Neutrinos and Flavor Physics

Yuval Grossman

Cornell

Outline

- A reminder: a few words about the big picture
- Flavor in the SM and in the νSM
- Flavor changing for quarks and leptons
- Beyond the νSM

What is HEP

A very simple question

$$\mathcal{L} = ?$$

Building Lagrangians

- Choosing the generalized coordinates (fields)
- Imposing symmetries and how fields transform (input)
- The Lagrangian is the most general one that obeys the symmetries
- We truncate it at some order, usually fourth

Accidental symmetries

Two kinds of symmetries

- Input: symmetries we impose
- Output: symmetries due to the truncation (accidental)
- Example: The period of a pendulum does not depend on the amplitude

The Standard Model (SM)

It explains almost everything we see in Nature

- The symmetry is $SU(3)_C \times SU(2)_L \times U(1)_Y$
- There are three generations of fermions (flavors) and one scalar (Higgs)

$$Q_L(3,2)_{+1/6} \qquad U_R(3,1)_{+2/3} \qquad D_R(3,1)_{-1/3}$$
$$L_L(1,2)_{-1/2} \qquad E_R(1,1)_{-1} \qquad H(1,2)_{+1/2}$$

- H gives $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$
- C, P, and CP are violated. CPT is conserved
- At $d=4$, B and L_i are accidental symmetries
- In the SM neutrinos are exactly massless

A SM vs The SM

- “A SM” is the theory without the values of the parameters
- “The SM” is the one we have with a given set of values for the parameters

It is important to understand what predictions are from “A SM” and what are only in “The SM”

Can you think of a few examples for each case?

The νSM

The SM up to dim 5 is called the νSM

- The only new terms are of the form

$$\mathcal{L}_{d=5} \sim \frac{LL\phi\phi}{\Lambda}$$

  - Neutrino masses
  - Lepton mixing
  - All L_i are broken (B is broken at $d = 6$)
- The νSM is one way to explain ν masses but not the only way
- There are many ways to “UV-complete” the νSM. Type 1 seesaw is a well known example

The SM: Flavor physics

Flavor physics

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

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

- For quark we have six flavors, one for each quark. It is a $U(1)$ charge
- For the leptons we use flavor for doublets, e and ν_e carry the same flavor

What is flavor physics

- Flavor is conserved by the strong and EM interactions
- Quark flavor is not conserved by the weak interaction
- Quark flavor is an approximate quantum number (the weak interaction is weak)
- When we know all the flavors we do not know all the masses and vice versa
- This is manifested by the fact that in the mass bases the couplings of the W are not diagonal

The bases

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

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

- Flavor is all about moving between the bases
- The unitary matrix that rotates between these two bases is called
  - the CKM matrix for quarks
  - the PMNS matrix for leptons

The CKM matrix

- 4 parametrs 3 angles and a CPV phase

$$V_{ij} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- There are many ways to parametrize it
- CPV require $\sin\delta \neq 0$

The CKM matrix in *the SM*

- The CKM matrix is close to a unit matrix ($\lambda \sim 0.2$)

