What is the Energy Scale of the Physics Responsible for Neutrino Masses?

NORTHWESTERN UNIVERSITY

André de Gouvêa, James Jenkins (Northwestern University)

Based on Phys. Rev. **D77**, 013008 (2008)

Motivation

Oscillation, kinematic and cosmological experiments indicate that neutrino masses are non-zero but unusually small. A popular attempt at explaining this fact is to introduce "naturally coupled" (*i.e.* order one dimensionless parameters) new physics at 10^{12} TeV or so, well beyond the reach of direct search experiments. "Theoretical simplicity" is behind this prediction. In general, any ultraviolet new physics that breaks lepton number will induce non-zero Majorana neutrino masses, and the new physics scale that leads to the observed neutrino masses can be significantly less than 10^{12} TeV. We perform a model independent study of all scenarios in order to understand the allowed theory space and gauge whether the mechanism behind neutrino masses can be subject to direct experimental confirmation.

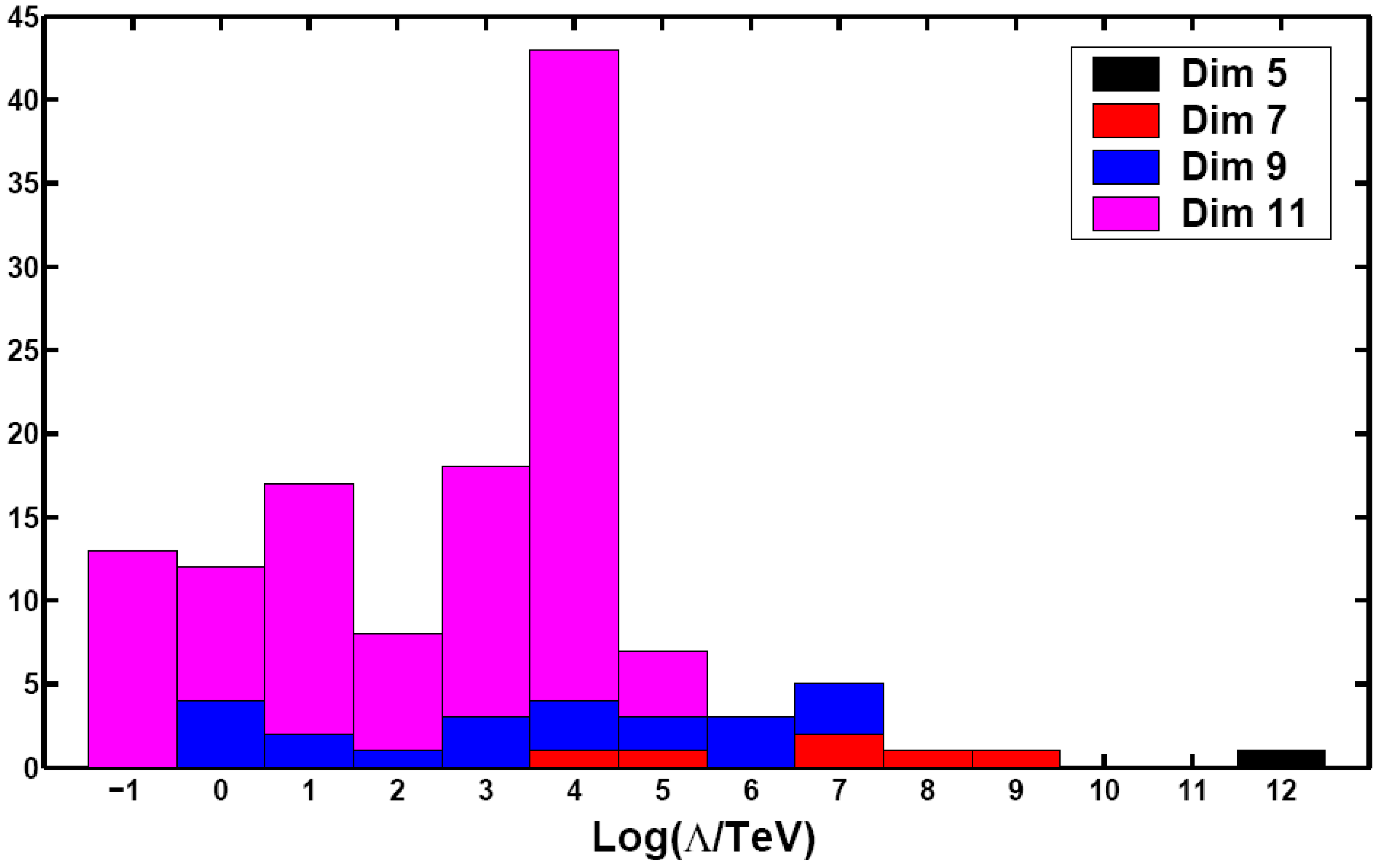
The Scale Of New Physics: Λ

The new high scale (at or above the electroweak scale) physics responsible for neutrino mass generation will manifest itself via higher-dimension effective operators to low energy observers. These operators must be Lepton Number Violating (LNV) by two units to yield Majorana neutrino masses. In general, any LNV operator will yield a Majorana neutrino mass at some order in perturbation theory.

We survey all LNV operators of mass dimension up to and including eleven. These are 129 $SU(3)_c \times SU(2)_L \times U(1)_Y$ operators composed of the standard model field content, and we assume no new sources of electroweak symmetry breaking. For physics captured at leading order by a new $d \geq 5$ dimensional operator $\mathcal{O}^d$, the relevant leading-order effective Lagrangian is

