Differentiating solutions to the gauge hierarchy problem through rare muon decay

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Motivation

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

$\mu \rightarrow e\gamma$?

Muon conversion ?

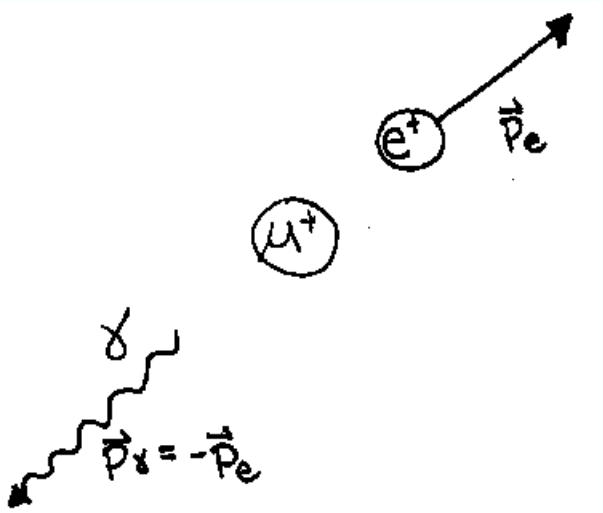
Motivation

- 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.

$\mu \to e\gamma$ experimental status

- Main observable:

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

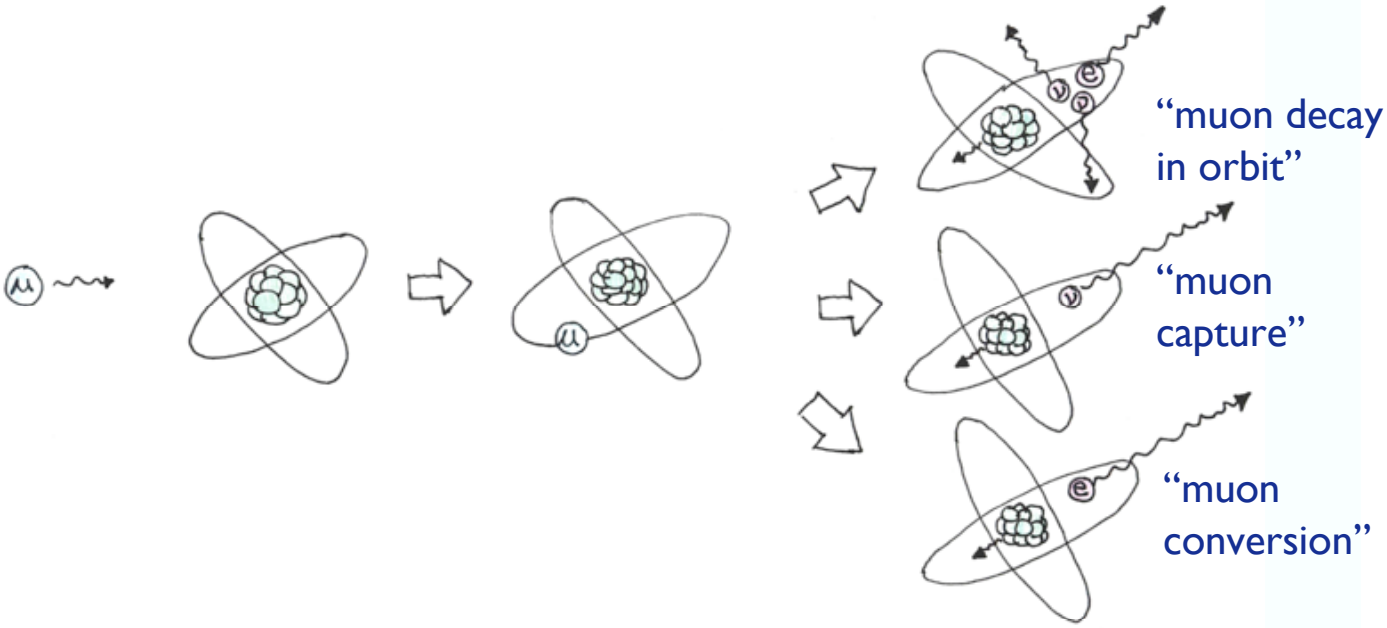
- The current limit:
  - $\mathrm{BR}(\mu \to e\gamma) < 1.2 \times 10^{-11}$
  - Set by MEGA at LANL (1999)

- 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 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)

