Theory of Charged Lepton Flavor Violation

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Flavor Physics and CP-Violation

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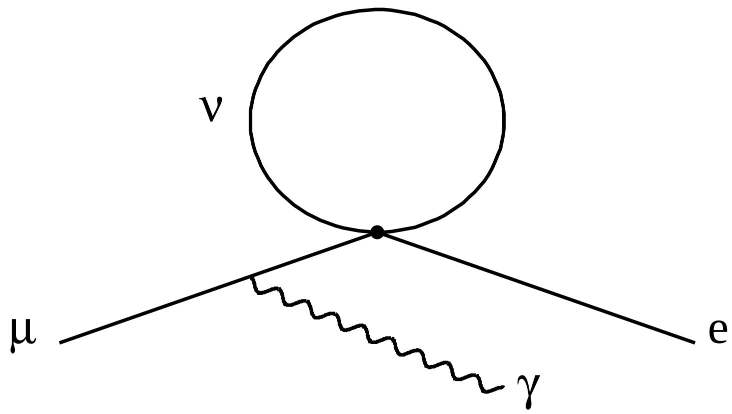
Outline

1. Brief Introduction;
2. Old and New Standard Model Expectations;
3. Model Independent Approach;
4. Examples;
5. Expectations, Complaints, and Conclusions.

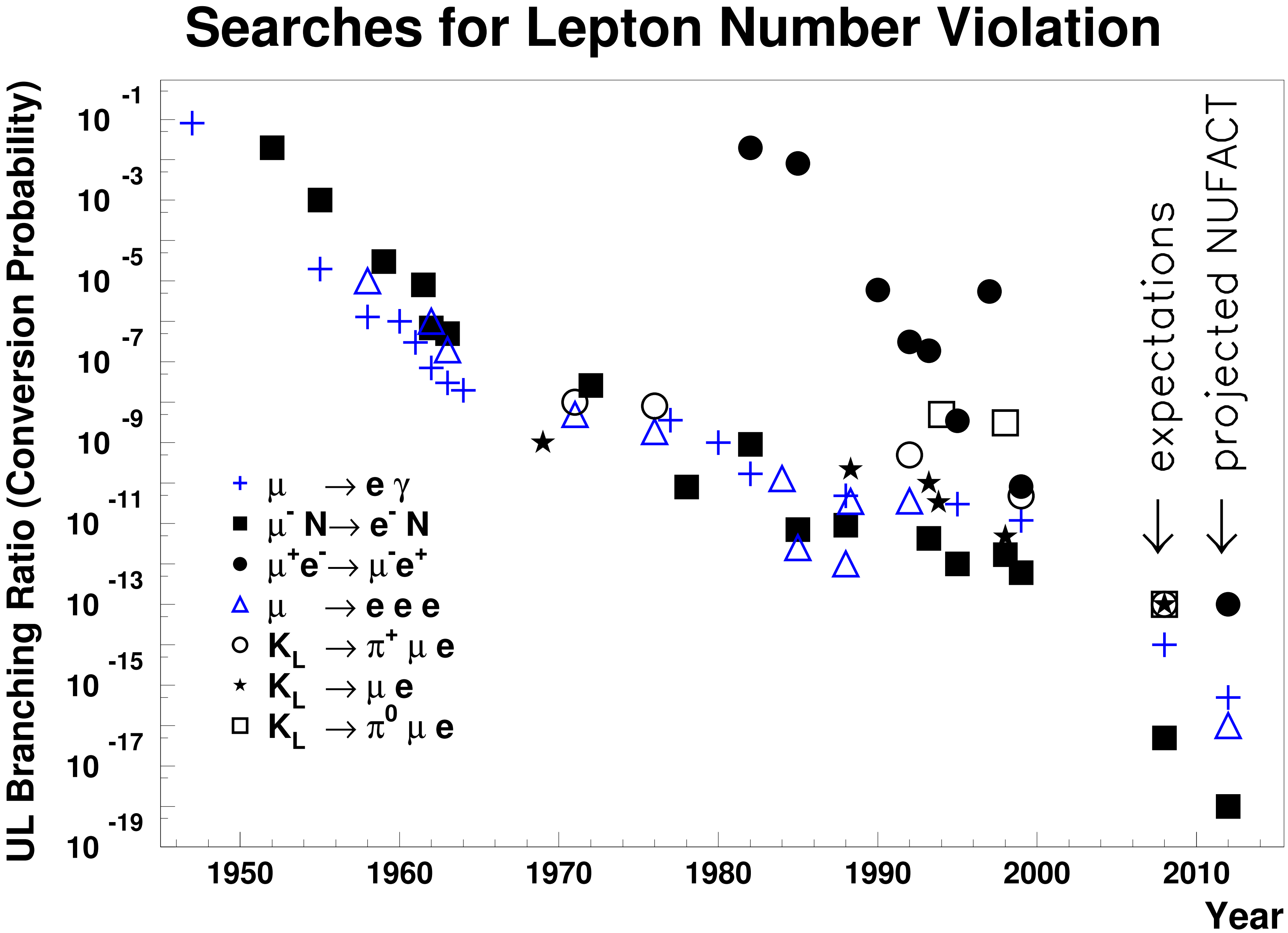
NOTE: Due to time constraints, I'll concentrate on muon processes and will only comment on tau processes in passing. [talk by Stefano Passaggio]

Ever since it was established that $\mu \to e\nu\bar{\nu}$, people have searched for $\mu \to e\gamma$, which was thought to arise at one-loop, like this:



The fact that $\mu \to e\gamma$ did not happen, led one to postulate that the two neutrino states produced in muon decay were distinct, and that $\mu \to e\gamma$, and other similar processes, were forbidden due to symmetries.

To this date, these so-called individual lepton-flavor numbers seem to be conserved in the case of charged lepton processes, in spite of many decades of (so far) fruitless searching…



[hep-ph/0109217]

SM Expectations

In the old SM, the rate for charged lepton flavor violating processes is trivial to predict. It vanishes because individual lepton number is conserved:

- $N_\alpha(\text{in}) = N_\alpha(\text{out})$, for $\alpha = e, \mu, \tau$.

However, the old SM is wrong: NEUTRINOS change flavor after propagating a finite distance.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric experiments ["indisputable"];
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments ["indisputable"];
- $\bar{\nu}_e \to \bar{\nu}_{\text{other}}$ — reactor neutrinos ["indisputable"];
- $\nu_\mu \to \nu_{\text{other}}$ from accelerator experiments ["really strong"].

