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10/7/04

Fundamental Muon Physics

Outline

1. Muon Economics

2. Precision Measurements
   i) m_μ, τ_μ, μ^+e^- hyperfine, $\mu^- N \to \nu_\mu N'$, $\mu^- N$ (PV)...
   * ii) $a_\mu = (g_\mu - 2)/2$ (First Sign of Supersymmetry?)

3. Electric Dipole Moment

4. Rare - Forbidden Reactions
   * i) $\mu^+ \to e^+ \gamma$ (MEG at PSI)
   * ii) $\mu^- N \to e^- N$ (MECO at BNL)
   iii) $\mu^+ \to e^+ e^- e^+$
   iv) $\mu^+ e^- \to \mu^- e^+$

5. Outlook + Other

1.) Muon Economics

Copious production: $p + N \rightarrow X + \pi^{\pm}$, $\pi^{\pm} \xrightarrow{99.99\%} \mu^{\pm}\nu$ (100% pol.)

If fully optimized $1\ (5\sim8\ \mathrm{GeV})\ p \rightarrow 1\ \mu^{\pm}$!
(Assumption of μ^-CF)

Reality pion factories PSI, TRIUMF, RAL
$E_p < 1\,\mathrm{GeV}$ $I_p \simeq 10^{15}\text{-}10^{16}\ p/\mathrm{sec}$
$10^{-8}\ \mu/p \rightarrow 10^{7}\sim10^{8}\ \mu^{\pm}/\mathrm{sec}$ $N_{\mu^+} > N_{\mu^-}$
(proposals $\sim 10^{-4}\ \mu/p$)

AGS (Current) $E_p \sim 8\text{-}32\,\mathrm{GeV}$, $4\times10^{13}\ p/\mathrm{sec}$
$0.3\ \mu^{\pm}$/proton possible

In principle $10^{13}\ \mu^{\pm}/\mathrm{sec}$!

MECO expects $E_p = 8\,\mathrm{GeV} \rightarrow 10^{11}$ stop μ^-/sec

A new 2MW proton driver should be able to provide
$\sim 10^{13}\ \mu^{\pm}/\mathrm{sec}$ More? Usable?

What can be done with $10^{13}\ \mu^{\pm}/\mathrm{sec}$?
ν factory, Applied Muon Physics, Fundamental $\mu^{\pm}$ studies
(currently $10^{5}\sim10^{6}\ \mu/\mathrm{sec}$)

