Differentiating solutions to the gauge hierarchy problem through rare muon decay

Brandon Murakami
Argonne National Laboratory
February 17, 2004

with David Maybury (University of Alberta)
hep-ph/0401170

Motivation

What is the most we can learn from near future *non-collider* lepton flavor violation (LFV) experiments?

$\mu \rightarrow e\gamma$?

Muon conversion ?

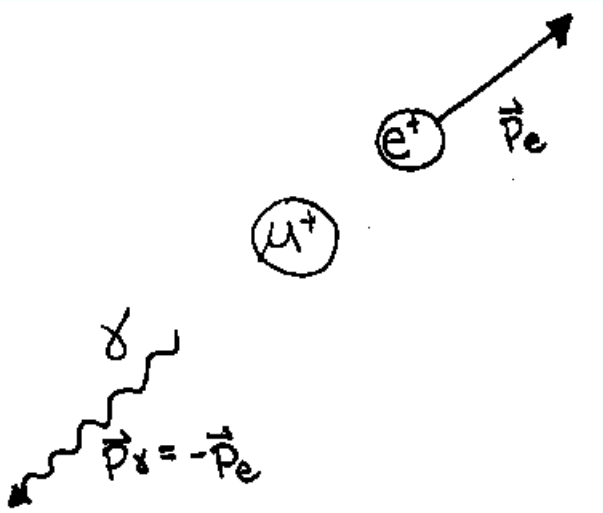
Motivation

- The gauge hierarchy problem (GHP) is the biggest *bottleneck* to future understanding.
  - Structure of spacetime?
  - Supersymmetry?
  - Gauge unification?
  - Quantum gravity? (string theory)

- Solutions to the hierarchy problem, as with any extension of the SM, generically have LFV.
  - dynamical EWSB,
  - little Higgs,
  - supersymmetry,
  - and extra dimensions

- What can LFV say here?

What is $\mu \to e\gamma$?



- Actually, $\mu^+ \to e^+\gamma$.
- Signal:
  - Back-to-back e^+ and γ
  - Each with $m_\mu/2 = 52.8$ MeV.

$\mu \to e\gamma$ backgrounds

- Radiative muon decay:

$$\mu^+ \to e^+ \gamma \nu_e \bar{\nu}_\mu$$

  - Low momentum neutrinos can mimic the $\mu \to e\gamma$ signal.
  - Background BR is 1.4% (for $E\gamma > 10$ MeV).
  - Finite energy resolution limits $\mu \to e\gamma$ search.

- Accidental background:
  - Possibly from an electron from normal muon decay and a photon from radiative muon decay.
  - Or a photon from positron anihilation within the stopping target.
  - Angular and timing resolution also limits $\mu \to e\gamma$ search.

$\mu \to e\gamma$ experimental status

- Main observable:

$$\mathrm{BR}(\mu \to e\gamma) \equiv \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu_e\nu_\mu)}$$

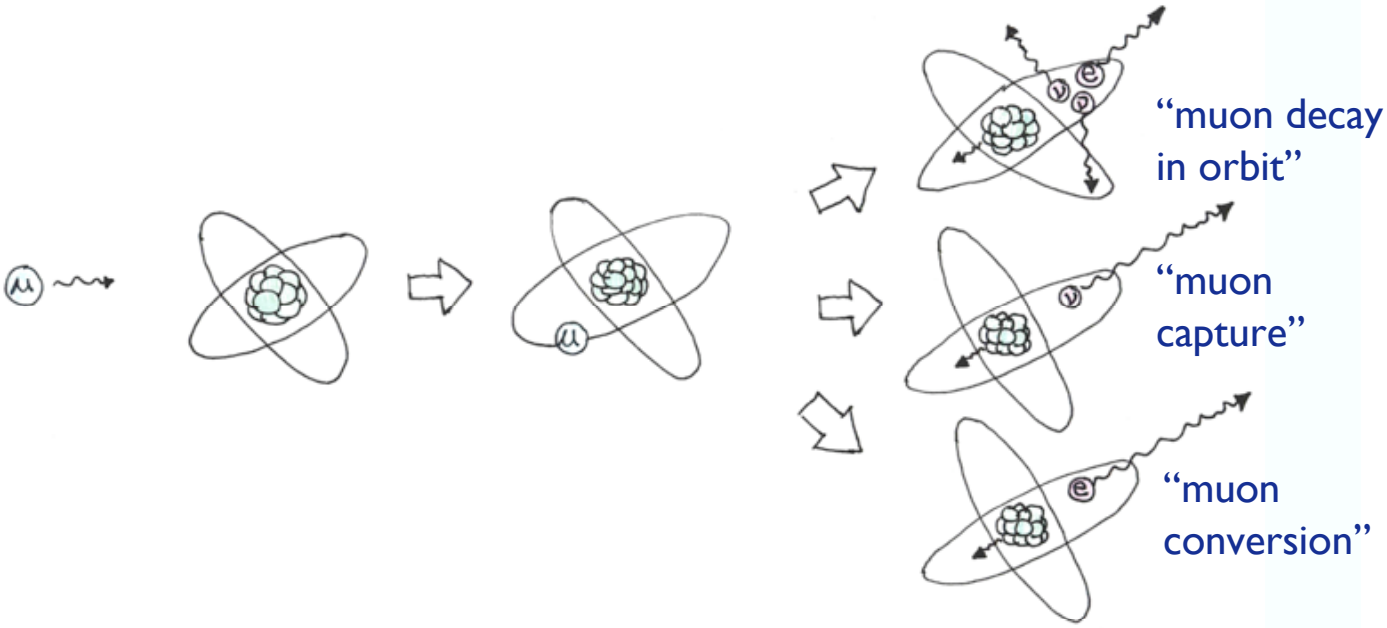
- The current limit:
  - $\mathrm{BR}(\mu \to e\gamma) < 1.2 \times 10^{-11}$
  - Set by MEGA at LANL (1999)

- The future:
  - MEG at the PSI (2005?)
  - Goal: $\mathrm{BR}(\mu \to e\gamma) < 4.5 \times 10^{-14}$ (2.4 orders better)

What is muon conversion?

