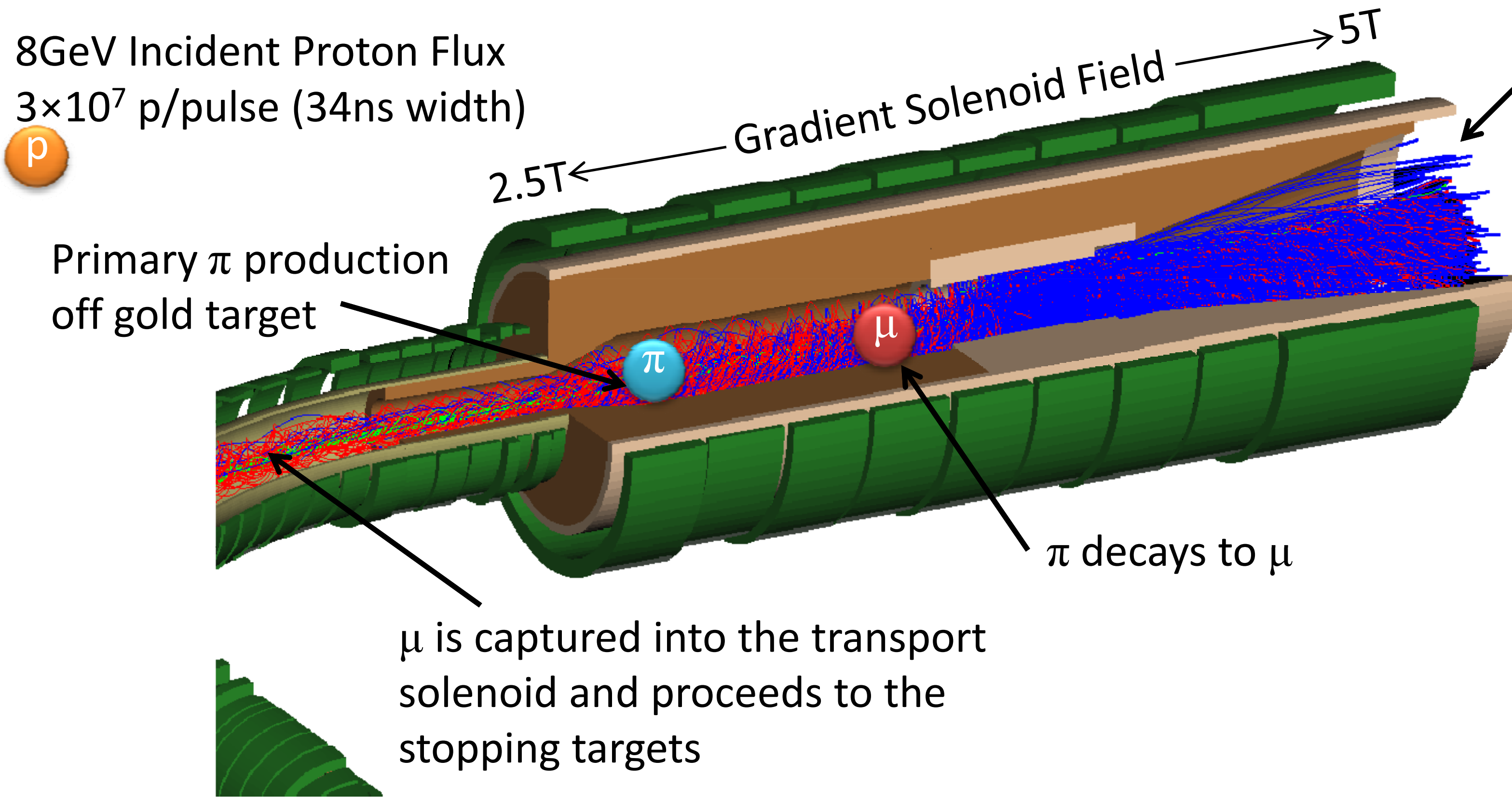
$$\frac{S}{\sqrt{B}} \sim 5.5$$



The Mu2e Detector in Detail

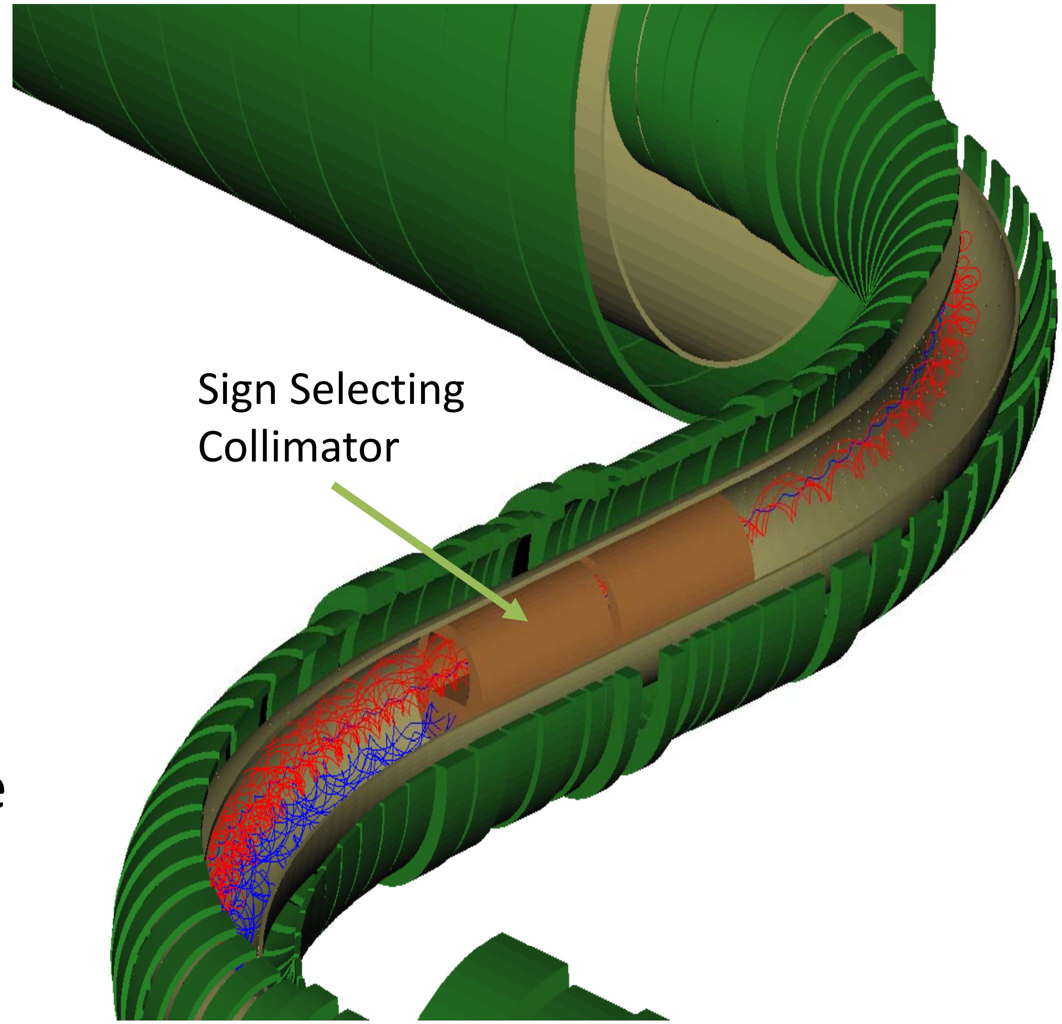


Production Solenoid

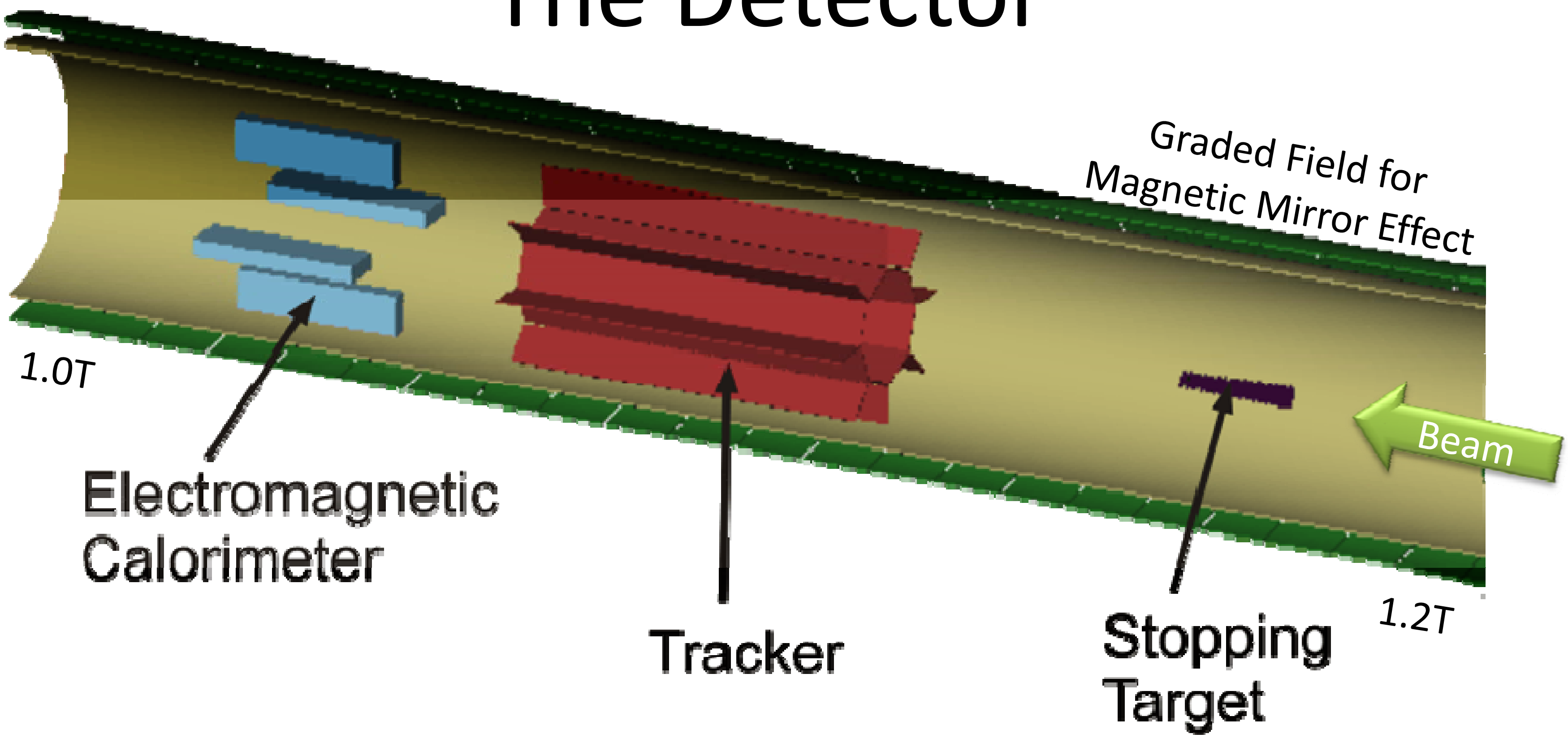


Transport Solenoid

- Designed to sign select the muon beam