$$V_{ij} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

- The Wolfenstein parametrization

$$V_{ij} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

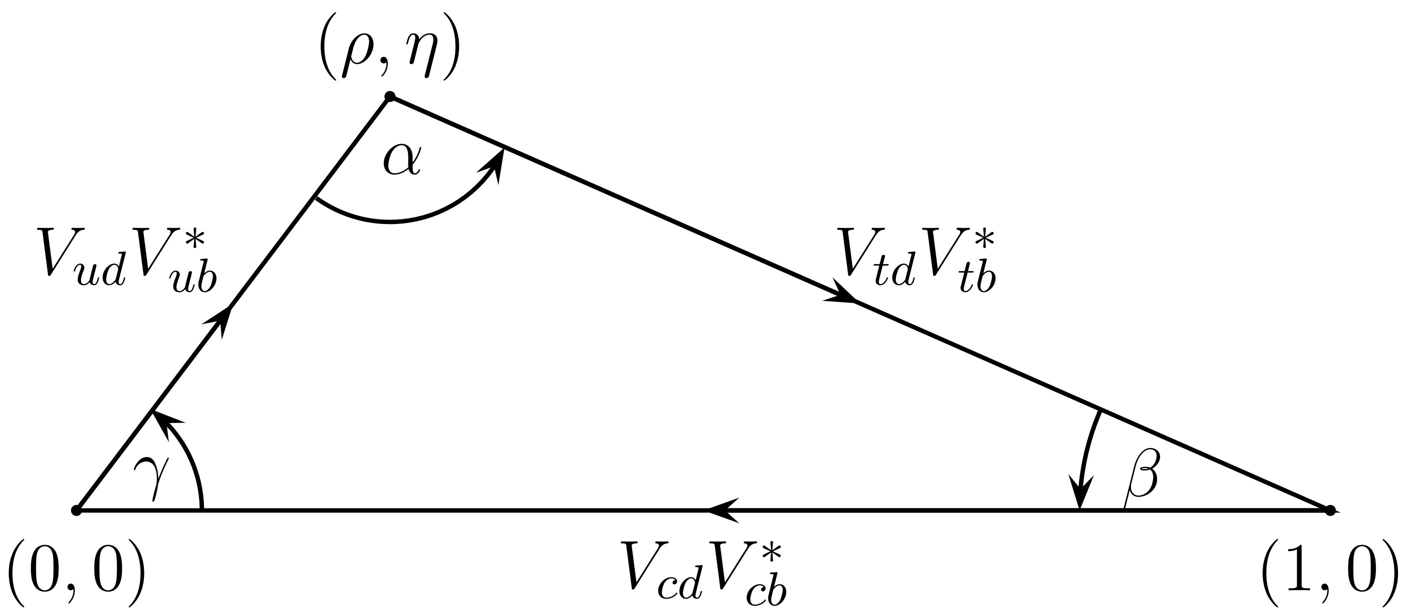
- $\lambda \approx 0.22$ and $A \approx 0.83$ are well determined while ρ and η are harder to probe

The Unitarity Triangle

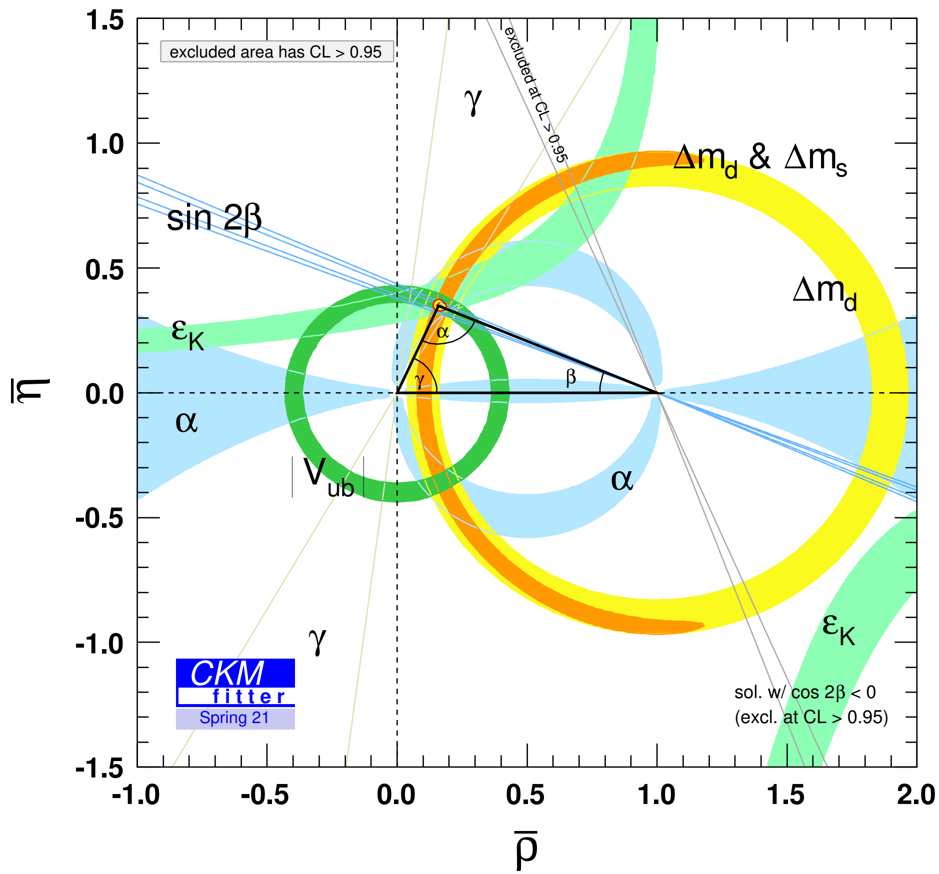
- Since the CKM is unitary its elements satisfy

$$\sum_k V_{ik} V_{jk}^* = \delta_{ij}$$

- A nice way to describe it



The data



The CKM picture of quark flavor is confirmed

Lepton flavor in the νSM

The PMNS matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} =$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix}$$

