The neutrinoless $\beta\beta$ process at the LHC

#Pheno21, University of Pittsburgh

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a fun idea: is it possible to see the (standard mechanism for) neutrinoless $\beta\beta$ process ($0\nu\beta\beta$) at accelerators?

**Why?** Colliders, beam dumps, etc., can access $\mu$ and $\tau$ sectors!

for reviews on LNV/LFV at colliders, see w/ Y. Cai, T. Li, T. Han [1711.02180], and w/ S. Pascoli, et. al. [1812.08750]
Many ways to explain $m_\nu \neq 0$, so take an effective field theory approach:

The **Weinberg operator** is the only SMEFT operator at $d = 5$:  

$$\mathcal{L} = \frac{C_{5}^{\ell\ell'}}{\Lambda} [\Phi \cdot \overline{L}_{\ell}^{c}] [L_{\ell'} \cdot \Phi]$$

Can be generated in **many** ways at tree- and loop-level

Eg. Ma ('98), Bonnet, et al [1204.5862]

**Importantly**, after EWSB, generates a Majorana mass matrix for $\nu$

$$m_{\ell\ell'} = C_{5}^{\ell\ell'} \langle \Phi \rangle^2 / 2\Lambda \quad \leftarrow \text{(flavor basis!)}$$

**Type-I See-Saw Completion of the Weinberg Operator**

one interesting way to generate the Weinberg operator is if a heavy gauge-singlet fermion has Yukawa couplings to the left-handed leptons

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R. Ruiz - IFJ PAN  #Pheno21 - $0\nu\beta\beta@LHC$  3 / 15
constraints on the Weinberg operator from nuclear $0\nu\beta\beta$ decay
The Weinberg operator:

\[ \mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda} [\Phi \cdot \bar{L}_\ell^c][L_{\ell'} \cdot \Phi] \]

generates \( \nu \) mass matrix:

\[ m_{\ell\ell'} = C_5^{\ell\ell'} \langle \Phi \rangle^2 / 2\Lambda \]

since

\[ |m_{ee}| = \left| \sum_{k=1}^{3} U_{ek} m_{\nu_k} U_{ek} \right| \]

“mass” in flavor space

\[ \implies \text{nuclear } 0\nu\beta\beta \text{ decay rate:} \]

\[ \frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim |M_{0\nu\beta\beta}|^2 \sim |m_{ee}|^2 \]
The Weinberg operator:

\[ \mathcal{L} = \frac{C_5^{\ell\ell'}}{\Lambda} \left[ \Phi \cdot \overline{L}_\ell \right] \left[ L_{\ell'} \cdot \Phi \right] \]

generates \( \nu \) mass matrix:

\[ m_{\ell\ell'} = C_5^{\ell\ell'} \langle \Phi \rangle^2 / 2\Lambda \]

since

\[ |m_{ee}| = \left| \sum_{k=1}^{3} U_{ek} m_{\nu_k} U_{ek} \right| \]

implies nuclear \( 0\nu\beta\beta \) decay rate:

\[ \frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim |M_{0\nu\beta\beta}|^2 \sim |m_{ee}|^2 \]

Searches for nuclear \( 0\nu\beta\beta \) set strong constraints, e.g., GERDA [2009.06079]

\[ \Lambda/C_{5e}^{ee} \gtrsim (3.3 - 7.6) \times 10^{14} \text{ GeV} \]

\( C_{5e}^{ee} \) can naturally be zero/small Eg. symmetry [0810.1263] or interference [Asaka('20)x3]
So what about the other $C_{5}^{\ell\ell'}$?
$W^± W^±$ scattering at dimension five
The helicity amplitude for the $0\nu\beta\beta$ process $q q' \rightarrow \ell_1^+ \ell_2^+ f f'$ is

$$M_{LNV} = J_{f_1 f_1'}^\mu J_{f_2 f_2'}^\nu \Delta_W^\mu \Delta_W^\nu T_{LNV}^{\alpha\beta} D(p_\nu)$$