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_i \frac{\lambda_i \mathcal{O}_i^d}{\Lambda^{d-4}}, \qquad (1)$$

where the sum is over the flavor content of the operator. *Λ is the ultraviolet energy scale associated to the operator, below which new degrees of freedom are guaranteed to exist.* For this analysis we assume that the dimensionless constants λ_i are universally order one, and that Majorana neutrino masses can be estimated from $\mathcal{O}^d$. Setting the derived radiatively generated mass equal to the experimental lower bound $m_\nu^{\max} > 0.05$ eV, we extract Λ for each operator.



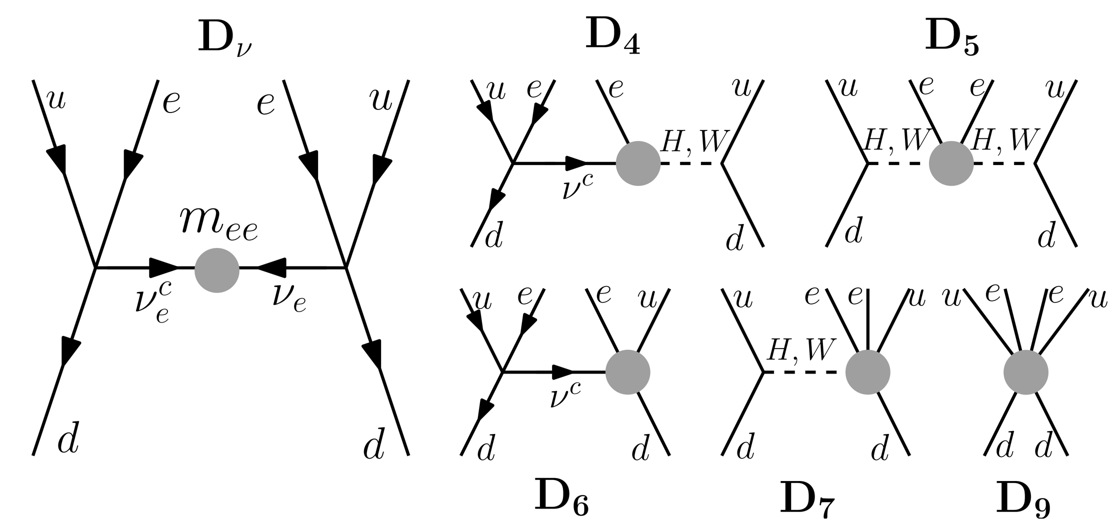
The distribution above spans over 13 orders of magnutude. While most are still out of experimental reach, several dimension 9 and 11 operators – if responsible for neutrino masses – point to new, naturally coupled *TeV* scale physics! This is due to the fact that neutrino masses generated from some higher dimensional operators are suppressed by multiple loop-factors and charged fermion Yukawa couplings. The results above are insensitive to the flavor structure of the effective operator, provided couplings to third generation charged fermions are order one. As far as neutrino mixing is concerned, the majority of the operators predict anarchic mass matrices – allowed by the neutrino data – while 20 predict more structured textures with a normal hierarchy. Only three of the 129 "types" of operators are disfavored by oscillation data.