- 6 parametrs: 3 mixing angles, one Dirac phase, and two Majorana phases

The PMNS matrix in *the* νSM

$$\sin^2\theta_{12} = 0.310 \pm 0.013,$$
$$\sin^2\theta_{23} = 0.565 \pm 0.022,$$
$$\sin^2\theta_{13} = 0.0226 \pm 0.0007$$

$$|U| = \begin{pmatrix} 0.80 - 0.84 & 0.52 - 0.59 & 0.14 - 0.16 \\ 0.23 - 0.48 & 0.46 - 0.67 & 0.65 - 0.78 \\ 0.30 - 0.53 & 0.50 - 0.70 & 0.61 - 0.75 \end{pmatrix}$$

- The Dirac phase, δ, and the two Majorana phases, α_1 and α_2 are still not experimentally determined

CKM vs PMNS

- Both are 3×3 unitary matrix (why both?)
- The index ordering is different ($U^\dagger \sim V$)
- Majorana phases only in the PMNS
- How we use them
  - Quarks: the W coupling not diagonal
  - Leptons: The neutrino mass matrix non diagonal
- in the CKM all three angles are small. In the PMNS only one is small
- The experimental determinations of the CKM is much better

Flavor changing

FCNC and FCCC

How flavor is changed?

- FCCC: Flavor changing charged current (quarks vs leptons)

$$s \to u e \bar{\nu}_e, \qquad \mu \to \nu_\mu e \bar{\nu}_e$$

- FCNC: Flavor changing neutral current

$$c \to u e^+ e^-, \qquad \mu^- \to e^- e^+ e^-$$

- We have FCNC in the up sector and in the down sector. FCCC always involve both sectors

FCNC for quarks

- For quarks, FCCC are the dominant decay, by far
- In Nature FCNC are highly suppressed
  - Historically, $K \to \mu\nu$ vs $K_L \to \mu\mu$
  - The suppression was also seen in charm and B
- In the SM there are no FCNC at tree level. Very nice!
  - In the SM we have four neutral bosons, g, γ, Z, h. Their couplings are diagonal
  - The reasons why they are diagonal, and what it takes to have FCNC, is not always trivial
  - Of course we have FCNC at one loop (two charged current interactions give a neutral one)

Tree level FCNC

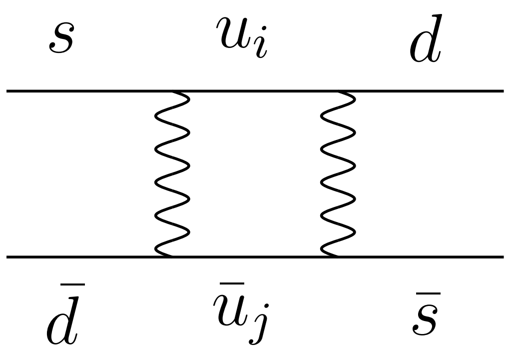
- For exact gauge interactions the couplings are always diagonal
- With one Higgs doublet, the mass matrix is aligned with the Yukawa couplings
- For broken gauge symmetry there is no FCNC when: "All the fields with the same QN in the unbroken symmetry also have the same QN in the broken part"
- In the 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 FCNC Z couplings, like $\psi_L(3, 1)_{-1/3}$

FCNC at one loop

- We understand why FCNC are suppressed in “a SM”: There is no tree level exchange
- Yet, there are more suppression factors in “The SM”
  - CKM factors
  - Mass factors: GIM mechanism
- The loop factor in “a SM” is universal
- The other factors in “the SM” are not universal

Example: FCNC in Meson mixing

- In the SM the mixing is giving by the box diagram



- The result is:

$$\frac{\Delta m_K}{m_K} \approx C \times \frac{g^4}{16\pi^2} \times |V_{cs}V_{cd}|^2 \times \frac{m_c^2}{m_W^2}.$$

- We see the loop, CKM, and GIM factors explicitly

Lepton flavor changing

Lepton Flavor Violation (LFV)

- By LFV we refer to change of generation number. This is not what we refer to as flavor in the quark sector.
- Muon decay is not LFV
- LFV was only observed in neutrino oscillation experiments
- We cannot observed generation changing FCCC with leptons (why is that?)
- We cannot observe FCNC with neutrinos (why is that?)
- All we saw and keep looking for is FCNC in the charged lepton sector

LFV with charged leptons

Compare

$$\mu \to e\gamma \qquad \text{vs} \qquad \nu_e \to \nu_\mu \text{ oscillations}$$

- Oscillations were observed, and it is explain in $the\ \nu SM$
- In the νSM we expect

$$BR(\mu \to e\gamma) \sim 10^{-50}$$

- Why, within the νSM we expect to see one and not the other?

