Muon-Electron Conversion in the Field of a Nucleus

Mu2e at Fermilab

Argonne National Lab Seminar

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Based on: "Charged Lepton Flavor Violation Exp." by Marciano, Mori and Roney Ann Rev.NPP

"Mu2e: A Muon to Electron Conversion Exp at Fermilab" by J. Miller (talk) Slides

"Muon Decay and Physics Beyond the Standard Model" by Kuno & Okada RMP

and references therein

OUTLINE

1. Charged Lepton Flavor Violation
2. $\mu N \to eN$ Atomic Conversion vs Scattering
3. $B(\mu \to e\gamma)$ vs $R(\mu N \to eN)$
4. Neutrino Mass Effects
5. Muon g-2 (SUSY?) & LFV
   $a_\mu^{exp} - a_\mu^{SM} = 292(63)(58) \times 10^{-11}$ 3.4sigma!
6. μ2e at Fermilab: $R(\mu Al \to eAl) \to 2 \times 10^{-17}$!
   vs MEG($\mu \to e\gamma$) at PSI at $2 \times 10^{-13} \to 2 \times 10^{-14}$
7. Conclusion and Outlook

1. Charged Lepton Flavor Violation

- 1947 Muon established as independent elementary lepton: No $\mu \to e+\gamma$ implies μ not excited electron
- 1958 Feinberg loop calculation of $\mu \to e+\gamma$

  $B(\mu \to e\gamma) < 10^{-4} \sim 10^{-5}$ implies second neutrino!

  1959 Feinberg and Weinberg Study $\mu^- N \to e^- N$

  Coherent $E_e \approx 105$MeV Very Clean-Distinct

Stop μ^- in material (10^{-10}sec)$\to \mu^- N(1S)$ atom

i) $\mu \to e\nu\bar{\nu}$ Rate$\approx 0.5 \text{x} 10^6$/sec

ii) $\mu N \to \nu_\mu N'$ $\omega(N=Al) \approx 0.7 \text{x} 10^6$/sec

$\omega(N=Ti) \approx 2.6 \text{x} 10^6$/sec

grows $\propto Z^4$ (very roughly)

- iii) $R(\mu N) \equiv \omega(\mu N \rightarrow eN)/\omega(\mu N \rightarrow \nu_\mu N') \propto Z$ (for low Z)

  $R(\mu Au) < 7x10^{-13}$ SindrumII at PSI

  $R(\mu Ti) < 7x10^{-13}$ Unpublished

Conversion can take very high rate-No Accidentals

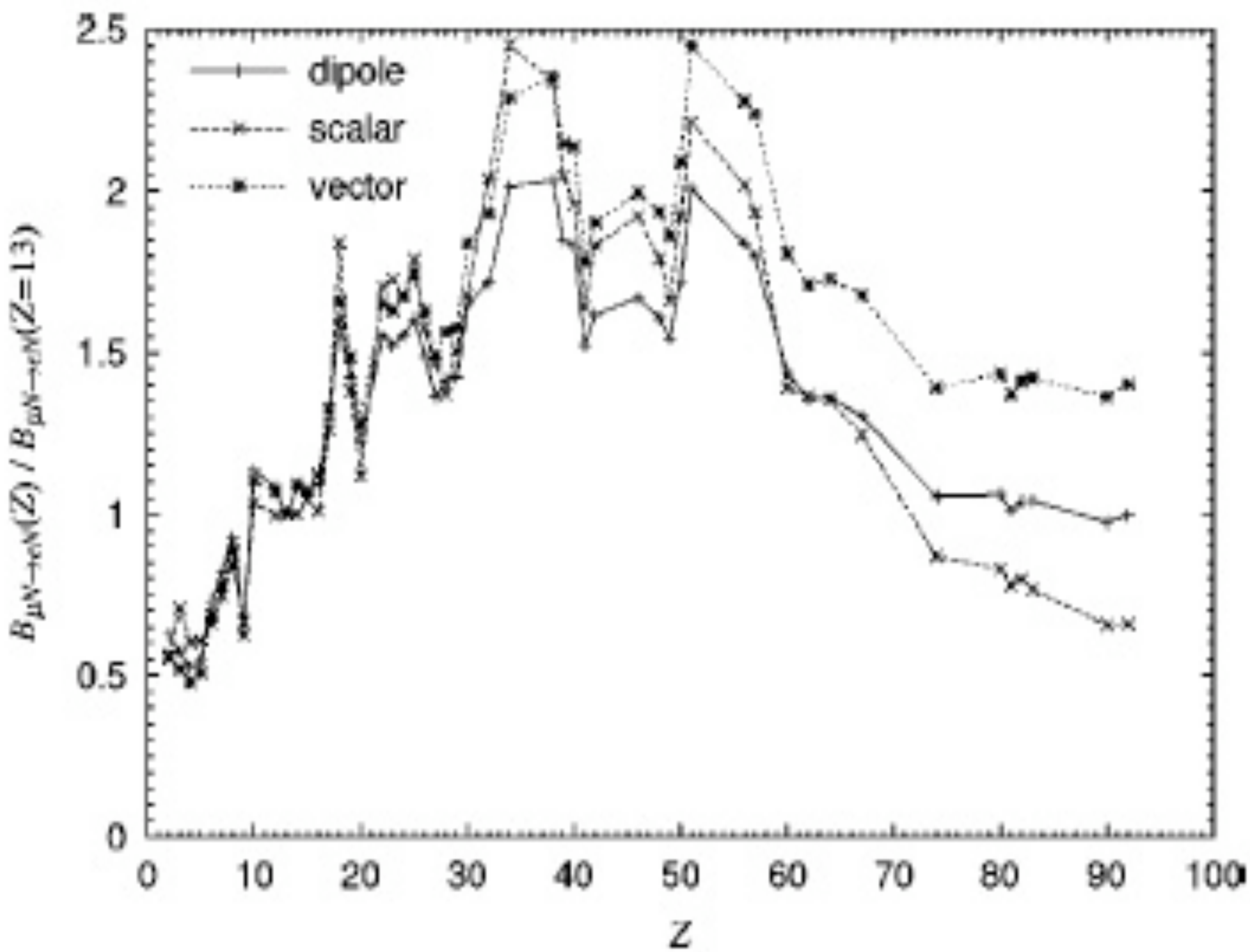
Every Muon We Can Produce

mu2e would stop $10^{11}\mu$/sec!

Needs Clean Beam & Good E_e Resolution

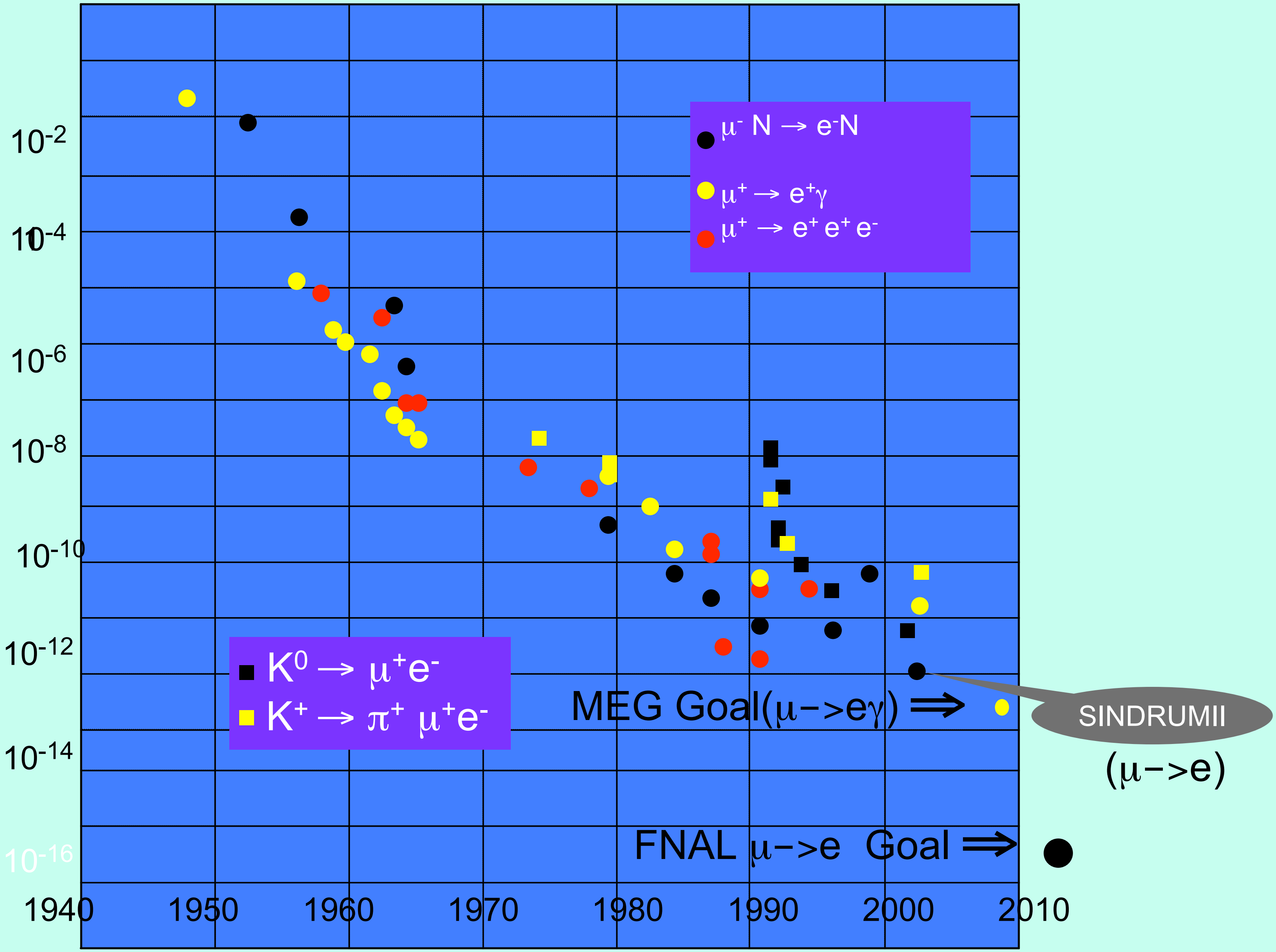
$\mu^+ \rightarrow e^+ + \gamma$ Accidentals a problem (for $B(\mu \rightarrow e\gamma) < 10^{-14}$)

