Title: New physics searches in low-energy experiments

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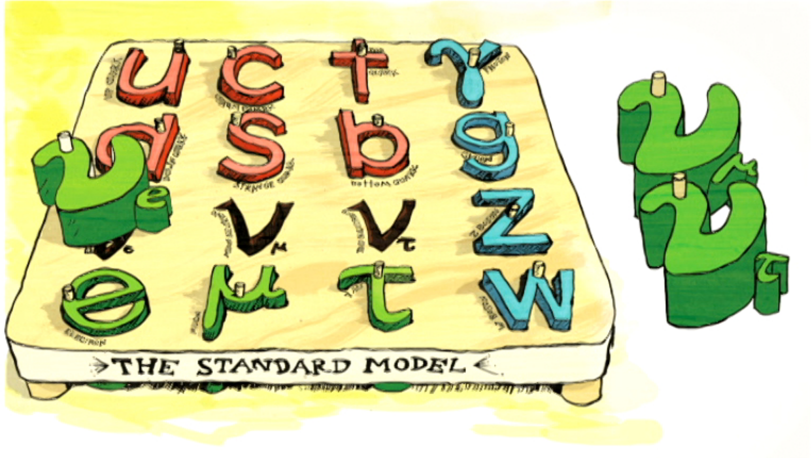
Abstract:

New Physics Searches in Low-Energy Experiments (Mostly Neutrinos)



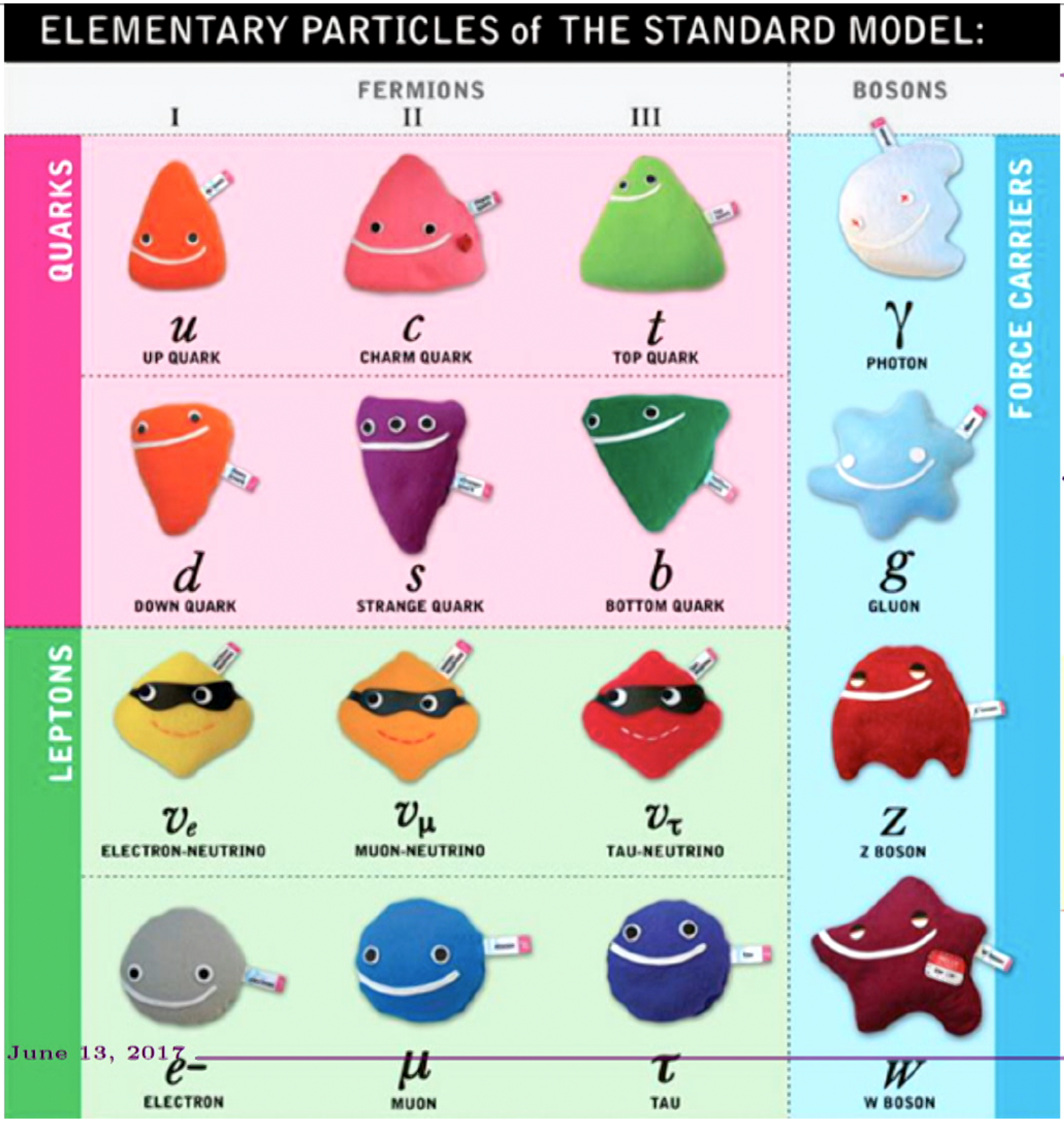
André de Gouvêa – Northwestern University

Radiative Corrections at the Intensity Frontier of Particle Physics

June 12–14, 2017, Perimeter Institute, Waterloo

Very Brief Outline

- New Phenomena. Where are We?;
- What I Won't Talk About;
  - EDMs;
  - Searches for very weakly coupled, very light particles;
  - Dark matter searches;
  - very-low-energy coherent elastic neutrino–nucleus scattering;
  - etc.
- New Physics with Charged Leptons (Brief);
- New Physics in the Neutrino Sector;
- More New Physics in the Neutrinos Sector?



This meeting is about figuring out what the SM predicts (very precisely!) happens when one measures something. . .

. . . except for this talk

(Now with Higgs boson!)

http://www.particlezoo.net

Evidence for Physics Beyond the Standard Model

1. The expansion rate of the universe seems to accelerate, both early on (inflation) and right now (dark energy).
2. Dark matter seems to exist.
3. Why is there so much baryonic matter in the universe?
4. Neutrino masses are not zero.

1. and 2. are consequences of astrophysical/cosmological observations. It is fair to ask whether we are sure they have anything to do with particle physics.

3. is also related to our understanding of the early history of the universe and requires some more explaining.

4. is the most palpable evidence for new physics.

How Do We Learn More?