…short for "coherent μ-e conversion in nuclei"

$$\mu N \rightarrow eN$$



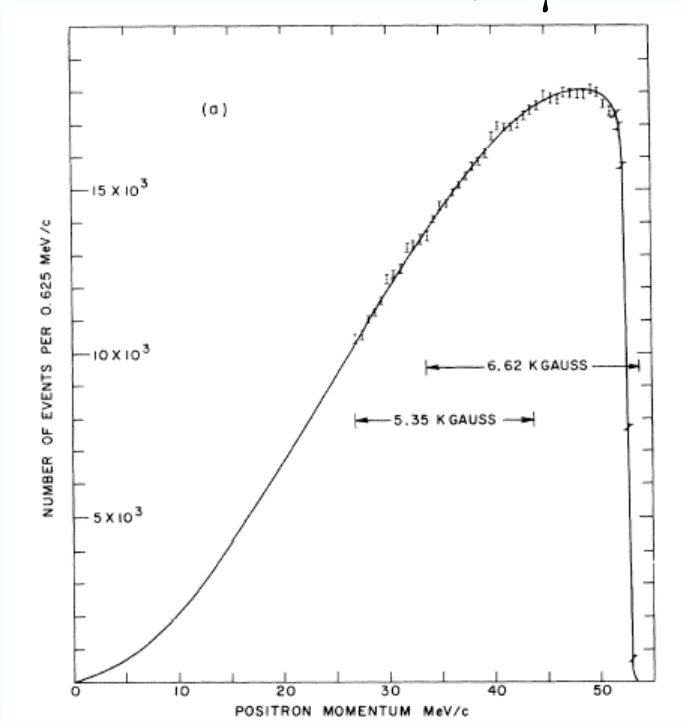
1. Slow muons are captured

2. A ground state muonic atom is formed.

3. The bound state decays.

μ-e backgrounds: normal μ decay

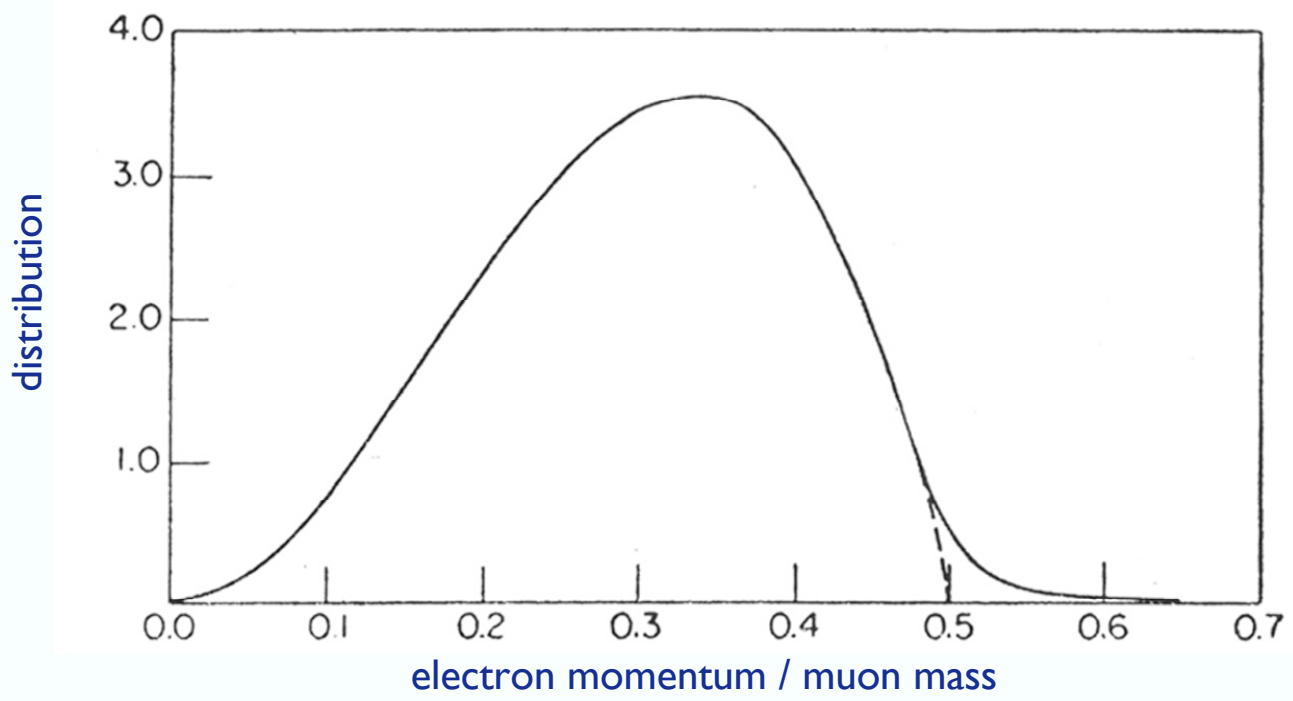
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$



- The positron has a maximum energy of 56 MeV.
- Muon conversion will have an electron with a momentum of nearly all of the muon's rest mass, typically ~104 MeV.

