Phenomenological Perspective on (Charged-)LFV Processes

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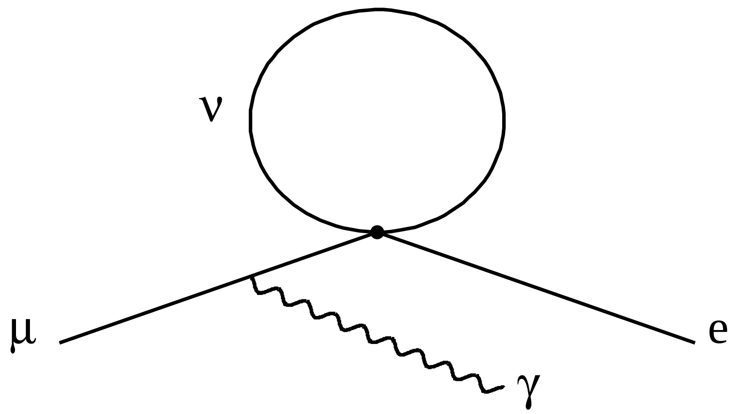
[session: interplay between neutrino masses and other phenomenological signatures]

Outline

1. Brief Introduction;
2. Old and ν Standard Model Expectations;
3. A Model Independent Approach;
4. Interplay with ν Masses, Leptogenesis and the LHC via Examples;
5. Conclusions.

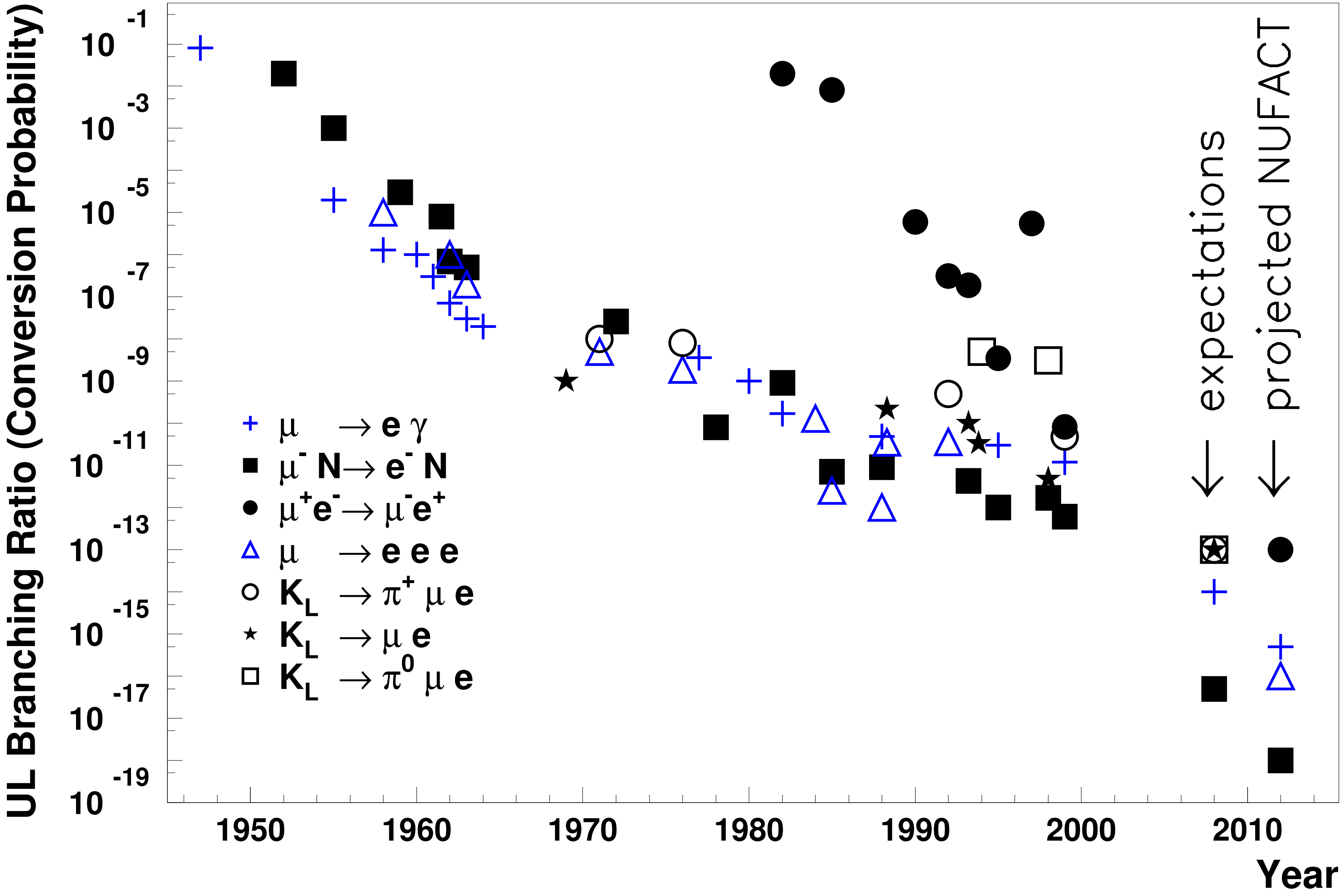
Ever since it was established that $\mu \to e\nu\bar{\nu}$, people have searched for $\mu \to e\gamma$, which naively could arise at one-loop:



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…

Searches for Lepton Number Violation (μ and e)



[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 flavor 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 ["indisputable"].

Lepton Flavor Number NOT a good quantum number.

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 (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

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

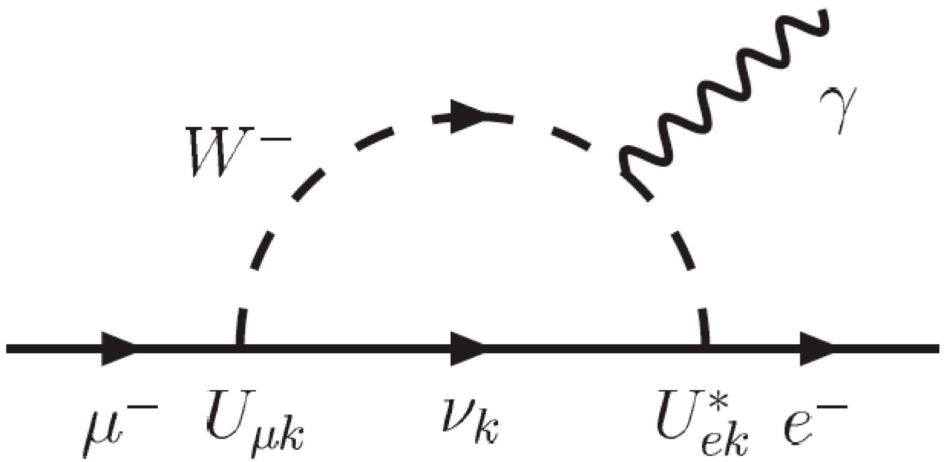
One contribution known to be there: active neutrino loops (same as quark sector).

In the case of charged leptons, the **GIM suppression is very efficient**...

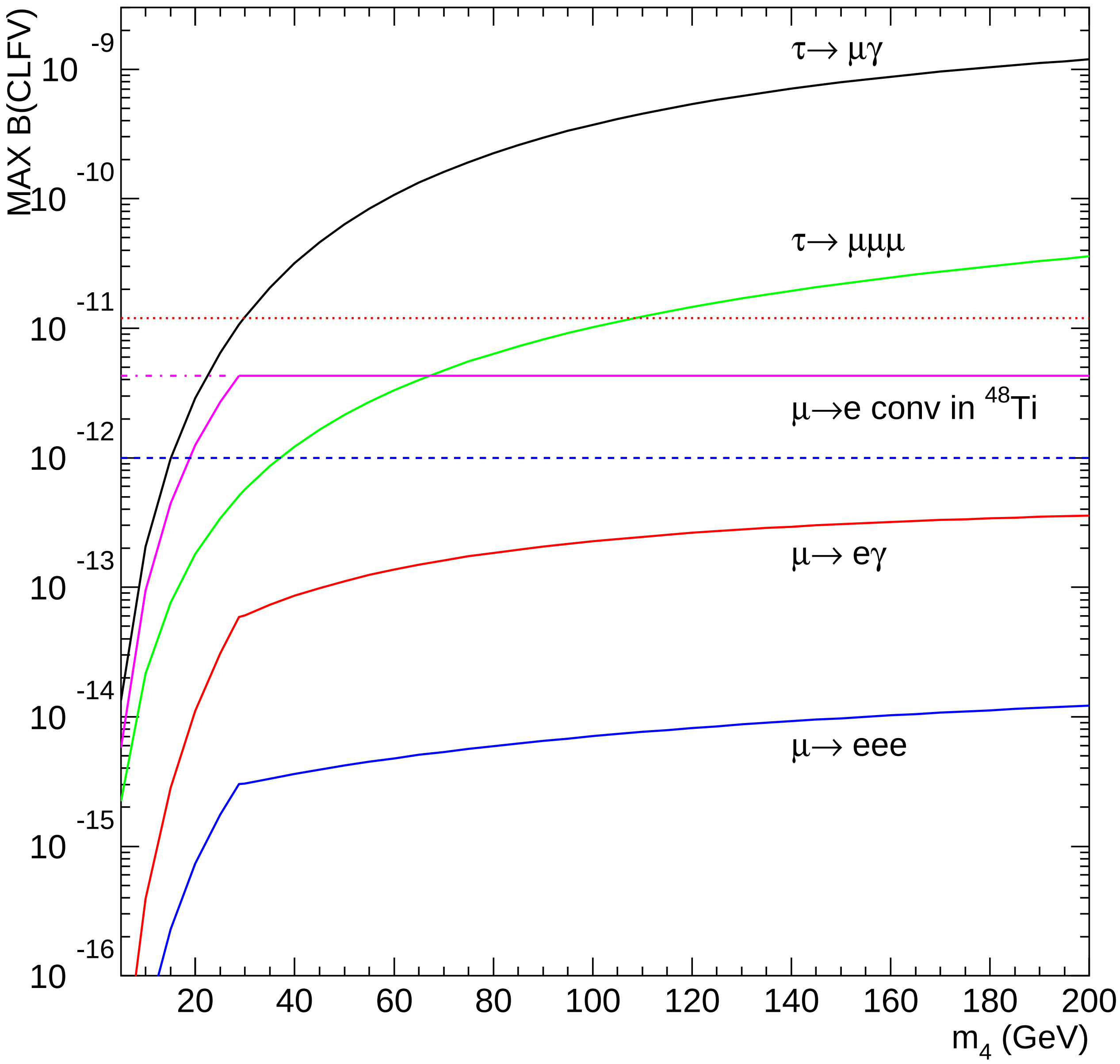
e.g.: $Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W} \right|^2 < 10^{-54}$

