Exploring New Leptonic Physics With Effective Operators

A model independent survey of lepton number violation

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Why Lepton Number Violation (LNV)?

The Standard model is very successful... But there is reason to look beyond it!

Peculiar neutrino properties

- Only neutral fermion
- Unusually tiny masses compared to charged fermions
- Unusually large mixing compared to quarks

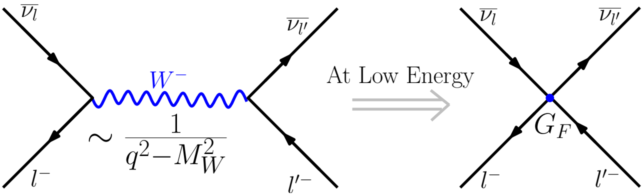
These properties may be related

$$\Delta\mathcal{L}_M = \frac{1}{2}m_M(\overline{\nu^c}\nu + \overline{\nu}\nu^c) \qquad \text{Majorana Mass Term}$$

Generated by some non-renormalizable LNV operator?

Effective Operators

What does new physics look like to a low energy observer?

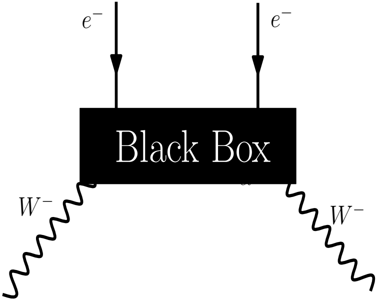


Effective Lagrangian at low energy

$$\mathcal{L}_{eff} = \mathcal{L}_{SM}(d = 4) + \sum_n \frac{1}{\Lambda^n} \mathcal{O}^{4+n}$$

Majorana neutrinos and Lepton Number Violation

The Black Box and extended Black Box theorems



- Black Box Theorem Schechter & Valle, 1982
  - LNV operators yield Majorana neutrino mass
  - Majorana neutrino mass yields effective LNV operators
- $m_{ee}^{eff} = \sum_i (\mathcal{O}_i + m_{ee}^{\mathcal{O}_i})$
  Exact cancelations are possible but require fine tuning

Extended Black Box Theorem: Assuming 3 ν mixing & arbitrary LNV, $m_{ee} = 0$ is *not* consistent with oscillation data!

Hirsch, Kovalenko & Schmidt 2006

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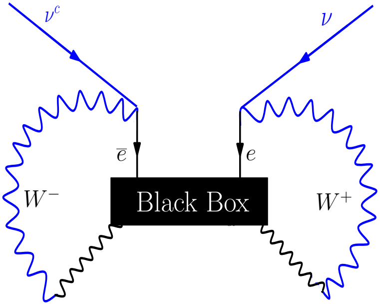
Majorana neutrinos and Lepton Number Violation

The Black Box and extended Black Box theorems



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Motivation

I perform an exhaustive survey of *all* LNV nonrenormalizable operators up to dimension 11

Questions to answer

- Is $\beta\beta 0\nu$ always the best probe of LNV? No
  - Should we look for other signals of LNV? Where?
  - What is the nature of models predicting large LNV?
- If the neutrino Majorana mass is highly suppressed can we still expect to observe $\beta\beta 0\nu$ in next generation experiments? Yes
  - What is the nature of these models?
  - What are the other observable features of these models?
- What can we generally learn about LNV models from future experiments/observations? much...

Plan of attack

1. *Categorize* all effective LNV operators up to dimension 11
   - All $SU(3)_c \times SU(2)_L \times U(1)_y$ invariant SM operators

     Babu & Leung, 2001
   - All possible Lorentz contractions
2. *Calculate* radiatively generated neutrino mass
3. *Extract* the scale (Λ) of new physics from observed neutrino mass $(0.05 - 1)$ eV
4. *Check* for additional constraints
5. *Predict* possible modes of future observation
6. *Select interesting* operators for further detailed study
   - Highly suppressed m_ν and $\beta\beta0\nu \Rightarrow$ Tree level phenomenology
   - Suppressed m_ν, but enhanced tree level $\beta\beta0\nu$