I.Bardon et al (1965)

μ-e backgrounds: μ decay in orbit



- Muon decay in orbit: $\mu N \to eN\nu\nu$ has a finite probability of mimicking the muon conversion signal.

Porter and Primakoff (1951)

μ-e experimental status

- Main observable:

$$\mathrm{BR}(\mu N \to eN) \equiv \frac{\Gamma(\mu N \to eN)}{\Gamma(\mu N \to \nu_\mu N')}$$

- Current limit:

$$\mathrm{BR}(\mu N \to eN) < 6.1 \times 10^{-13} < 10^{-12.2}$$

(SINDRUM II at PSI, 1998)

- Next generation experiments:

$$\mathrm{BR}(\mu N \to eN) \Rightarrow \text{ under } 10^{-16}$$ (MECO at BNL)

$$\mathrm{BR}(\mu N \to eN) \Rightarrow 10^{-18}$$ (PRIME at J-PARC)

- If muon conversion occurs at BR = 10^{-16}, MECO will see 5 events with a background of 0.45 for 10^7 s (117 days).

MECO status

MECO Sensitivity & Background

Expected Sensitivity

Contributions	Factor
Running time (s)	10^7
Proton flux (Hz)	4×10^{13}
μ reaching stopping target per incident proton	0.0043
μ stopping probability	0.58
μ capture probability	0.60
Fraction of μ capture in detection time window	0.49
Electron trigger efficiency	0.90
Fitting and selection criteria efficiency	0.19
Single Event Sensitivity	$R_{\mu e} = 2 \times 10^{-17}$

Expected Background

Source	Events
μ decay in orbit	0.25
Tracking errors	< 0.006
Radiative μ decay	< 0.005
Beam e^-	< 0.04
μ decay in flight	< 0.03
μ decay in flight	0.04
π decay in flight	< 0.001
Radiative π capture	0.07
Anti-proton induced	0.007
Cosmic ray induced	0.004
Total Background	0.45

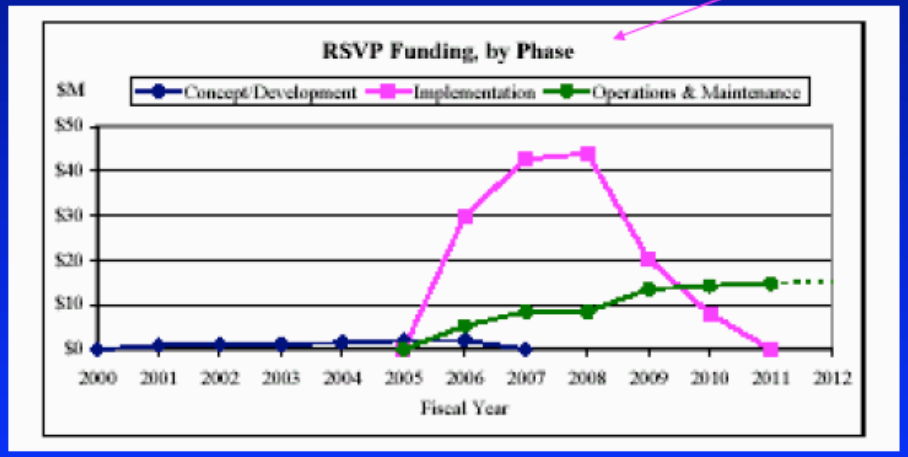
Michael Hebert, UC Irvine Status and Perspectives of MECO, the Muon to Electron Conversion Exp. June 10, 2003 19

M. Hebert for MECO (2003)

MECO status

Where are we? (Funding)

RSVP is in NSF budget, beginning in FY06; MECO represents about 60% of its capital cost.