[$U_{\alpha i}$ 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]



e.g.: SeeSaw Mechanism [minus "Theoretical Prejudice"]



arXiv:0706.1732 [hep-ph]

Independent from neutrino masses, 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 $\mu + N \to e + N$ (μ-e–conversion in nuclei) are considered ideal laboratories to probe effects of new physics at or even 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?

Model Independent Approach

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:

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

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

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

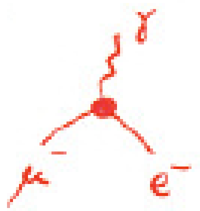
Λ is the "scale of new physics". κ interpolates between transition dipole moment and four-fermion operators.

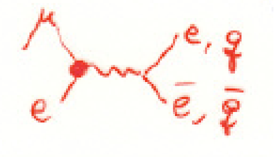
Which term wins? $\to$ Model Dependent

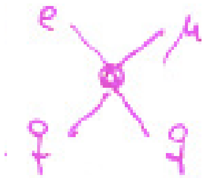
- $\mu \to e$-conv at 10^{-17} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.

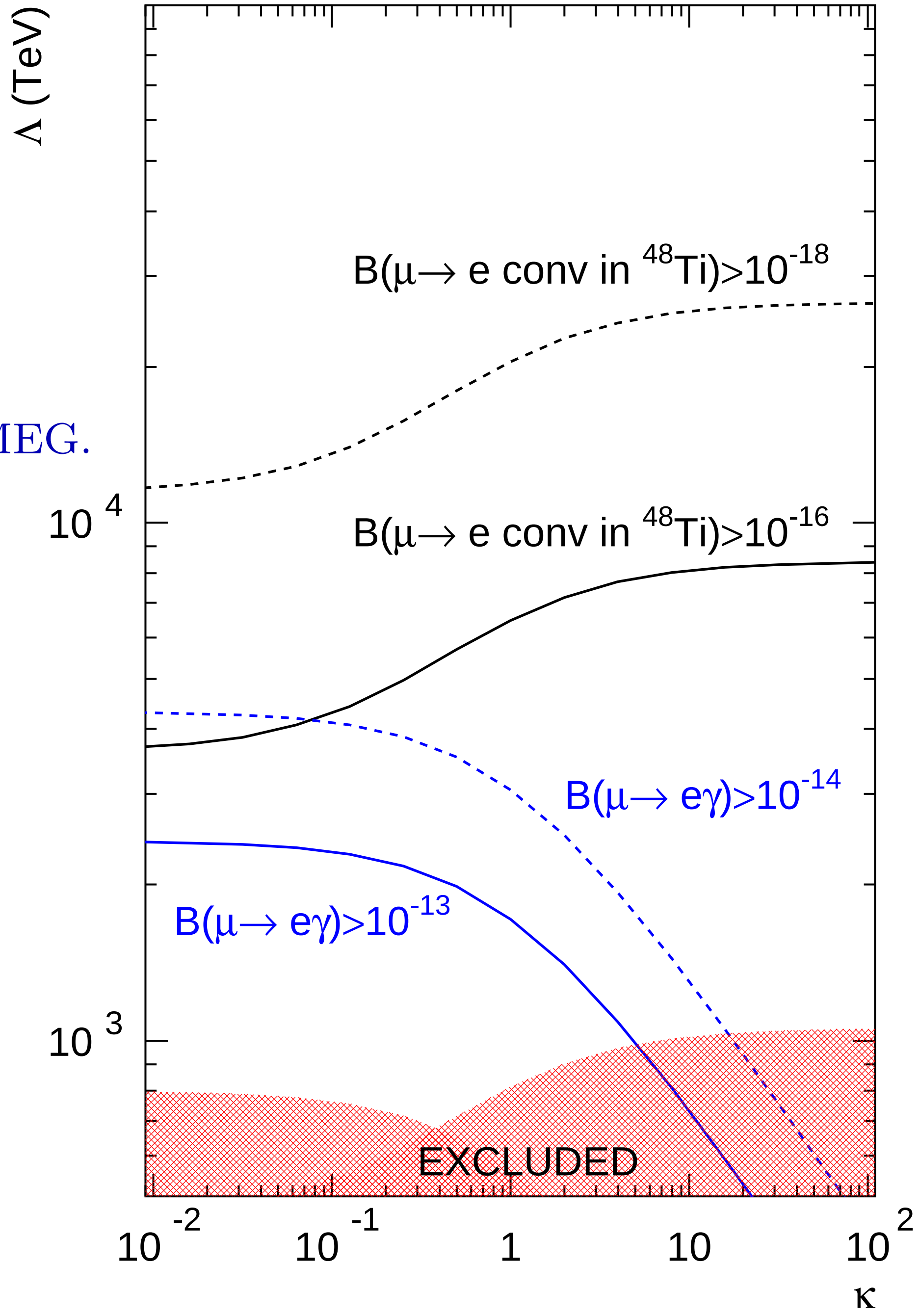
- We don't think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$–conv "only" way forward after MEG.

- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 10,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.





