W. Marciano
9/15/06

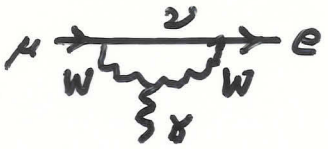
Muon - Electron Conversion

Historical Perspective:

1947 $\mu^{\pm}$ established as lepton

Excited Electron? No $\mu \to e\gamma$! Not seen

1958 G. Feinberg One Neutrino?



$BR(\mu \to e\gamma) \sim 10^{-4}$ Not Seen $\sim 10^{-5}$

$\to \nu_e + \nu_\mu$ Two Neutrinos

Leptonic GIM (analog of charm)

1959 Feinberg + Weinberg

Coherent Conversion $\mu^- + N \to e^- + N$ $E_e = 105$ MeV

Very Clean Experimentally Special

Stop μ^- in atoms, $\mu^- \to$ 1S state

1) Capture $\mu^- N \to \nu_\mu N'$

2) Decay $\mu^- \to e^- \nu \bar{\nu}$

* 3) Conversion $\mu^- N \to e^- N$

III. Muon-Electon Conversion ($\mu^- N \to e^- N$)

Stop μ^- in target $\xrightarrow[10^{-10}s]{}$ 1s orbit $\mu^- N$ atom

Possibilities: $\mu^- N \to \nu_\mu N'$ (Dominates for $Z \gtrsim 10$) $\sim Z^4$

$\mu^- \to e^- \nu \bar{\nu}$

or Coherent Conversion $\mu^- N \to e^- N$ $\sim Z^5$ $\quad E_e = m_\mu - (BE) \simeq 105\,MeV$

* Very Distinct Signature - Monoenergetic Electon ~ 105 MeV

Reject Background - Very Good Energy Resolution ~ 300 keV

* Can Take High Rate - No Accidentals (Unique)

Physics Background - Decay in orbit $\nu\bar{\nu}$ with 0 energy

Highly Suppressed

Becomes a problem $< 10^{-18} \sim 10^{-19}$

MECO at BNL $\to 10^{-16}$ using $\sim 10^{11}\,\mu^-/sec$

FMC Front End $\to 10^{-18} \sim 10^{-19}$ $\quad 10^{13} \sim 10^{14}\,\mu^-/sec$ (Very Clean Beam)

Observation of Signal - Change Targets, Dope, Sort Out...

(Also, Push $\mu^+ \to e^+\gamma$ + $\mu^+ \to e^+e^-e^+$)

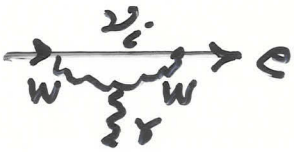
Probe CP Violation (?)

Current Bounds: $BR(\mu^+ \to e^+\gamma) < 1.2\times10^{-11}$

$R(\mu^- Ti \to e^- Ti) < 7\times10^{-13}$

$BR(\mu^+ \to e^+e^-e^+) < 1\times10^{-12}$

Effect of Neutrino Mixing



$$BR(\mu\to e\gamma) = \frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\nu\bar{\nu})} = \underbrace{\frac{3\alpha}{32\pi}}_{2\times10^{-4}}\underbrace{\left(\frac{m_{\nu_3}^2-m_{\nu_2}^2}{m_W^2}\right)^2}_{2\times10^{-49}}\underbrace{s_{13}^2c_{13}^2s_{23}^2}_{<0.02} < 10^{-54}!$$

Conversion Larger

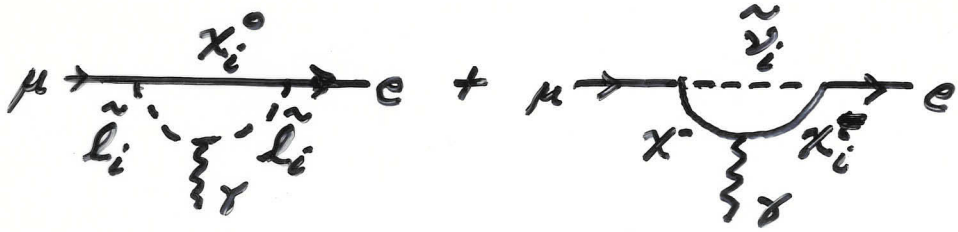
Accidental Suppression - Small $\Delta m_{32}^2 \sim 3\times10^{-3}\,eV^2$

Many theories predict observable $\mu\to e\gamma$, $\mu N\to eN$...