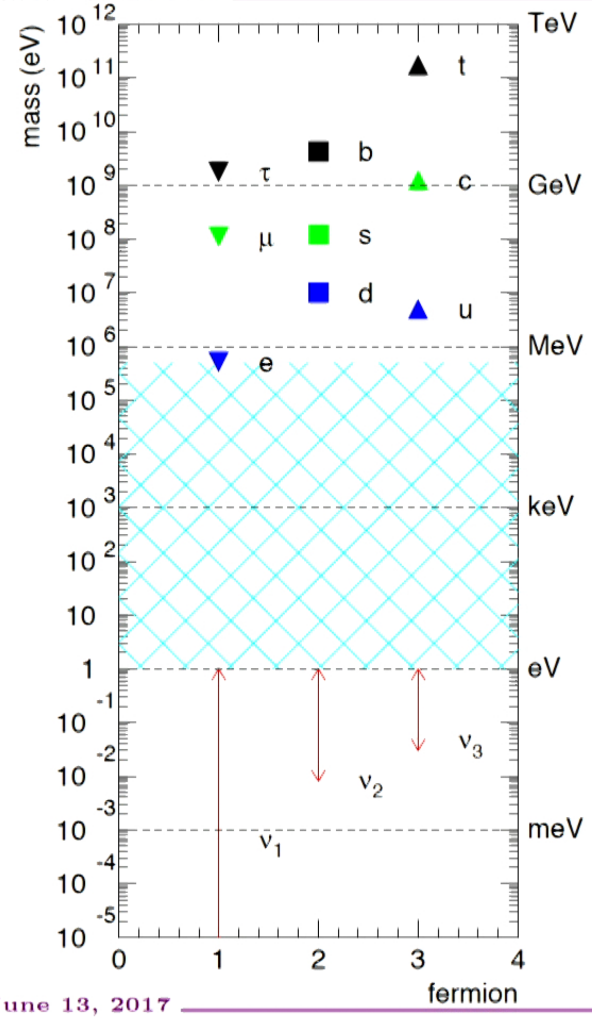
Something Funny Happened on the Way to the 21st Century

ν Flavor Oscillations

Neutrino oscillation experiments have revealed that neutrinos change flavor after propagating a finite distance. The rate of change depends on the neutrino energy E_ν and the baseline L. The evidence is overwhelming.

- $\nu_\mu \to \nu_\tau$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ — atmospheric and accelerator experiments;
- $\nu_e \to \nu_{\mu,\tau}$ — solar experiments;
- $\bar{\nu}_e \to \bar{\nu}_{\rm other}$ — reactor experiments;
- $\nu_\mu \to \nu_{\rm other}$ and $\bar{\nu}_\mu \to \bar{\nu}_{\rm other}$— atmospheric and accelerator expts;
- $\nu_\mu \to \nu_e$ — accelerator experiments.

The simplest and **only satisfactory** explanation of **all** this data is that neutrinos have distinct masses, and mix.



NEUTRINOS HAVE MASS

[albeit very tiny ones...]

So What?

⇓

NEW PHYSICS

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Neutrino Masses, EWSB, and a New Mass Scale of Nature

The LHC has revealed that the minimum SM prescription for electroweak symmetry breaking — the one Higgs double model — is at least approximately correct. What does that have to do with neutrinos?

The tiny neutrino masses point to three different possibilities.

1. Neutrinos talk to the Higgs boson very, very **weakly** (Dirac neutrinos);
2. Neutrinos talk to a **different Higgs** boson – there is a new source of electroweak symmetry breaking! (Majorana neutrinos);
3. Neutrino masses are small because there is **another source of mass** out there — a new energy scale indirectly responsible for the tiny neutrino masses, a la the seesaw mechanism (Majorana neutrinos).

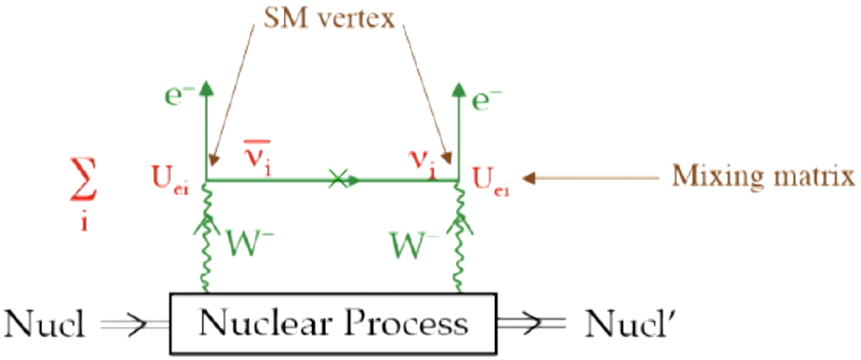
Searches for $0\nu\beta\beta$ help tell (1) from (2) and (3), the LHC, charged-lepton flavor violation, *et al* may provide more information.

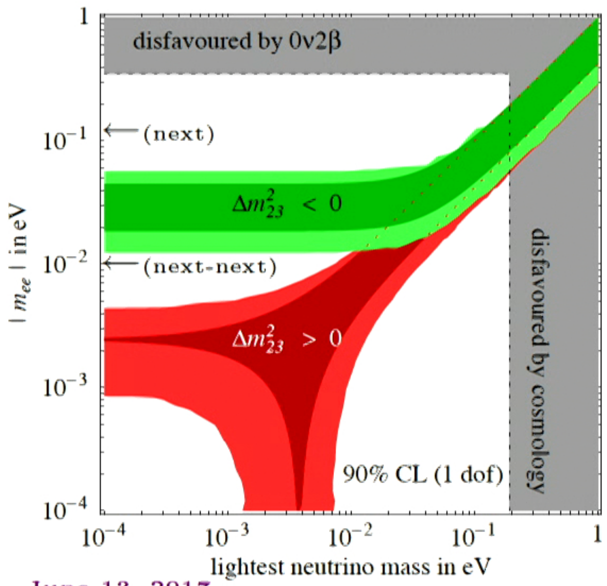
Search for the Violation of Lepton Number (or $B - L$)

Best Bet: search for

Neutrinoless Double-Beta

Decay: $\boxed{Z \to (Z+2)e^- e^-}$





Helicity Suppressed Amplitude $\propto \frac{m_{ee}}{E}$

Observable: $m_{ee} \equiv \sum_i U_{ei}^2 m_i$

WANTED: NUCLEAR MATRIX ELEMENTS

Any other competitive probes? Model Dependent

We Will Still Need More Help . . .

νSM – One Path

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\text{SM}} \supset -y_{ij}\frac{L^iHL^jH}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\text{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \to m_\nu \ll m_f$ $(f = e, \mu, u, d, \text{etc})$
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above at most Λ.
- What is Λ? First naive guess is that Λ is the Planck scale – does not work. Data require $\Lambda \sim 10^{14}$ GeV (related to GUT scale?) [note $y^{\max} \equiv 1$]

What else is this "good for"? Depends on the ultraviolet completion!