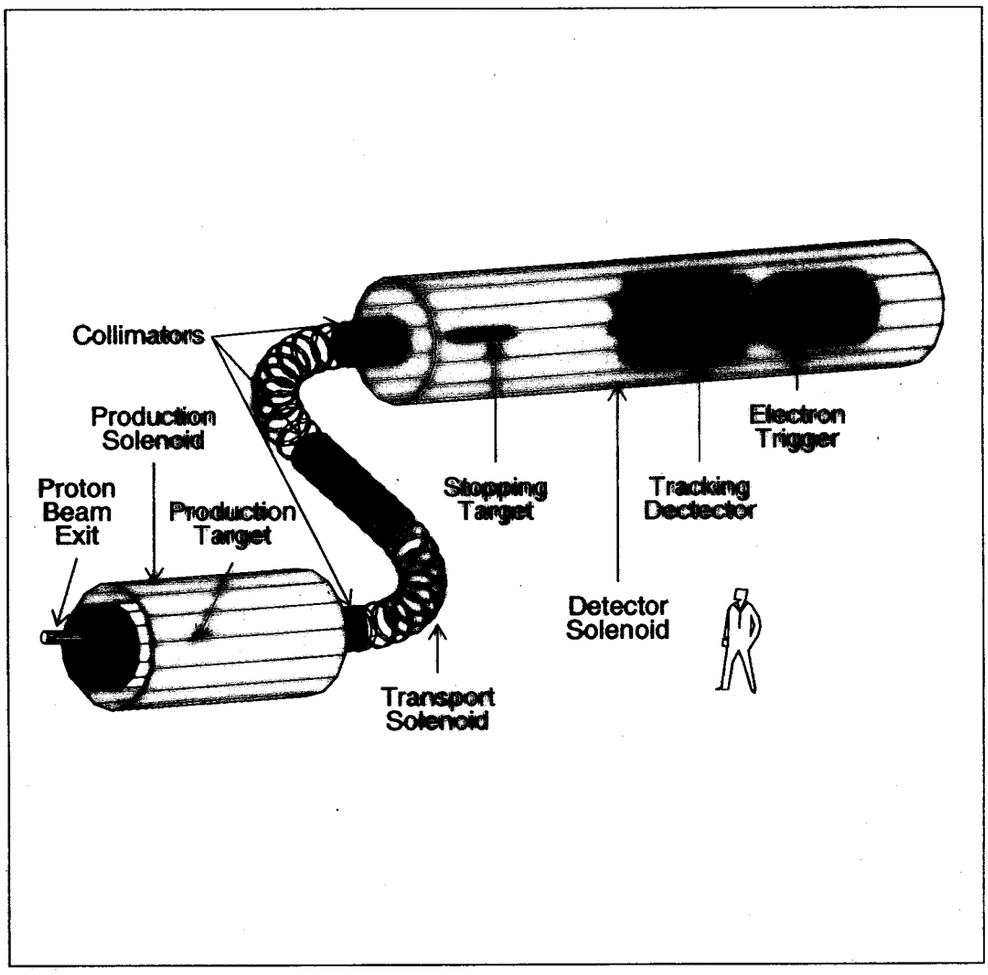


FIG. 31. Schematic layout of the MECO detector (provided by W.R. Molzon).

2.) Precision Measurements

i) m_μ, τ_μ, Michel Par., μ^+e^-, μ^-N ...

$m_\mu = 105.658389(34)$ MeV

Michel Par. New Exp at TRIUMF p... 10 times better

$\tau_{\mu^+} = 2.19703(4) \times 10^{-6}$ sec $\rightarrow G_\mu = 1.16637(1) \times 10^{-5}$ GeV^{-2}

New PSI exp $\rightarrow$ 20 times better! $\sim$ 1ppm

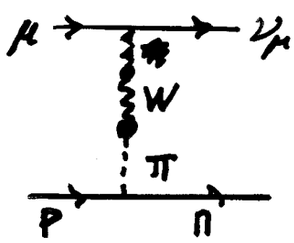
μ^+ lifetime in stopping material not affected to $\ll$ 1ppb
Czarnecki, Lepage, W.M

Go for it!

Utility $\rightarrow G_\mu$ better (already too good)

τ_{μ^+} vs τ_{μ^-} in material $\rightarrow \mu^- N \rightarrow \nu_\mu N^-$ capture rate

g_P



discrepency with χPT

New $\mu^- p \rightarrow \nu_\mu n$ via τ_{μ^-} also at PSI

Better μ^+e^- muonium HFS $\rightarrow$ Better α

etc.

ii) Muon Anomalous Magnetic Moment $a_\mu = g_\mu - 2/2$

$$\langle \mu | J_\beta^{em} | \mu \rangle$$

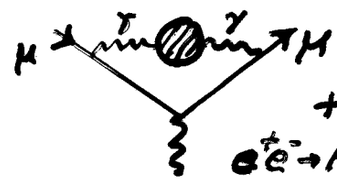
$$= \bar{u}_\mu \left[e F_1(q^2) \gamma_\beta + \frac{ie}{2m_\mu} \underbrace{F_2(q^2) \sigma_{\beta\delta} q^\delta}_{\text{chiral changing } LR} \right] u_\mu$$

$F_1(q^2 = 0) = 1$ $\qquad$ $\underline{F_2(0) = a_\mu}$

E821 at BNL $\quad a_\mu^{exp} = \underline{116\,592\,080\,(58) \times 10^{-11}}$

E969 at BNL goal 2.5 improvement $\rightarrow \pm 23 \times 10^{-11}$

<u>SM Theory</u> $\quad a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{Hadronic}$