General Predictions of LNV

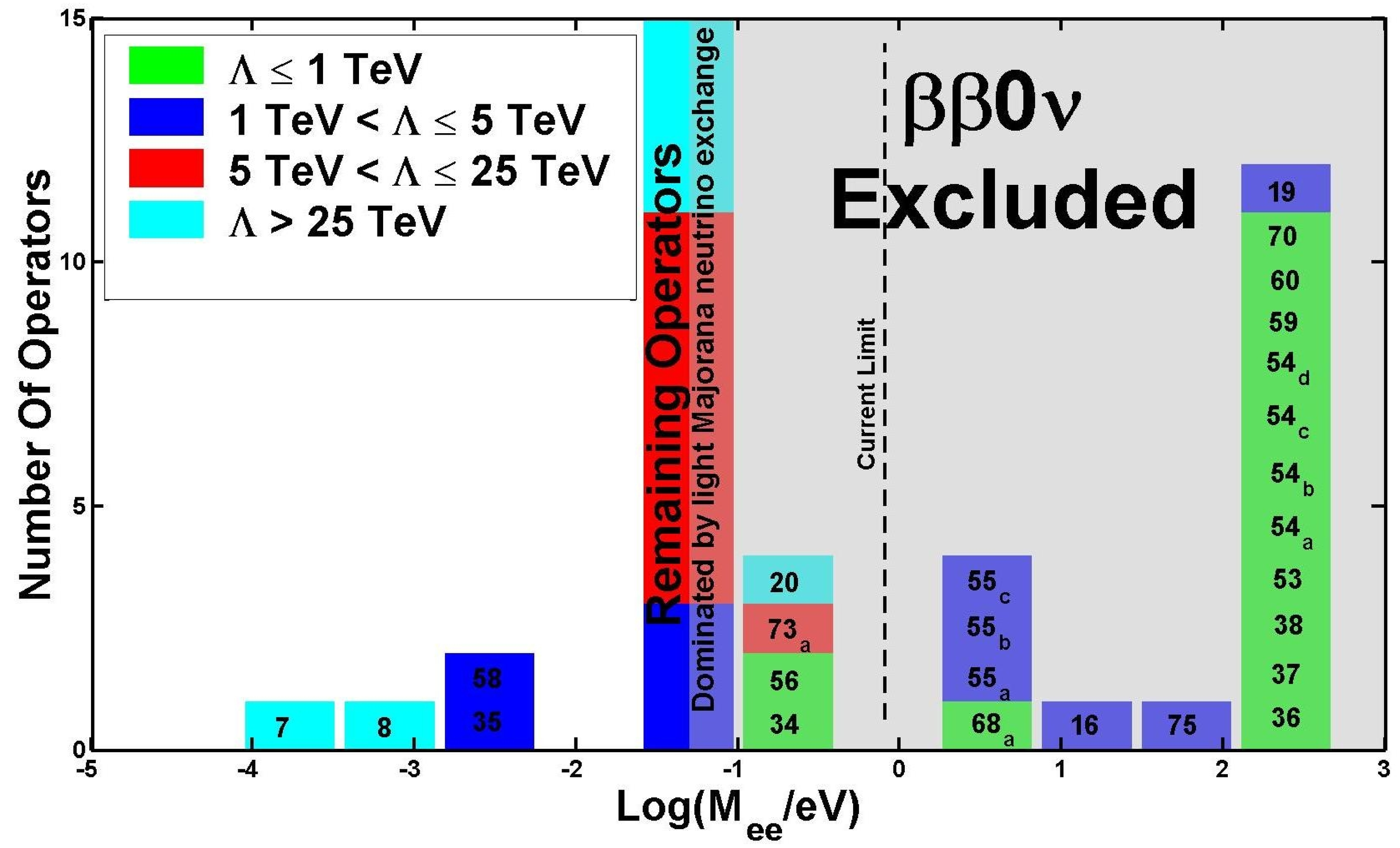
Given the derived scale Λ that yields naturally small neutrino masses with universal order one coupling constants, we estimate other observable consequenses for each operator. Below are histograms with estimates of rates for a variety of LNV experimental observables, color-coded by operator scale.