  - Colimator blocks the positives after the first bend
  - Negatives are brought back on axis by the second bend
- Gradient along solenoid prevents particles getting “trapped” to reduce long transit time trajectories



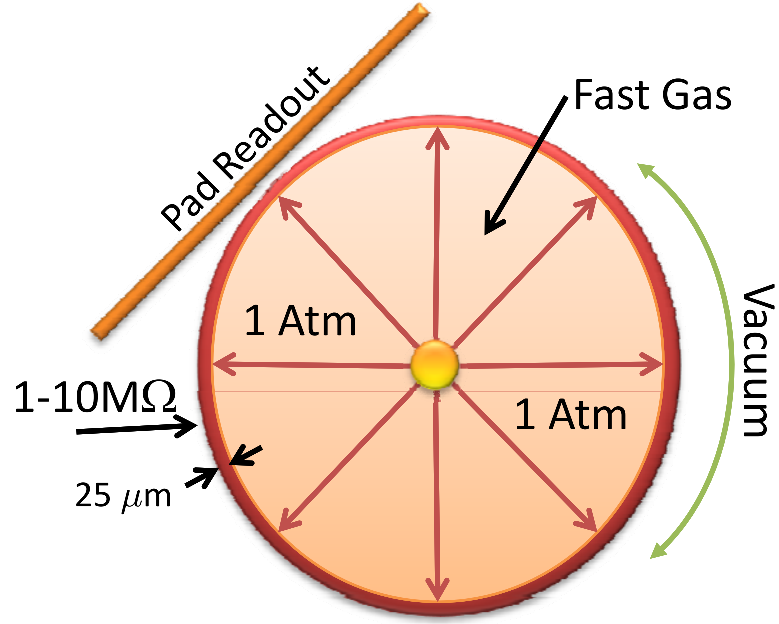