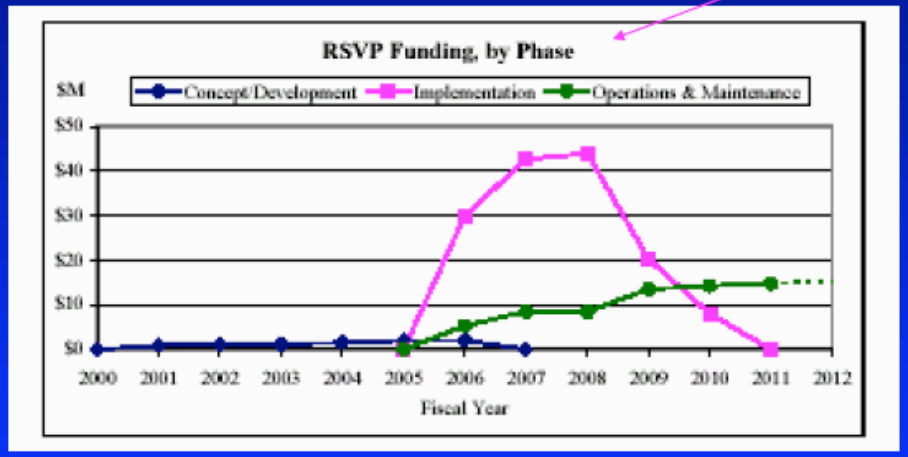
$$\mathrm{BR}(\mu N \to eN) \Rightarrow 10^{-18}$$ (PRIME at J-PARC)

- 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

Where are we? (Funding)

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

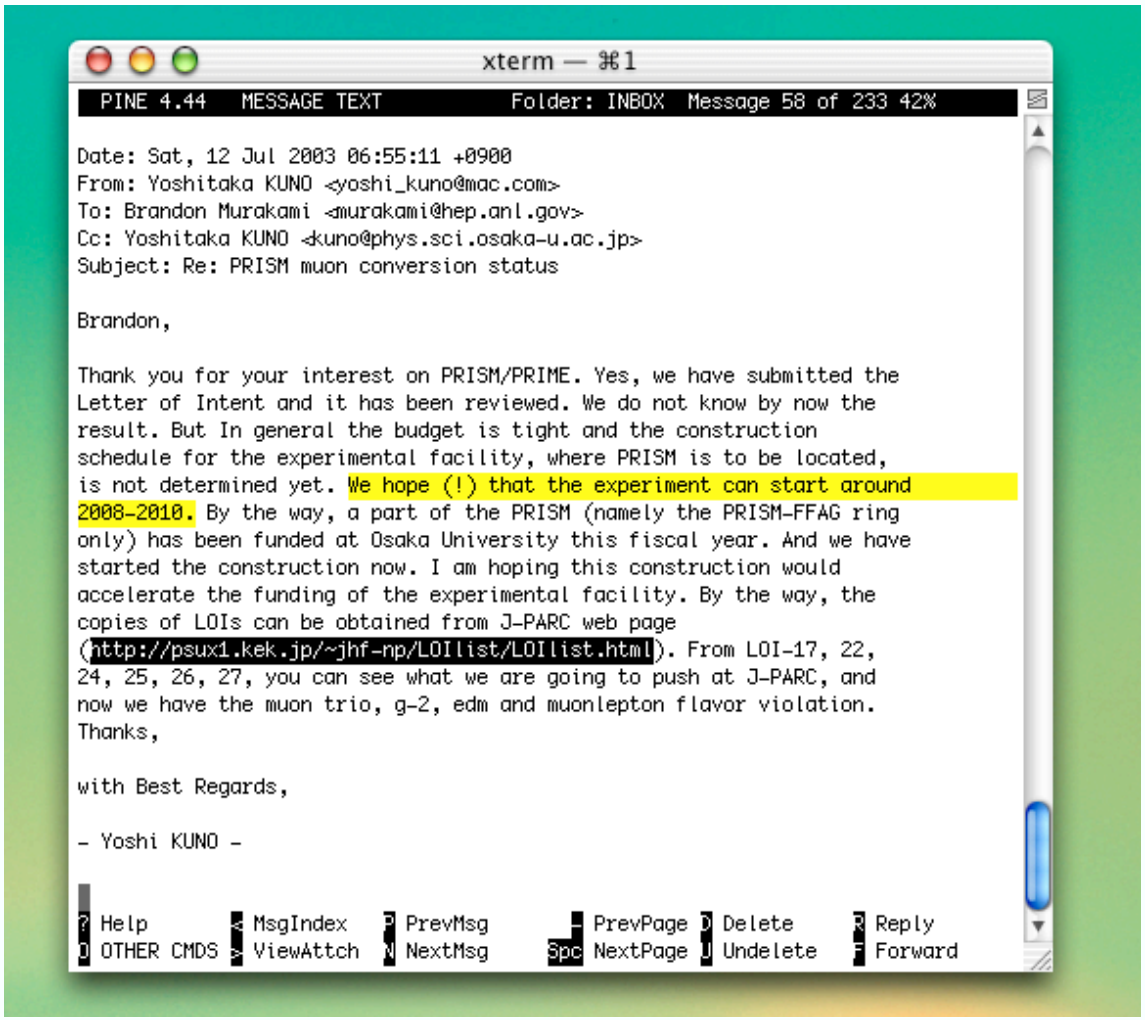


"I can say that RSVP is now the highest priority construction project from the division of Mathematical and Physical Sciences…." (R. Eisenstein to J. Sculli, 1/29/02)