MEG at PSI Ongoing Goal $2x10^{-13} \rightarrow 2x10^{-14}$



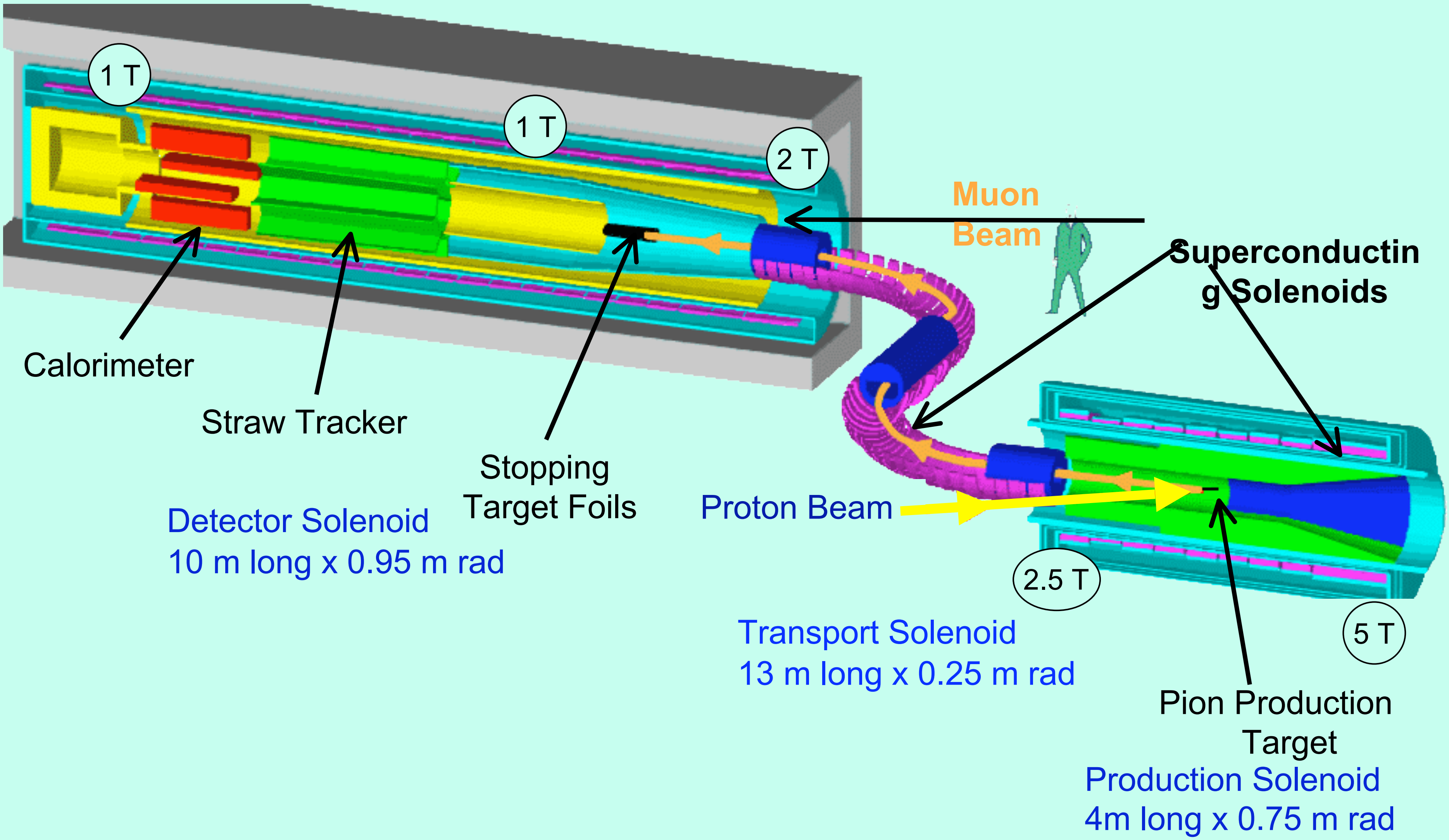
dipole
scalar
vector
$B_{\mu N \to eN}(Z) / B_{\mu N \to eN}(Z=13)$
Z
0
0.5
1
1.5
2
2.5
0
10
20
30
40
50
60
70
80
90
100

History of Lepton Flavor Violation Searches



Reaction	Current Bound	Expected	Possible
$B(\mu \rightarrow e\gamma)$	$<1.2\times10^{-11}$	2×10^{-13}	2×10^{-14}
$B(\mu \rightarrow eee)$	$<1.0\times10^{-12}$	-	10^{-14}
$R(\mu Au)$	$<7\times10^{-13}$	-	
$R(\mu Ti)$	$<7\times10^{-13}$		
$R(\mu Al)$	-	2×10^{-17} !	10^{-18}
$B(\tau \rightarrow \mu\gamma)$	$<6.8\times10^{-8}$		10^{-9}
$B(\tau \rightarrow \mu\mu\mu)$	$<1.9\times10^{-7}$		10^{-10}
$B(Z \rightarrow \mu e)$	$<1.7\times10^{-6}$		
$B(K_L \rightarrow e\mu)$	$<4.7\times10^{-12}$		10^{-13}
$B(B \rightarrow e\mu)$	$<1.7\times10^{-7}$		10^{-9}

Candidate Approach for an FNAL-Based Experiment: MECO Apparatus



2. $\mu N \rightarrow eN$ Atomic Conversion vs Scattering

- What about scattering $e+N \rightarrow \mu+N$?

#events=$\sigma(eN \rightarrow \mu N)$xLuminosity

$\sigma < 10^{-54} Z^2_{eff} cm^2$ (current μN bound)

$L < 3x10^{47} cm^{-2}/yr$ (Hot Beam&Large Target)

Expect $< 3x10^{-7} Z^2_{eff}/yr$ impossible

For Muonic Atom $|\Psi(0)|^2 \approx (Z\alpha m_\mu)^3/\pi$

$L \approx 10^{45} cm^{-2} s^{-1} x 3x10^{18} x 10^{-6} sec \approx 3x10^{57} cm^{-2}/yr$

Atomic Conversion~10^{10} times better!

3. $B(\mu\to e\gamma)$ vs $R(\mu N\to eN)$

Loop Induced $\mu\to e\gamma$ Amplitude

$M = eG_F m_\mu/16\sqrt{2}\pi^2\varepsilon^\alpha q^\beta \bar{e}\sigma_{\alpha\beta}D_{R,L}(1\pm\gamma_5)/2\mu$

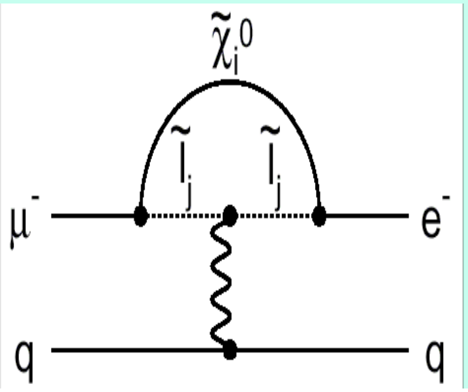
Chiral Changing L<–>R

$B(\mu\to e\gamma)=3\alpha/32\pi(|D_L|^2+|D_R|^2)$

Also gives rise to coherent $\mu N\to eN$

Depends on atomic and nuclear effects

(Czarnecki, Marciano, Melnikov), (Kitano, Koike, Okada)



We find: $R(\mu Al)=B(\mu\rightarrow e\gamma)/389$

$R(\mu Ti)=B(\mu\rightarrow e\gamma)/238$

$R(\mu Pb)=B(\mu\rightarrow e\gamma)342$

But conversion can be done 1,000-10,000 times better!

Scale Λ of New Physics Probed: $D_{R,L}=16\sqrt{2}\pi^2/G_F\Lambda^2$

Currently $\Lambda>340$TeV $\rightarrow$1000-3000TeV!

Coherent Conversion $R(\mu N)$ larger for non-chiral changing and non-photonic interactions

$R(\mu N)\approx 1\text{-}200\text{x}B(\mu\rightarrow e\gamma)$! More Robust

4. Neutrino Mass Effects

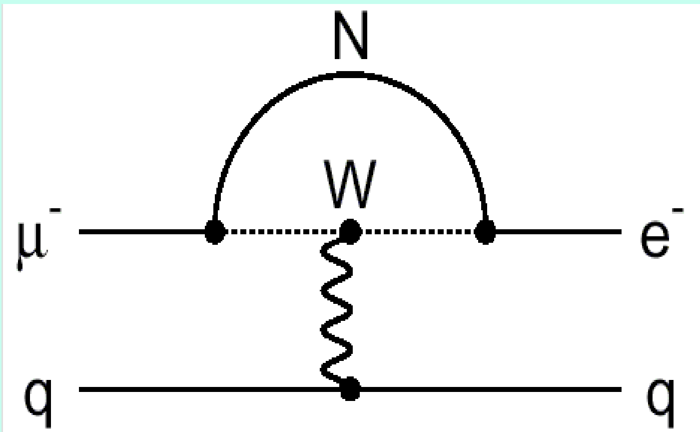
Lepton Flavor Violated by Neutrino Masses

$\Delta m^2_{32} \approx \pm 2.5 \times 10^{-3} eV^2$ $\Delta m^2_{21} \approx 8 \times 10^{-5} eV^2$

$D_L \propto \Delta m^2_{32} \rightarrow B(\mu \rightarrow e\gamma) \approx 10^{-54} (\sin^2 2\theta_{13}/0.15)$

$R(\mu N) \approx 200 B(\mu \rightarrow e\gamma)$

Both Tiny. What if we have a heavy Neutrino?