The Detector



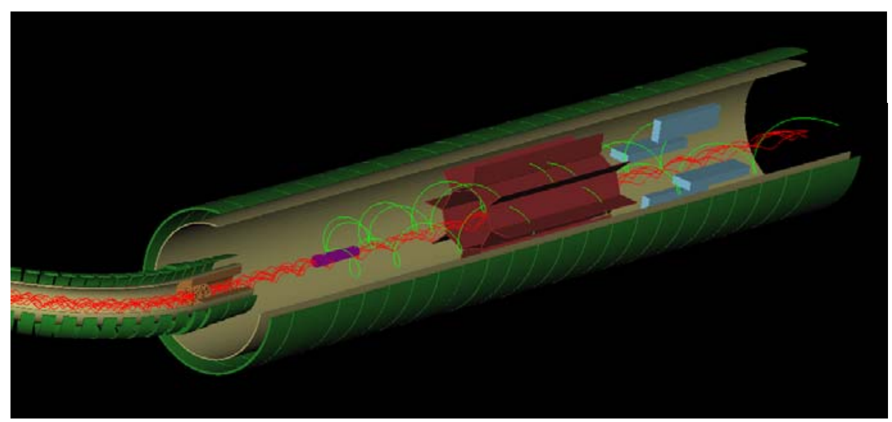
- The detector is specifically design to look for the helical trajectories of 105 MeV electrons
- Each component is optimized for maximizing signal detection and suppressing *Decay in Orbit* Backgrounds