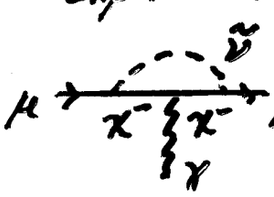
$+ \cdots$

$e^+e^- \rightarrow$ hadrons data

$a_\mu^{SM} = \underline{116\,591\,829\,(73) \times 10^{-11}}$ well matched

$\underline{\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251\,(93) \times 10^{-11} \quad 2.7 \text{ sigma}}$ Big Effect

Exp? SM? or New Physics (Supersymmetry)?



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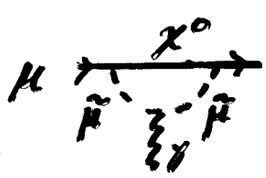

2 Charginos
4 Neutralinos
$\tilde{\nu}$ + $\tilde{\mu}$ mixing

$$a_\mu^{SUSY} \simeq \underset{+/-}{(\mathrm{sgn}\,\mu)} \times 130\times10^{-11} \underbrace{\tan\beta}_{3\sim40} \left(\frac{100\,\mathrm{GeV}}{m_{SUSY}}\right)^2$$

$$\underline{E821 \rightarrow \quad m_{SUSY} \simeq 74\sqrt{\tan\beta}\ \mathrm{GeV} \sim 100\text{-}500\,\mathrm{GeV}}$$

That's where it is expected!

LR Chiral Changing Amplitudes Sensitive $\sim \tan\beta$

a_μ, $b\to s\gamma$, edm, $\mu\to e\gamma$, $\mu^- N\to e^- N$, $\tau\to\mu\gamma$...

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3. <u>Muon Electric Dipole Moment</u> (See Insert)

4. <u>Rare- Forbidden Reactions</u>

$BR(\mu\to e\gamma) \lesssim 10^{-11}$ $\rightarrow 10^{-13} \rightarrow 10^{-14}$ MEG at PSI

$BR(\mu\to 3e) \lesssim 10^{-12}$

$R(\mu^- Ti\to e^- Ti) \lesssim 6\times10^{-13}$ $\rightarrow$ <u>10^{-17} MECO at BNL ses</u>

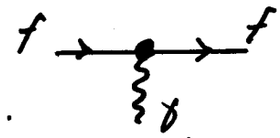
great discovery potential
Follow-up JPARC $\rightarrow 10^{-18}$
10^{-19} possible!

Lecture 3

Topics: 1) Electric Dipole Moments
2) Neutrino Oscillations

Next Lecture: 1) Resonant Neutrino Spin-Flavor Precession
2) $\mu \to e\gamma$, $\mu^- N \to e^- N$

1) Electric Dipole Moments



$\langle f | J_\mu^{em} | f \rangle$

$$= \bar{u}_f \left[\frac{ie}{2m_f} F_2(q^2) - F_3(q^2)\gamma_5 \right] \sigma_{\mu\nu} q^\nu u_f \rightarrow \frac{ie}{2m_f} \bar{u} \left[a_f e^{i\phi} \frac{1-\gamma_5}{2} + a_f e^{-i\phi} \frac{1+\gamma_5}{2} \right] \sigma_{\mu\nu} q^\nu u$$

$F_2(0) = a_f = \frac{g-2}{2}$ = Anomalous Magnetic Moment

$F_3(0) = d_f$ = electric dipole moment violate P+T

Current Exp Bounds:

$|d_e| \lesssim 4 \times 10^{-27}$ e-cm
$|d_n| \lesssim 10^{-25}$ e-cm $\quad (\theta_{QCD} \lesssim 10^{-10}!)$
$|d_\mu| \lesssim 7 \times 10^{-19}$ e-cm

Significant Improvements Expected: $d_e \to 10^{-30}$ e-cm!
$d_n \to 10^{-27}$ e-cm!