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and leptons mix. (talk by David Wark)

Hence, in the "New Standard Model" (νSM, equal to the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed, like other Flavor Changing Neutral Current processes which have already been observed in the quark sector (like $b \to s\gamma$).

Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes → **we don't know the νSM Lagrangian !**

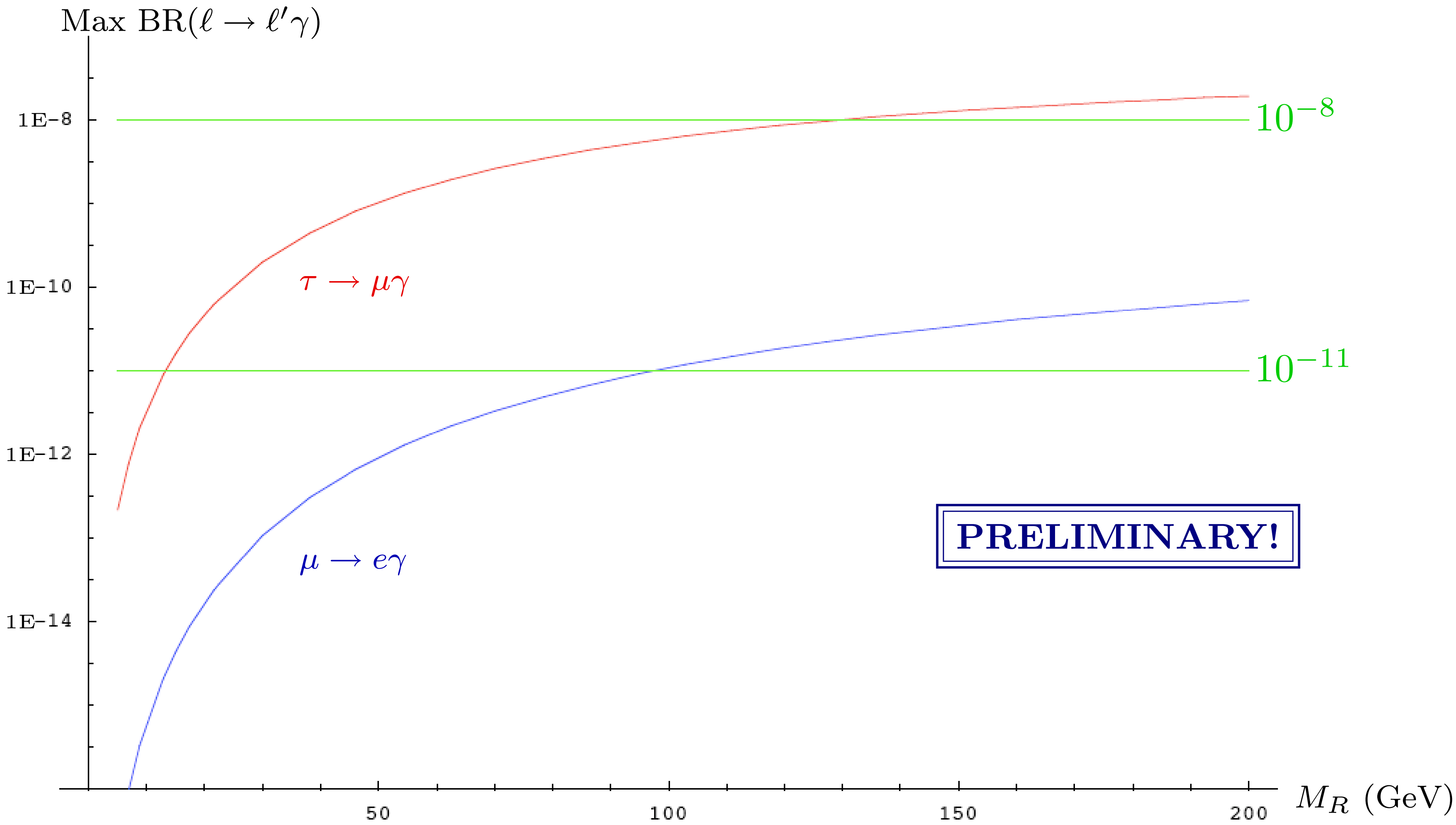
However, one contribution is known to be there: neutrino–W-boson loops (exact analog to the quark sector). In the case of charged leptons, the **GIM suppression is very efficient**...

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54},$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix, $\Delta m^2_{1i} \equiv m^2_i - m^2_1$, $i = 2,3$ are the neutrino mass-squared differences]

Example: Seesaw Lagrangian, minus theoretical prejudices:

[AdG to appear]



Furthermore, there are strong theoretical reasons to believe that the expected rate for flavor changing violating processes is much, much larger than naive νSM predictions and that discovery is just around the corner.

Due to the lack of SM "backgrounds," searches for rare muon processes, including $\mu \to e\gamma$, $\mu \to e^+e^-e$ and $\mu + Z \to e + Z$ (μ-e–conversion in nuclei) are considered ideal laboratories to probe effects of new physics at or even slightly above the electroweak scale.

Indeed, if there is new physics at the electroweak scale (as many theorists will have you believe) and if mixing in the lepton sector is large "everywhere" the question we need to address is quite different:

Why haven't we seen charged lepton flavor violation yet?

Phenomenology of selected CLFV processes

As far as charged lepton flavor violating processes are concern, new physics effects can be parameterized via a handful of higher dimensional operators. For example, say that the following effective Lagrangian dominates CLFV phenomena:

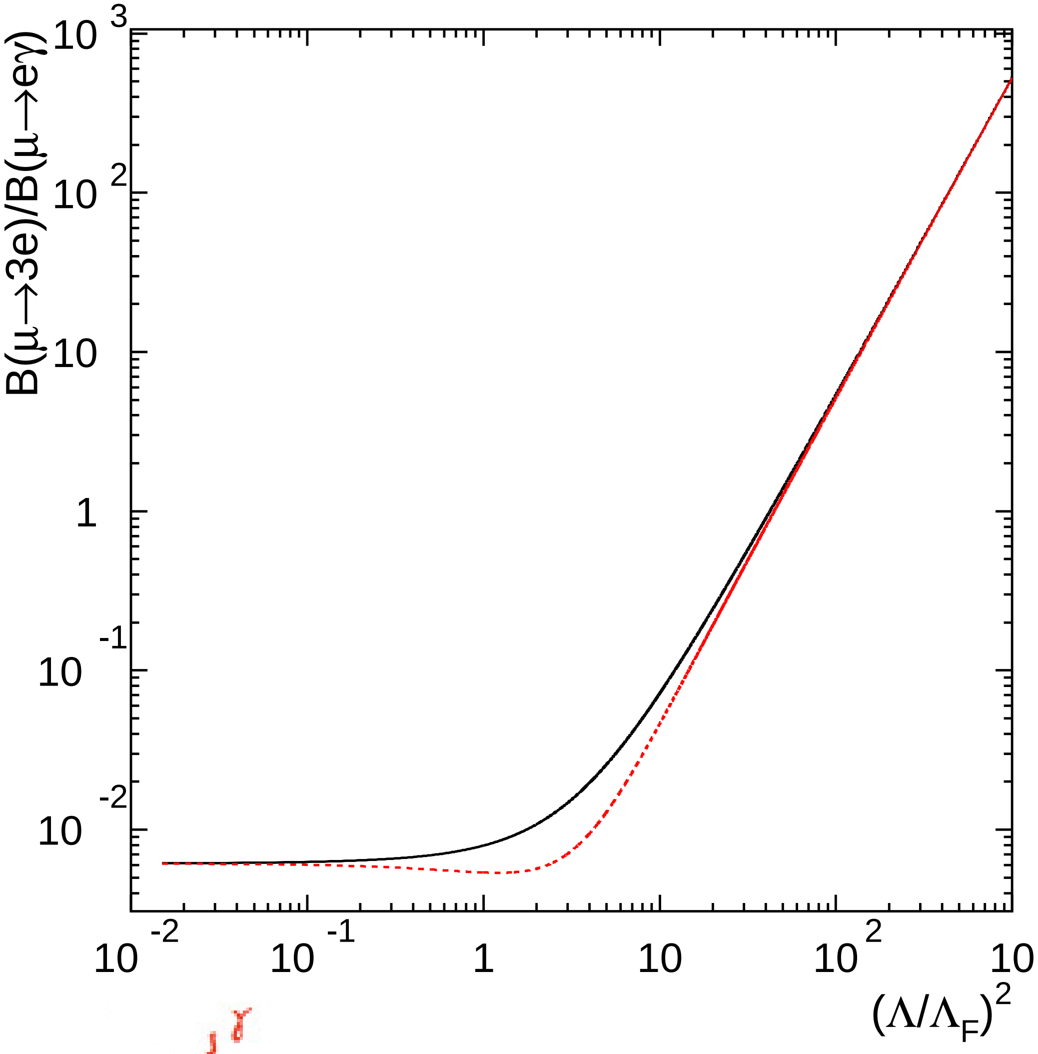
$$\mathcal{L} = \frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{1}{\Lambda_F^2}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{e}_L\gamma_\mu e_L\right) + \frac{1}{\Lambda_F^2}\left(\bar{\mu}_L\gamma^\mu e_L\right)\left(\bar{q}_L\gamma_\mu q_L\right) + \text{h.c.}$$

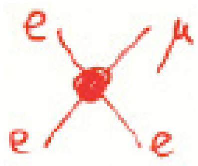
First term: mediates $\mu \to e\gamma$ and, at order α, $\mu \to eee$ and $\mu + Z \to e + Z$

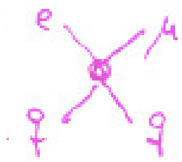
Second term: mediates $\mu \to eee$ and, at one-loop, $\mu \to e\gamma$

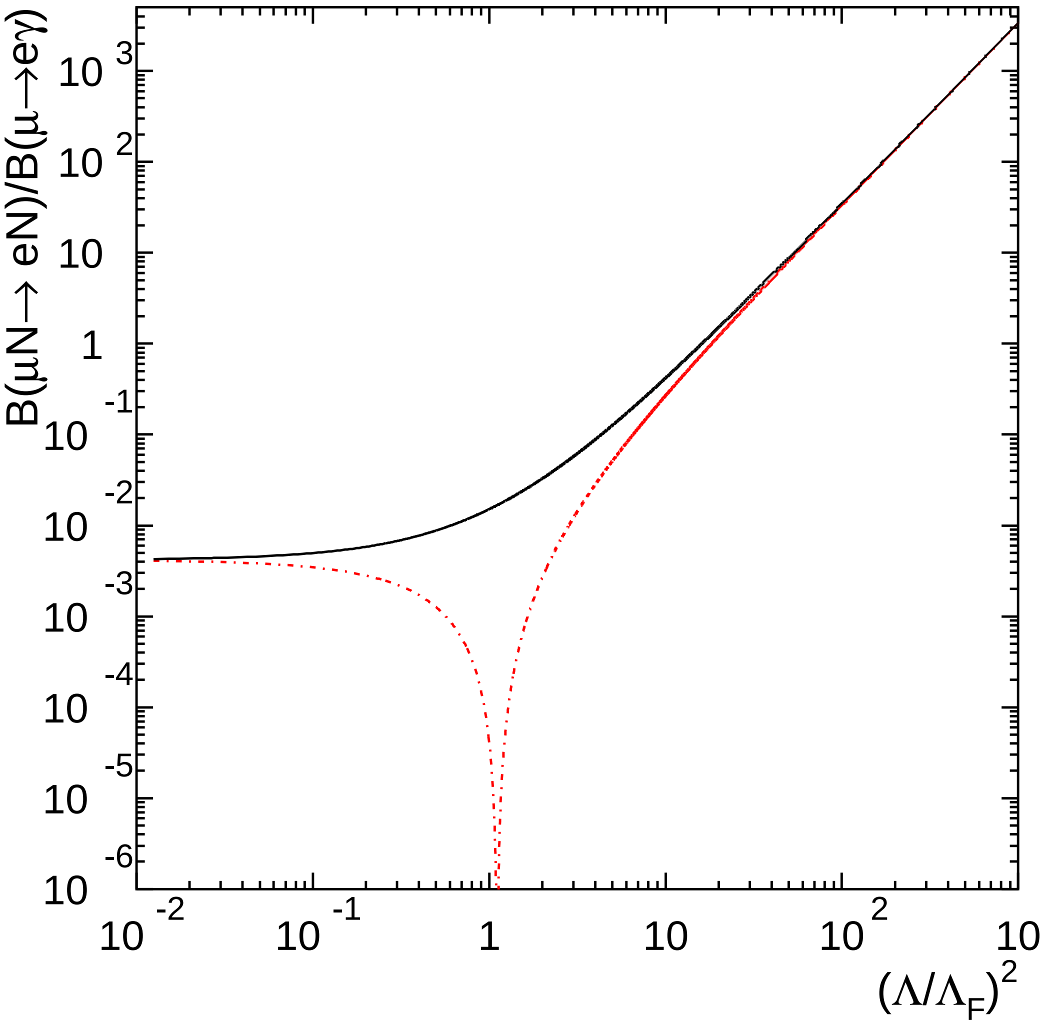
Third term: mediates $\mu + Z \to e + Z$ and, at one-loop, $\mu \to e\gamma$