Straw Tracker

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



Diameter Swell > 1%



Straw Tracker

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- Discu
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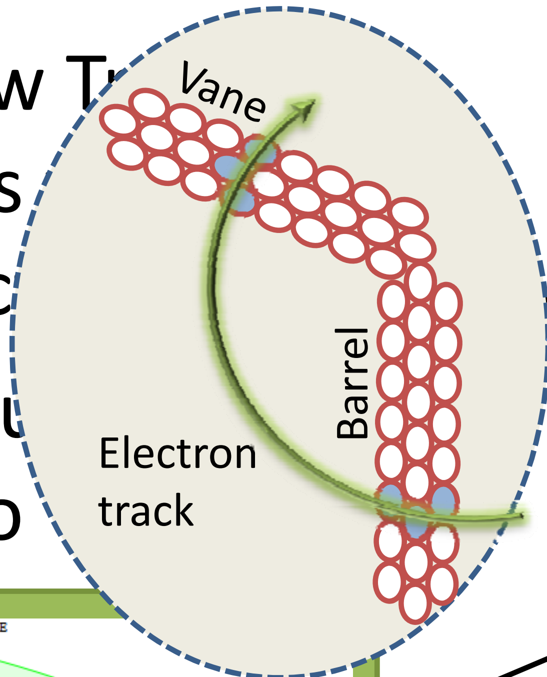
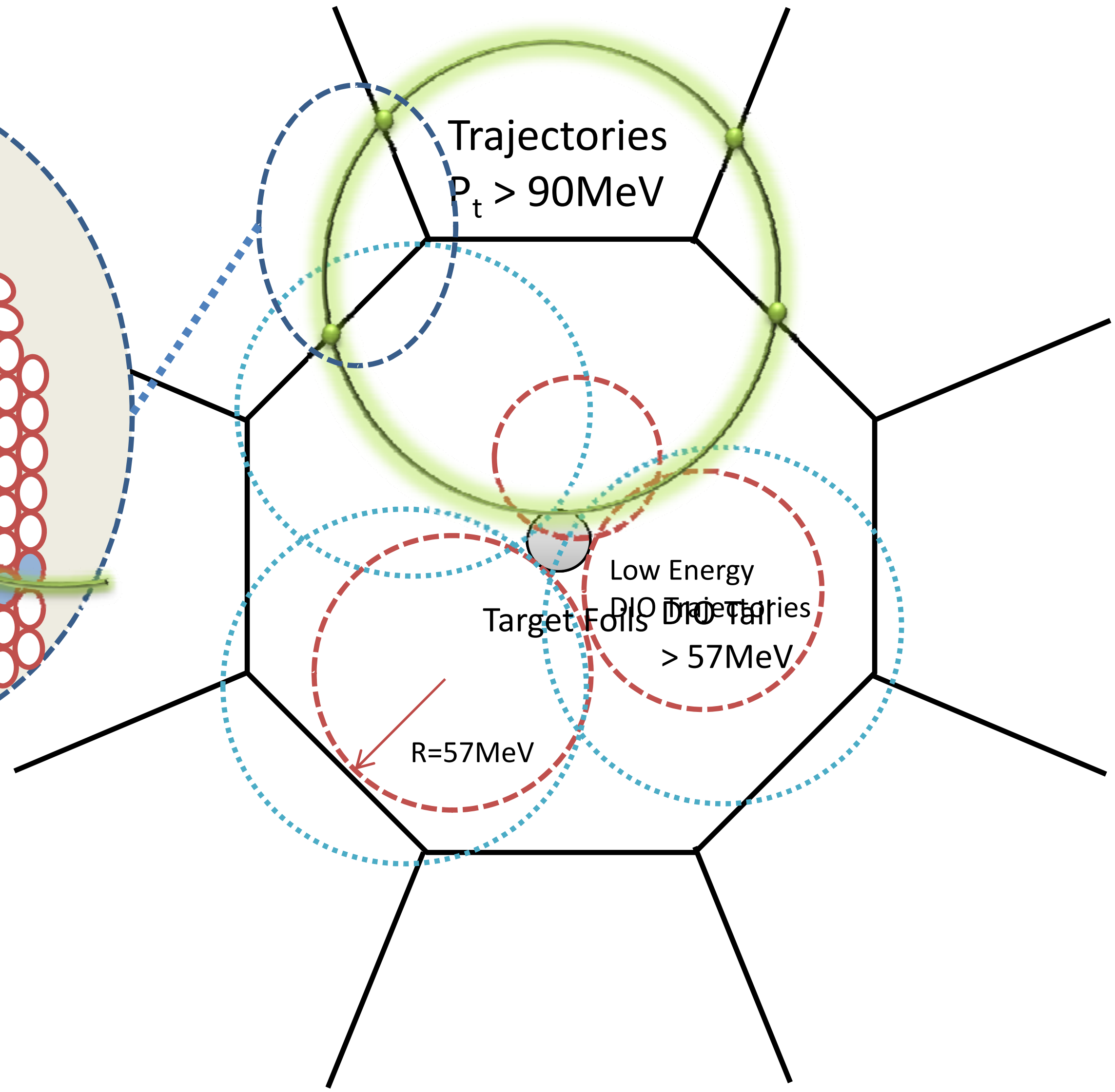
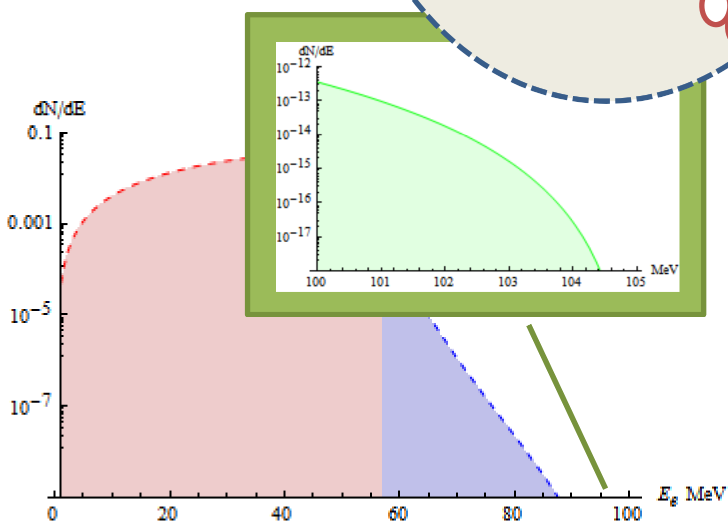