LFV in the νSM

- We cannot measure neutrino mass eigenstates, so we cannot see LFV FCCC
- We only see LFV with FCNC in the charged lepton sector
- LFV effects are very small in processes like $\mu \to e\gamma$ due to the leptonic GIM mechanism
- We can see them in neutrino oscillations due to the large L
- Both neutrino oscillations and $\mu \to e\gamma$ are FCNC in the charged lepton sector
- Any signal of FCNC in charged lepton decays is a signal of physics beyond the νSM

The νSM picture of flavor

- The only LFV effects we can see are in neutrino oscillation
- We do not have sterile neutrinos
- The PMNS is a unitary 3×3 matrix
- The neutrinos have Majorana masses

Beyond the νSM

LFV Beyond the νSM

Many ways to go beyond the νSM

- Adding more states that cause LFV charged lepton decays
- Adding sterile neutrinos
  - Non-unitary PMNS
  - Tree level FCNC
- Adding other interactions (NSI)

CLFV processes

- Fully leptonic with muons

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

- Similar with taus

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

- Conversions

$\mu \to e$ conversion

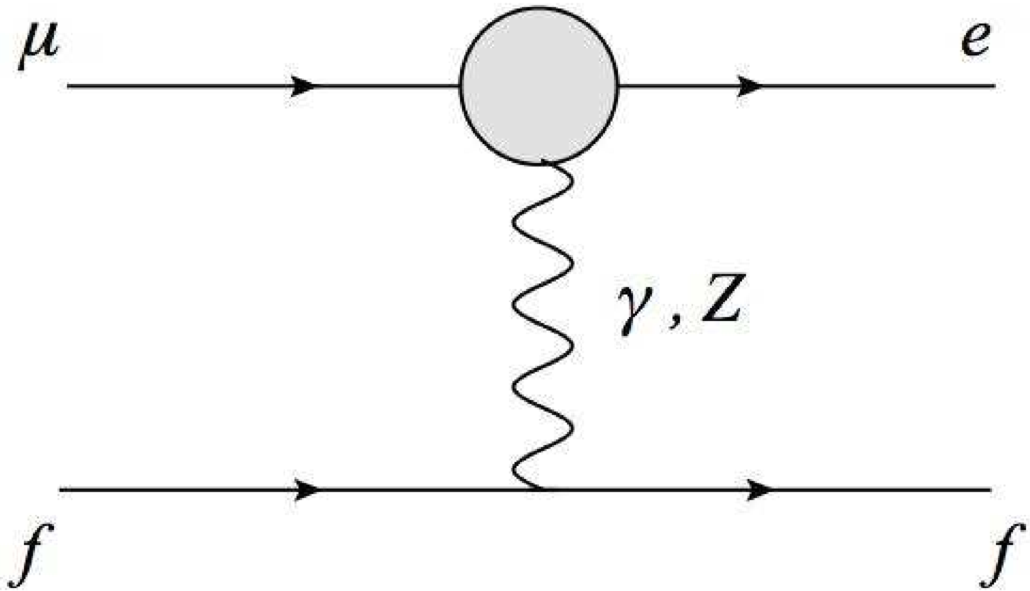
- Leptonic and semileptonic decays of hadrons

