LHC as a complementary probe to study $0\nu\beta\beta$ mechanisms?

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Why LHC might be relevant for $0\nu\beta\beta$

Example: same sign di-electron + 2 jets in R-parity violating SUSY

Allanach, CHK, Päs 0902.4697, 0903.0347

Charge asymmetry ratio

CHK, Stirling appear soon
‘Reference’ model: light mass mechanism

\[ \mathcal{L}_{\text{EW}}^{\text{eff}, \Delta L_e=2}(x) = G_F^2 m_{\beta\beta} \left[ \bar{e}_1 \gamma_\mu (1 - \gamma_5) \frac{1}{q^2} \gamma_\nu e_2 \right] \times \left[ J_{1, V-A}(q) J_{2, V-A}(-q) \right] \]
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Heidelberg-Moscow, CUORICINO & NEMO3

\[ |m_{\beta\beta}| \lesssim 0.35\text{eV} \]

(Also \( |m_{\beta\beta}| \sim 0.5\text{eV} \))

Klapdor-Kleingrothaus et. al.)
Other possibilities

However many lepton number violating theories:

- RPV SUSY, heavy Majorana neutrinos,
- type II, type III see-saws, lepto-quarks, KK neutrinos ...
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- $0\nu\beta\beta$-based strategies to distinguish different mechanisms, e.g.
  - Electron kinematics  \( \text{Ali,Borisov,Zhuridov } 07 \),  \( \text{SuperNEMO } \& \text{ Flack’s talk} \)
  - \( T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge}) \) ratios of different isotopes  \( \text{Deppisch,Päs } 06 \),  \( \text{Gehman,Elliot } 07 \),  \( \text{Fogli et. al. } 09 \)
  - Excited daughter nuclei  \( \text{Simkovic et. al. } 01 \),  \( \text{Iachello’s talk} \)
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- We focus on $0\nu\beta\beta$ mediation involving TeV scale particles.

- Investigate interplay between LHC signatures and $0\nu\beta\beta$ rate predictions.
Relative strength of ‘light’ and ‘heavy’ $0\nu\beta\beta$ amplitudes:
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$LHC$ as a complementary $0\nu\beta\beta$ probe – p. 5/20
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$M_{\text{light}} \sim M_{\text{heavy}} : m_{\beta\beta} \sim \mathcal{O}(0.1)\text{eV} \leftrightarrow \Lambda \sim \mathcal{O}(1)\text{TeV}.$

$\mathcal{O}(1)\text{TeV}$ resonances via same-sign di-electron + 2 jets:

RPV SUSY  Allanach, CHK, Päss 0902.4697, Heavy Majorana neutrinos  Keung, Senjanovic 83, Hirsch et. al. 96

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  - RPV SUSY \cite{Allanach2009, CHK2009, Pas2009}, \textit{Heavy Majorana neutrinos} \cite{Keung1983, Senjanovic1983, Hirsch1996}

- 4 leptons f.s. BRs in Higgs triplets \cite{Petcov2009}

- $B_d^0 - \bar{B}_d^0$ mixing \cite{Allanach2009, Pas2009}

LHC as a complementary $0\nu\beta\beta$ probe – p. 5/20
Example: $0\nu\beta\beta$ in RPV SUSY

RPV SUSY: renormalisable lepton number violating parameters.

$$\mathcal{W}_{\text{RPV}} = \lambda'_{111} L_1 Q_1 D_1^c + \cdots$$
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$$\mathcal{L}_{\lambda'_{111} \lambda'_{111}, \Delta L_e=2}(x) = \frac{G_F^2}{2} m_p^{-1} [\bar{\epsilon}(1 + \gamma_5)\epsilon^c]$$

$$\times \left[ (\epsilon_{\tilde{g}} + \epsilon_\chi)(J_{PS} J_{PS} - \frac{1}{4} J^\mu_{T \nu} J_{T \mu \nu}) + (\epsilon_{\chi \tilde{e}} + \epsilon_{\tilde{g}}' + \epsilon_{\chi f}) J_{PS} J_{PS} \right]$$

LHC as a complementary $0\nu\beta\beta$ probe – p. 6/20
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\[ \epsilon \sim \lambda'^2_{111} \left( \frac{\Lambda_{SM}}{\Lambda_{SUSY}} \right)^5 : \]

\[ \lambda'_{111} \text{ bound relaxes rapidly with increasing } \Lambda_{SUSY}. \]
Resonant selectron production

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SS di-electron, 2 jets, small $E_T$. 