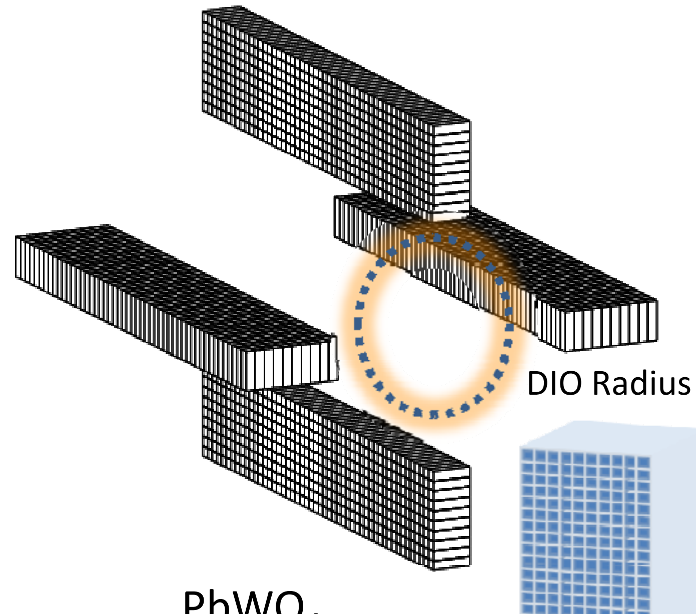




Crystal Calorimeter

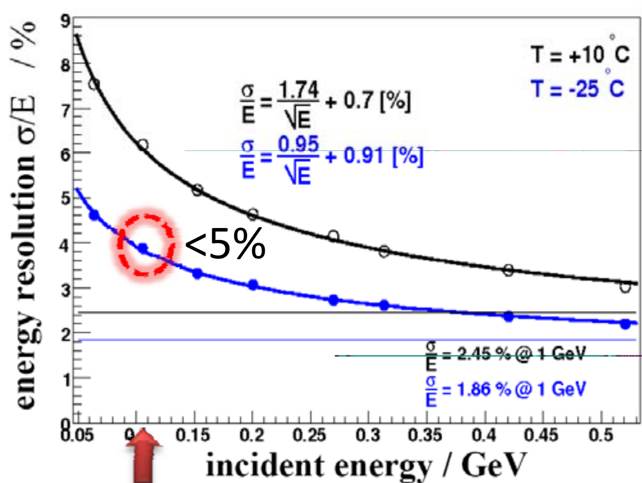
Original Design:

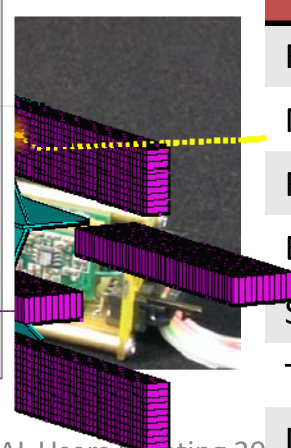
- 5% energy measure for trigger decision (1Hz rate)
- Timing edge for event reconstruction
- Provide PID verification (E/P)
- Spatial match to tracker trajectory
- Immune to DIO rates