Difficult to simulate events since *Weinberg op.* modifies propagator of $\nu_\ell$

modern Monte Carlo tools work in mass basis and do not like the idea of modifying $\langle 0|\nu_{\ell}\nu_\ell|0\rangle$

$$\nu_\ell(p) \nu_\ell^c(-p) = \frac{ip'}{p^2} - \frac{iC_{5}^{\ell\ell'}}{\Lambda} \frac{v^2}{p^2} \frac{ip'}{p^2} = \frac{im_{\ell\ell'}}{p^2}$$

**Solution:** Treat vertex as a particle! Invent unphysical Majorana fermion with (small) mass $m_{\ell\ell}$ that couples to all lepton flavors

recovers right behavior!

$$T_{LNV}^{\alpha\beta} D(p_\nu) \propto \gamma^\alpha P_L \frac{i(p^4+m_{\ell\ell'})}{p^2-m_{\ell\ell'}^2} \gamma^\beta P_R = \gamma^\alpha P_L \frac{im_{\ell\ell'}}{p^2} P_L \gamma^\beta \times \left[ 1 + O \left( \left| \frac{m_{\ell\ell'}^2}{p^2} \right| \right) \right]$$
**Plotted:** Normalized production rate \((C_5 = 1)\) vs scale \((\Lambda)\)

Full 2 → 4 calculation at NLO(+PS) in QCD is more involved

Used mg5amc + NEW SMWeinberg UFO libraries

Driven by \(W^0_+ W^0_+\) scattering

\[
\hat{\sigma}(W^+ W^+ \to \ell^+ \ell^+) \sim \frac{|C_{\ell\ell}'|^2}{18\pi \Lambda^2}
\]

Once \(\sigma\) is obtained for a “high” scale, i.e., \(C_{\ell\ell}' = 1, \Lambda = 200\) TeV, rescale for other \(\Lambda/C_5\).

\(C_{\ell\ell}'/\Lambda\) is heavily constrained. **What can the LHC say about \(C_{\ell\ell}'\)?**
The collider signature exhibits both **LNV** and **VBS** characteristics

\[ pp \rightarrow \mu^+ \mu^- jj + X \]

(L) \( E_T^{\text{miss}} \)    (R) \( H_T / p_T^{\mu 1} \)

\[ \sqrt{s} = 13.0 \text{ TeV} \]  \[ \mathcal{L} = 300.0 \text{ fb}^{-1} \]

- All Backgrounds
- \( W^\pm V (3l\nu) \)
- \( W^\pm W^\mp (\text{EW}) \)
- \( W^\pm W^\mp (\text{QCD}) \)

Weinberg Operator (\( \times 1000 \))
The collider signature exhibits both LNV and VBS characteristics

\[ pp \rightarrow \mu^\pm \mu^\pm jj + X \]

- same-sign, high-\( p_T \) charged leptons without MET and back-to-back
- forward, high-\( p_T \) with rapidity gap
- See backup slides for kinematic distributions at NLO+PS

### Built simplified analysis for expedience:

**TABLE II. Particle identification and signal region definitions**

<table>
<thead>
<tr>
<th>Particle Identification Cuts</th>
<th>Signal Region Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^{\mu} [j] &gt; 10 (10) [25] ) GeV, ( \text{Anti-} k_T(R=0.4) )</td>
<td>( p_T^{\mu_1,\mu_2} &gt; 27 (10) ) GeV, ( n_\mu = 2, n_j \geq 2, )</td>
</tr>
<tr>
<td>(</td>
<td>\eta^{\mu} [j]</td>
</tr>
</tbody>
</table>

\( E_T^{\text{miss}} < 30 \) GeV, \( (H_T/p_T^{\mu_1}) < 1.6 \)

**TABLE III. Expected number of background and 0\( \nu\beta\beta \) signal events in the signal region with \( \mathcal{L} = 300 \) fb\(^{-1} \) (3 ab\(^{-1} \)).**