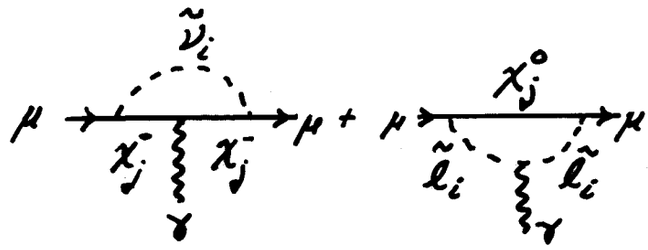
BNL LOI $|d_\mu| \to 10^{-23} \to 10^{-24}$ e-cm $\quad$ 6 orders improvement

Require 7×10^7 pd μ/sec $\quad$ Challenging
MECO 10^{11} μ^-/sec
ν-factory, $\mu^+\mu^-$ collider $\sim 10^{13}$ μ/sec!

<u>Standard Model</u> → Tiny (3loop or higher) edms

Observation → "New Physics" - New $\not{C}\not{P}$!

<u>Generic SUSY</u>



<u>General Mixing + Phases</u> → Δa_μ + d_μ

$$|d_\mu| \simeq \underbrace{\frac{e}{2m_\mu}}_{10^{-13}\,e\text{-cm}} \Delta a_\mu(\text{susy}) \underbrace{(\text{Im}\, e^{i\phi_\mu})}_{\text{suppression}}$$

If $\Delta a_\mu(\text{susy}) \simeq 300 \times 10^{-11}$ → $|d_\mu| \simeq 3 \times 10^{-22}$ e-cm $\underbrace{\sin\phi_\mu}_{\text{suppression}}$

Dedicated d_μ exp. will push $\sin\phi_\mu \lesssim 10^{-2}$ pretty good

<u>Electron</u> $d_e : d_\mu :: m_e \sin\phi_e : m_\mu \sin\phi_\mu$

→ $|d_e| \simeq 1.5 \times 10^{-24}$ e-cm $\underbrace{\sin\phi_e}_{< 2\times10^{-3}! \,\to\, 10^{-6}!}$ Already!

Pessimist SUSY Ruled Out! (Problem?)

Optimist EDMs will soon be observed

5) Lepton Electric Dipole Moments

Current $|d_e| \lesssim 4\times10^{-27}$ e-cm

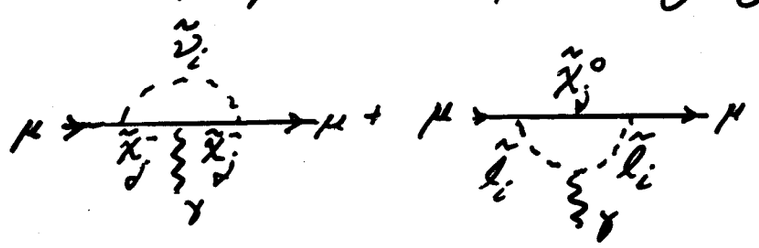
$|d_n| \lesssim 10^{-25}$ e-cm $(\theta_{QCD} \lesssim 10^{-10})$

$|d_\mu| \lesssim 7\times10^{-19}$ e-cm (Not Competitive)

BNL L.O.I $|d_\mu|^{exp} \to \underline{10^{-24}\text{ e-cm}}$ 6 orders of mag. improvement!

Require 7×10^{7} pol. μ /sec Very Challenging

Generic SUSY



General Mixing + Phases: $\to$ P + T violating e.d.m.

expect $$|d_\mu| \simeq \underbrace{\frac{e}{2m_\mu}}_{10^{-13}\text{e-cm}} \Delta a_\mu^{SUSY} (\mathrm{Im}\, e^{i\phi_\mu})$$

If $\Delta a_\mu^{SUSY} \sim 350\times10^{-11} \to |d_\mu| \simeq 3.5\times10^{-22}$ e-cm $(\underbrace{\mathrm{Im}\, e^{i\phi_\mu}}_{\sin\phi_\mu})$

suppression?