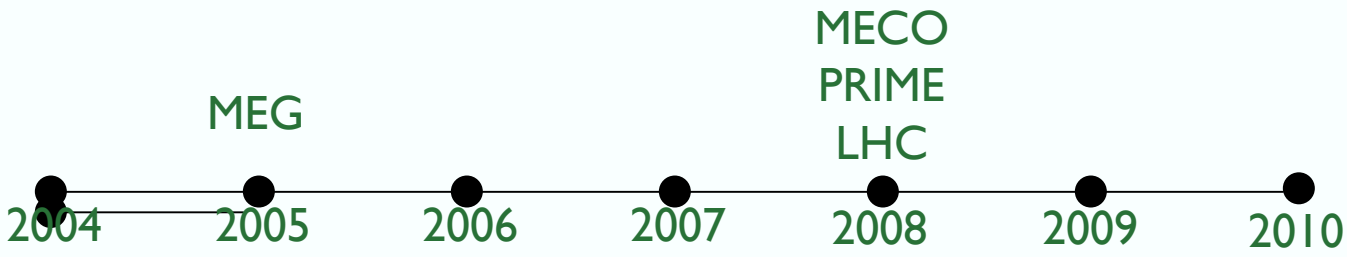
P. Yamin, BNL NuFact03 6/6/03 16

P. Yamin for MECO (2003)

PRIME status



The race for new physics



(most optimistic start dates)

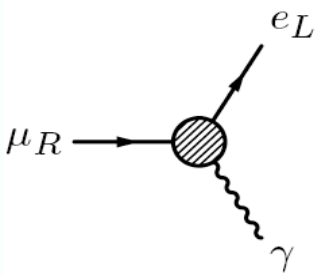
- MEG, MECO, and PRIME will run for ~1 year.
- The LHC will calibrate for ~1 year.
- Non-collider LFV has potential to be the first to find new physics.

LFV and the GHP

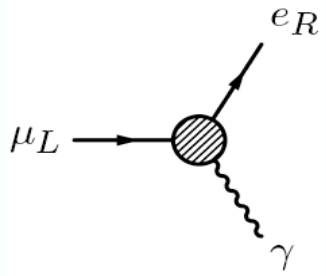
- Origins for LFV, in general, may have no relation to the GHP.
- *Minimal* solutions of the GHP may be accompanied by incidental LFV. Examples:
  - Neutrino LFV → charged LFV.
  - Non-universal gauge or scalar bosons.

Amplitudes

$\mu \to e\gamma$:

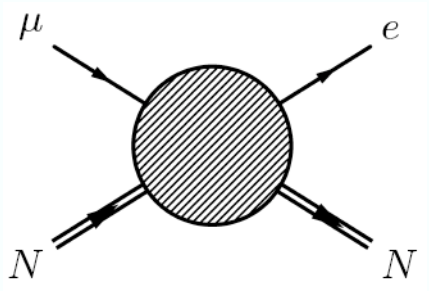


$$= im_\mu A_2^L \sigma_{\mu\nu} q^\nu$$



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

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

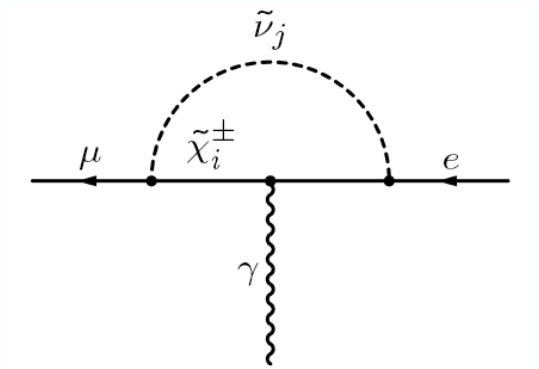
$$+[\bar{e}\gamma^\mu (a_{Vq}^L P_L + a_{Vq}^R P_R)\mu][\bar{q}\gamma_\mu q]$$ vector

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



- If on-shell photon exchange dominates:

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

- 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

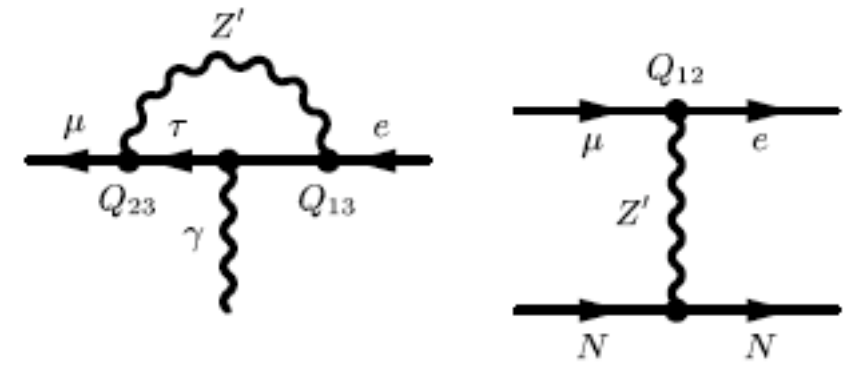
- Pure technicolor does not address quark and lepton masses.
- Extended technicolor (ETC)
  - A new gauge interaction between ordinary matter and techniquarks.
  - Difficult to accommodate acceptable masses and electroweak precision data.
- Create more freedom:
  - 3rd generation ETC different from light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

- 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

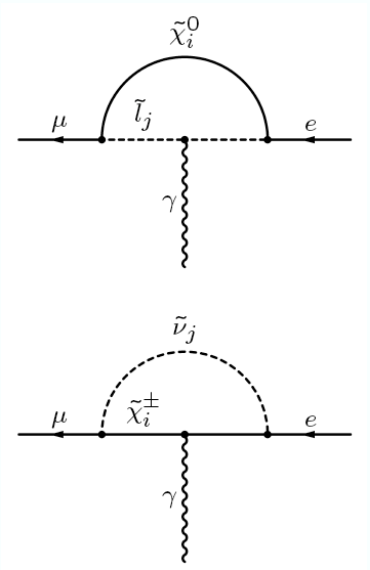
Supersymmetry Basics

- 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.

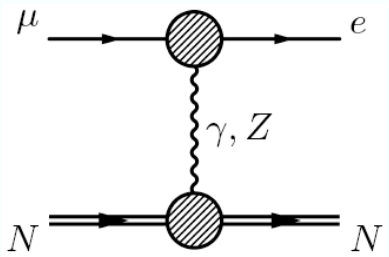
LFV and the MSSM

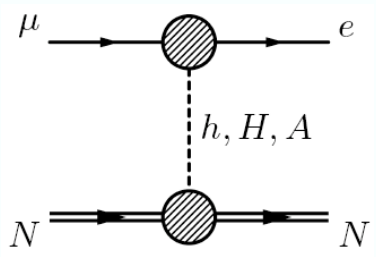
- No LFV in: mSUGRA, GMSB, and AMSB
- LFV sources:
  - Neutrino oscillations
  - GUTs
  - Flavor physics, soft breaking, R-parity violation

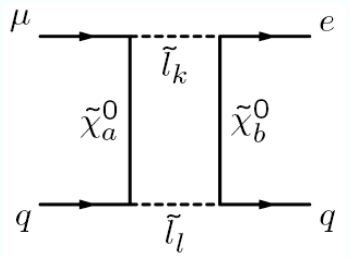
$\mu \to e\gamma$



muon conversion







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LFV and the MSSM

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

1. Other diagrams propagator suppressed.
2. Dominant $\mu \to e\gamma$ diagrams are $\tan\beta$ 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.

- Ingredients:
  - Extension of spacetime
  - Unmodified SM
  - High scale physics to stabilize the brane world

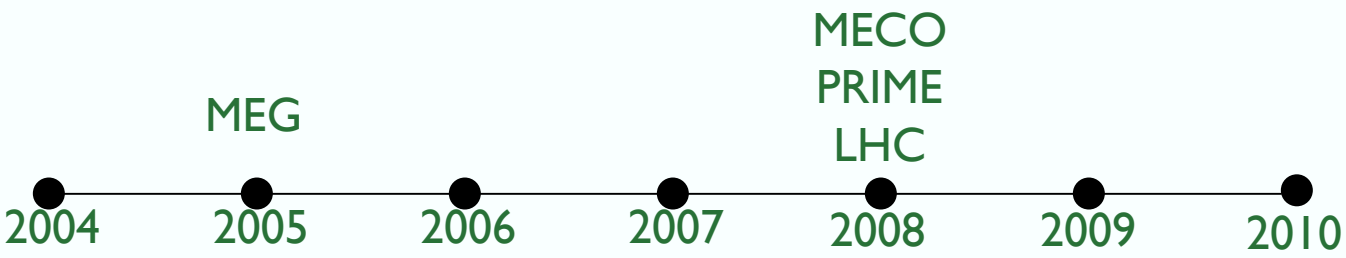
LFV and extra dimensions

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.

Perspective



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

- Uncorrelated branching ratios may be ambiguous.