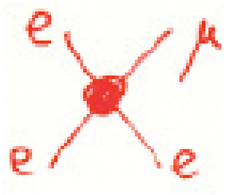


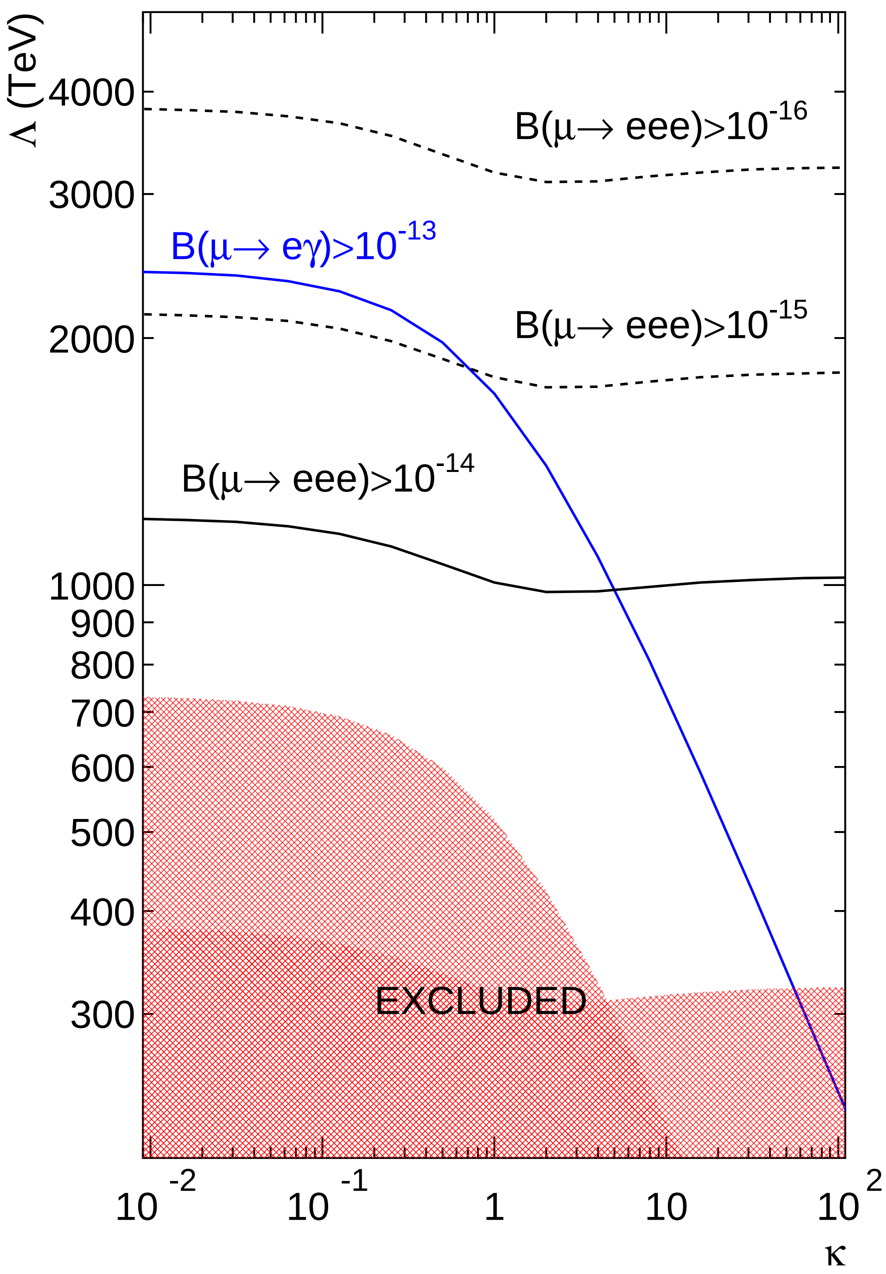


Other Example: $\mu \to e e^+ e^-$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + $$
$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

- $\mu \to eee$-conv at 10^{-16} "guaranteed" deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- $\mu \to eee$ another way forward after MEG?
- If the LHC does not discover new states $\mu \to eee$ among very few process that can access 1,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.



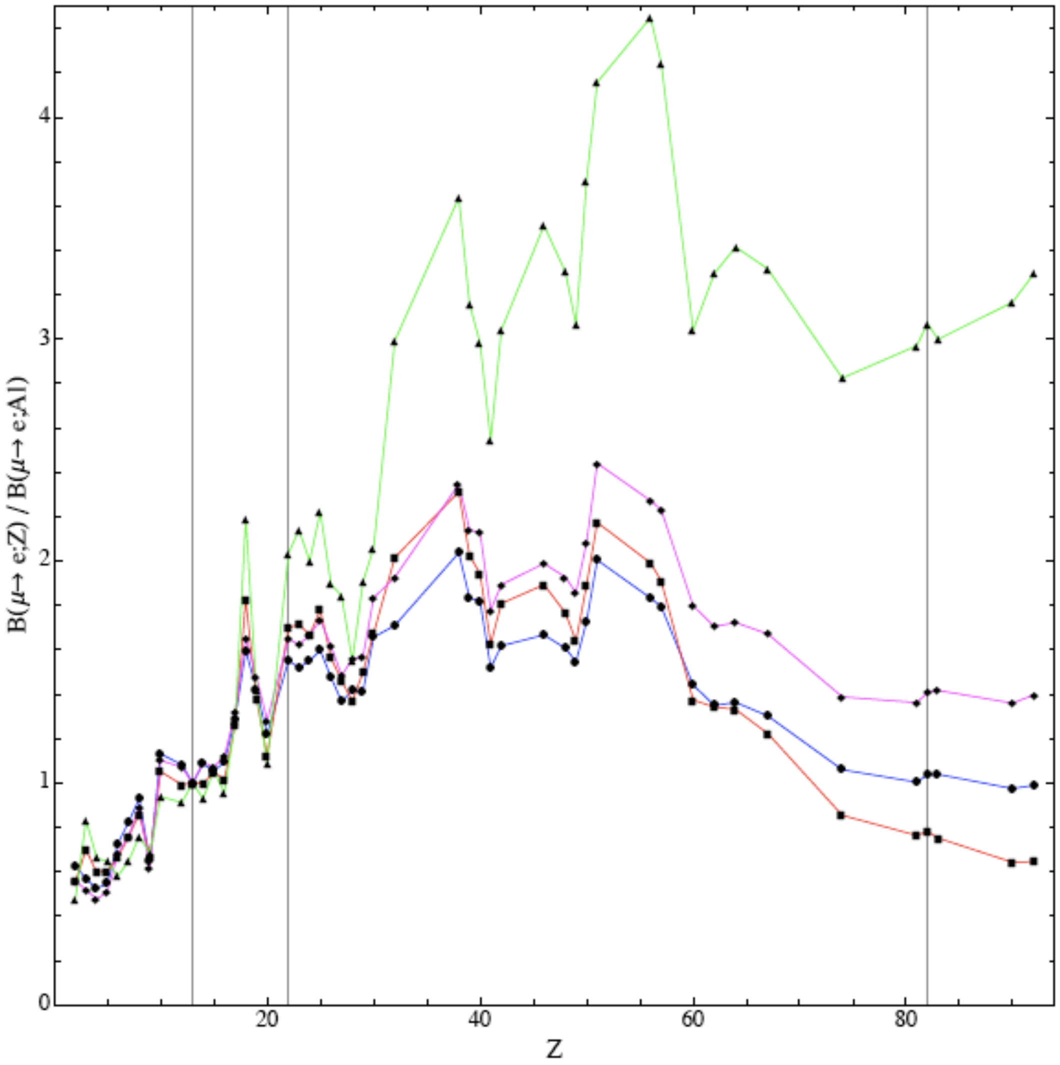


What is This Good For?

While specific models (discussed in several earlier talks) provide estimates for the rates for CLFV processes, the observation of one specific CLFV process cannot determine the underlying physics mechanism (this is always true when all you measure is the coefficient of an effective operator).

Real strength lies in combinations of different measurements, including:

- kinematical observables (e.g. angular distributions in $\mu \to eee$);
- other CLFV channels;
- neutrino oscillations;
- measurements of $g-2$ and EDMs;
- collider searches for new, heavy states;
- etc.



Vector 4-Fermion Interaction (Z)

$\propto (\bar{\mu}\gamma_\alpha e)(\bar{q}\gamma^\alpha q)$

Vector 4-Fermion Interaction (γ)

Dipole $(\propto \bar{\mu}\sigma_{\alpha\beta} e F^{\alpha\beta})$

Scalar 4-Fermion Interaction

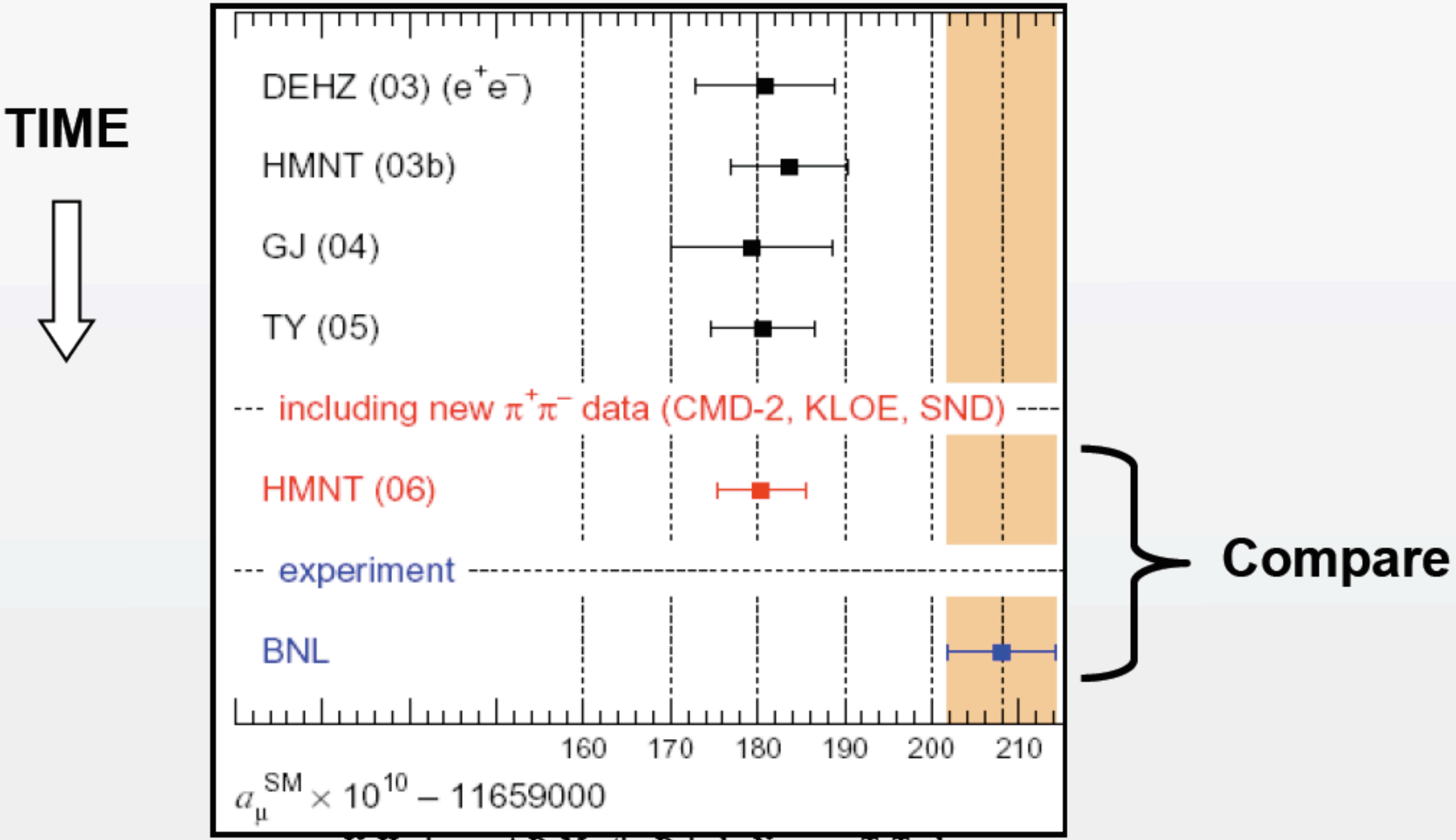
$\propto (\bar{\mu}e)(\bar{q}q)$

Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

[Cirigliano, Kitano, Okada, Tuzon, 0904.0957]