Potentially Enormous

However, if $d_e : d_\mu :: m_e \sin\phi_e : m_\mu \sin\phi_\mu$

Expect $|d_e| \simeq 1.7\times10^{-24}$ e-cm $(\times \sin\phi_e)$

Experiment $\to \sin\phi_e < 2\times10^{-3}$ suppression needed

Pessimist - Doesn't $|d_e|$ rule out SUSY?

Optimist - $|d_e|$ will be observed soon!

6.) Flavor Violating Decays ($\mu^+ \to e^+\gamma$ vs $\mu^- N \to e^- N$)

pros + cons.

Current Bounds: $B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$

$\frac{\omega(\mu^- Ti \to e^- Ti)}{\omega(\mu^- \text{capture})} < 6.1 \times 10^{-13}$ (see A. van der Schaaf)

Future (single event sensitivity)

$B(\mu^+ \to e^+\gamma) \to 2 \times 10^{-14}$ PSI

$N = Al$ $\quad B(\mu^- N \to e^- N) \to 2 \times 10^{-17}$ BNL (MECO)

$N = Ti$ $\quad B(\mu^- N \to e^- N) \to 10^{-18}$ JHF (PRIME)

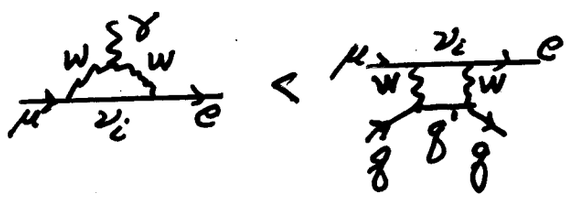
Potentially one might go to 10^{-19}!

(But I anticipate discovery long before that!)

Some Models $\quad B(\mu^+ \to e^+\gamma) > B(\mu^- N \to e^- N)$ very complementary

Others $\quad B(\mu^+ \to e^+\gamma) < B(\mu^- N \to e^- N)$

eg massive neutrinos



Both $\sim \left[\frac{\Delta m_{ij}^2}{m_W^2}\right]^2 \to$ unobservable $BR < 10^{-54}$!

Best case for $\mu \to e\gamma$, chiral changing amplitudes dominate

$$\mathcal{M}(\mu \to e\gamma) = \bar{u}_e \, i \frac{e}{m_\mu} (F_{M1} + F_{E1}\gamma_5) \sigma_{\mu\nu} q^\nu u_\mu \, \varepsilon^\mu(k)$$

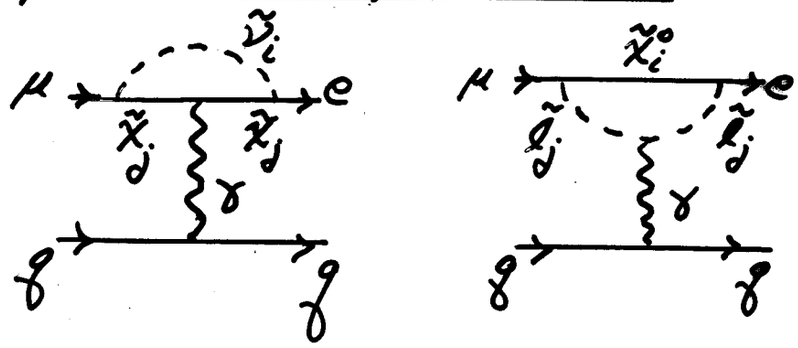
$$\Gamma(\mu \to e\gamma) = \frac{\alpha}{2} m_\mu \left[|F_{M1}|^2 + |F_{E1}|^2 \right]$$

$$B(\mu \to e\gamma) \simeq 1 \times 10^{15} \left[|F_{M1}|^2 + |F_{E1}|^2 \right]$$

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

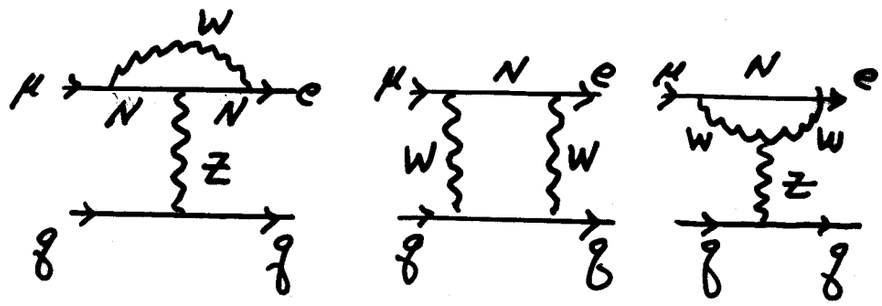
SUSY

see fig.