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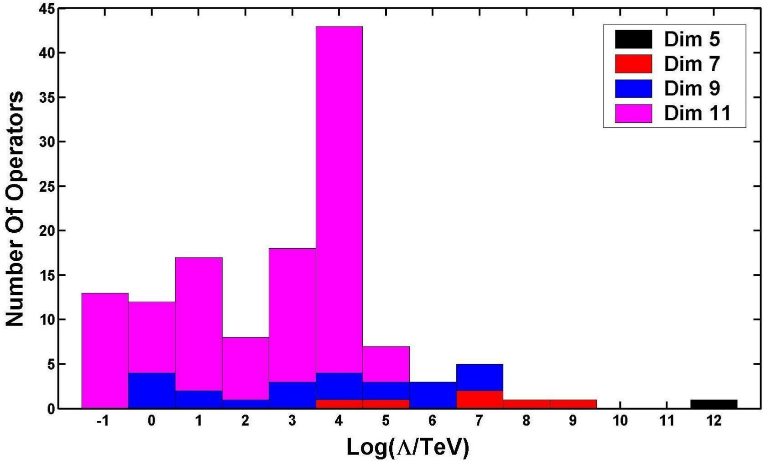
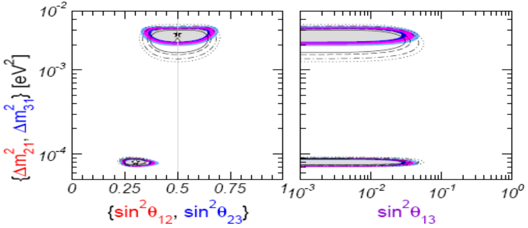
Λ Scale distribution



Implied neutrino mass textures

Maltoni, Schwetz, Tortola and Valle, New J. Phys. **6**, 122 (2004)



$$M \propto \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

20 of these

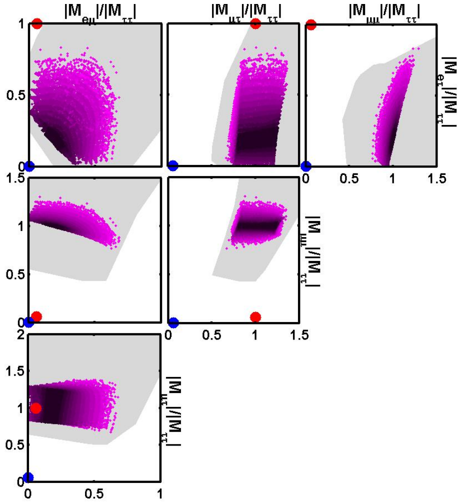
$$M \propto \begin{pmatrix} \lambda_e & \lambda_\mu & \lambda_\tau \\ \lambda_\mu & \lambda_\mu & \lambda_\tau \\ \lambda_\tau & \lambda_\tau & \lambda_\tau \end{pmatrix}$$

3 of these

$$M \propto \begin{pmatrix} \lambda_e\lambda_e & \lambda_e\lambda_\mu & \lambda_e\lambda_\tau \\ \lambda_e\lambda_\mu & \lambda_\mu\lambda_\mu & \lambda_\mu\lambda_\tau \\ \lambda_e\lambda_\tau & \lambda_\mu\lambda_\tau & \lambda_\tau\lambda_\tau \end{pmatrix}$$

- 9 parameters in a Majorana mixing matrix $\{m_1, m_2, m_3, \theta_{12}, \theta_{23}, \theta_{13}, \delta, \phi_2, \phi_3\}$
- Oscillation Constraints
  - Solar: $\Delta^2_S = m^2_2 - m^2_1$, $\theta_S = \theta_{12}$
  - Atmospheric: $|\Delta^2_A| = |m^2_3 - m^2_2|$, $\theta_A = \theta_{23}$
  - Reactor: $\theta_R = \theta_{13}$
- $m_{ee} \approx 0$ implies Normal hierarchy

Implied neutrino mass textures (numerical results)



- Require $m_{ee} < 10^{-4}$ eV
- all phases vary freely
- 95% confidence limits
- θ_{13} varies from $0^\circ - 14^\circ$

$$M \propto \begin{pmatrix} \lambda_e & \lambda_\mu & \lambda_\tau \\ \lambda_\mu & \lambda_\mu & \lambda_\tau \\ \lambda_\tau & \lambda_\tau & \lambda_\tau \end{pmatrix}$$

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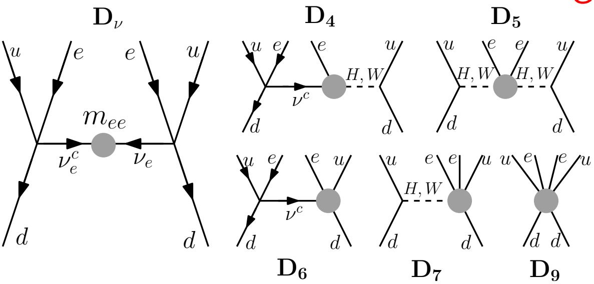
Neutrinoless double β-decay