Depends on mixing U_{eN}&$U_{\mu N}$ and M_N

For $M_N \approx M_W$, $|U^*_{eN} U_{\mu N}| < 2\times10^{-7}$ probed!

Coherent Conversion Very Sensitive To Heavy Neutrinos

Also very sensitive to extra dimensions, compositeness, extra Z' bosons, strong dynamics etc. (Chiral Conserving Effects)

What about supersymmetry? The New Flavor Problem! Chiral Changing Flavor Violation

Right now, flavor changing neutral currents are the Biggest problem faced by supersymmetry or a sensitive way to access it.

5. Muon Anomalous Magnetic Moment

See: Hoecker & Marciano PDG update 2007

- Experimental Result: E821 at BNL

$a_\mu^{exp} \equiv (g_\mu-2)/2 = 116592080(54)_{stat}(33)_{sys} \times 10^{-11}$

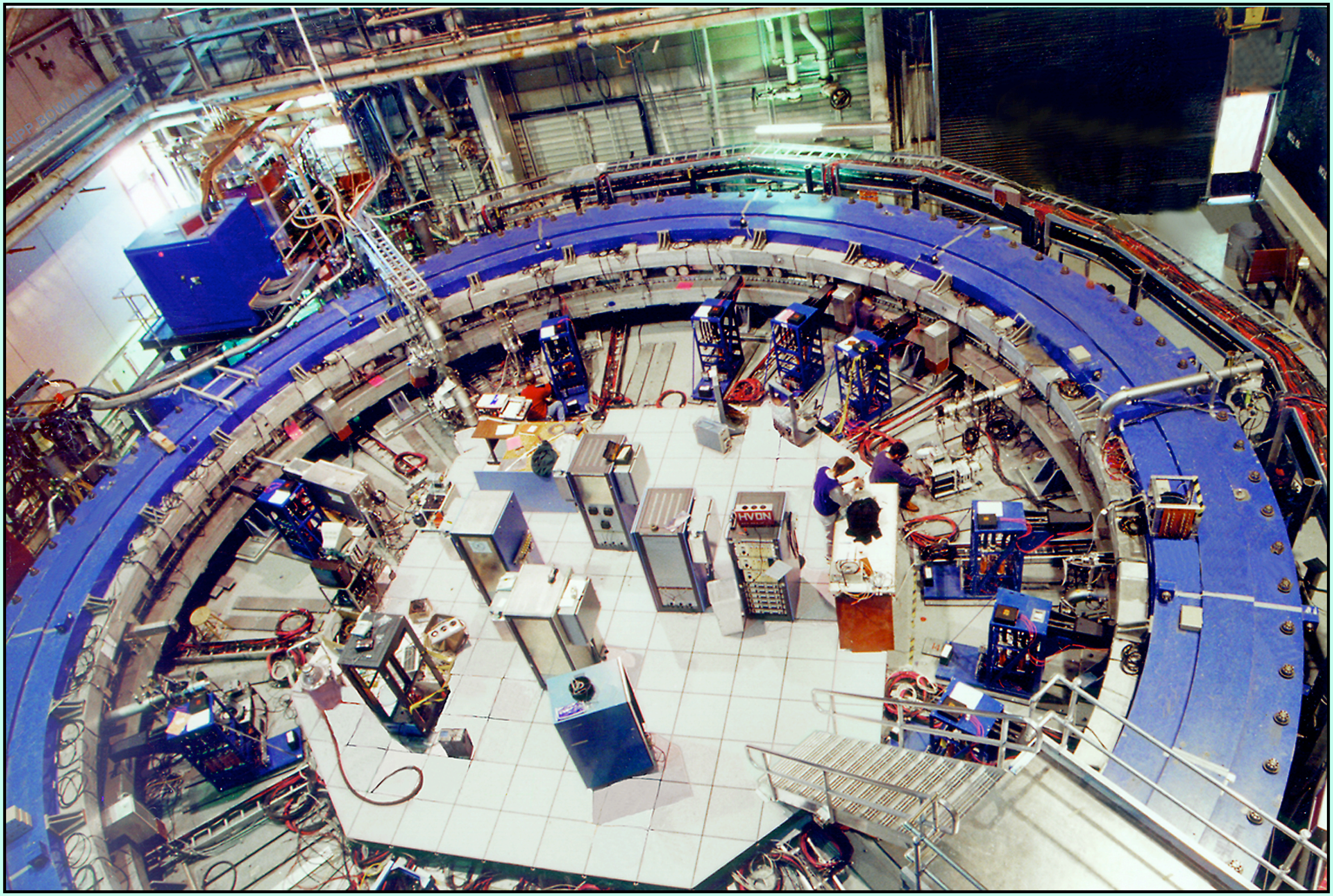
$= 116592080(63) \times 10^{-11}$

Factor of 14 improvement over CERN results

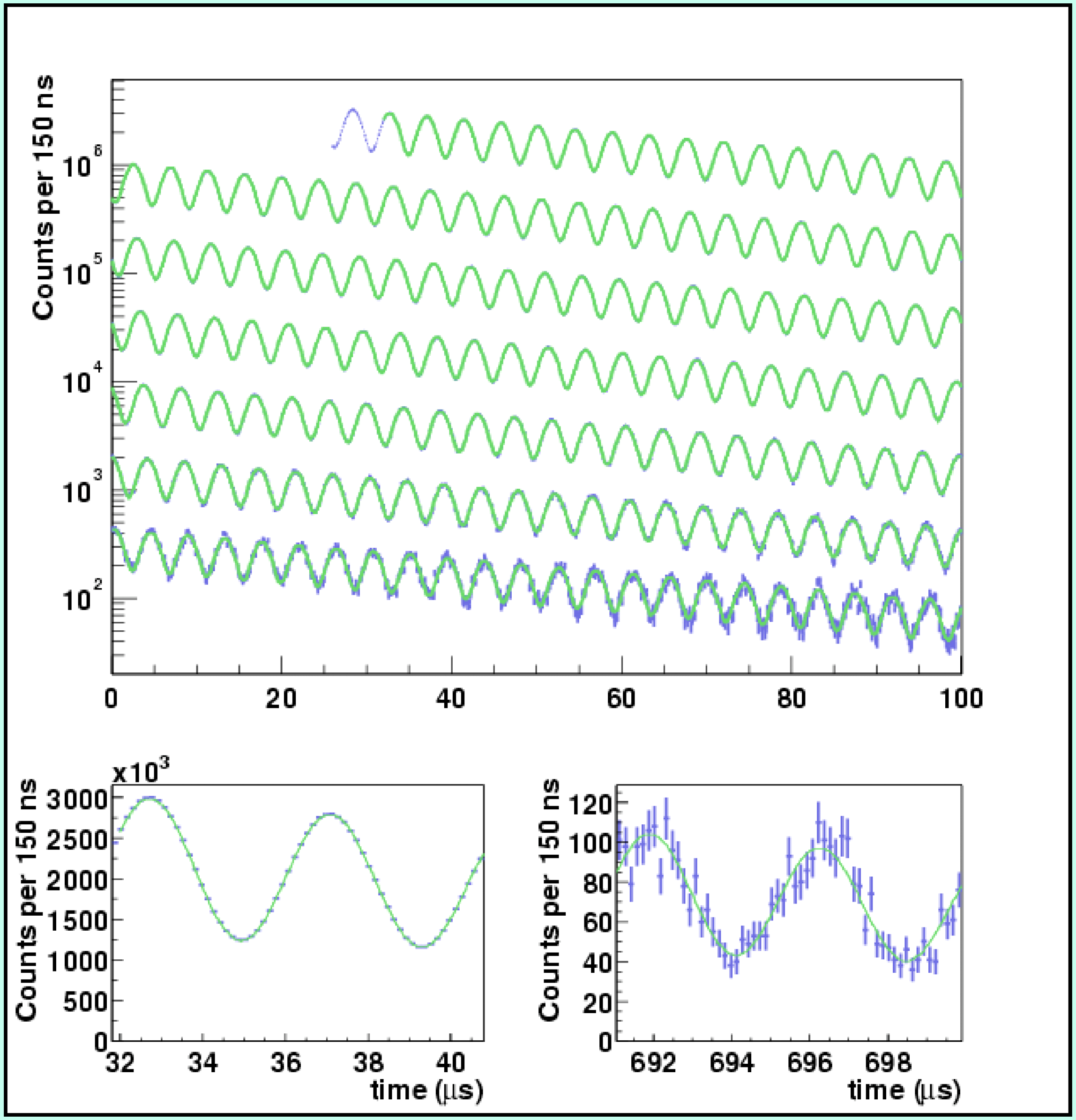
- E969 Goal: Further Factor ~2 Improvement

