Experiments Using Intense Muon Beams Leading up to Project X: Mu2e and Muon g-2

Precision windows into physics beyond the standard model

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The Mu2e and Muon g-2 Experiments

- Mu2e: A search for charged lepton flavor violation (CLFV)
  - New, sensitive search for muon to electron conversion in the field of a nucleus
  - Example of a reaction forbidden to a high level in the SM ($<10^{-52}$)
  - Stage I approval at Fermilab
  - Based on the MECO experimental approach that was developed to a high level of technical and cost understanding
  - Improve sensitivity of measurement by x10000 compared to previous measurements
- New Muon g-2: Measurement of the anomalous magnetic moment of the muon
  - Example of a precision measurement: can be predicted with high precision in SM
  - In proposal stage
  - Improved measurement based on extrapolation of techniques used for the successful E821 experiment at BNL
  - Improve previous precision by factor of 4 (to 0.14 ppm) for a measurement that currently has $>3\sigma$ difference with Standard Model prediction

μe Conversion

Muon converts to monochromatic electron in the field of a nucleus, with no accompanying neutrinos

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

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

- Charged Lepton Flavor Violation (CLFV)
- Related Processes: μ or $\tau \to e\gamma$, e^+e^-e, and more

Current limit: $R_{\mu e} = \frac{\mu^- Au \to e^- Au}{\mu^- Au \to \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Mu2e goal : $R_{\mu e} = \frac{\mu^- Al \to e^- Al}{\mu^- Al \to \text{capture}} < 6\text{x}10^{-17}$ (90% c.l.)

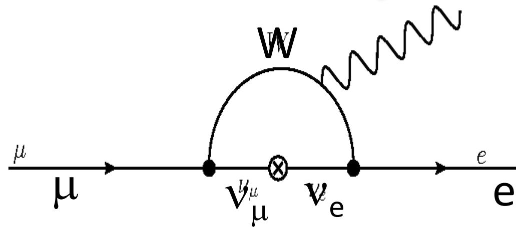
x10000 improvement over current limit

Mu2e: Muon to Electron Conversion

- Search for $\mu^{-}N \rightarrow e^{-}N$ is an exceptional opportunity to study CLFV
  - Experimental signature is an electron with E_e=105 MeV coming from a target in which muons stop
  - Largely unaffected by backgrounds from overlapping decays, allowing high data rates and therefore ultimate precision
  - Contrast with $\mu \rightarrow e\gamma$: BR sensitivity limited to 10^{-13} to10^{-14} by accidental backgrounds at high rates
  - Fermilab using Booster protons can deliver:
    - high flux of low energy muons
    - just the right time structure
    - modest upgrades to existing facilities
    - minimal impact on the neutrino program

Contributions to μe Conversion

In SM:

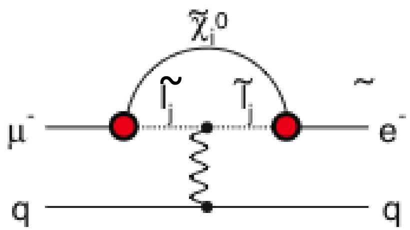


$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W}\right|^2$$

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

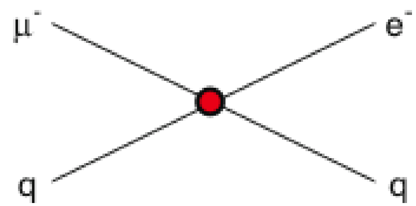
Supersymmetry

rate ~ 10^{-15}



Compositeness

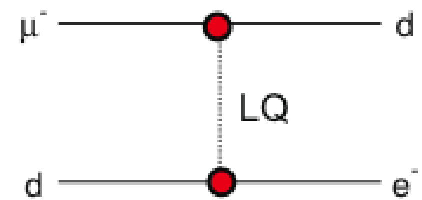
Λ_c ~ 3000 TeV



Leptoquark

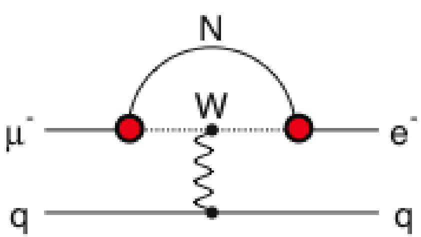
M_{LQ} =

3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



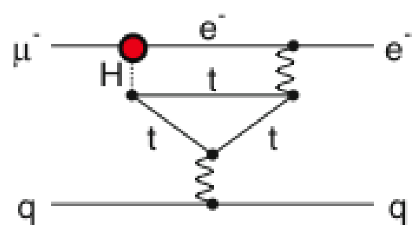
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



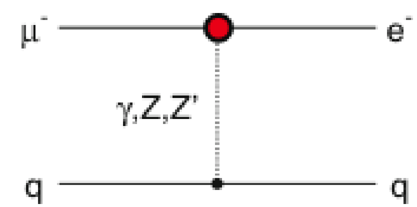
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

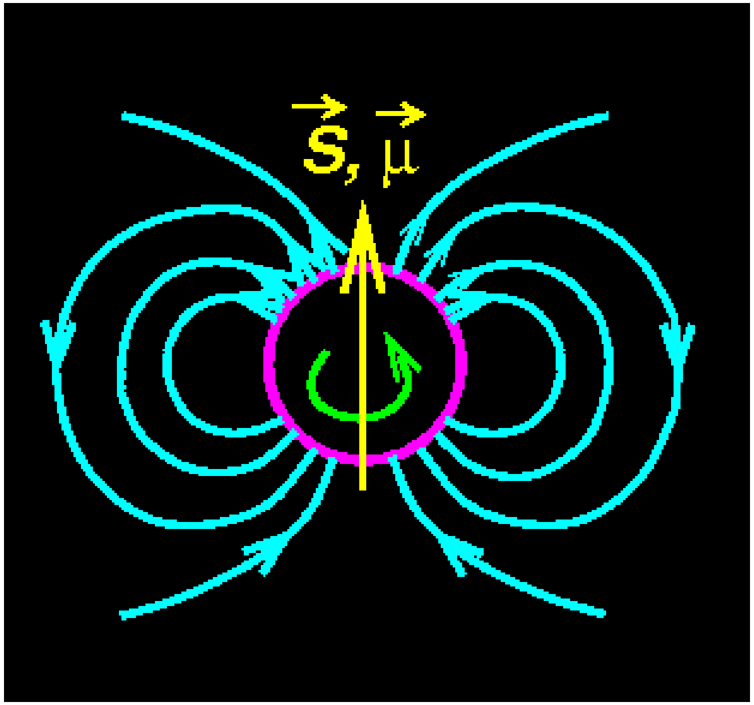
Muon g-2: Spin magnetic moment μ_S

$$\vec{\mu}_s = g_s \left(\frac{e\hbar}{2m} \right) \vec{s}$$

the moment consists of 2 parts

$$\mu = (1 + a) \frac{e\hbar}{2m}$$

Dirac + Pauli moment

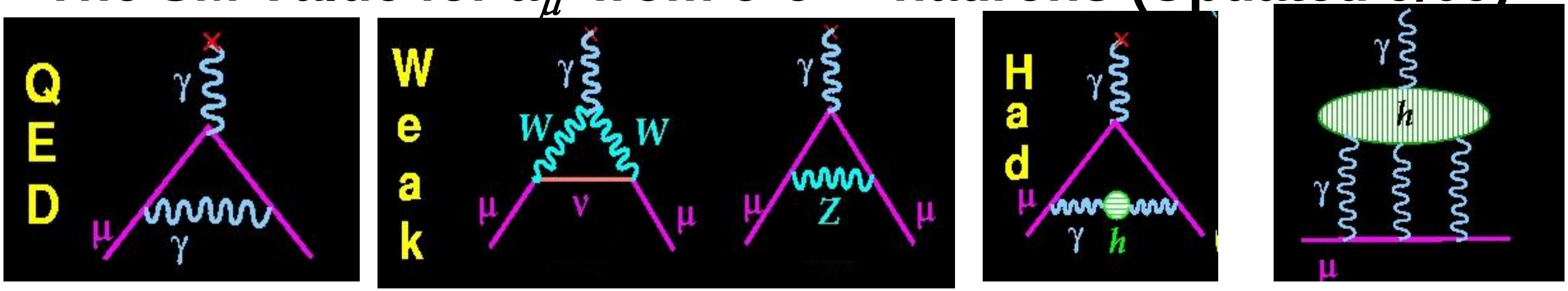


the anomaly $a = \left(\frac{g-2}{2} \right)$; or $g = 2(1 + a)$

SM predicts a

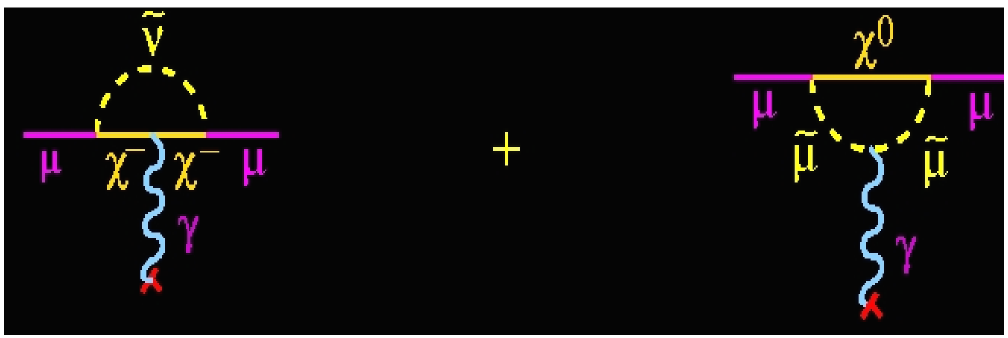
$$a^{SM} = a^{QED} + a^{Had} + a^{EW}$$

The SM Value for a_μ from $e^+e^- \rightarrow$ *hadrons* (Updated 9/09)



well known SM

SM: significant work ongoing



Beyond SM:
SUSY1-Loop

$$a_\mu^{SUSY} \approx 130x10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 \tan\beta\ \text{Sign}(\mu)$$

Davier et al,

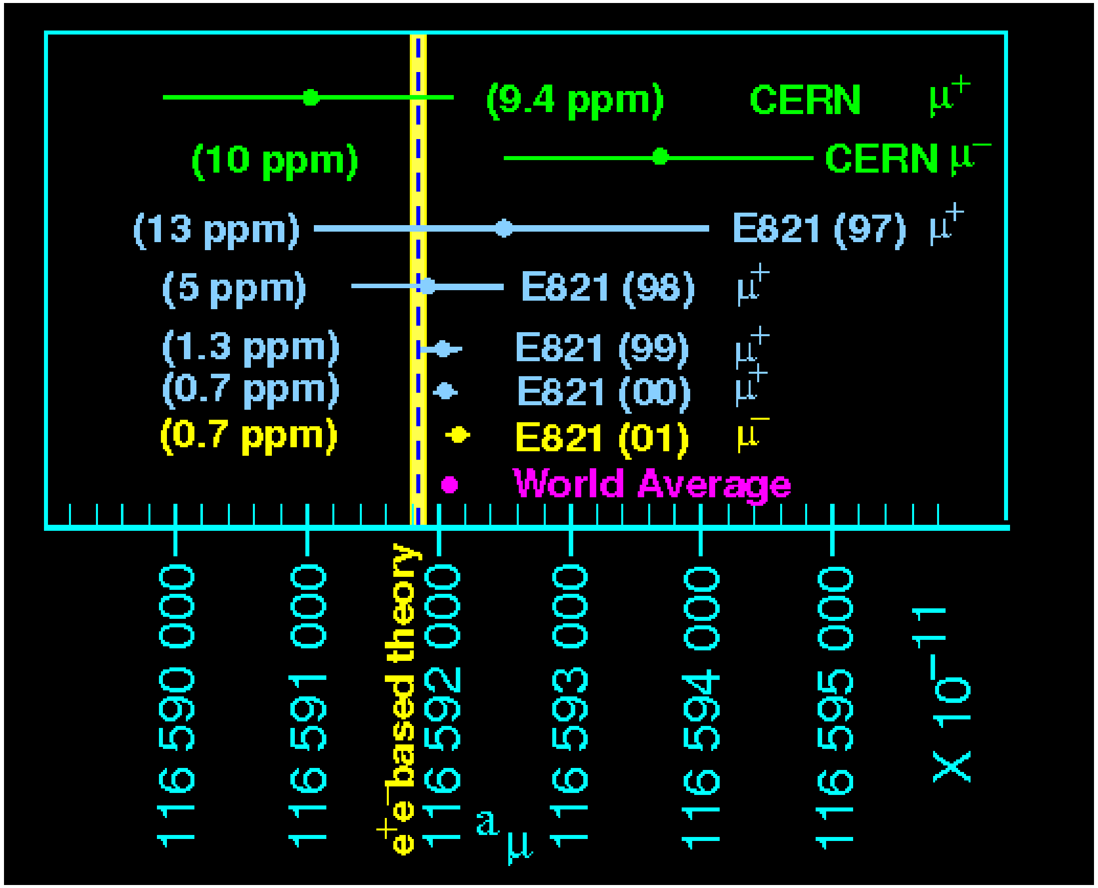
hep-ph

arXiv:0908.4300

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.10 \pm 0.16$
HVP(lo) **w. BaBar, no KLOE LA**	$6\,955 \pm 40_{\text{exp}} \pm 7_{\text{pQCD}}$
HVP(ho)	$-97.9 \pm 0.8_{\text{exp}} \pm 0.3_{\text{rad}}$
HLxL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,834 \pm 41_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

$$a_\mu^{exp} = 116\,592\,089(63) \times 10^{-11}\ (0.54\ \text{ppm})$$

E821: Brookhaven Muon g-2 Experiment Results from early 2000's



a_μ^{Exp}=116 592 089(63)x10^{-11} (0.54 ppm)

a_μ^{SM}=116 591 834(49)x10^{-11} (0.42 ppm)