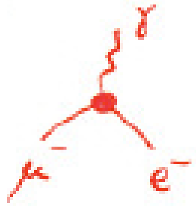
Which term wins? $\to$ Model Dependent

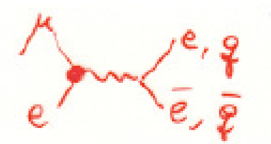




$\longrightarrow \quad \Lambda \gg \Lambda_F \quad \longleftarrow$








$\longrightarrow \quad \Lambda \ll \Lambda_F$

On Model Dependency

Specific Models will provide estimates for the rates for CLFV processes.

On the flip side, the observation of one specific CLFV process will not determine the underlying physics mechanism.

Real strength lies in combinations of different measurements, including:

- other CLFV channels (including those involving taus);
- neutrino oscillations;
- measurements of $g-2$ and EDMs;
- collider searches for new, heavy states;
- etc.

Brief Comment on $g-2$ and $\mu\to e\gamma$:

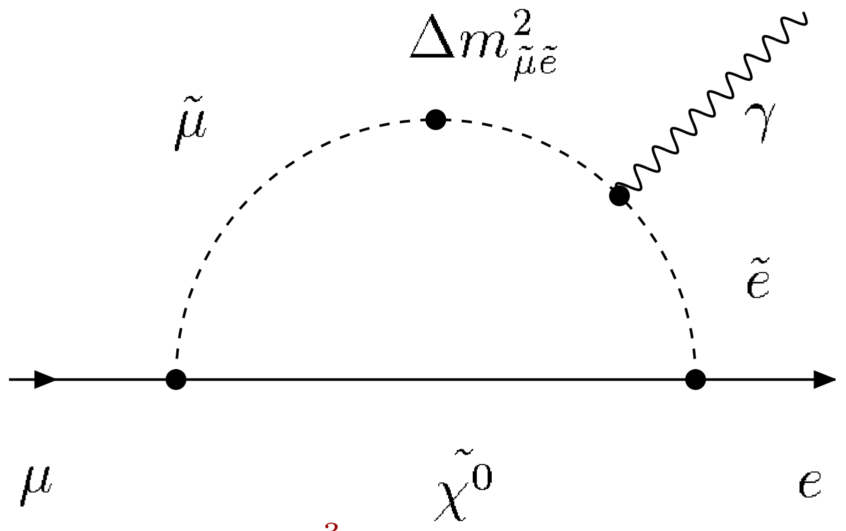
The effective operators that mediate $\mu\to e\gamma$ and contribute to a_μ are virtually identical:

$$\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad \times \qquad \theta_{e\mu}\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}$$

If $\theta_{e\mu}\sim 1$, $\mu\to e\gamma$ is a much more stringent probe of Λ.

On the other hand, if the current discrepancy in a_μ is due to new physics, $\theta_{e\mu}\ll 1$. This is hard to satisfy in, say, high energy SUSY breaking models… [Hisano, Tobe, hep-ph/0102315]

"Bread and Butter" SUSY plus High Energy Seesaw



$\rightarrow \; \theta_{\tilde{e}\tilde{\mu}} \sim \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}}$

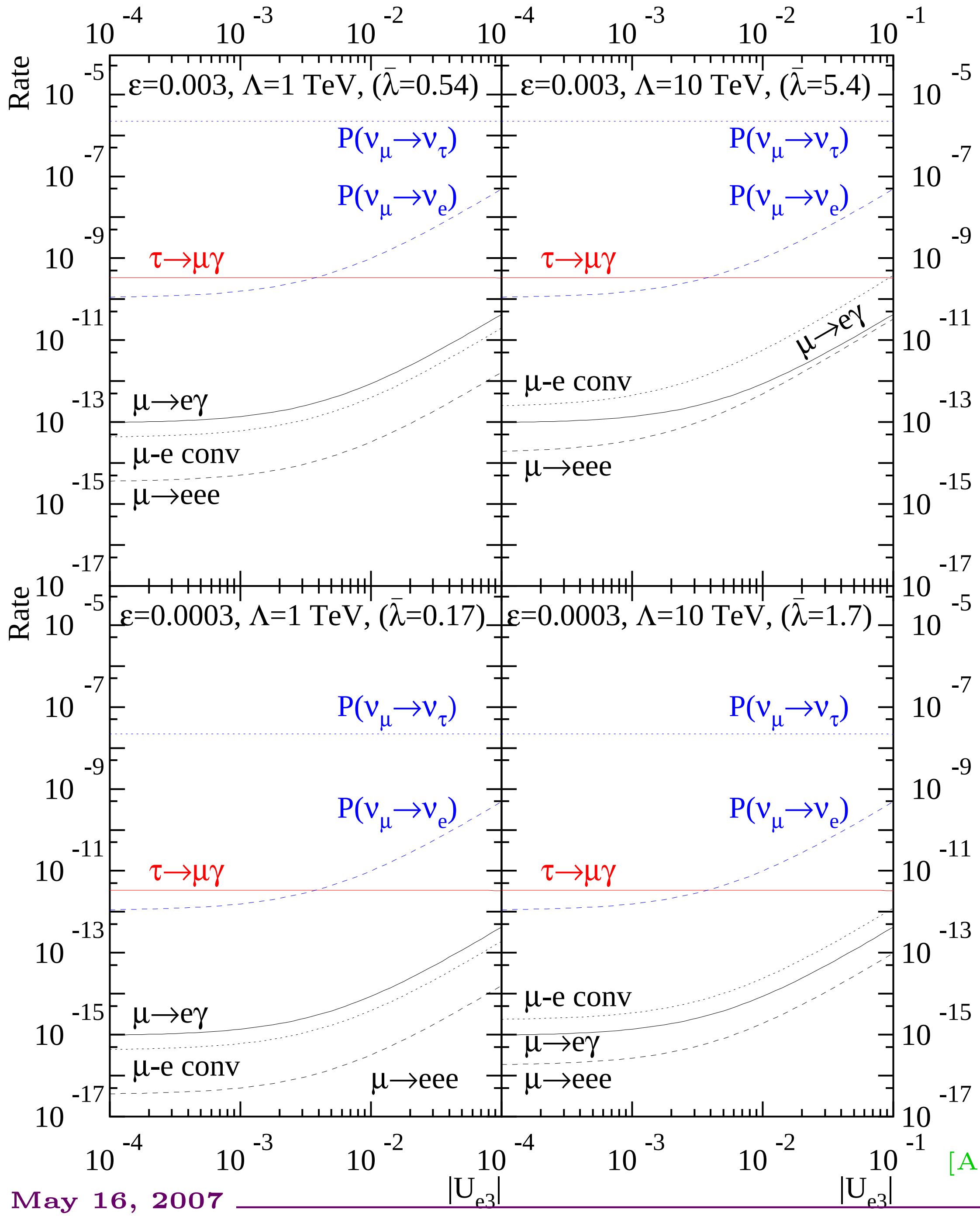
$Br(\mu \rightarrow e\gamma) \simeq \frac{\alpha^3 \pi}{G_F^2 \tilde{m}^4} \theta^2_{\tilde{e}\tilde{\mu}}$, $\quad \tilde{m}^2$ is a typical supersymmetric mass.