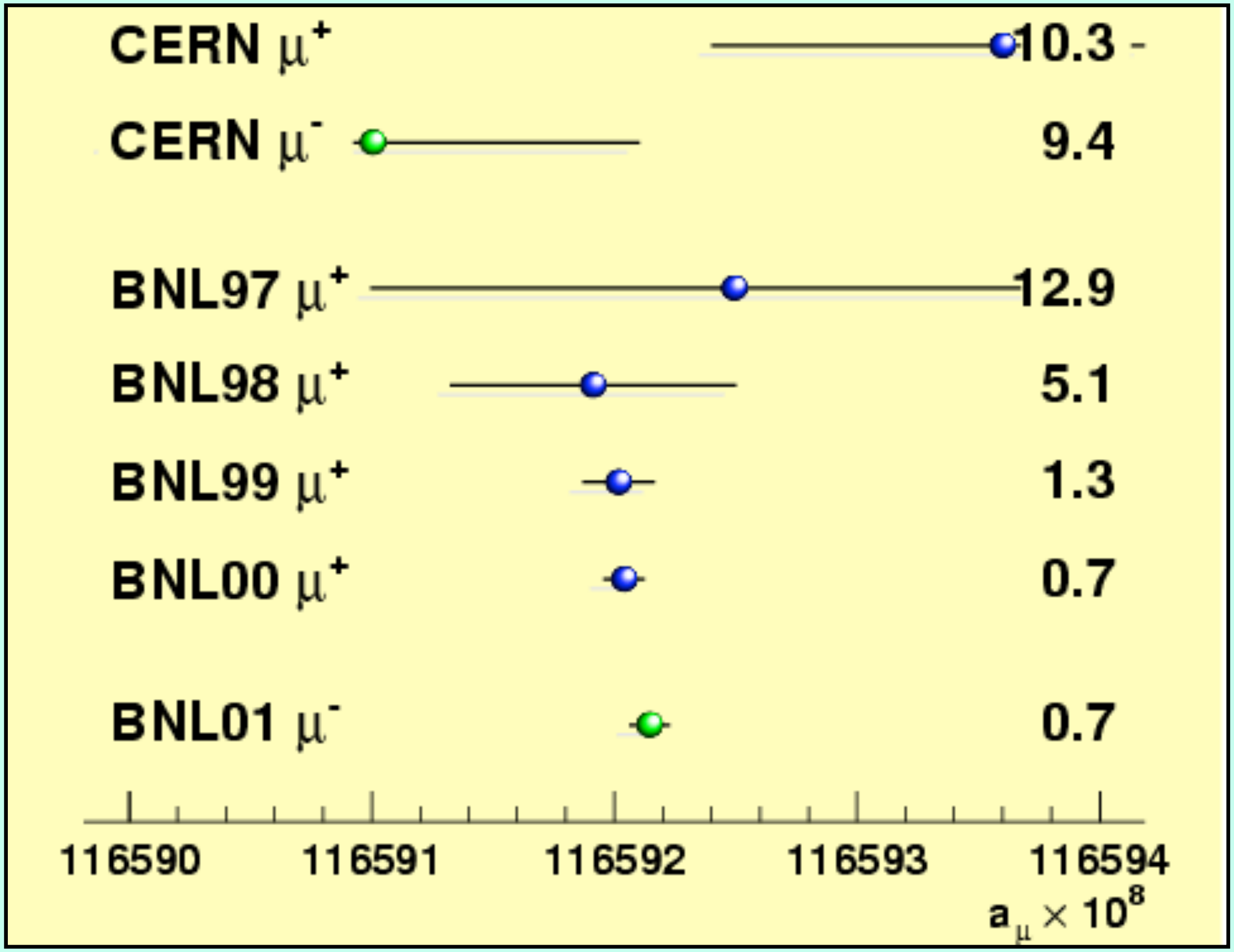
(Examining Possible Factor 5 Upgrade)

BNL Muon *g*-2 Experiment



$$N(t) = N_0\, e^{-t/t}\, [1+A\cos(w_a t + f)]$$





Muon g-2 Collaboration: Bennett et al, PRD **73**, 072003 (2006)

Standard Model Prediction

$$a_\mu^{SM} = a_\mu^{QED}+a_\mu^{EW}+a_\mu^{Hadronic}$$

QED Contributions:

- $a_\mu^{QED}=0.5(\alpha/\pi)+0.765857410(27)(\alpha/\pi)^2+$
  $24.05050964(87)(\alpha/\pi)^3+$
  $130.8055(80)(\alpha/\pi)^4+$
  $663(20)(\alpha/\pi)^5+\ldots$ (5 loops)

$\alpha^{-1}=137.035999070(98)$ From a_e (new)

$a_\mu^{QED}=116584718.1(2)\times10^{-11}$ Very Precise!

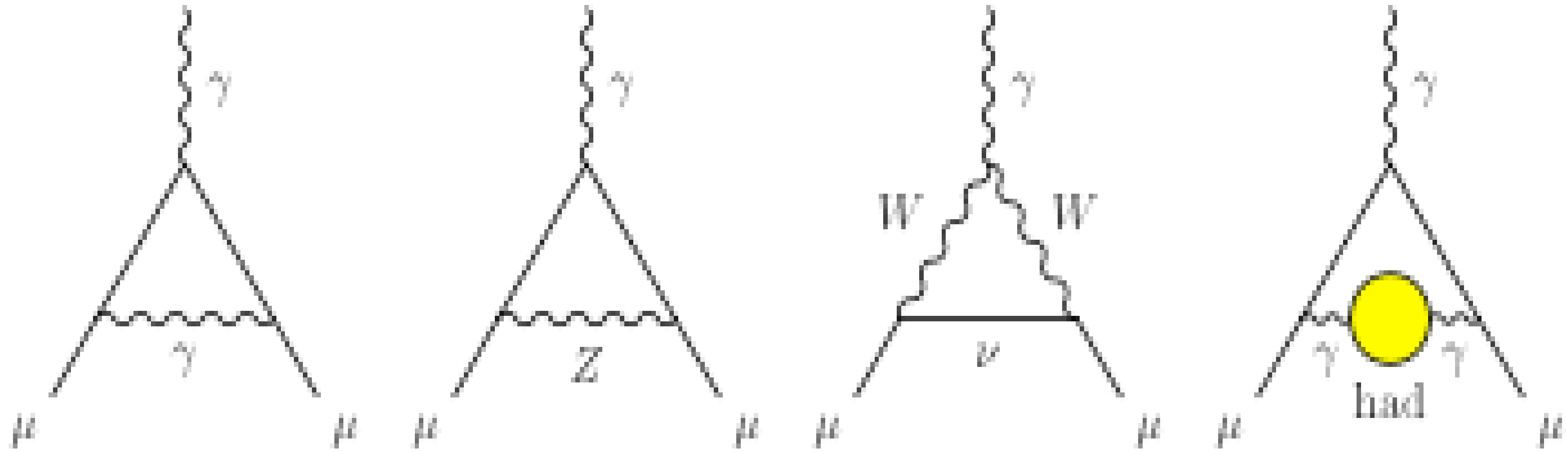


Figure 1: Representative diagrams contributing to a_μ^{SM}. From left to right: first order QED (Schwinger term), lowest-order weak, lowest-order hadronic.

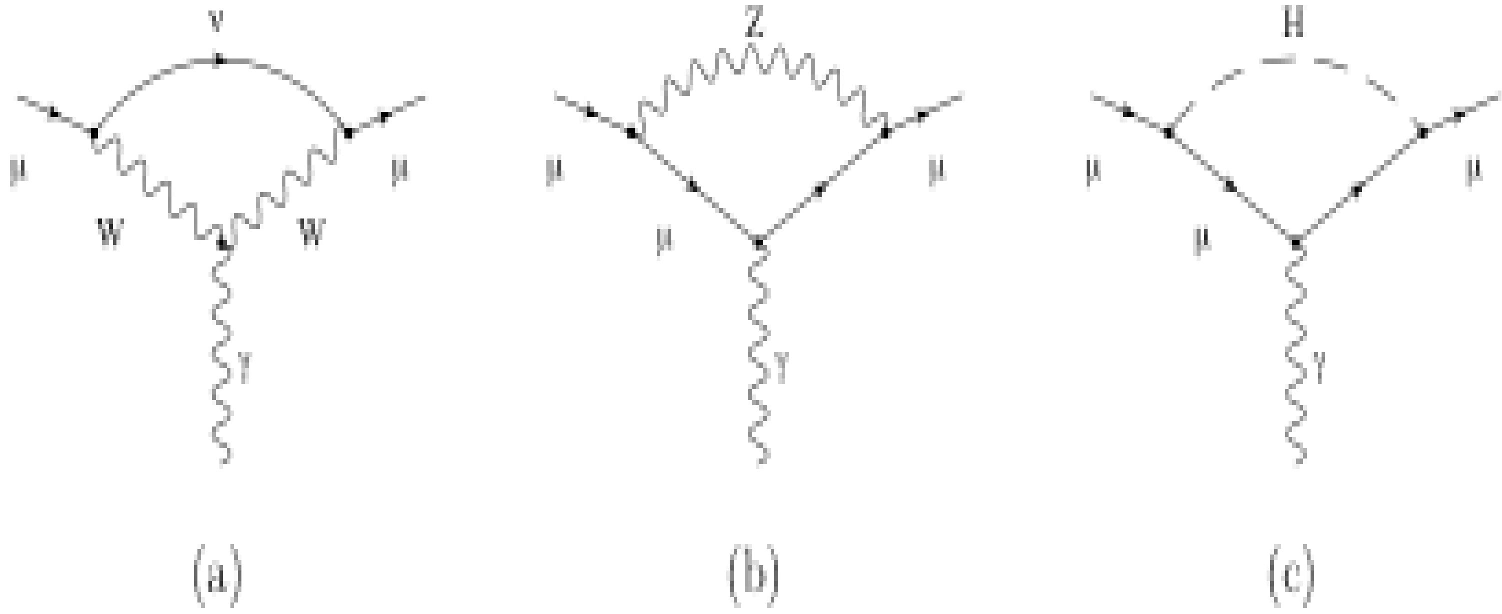


Figure 2: One-loop electroweak radiative corrections to a_μ.