Contributing diagrams and assumptions



General Observations

- Tree level contributions are dominant at sufficiently low scales!
    - D_9 dominates low Λ
    - D_ν dominates high Λ
    - D_6 dominates middle Λ
      ν yields Q^{-1} factor
- $D_\nu > D_4$ in most cases

- Neglect variations in nuclear matrix element
- Diagrams are added incoherently due to chiral structure

$$m_{ee}^{eff} = \frac{Q^2}{G_f^2 |V_{ud}|^2} \sqrt{\sum_i \mathcal{A}_{D_i}^2}$$

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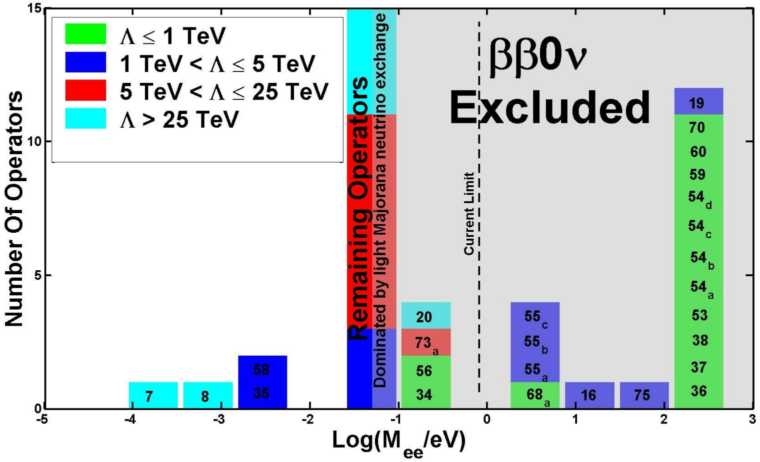
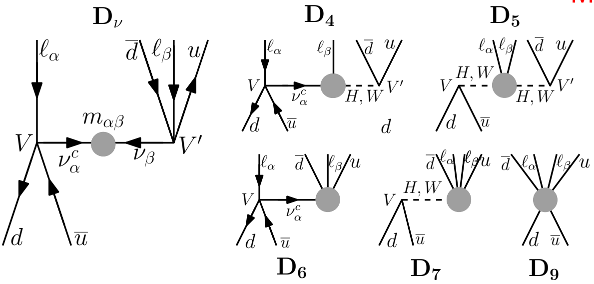
Neutrinoless double β-decay

m_{ee} distribution



Meson and τ decays

Contributing diagrams and assumptions



Modification

- Use crossing symmetry relate amplitudes
- CKM matrix element V
- Include new Q
- Modify phase space
- Lorentz structure: $\sigma_{\mu\nu}$

- Neglect variations in hadronic matrix element
- Diagrams are added incoherently due to chiral structure
- $m_{\alpha\beta}$ bounds calculated for dominant decays

A. Atre, V. Barger and T. Han, 2005

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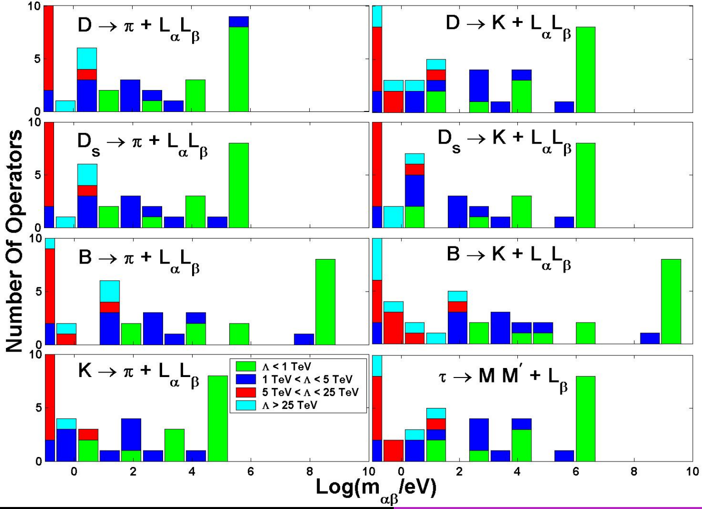
Meson and τ decays

$m_{\alpha\beta}$ distributions



International Linear Collider (ILC)

Consider ILC in e^-e^--mode at 1 TeV COM energy and 100 fb^{-1} characteristic integrated luminosity.