<table>
<thead>
<tr>
<th>Collider</th>
<th>QCD ( W^{\pm}W^{\pm}jj )</th>
<th>EW ( W^{\pm}W^{\pm}jj )</th>
<th>( W^{\pm}V )</th>
<th>Total</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>&lt; 0.01</td>
<td>6.40</td>
<td>1.16</td>
<td>7.56</td>
<td>0.013</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>&lt; 0.01</td>
<td>64.0</td>
<td>11.6</td>
<td>75.5</td>
<td>0.13</td>
</tr>
</tbody>
</table>
the big picture
With a minimal cuts (= can be improved) $\mathcal{L} = 300 \ (3000) \ \text{fb}^{-1}$

$$\Lambda/|C_5^{\mu\mu}| \lesssim 8.3 \ (11) \ \text{TeV} \implies |m_{\mu\mu}| \gtrsim 7.3 \ (5.4) \ \text{GeV}$$

**Plotted:** Allowed and projected reach of $|m_{\mu\mu}|$ vs lights $\nu$ mass

$$|m_{\ell\ell'}| = |C_5^{\ell\ell'}|\langle \Phi \rangle^2/2\Lambda = |\sum_k U_{\ell k} m_{\nu_k} U_{\ell' k}|$$

**LHC is most competitive but all can be improved!**
Colliders are **incredibly complementary** to oscillation facilities:

- Direct production of Seesaw and heavy flavors particles
- Test both neutrino NSIs and UV realizations of EFTs

If BSM is heavy, the Weinberg op. parametrizes the origin of $m_\nu$

- $0\nu\beta\beta$ experiments strongly constrain $\Lambda/C^\text{ee}_5$ but insensitive to $\mu, \tau$

- For high-energy scattering and decay processes, a prescription for describing the Weinberg op. has been developed [and implemented into a UFO!]


- For first time, there is a roadmap for probing Weinberg op. with $\mu, \tau$ at accelerators (LHC, HL-LHC, beam dumps, etc.)

Lots not covered, so see papers for details! [2011.02547; 2012.09882]
Thank you.
anatomy of the $0\nu\beta\beta$ process
helicity preservation in $W^- W^+ \rightarrow \ell_i^- \ell_j^+$

The helicity amplitude for the LNC process $q_1 q_2 \rightarrow \ell_1^- \ell_2^+ q'_1 q'_2$ is

$$\mathcal{M}_{LNC} = J_{q_1 q'_1}^\mu J_{q_2 q'_2}^\nu \Delta^W_{\mu \rho} \Delta^W_{\nu \sigma} T_{LNC}^{\rho \sigma} \mathcal{D}(p_N)$$
helicity preservation in $W^- W^+ \rightarrow \ell_i^- \ell_j^+$

The helicity amplitude for the LNC process $q_1 q_2 \rightarrow \ell_1^- \ell_2^+ q_1' q_2'$ is

$\mathcal{M}_{LNC} = \mathcal{J}_{q_1 q_1'}^{\mu} \mathcal{J}_{q_2 q_2'}^{\nu} \Delta_{\mu \rho}^W \Delta_{\nu \sigma}^W T_{LNC}^{\rho \sigma} \mathcal{D}(p_N)$

$T_{LNC}^{\rho \sigma} = \overline{u_L}(p_1) \gamma^\rho P_L \times (\hat{p}_N + m_N) \times \gamma^\sigma P_L v_R(p_2)$

LH helicity state $P_L m_N P_R = 0$
The helicity amplitude for the LNC process $q_1 q_2 \rightarrow \ell_1^- \ell_2^+ q_1' q_2'$ is

$$\mathcal{M}_{\text{LNC}} = J_{q_1 q_1'}^{\mu} J_{q_2 q_2'}^{\nu} \Delta_{\nu \sigma}^{W} \Delta_{\mu \rho}^{W} T_{\text{LNC}}^{\rho \sigma} \mathcal{D}(p_N)$$

$$T_{\text{LNC}}^{\rho \sigma} = \bar{u}_L(p_1) \gamma^\rho P_L \times \left( \begin{array}{c} p_N \\ m_N \end{array} \right) \times \gamma^\sigma P_L v_R(p_2)$$

LH helicity state $P_L m_N P_R = 0$

$$\Rightarrow \mathcal{M}_{\text{LNC}} \sim \frac{p_N}{(p_N^2 - m_N^2)}$$ scales with momentum-transfer!
helicity inversion in $W^+W^+ \rightarrow \ell_i^+\ell_j^+$