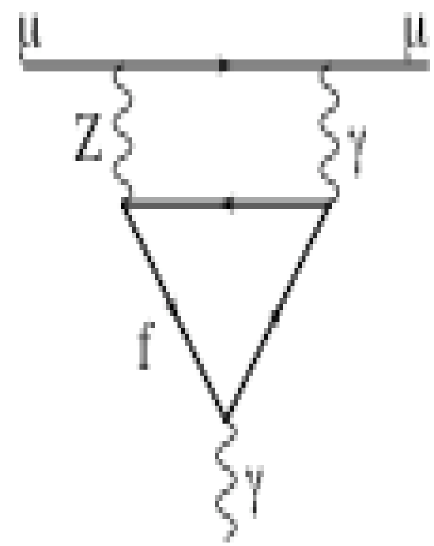
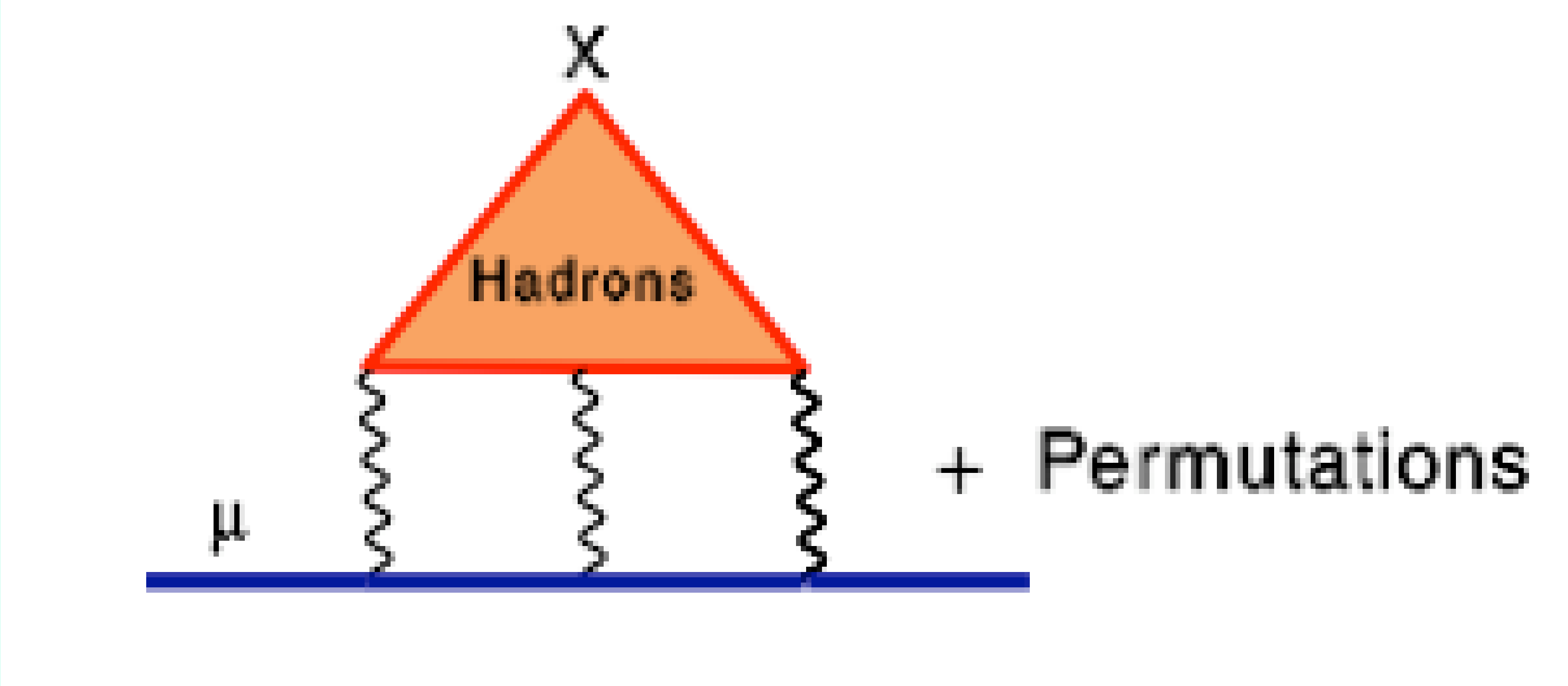


FIG. 3: Effective $Z\gamma\gamma^*$ coupling induced by a fermion triangle, contributing to a_μ^{EW}.

Light by Light Hadronic Contribution To a_μ

(Fig. from Miller, de Rafael and Roberts)



Electroweak Loop Effects

a_μ^{EW}(1 loop)=194.8x10^{-11} goal of E821

2 loop EW corrections are large -21%

a_μ^{EW}(2 loop)=-40.7(1.0)(1.8)x10^{-11}

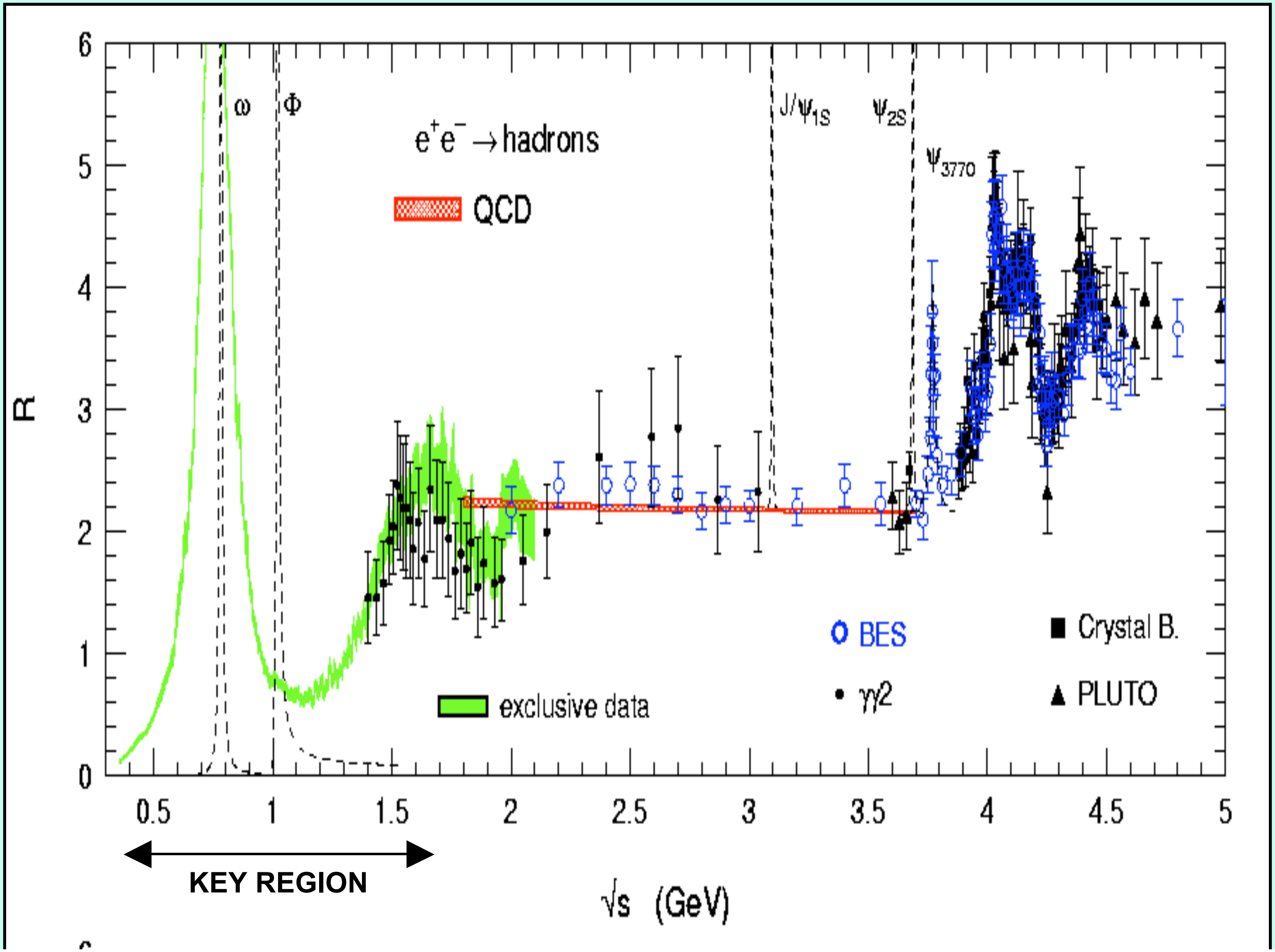
3 loop EW leading logs very small O(10^{-12})

- a_μ^{EW}=154(2)x10^{-11} Non Controversial

- **Hadronic Contributions**

  (some controversey)

$e^+e^- \rightarrow$hadrons vs $\tau \rightarrow$hadrons+ν_τ(isospin)



e+e− → hadrons
QCD
ω
Φ
J/ψ1S
ψ2S
ψ3770
R
exclusive data
BES
γγ2
Crystal B.
PLUTO
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
1
2
3
4
5
6
√s (GeV)
KEY REGION

From $e^+e^- \to$ hadrons data + dispersion relation

$a_\mu^{Had}(V.P.)^{LO}=\underline{6894(42)(18)}\times 10^{-11}$ (Hagiwara et al)

<u>3 loop</u>$=a_\mu^{Had}(V.P.)^{NLO}+a_\mu^{Had}(LBL)$

$a_\mu^{Had}(V.P.)^{NLO} = -98(1)\times 10^{-11}$

$a_\mu^{Had}(LBL) = 120(35)\times 10^{-11}$

$a_\mu^{Had}=6916(42)(18)(35)\times 10^{-11}$

$a_\mu^{SM}=\underline{116591788(2)(46)(35)}\times 10^{-11}$

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 292(63)(58) \times 10^{-11}$ (3.4σ!)

- New Physics? Nearly 2xStandard Model!