$PbWO_4$

Tracker project



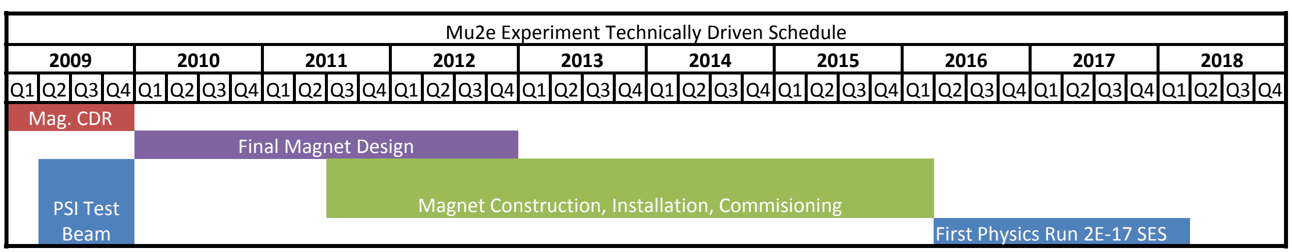


Calorimeter Properties	
Resolution	5%
Material	$PbWO_4$
Readout	Dual APD
Blocks	500 per fin, 4 fins
Segmentation	$30\times30\times120mm^3$
Trigger Rate	1kHz
Light yield	20-30p.e./MeV

$13.6X_0$

Cost and Schedule

- Total Project Cost Est. $200M (fully loaded, escalated, appropriate contingencies)
- Received Stage-1 Approval and CD-0 anticipated shortly
- Technically Driven Schedule (magnet wholely magnet driven) results in 2016 start of data taking
- Signification R&D, Auxiliary Measurements and Test Beam work proceed in parallel to construction