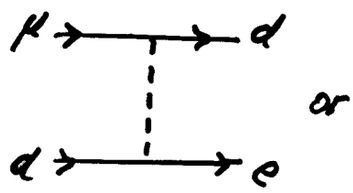
Heavy Neutrinos
(Mixing)

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

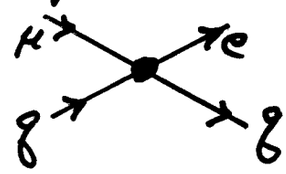


Leptoquarks ($\not{R}$)

$M_{LQ} \gtrsim 3000$ TeV!

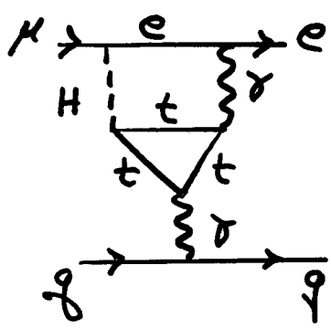


Compositeness



Neutral Higgs

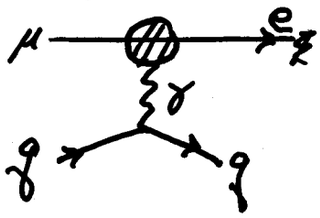
$g_{H\mu\bar{e}} < 10^{-4} g_{H\mu\bar{\mu}}$!



+ many other examples

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

In those scenarios



$B(\mu\to e\gamma) \simeq 238\, B(\mu^- Ti \to e^- Ti)$

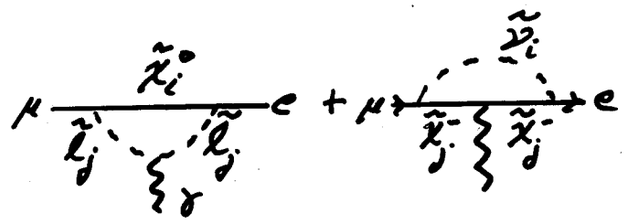
$B(\mu\to e\gamma) \simeq 389\, B(\mu^- Al \to e^- Al)$

$B(\mu^- Ti \to e^- Ti) \simeq 1.6\, B(\mu^- Al \to e^- Al)$ Nice Test

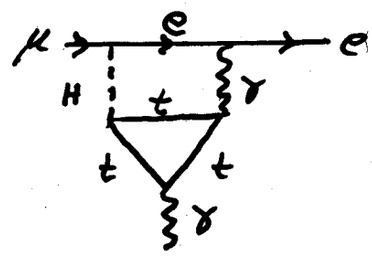
$B(\mu\to e\gamma)$ at $2\times10^{-14} \sim B(\mu^- Al\to e^- Al)$ at 5×10^{-17}

Examples SUSY

Best Bet



(1977) Bjorken-Weinberg



If $\Delta a_\mu \simeq 350\times10^{-11}$ in such theories $\tan\beta > 3\text{-}4$

$\rightarrow$ $B(\mu\to e\gamma) \simeq 1.4\times10^{-3}$ $\underbrace{\text{(suppression factor)}}_{\text{Mixing, } \underbrace{\text{GIM cancel}}_{m^2_{\tilde{\ell}_2}-m^2_{\tilde{\ell}_1}}\ldots}$