  Most Natural Explanation: SUSY Loops

Generic 1 loop SUSY Conribution:

$a_\mu^{SUSY} = (\text{sgn}\mu) 130 \times 10^{-11} (100\text{GeV}/m_{susy})^2 \tan\beta$

$\tan\beta \approx 3\text{-}40$, $m_{susy} \approx 100\text{-}500$GeV

Natural Explanation Range

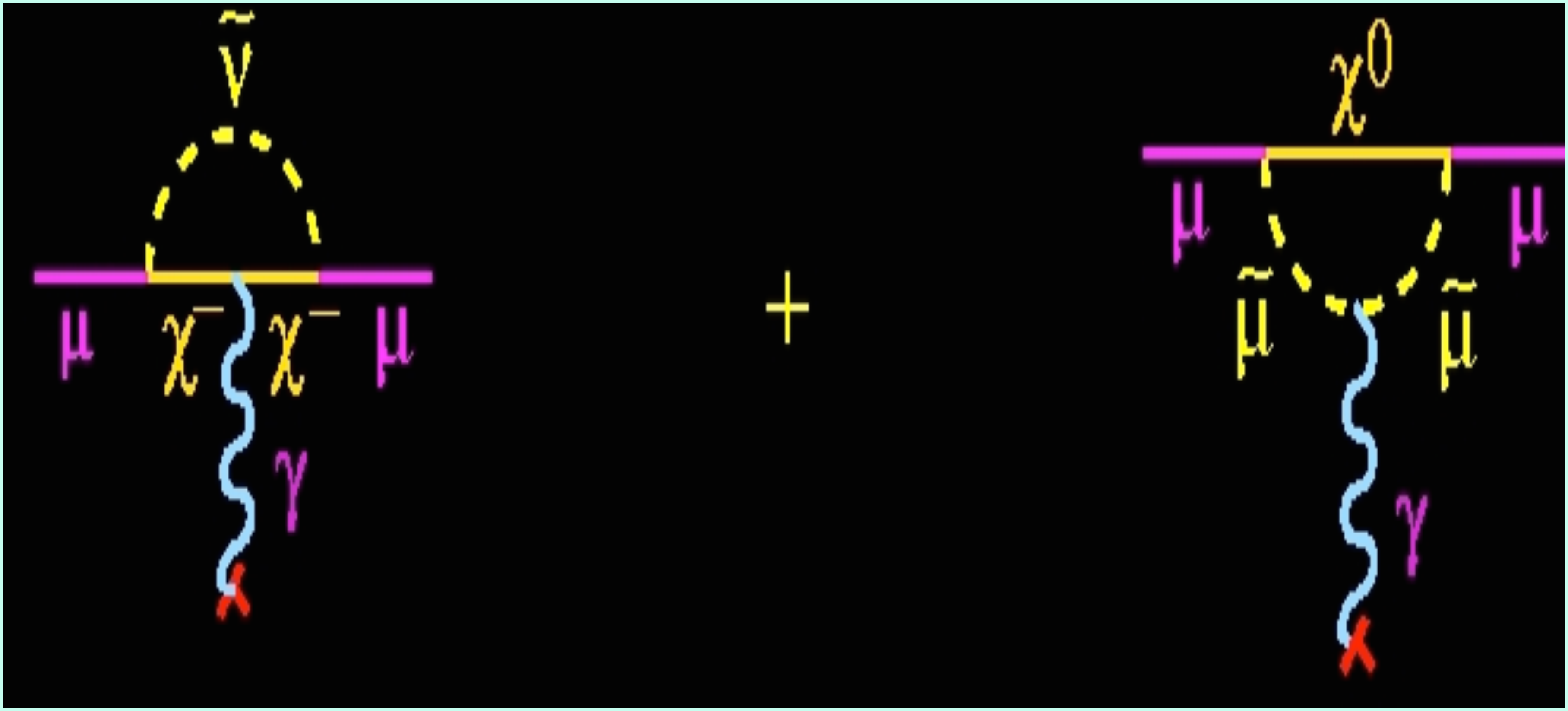
Other Explanations: Hadronic? $\tau \to \pi^- \pi^0 \nu_\tau$ +isospin data

($\Delta a_\mu = 83(92) \times 10^{-11}$ agreement!)

Other New Physics ~ 2TeV

Experiment?

SUSY 1 loop a_μ Corrections



Muon g-2 and LFV

- If SUSY or any other New Physics is responsible for Δa_μ, it will also induce LFV via mixing effects. (Chiral Changing)

$D_{L,R}=16\sqrt{2}\pi^2\Delta a_\mu \varepsilon_{\mu e}/G_F m_\mu{}^2$ $\varepsilon_{\mu e}<4.5\times10^{-5}$

Large Slepton Mixing$\rightarrow(M_2-M_1)/M_1<4.5\times10^{-5}$!

Very Near Degeneracy (R Symmetry?)

MEG($\mu\rightarrow e\gamma$) at 2×10^{-13} may see an effect

or $\varepsilon_{\mu e}<6\times10^{-6}$! $\rightarrow$ $M_2-M_1\approx O(1\text{MeV})$

6. μ2e at Fermilab(LOI): $R(\mu Al \rightarrow eAl) \rightarrow 2x10^{-17}$!

- Coherent μ-e Conversion in Nuclei ($\mu N \rightarrow eN$)

Stop μ^- in material, ~10^{-10}sec, $\mu^- N$ (1S) atom forms

i) $\Gamma(\mu^- \rightarrow e^- \nu \bar{\nu})$ = $0.5x10^6$/sec

ii) $\omega(\mu^- N \rightarrow \nu_\mu N')$ = $0.7x10^6$/sec (N=Al)

= $2.6x10^6$/sec (N=Ti)

iii) $\mu^- N \rightarrow e^- N$ $\omega(\mu^- Ti \rightarrow e^- Ti) < 7x10^{-13} \omega(\mu^- Ti \rightarrow \nu_\mu)$ (Prelim.)

*Signature: m_μ-BE=105 MeV monoenergetic electron

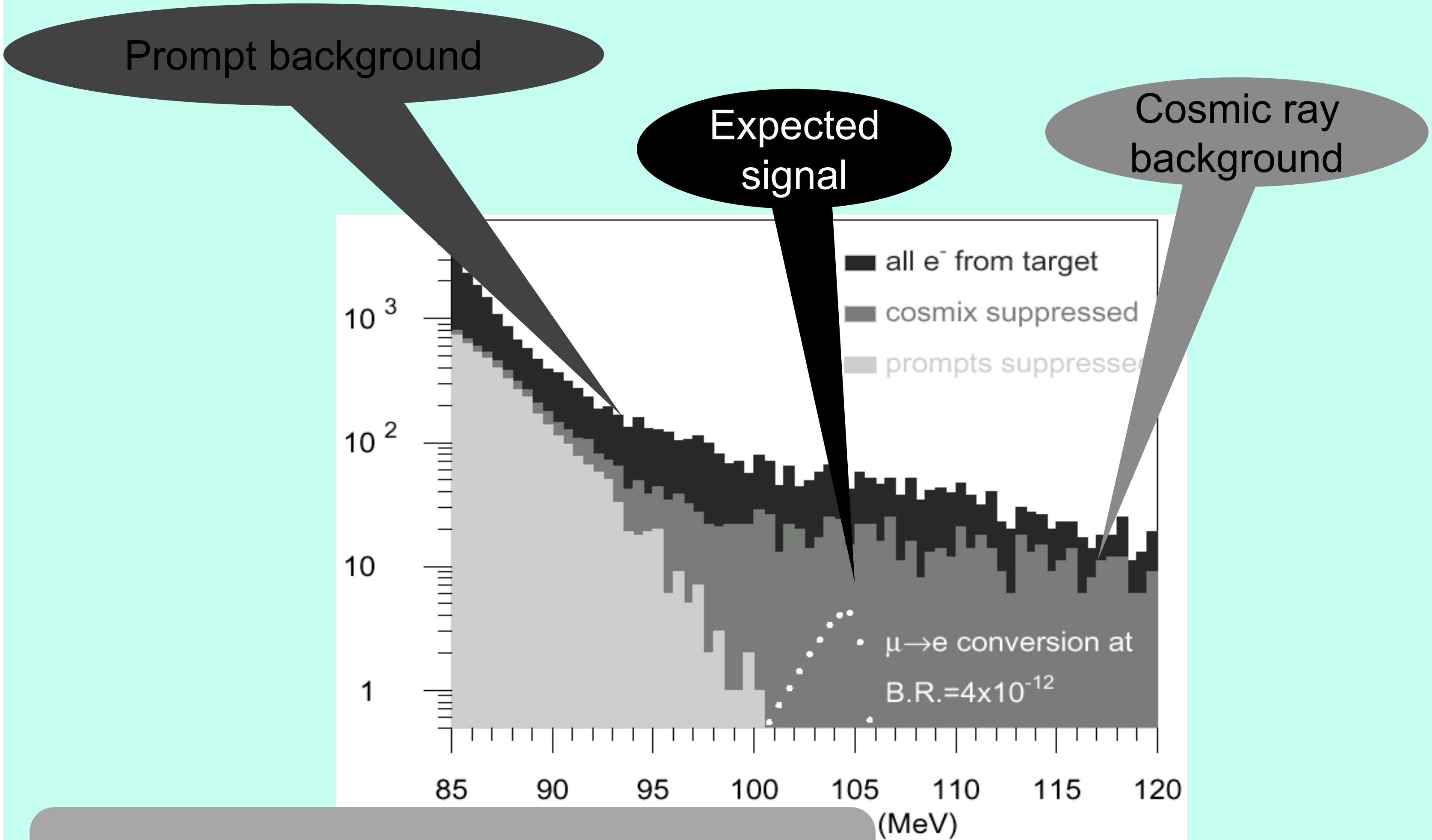
single particle→no accidentals→high rate capability!

It can take every muon we can provide!

MECO at BNL would have stopped $10^{11} \mu^-$/sec!

wait ~$0.6x10^{-6}$sec (reject prompt background)

Requires ~300keV resolution & Clean beam between pulses potential sources of fake backgrounds specify much of the design of the beam and experimental apparatus.