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

Beyond νSM models, in general, contribute to all of them

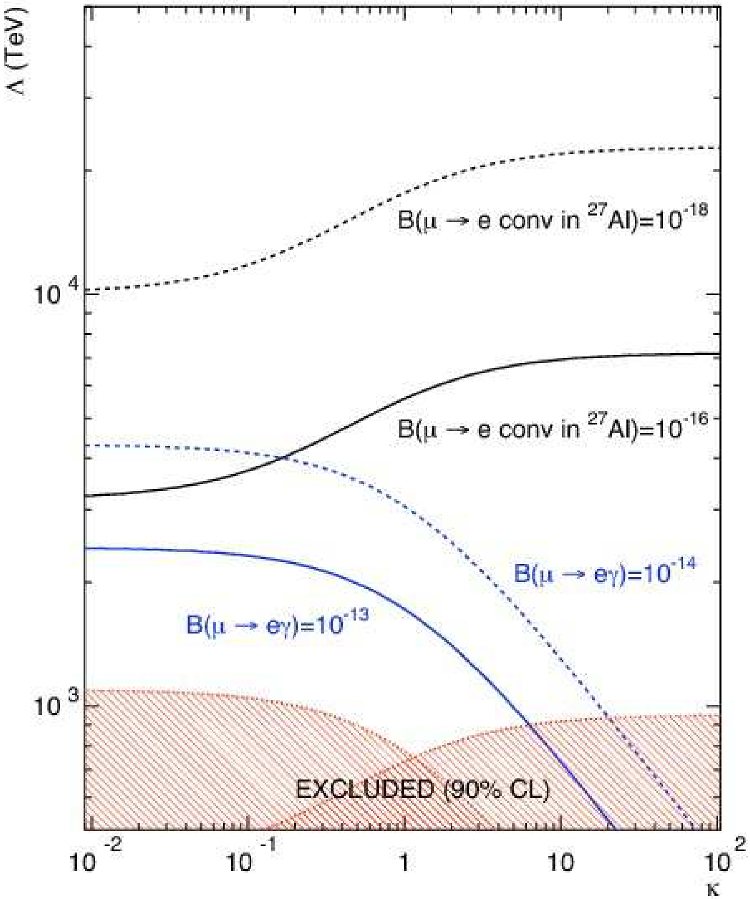
Interplay within the charged leptons

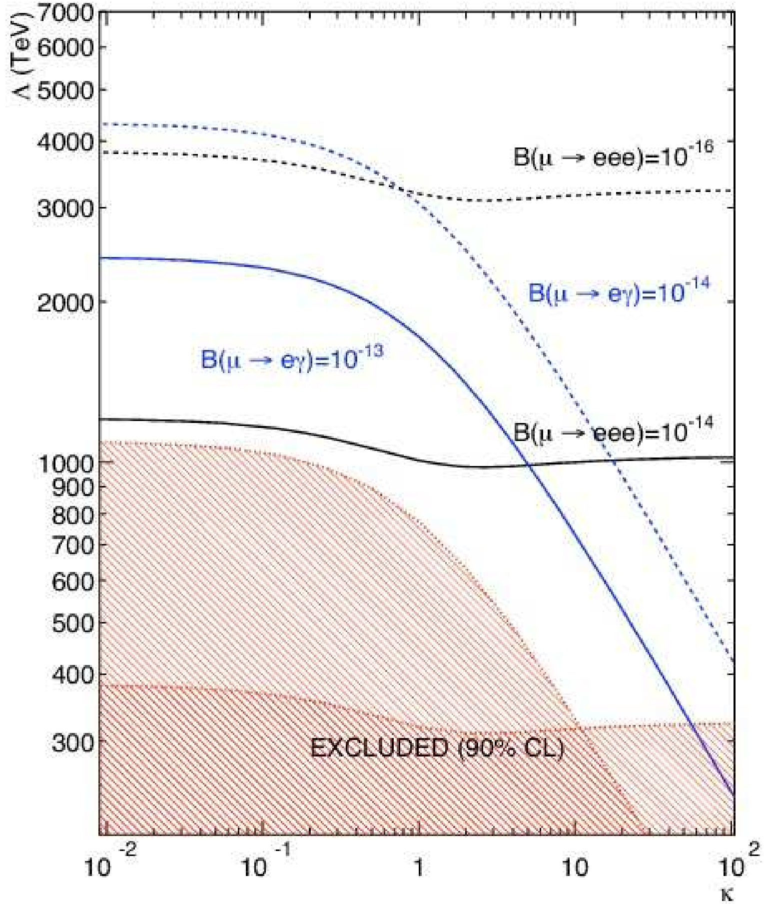
- There are many operators that gives LFV beyond the νSM. Each mode is sensitive to a different set of them
- Example: $\mu \to e\gamma$ vs $\mu \to eee$ vs $\mu \to e$ conversion



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

Exmaple of beyond the νSM: NSI

Adding new interaction to the SM

$$\mu e L_e L_\tau \to \mu e \nu_e \nu_\tau$$

- How it affects neutrino oscillation experiments in vacuum?
- How it affects neutrino oscillation experiments in matter?
- How it is related to LFV tau decay?

NSI in BνSM

- Neutrino oscillations are sensitive to NSI. For example, $\mu \to e\bar{\nu}_e\nu_\tau$ can give τ at the detector even at $L = 0$.
- NSI 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

Conclusions

Flavor is fun

$$\mathcal{L} = ?$$

- We learned so much from flavor
- The CKM picture for quarks is confirmed
- The PMNS picture for leptons is actively probed