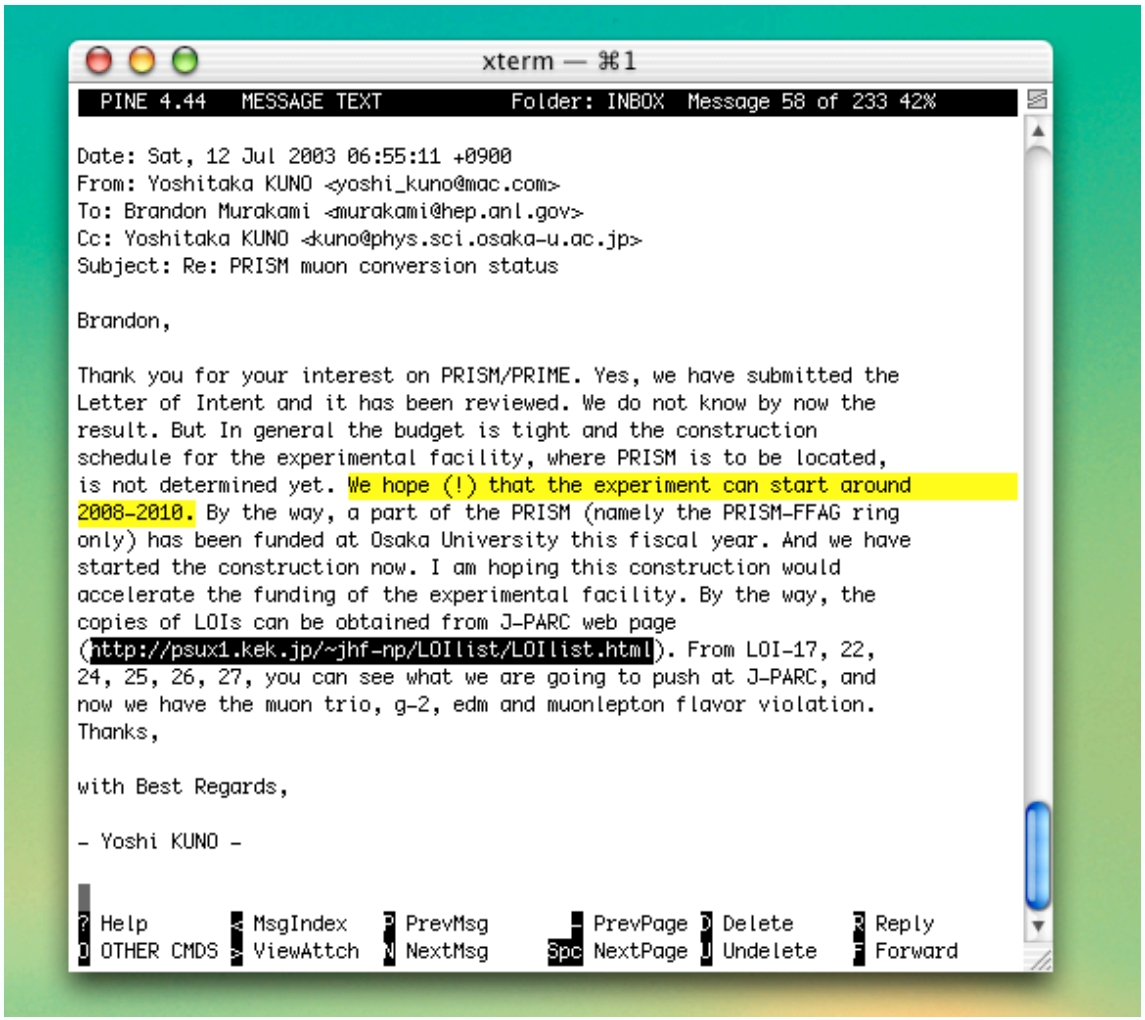


"I can say that RSVP is now the highest priority construction project from the division of Mathematical and Physical Sciences…." (R. Eisenstein to J. Sculli, 1/29/02)

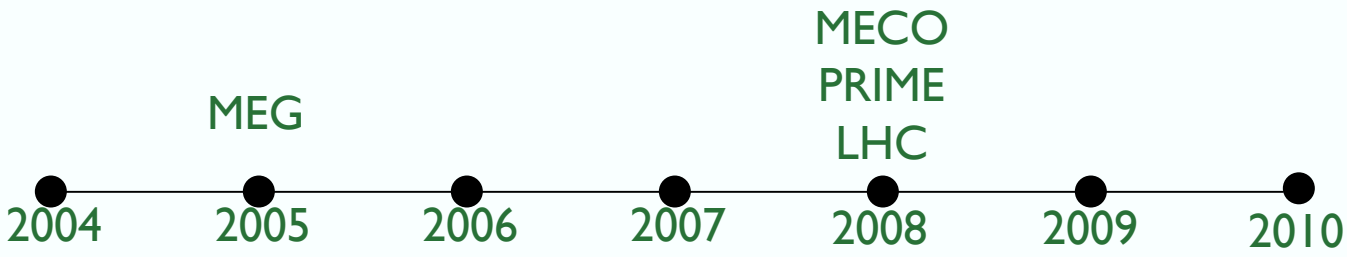
P. Yamin, BNL NuFact03 6/6/03 16

P. Yamin for MECO (2003)

PRIME status



The race for new physics



(most optimistic start dates)

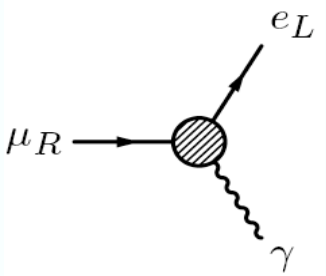
- MEG, MECO, and PRIME will run for ~1 year.
- The LHC will calibrate for ~1 year.
- Non-collider LFV has potential to be the first to find new physics.

LFV and the GHP

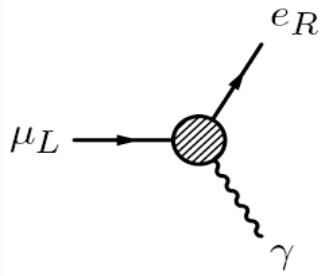
- Origins for LFV, in general, may have no relation to the GHP.
- *Minimal* solutions of the GHP may be accompanied by incidental LFV. Examples:
  - Neutrino LFV → charged LFV.
  - Non-universal gauge or scalar bosons.