Example: the Seesaw Mechanism

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions. $\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

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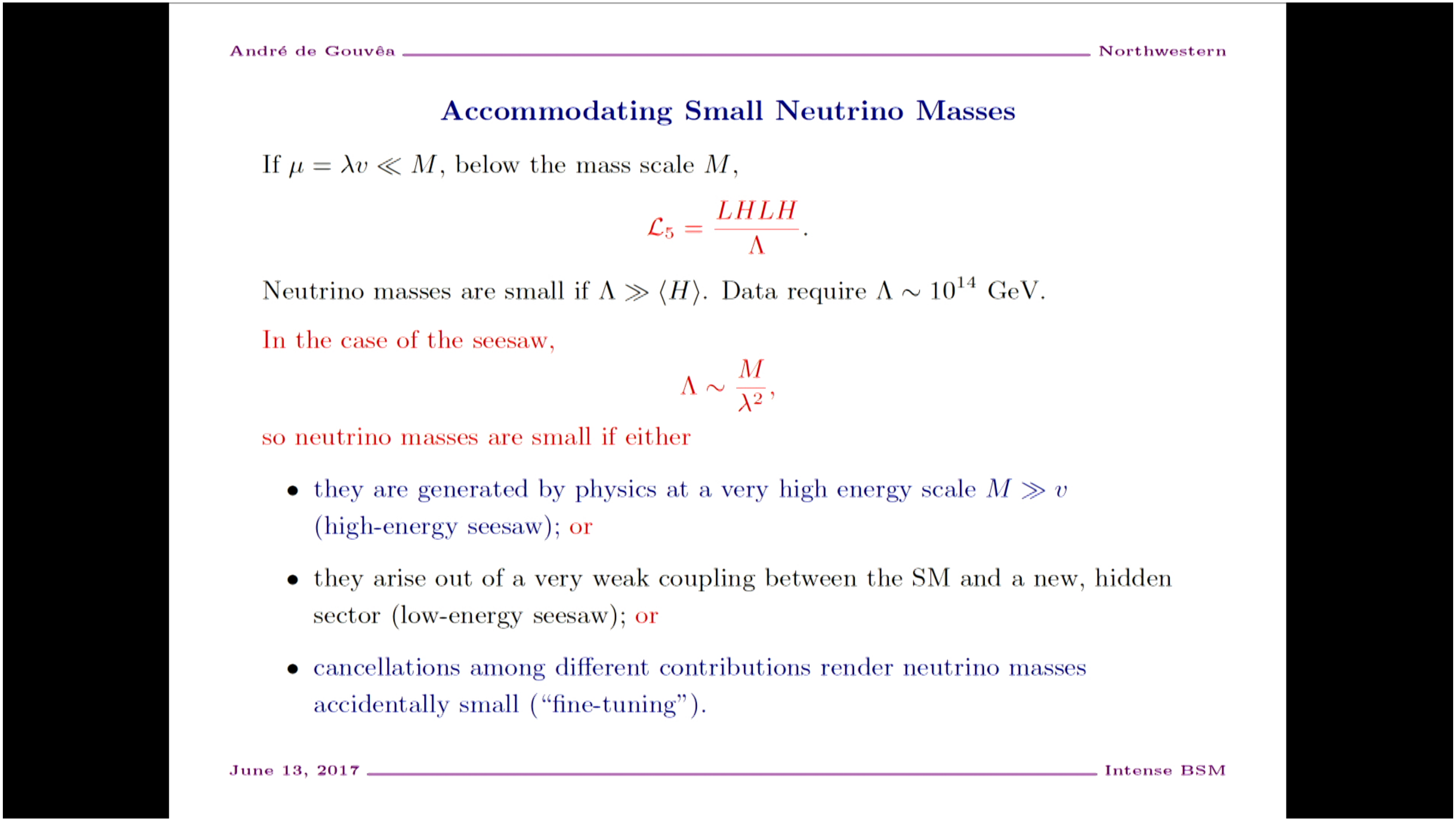
[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.



Accommodating Small Neutrino Masses

If $\mu = \lambda v \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

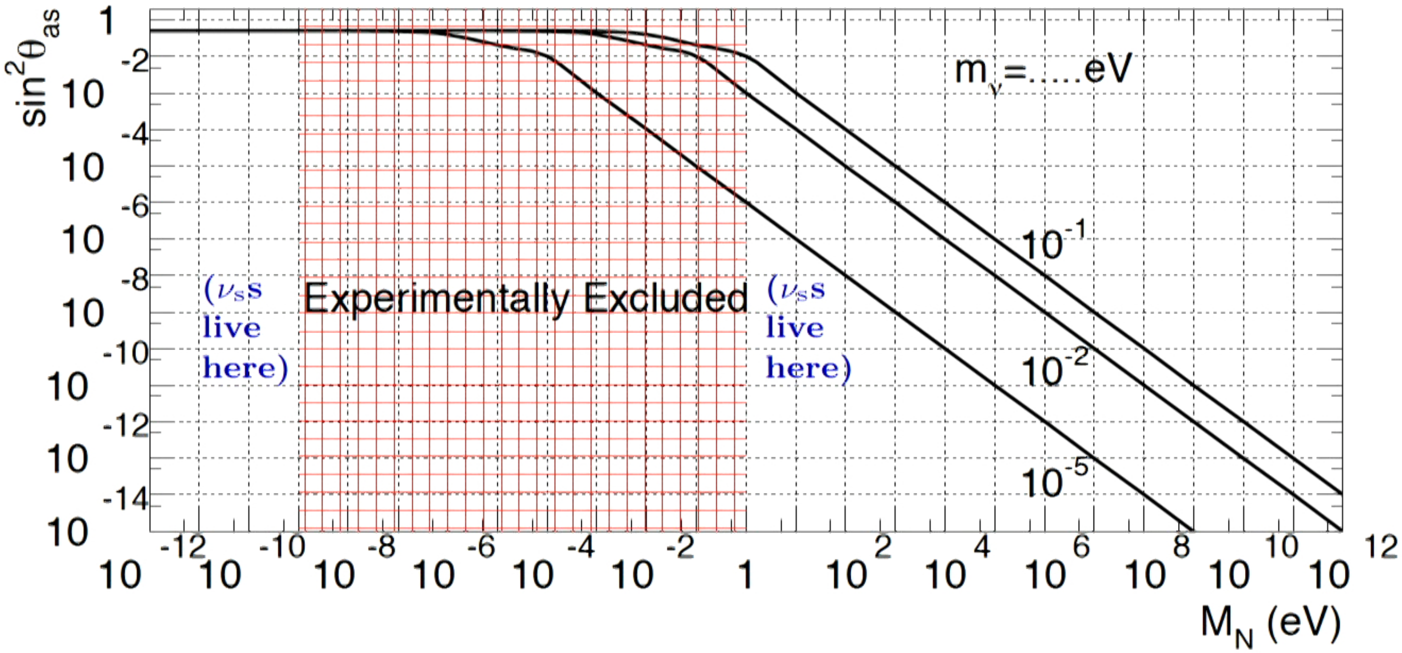
In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