eg Heavy Neutrinos

Supersymmetry

⋮



Very Similar to $(g_\mu-2)/2 = a_\mu$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} \simeq 275\,(85)\times10^{-11}$$ SUSY?

$$\Delta a_\mu(susy) \simeq 130\times10^{-11}\times\tan\beta\left(\frac{100\,GeV}{m_{susy}}\right)^2$$

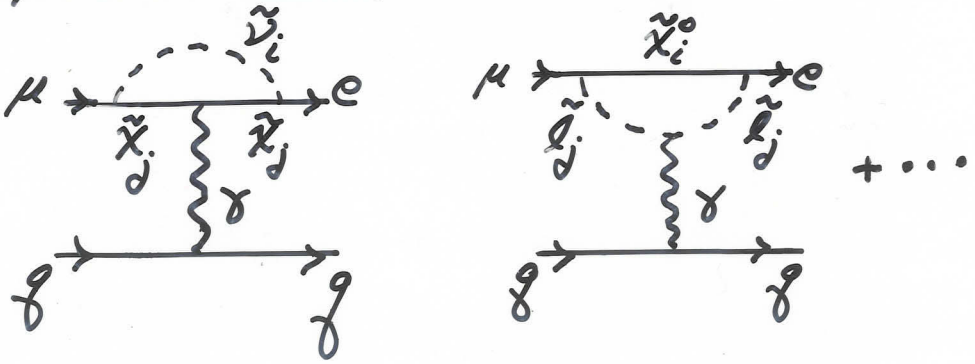
$\to BR(\mu\to e\gamma) \sim 5\times10^{-3}\,\delta_{\mu e}^2$

$\delta_{\mu e}$: mixing, cancellations

Examples of "New Physics" Probed by $\mu^- N \to e^- N$

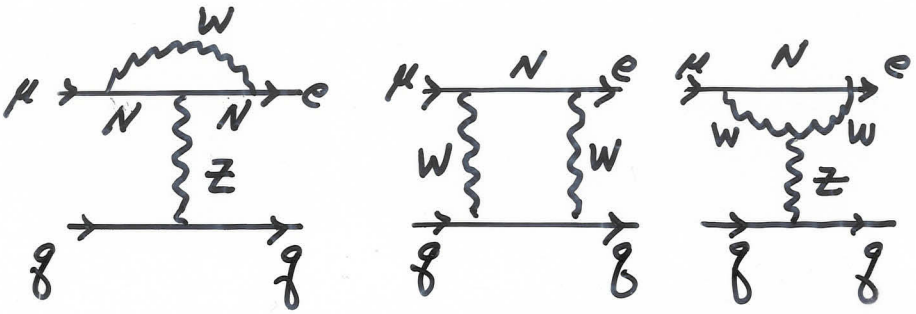
SUSY

see fig.



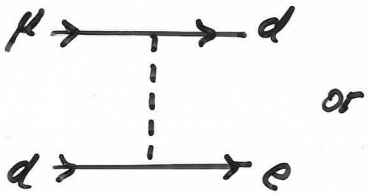
Heavy Neutrinos (Mixing)

$|U^*_{\mu N} U_{eN}|^2 \lesssim 10^{-12}$

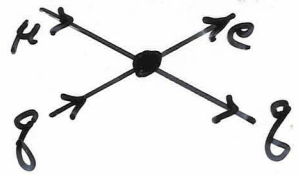


Leptoquarks ($\not R$)

$M_{LQ} \gtrsim 3000$ TeV!

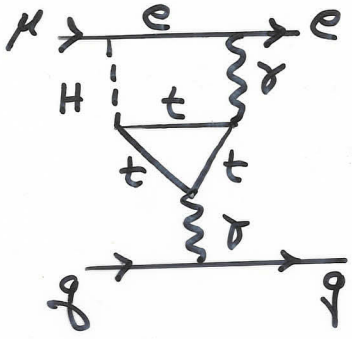


Compositeness



Neutral Higgs

$g_{H\mu\bar{e}} < 10^{-4} g_{H\mu\bar{\mu}}$!



Bjorken & Weinberg

+ many other examples (Extra Dimensions...)