Example: Anomalous Magnetic Moment of the Muon, $(g-2)/2 \equiv a_\mu$

Δa_μ(expt-thy) = $(295 \pm 88) \times 10^{-11}$ (3.4 σ)



K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner Rep.Prog.Phys. 70, 795 (2007).

Model Independent Comparison Between $g-2$ and CLFV:

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

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

$\theta_{e\mu}$ measures how much flavor is violated. $\theta_{e\mu}=1$ in a flavor indifferent theory, $\theta_{e\mu}=0$ in a theory where individual lepton flavor number is exactly conserved.

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, $\theta_{e\mu}\ll 1$ ($\theta_{e\mu}<10^{-4}$). This is hard to satisfy in, say, high energy SUSY breaking models… [Hisano, Tobe, hep-ph/0102315]

Comparison restricted to dipole operator. If four-fermion operators are relevant, they will "only" enhance rate for CLFV with respect to expectations from $g-2$.

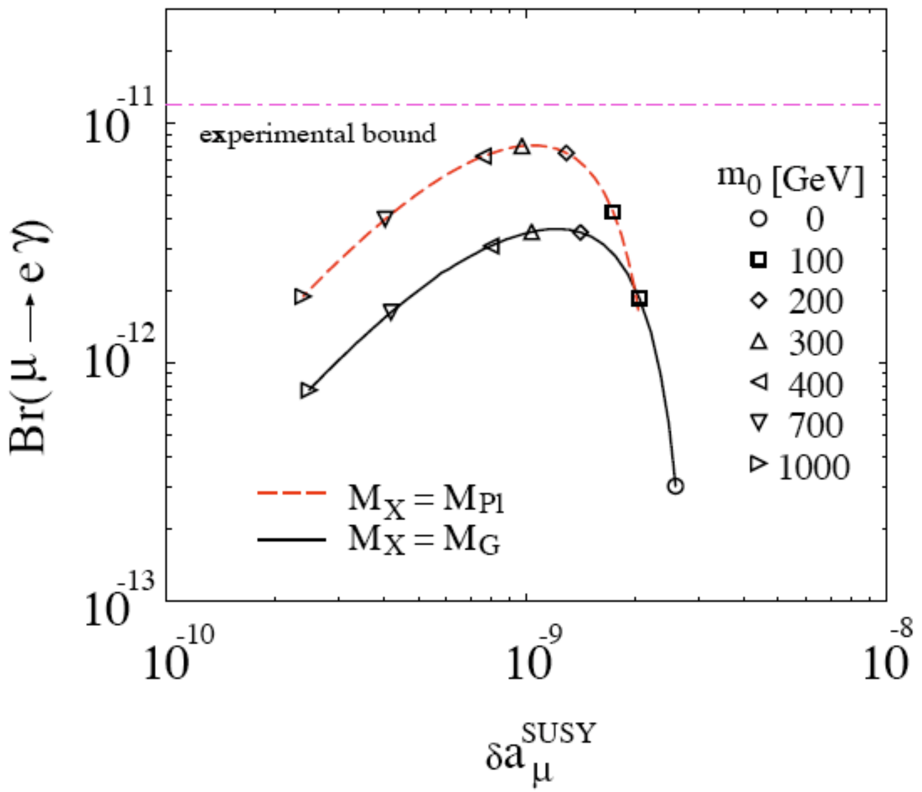


Figure 1: $\mathrm{Br}(\mu \to e\gamma)$ and $\delta a_\mu^{\mathrm{SUSY}}$ as a function of universal mass m_0. Here we take $V_{13} = 0.01$, $V_{23} = 1/\sqrt{2}$, $\tan\beta = 10$ and $M_2 = 250$ GeV. We assume unification between the top-quark and tau-neutrino Yukawa couplings ($m_t = 175$ GeV and $m_{\nu_\tau} = 0.055$ eV). The solid and dashed lines are for cases where the scale for the generation of the SUSY-breaking terms in the SUSY SM (M_X) are the GUT scale and the reduced Planck scale, respectively.

[Hisano, Tobe, hep-ph/0102315]

Example: Input From/To Leptogenesis (⇒ talk by Asmaa Abada, plus Discussion)

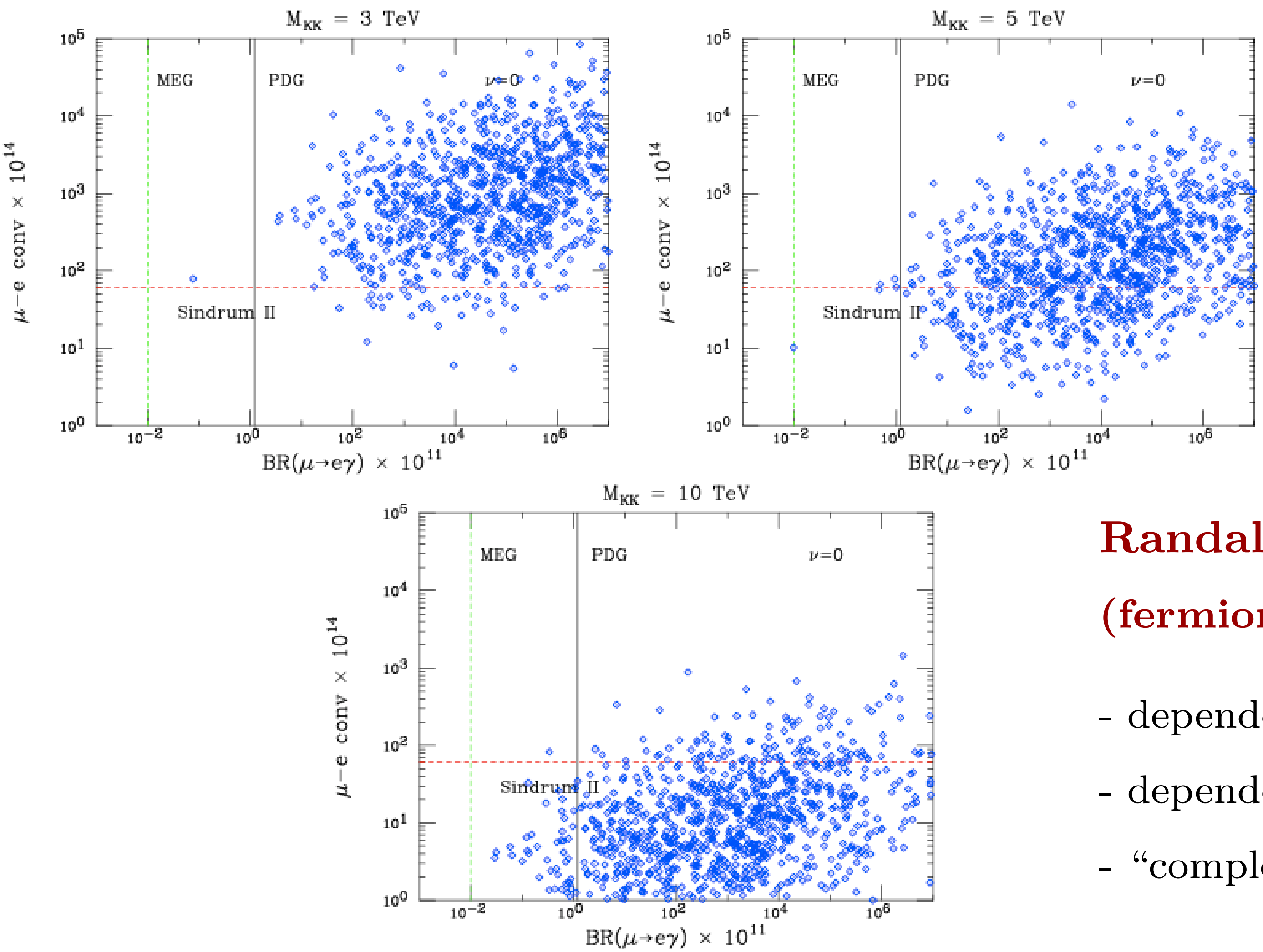
In the case of the seesaw mechanism, the matter-antimatter asymmetry generated via leptogenesis is (yet another) function of the neutrino Yukawa couplings:

If one is to hope to ever reconstruct the seesaw Lagrangian and test leptogenesis, LFV needs to be measured.