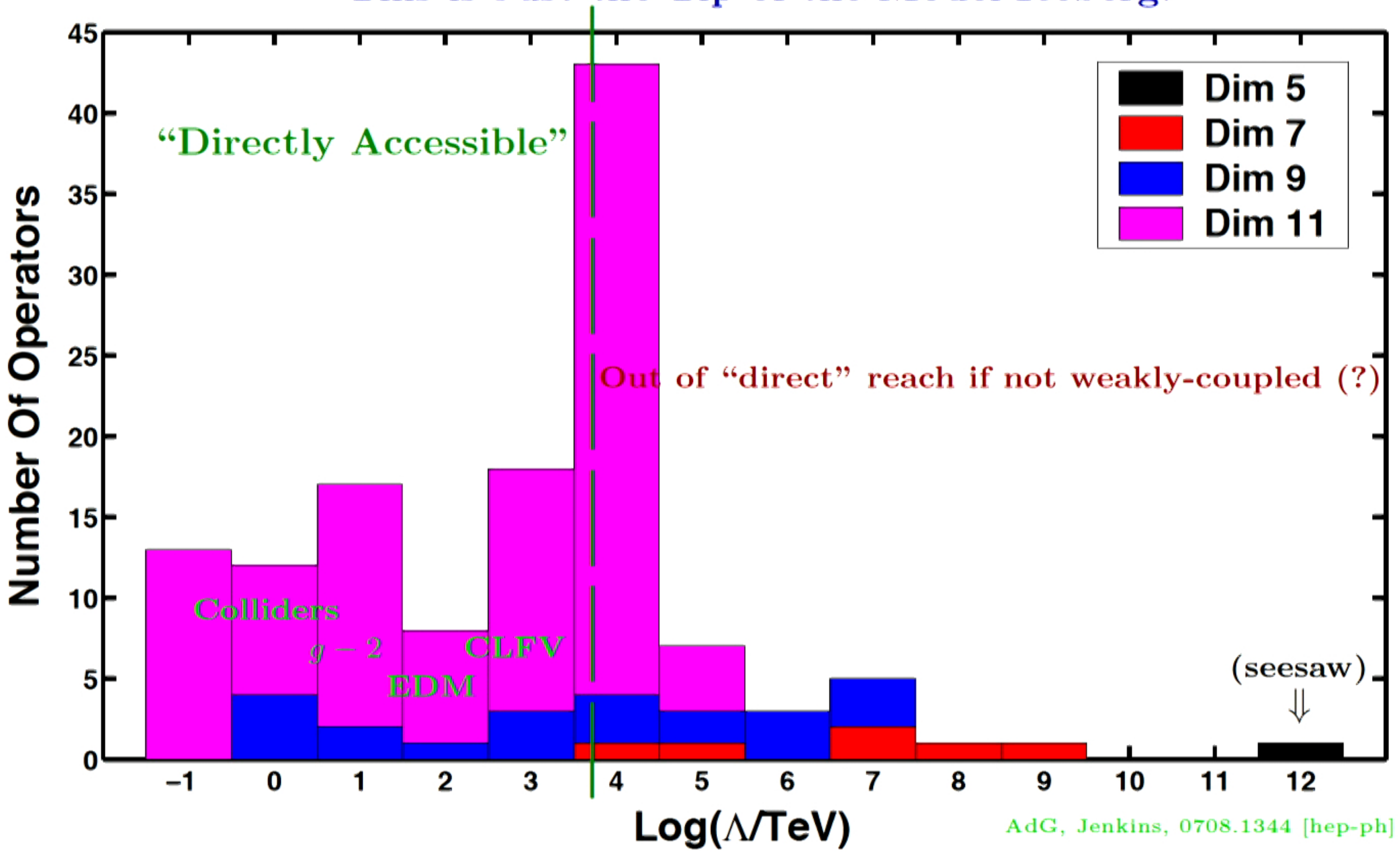
- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

This is Just the Tip of the Model-Iceberg!



AdG, Jenkins, 0708.1344 [hep-ph]

Piecing the Neutrino Mass Puzzle

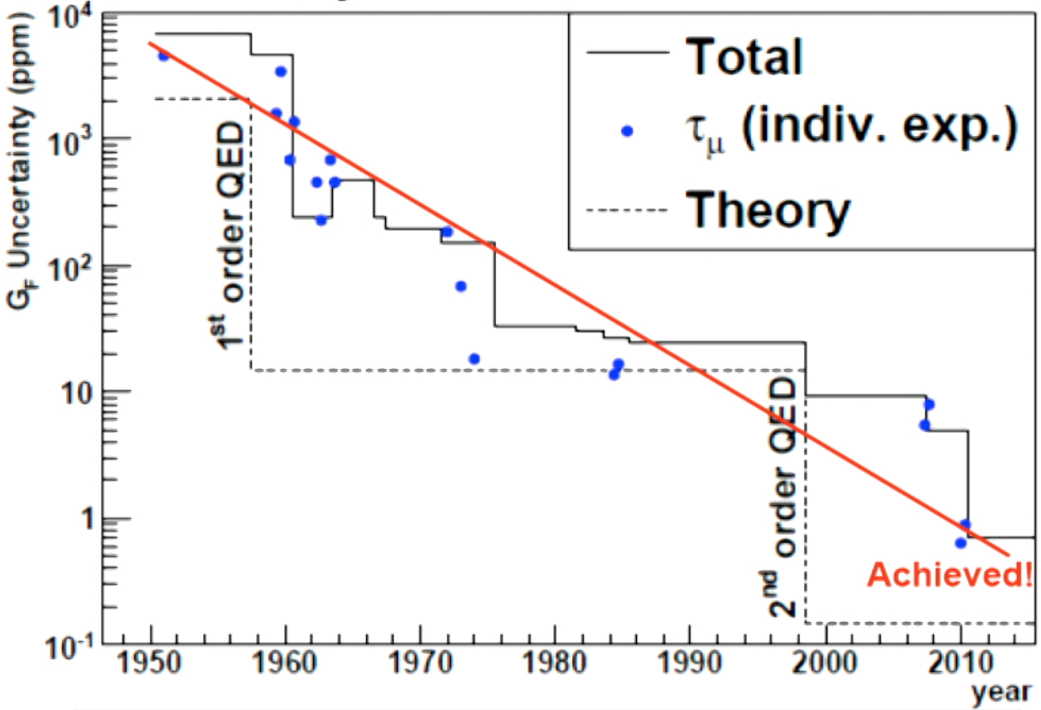
Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including …

- understanding the fate of lepton-number. Neutrinoless double beta decay!
- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- other probes of neutrino properties, including neutrino scattering.
- precision studies of charged-lepton properties ($g-2$, edm), and searches for rare processes ($\mu \to e$-conversion the best bet at the moment).
- collider experiments. The LHC and beyond may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- searches for baryon-number violating processes.

G_F & τ_μ precision has improved by ~4 orders of magnitude over 60 years.

tern

[David Hertzog, 2010 DNP Meeting]



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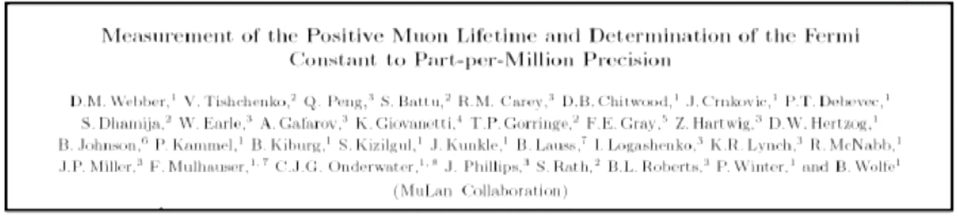


Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

D.M. Webber,[1] V. Tishchenko,[2] Q. Peng,[3] S. Battu,[2] R.M. Carey,[3] D.B. Chitwood,[1] J. Crnkovic,[1] P.T. Debevec,[1] S. Dhamija,[2] W. Earle,[3] A. Gafarov,[3] K. Giovanetti,[4] T.P. Gorringe,[2] F.E. Gray,[5] Z. Hartwig,[3] D.W. Hertzog,[1] B. Johnson,[6] P. Kammel,[1] B. Kiburg,[1] S. Kizilgul,[1] J. Kunkle,[1] B. Lauss,[7] I. Logashenko,[3] K.R. Lynch,[3] R. McNabb,[1] J.P. Miller,[3] F. Mulhauser,[1,7] C.J.G. Onderwater,[1,8] J. Phillips,[3] S. Rath,[2] B.L. Roberts,[3] P. Winter,[1] and B. Wolfe[1]