$\mu^- Al \to e^- Al$ Must Do Experiment

Comparison of $\mu \to e\gamma$ & $\mu N \to eN$

Amplitude: $\langle e | J_\alpha^{em} | \mu \rangle$

$$= \bar{u}_e \, i \frac{e}{2m_\mu} \left(F_{M1}(q^2) + F_{E1}(q^2) \gamma_5 \right) \sigma_{\alpha\beta} q^\beta u_\mu$$

Chiral Changing

$$\Gamma(\mu \to e\gamma) = \frac{\alpha}{2} m_\mu \left(|F_{M1}(0)|^2 + |F_{E1}(0)|^2 \right)$$

If $F_{E1} \sim -F_{M1} \sim \Delta a_\mu(\text{susy})\, \varepsilon_{\mu e} \simeq 275 \times 10^{-11} \varepsilon_{\mu e}$

$BR(\mu \to e\gamma) < 10^{-11} \to \underline{\varepsilon_{\mu e} < 5 \times 10^{-5}}$

small mixing or near degeneracy of sleptons

$$m_{\tilde{\ell}_2} - m_{\tilde{\ell}_1} \simeq \lesssim 3 \times 10^{-4} m_{\tilde{\ell}} \simeq \underline{\quad} \; 30\,\text{MeV}$$

MEG at PSI $BR(\mu \to e\gamma) \to 2 \times 10^{-13} \xrightarrow[\text{phase II}]{} 2 \times 10^{-14}$

What should μ-e Conversion Aim For?

If F_{M1} & F_{E1} Dominate

$$R(\mu^- Al \to e^- Al) \simeq \frac{1}{389} BR(\mu \to e\gamma)$$

$$R(\mu^- Ti \to e^- Ti) \simeq \frac{1}{238} BR(\mu \to e\gamma)$$

Goal $\mu^- Al \to e^- Al \sim \frac{1}{389} \times 2\times10^{-14} \sim 5\times10^{-17}$

Roughly same sensitivity as MEG Phase II

* But in some models $R(\mu Al \to eAl) > BR(\mu \to e\gamma)$!

Note, in $R(\mu^- Al \to e^- Al)$ all amplitudes interfere

If SUSY Dominates, Measure

$$\frac{R(\mu^- Al \to e^- Al)}{BR(\mu \to e\gamma)} \simeq \frac{1}{389}$$ with precision ±10%

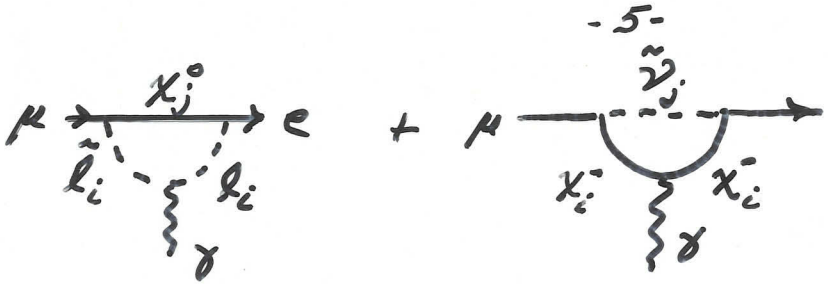
Change Atoms - Look for High Mass Scales

$\sim$ 3000 TeV

If No SUSY, Still 3000 TeV Sensitivity

Longer Term (More Muons) $R(\mu^- Al \to e^- Al) \to 5\times10^{-19}$!

Major Program



like $g_\mu - 2$
tan β enhanced
$\varepsilon_{\mu e}$ mixing suppressed

$B(\mu \to e\gamma) < 10^{-11} \rightarrow \varepsilon_{\mu e} < 5 \times 10^{-5} \rightarrow$ susy degeneracy

Meg at PSI (Phase I) $\rightarrow 2 \times 10^{-13} \xrightarrow{II} 2 \times 10^{-14}$

MECO $(\mu^- Al \to e^- Al) \rightarrow 10^{-16}$ BNL or FNAL
under study

If seen $\rightarrow 10^{-19}$ sensitivity

Precision Studies

Does $B(\mu \to e\gamma) \simeq 389\, R(\mu^- Al \to e^- Al)$

*No → Interfering Amplitudes!

