Lepton flavor violation

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Lepton Flavor Violation

Compare

$\mu \to e\gamma$ vs $\nu_e \to \nu_\mu$ oscillations

- Measurements?
- Lepton flavor conservation?
- Predictions in the SM and in the νSM?

Bottom line

Any observation of LFV beside neutrino oscillations will be a sign of physics beyond the νSM

Outline

- What is flavor and how it is broken
- Flavor in the SM and in the νSM
- Specific charged leptons processes and their interplay
- BνSM LFV in neutrino oscillation experiments

What is flavor?

What is flavor?

- A name of a global accidental symmetry!
- In the SM the lepton sector has a symmetry of

$$U(1)_e \times U(1)_\mu \times U(1)_\tau$$

- I will not talk today about total lepton number
- All accidental symmetries are broken by NR terms
  - At what order Lepton flavor is broken?
  - Dimension 5. This is the $LLHH$ term that gives Majorana masses to the neutrinos

Flavor in the SM

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Flavor is all about moving between the bases

- Flavor basis: The couplings to the W are diagonal: $u \leftrightarrow d$, $c \leftrightarrow s$, $t \leftrightarrow b$ and $\nu_e \leftrightarrow e$, $\nu_e \leftrightarrow \mu$, $\nu_\tau \leftrightarrow \tau$
- Mass basis: Where the mass matrix is diagonal
- Flavor violation is when these two cannot be the same

Approximate symmetries

- When the breaking is governed by a small parameter
- For example, m_u/Λ_{QCD} and Λ_{QCD}/m_b
- When we have approximate symmetries we usually use the symmetry basis and apply perturbation theory
- All that is at the level of $\mathcal{L}$
- What is the small parameter in the lepton sector?

Small parameters

How about

$$m_\nu$$

Is it small?

Small parameters

How about

$$m_\nu$$

Is it small?

It depends on the experiment!

- For oscillation experiments we have

$$m_\nu \tau = m_\nu \frac{t}{\gamma} = m_\nu t \frac{m_\nu}{E} = \frac{m_\nu^2 L}{E}$$

- The point is: the small $1/L$ makes $m_\nu \tau$ large
- What about processes like $\mu \to e\gamma$?

Flavor in the SM

Flavor in the SM

- We can always diagonal the mass basis of the fermions
- Are the couplings in this basis diagonal?
- For the photon and gluon it must be (why?)
- For the Higgs and the Z it is diagonal, but it is delicate
- For the W, in general, it is not diagonal
  - Unless, one type of fermions is degenerate

Flavor in the SM is far from generic

FCCCs and GCCCs

- FCCCs $\equiv$ Flavor Changing Charged Currents
- GCCCs $\equiv$ Generation Changing Charged Currents

In particular we care about GCCCs as it violates flavor

- In the quark sector we have GCCCs like $b \to c\ell\nu$
- In the leptons we have FCCCs like $\mu \to e\nu\bar{\nu}$
- Can $\mu \to e\nu\bar{\nu}$ also be GCCCs?

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- If we could measure the neutrino mass eigenstate

$$\mu \to e\nu_1\bar{\nu}_1$$

Since we cannot measure neutrino mass eigenstates, we cannot measure GCCCs in the lepton sector

FCNCs

FCNCs $\equiv$ Flavor Changing Neutral Currents

- $\mu \to eee$ vs $\mu \to e\nu\bar{\nu}$. Also $b \to c\ell\nu$ vs $b \to s\ell^+\ell^-$
- In Nature, FCNCs are highly suppressed (check!)
  - Historically, $K \to \mu\nu$ vs $K_L \to \mu\mu$
  - FCNSs in charm, B and top are also small
- In the SM there are no FCNCs at tree level. Very nice!
- The coupling of the four neutral bosons of the SM: g, γ, Z, h, are diagonal
- We can have FCNCs at one loop (two charged current interactions give a neutral one)

FCNCs are a big issue for BSM !