$$e^-e^- \to 4j + (\text{no missing energy})$$

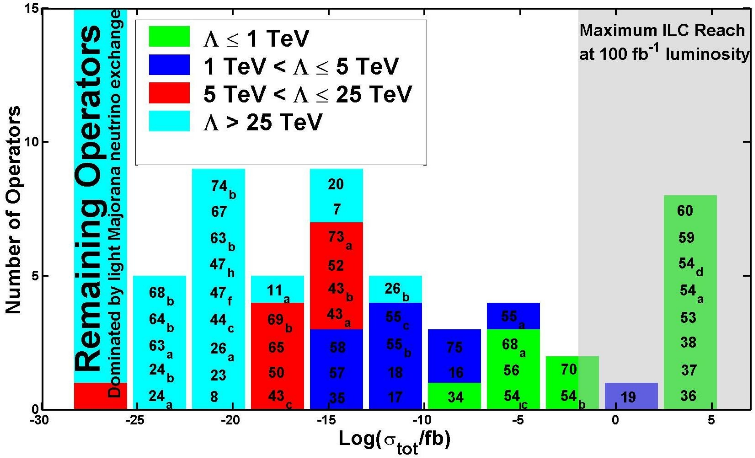
Characteristics and assumptions

- Resonance production is important... Assume $\Lambda > \mathrm{TeV}$
- Structurally equivalent to $0\nu\beta\beta$ process
- Little or no SM background
- $\gamma\gamma$ collider possibilities
- $\mu^-\mu^-$ collider possibilities

Final state leptons also possible: $e^-e^- \to \mu\nu + 2j$

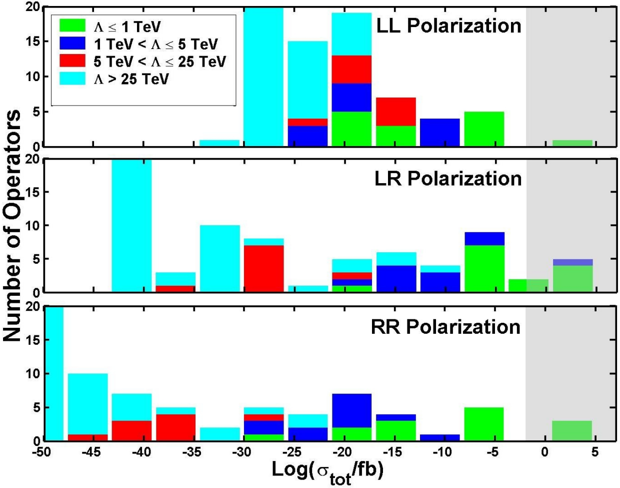
ILC in e^-e^- mode

Cross-section distribution

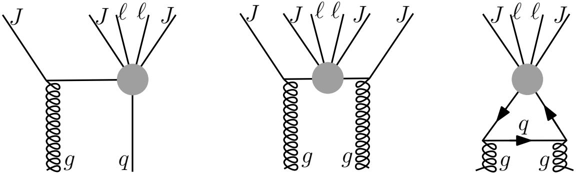


ILC in e^-e^- mode

Cross-section distribution assuming polarized initial state



Large Hadron Collider (LHC)



- Two jets preferable
- Color enhancements
- $\gamma\gamma$ collider diagrams?

Assume same parameters as ILC $\Rightarrow$ similar cross-sections
$\Lambda > Q \sim \mathrm{TeV}$ and $L = 100\ \mathrm{fb}^{-1}$

- qg and gg events dominate qq at LHC energies
- Probe different coupling constants: light quark/heavy lepton.
- Higher possibility of resonant production

Tevatron has little hope of LNV discovery from this perspective!

Hadron collider search backgrounds

Dilepton signal + jets and no missing energy!

- Ideally no SM background
- Real world is not ideal!
  - Processes with missing energy
  - Missed final state leptons
  - Misidentified lepton charge: $\mu^+ \leftrightarrow \mu^-$
- Reduce Background... no jet kinematic cuts!
  - Well isolated final state leptons
  - Look for μe final state events

Luckily, experimentalists have vast experience searching for this signal in simple SUSY scenarios!

Distinguishing LNV from SUSY at LHC is difficult

Summary

We expect new physics above the TeV scale to generate Majorana neutrino masses

- The categorization and exploration of effective low energy operators is a model independent way to explore this
- I consider effective LNV operators to:
  - Categorize *all* relevant operators by scale
  - Extract current constraints
  - Predict/suggest future probes
- Future work still needed... Great model building prospects!

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This illustrates the need for complementary experimental searches to truly understand LNV.

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