Part II

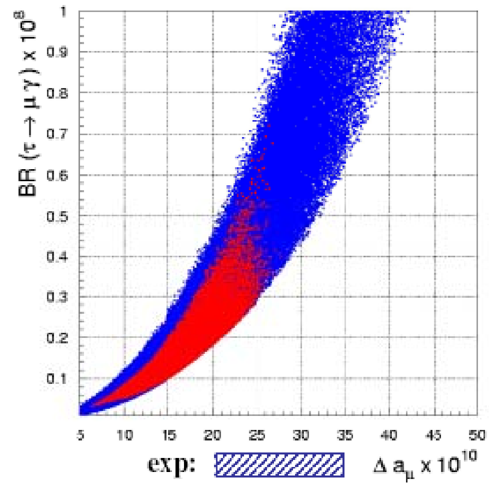
G-2 AT FNAL

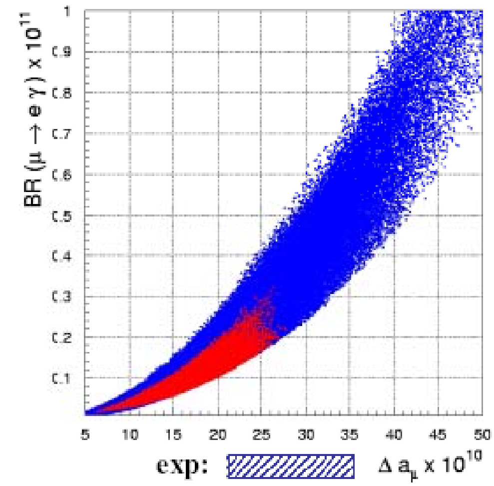
Intro & Theory

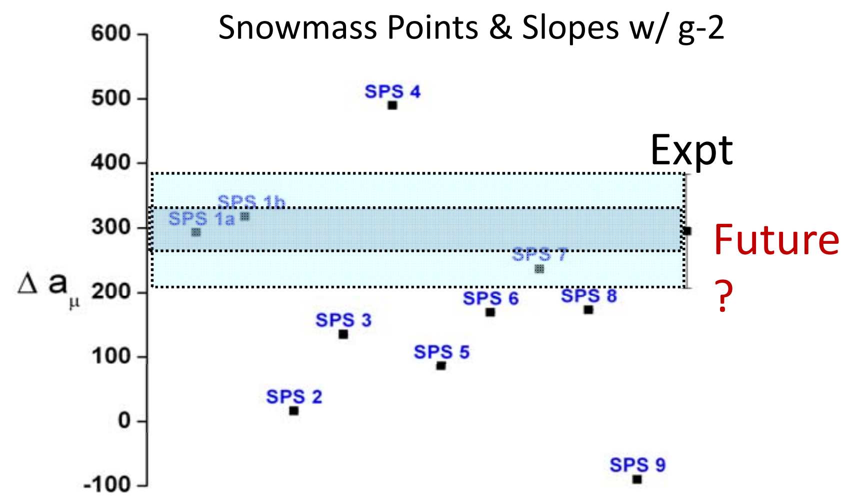
- I owe you a good theory slide

g-2 and SUSY

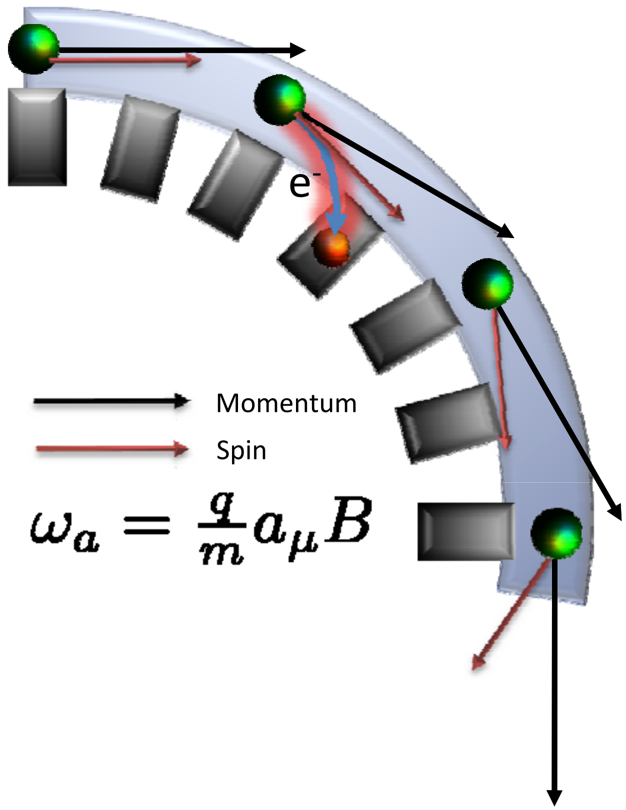
- g-2 is extremely sensitive to SUSY through the same dipole like interactions that cLFV channels are
- These are amplified by tanβ and can be used with LFV results to constrain many models