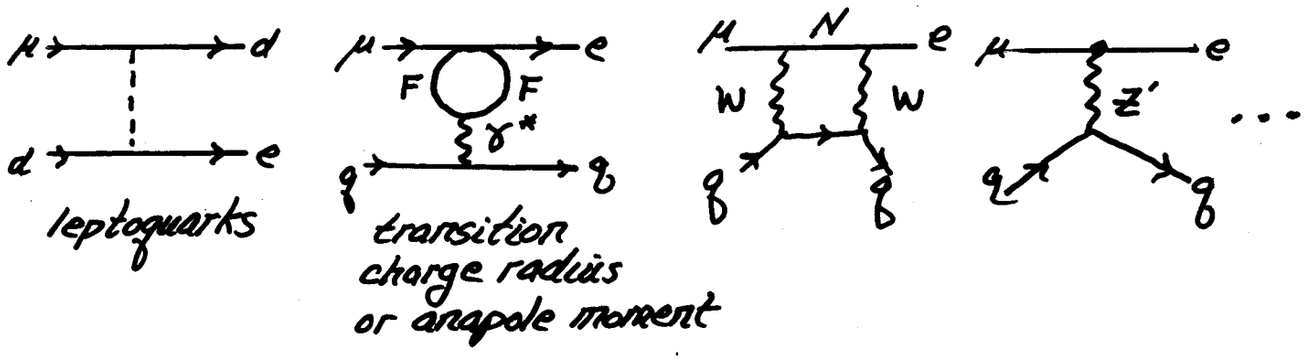
eg $m_{\tilde{\ell}_1} \simeq m_{\tilde{\ell}_2} + \Delta m_{\tilde{\ell}} \simeq 200\,\text{GeV}$

$B(\mu\to e\gamma)$ at 2×10^{-14} probes $\Delta m_{\tilde{\ell}}$ at <u>0.3 MeV</u>!
($B(\mu^- Al\to e^- Al)$ at 1×10^{-16})

I would expect $\mathcal{O}(10\text{-}100)$ events in $\mu\to e\gamma + \mu^- N\to e^- N$
if $\Delta a_\mu \simeq 350\times10^{-11}$!

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

Chiral Conserving Amplitudes (Robust)



$B(\mu^- Al \to e^- Al)$ 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

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

Very Distinct Signature - Monoenergetic Electon $\sim 105\,MeV$

Reject Background - Very Good Energy Resolution $\sim 300\,keV$

Can Take High Rate - No Accidentals (Unique)