(MuLan Collaboration)

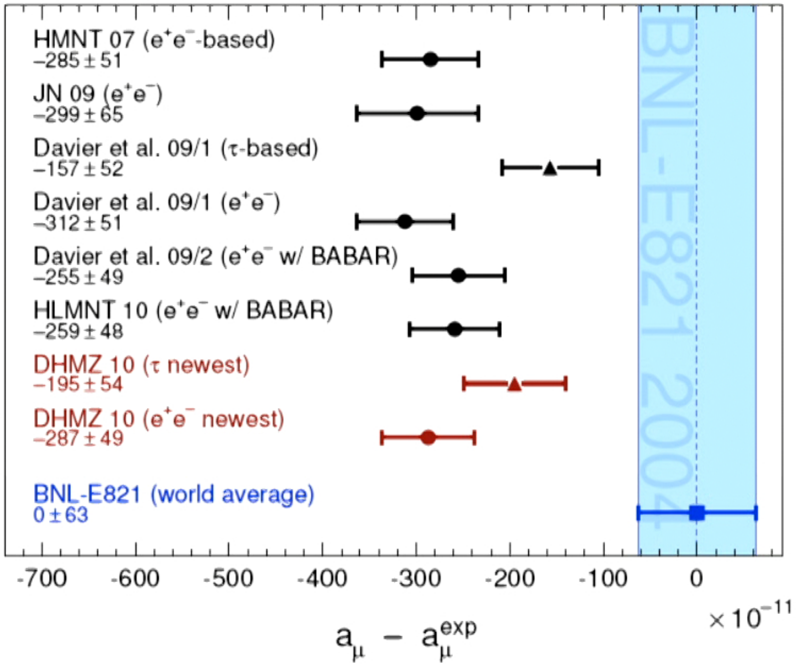


FIG. 9: Compilation of recent results for $a_\mu^{\rm SM}$ (in units of 10^{-11}), subtracted by the central value of the experimental average [12, 57]. The shaded vertical band indicates the experimental error. The SM predictions are taken from: this work (DHMZ 10), HLMNT (unpublished) [58] (e^+e^- based, including BABAR and KLOE 2010 $\pi^+\pi^-$ data), Davier *et al.* 09/1 [15] (τ-based), Davier *et al.* 09/1 [15] (e^+e^--based, not including BABAR $\pi^+\pi^-$ data), Davier *et al.* 09/2 [10] (e^+e^--based including BABAR $\pi^+\pi^-$ data), HMNT 07 [59] and JN 09 [60] (not including BABAR $\pi^+\pi^-$ data).

NOTE: $a_\mu^{LbL} = 105 \pm 26 \times 10^{-11}$

[Davier *et al*, 1010.4180]

Sensitivity to New Physics

If there is new ultra-violet physics, it will manifest itself, as far as a_μ is concerned, via the following effective operator (dimension 6):

$$\frac{\lambda H}{\Lambda^2}\bar{\mu}\sigma_{\mu\nu}\mu F^{\mu\nu} \to \frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma_{\mu\nu}\mu F^{\mu\nu},$$

where Λ is an estimate for the new physics scale. (dependency on muon mass is characteristic of several (almost all?) models. It is NOT guaranteed)

Contribution to a_μ from operator above is

$$\delta a_\mu = \frac{4m_\mu^2}{e\Lambda^2}$$

Current experimental sensitivity: $\Lambda \sim 10$ TeV.

Note that, usually, new physics scale can be much lower due to loop-factors, gauge couplings, etc. In the SM the heavy gauge boson contribution yields

$$\frac{1}{\Lambda^2} \sim \frac{eg^2}{16\pi^2 M_W^2} \longrightarrow \delta a_\mu \sim \frac{m_\mu^2 G_F}{4\pi^2}$$

Not A Bad Estimate!

Very quick comments on the muon electric-dipole moment, d_μ

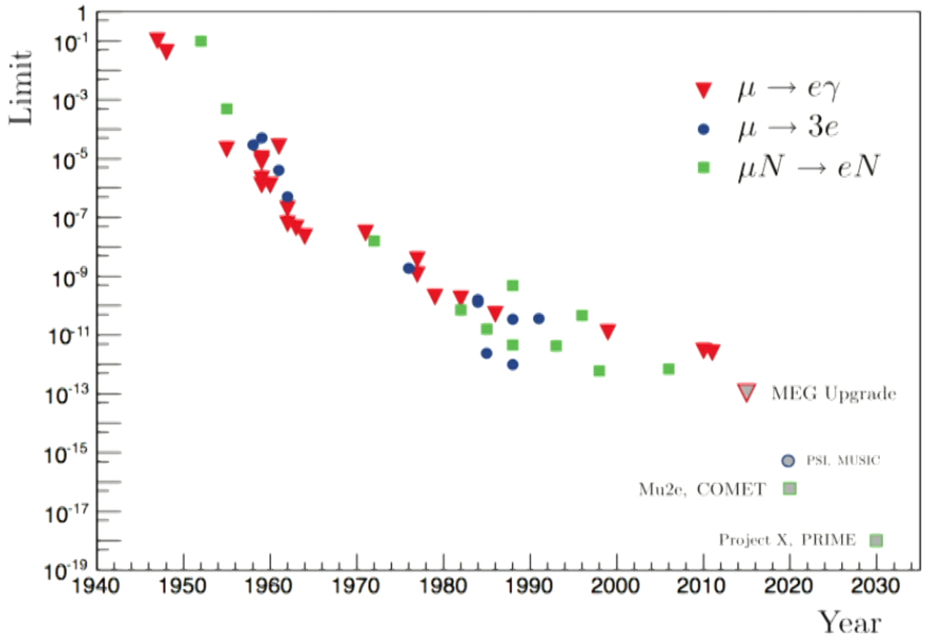
- CP-violating observable;
- Predicted to be non-zero-but-tiny in the SM: $d_\mu < 10^{-36}$ e-cm. Great place to look for new physics!
- Current bounds: $d_\mu < 1.8 \times 10^{-19}$e-cm. Compare to $d_e < 10^{-28}$ e-cm.
- In general, $d_\ell \propto m_\ell$, so $d_\mu \sim d_e \times (m_\mu/m_e)$.
- New $g-2$ experiment at FNAL would be sensitive to $d_\mu > 10^{-21}$e-cm. Dedicated effort could reach $d_\mu > 10^{-24}$e-cm. Is it worth it? [yes!]
- Same effective operator contributes to a_μ and d_μ

$$\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma_{\mu\nu}\mu F^{\mu\nu} \quad \text{versus} \quad \epsilon_{\rm CP}\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma_{\mu\nu}\gamma_5\mu F^{\mu\nu}.$$

$\epsilon_{\rm CP}$ measures how much the new physics violates CP.

If $\Lambda \sim 10$ TeV, $\epsilon_{\rm CP} \ll 1$.

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



[R. Bernstein, P. Cooper, arXiv 1307.5787]

Figure 3: The history of CLFV searches in muons (not including muonium.) One sees a steady improvement in all modes and then a flattening of the rate improvement throughout the 1990s. MEG has upgrade plans for the $\mu \to e\gamma$ search. The two next generations of $\mu N \to eN$, Mu2e/COMET at FNAL and J-PARC are labeled, and possible extensions at Project X and PRIME are shown. Letters-of-intent are in process for $\mu \to 3e$ experiments at PSI and Osaka's MUSIC facility. Individual experiments are discussed in the text.