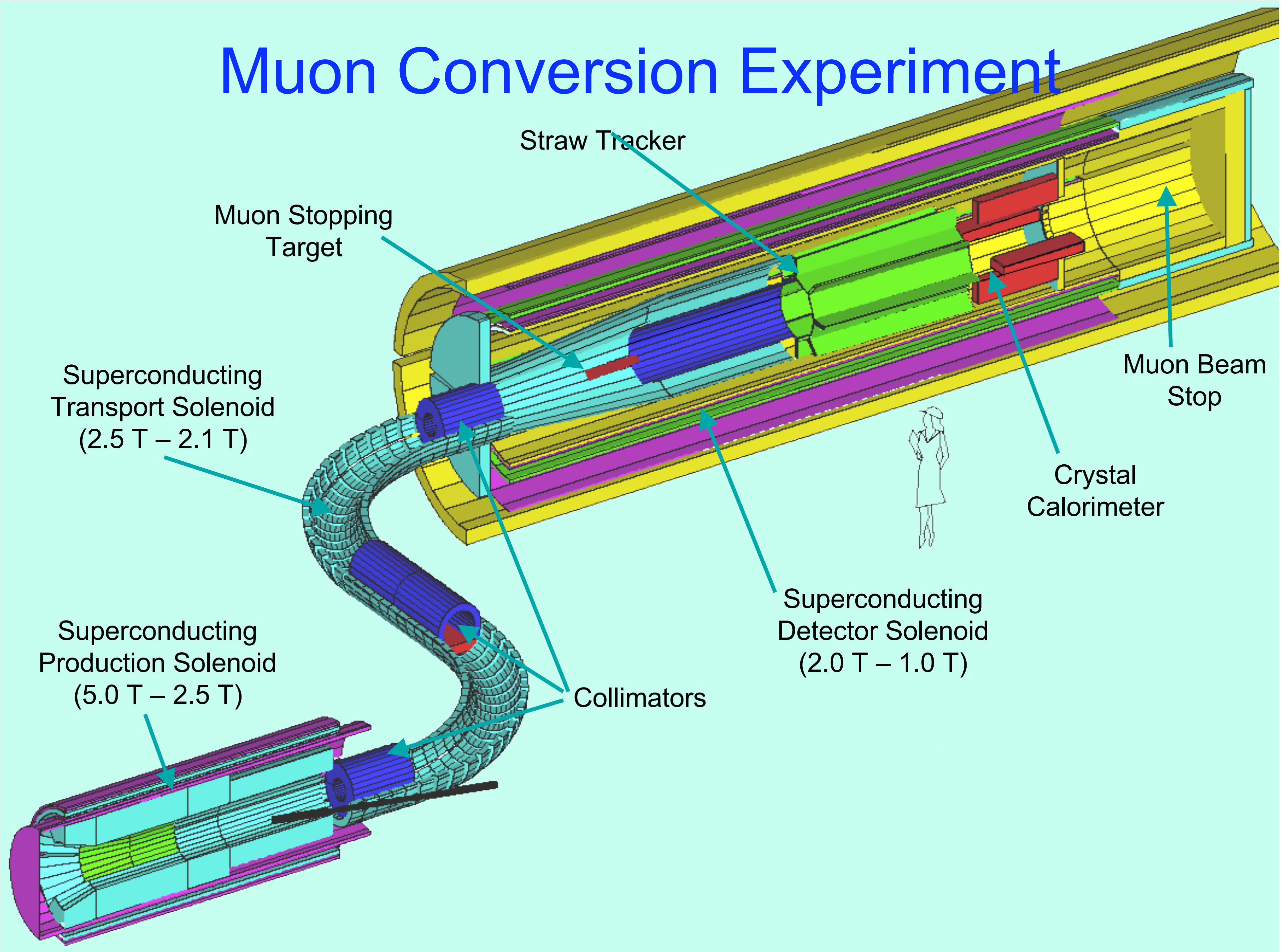


Experimental signature is105 MeV e⁻ originating in a thin stopping target.

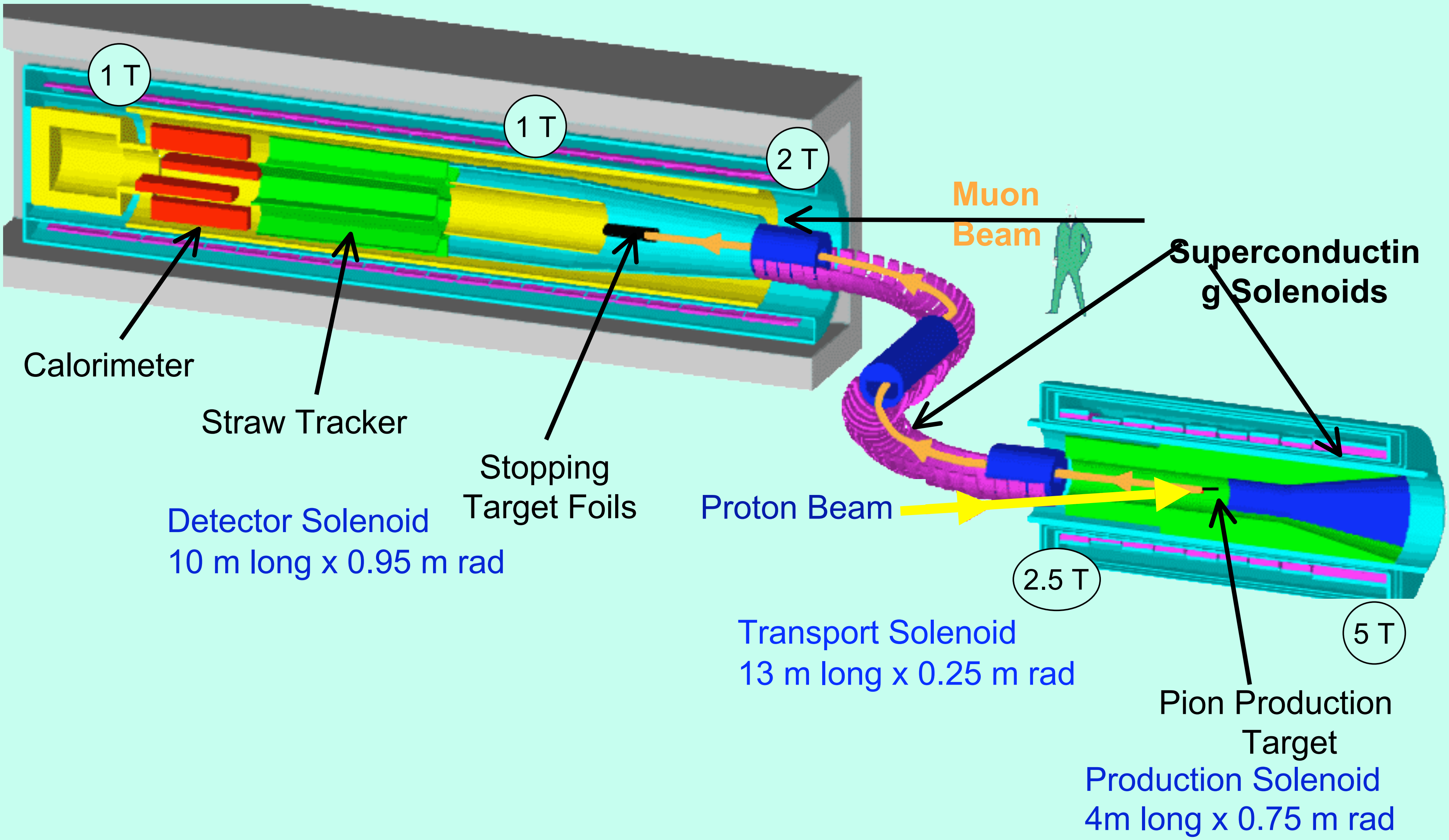
- The key to reaching $2x10^{-17}$ SES in μ2e is to copiously produce and stop 10^{11} μ^- using an intense 8GeV proton beam on target in a trapping solenoid.

  The proton beam must be clean to 1 part in 10^9-10^{10} between pulses.

Muon Conversion Experiment



Candidate Approach for an FNAL-Based Experiment: MECO Apparatus



Why $\mu N \rightarrow eN$ at Fermilab?

- Tens of man-years are invested in a MECO design which is applicable to FNAL.
- Physics case was reviewed repeatedly w/excellent outcome
- Well developed conceptual design exists, magnets have preliminary engineering design, some detector prototype work has been completed
- Technical case reviewed repeatedly w/excellent outcome
- An advanced cost estimate was produced
- The continuing neutrino program at FNAL provides facilities and an accelerator operation well-matched to μ->e experimental needs.
- A working group has been established to understand how the appropriate proton beam can be supplied at FNAL.