Note that this is VERY ambitious, and we need to get lucky a few times:

- Weak scale SUSY has to exist;
- "Precision" measurement of $\mu \to e$, $\tau \to \mu$, $\tau \to e$;
- "Precision" measurement of SUSY masses;
- Very good understanding of mechanism of SUSY breaking;
- There are no other relevant degrees of freedom between the weak scale and $> 10^9$ GeV;
- etc

Other ways to do this would be much appreciated!



Randall-Sundrum Model

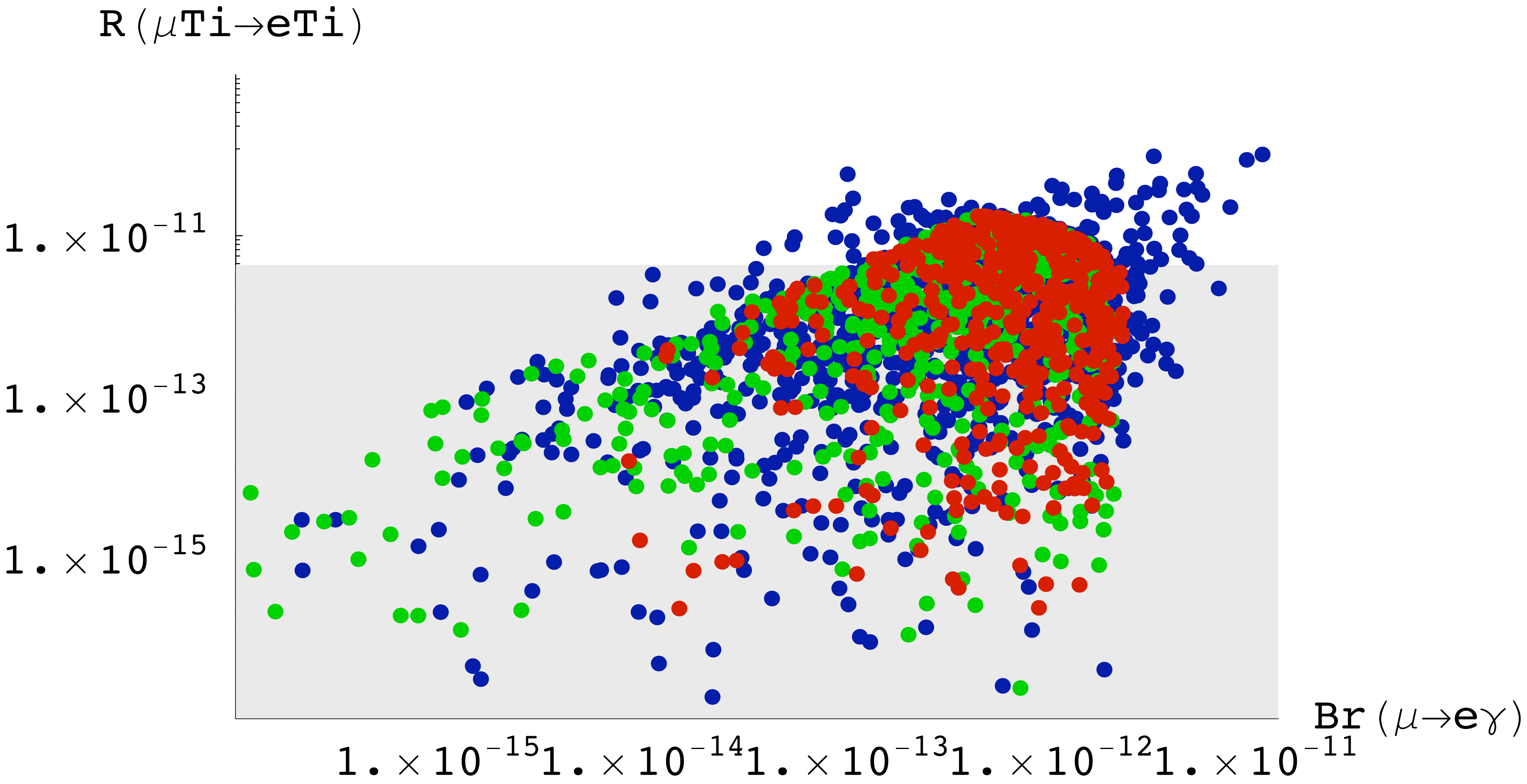
(fermions in the bulk)

- dependency on UV-completion(?)
- dependency on Yukawa couplings
- "complementarity" between $\mu \to e\gamma$, $\mu \to e$ conv

FIG. 6: Scan of the $\mu \to e\gamma$ and $\mu - e$ conversion predictions for $M_{KK} = 3, 5, 10$ TeV and $\nu = 0$. The solid line denotes the PDG bound on $BR(\mu \to e\gamma)$, while the dashed lines indicate the SINDRUM II limit on $\mu - e$ conversion and the projected MEG sensitivity to $BR(\mu \to e\gamma)$.

[Agashe, Blechman, Petriello, hep-ph/0606021]

Little Higgs Models: M. Blanke, *et al*, JHEP 0705, 013 (2007).



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]

Bottom Line: This is simple a scenario where:

$$\kappa \gg 1, \qquad \frac{1}{\Lambda^2} \sim \frac{\lambda^2}{\tilde{m}^2}$$

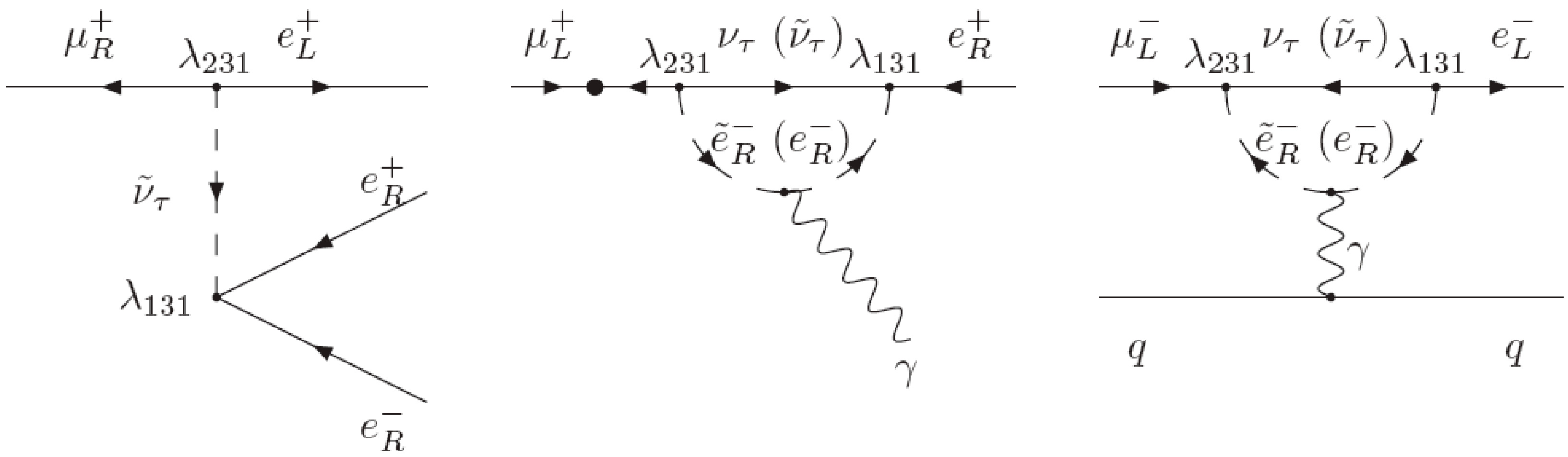


Figure 1: *Lowest order Feynman diagrams for lepton flavour violating processes induced by* $\lambda_{131}\lambda_{231}$ *couplings (see Eq. (2.1)).*

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

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

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

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

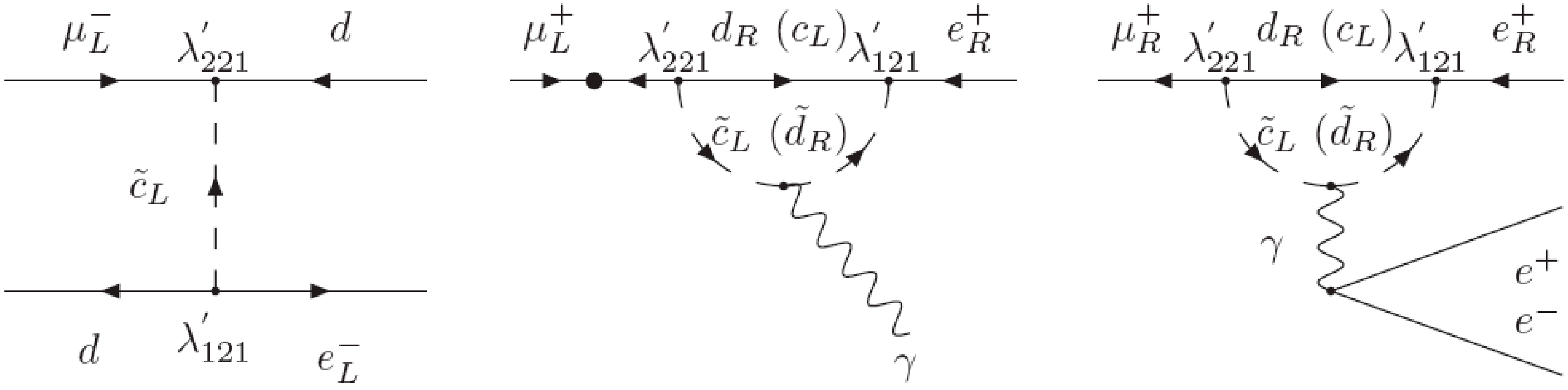


Figure 4: *Lowest order Feynman diagrams of lepton flavour violating processes induced by $f'_{121}f'_{221}$ couplings (see Eq. (2.1)).*

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

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

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

$\mu \to e$-conversion “only hope”!