LHC as a complementary $0\nu\beta\beta$ probe – p. 7/20
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Signal believed tiny due to ‘stringent’ $0\nu\beta\beta$ bound.
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Lower $T^{0\nu\beta\beta}_{1/2} (^{76}\text{Ge})$ limit: $\lambda'_{111} \lesssim 5 \cdot 10^{-4} \left( \frac{\Lambda_{\text{SUSY}}}{100 \text{GeV}} \right)^{2.5}$.

Single slepton production: $\sigma(pp \rightarrow \tilde{l}) \propto |\lambda'_{111}|^2 / m_{\tilde{l}}^3$

→ production upper limit increases with $\Lambda_{\text{SUSY}}$. 

LHC as a complementary $0\nu\beta\beta$ probe – p. 7/20
Numerical analysis

RPV MSSM model parameters:

- ‘RPC’ mSUGRA mass spectrum:
  Vary $m_0$, $M_{1/2}$, keeping other SUSY parameters fixed
- Consider regions with neutralino LSP.
- Determine $\lambda'_{111}$ for 5$\sigma$ excess.
- SS di-lepton analysis follows Dreiner et. al. 99.
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NME model $\Gamma_{0\nu\beta\beta} = G_{0\nu}|M|^2$:

- Include both $\pi$ and nucleon modes ($^{76}$Ge):
  $M_{\lambda'_{111}} = \epsilon M_{\tilde{g}N}^2 + \epsilon' M_{\tilde{f}N}^2 + \left(\epsilon + \frac{5}{8}\epsilon'\right)\left(\frac{4}{3}M_{1\pi}^1 + M_{2\pi}^2\right)$

- $M_{\tilde{g}N}^2 = 283$, $M_{\tilde{f}N}^2 = 13.2$, $M_{1\pi}^1 = -18.2$, $M_{2\pi}^2 = -601$

[Hirsch et al. 96, Faessler et al. 98]
Infer $T_{1/2}^{0
u\beta\beta}(^{76}\text{Ge})$ from SSDL @ 5-\(\sigma\) (10 fb\(^{-1}\), 14 TeV, $m_{\beta\beta} = 0$):

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\[ 1 \cdot 10^{27} \text{ yrs} < T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge}) \]

\[ 1.9 \cdot 10^{25} < T^{0\nu\beta\beta}_{1/2}(^{76}\text{Ge}) < 1 \cdot 10^{27} \text{ yrs} \]

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Other models (e.g. Heavy neutrinos ($N$) in $W'$ models) can have same signal:
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$\bar{d} + W_R l^+_{\nu\beta\beta}$

However quark coupling structure different can be very different

- LHC (p-p) produces more +ve over -ve charged final states.
- Proton has non-universal flavour content of course!

Charge asymmetry ratio $R^{\pm} \equiv \frac{N(+)\text{ to } N(-)}{N(-)\text{ to } N(+)}$ depends on how quarks couple to the resonance.
$R^\pm$ tracks parton luminosity ratio $\tilde{R}^\pm$:

$$
\tilde{R}^\pm = \frac{\int \frac{dx}{x} |\tilde{V}_{ab}|^2 f_a(x) f_b\left(\frac{M_V^2}{xs}\right)|(+)}{\int \frac{dx}{x} |\tilde{V}_{cd}|^2 f_c(x) f_d\left(\frac{M_V^2}{xs}\right)|(-)}
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(c.f. $R^\pm = \frac{N(+)}{N(-)}$)
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- $R^\pm$ vs $\tilde{R}^\pm$ ($W'$ model with MSTW08 NLO pdfs):
**Charge asymmetry ratio**

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- $R^\pm$ vs $\tilde{R}^\pm$ ($W'$ model with MSTW08 NLO pdfs):