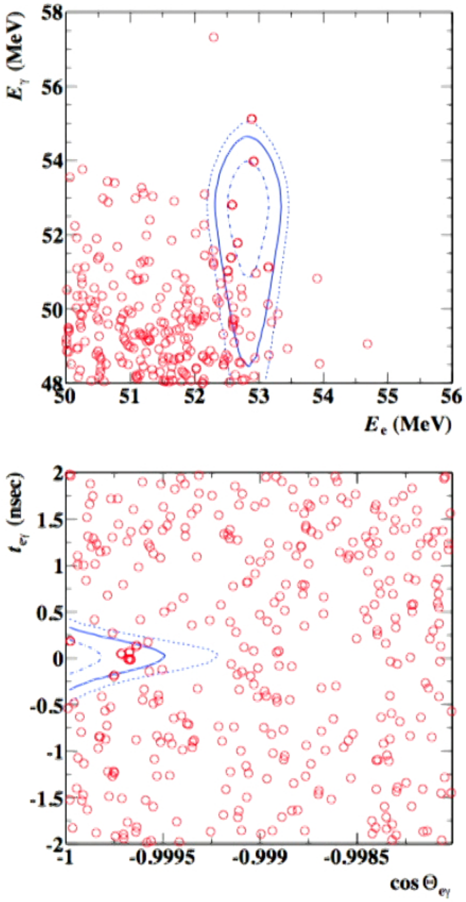
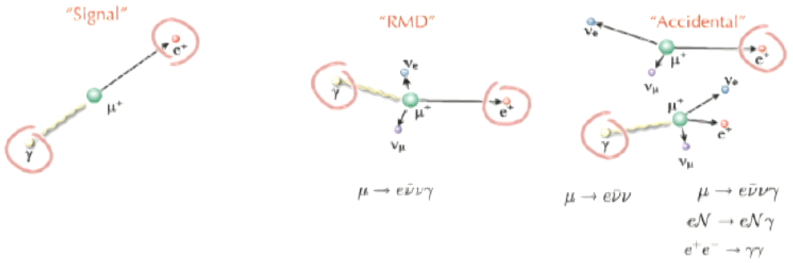


FIG. 2: Event distributions for the combined 2009–2011 dataset in the (E_e, E_γ)- and $(\cos\Theta_{e\gamma}, t_{e\gamma})$-planes. In the top (bottom) panel, a selection of $|t_{e\gamma}| < 0.244$ ns and $\cos\Theta_{e\gamma} < -0.9996$ with 90% efficiency for each variable ($52.4 < E_e < 55$ MeV and $51 < E_\gamma < 55.5$ MeV with 90% and 74% efficiencies for E_e and E_γ, respectively) is applied. The signal PDF contours (1, 1.64 and 2 σ) are also shown.

$$\mathbf{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}\ \mathbf{(90\%\ CL)}$$



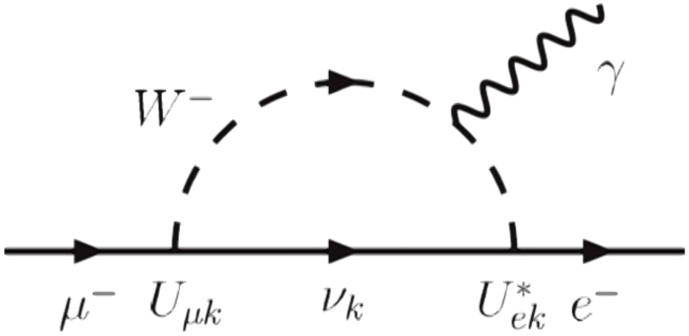
[MEG Coll. arXiv:1303.0754]

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

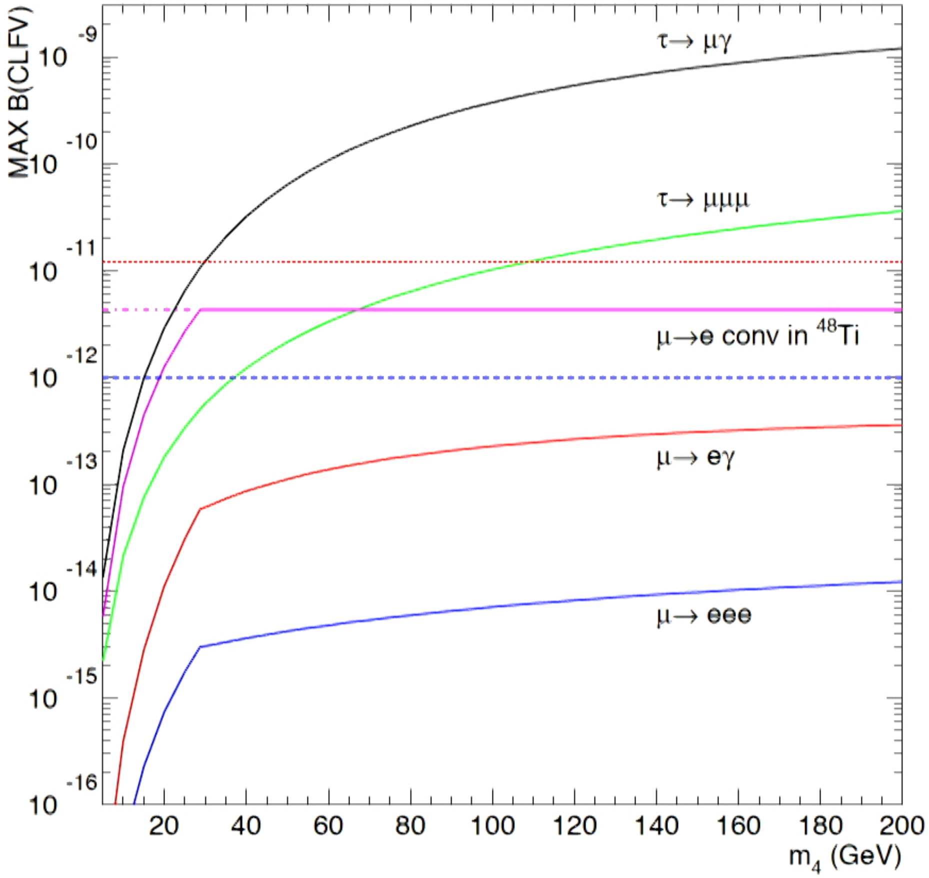
In the case of charged leptons, the **GIM suppression is very efficient**…