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

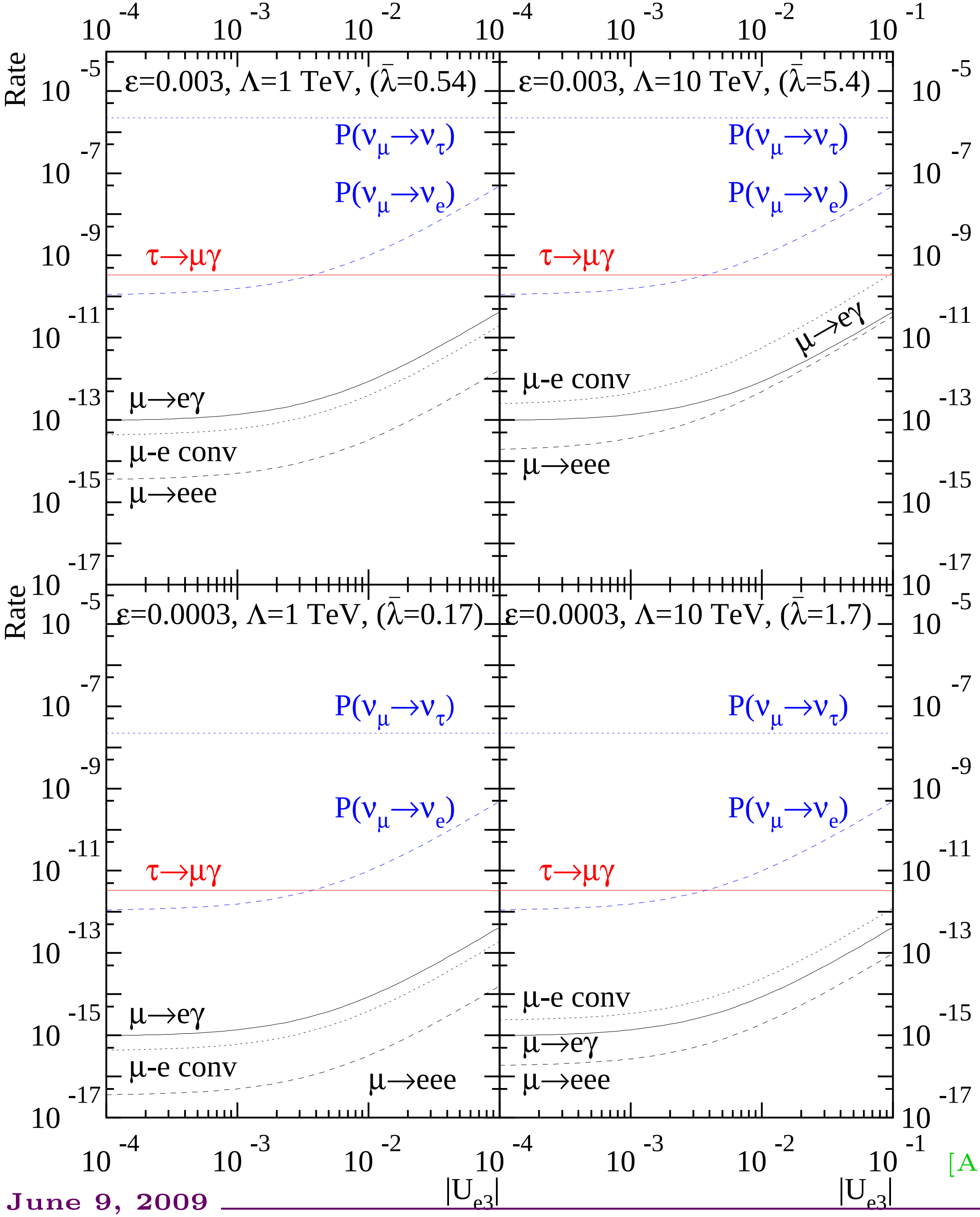
On CLFV Processes Involving τ Leptons (Brief Comment)

Current Bound On Selected τ CLFV Processes (All from the B-Factories):

- $B(\tau \to e\gamma) < 1.1 \times 10^{-7}$; $B(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$. ($\mu \to e\gamma$)
- $B(\tau \to e\pi) < 8.0 \times 10^{-8}$; $B(\tau \to \mu\pi) < 1.1 \times 10^{-7}$. ($\mu \to e$–conversion)
- $B(\tau \to eee) < 3.6 \times 10^{-8}$; $B(\tau \to ee\mu) < 2.0 \times 10^{-8}$, ($\mu \to eee$)
- $B(\tau \to e\mu\mu) < 2.3 \times 10^{-8}$; $B(\tau \to \mu\mu\mu) < 3.2 \times 10^{-8}$. ($\mu \to eee$)

Relation to $\mu \to e$ violating processes is model dependent. Typical enhancements, at the amplitude-level, include:

- Chirality flipping: $m_\tau \gg m_\mu$;
- Lepton mixing effects: $U_{\tau 3} \gg U_{e3}$;
- Mass-Squared Difference effects: $\Delta m^2_{13} \gg \Delta m^2_{12}$;
- etc



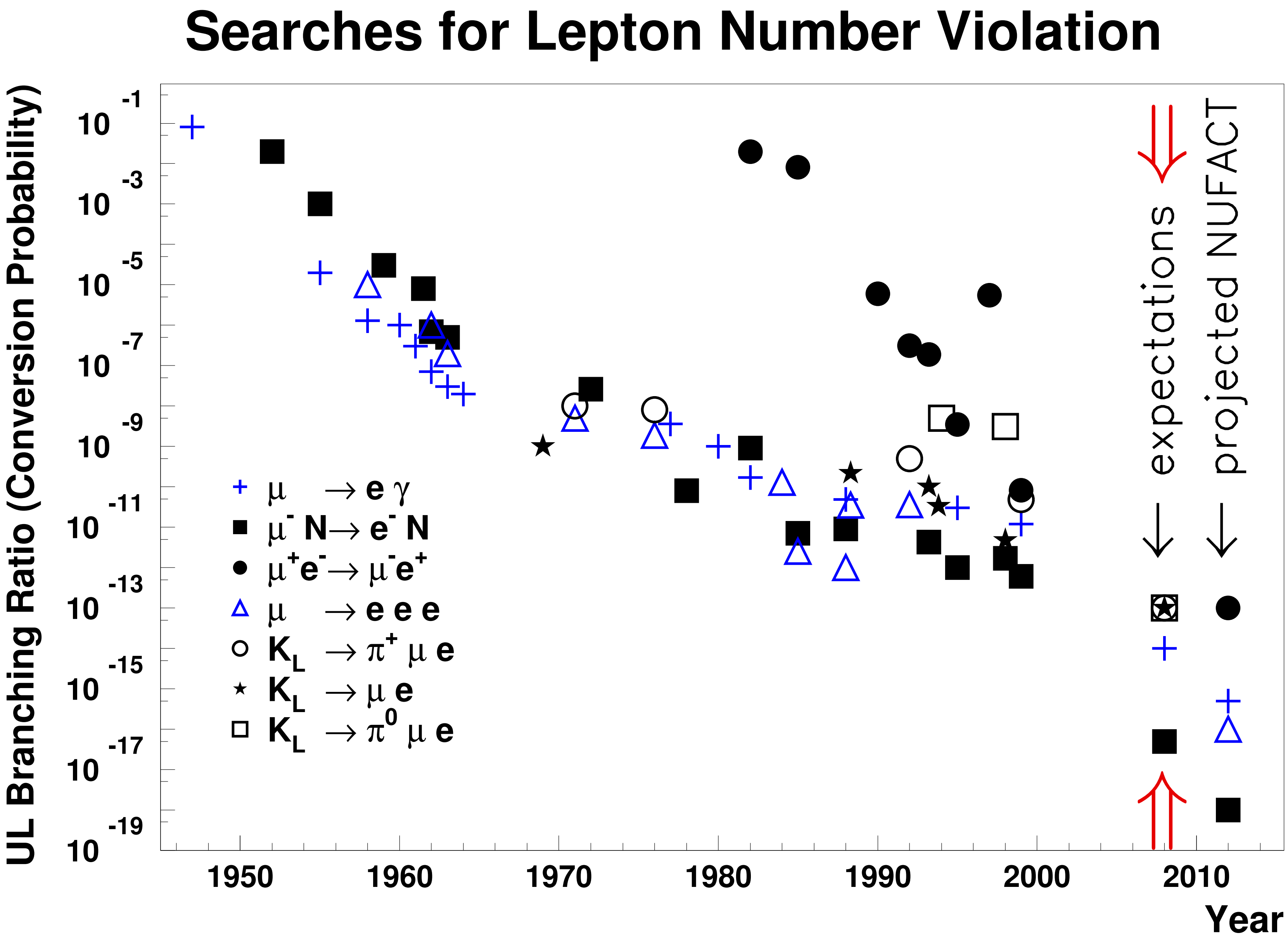
e.g.: Large Extra-Dimensions

-no ambiguity in y (neutrinos Dirac)

-dependency on UV-completion

Other example: neutrino masses from Higgs triplets

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



[hep-ph/0109217]

Brief: where is CLFV going (experiments)?