The helicity amplitude for the LNV process $q_1 q_2 \rightarrow \ell_1^+ \ell_2^+ q_1' q_2'$ is

$$\mathcal{M}_{LNV} = J_{q_1 q_1'}^\mu J_{q_2 q_2'}^\nu \Delta_W^{\mu \rho} \Delta_W^{\nu \sigma} T_{LNV}^{\rho \sigma} D(p_N)$$
The helicity amplitude for the LNV process $q_1 q_2 \rightarrow \ell^+_1 \ell^+_2 q'_1 q'_2$ is

$$M_{LNV} = J^\mu_{q_1 q'_1} J^\nu_{q_2 q'_2} \Delta^W_{\mu \rho} \Delta^W_{\nu \sigma} T^{\rho \sigma}_{LNV} \mathcal{D}(p_N)$$

Intuition: CPT Theorem $\implies$ CT-inversion $= P$-inversion

$$T^{\rho \sigma}_{LNV} = \bar{u}_R(p_1) \gamma^\rho P_R \times (p_N + m_N) \times \gamma^\sigma P_L v_R(p_2)$$

CPT: $P_L \rightarrow P_R$  $P_R$ $p_N$ $P_R=0$  RH helicity state
The helicity amplitude for the LNV process \( q_1 q_2 \rightarrow \ell_1^+ \ell_2^+ q_1' q_2' \) is

\[
\mathcal{M}_{LNV} = J_1^\mu J_2^\nu \Delta_{\mu \rho} \Delta_{\nu \sigma} T_{LNV}^{\rho \sigma} \mathcal{D}(p_N)
\]

Intuition: CPT Theorem \( \implies \) CT-inversion = P-inversion

\[
T_{LNV}^{\rho \sigma} = \bar{u}_R(p_1) \gamma^\rho \quad P_R \quad \gamma^\sigma P_L v_R(p_2)
\]

\[\text{CPT: } P_L \rightarrow P_R \quad P_R p_N P_R = 0 \quad \text{RH helicity state} \]

\[\implies \mathcal{M}_{LNV} \sim \frac{m_N}{(p_N^2 - m_N^2)} \quad \text{scales with mass!} \]
The remainder of $\mathcal{M}_{MNV}$ depends on:
- $WW$ scattering system
- $N$'s pole structure
The remainder of $\mathcal{M}_{LNV}$ depends on:
- $WW$ scattering system
- $N$’s pole structure

Explicit computation shows amplitude is driven by $W_0^\pm W_0^\pm$ scattering

$$\mathcal{M}_{LNV} \sim \varepsilon_\mu^W_1(\lambda_1)\varepsilon_\mu^W_2(\lambda_2) \sim \frac{M_{WW}^2}{M_W^2}$$

“Low-mass” limit ($M_{WW} \gg m_N$):

$$\frac{m_N}{(p_N^2-m_N^2)} \sim \frac{m_N}{(M_{WW}^2-m_N^2)} \sim \frac{m_N}{M_{WW}^2} + \mathcal{O}\left(\frac{M_N^2}{M_{WW}^2}, \frac{M_N^2}{M_{WW}^2}\right)$$

(derivatives grows with mass!)

“High-mass” limit ($M_{WW} \ll m_N$):

$$\frac{m_N}{(p_N^2-m_N^2)} \sim \frac{m_N}{(M_{WW}^2-m_N^2)} \sim \frac{-m_N}{m_N^2} + \mathcal{O}\left(\frac{M_{WW}^2}{m_N^2}\right)$$

(slower decoupling since $d = 7$, not $d = 8$)
Plotted: Normalized production rate \( \sigma/|V|^2 \) vs mass \( m_N \)

w/ Fuks, Neundorf, Peters, Saimpert [2011.02547]

Full 2 → 4 calculation at NLO (+PS) in QCD is more involved

Used mg5amc + HeavyN UFO libraries

"Low-mass" limit \( (M_{WW} \gg m_N) \):
\[ \hat{\sigma}(W^+W^+ \rightarrow \ell^+\ell^+) \sim g_W^4 |V_{\ell N}|^4 \frac{m_N^2}{m_W^4} \]