Higgs tree level FCNCs

- The Higgs is a possible source of FCNCs
- Yet, the Higgs couplings are aligned with the masses
- With one Higgs doublet, the mass matrix is aligned with the Yukawa. $\phi \sim v + H$

$$\mathcal{L}_m \sim Y\, v\, \bar{d}_L d_R \qquad \mathcal{L}_{int} \sim Y\, H \bar{d}_L d_R$$

- With two doublets we have tree level FCNCs

$$\mathcal{L}_m \sim \bar{d}_L (Y_1 v_1 + Y_2 v_2) d_R \qquad \mathcal{L}_{int} \sim H_1 \bar{d}_L Y_1 d_R$$

- What about the νSM and the lepton sector?

Z exchange FCNCs

- For broken gauge symmetry there are no FCNCs when: "All the fields with the same QN in the unbroken symmetry also have the same QN in the broken part"
- When you have time try to prove it
- In the SM the Z coupling is diagonal since all $q = -1/3$ RH quarks are $(3,1)_{-1/3}$ under $SU(2) \times U(1)$
- Adding quarks with different representations can generate tree level FCNCs Z couplings, for example adding a LH fermion with $\psi_L(3,1)_{-1/3}$
- Same condition for new neutral gauge bosons (usually denoted by Z')
- What about the lepton sector?

GIM and FCNCs

- In the SM (as well as in the νSM) FCNCs arise only at one loop
- It is further suppressed by the GIM mechanism
- The small parameter is m_f/m_W
- Rates goes like $(m_f/m_W)^4$
- FCNCs in charged leptons are down by

$$\left(\frac{m_\nu}{m_W}\right)^4 \sim 10^{-48}$$

LFV in the νSM

Just like in the quark sector but...

- We cannot measure neutrino mass eigenstates, so we cannot see GCCCs
- We only can probe FCNCs
  - We can see them in neutrino oscillations due to the large L
  - LFV effects are very small in processes like $\mu \to e\gamma$ due to the leptonic GIM mechanism

Bottom line (restated)