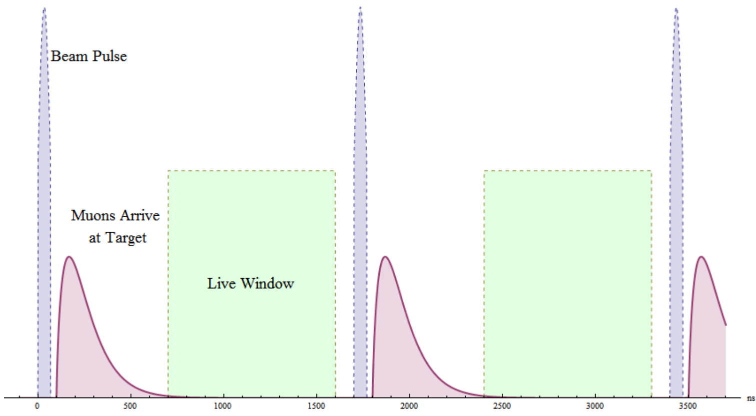
Δa_μ= 255(80)x10^{-11} (3.2 σ)

If this is due to new physics, it has a big effect!

(Almost 2x bigger than EW diagrams)

New g-2 experimental goal: 0.14 ppm

The μN$\rightarrow$eN measurement at Br(6x10^{-17})



- Produce muons with a pulsed proton beam, spacing=1695 ns
- Stop $\sim\mathcal{O}(5\times10^{10})$ μ^- per second on a target (Al, Ti), become bound in atomic 1S orbital: muon w.f. overlaps with nucleus
- Wait 700ns (to let prompt backgrounds clear))
- Look for the coherent conversion of a muon to a mono-energetic electron:

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

- Report the rate relative to nuclear capture

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

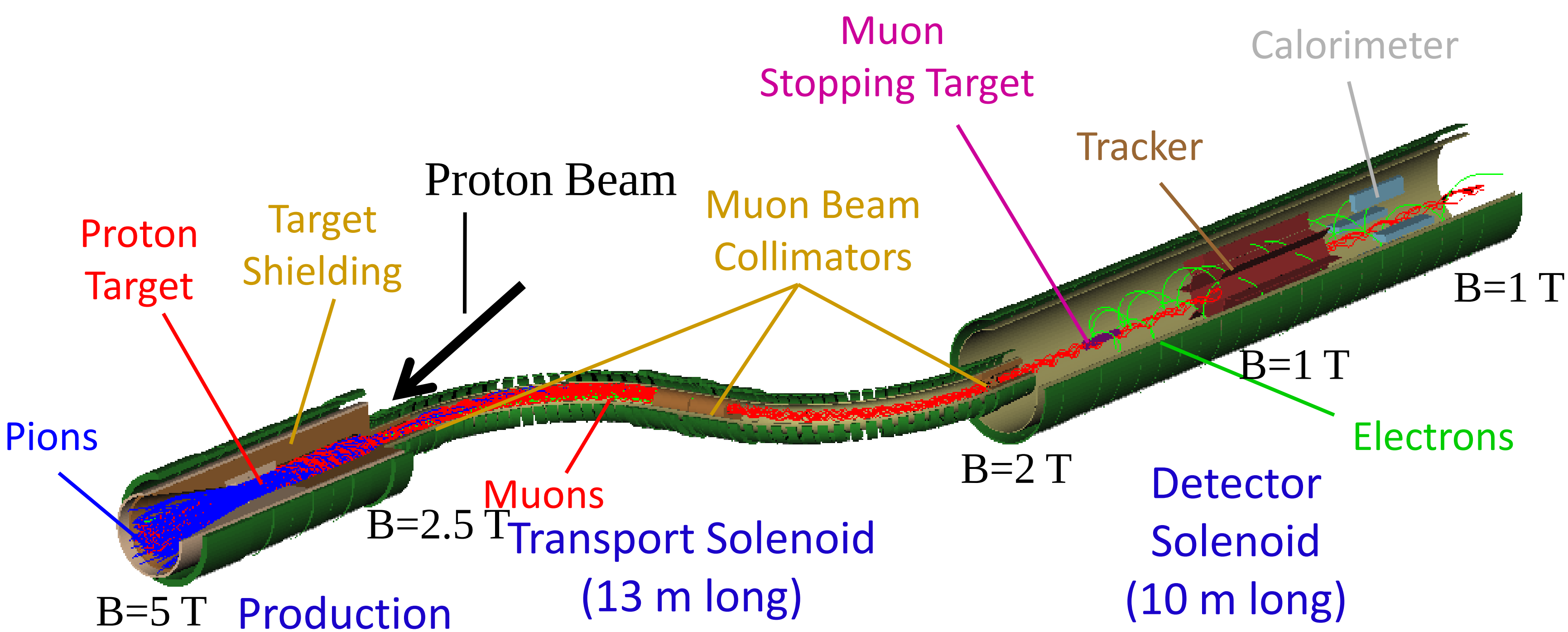
- *If a signal is seen, it's compelling evidence for physics beyond the standard model!*

Features of Mu2e

- > 1000 fold increase in muon intensity
  - Solenoid beam line with gradient at production target to maximize pion/muon collection near production target and for optimal transmission downstream
- Pulsed beam to eliminate prompt backgrounds
  - Proton pulse duration << τ_μ (τ_μ=Lifetime of muonic aluminum=864 ns)
  - Pulse spacing ~ $2\tau_\mu$
    - Fermilab spacing is ideal(=debuncher cyclotron period=1635 ns)
  - Large duty cycle
  - Extinction of beam between pulses 10^{-9}
- Improved detector
  - Higher rate capability: detectors displaced downstream from stopping target, configured to minimize backgrounds
  - Electron spectrometer with high resolution
  - Stopping target placed in graded magnetic field: improves detector acceptance(mirror effect), reduces background

Mu2e Muon Beamline

Muons are collected, transported, and detected in superconducting solenoidal magnets



Production Solenoid (4m long)

Transport Solenoid (13 m long)

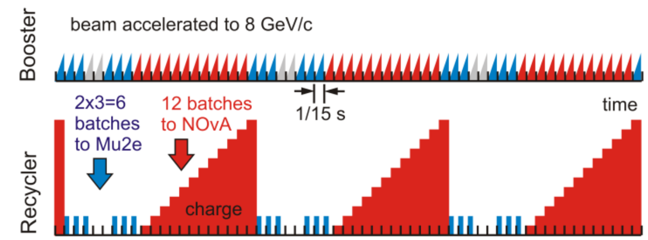
- Selects low momentum μ^-
- Avoids straight line from production target to detectors

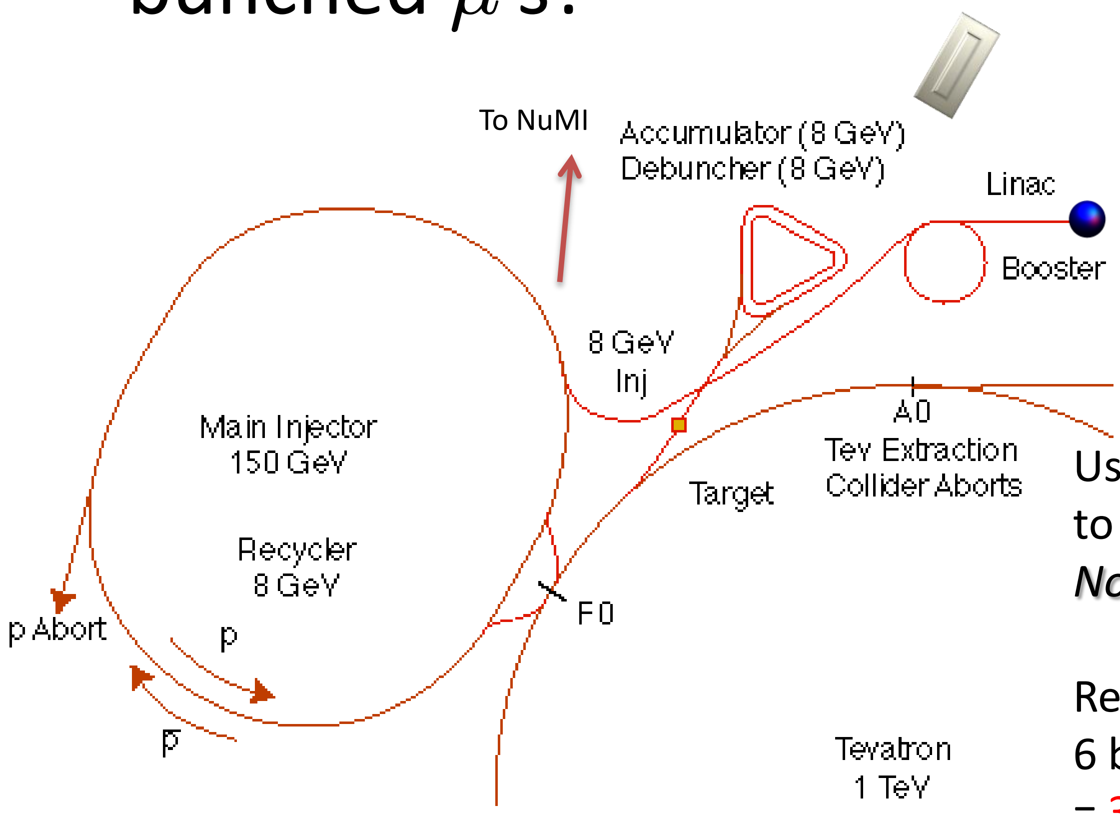
Detector Solenoid (10 m long)