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

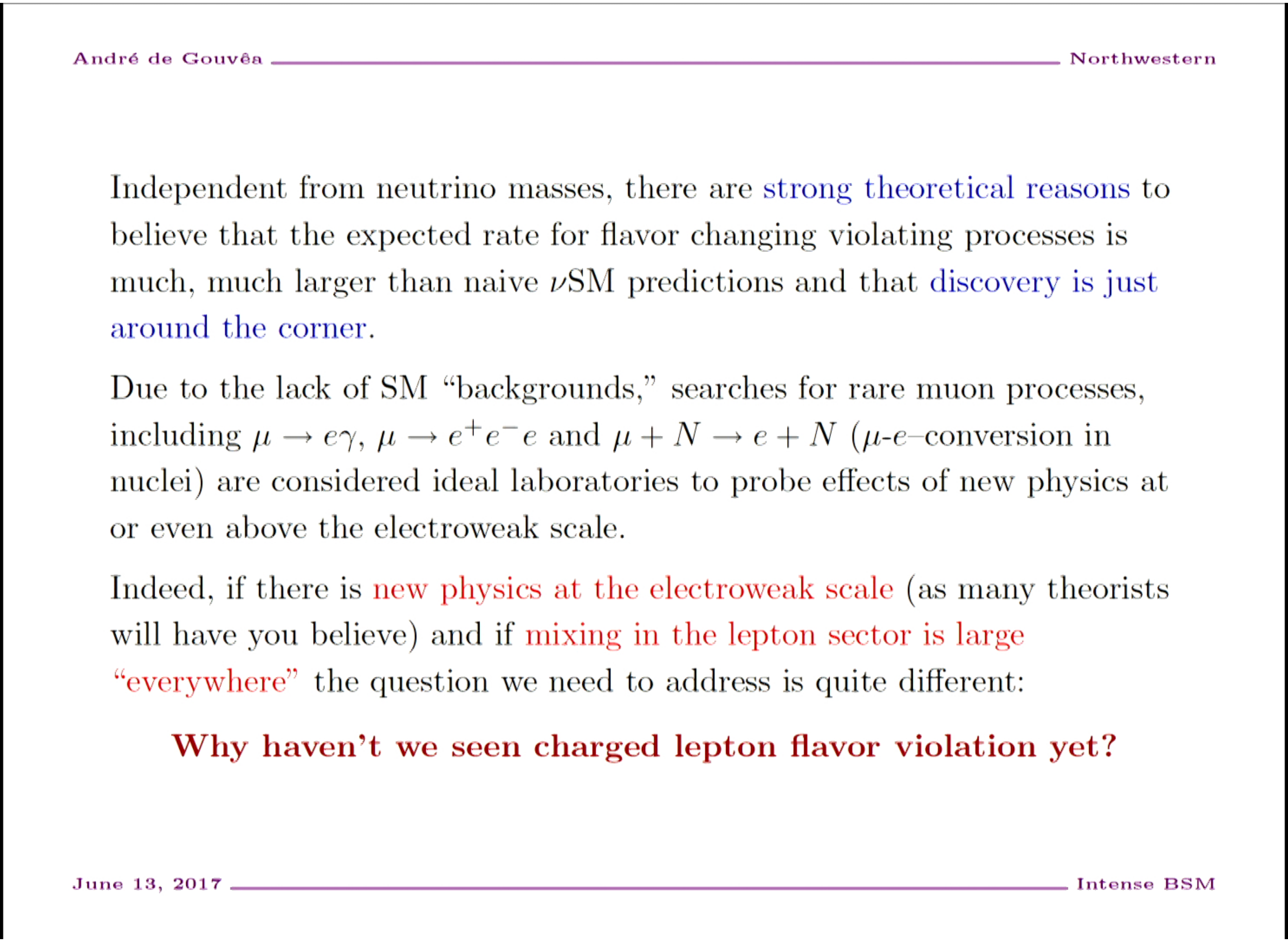
[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,
$\Delta m^2_{1i}\equiv m^2_i-m^2_1$, $i=2,3$ are the neutrino mass-squared differences]



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.

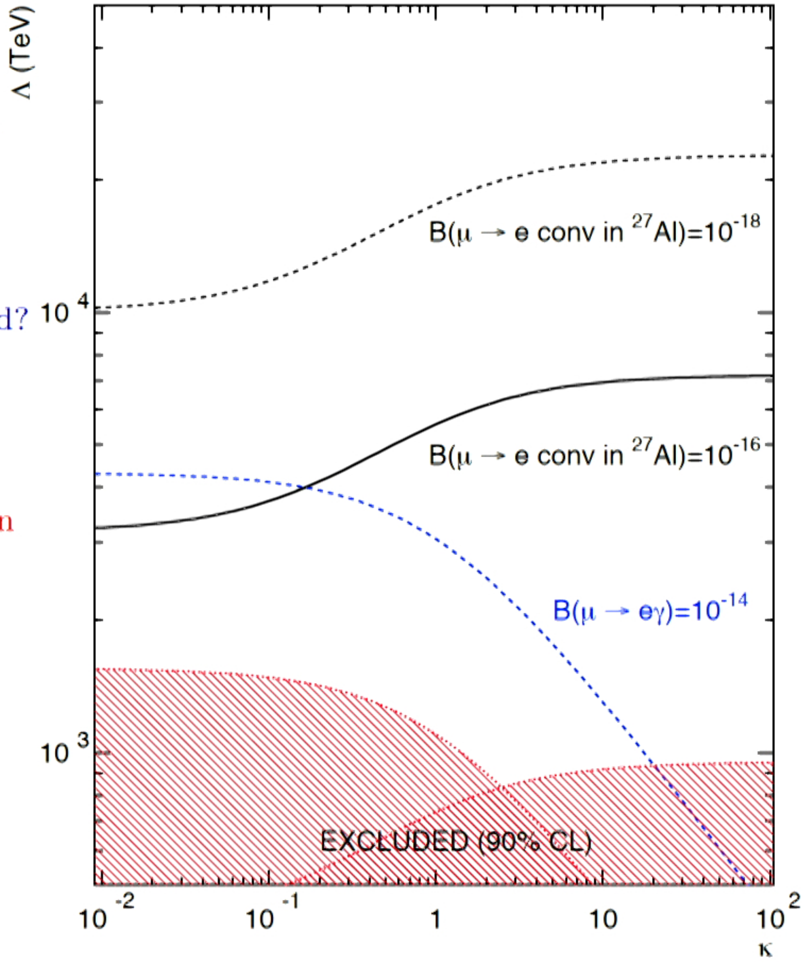
Indeed, if there is new physics at the electroweak scale (as many theorists will have you believe) and if mixing in the lepton sector is large "everywhere" the question we need to address is quite different:

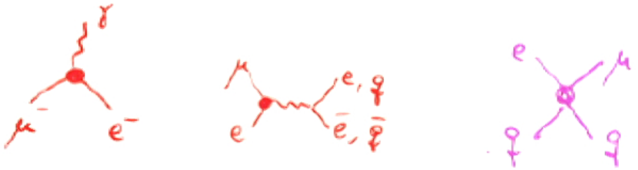
Why haven't we seen charged lepton flavor violation yet?

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

- It is really hard to do $\mu \rightarrow e\gamma$ much better than 10^{-14}. $\mu \rightarrow e$–conv "best" way forward?