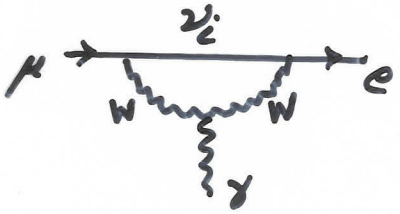
Rich Program for 10^{13} μ^-/sec source

MECO is pathway for intense muon source

RSUP Cancellation - Big NSF Mistake

Fermilab Golden Opportunity

i) Small Neutrino Masses



Transition Moments

$$\langle e | J_\alpha^{em} | \mu \rangle$$

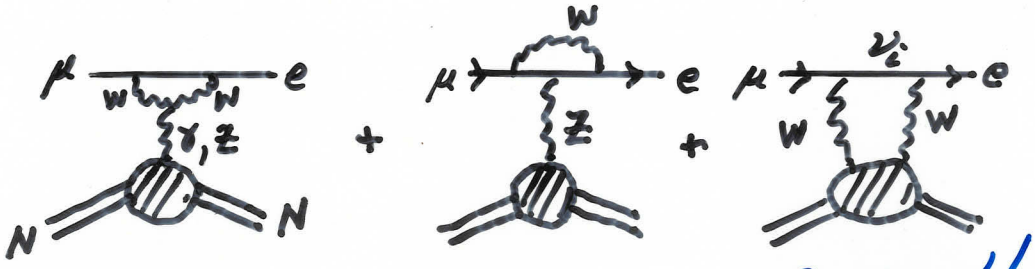
$$= \bar{u}_e \, i \frac{e}{m_\mu} \left(F_{M1}(q^2) + F_{E1}(q^2)\gamma_5 \right) \sigma_{\alpha\beta} q^\beta u_\mu$$

$$\Gamma(\mu \to e\gamma) = \frac{\alpha}{2} m_\mu \left(|F_{M1}(0)|^2 + |F_{E1}(0)|^2 \right)$$

$$F_{M1} = -F_{E1} = \frac{g^2 m_\mu^2}{256\pi^2 m_W^4} \underbrace{(m_3^2 - m_2^2)}_{2.3\times10^{-3}\,eV^2} s_{13} s_{23} c_{13} e^{-i\delta}$$

$$B(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \underbrace{\frac{3\alpha}{32\pi}}_{2\times10^{-4}} \underbrace{\left(\frac{m_3^2 - m_2^2}{m_W^2} \right)^2}_{2\times10^{-49}!} \underbrace{s_{13}^2 c_{13}^2 s_{23}^2}_{\lesssim 0.025} \quad < 10^{-54}!$$

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



Dominant!
Chiral Conserving

All $\propto \frac{m_{\nu_i}^2 - m_{\nu_j}^2}{m_W^2}$ tiny

$R(\mu^- N \to e^- N) > B(\mu \to e\gamma)$!

Amplitudes Interfere!

Chiral Changing + Conserving

If $\bar{e}\sigma_{\alpha\beta}q^\beta\mu$ dominates $R(\mu^- N \to e^- N) \simeq \frac{1}{300} B(\mu^+ \to e^+\gamma)$

eg Many Susy Models

eg $B(\mu^+ \to e^+\gamma) \simeq 238\, R(\mu^- Ti \to e^- Ti) \simeq 389\, R(\mu^- Al \to e^- Al)$

Czarnecki, Melnikov + W.M.

Expect $B(\mu^+ \to e^+\gamma) \gtrsim 10^{-13}$ in SUSY

$R(\mu^- Al \to e^- Al) \gtrsim 3\times 10^{-16}$ in SUSY

(Potentially much larger in other theories)

Generic $\mathcal{M}(\mu \to e\gamma) = e\frac{m_\mu}{\Lambda^2}\underbrace{\varepsilon_{\mu e}}_{\text{suppression factor}}\bar{e}\sigma_{\alpha\beta}q^\beta\mu$

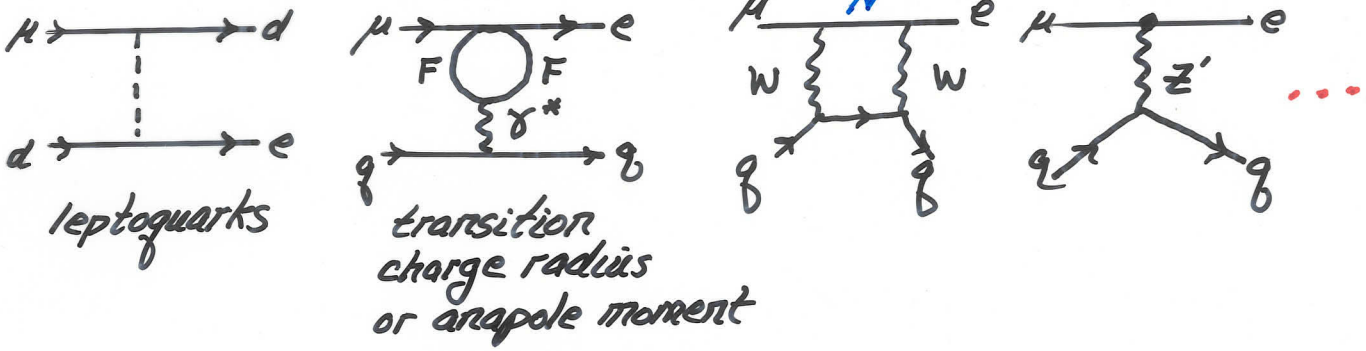
$$B(\mu \to e\gamma) \simeq \frac{1}{389} R(\mu^- Al \to e^- Al) \simeq \frac{10\,\varepsilon_{\mu e}^2}{G_F^2\Lambda^4} \simeq 0.06\,\varepsilon_{\mu e}^2 \left(\frac{1\,TeV}{\Lambda}\right)^4$$