Delivers 0.0025 stopped muons per 8 GeV proton

Mu2E & NOνA/NuMI

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

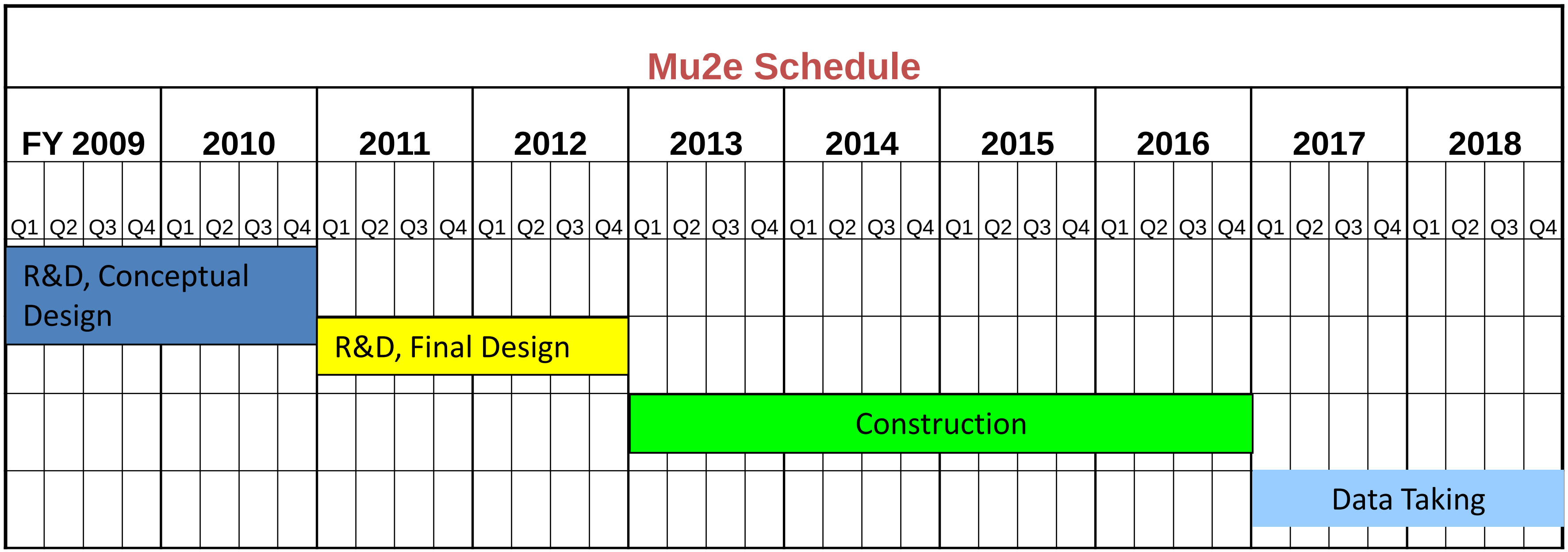




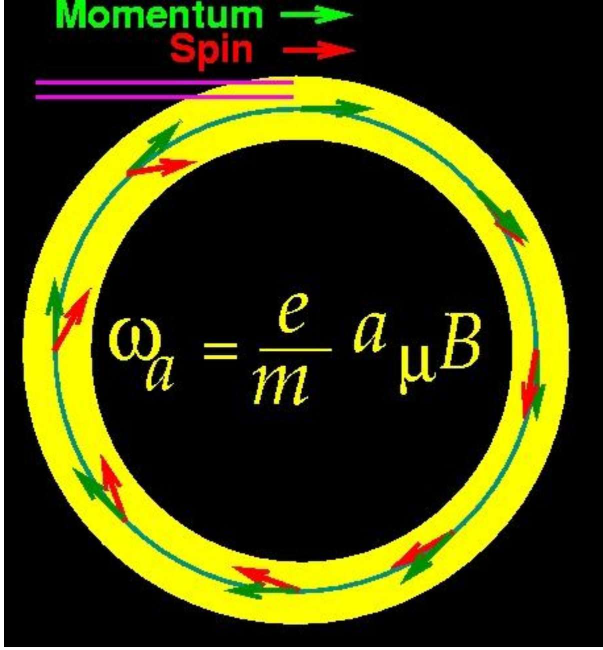
Use NuMI cycles in the Main injector to slow spill to Mu2e.
No Impact on NOvA

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

Mu2e Technically Limited Schedule



The a_μ Experiments:



- E821 at Brookhaven
- $$\left.\begin{array}{l}\sigma_{stat} = \pm 0.46 \text{ ppm} \\ \sigma_{syst} = \pm 0.28 \text{ ppm}\end{array}\right\} \sigma = \pm 0.54 \text{ ppm}$$

Spin motion: difference frequency between ω_s and ω_c – rate at which S precesses relative to p

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_p$$

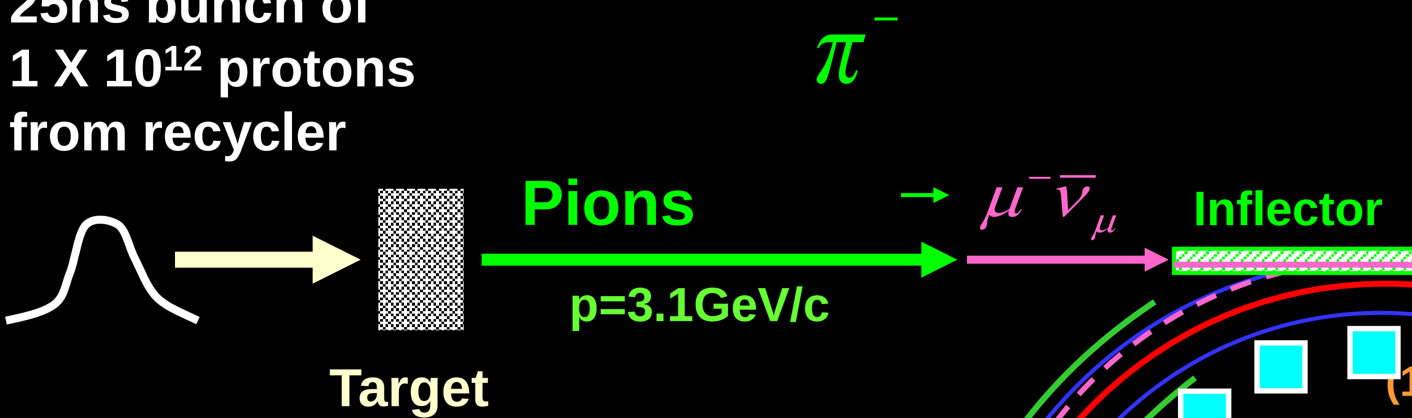
$$= -\frac{q}{m}\left[a_\mu \vec{B} - (a_\mu - \frac{1}{\gamma^2 - 1})\vec{\beta} \times \vec{E}\right]$$

0

γ_{magic}=29.3
p_{magic}=3.09 GeV/c
Ring radius=7.1 m
Muon lifetime=64 μs

Experimental Technique

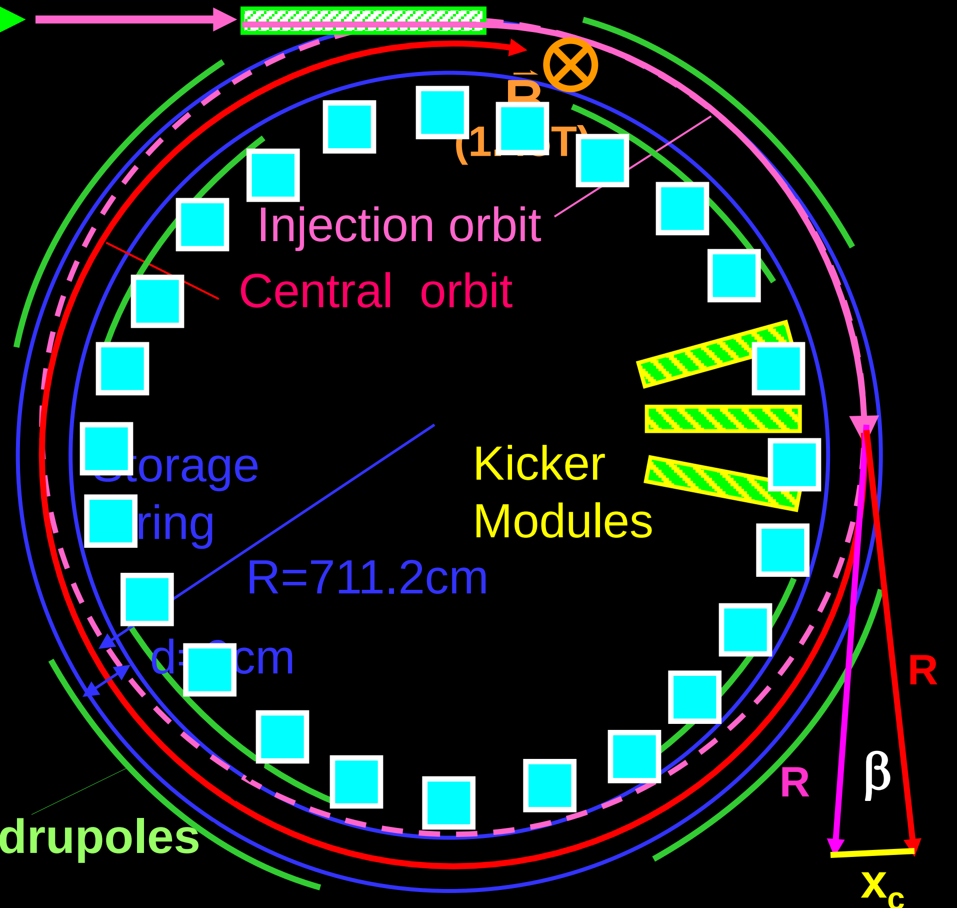
25ns bunch of
1 X 10[12] protons
from recycler



$x_c \approx 77$ mm

$\beta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm



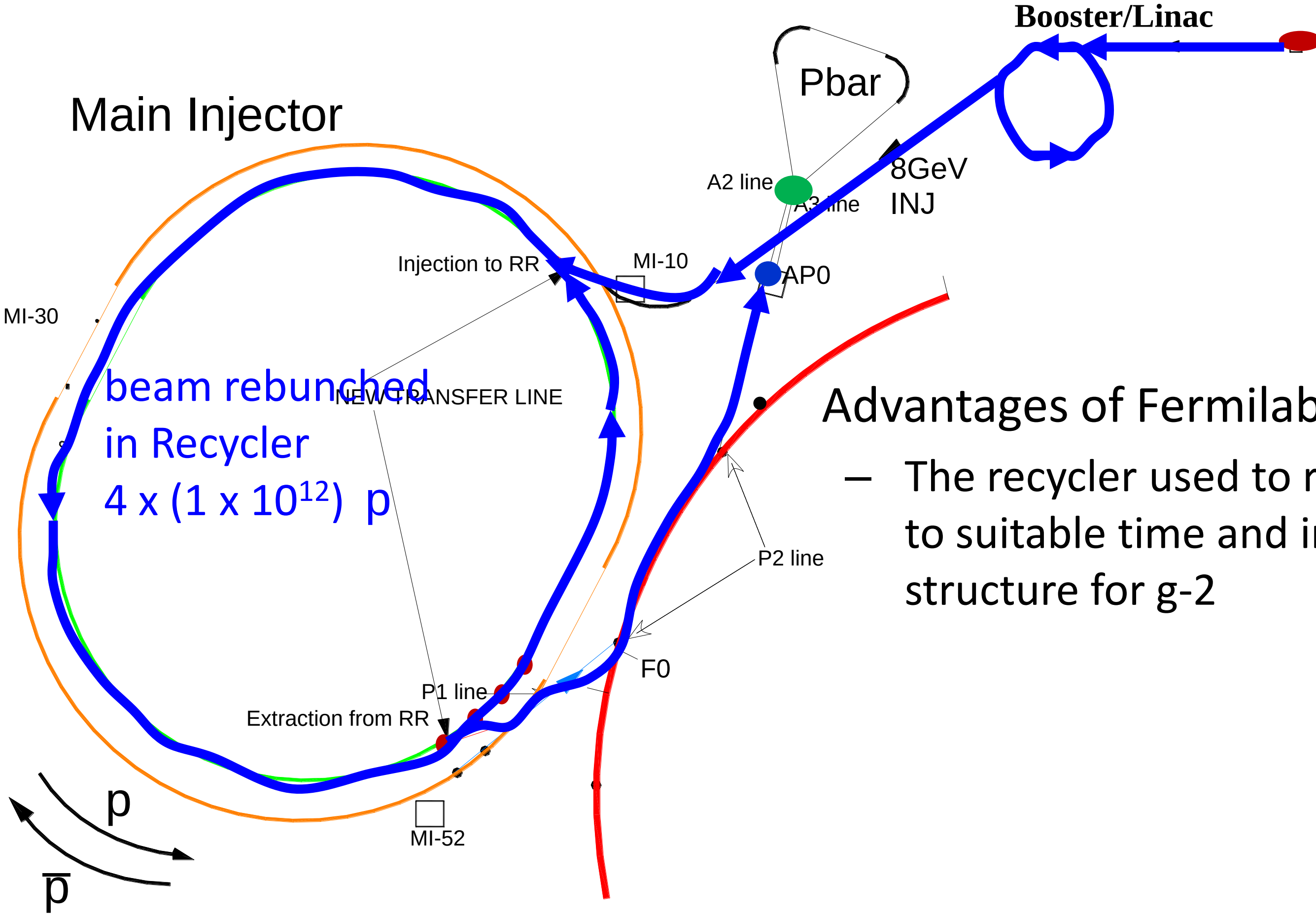
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

(thanks to Q. Peng)