Neutrinoless Double Beta-Decay ($\beta\beta0\nu$)

$\beta\beta0\nu$ is typically the most powerful probe of LNV and Majorana neutrino masses. In the standard picture it proceeds via Majorana neutrino exchange (Diagram D_ν right) and $\Gamma_{\beta\beta0\nu} \propto m_{ee}^2$ in the flavor basis. With new LNV effective operators, other diagrams ($D_4 - D_9$) may yield dominant contributions leading to an effective $m_{ee}^{eff} \neq m_{ee}$. For low Λ scales, D_9 can greatly enhance $\Gamma_{\beta\beta0\nu}$ over naive mass matrix expectations.



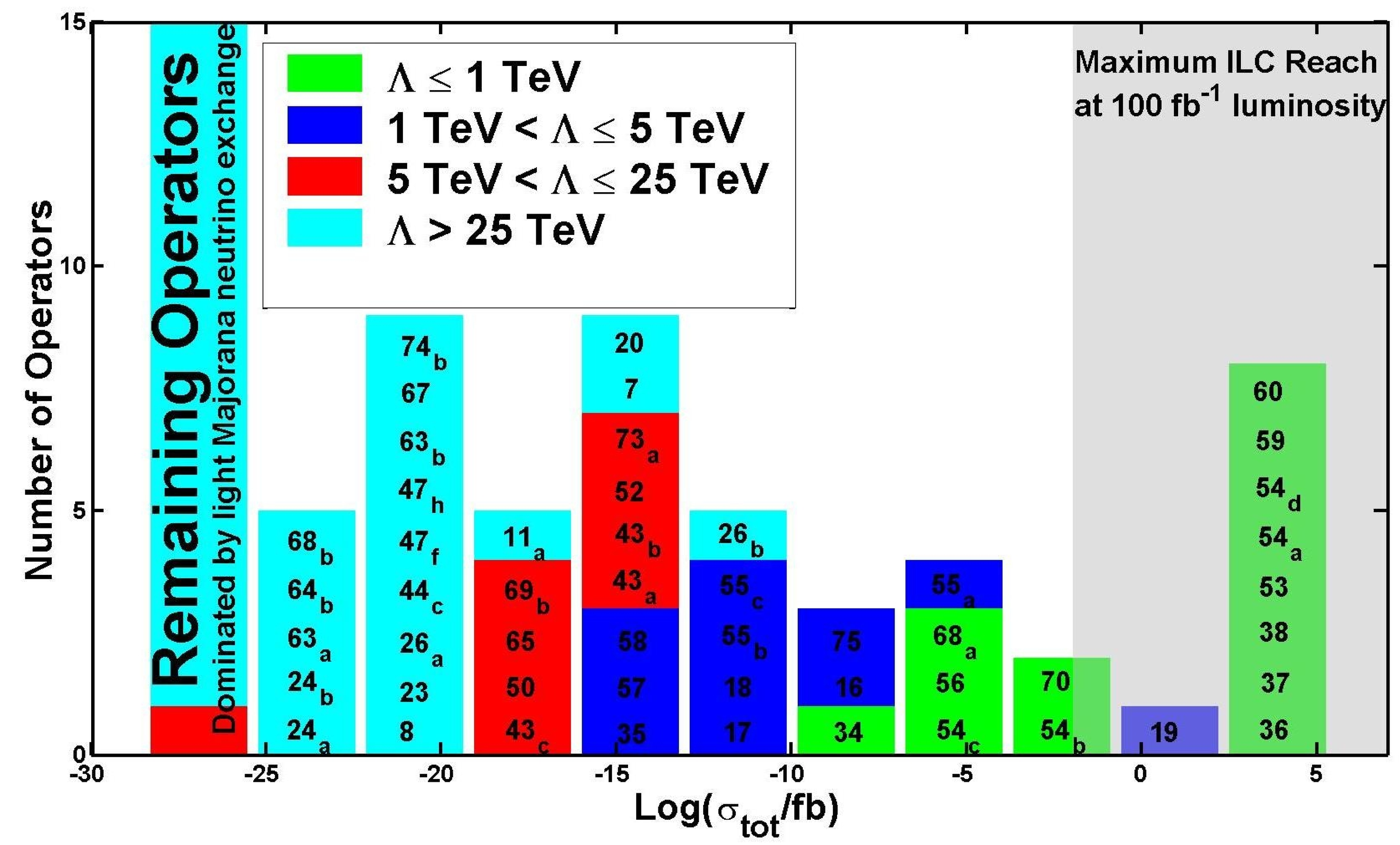
Below is a histogram of m_{ee}^{eff} for each effective operator. The shaded region will be probed by next generation experiments. Most predictions fall near the assumed $m_{ee} = 0.05$ eV, while a handful are greatly enhanced and disfavored by current data. These estimates depend on the new physics flavor structure and several estimates can be significantly reduced by suppressing couplings of the LNV new physics to first generation quarks.