- MEG will aim at $B(\mu \to e\gamma) >$ several$\times 10^{-14}$. Can anyone do better? Looks very challenging!
- Different new initiatives in Fermilab (*Mu2e*) and in Japan (COMET) will aim at $B(\mu Z \to eZ) > 10^{-16}$. No showstopper for doing (much?) better. Concrete discussions at Fermilab (with Project X) and Japan (PRISM). See also NuFact study at CERN, hep-ph/0109217
- Recent discussions of new $\mu \to eee$ effort at PSI. Perhaps $B(\mu \to eee) > 10^{-14}$ or 10^{-15}. Is it possible to do better? How much?
- Sensitivity to CLFV involving taus can improve past the 10^{-8} level with Super-B factories. $B(\tau \to \ell X) > 10^{-9}$ seems feasible. Naively unlikely that LHC can contribute (in spite of huge τ event sample). LHCb?

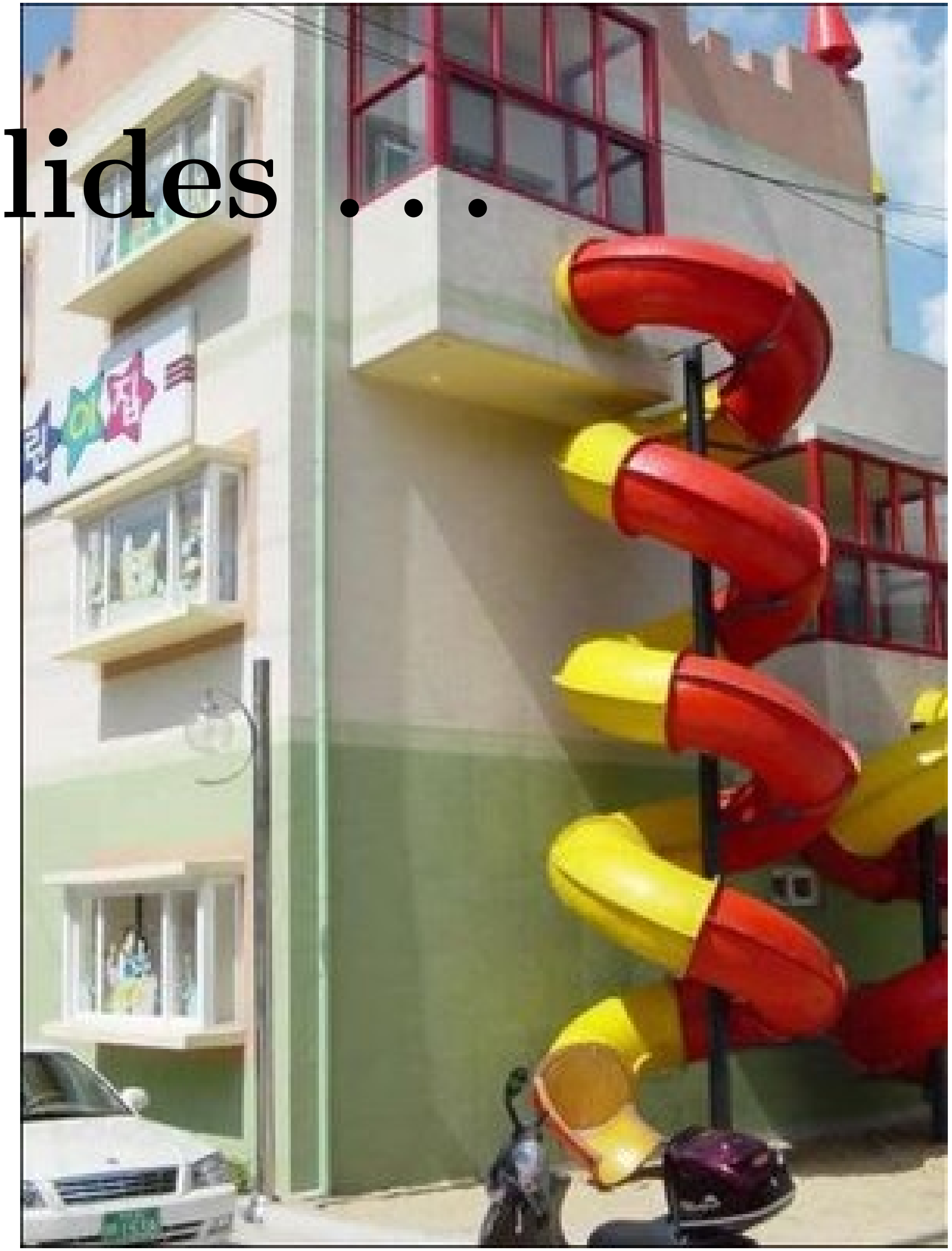
Summary and Conclusions

- 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).
- 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!

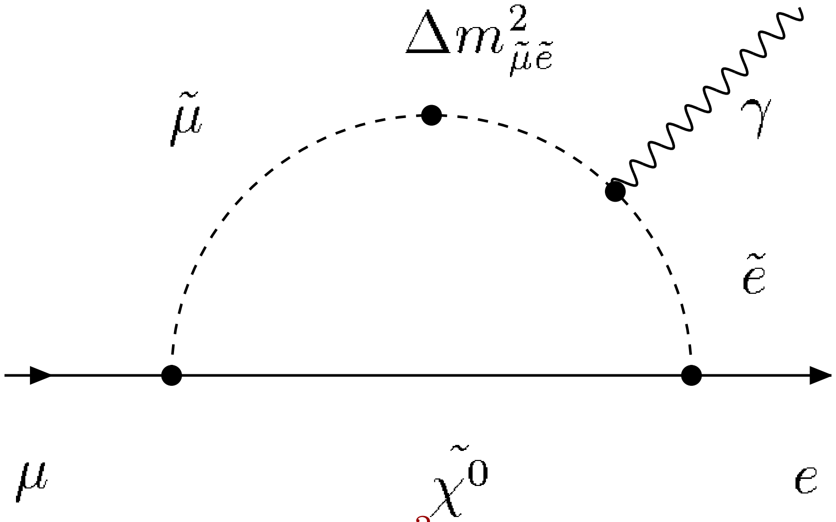
$\Rightarrow$

- Complementary to LHC and other searches for new physics. Guaranteed to learn something regardless of scenario:
  - New d.o.f. at LHC and positive signal for next-generation CLFV: best case scenario. Differentiate new scenarios for the new physics. Connections to neutrino masses?
  - New d.o.f. at LHC and negative signal for next-generation CLFV: New physics flavor blind. Why? Neutrino masses are very high energies? Leptogenesis disfavored? Neutrino Mass Physics Weakly Coupled?
  - No new d.o.f. at LHC and positive signal for next-generation CLFV: New physics beyond the reach of LHC. Can we learn more? How?
  - No new d.o.f. at LHC and negative signal for next-generation CLFV: Next-next generation CLFV (possibly $\mu \to e$-conversion) among very few probes of new physics scales (along with neutrino oscillation experiments, astrophysics, cosmology, etc). How do we learn more?

Backup Slides . . .



"Bread and Butter" SUSY plus High Energy Seesaw



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

$\kappa \ll 1$ while $\frac{1}{\Lambda^2} \sim \frac{g^2 e}{16\pi^2 \tilde{m}^2}\theta_{e\mu}$, where $\tilde{m}^2$ is a typical supersymmetric mass.

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

The Seesaw Mechanism

$\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.,$ $\Rightarrow$ N^α gauge singlet fermions,
$y_{i\alpha}$ dimensionless Yukawa couplings, $M_N^{\alpha\beta}$ (very large) mass parameters.

