Non-standard neutrino interaction at one loop

Itay Nachshon

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In collaboration with Brando Bellazzini, Yuval Grossman, and Paride Paradisi.

Cornell University

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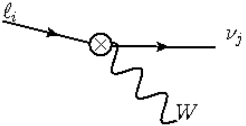
Non standard interactions

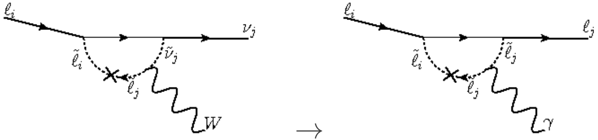
- Usually neutrinos are produced in lepton flavor states. Then they oscillate causing LFV.
- Non standard interaction can cause LFV to happen at production or detection. Thus, without oscillation we can have an amplitude with LFV:

$$\langle \nu_{\mu,\text{source}} | \nu_{\tau,\text{detector}} \rangle = \epsilon_{\mu,\tau} \neq 0.$$



Lepton flavor constraints

- If we have new physics at the TeV scale that has LFV in neutrinos then we can also expect LFV for charged leptons: $\mu \to e\gamma$, $\mu \to eee$, $\tau \to \mu\gamma$.
- We expect these processes to be of the same order,



$$BR(\tau \to \mu\gamma) \sim \left|\mathcal{A}_{\rm NSI}\left(\tau \to \mu\gamma\right)\right|^2 \sim \left|\epsilon_{\tau,\mu}\right|^2.$$

- Thus one can expect LFV NSI in neutrinos to be constrained.

NSI + oscillations

- Consider the case where the detector is at a distance much smaller then one oscillation length, $\left(x = \Delta m^2 L/4E \ll 1\right)$.
- Then we will have an amplitude with,
  - standard interactions + oscillation $\mathcal{A}_{\text{osc}}\left(\nu_\mu \to \nu_\tau\right) \approx ix$,
  - and NSI + no oscillation $\mathcal{A}_{\text{NSI}}\left(\nu_\mu \to \nu_\tau\right) = \epsilon_{\mu\tau}$.
- Thus the total probability is given by,

$$\mathcal{P}\left(\nu_\mu \to \nu_\tau\right) \approx \left|\mathcal{A}_{\text{osc}} + \mathcal{A}_{\text{NSI}}\right|^2 \approx x^2 + \left|\epsilon_{\mu\tau}\right|^2 + 2x\mathcal{I}m\left(\epsilon_{\mu\tau}\right).$$

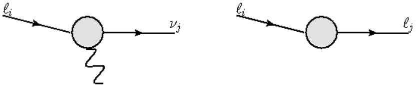
NSI + oscilations enhancement

$$\mathcal{P}(\nu_\mu \to \nu_\tau) \approx |\mathcal{A}_{\rm osc} + \mathcal{A}_{\rm NSI}|^2 \approx x^2 + |\epsilon_{\mu\tau}|^2 + 2x\mathcal{I}m(\epsilon_{\mu\tau}).$$

- The different x dependent make it measurable.
- If $x \gg \epsilon_{\mu\tau}$, then the NSI term appears linearly in the interference term.
- A square root enhancement relative to the bound set by LFV decays of charged leptons. (This is why we pick here $\nu_\mu \to \nu_\tau$. It has the smallest bound coming from $\tau \to \mu\gamma$.)
- To get interference we need CPV.

One loop effective theories

- To study NP contribution to $\epsilon_{\alpha\beta}$ we can study large number of diagrams but we may double count.
  Instead, since the NP is at the TeV scale calculate the effective vertices to some loop order. For example



- Then choose a convenient basis (mass basis) and perform a tree-level calculation.
- In general we will have contributions to the kinetic term, the interaction term and the mass term.

EW symmetry breaking

- Consider corrections to the W interaction. Without electroweak breaking, we should find that the kinetic term and the interaction term are aligned,

$$\mathcal{L}_{\text{eff}} \supset Z_{\alpha\beta}\bar{\ell}_\alpha i \not{D}\ell_\beta.$$

  $\Rightarrow$ After canonical quantization the effect should go away.

- Thus, the correction to these interaction should depend on the VEV of EWSB.
  (Clearly not considering the kinetic term would be a mistake.)

Finding $\epsilon_{\alpha\beta}$ for W interactions.

- After calculating the one-loop effective terms, move the mass basis.
- We have two diagrams for NSI: we have to consider the effect both at the source of the neutrinos and at the detection.
- With the off-diagonal correction of the NP to the kinetic term η^{ℓ}, η^{ν} and the interaction term η^{W}, we can find,

$$\epsilon^{W}_{\alpha\beta} = \epsilon^{s*}_{\alpha\beta} + \epsilon^{d}_{\beta\alpha} = \eta_L^{W\dagger} + \eta_L^{W} - \eta_L^{\ell} - \eta_L^{\nu}.$$

(If $SU(2)_L$ is a good symmetry, all terms cancel.)

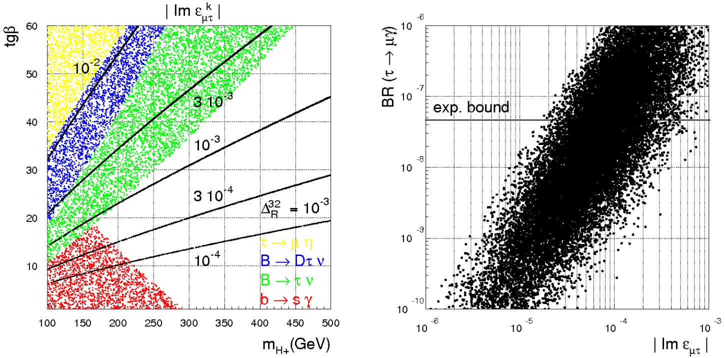
Notes on the effective interactions

- The rotation to the mass basis of the leptons, only comes in at two-loop order.
- $\epsilon^{W}_{\alpha\beta}$ is finite. While diagonal η^{a} terms may diverge, $SU(2)_L$ protects the physical result.
- We need CPV terms. These happens when the η's (correction to the different terms from NP) have imaginary parts.

Notes on the effective interactions

- We also need to consider contributions arising from dimension-six, four-fermion operators.
  May come, for example, from box diagrams like gaugino/sfermion boxes.
- Also consider charged scalar LFV interaction (such as Higgs mediated LFV in the MSSM).
- The same $\epsilon_{\alpha\beta}$ term can also arise when the 3×3 PMNS matrix for the light neutrinos is not unitary (take *k* heavy singlet neutrinos). We cannot disentangle the underlying mechanism which generates the $\epsilon_{\alpha\beta}$ term.
- We can calculate the corrections to the kinetic, interaction and mass term to any TeV NP theory. By using the method that was described here, we can find ϵ.

MSSM example



Left: NSIs in the process $K \to \ell\nu$ induced by Higgs mediated effects. Right: NSIs in the process $\mu \to e\nu\bar{\nu}$ induced by W-penguin and gaugino/slepton boxes.

Conclusions

- Neutrino oscillations can probe NSIs
- NSI in neutrino can be observed even when there are bounds on LFV from charged leptons because of an enhancement due to interference with the tree-level contribution.
- In general, the size of one-loop NSIs is quite small, $\epsilon \approx \mathcal{O}\left(10^{-3}\right)$. That could be probed in the next generation of neutrino oscillation experiments.
- To calculate the effect, one only needs to calculate loop corrections from NP to the kinetic, interaction and mass terms. Then rotating to the mass basis will give the interaction term $\epsilon_{\alpha\beta}$.