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

$N \longleftarrow \bigcirc \bullet \longrightarrow e$ Highly Suppressed

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

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

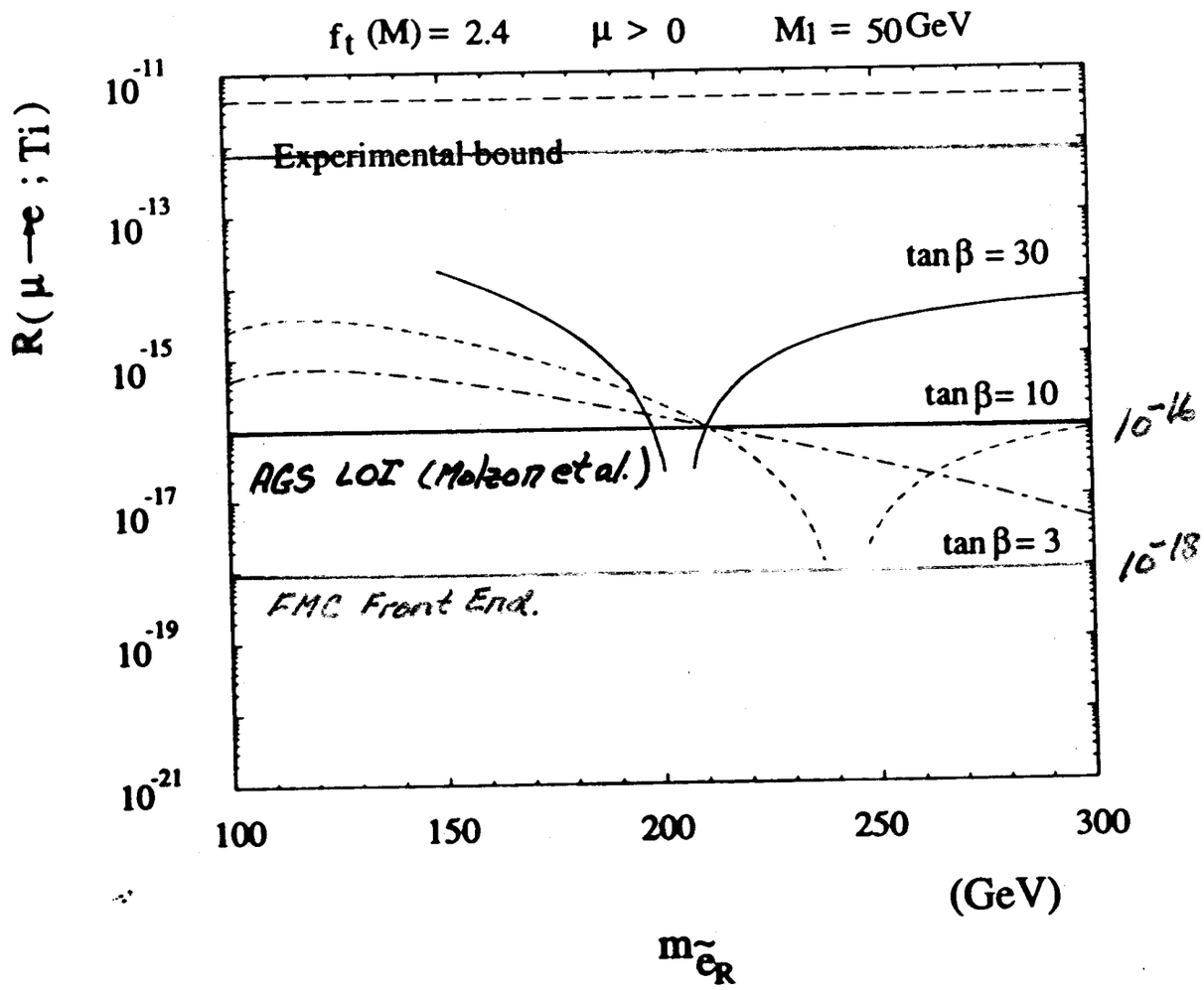
FMC Front End $\to 10^{-18} \sim 10^{-19}$ $10^{13} \sim 10^{14}\,\mu^-/sec$ (Very Clean Beam)

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

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

$\mu^- Ti \to e^- Ti$ in SUSY SU(5) Model, (Hisano, Moroi, Tobe & Yamaguchi)

$\sim \left(\frac{m_\tau}{m_\mu}\right)^2$ larger is some SUSY SO(10) (Barbieri, Hall...)



(a)

5. <u>Outlook</u> (Expectations, Hopes, Fantasies)

i) <u>Precision</u>: $g_\mu - 2$, τ_μ, $\mu \to e$ spectrum, $\mu^- N$ (watch $g_\mu - 2$)

ii) <u>Muon edm</u> - Dedicated Effort ($10^{-24} \to 10^{-28}$ e-cm)

iii) <u>MECO</u> ($\mu^- Al \to e^- Al$ at 2×10^{-17}!) Modern Muon Factory 10^{11} μ/sec

Other Applications? <u>PRISM $\to 10^{12}$ μ/sec</u>

Condensed Matter ...

iv) <u>Muon Storage Ring</u> 10^{13} μ/sec $\to$ ν factory osc., $\not{CP}$... Communications

v) <u>$\mu^+\mu^-$ Collider</u> ($\sqrt{s} \gtrsim 3$ TeV) $\gtrsim$ 2025 An idea whose time has come?

vi) <u>$\mu^+ e^-$ Medical Tool</u>? (Brain Scans)

vii) <u>μCF will likely fail</u>, but ~~spawn~~ new ideas ($\gtrsim 10^{17}$ μ/sec)

viii) <u>Surprises</u>

Will Muon Technology Prosper?

<u>Cosmic Connection</u>?

<u>To Discover, You Must Explore</u>