At low energies, integrate out the "right-handed neutrinos" N_α:

$$\mathcal{L} \supset \left(y M_N^{-1} y^t\right)_{ij} L^i H L^j H + \mathcal{O}\left(\frac{1}{M_N^2}\right) + H.c.$$

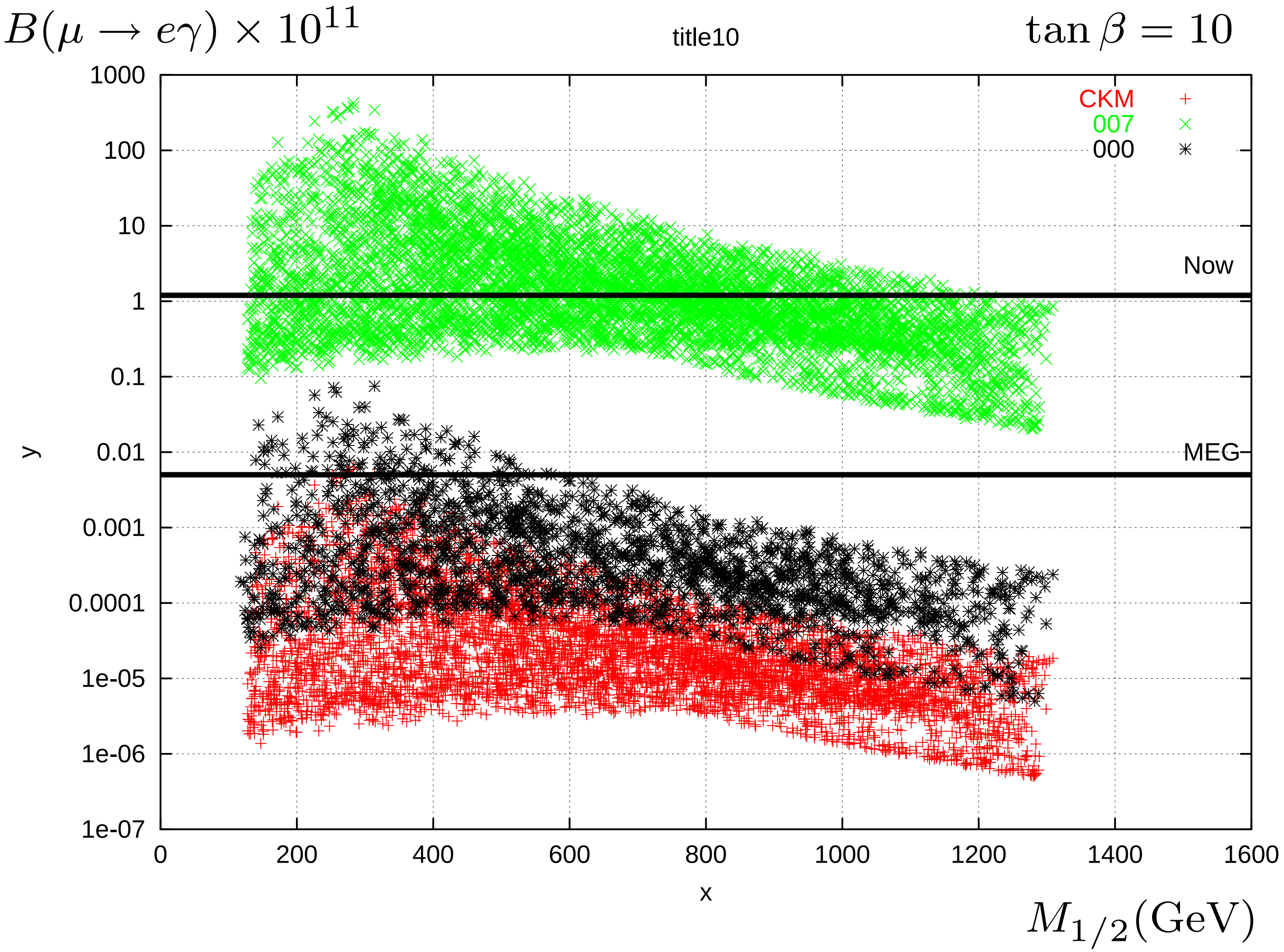
y are not diagonal $\rightarrow$ right-handed neutrino loops generate non-zero $\Delta m^2_{\tilde{e}\tilde{\mu}}$

$$\left(\Delta m^2_{\tilde{\ell}_L}\right)_{\alpha\beta} \simeq -\frac{3m_0^2 + A_0^2}{8\pi^2} \sum_k (y)^*_{k\alpha} (y)_{k\beta} \ln \frac{M_{UV}}{M_{N_k}} \,, \quad M_{UV} = M_{\rm Planck}, M_{GUT}, \ldots$$

If this is indeed the case, CLFV would serve as another channel to probe neutrino Yukawa couplings, which are not directly accessible experimentally.

Fundamentally important for "testing" the seesaw, leptogenesis, GUTs, etc.

What are the neutrino Yukawa couplings → ansatz needed!



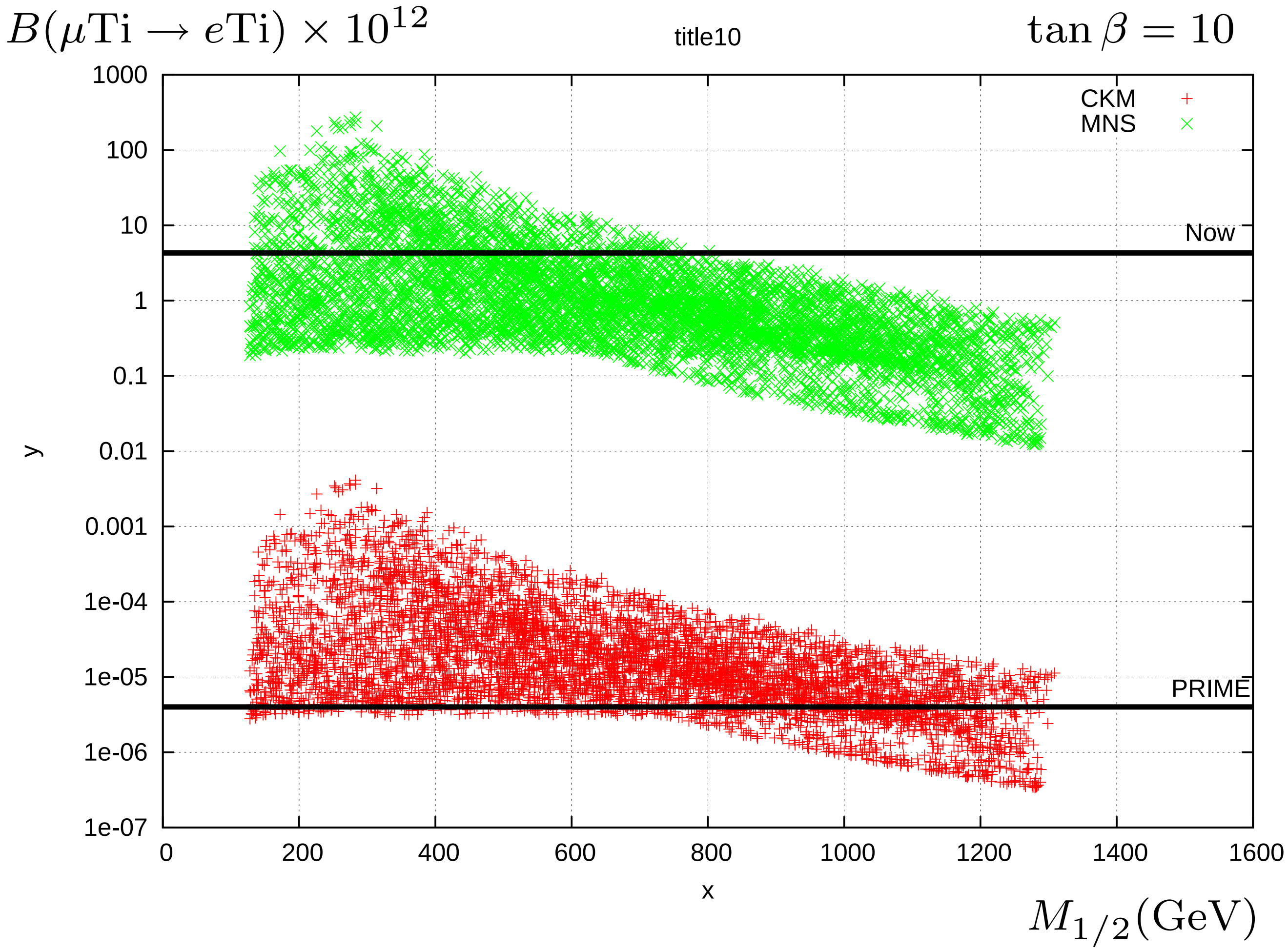
$SO(10)$ inspired model.

remember B scales with y^2.

$B(\mu \to e\gamma) \propto M_R^2 [\ln(M_{Pl}/M_R)]^2$

[Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139]

$\mu \to e$ conversion is at least as sensitive as $\mu \to e\gamma$



$SO(10)$ inspired model.

remember B scales with y^2.

$B(\mu \to e\gamma) \propto M_R^2 [\ln(M_{Pl}/M_R)]^2$

[Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139]