Amplitudes

$\mu \to e\gamma$:

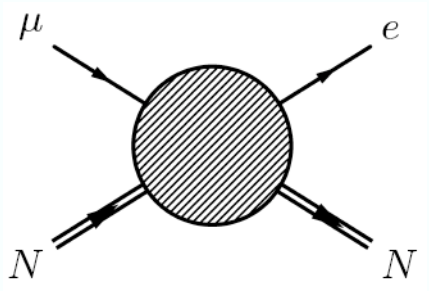


$$= im_\mu A_2^L \sigma_{\mu\nu} q^\nu$$



$$= im_\mu A_2^R \sigma_{\mu\nu} q^\nu$$

Muon conversion:



Operator Structure

$\mu \to e\gamma$:

$$-\mathcal{L} \supset e m_\mu [\bar{\mu}\sigma^{\mu\nu}(A_2^R P_L + A_2^L P_R)e]F_{\mu\nu} + \text{c.c.}$$

Muon conversion:

$$-\mathcal{L} \supset \sum_q \{e^2 Q_q [\bar{\mu}\gamma^\mu (A_1^L P_L + A_1^R P_R)e][\bar{q}\gamma_\mu q]$$ off-shell γ

$$+e^2 Q_q [\bar{\mu} i m_\mu \sigma^{\mu\nu} q_\nu (A_2^R P_L + A_2^L P_R)e][\bar{q}\gamma_\mu q]$$ on-shell γ

$$+[\bar{e}(a_{Sq}^L P_L + a_{Sq}^R P_R)\mu][\bar{q}q]$$ scalar

$$+[\bar{e}(a_{Pq}^L P_L + a_{Pq}^R P_R)\mu][\bar{q}\gamma^5 q]$$ pseudo-scalar

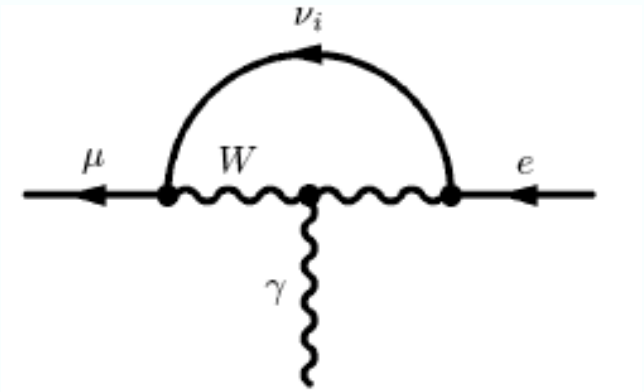
$$+[\bar{e}\gamma^\mu (a_{Vq}^L P_L + a_{Vq}^R P_R)\mu][\bar{q}\gamma_\mu q]$$ vector

$$+[\bar{e}\gamma^\mu (a_{Aq}^L P_L + a_{Aq}^R P_R)\mu][\bar{q}\gamma_\mu \gamma^5 q]$$ pseudo-vector

$$+[\bar{e}\sigma^{\mu\nu}(a_{Tq}^L P_L + a_{Tq}^R P_R)\mu][\bar{q}\sigma_{\mu\nu} q]\}$$ tensor

On-shell $\mu \to e\gamma$

- Example diagram (SM):



- If on-shell photon exchange dominates muon conversion:

$$\mathrm{BR}(\mu\mathrm{Al} \to e\mathrm{Al}) \approx \mathrm{BR}(\mu \to e\gamma)/389$$

- What minimal GHP solutions admit this?
  - the MSSM
  - others?

Dynamical EWSB

Technicolor Basics

- Ingredients:
  - SM without Higgs sector
  - Technicolor gauge group
  - Techniquarks
- Rules:
  - Technicolor gauge group is asymptotically free
  - Technicolor becomes strong at some scale
- Breaking EWSB:
  - Techniquarks ➡ technipions
  - Technipions ➡ Higgs or eaten by Z and Ws.

LFV and Dynamical EWSB

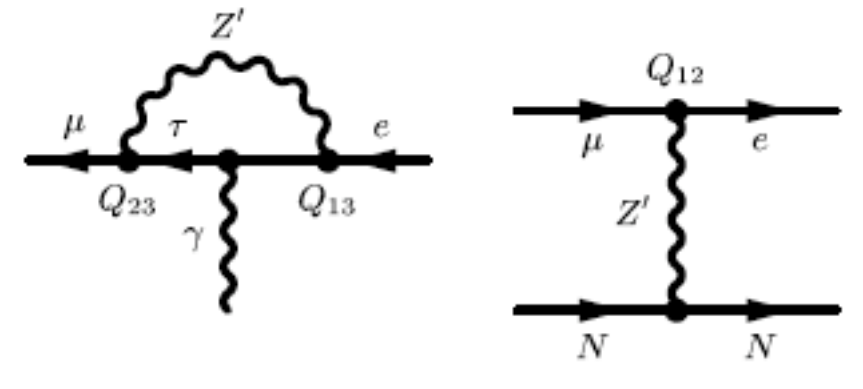
- Pure technicolor does not address quark and lepton masses.
- Extended technicolor (ETC)
  - A new gauge interaction between ordinary matter and techniquarks.
  - Difficult to accommodate acceptable masses and electroweak precision data.
- Create more freedom:
  - 3rd generation ETC different from light generations.
  - Non-universal gauge interactions ➡ FCNC (LFV).

$$\mathcal{L} \supset g Z'_\mu (\bar{L}_i q_i \gamma^\mu L_i)$$

FCNC upon rotation to mass basis

LFV and Dynamical EWSB

- Dominant amplitudes:



- If $Q_{23}Q_{13} \gg Q_{12}Q_{qq}$, photon exchange may dominate muon conversion.
  - …provided off-shell photons are somehow irrelevant.

- Otherwise, no distinct correlation prediction.