$\theta_{\tilde{e}\tilde{\mu}}$ measures the "amount" of flavor violation.

For $\tilde{m}$ around 1 TeV, $\theta_{\tilde{e}\tilde{\mu}}$ is severely constrained. Very big problem.

"Natural" solution: $\boxed{\theta_{\tilde{e}\tilde{\mu}} = 0}$ $\rightarrow$ modified by quantum corrections.

[SUSY plus high energy seesaw example: poster by Ana Teixeira]



Large Extra-Dimensions

-no ambiguity in y (neutrinos Dirac)

-dependency on UV-completion

[AdG, Giudice, Strumia, Tobe, hep-ph/0107156]

SUSY with R-parity Violation

The MSSM Lagrangian contains several marginal operators which are allowed by all gauge interactions but violate baryon and lepton number.

A subset of these (set λ'' to zero to prevent proton decay, and ignore bi-linear terms, which do not contribute as much to CLFV) is:

$$\begin{aligned}\mathcal{L} &= \lambda_{ijk}\left(\bar{\nu}^c_{Li}e_{Lj}\tilde{e}^*_{Rk} + \bar{e}_{Rk}\nu_{Li}\tilde{e}_{Lj} + \bar{e}_{Rk}e_{Lj}\tilde{\nu}_{Li}\right) \\ &+ \lambda'_{ijk}V^{j\alpha}_{KM}\left(\bar{\nu}^c_{Li}d_{L\alpha}\tilde{d}^*_{Rk} + \bar{d}_{Rk}\nu_{Li}\tilde{d}_{L\alpha} + \bar{d}_{Rk}d_{L\alpha}\tilde{\nu}_{Li}\right) \\ &- \lambda'_{ijk}\left(\bar{u}^c_{j}e_{Li}\tilde{d}^*_{Rk} + \bar{d}_{Rk}e_{Li}\tilde{u}_{Lj} + \bar{d}_{Rk}u_{Lj}\tilde{e}_{Li}\right) + \text{h.c.},\end{aligned}$$

The presence of different combinations of these terms leads to very distinct patterns for CLFV. Proves to be an excellent laboratory for probing all different possibilities. [AdG, Lola, Tobe, hep-ph/0008085]

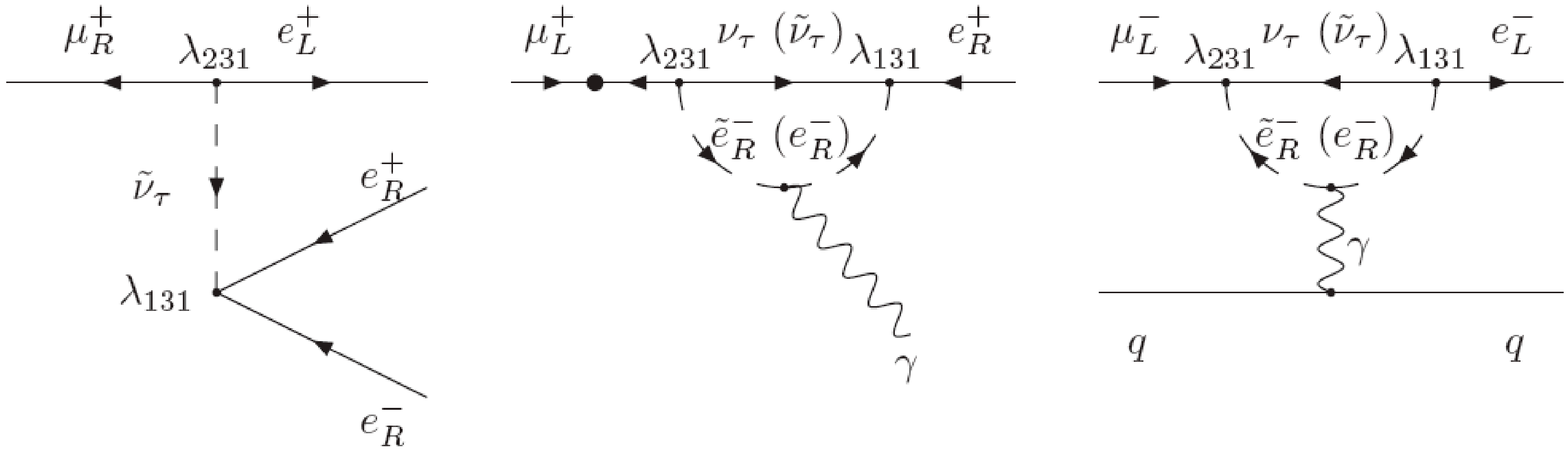


Figure 1: *Lowest order Feynman diagrams for lepton flavour violating processes induced by* $\lambda_{131}\lambda_{231}$ *couplings (see Eq. (2.1)).*