Any signal of FCNCs in charged leptons is a signal of physics beyond the νSM

The specifics of LFV

CLFV processes

- Fully leptonic with muons

$$\mu \to e\gamma, \quad \mu \to eee, \quad \mu^+ e^- \to \mu^- e^+$$

- Similar with taus

$$\tau \to eee, \quad \tau \to \mu ee, \quad ...$$

- Conversions

$$\mu \to e \text{ conversion}$$

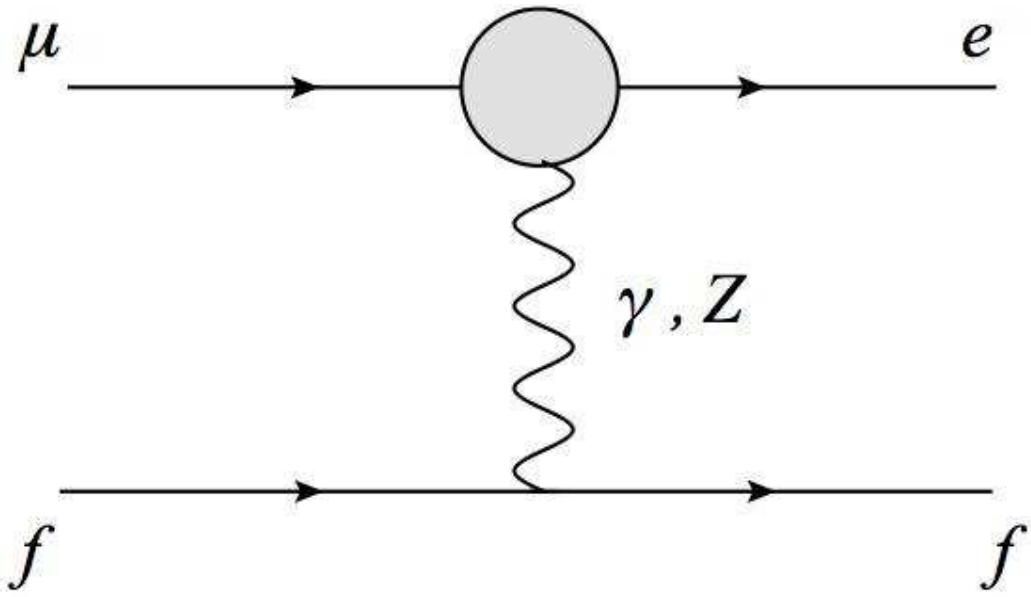
- Semileptonic decays

$$K_L \to \mu e, \quad B \to \mu e, \quad \tau^- \to \pi^- e^+ e^-, \quad ...$$

NP model in general contribute to all of them

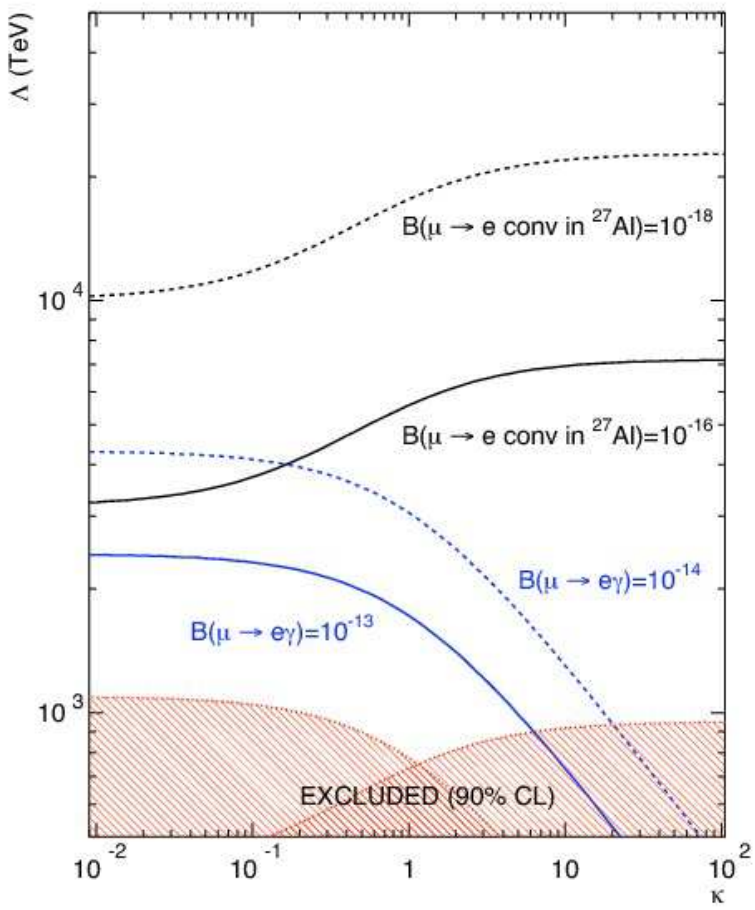
Interplay within the charged leptons

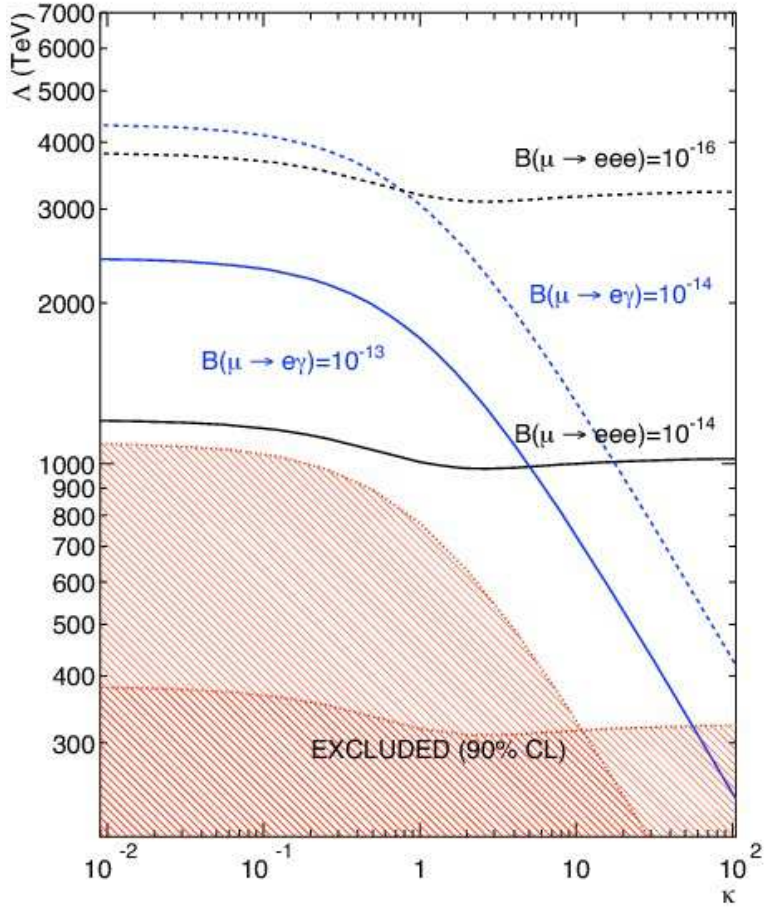
- There are many operators. Each mode is sensitive to a different set of them
- Example: $\mu \to e\gamma$ vs $\mu \to eee$ vs $\mu \to e$ conversion



Discriminating power

DeGouvea, Vogel, 2013





$\kappa \sim C_1/C_2$ is the ratio of the $\mu e \gamma$ to the $\mu e f \bar{f}$ operators

Relation to neutrinos

BνSM, CLFV and NSIs

If we find $\tau \to eee$, will it affect neutrino oscillations?

BνSM, CLFV and NSIs

If we find $\tau \to eee$, will it affect neutrino oscillations?

Yes

- Neutrino oscillations are sensitive to Non Standard Interactions (NSIs) or we can call them BνSM
- NSIs can show up in matter effects or in the production or detection processes