Little Higgs

Littlest Higgs Basics

- Ingredients:
  - SM without Higgs sector
  - SU(5) symmetry with $[SU(2)xU(1)]^2$ subgroup
  - Scalars to break SU(5)

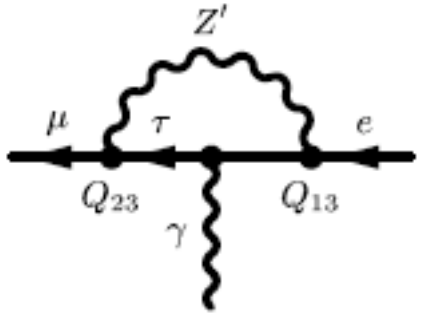
- Rules:
  - At ~10 TeV, SU(5) → SO(5) yielding 14 Goldstones
    - Real singlet
    - Real triplet
    - Complex doublet
    - Complex triplet

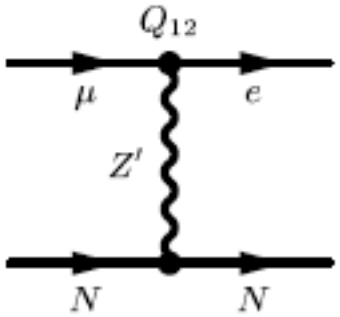
- Breaking EWSB:
  - $[SU(2)xU(1)]^2$ → $SU(2)_L xU(1)_Y$ (at ~10 TeV)
  - EWSB broken by complex doublet.

LFV and Little Higgs

Two sources of LFV

- Flavor physics
  - Fermion mass hierarchy from flavor aware gauge bosons. ⇒ *LFV gauge bosons*.
  - No distinct correlation prediction.





LFV and Little Higgs

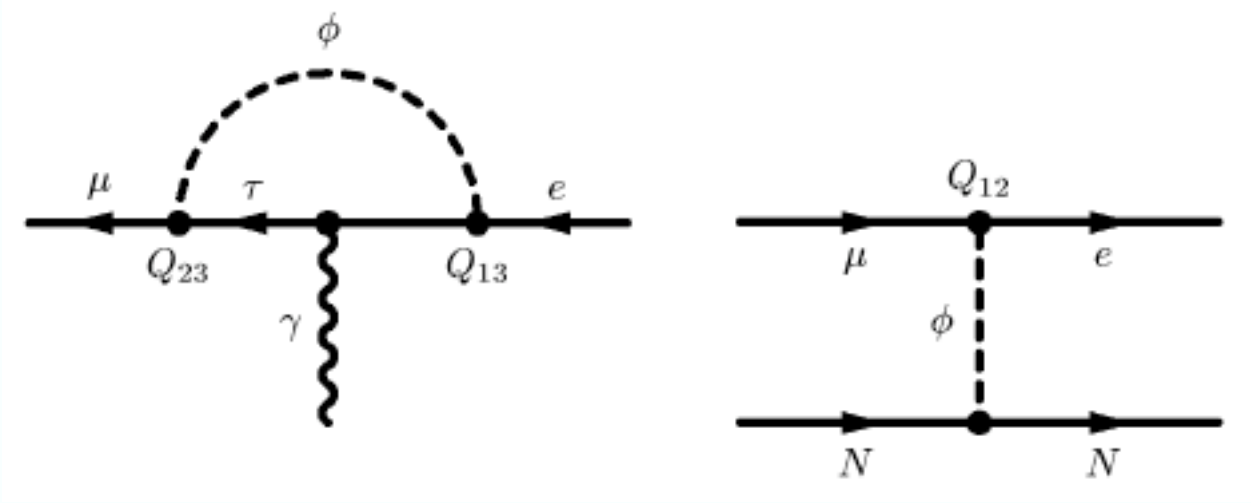
- A little hiearchy
  - Radiative corrections ⇒ 1 TeV Higgs mass
  - Solution: new top-like quarks designed to cancel Higgs mass contribution.
  - If extended to leptons, the *complex triplet would mediate LFV*.
  - No distinct correlation prediction.

$\Phi^0 \bar{T} t$	$-\frac{im_t}{\sqrt{2}v}\left(\frac{v}{f}-\sqrt{2}s_0\right)\frac{\lambda_1}{\lambda_2}P_L$	$\Phi^0 \bar{t} T$	$-\frac{im_t}{\sqrt{2}v}\left(\frac{v}{f}-\sqrt{2}s_0\right)\frac{\lambda_1}{\lambda_2}P_R$
$\Phi^P \bar{T} t$	$\frac{m_t}{\sqrt{2}v}\left(\frac{v}{f}-\sqrt{2}s_0\right)\frac{\lambda_1}{\lambda_2}P_L$	$\Phi^P \bar{t} T$	$\frac{m_t}{\sqrt{2}v}\left(\frac{v}{f}-\sqrt{2}s_0\right)\frac{\lambda_1}{\lambda_2}P_R$

Complex triplet couplings (mass states)
Han, Logan, McElrath, & Wang. PRD 67, 095004

LFV and Little Higgs

- A little hiearchy
  - Radiative corrections ⇒ 1 TeV Higgs mass
  - Solution: new top-like quarks designed to cancel Higgs mass contribution.
  - If extended to leptons, the *complex triplet would mediate LFV*.
  - No distinct correlation prediction.