$$\frac{\mathrm{Br}(\mu^+\to e^+\gamma)}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = \frac{4\times 10^{-4}\left(1-\frac{m^2_{\tilde{\nu}_\tau}}{2m^2_{\tilde{e}_R}}\right)^2}{\beta} \simeq 1\times 10^{-4} \qquad (\beta\sim 1)$$

$$\frac{\mathrm{R}(\mu^-\to e^- \text{ in Ti (Al)})}{\mathrm{Br}(\mu^+\to e^+e^-e^+)} = \frac{2\ (1)\times 10^{-5}}{\beta}\left(\frac{5}{6}+\frac{m^2_{\tilde{\nu}_\tau}}{12m^2_{\tilde{e}_R}}+\log\frac{m^2_e}{m^2_{\tilde{\nu}_\tau}}+\delta\right)^2 \simeq 2\ (1)\times 10^{-3},$$

$\mu^+ \to e^+e^-e^+$ most promising channel!

[AdG, Lola, Tobe, hep-ph/0008085]

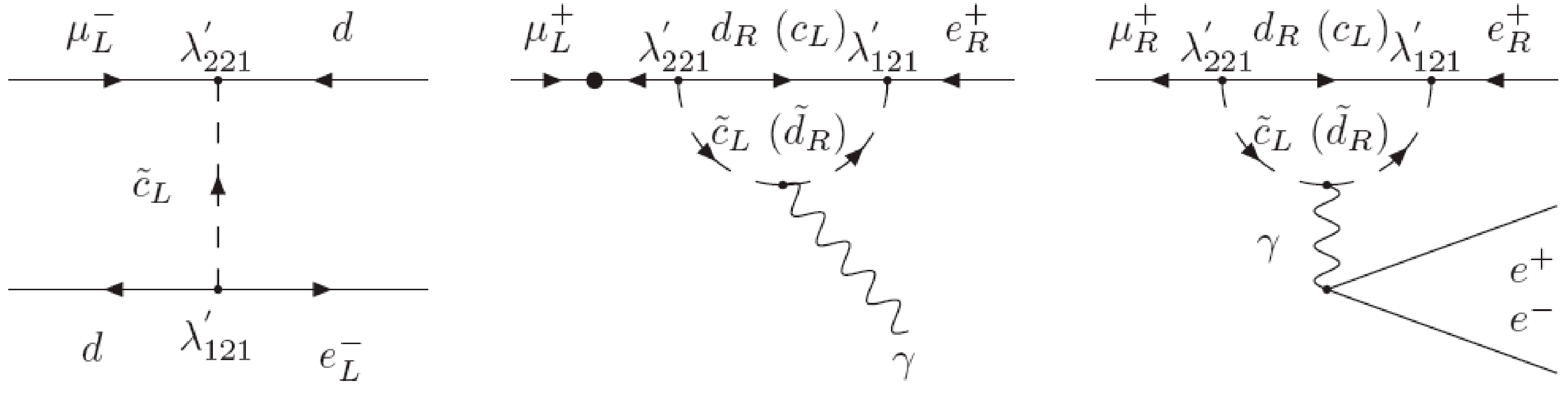


Figure 4: *Lowest order Feynman diagrams of lepton flavour violating processes induced by $f'_{121}f'_{221}$ couplings (see Eq. (2.1)).*

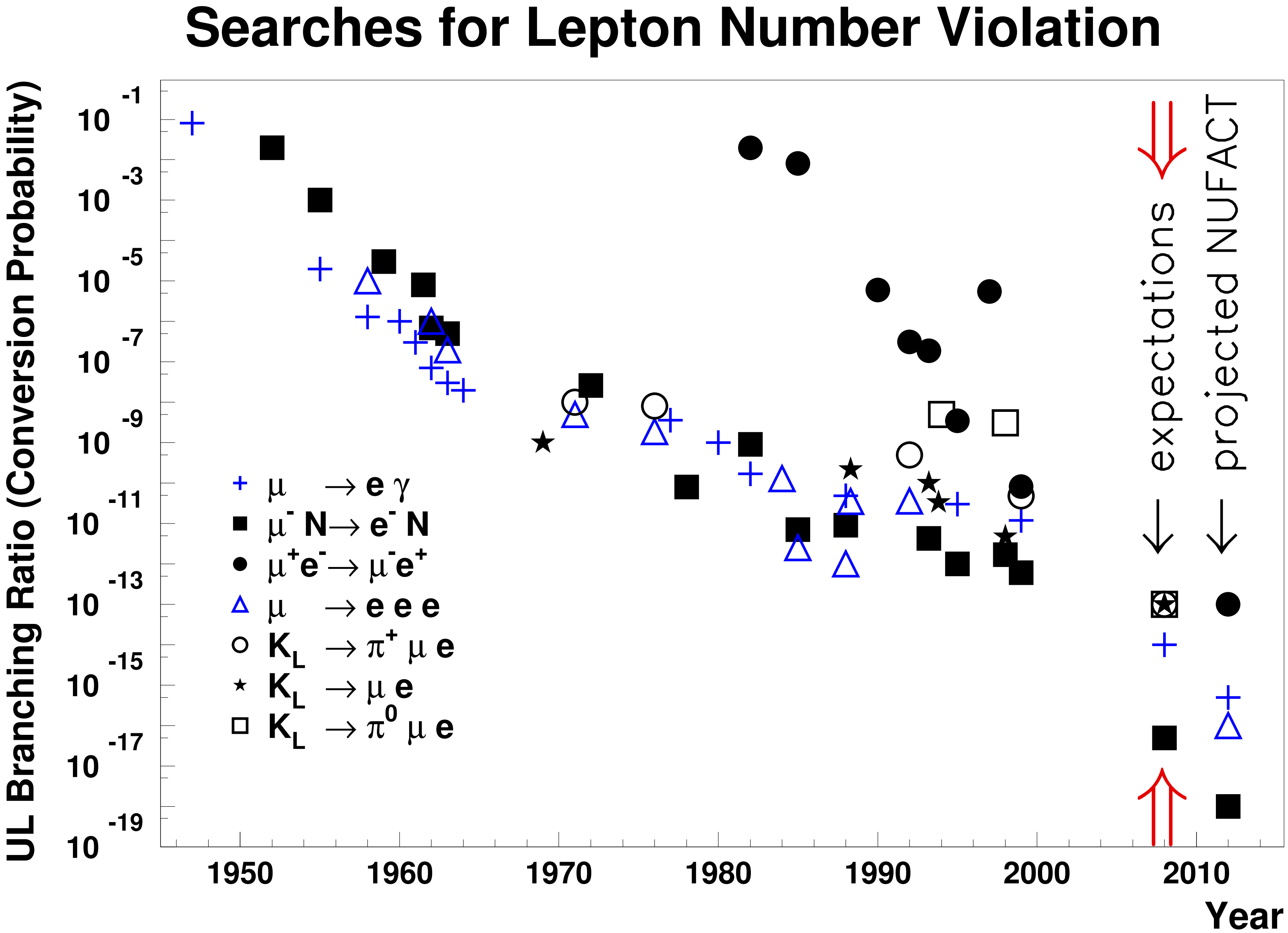
$$\frac{\text{Br}(\mu^+\to e^+\gamma)}{\text{Br}(\mu^+\to e^+e^-e^+)} = 1.1$$