J. Miller,
Boston U.

At Fermilab: Polarized muons produced and stored in the ring at the magic momentum, 3.094 GeV/c

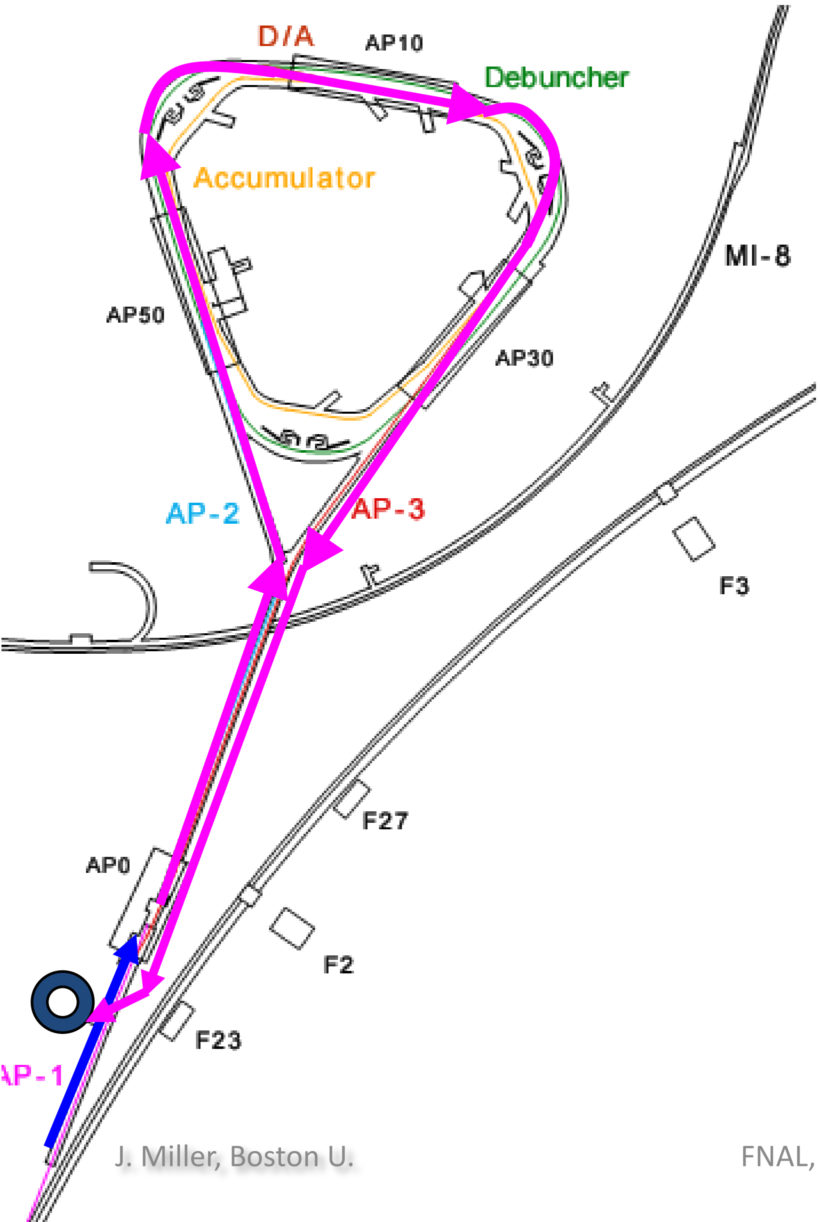


Advantages of Fermilab

– The recycler used to re-bunch beam to suitable time and intensity structure for g-2

*Can use all 20 if MI program is off

The 900-m long decay beam reduces the pion "flash" by x20 and leads to 6 – 12 times more stored muons per proton (compared to BNL. A full beamline simulation is underway.)



■Advantages of Fermilab

- ◆The recycler used to re-bunch beam to time structure for g-2
- ◆The antiproton debuncher plus beam lines serve as a 900 m decay line: problematic pions largely decay
- ◆The net effect is more muons stored per hour, with a minimal increase in instantaneous rates in the new segmented detectors

Possible g-2 Schedule?

- CY 2009
  - PAC proposal defended in March 2009 (Well received, but how many$?)
  - Laboratory supports costing exercise July-October
  - Report to PAC meeting November
- CY 2010 Approval?
  - building design finished
  - other preliminary engineering and R&D
- CY 2011 Tevatron running finishes in Oct.
  - building construction begins
  - ring disassembly begins FY2012
- CY 2012
  - building completed mid-year
  - ring shipped
- CY 2013-2014
  - re-construct ring
  - shim magnet
- CY 2015 Beam to experiment
  - **2 year data collection on μ^+**

CLFV and g-2 at Other Labs

- CLFV
  - MEG(PSI), $\mu \rightarrow e\gamma$ (current limit $< 1.2 \times 10^{-11}$)
    - running now
    - goal in ~2 years ~10^{-13}
    - Ultimate goal with upgrades ~10^{-14}
  - COMET, $\mu N \rightarrow eN$
    - Recently received Stage I approval at JPARC
    - Also based on MECO concepts, with some changes to transport and detector solenoids
    - Goal: 10^{-16} single event sensitivity
    - Needs dedicated beam at JPARC
  - $\tau \rightarrow eee, \mu\mu\mu, e\gamma, \mu\gamma$,… ~$10^{-10}$ at Flavor Factories?
- Muon g-2
  - Low energy muon storage solenoid at JPARC in proposal stage
  - Comparable in sensitivity to New g-2 Experiment at Fermilab, but with quite different approach

Conclusions

- Mu2e and Muon g-2 will provide important information on new physics which is hard to access at the LHC: powerful complements to LHC results.
- The experiments are very well-suited to the pre-Project X Fermilab environment and schedule, with minimal impact on the neutrino program.
- Mu2e
  - Improve the measurement of muon to electron conversion by four orders of magnitude, 2×10^{-17} single-event sensitivity, probing CLFV to new levels of precision
  - Physics reach that can extend to 1000's of TeV
  - Upgrades and Project X beams could deliver another two orders of magnitude in sensitivity.
- Muon g-2
  - Brookhaven result from early 2000's differs from SM by > 3 σ
  - Result suggests there may be a big effect from new physics– SUSY?
  - Improve on the Brookhaven number by crucial factor of four
  - Expect modest improvements in SM value as well for better comparison with experiment.
  - Can use increased proton flux from Project X to make further improvements and measure $\mu-$ (the production cross section is 2-3 times smaller than for $\mu+$) .

BACKUP SLIDES

General CLFV Lagrangian

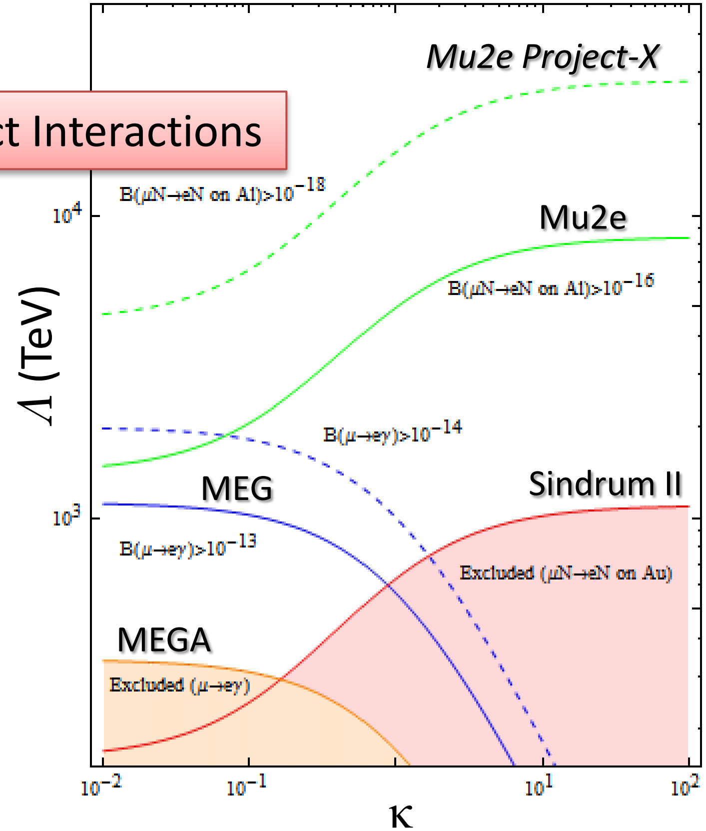
- Recharacterize these all these interactions together in a model independent framework:

Loops

Contact Interactions

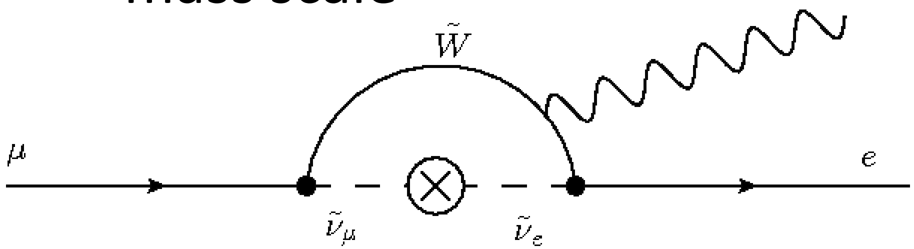
$$\mathcal{L}_{\mathcal{LFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L\right)$$

  - Splits 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

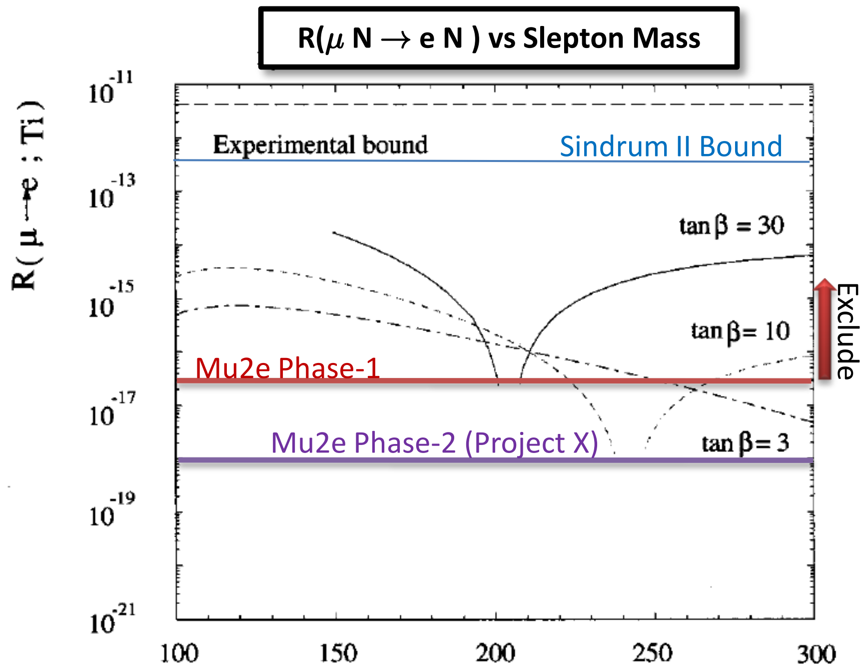


μN$\rightarrow$eN Sensitivity to SUSY

- 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(μ N $\rightarrow$ e N) ~10^{-15}
- Makes μN$\rightarrow$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

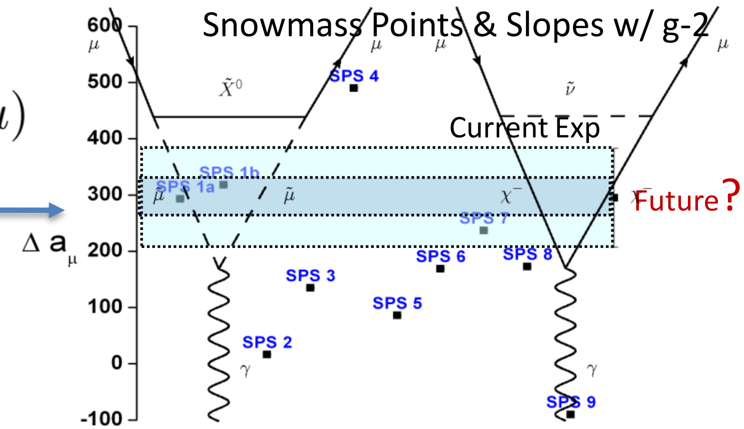
Hisano et al. 1997

g-2 Sensitivity to SUSY

- SUSY contributes to a_μ= (g-2)/2:

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

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

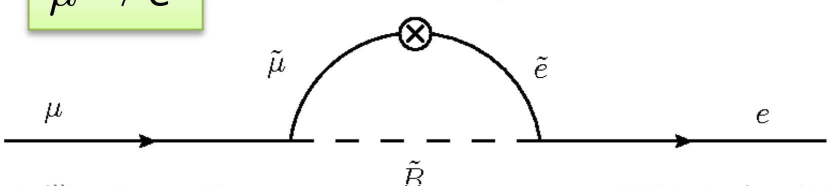


- a_μ's sensitivity to SUSY is through the same loop interactions as CFLV channels
- Gives us access to Slepton Mixing

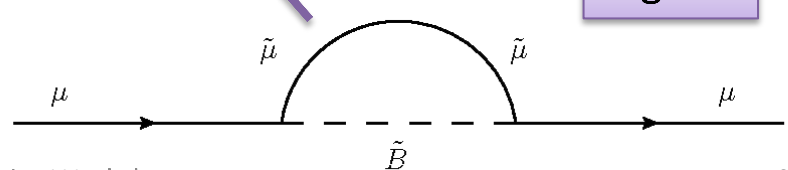
Slepton Mixing Matrix

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

$\mu \rightarrow$ e



g-2



μN$\rightarrow$eN, $\mu\rightarrow$eγ, g-2 Work Together

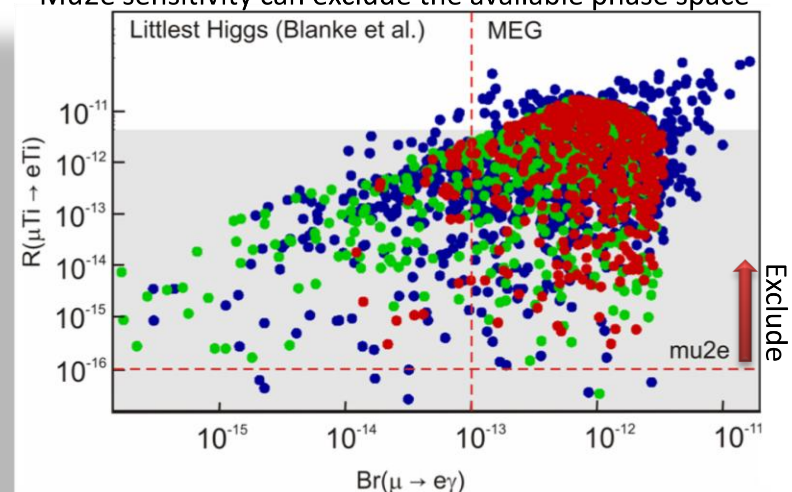
Example:

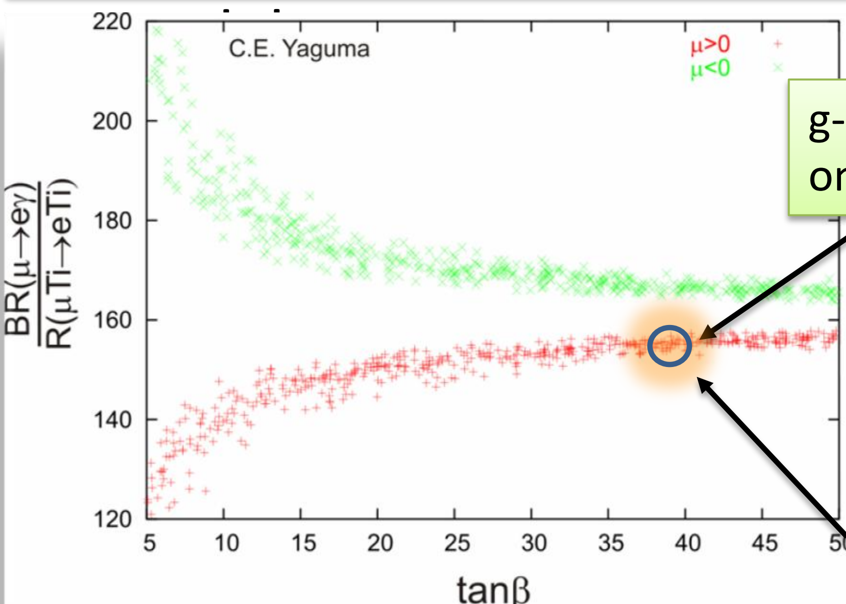
- From LHC we have the SUSY masses
- From g-2 we know tanβ
- From g-2 we know also know μ>0
- Combining these we get an a priori PREDICTION for:

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

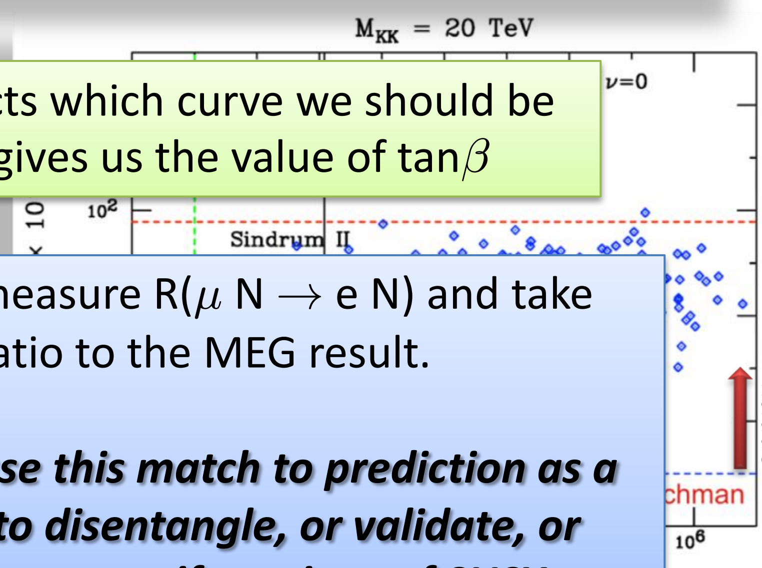
under MSSM/MSUGRA

Mu2e sensitivity can exclude the available phase space





MSSM/msugra/seesaw



Randall-Sundrum

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

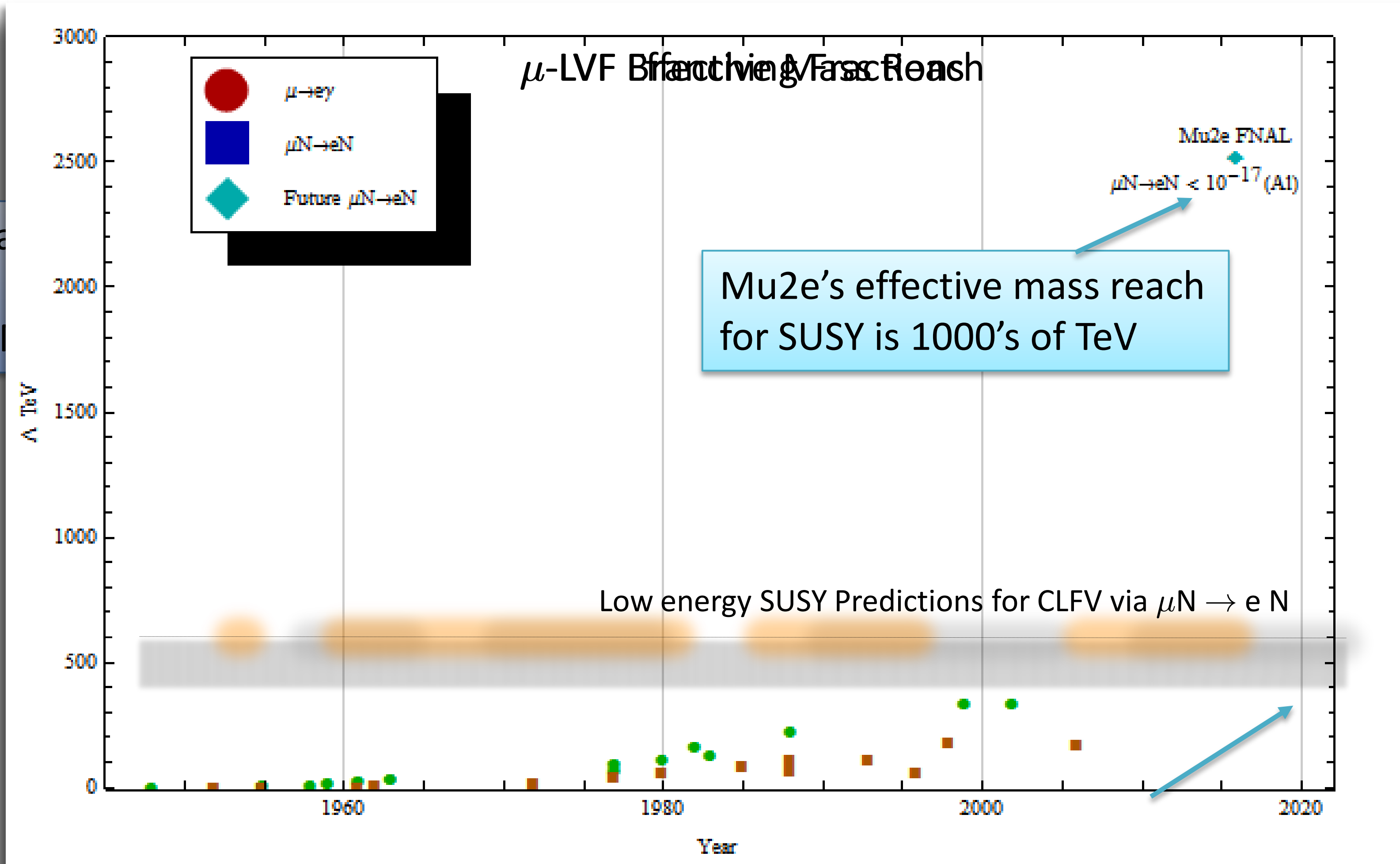
We measure R(μ N $\rightarrow$ e N) and take the ratio to the MEG result.

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 Mea

Effective I



1.2×10^{-11} (MEGA $\mu\rightarrow e\gamma$)

7×10^{-13} (Sindrum II on Au)

Total Backgrounds

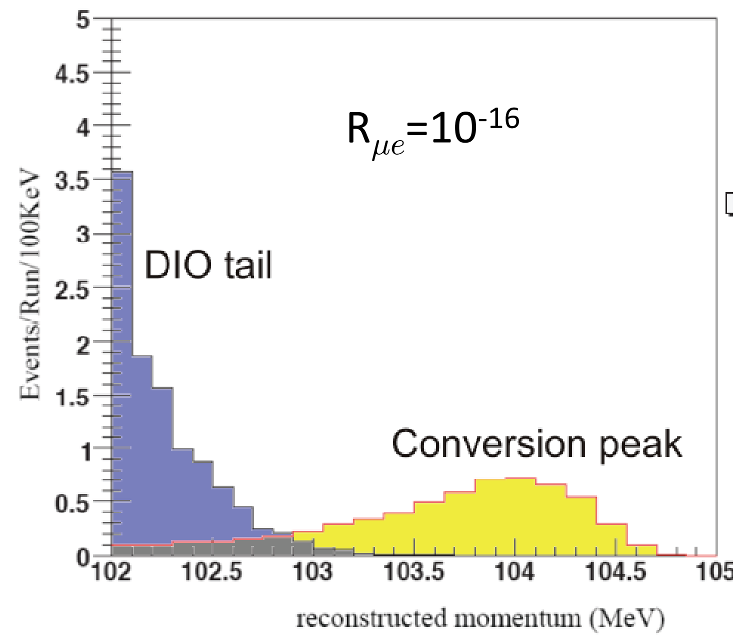
- Largest Background
  - Decay in Orbit (DIO)
  - Rad π Capture (RPC)
- Limiting Backgrounds
  - Can limit prompt backgrounds w/ extinction
  - In particular, Rad π Cap. drives the extinction requirement
  - Current Background Estimates require 10^{-9} extinction
  - BNL AGS already has demonstrated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