"High-mass" limit \( (M_{WW} \ll m_N) \):
\[ \hat{\sigma}(W^+W^+ \rightarrow \ell^+\ell^+) \sim g_W^4 \frac{|V_{\ell N}|^4 M_{WW}^4}{m_N^2 m_W^4} \]
The collider signature exhibits both LNV and VBS/F characteristics

\[ pp \rightarrow \mu^\pm \mu^\pm jj + X \]

- same-sign, high-\( p_T \) charged leptons without MET and back-to-back forward, high-\( p_T \) with rapidity gap
- See next few slides for kinematic distributions at NLO+PS

Built simplified analysis for expedience:

<table>
<thead>
<tr>
<th>TABLE III. Pre-selection and signal region cuts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-selection Cuts</td>
</tr>
<tr>
<td>( p_T^{\mu_1} (\mu_2) &gt; 27 , (10) , \text{GeV}, \quad</td>
</tr>
<tr>
<td>( p_T^{j_1} &gt; 25 , \text{GeV}, \quad</td>
</tr>
<tr>
<td>( Q_{\mu_1} \times Q_{\mu_2} = 1, \quad M(j_1, j_2) &gt; 700 , \text{GeV} )</td>
</tr>
<tr>
<td>Signal Region Cuts</td>
</tr>
<tr>
<td>( p_T^{\mu_1}, ; p_T^{\mu_2} &gt; 300 , \text{GeV} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE I. Generator-level cross sections [fb] and cuts, ( \mu_f, \mu_r ) scale uncertainty [%], PDF uncertainties [%], and perturbative order for leading backgrounds at ( \sqrt{s} = 13 , \text{TeV} ).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>( W^\pm W^\pm jj ) (QCD)</td>
</tr>
<tr>
<td>( W^\pm W^\pm jj ) (EW)</td>
</tr>
<tr>
<td>Inclusive ( W^\pm V(3\ell\nu) ) FxFx (1j)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE IV. Visible signal cross sections (and efficiencies) after applying different selections to the simulated events.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_N )</td>
</tr>
<tr>
<td>150 GeV</td>
</tr>
<tr>
<td>1.5 TeV</td>
</tr>
<tr>
<td>5 TeV</td>
</tr>
<tr>
<td>15 TeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TABLE V. Expected number of SM background events in the Signal Region at the (HL-)LHC with ( \mathcal{L} = 300 , \text{fb}^{-1} ) (3 ab^{-1}).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collider</td>
</tr>
<tr>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>LHC</td>
</tr>
<tr>
<td>HL-LHC</td>
</tr>
</tbody>
</table>
Kinematics at NLO+PS

after basis pre-selection
Top: $p_T^{\mu_1}, p_T^{\mu_2}$, Btm: $\Delta \varphi(\mu_1, \mu_2)$, MET

$pp \to \mu^{\pm} \mu^{\pm} jj + X$, $\sqrt{s} = 13$ TeV, $\mathcal{L} = 300$ fb$^{-1}$

- $m_N = 750$ GeV
- $m_N = 1500$ GeV
- $m_N = 5000$ GeV

$pp \to \mu^{\pm} \mu^{\pm} jj + X$, $\sqrt{s} = 13$ TeV, $\mathcal{L} = 300$ fb$^{-1}$

- $m_N = 750$ GeV
- $m_N = 1500$ GeV
- $m_N = 5000$ GeV
Top: $p_T^{j_1}, p_T^{j_2}$, Btm: $\eta^{j_1}, \Delta\eta(j_1,j_2)$

$p p \rightarrow \mu^\pm \mu^\pm jj + X, \sqrt{s} = 13$ TeV, $\mathcal{L} = 300$ fb$^{-1}$

$p p \rightarrow \mu^\pm \mu^\pm jj + X, \sqrt{s} = 13$ TeV, $\mathcal{L} = 300$ fb$^{-1}$
**Top:** $H_T = \sum |p_T^j|$, $X_T = H_T + \sum |p_T^\mu|$, **Btm:** $H_T/|p_T^\mu|$, $X_T/|p_T^\mu|$.