Supersymmetry

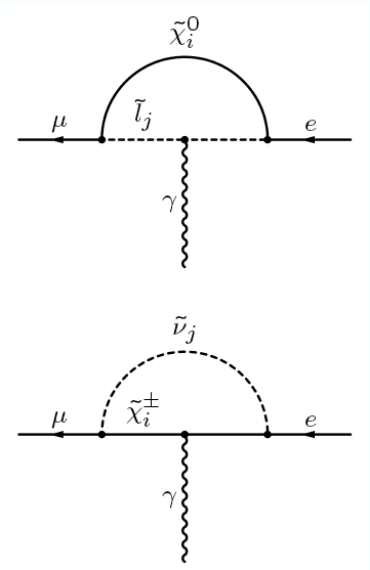
Supersymmetry Basics

- Ingredients:
  - SM with two Higgs doublets
  - Extend Poincare group to supersymmetry
  - A hidden sector
- Rules:
  - Spontaneously broken supersymmetry
  - "μ" term must be on sparticle mass scale.
- Breaking EWSB:
  - EWSB broken by two Higgs doublets.

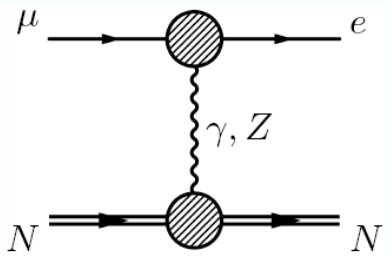
LFV and the MSSM

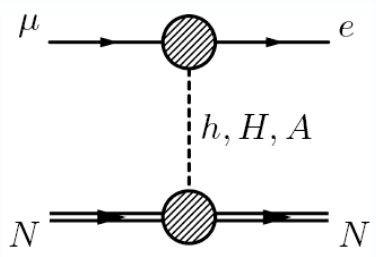
- No LFV in: mSUGRA, GMSB, and AMSB
- LFV sources:
  - Neutrino oscillations
  - GUTs
  - Flavor physics, soft breaking, R-parity violation

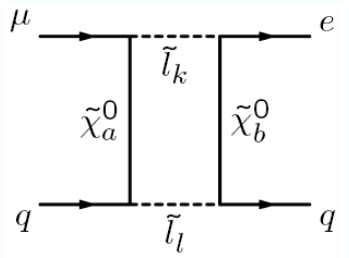
$\mu \to e\gamma$



muon conversion







• • •

LFV and the MSSM

- Muon conversion is dominated by $\mu \to e\gamma$ because:

1. Other diagrams propagator suppressed.
2. Dominant on-shell $\mu \to e\gamma$ diagrams are $\tan\beta$ enhanced. (Off-shell not enhanced.)
3. Smallness of Yukawas suppress Higgs exchange (except for large $\tan\beta$ and light H^0)
4. Box diagrams involve (heavy) squarks.

- Linearly correlated rates:

$$\mathrm{BR}(\mu\mathrm{Al} \to e\mathrm{Al}) \approx \mathrm{BR}(\mu \to e\gamma)/389$$

Extra dimensions

- Focus on usages that directly solve the GHP.
  - Dilution of high scales by volume suppression
  - Dilution of high scales by warp factor.

LFV and extra dimensions

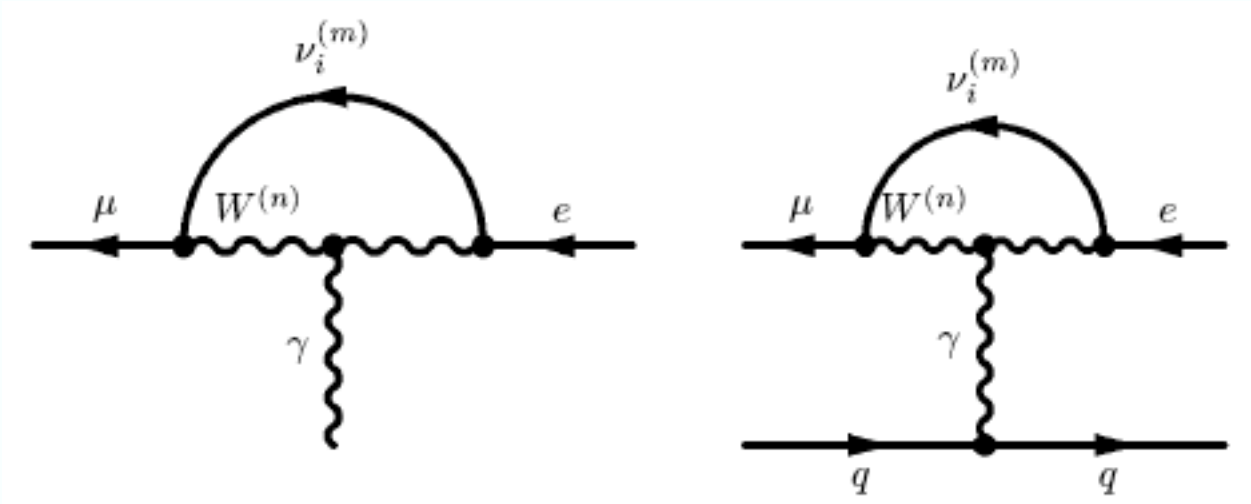
Two sources of LFV

- Bulk neutrinos:
  - Physical neutrinos include a tower of (mixed) KK states.
  - Loops with internal W and neutrinos $\Rightarrow \mu \to e\gamma$
  - Muon conversion is photon dominated.
  - But off-shell $\mu \to e\gamma$ may be of the same order as on-shell. $\Rightarrow$ No distinct correlation prediction.

- Fermion cartography:
  - Different overlap of photon and Z fields or their KK states with leptons $\Rightarrow$ non-universal gauge bosons.
  - No distinct correlation prediction.