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

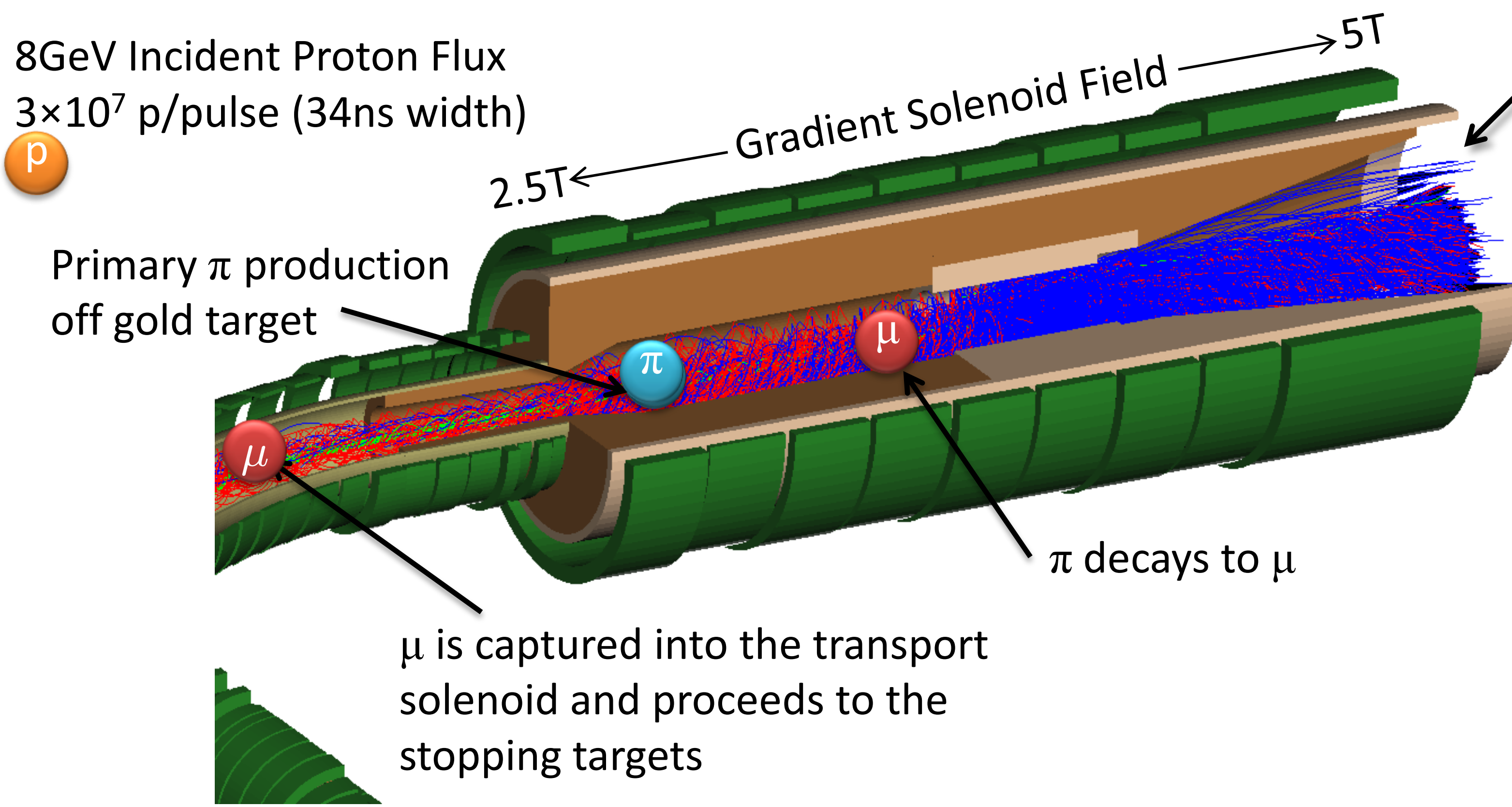


Production Solenoid

Magnetic Mirror Effect

8GeV Incident Proton Flux
3×10^{7} p/pulse (34ns width)

Primary π production off gold target

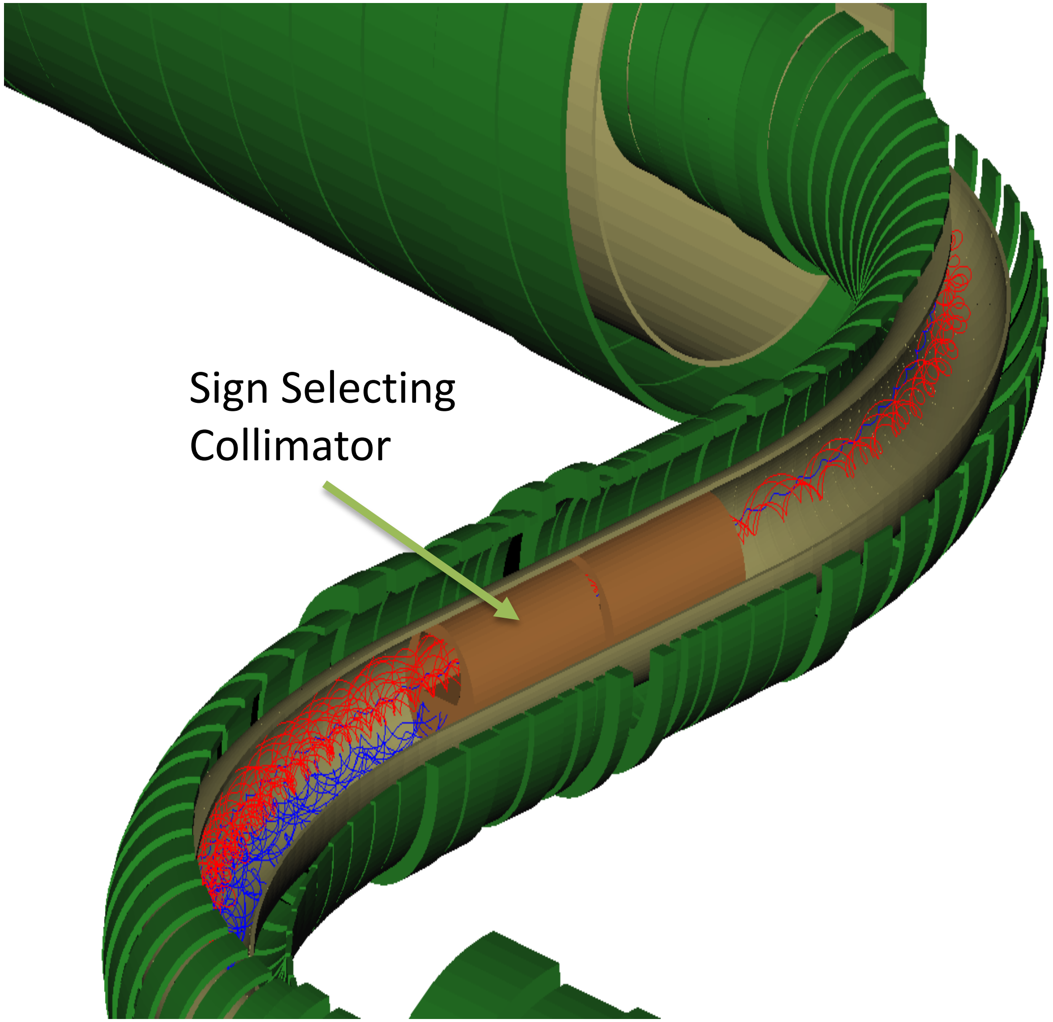


π decays to μ

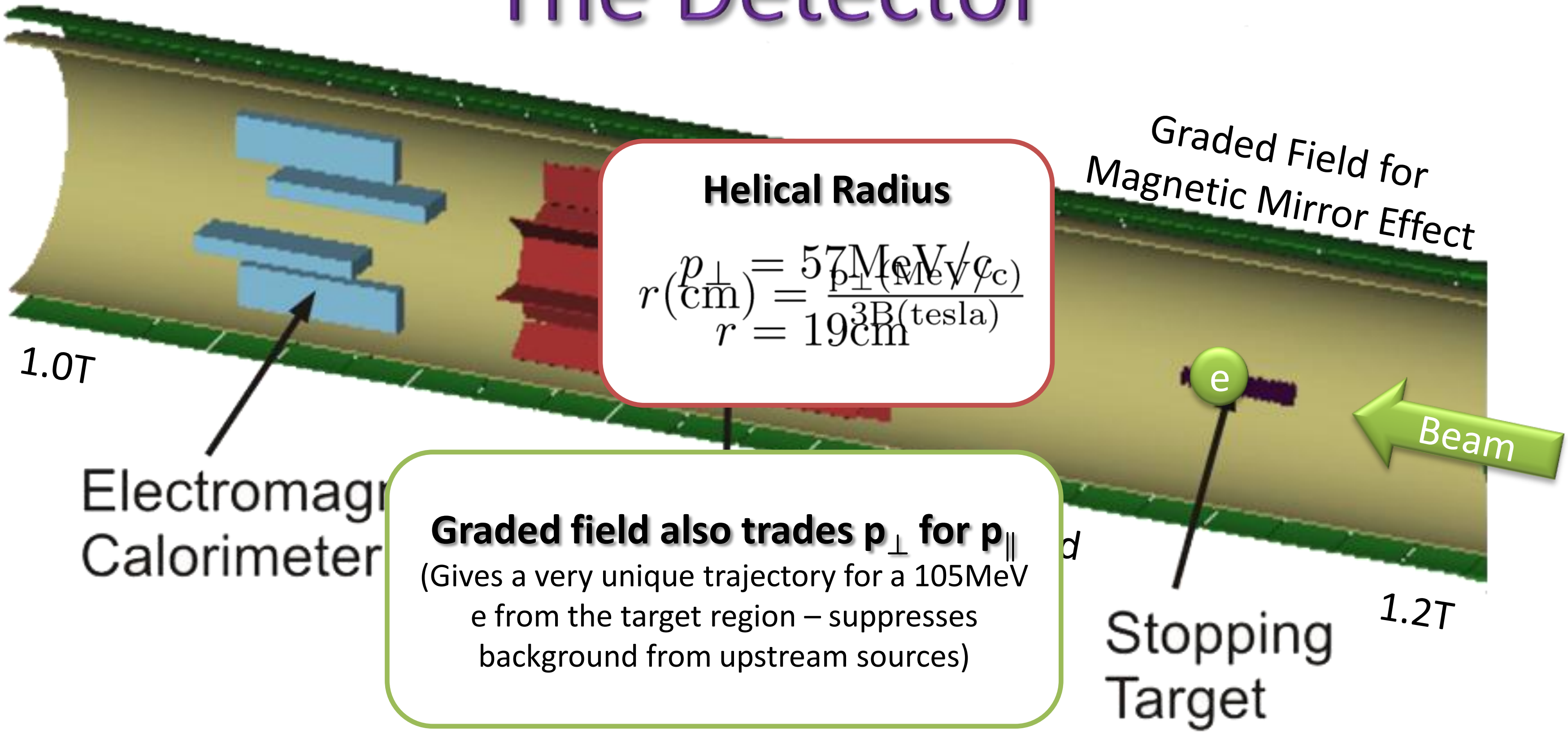
μ is captured into the transport solenoid and proceeds to the stopping targets