$B(\mu \to e\gamma) < 1\times 10^{-11} \to$ $\underbrace{\varepsilon_{\mu e} < 5\times 10^{-5}}_{\text{small mixing or near degeneracy or } \Lambda \gtrsim 300\,TeV\ (\text{if } \varepsilon_{\mu e} \sim 1)}$ for $\Lambda \simeq 2\,TeV$ (eg a_μ)

In SUSY if $m_{\tilde{\ell}} \simeq 300\,GeV$, $\underbrace{\Delta m \lesssim 3\,MeV}_{\text{Near Degeneracy}}$

In other scenarios $\mu^- N \to e^- N$ more powerful

Chiral Conserving Amplitudes (Robust)



leptoquarks

transition charge radius or anapole moment

$B(\mu^- Al \to e^- Al)$ Probes $\Lambda \simeq 3000$ TeV!

If $\mu^- Al \to e^- Al$ observed → change targets

Study Interference Chiral Changing ? Conserving

An Industry of Experiments

Anticipate Success - Join MECO

3) MEG at PSI Phase I → $BR(\mu^+ \to e^+\gamma) \simeq 2\times10^{-13}$

Phase II → " " $\simeq 2\times10^{-14}$

Results ~~2006~~ ? 2008?

SUSY People expect discovery

or $\varepsilon_{\mu e} \to 10^{-6}$ $\Delta m \to 200\,keV$

4) MECO at BNL (Fermilab)

Produce - Stop $2\times10^{11}\,\mu^-/sec$ in Al

2 yrs → SES $R(\mu^- Al \to e^- Al) \simeq 2\times10^{-17}$

IF MEG finds $\mu^+ \to e^+\gamma$ MECO will find $\mu^- Al \to e^- Al$

Could be $\frac{1}{389}$ or "much" larger!

MECO has sensitivity to chiral changing & conserving Amplitudes

(Interference!)

If MECO finds conversion: Upgrade Statistics ×10

Change Targets

Map out amplitudes

An Industry!

Conclusion Muon-Electron Conversion - Very Special
$\rightarrow 5\times10^{-17} \rightarrow 5\times10^{-19}$! Unique

1) If SUSY Seen At LHC, expect $BR(\mu\to e\gamma) \gtrsim 10^{-13}$
$R(\mu^- A\to e^- Al) \gtrsim 3\times10^{-16}$

Probe slepton mixing
Other "New Physics"? Interference

2) SUSY Not Seen - $\mu^- Al\to e^- Al$ probes $\Lambda \sim 3000$ TeV!

3) Complements Neutrino Program (Flavor Violation)

4) Phase II $\rightarrow 5\times10^{-19} \rightarrow$ Intense Proton Driver

5) Prepares Way For: Neutrino Factory
$\mu^+\mu^-$ Collider
(Muon Experience)

HEP + FNAL Need Muon-Electron Conversion

NSF Made A Big Mistake

Correct It!

Transition Rate Calculation (schematic)

$$\omega(\mu^- N \to e^- N) = \Sigma |V_{fi}|^2$$

μ, e wavefunctions: $\psi_\kappa^m = \begin{pmatrix} g^{(\kappa)}(r)\, \chi_\kappa^m \\ i f^{(\kappa)}(r)\, \chi_{-\kappa}^m \end{pmatrix}$ Coulombic

$$\omega \sim \left| \int d^3 r\, \rho_N(r) \left(g_e g_\mu \pm f_e f_\mu \right) \right|^2$$

or other $g \cdot f$ combinations - (depends on int.)

use $p \cdot n$ distributions

Solve Dirac Eq. for $\psi = \mu \cdot e$