- Can be complementary to charged lepton decays
  - The effect in oscillations scale like the amplitude
  - The effect in τ decays scale like the amplitude squared
- Enhanced sensitivity in neutrino oscillation experiments

NSIs in neutrinos

- If the new operators involve the lepton doublets

$$\mathcal{A}(\tau \to \mu) \sim \mathcal{A}(\nu_\tau \to \nu_\mu) = \varepsilon$$

- For neutrino oscillation we have interference

$$\Gamma(\tau \to \mu X) \propto |\varepsilon|^2 \qquad P(\nu_\mu \to \nu_\tau) \propto |\exp(-i\Delta E t) + \varepsilon|^2$$

- For small $x = \Delta m^2 L/(4E)$ we get

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2x\mathcal{I}m(\varepsilon)$$

Neutrinos and charged leptons

$$P(\nu_\mu \to \nu_\tau) \propto |\varepsilon|^2 + x^2 + 2xIm(\varepsilon) \qquad \Gamma(\tau \to \mu X) \propto |\varepsilon|^2$$

- NSIs affect oscillation experiments by changing the L/E dependence
- Both neutrinos and charged leptons can be relevant (linear vs quadratic)
- Charged lepton decays and neutrino oscillations can probe the same flavor violating operators
- The bound on muon CLFV are too strong to make NSIs in the $\mu - e$ sector relevant to neutrino oscillations

Conclusions

Bottom line (again)

Any observation of LFV beside neutrino oscillations will be a sign of physics beyond the νSM