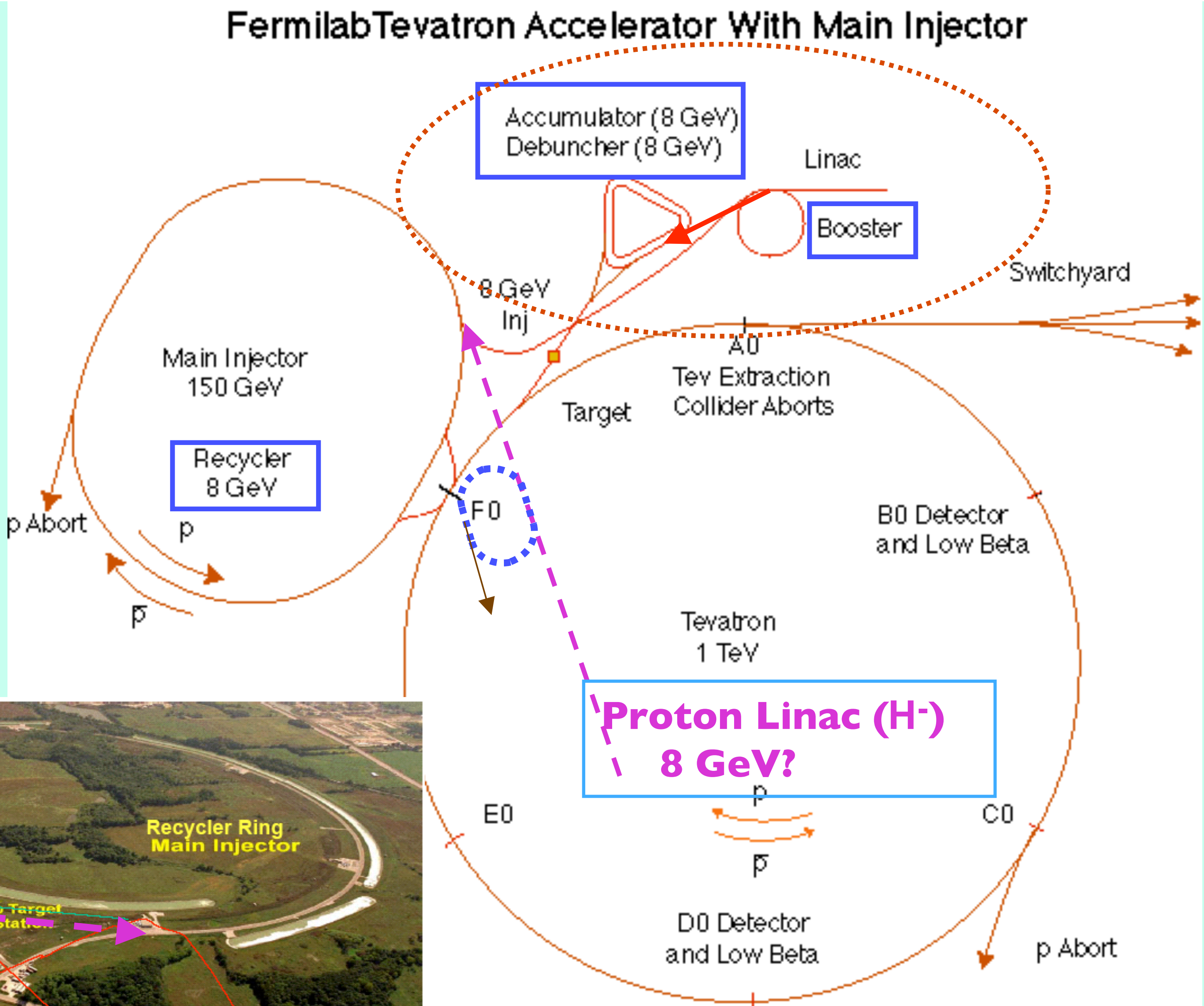
Beam Rates and Sensitivity

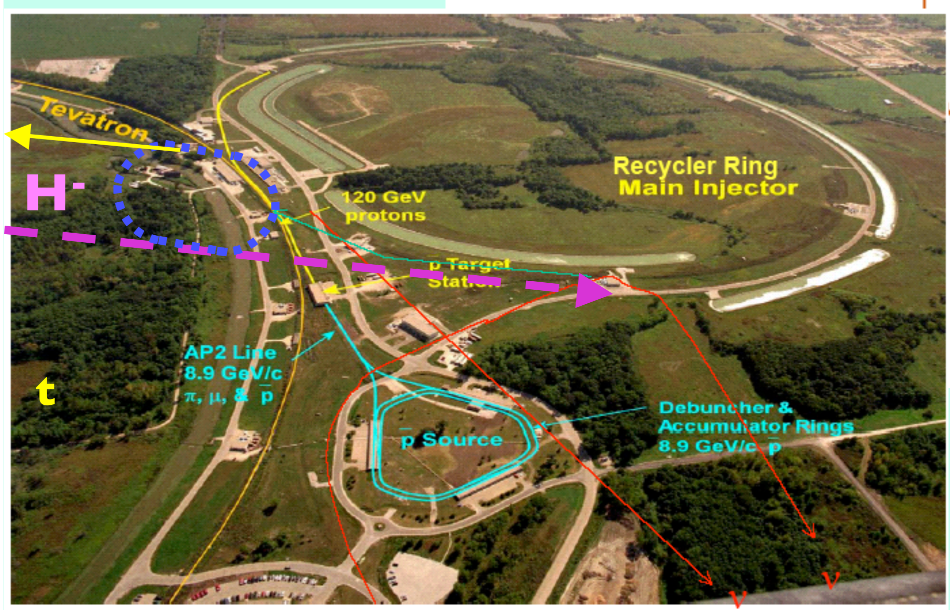
	Probability	Rate (proton flux=1-2x10^{13} Hz)	Events (run time= 2-4x10^{7} seconds, total p's =4x10^{20})
Prob. Muon stopped in target per proton	0.0025	0.25-0.5x10^{11} Hz	1x10^{18}
Prob. μ capture (Al target)	0.60	1.5-3x10^{10} Hz	6x10^{17}
Fraction of captures in detector time window	0.45 (> 700 ns)	0.7-1.4x10^{10} Hz	3x10^{17}
Track fitting and selection criteria	0.19	1.2-2.5x10^{9} Hz	5x10^{16}
Detected events for $R_{\mu e}=10^{-16}$	10^{-16}	1.2-2.5x10^{-7} Hz	5 –> single-event sensitivity 2x10^{-17}
Estimated background			0.45

Summary of Beam Requirements

- Pulsed ~4-8 GeV proton beam
- Width $<$ 100-200 ns (Narrower is better, but not critical)
- Repetition Period ~1.5 ms
- Proton Intensity $> 10^{13}$ Hz
- Integrated proton flux=$4x10^{20}$
- Beam Extinction $< 10^{-9}$

8 GeV
Proton sources





Some Theory Considerations:

If transition dipole operator (chiral changing) dominates
$BR(\mu \rightarrow e\gamma) = 389 R(\mu Al \rightarrow eAl) = 238 R(\mu Ti \rightarrow eTi)$

But conversion exp. can be more sensitive by 10^3-10^4!

Eg. Popular SUSY Models (may be related to Δa_μ)

Neutrino Mass & Mixing Effects→Lepton Flavor Violation

$BR(\mu \rightarrow e\gamma) \sim 3\alpha/32\pi[m_3^2 - m_2^2]^2/m_W^4(s_{13}c_{13}s_{23})^2 \leq 10^{-54}$

$R(\mu N \rightarrow eN) \sim 100 BR(\mu \rightarrow e\gamma) \sim 10^{-52}$ still tiny, but enhanced by Chiral conserving amplitudes.

(Lesson) Conversion better for Heavy Neutrino Mixing

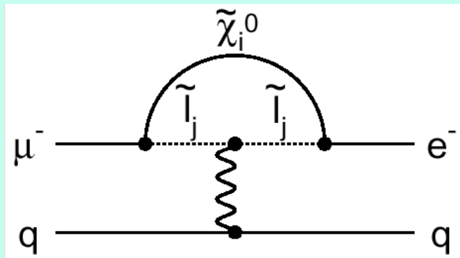
In General: $1/200 < BR(\mu \rightarrow e\gamma)/R(\mu N \rightarrow eN) < 200$

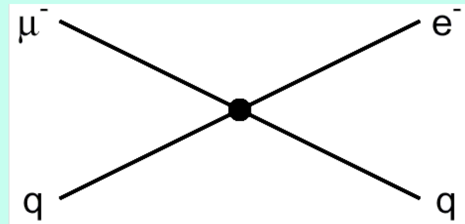
Conversion More Robust! Better Discovery Potential

Sensitivity to Different Muon Conversion Mechanisms

Supersymmetry

Predictions at 10^{-15}

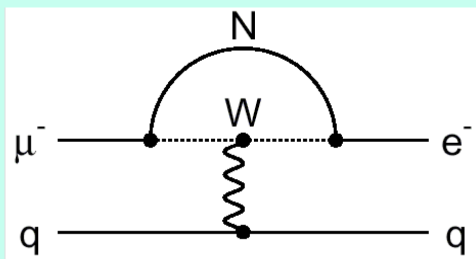


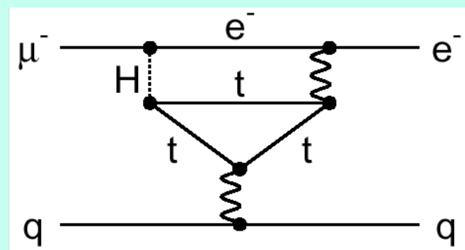


Compositeness

$\text{Ë}_C = 3000$ TeV

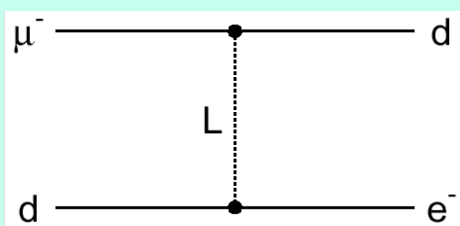
Heavy Neutrinos

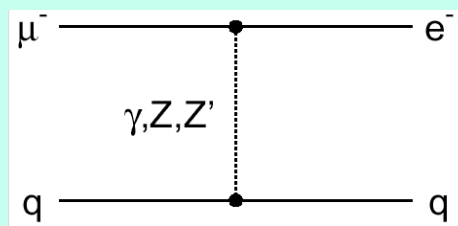




Second Higgs doublet

Leptoquarks





Heavy Z', Anomalous Z coupling

7. Conclusion and Outlook

μ2e at Fermilab aims for μAl→eAl with $2x10^{-17}$ SES!

Sensitive to “New Physics” up to 3000TeV (Robust)!

If MEG (μ→eγ), starting soon, sees several (5) events it will be a major discovery. μ2e at Fermilab should then see between 100-10,000 events from μAl→eAl!

If MEG sees nothing, μ2e could still see 10,000 events!

μ2e promises to be a flagship experiment.

With (project X) it could be extended to beyond 10^{-18}!

No better way to push muon technology while doing forefront physics! $\rightarrow$Muon Collider!

μ2e must do experiment (fast track)

PAC Encouragement - Proposal Preparation

Collaborators Welcome!

(see Eric Prebys or Jim Miller)