ILC Collider Limits

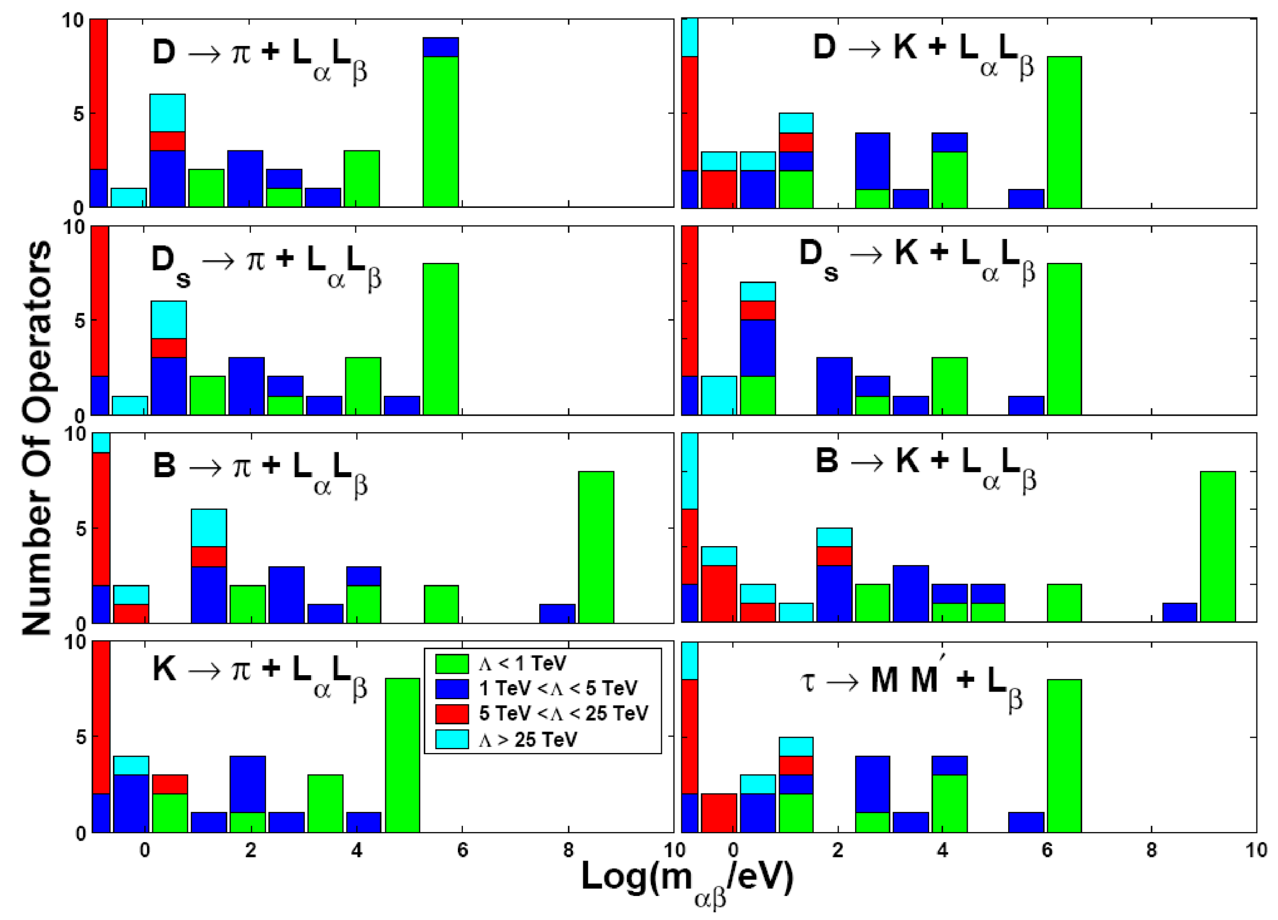
We study the process $e^-e^- \to 4$ jets and no missing energy at $\sqrt{s} = 1$ TeV. These are mediated by variants of the Feynman diagrams depicted above ($D_\nu - D_9$). The histogram below depicts estimates of the cross-section for these virtually mediated processes, along with the ILC reach assuming 100 fb^{-1} of integrated luminosity. Resonant effects in the case of sub-TeV new degrees of freedom will enhance this rate. The diagnostic power of the ILC is enhanced if one has access to polarized electron beams.

The LHC is also sensitive to the same physics via searches for same-sign dileptons plus jets, and no missing energy. Generally, high energy hadron colliders can probe the full flavor structure of these operators via gluon fusion, but backgrounds are much higher.



Other Signals

We also consider effective operator signatures for rare LNV meson and τ decays. Similar to the $\beta\beta0\nu$ case, we extract limits on an effective $m_{\alpha\beta}^{eff} \neq m_{\alpha\beta}$ using variants of diagrams $D_\nu - D_9$. These results are depicted in the histograms below for several meson decay modes. These reactions are also sensitive to the flavor structure of the different operators. Unfortunately, thanks to small center of mass energies and limited sensitivity, associated rates are far below current experimental bounds. For example, the best limits from rare K decays – $m_{e\mu}^{eff} < 90$ GeV – are nearly 7 orders of magnitude above the largest expectations. Current bounds come closest to expectations in the B meson system. These are likely to improve with new data from the LHC and the Super-B Factory.



Conclusions

New LNV ultraviolet physics may be responsible for the observed tiny neutrino masses. If this is the case, we currently know very little about this new physics, which may manifest itself in a variety of different ways. Parameterizing the effects of the new physics via higher dimensional effective operators, we find that, even assuming all new couplings are order one, the new physics scale may lie anywhere between 100 GeV and 10^{12} TeV.

We further extract predictions for "all" new LNV physics scenarios. Many are already constrained by current oscillation and $\beta\beta0\nu$ data, and many more will be directly tested by future experiments. We point out that $\beta\beta0\nu$ is *not always* the best probe of LNV and Majorana neutrino masses. Finally, high energy colliders experiments (LHC, ILC) may provide a novel handle on the neutrino mass generating mechanism.