$$(m_{\tilde{d}_R} = m_{\tilde{c}_L} = 300\ \text{GeV})$$

$$\boxed{\frac{\text{R}(\mu^-\to e^-\ \text{in Ti (Al)})}{\text{Br}(\mu^+\to e^+e^-e^+)} = 2\ (1) \times 10^5}$$

$\mu - e$-conversion "only hope"!

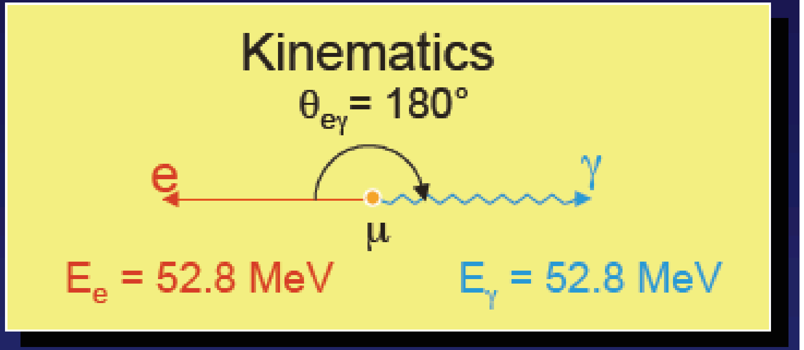
[AdG, Lola, Tobe, hep-ph/0008085]



[hep-ph/0109217]

Principal Features of $\mu^+ \rightarrow e^+\gamma$ Experiment

- Stop μ^+ in thin target
  - Measure energies of e^+ (E_e) and γ (E_γ)
  - Measure angle between e^+ and γ ($\Delta\theta$)
  - Measure time between e^+ and γ (Δt)



- Background from radiative decay – $\mu \rightarrow e\nu\nu\gamma$
  - Heavily suppressed for $E_\nu \rightarrow 0$, photon opposite electron
  - Not dominant background when rate high enough to reach 10^{-13} sensitivity

- Main source of background:
  - Accidental coincidences of e^+ from Michel decay ($\mu^+ \rightarrow e^+ \nu_e \nu_\mu$) + random γ from radiative decay or annihilation in flight
  - E_e distribution peaks near 53 MeV ($x = E_e / E_{max}$)
  - E_γ distribution in interval dy near y=1 given by $dN_\gamma \propto (1-y)dy$ ($y = E_\gamma / E_{max}$)

$\Rightarrow$ background/signal $\propto \Delta E_e \times (\Delta E_\gamma)^2 \times \Delta t \times (\Delta\theta)^2 \times$ Rate