<table>
<thead>
<tr>
<th>$M_{W'}$ (GeV)</th>
<th>$\tilde{R}^\pm$</th>
<th>$R^\pm$</th>
<th>$\tilde{R}^\pm$</th>
<th>$R^\pm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 TeV</td>
<td>2.12(4)</td>
<td>1.97(1)</td>
<td>1.92(4)</td>
<td>1.76(1)</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>2.50(6)</td>
<td>2.45(3)</td>
<td>2.22(7)</td>
<td>2.11(4)</td>
</tr>
<tr>
<td>2.0 TeV</td>
<td>2.82(9)</td>
<td>2.76(7)</td>
<td>2.53(10)</td>
<td>2.38(10)</td>
</tr>
</tbody>
</table>

with PDF (68%) & statistical (100 fb$^{-1}$) uncertainties
Many candidate \(0\nu\beta\beta\) mechanisms.

LHC could provide complementary information to direct \(0\nu\beta\beta\) observation.

More possibilities along this direction.
Gluino/neutralino mediation
Comparing $\lambda_{111}'$ bounds

- Infer $T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge})$ from SS di-election 5-$\sigma$ discovery reach at 10 fb$^{-1}$:

$$1 \cdot 10^{27} \text{ yrs} < T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge})$$

$$1.9 \cdot 10^{25} < T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge}) < 1 \cdot 10^{27} \text{ yrs}$$
LHC SS di-lepton cuts

From Dreiner, Richardson, Seymour 99

- Lepton $|\eta| < 2.0, p_T > 40$ GeV. Hadr. $E_T < 5$ GeV in R=0.4.
- Reject $65 < M_T < 80$ GeV, OSSF.
- $E_T < 20$ GeV.
- No more than 2 jets, each with $p_T > 50$ GeV.

Main bkgd after cuts from $WZ$. Other non-trivial bkgds include $t\bar{t}b\bar{b}$, single top, SUSY, detector ...
Including

\[ |m_{\beta\beta}| = 0.05 \text{ eV} \]

\[ (\sim \sqrt{\Delta m^{2}_{23}}) \]

- Destructive interference with \( m_{\beta\beta} \) increases \( T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge}) \) → dark yellow region shrinks.

- Fixing \( T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge}) \), destructive int. with \( m_{\beta\beta} \) increases SSL rate → better SSL discovery prospect.
Inference on $m_{\beta\beta}$

Given $5\sigma$ SSL observation ($M_0 = 680\text{GeV}, M_{1/2} = 440\text{GeV}$)

$\rightarrow T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge}) = 1 \cdot 10^{26}\text{yrs}$ if direct contribution only.

- Band of $m_{\beta\beta}$ depending on relative phase.
- Normal hierarchy possible if $0\nu\beta\beta$ observed.
$B_d^0 - \bar{B}_d^0$ mixing and RPV $0\nu\beta\beta$

**$B_d^0 - \bar{B}_d^0$ mixing limit:**

$$\langle B_d | M_{12}^{\text{SM} + \text{New Physics}} | \bar{B}_d \rangle = \Delta_d \langle B_d | M_{12}^{\text{SM}} | \bar{B}_d \rangle$$

$$\lambda'_{131} \lambda'_{131} \leq 4.0 \cdot 10^{-8} \frac{m_{\tilde{\nu}_e}^2}{(100 \text{GeV})^2}$$

$$\lambda'_{131} \lambda'_{131} \lesssim 2 \cdot 10^{-8} \left(\frac{\Lambda_{\text{SUSY}}}{100 \text{GeV}}\right)^3$$

- Bounds comparable, but with different mass dependence.

**LHC as a complementary $0\nu\beta\beta$ probe – p. 19/20**
Left: lower limit on $T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge})$ given upper bound from $B_d^0 - \bar{B}_d^0$.

Right: Effect of a near-future measurement of $T_{1/2}^{0\nu\beta\beta}(^{76}\text{Ge})$ for $m_0 = 680$ GeV, $M_{1/2} = 440$ GeV, given current $B_d^0 - \bar{B}_d^0$ constraints.