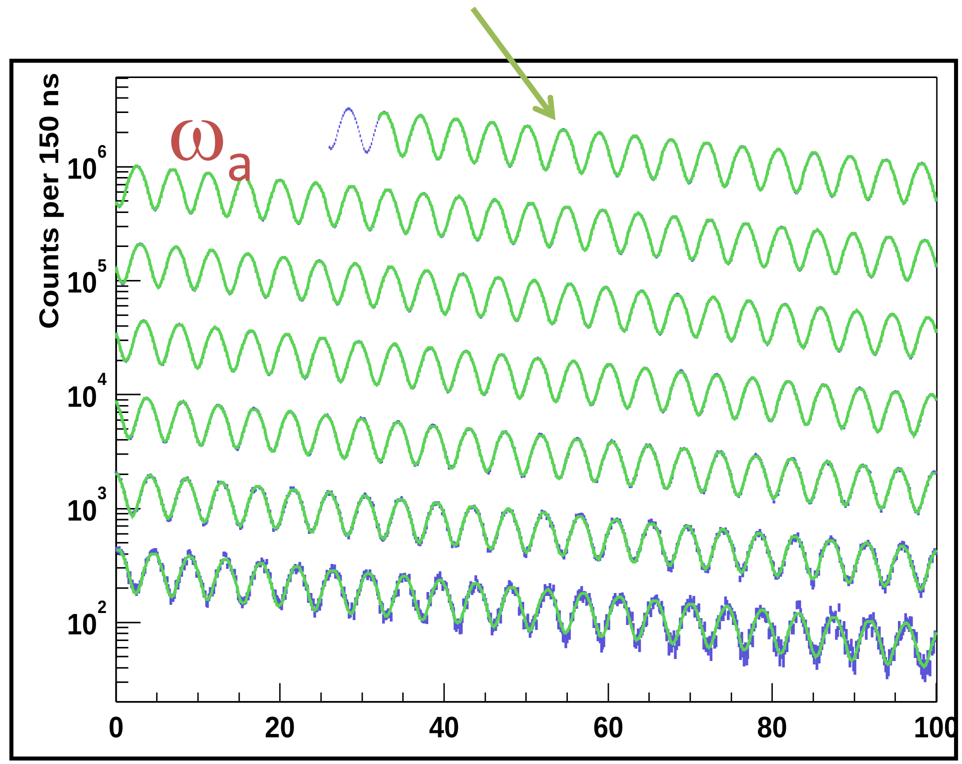
The g-2 Measurement



$$\omega_a = \frac{q}{m} a_\mu B$$

This method requires extremely precise knowledge of the B field

The muon is self analyzing, and the precession frequency is directly obtained



FNAL Beam

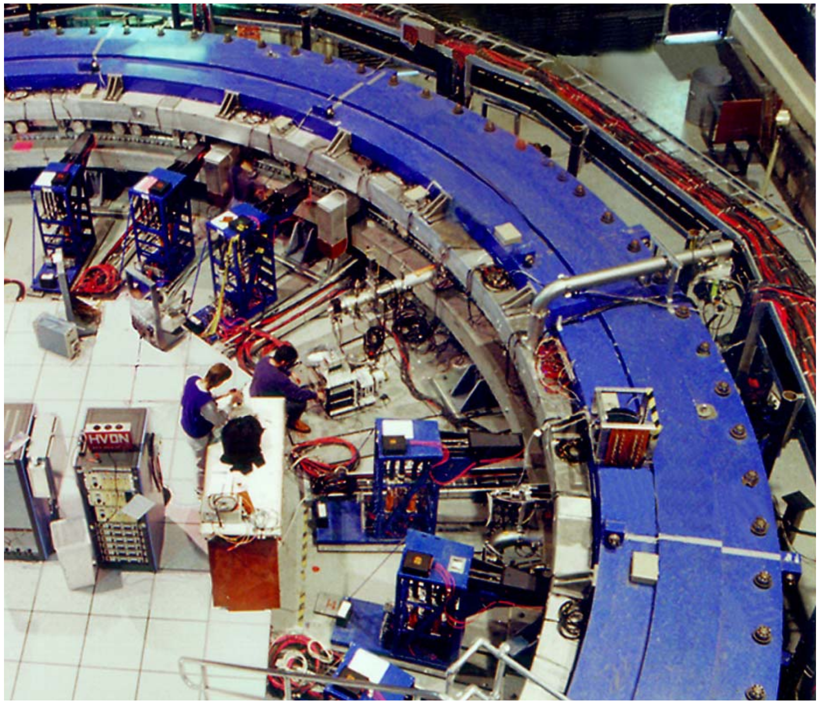
High Rep Rate

84 fills/1.4s $\rightarrow$ 60Hz $\rightarrow$ 14.5$\times$ BNL

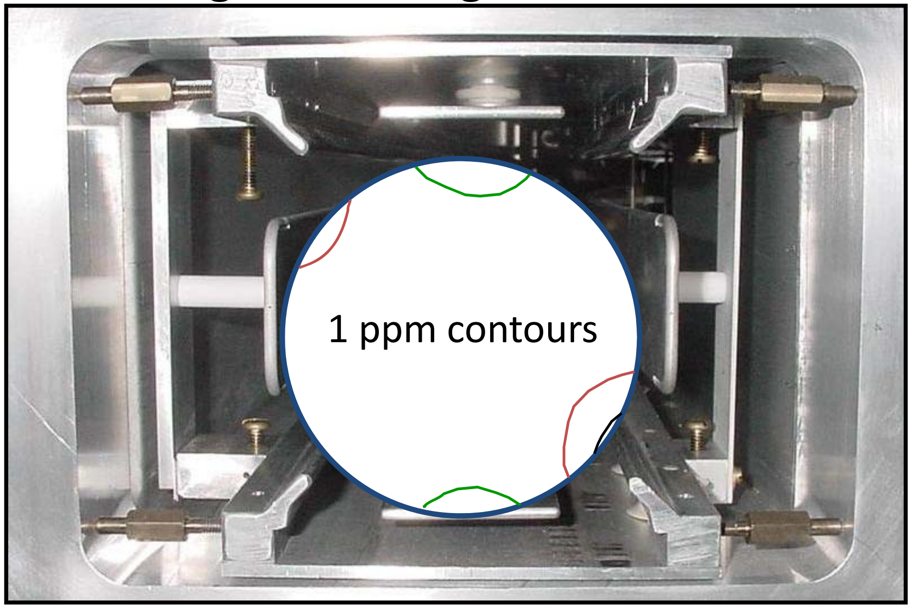
20 the statistics in one year of running!

upgrade

- BNL Storage Ring Flies to Chicago!



- Magnetic Field is improved through shimming and calibration



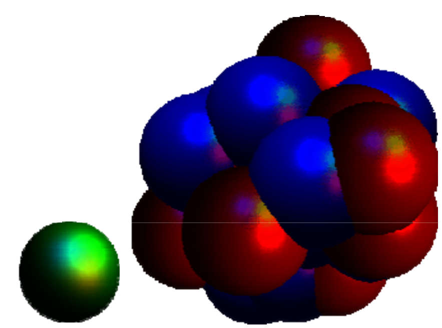
- FNAL beams offer more \mu

BACKUP SLIDES

Coherent \mu N \rightarrow e N

- Initial State is a target nucleous N
- First Stop a low energy \mu ^- beam in the material
- The muon sees the nucleous and cascades down to the 1S orbital with a Bohr Radius and nuclear size: $\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z e^2} \approx 19.6 fm \ (for\ Al)$

$$R \approx 1.2 A^{1/3} fm = 3.6 fm \ (for Al)$$



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