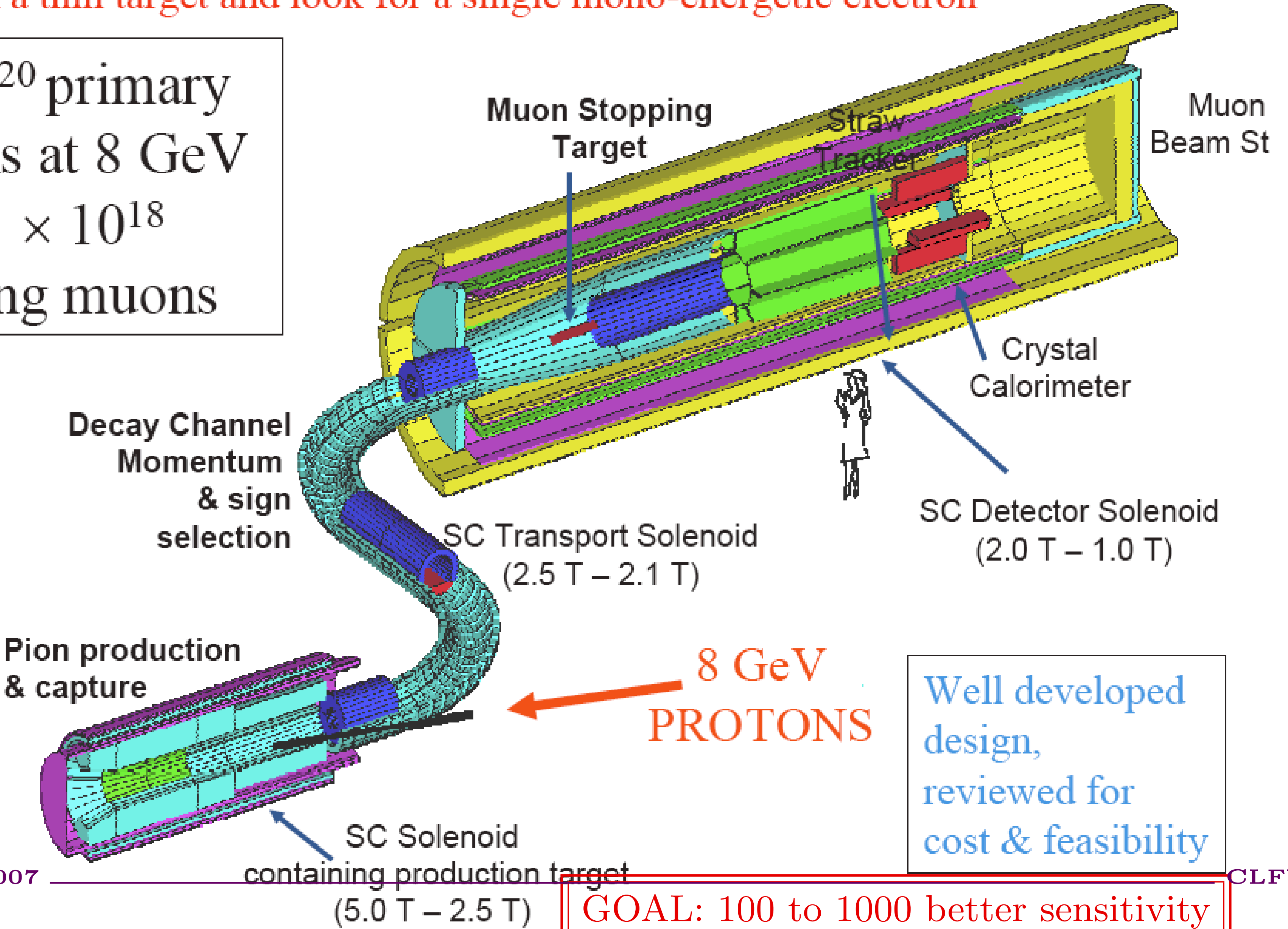
GOAL: 100 to 1000 better sensitivity

W. Molzon, UC Irvine — NuFact 2006 - Status of the MEG Experiment — August 28, 2006 — 3

MECO CONCEPT (Molzon et al.) ⇒ mu2e at FNAL?

Stop muons in a thin target and look for a single mono-energetic electron

4×10^{20} primary protons at 8 GeV yield 1×10^{18} stopping muons

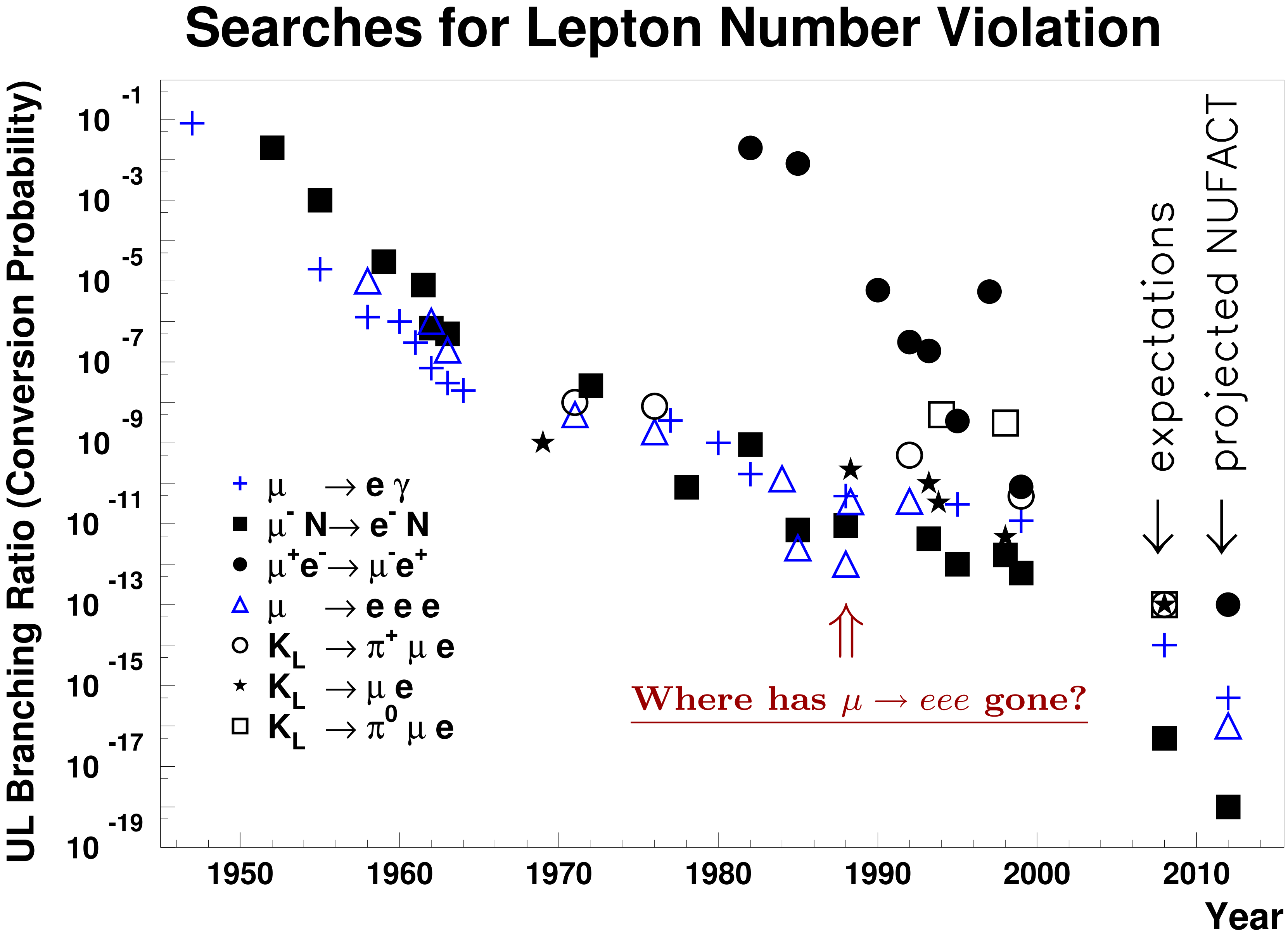


Well developed design, reviewed for cost & feasibility

GOAL: 100 to 1000 better sensitivity

Summary and Conclusions

- We know that charged lepton flavor violation must occur. Naive expectations are really tiny in the νSM (neutrino masses too small).
- If there is new physics at the electroweak scale, we "must" see CLFV very soon (MEG the best bet – stay tuned?). **'Why haven't we seen it yet?'**
- It is fundamental to probe **all** CLFV channels. While in many scenarios $\mu \to e\gamma$ is the "largest" channel, there is no theorem that guarantees this (and many exceptions). $\Rightarrow$
- CLFV may be intimately related to new physics unveiled with the discovery of non-zero neutrino masses. It may play a fundamental role in our understanding of the seesaw mechanism, GUTs, the baryon-antibaryon asymmetry of the Universe. We won't know for sure until we see it!



[hep-ph/0109217]