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



Helical Radius

$$p_\perp = 57\mathrm{MeV}/c$$

$$r(\mathrm{cm}) = \frac{p_\perp(\mathrm{MeV}/c)}{3B(\mathrm{tesla})}$$

$$r = 19\mathrm{cm}$$

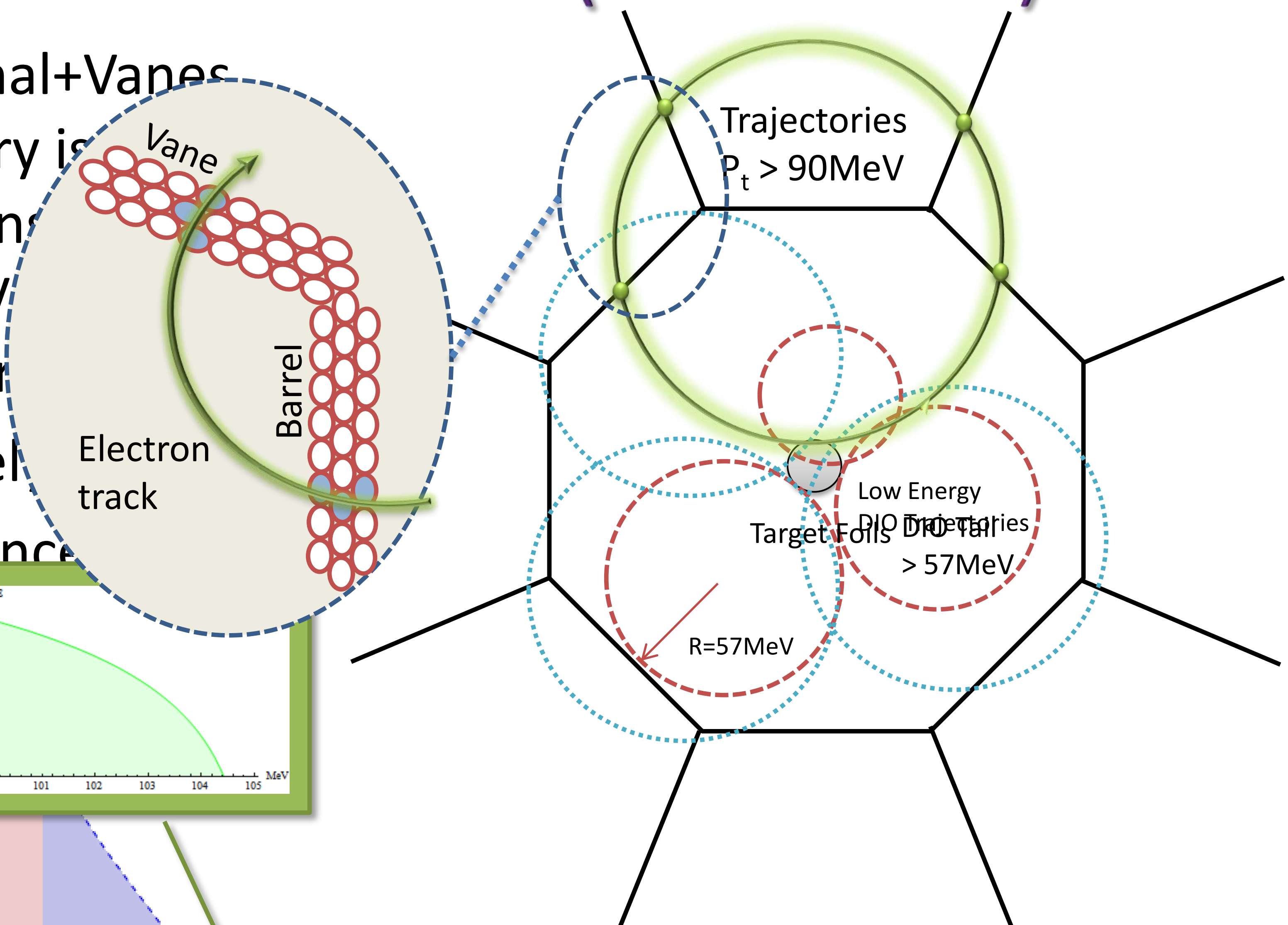
Graded field also trades $p_\perp$ for $p_\parallel$

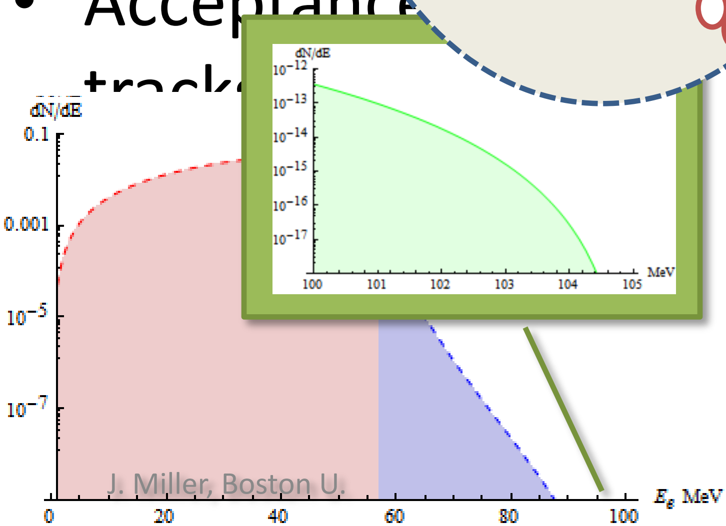
(Gives a very unique trajectory for a 105MeV e from the target region – suppresses background from upstream sources)

- 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 for recon 105MeV trajector
- Extremel
- Acceptance track





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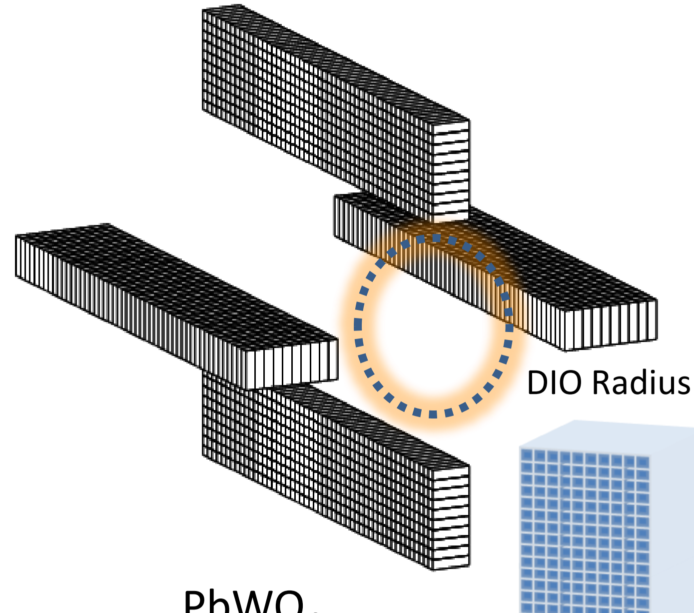
Crystal Calorimeter

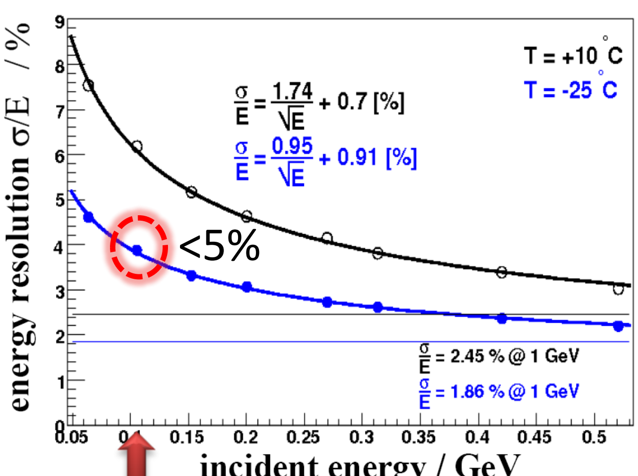
Original Design:

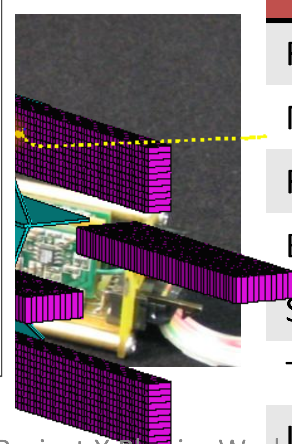
- 5% energy measure for trigger decision (1Hz rate)
- Timing edge for event reconstruction
- Spatial match to tracker trajectory
- Immune to DIO rates



$PbWO_4$

Tracker
project

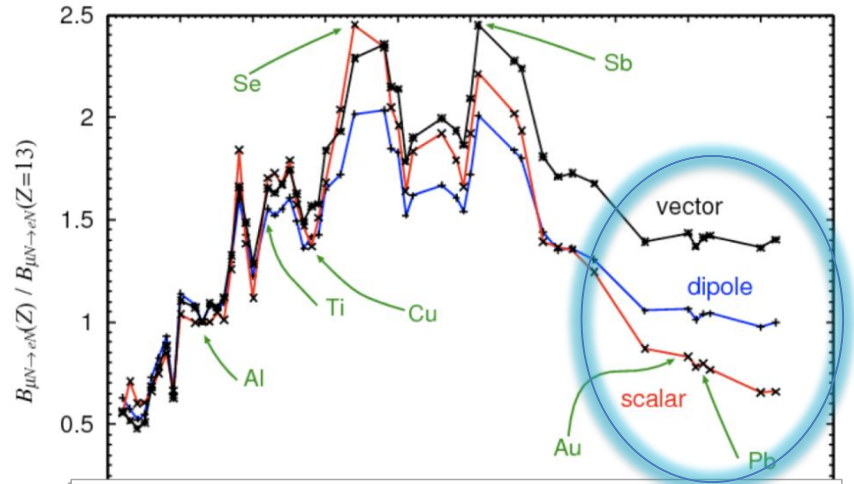


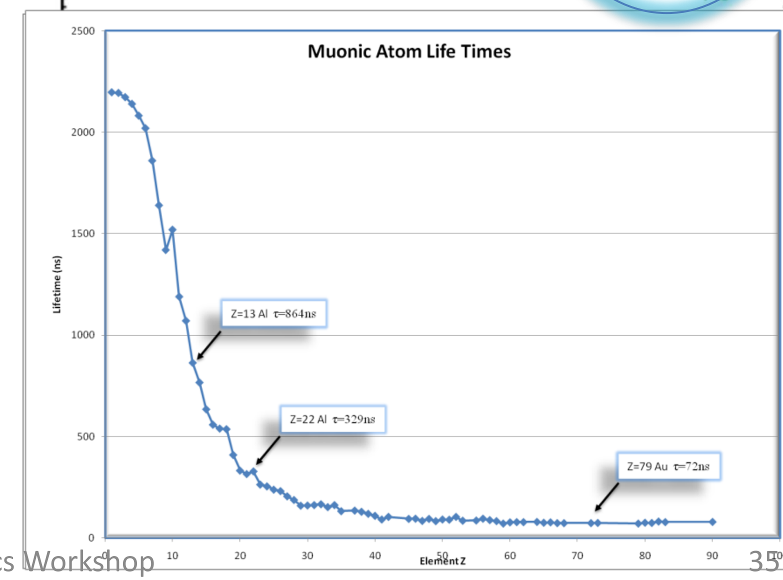


Calorimeter Properties	
Resolution	5%
Material 13.6X_0	$PbWO_4$
Readout	Dual APD
Blocks	500 per fin, 4 fins
Segmentation	$30\times30\times120mm^3$
Trigger Rate	1kHz
Light yield	20-30p.e./MeV

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





G-2 AT FNAL

Intro & Theory

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

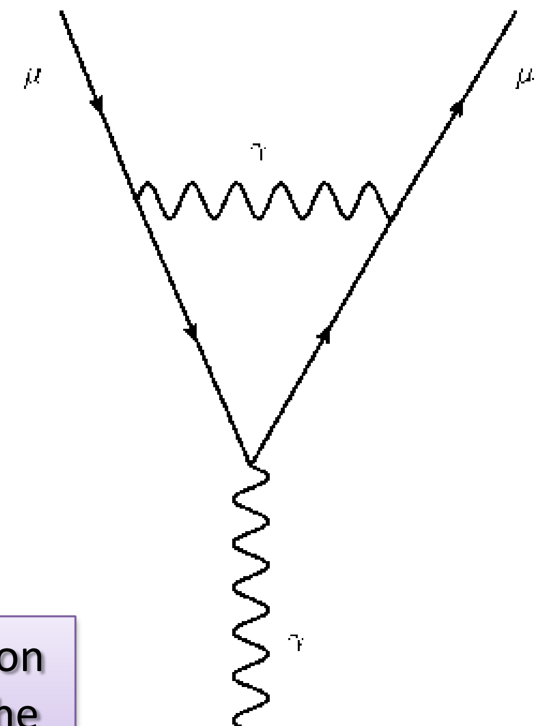
$$\mu = g_\mu \left(\frac{e}{2m_\mu} \right) \mathbf{S}$$

- 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

Intro & Theory

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

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

- Where g is the Lande g-factor, given by the muon-photon vertex form factors F_1 & F_2

$$g = 2[F_1(0) + F_2(0)]$$

F_1 is just the charge of the muon (1)

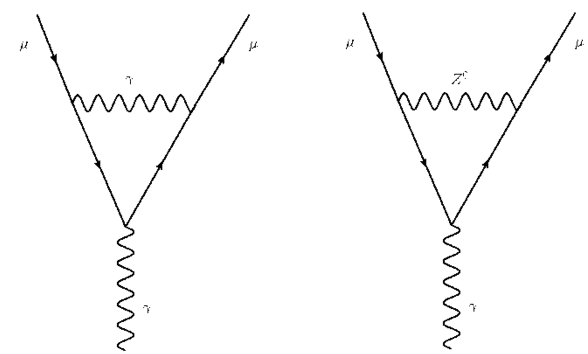
F_2 vanishes at leading order

ED prediction:

The purpose of g-2 is to measure with extreme precision the anomaly and compare it to the well known corrections that arise in SM and Beyond SM physics

of g from 2 as being the anomalous magnetic moment:

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



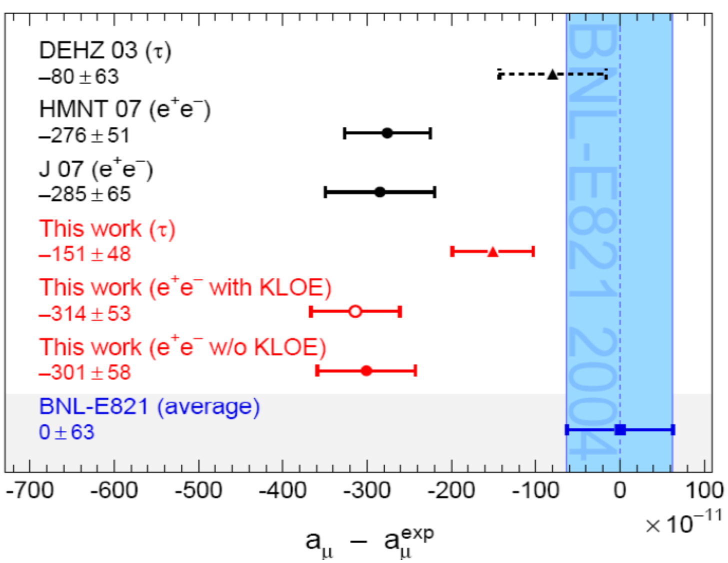
Current g-2 Numbers & Theory

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)

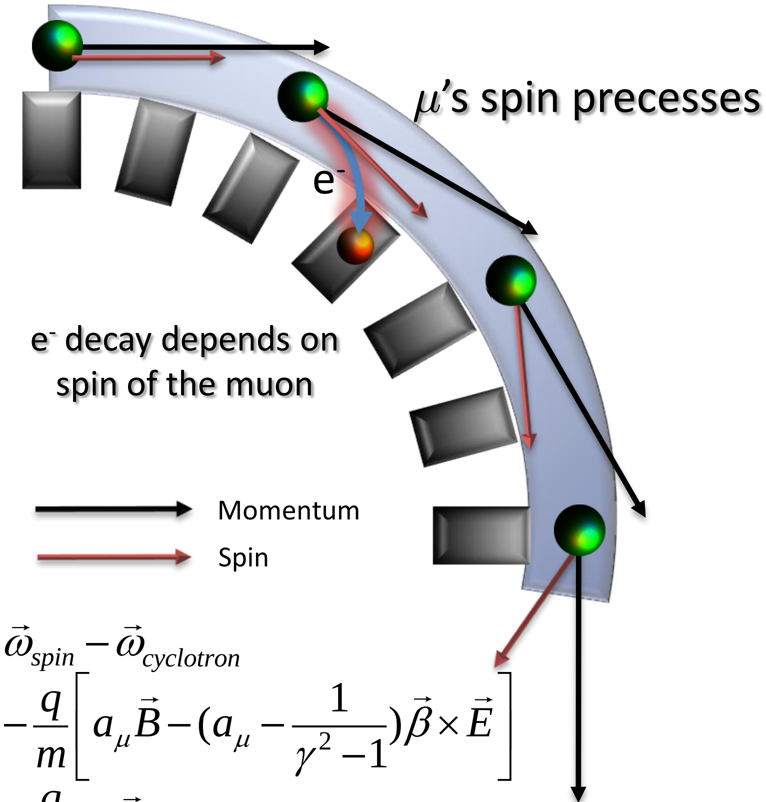
$$\Delta a_\mu^{MSSM} = 298 \times 10^{-11}$$

Extra Dimensions

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

The g-2 Measurement

Inject 96% longitudinally Polarized μ's



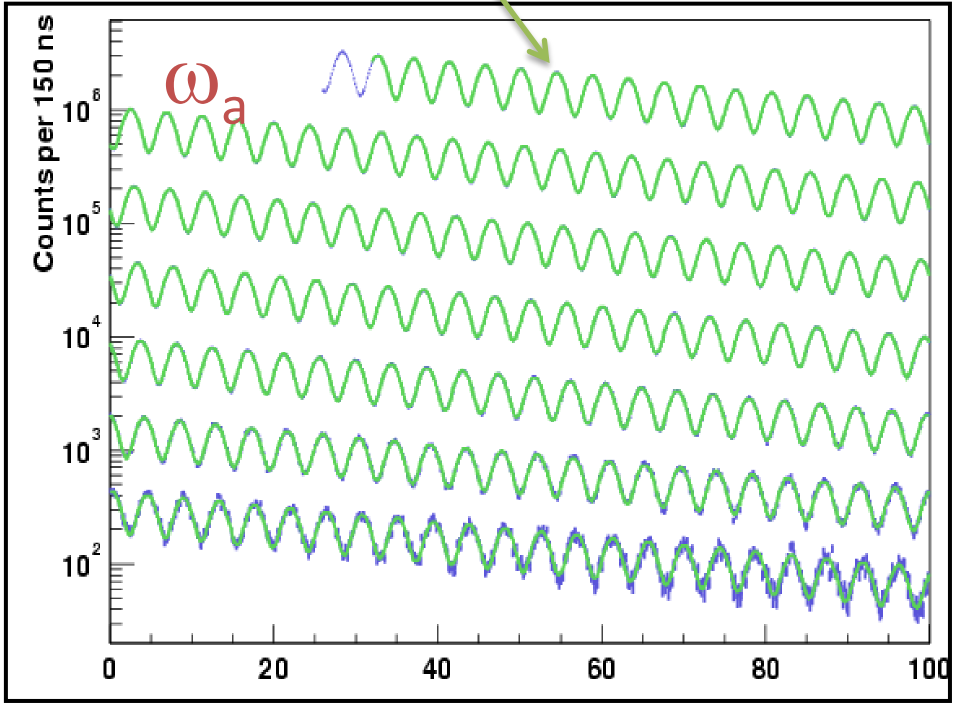
$$\vec{\omega}_a = \vec{\omega}_{spin} - \vec{\omega}_{cyclotron}$$

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

$$\vec{\omega}_a = -\frac{q}{m} a_\mu \vec{B} \quad \text{at magic momentum}$$

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



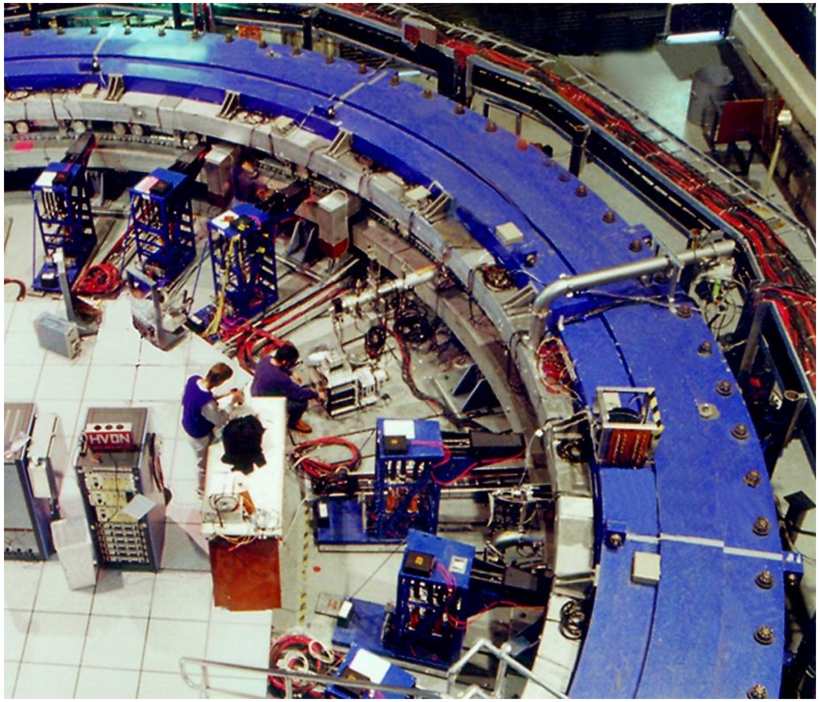
g-2 Goals

- 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)

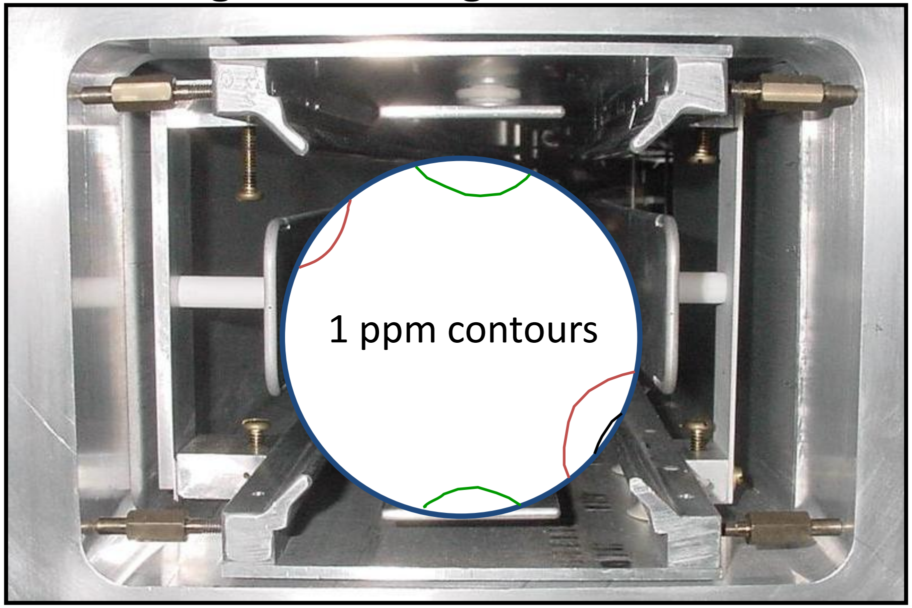
- Possible at FNAL because we can have:
  - More μ's
  - Less background

upgrade

- BNL Storage Ring Flies to Chicago!



- Magnetic Field is improved through shimming and calibration



- FNAL beams offer more \mu

FNAL Beam for g-2

Beam Related Gains for running at FNAL

Stored μ per PoT

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

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

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

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

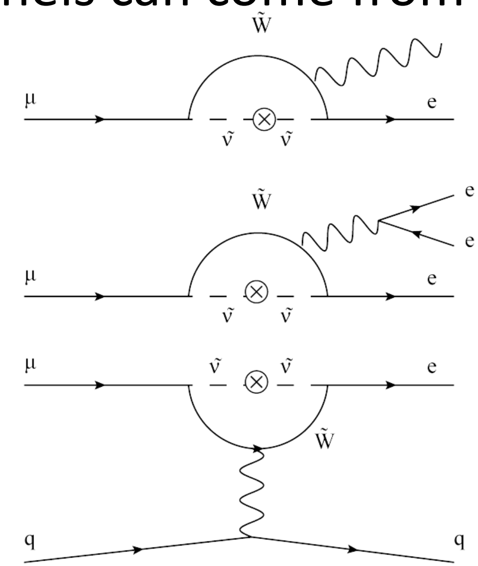
- If loop like interactions dominate we expect a ratio of rates:

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

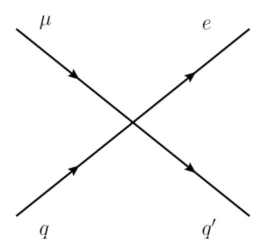
Ultimately Limits the measurement of:
Br($\mu \to e\ \gamma$)$\sim 10^{-14}$

No such limits on μN$\to$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



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 by direct production (LHC) or by the virtual production of heavy particles at low energies.
  - This means making precision measurements: look for ultra-rare decays or very small shifts from SM predictions.
  - Often these measurements are expected to provide information on new physics which is not easily accessible to the LHC experiments.
- Ideally we start with processes that are forbidden or highly suppressed in the standard model, or where the SM gives a very accurate prediction.
  - Any observation of a forbidden process or significant deviation from an expected SM value becomes proof of non-SM physics.
- Mu2e (rare decay) and Muon g-2 (precision measurement) are two examples at Fermilab which will exploit available Booster beam

Mu2e Technically Limited Schedule