LFV in UED

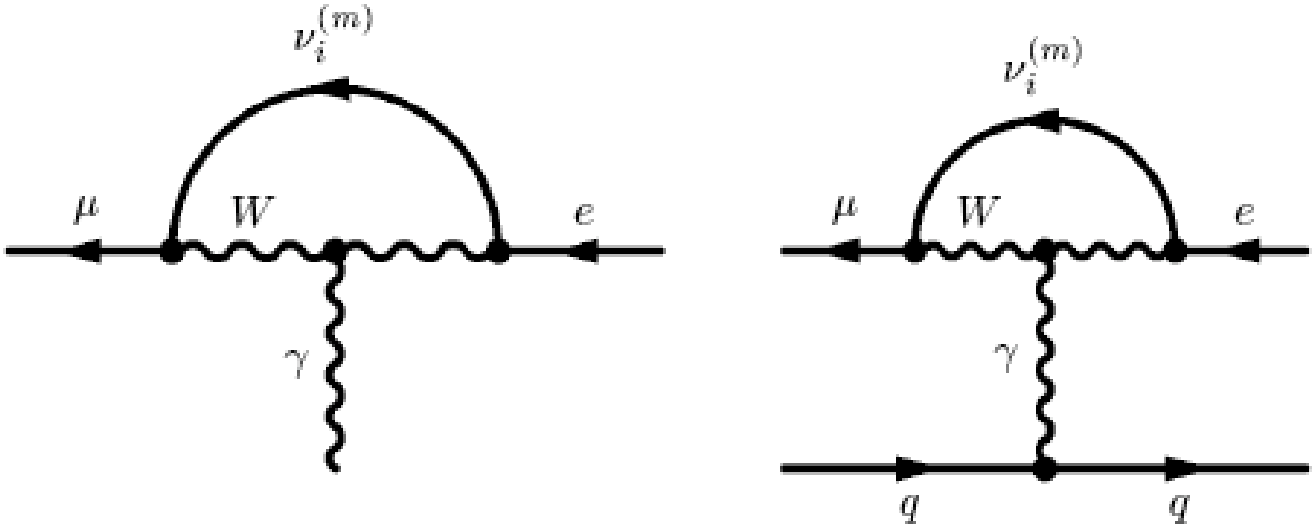
- Ingredients:
  - All SM fields in the bulk.
- LFV diagrams analogous to supersymmetry.



- A priori, no reason for off-shell photon exchange to be irrelevant in muon conversion.

LFV in ADD and RS

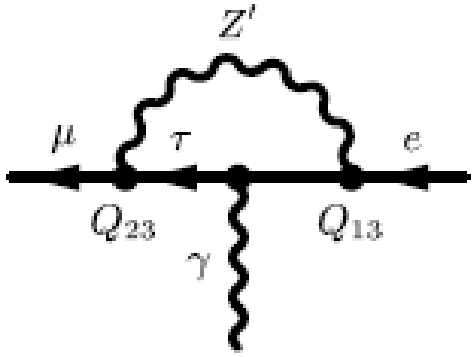
- Ingredients:
  - SM stuck on a brane.
  - Right handed neutrinos in bulk.
- Dominant LFV diagrams SM-like.

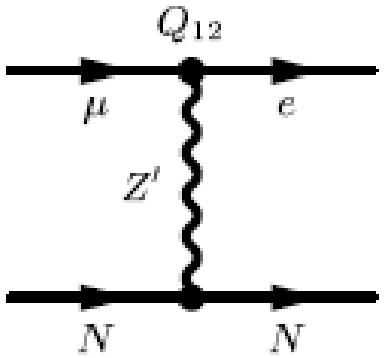


- A priori, no reason for off-shell photon exchange to be irrelevant in muon conversion.

LFV in ADD and RS

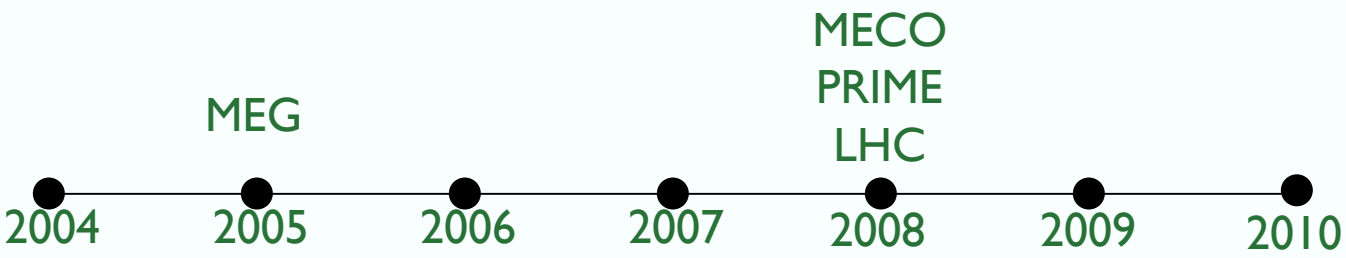
- Ingredients:
  - SM in bulk.
  - SM fermions localized in bulk.
- Photon & Z have different overlap with generations.
- Dominant LFV diagrams:





- No linear correlation of rates.

Perspective



- Linearly correlated $\mu \rightarrow e\gamma$ and muon conversion branching ratios have potential to implicate supersymmetry.

- Uncorrelated branching ratios may be ambiguous.