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



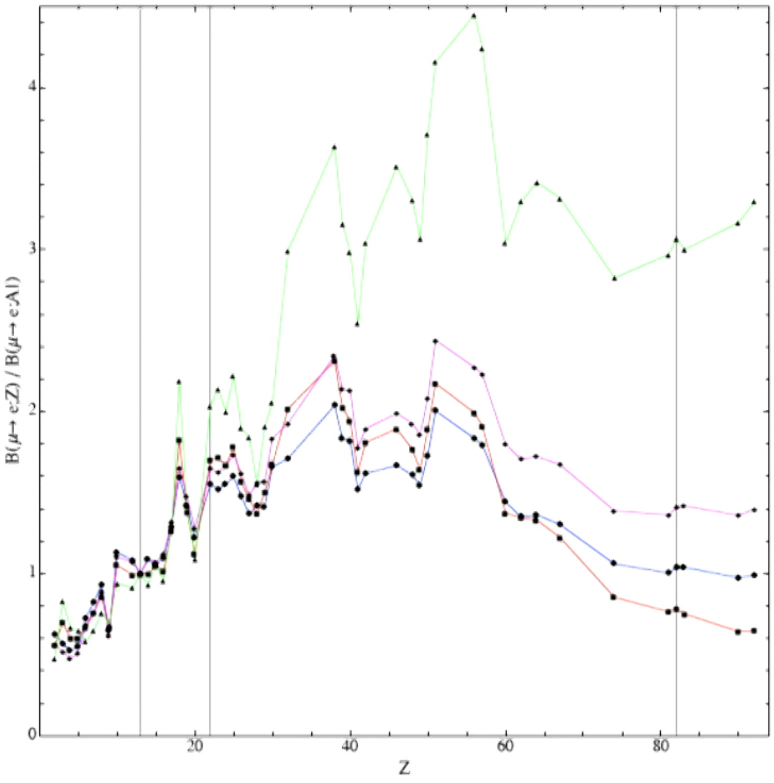


What is This Really Good For?

While specific models 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)

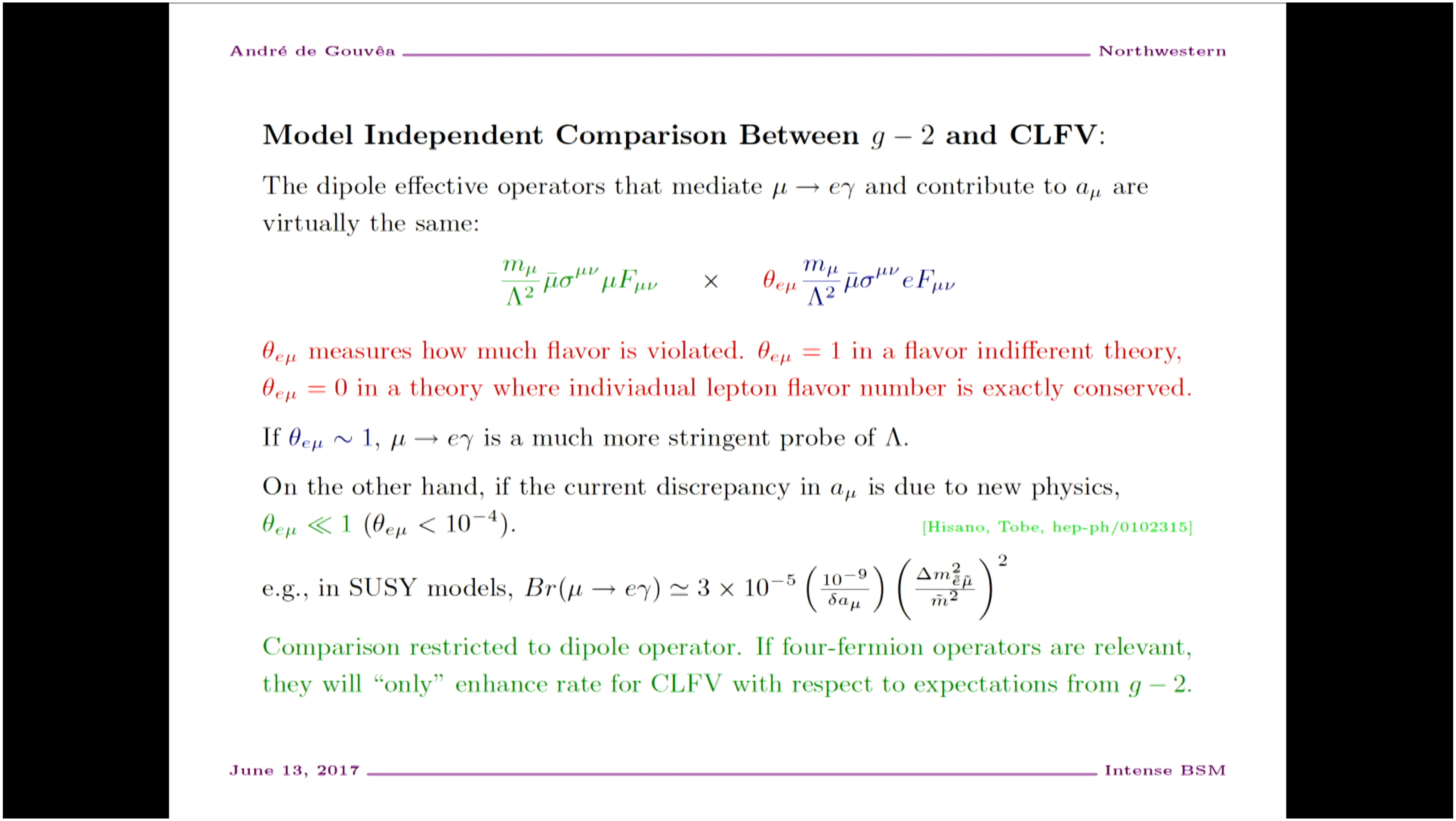
Dipole $(\propto \bar{\mu}\sigma_{\alpha\beta} e F^{\alpha\beta})$

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 $Z = 13\,(\mathrm{Al})$, $Z = 22\,(\mathrm{Ti})$, and $Z = 83\,(\mathrm{Pb})$.

[Cirigliano, Kitano, Okada, Tuzon, 0904.0957]



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 indiviadual 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, $\theta_{e\mu}\ll 1$ ($\theta_{e\mu}<10^{-4}$). [Hisano, Tobe, hep-ph/0102315]

e.g., in SUSY models, $Br(\mu\to e\gamma)\simeq 3\times 10^{-5}\left(\frac{10^{-9}}{\delta a_\mu}\right)\left(\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}^2}\right)^2$

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

On CLFV Processes Involving τ Leptons (Brief Comment)

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

- $B(\tau \to e\gamma) < 1.1 \times 10^{-7}$; $B(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$. ($\mu \to e\gamma$)
- $B(\tau \to e\pi) < 8.0 \times 10^{-8}$; $B(\tau \to \mu\pi) < 1.1 \times 10^{-7}$. ($\mu \to e$–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

Future: SuperB-factories will get to 10^{-10} level. (similar to LHCb (?))

What we can learn from CLFV and other searches for new physics at the TeV scale (a_μ and Colliders):

$g-2$	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Some Flavor Violation
YES	NO	New Physics at the TeV Scale; Tiny Flavor Violation
NO	YES	New Physics Above TeV Scale; Some Flavor Violation – How Large?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?

Colliders	CLFV	What Does it Mean?
YES	YES	New Physics at the TeV Scale; Info on Flavor Sector!
YES	NO	New Physics at the TeV Scale; New Physics Very Flavor Blind. Why?
NO	YES	New Physics "Leptonic" or Above TeV Scale; Which one?
NO	NO	No New Physics at the TeV Scale; CLFV only way forward?

HOWEVER. . .

We have only ever objectively "seen" neutrino masses in long-baseline oscillation experiments. It is the clearest way forward!

Does this mean we will reveal the origin of neutrino masses with oscillation experiments? We don't know, and we won't know until we try!