Testing the 2-TeV Resonance with Trileptons

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Right Handed W Boson Search at CMS (arXiv:1407.3683)

\[ \sigma(pp \rightarrow W_R) \times BR(W_R \rightarrow ee jj) \] [fb]

\[ M_{Ne} = M_{WR}/2 \]

19.7 fb\(^{-1}\) (8 TeV)

Expected events:
0.65 fb × 19.7 fb\(^{-1}\) 
\times (A=0.78) = 10 events

Same sign ee (eejj) events 1 out of 14 
→ (pseudo) Dirac N\(_R\)?

Hint of W\(_R\) = ?
Left-Right Model in Inverse Seesaw Framework

\[
\begin{array}{|c|c|c|c|}
\hline
 & SU(3)_c & SU(2)_L & SU(2)_R & U(1)_{B-L} \\
\hline
Q_{Li} & 3 & 2 & 1 & \frac{1}{3} \\
Q_{Ri} & 3 & 1 & 2 & \frac{1}{3} \\
L_{Li} & 1 & 2 & 1 & 0 \\
L_{Ri} & 1 & 1 & 2 & 0 \\
\Phi & 1 & 2 & 2 & 0 \\
H_R & 1 & 1 & 2 & 0 \\
S_{Li} & 1 & 1 & 1 & 0 \\
\hline
\end{array}
\]

\[\mathcal{L}_{\text{int}} = - y_{ij} Q_R^i \Phi Q_{L_j} - \tilde{y}_{ij} Q_R^i \tilde{\Phi} Q_{L_j} - y_{ij} L_R^i \Phi L_{L_j} - \tilde{y}_{ij} L_R^i \tilde{\Phi} L_{L_j}
- f_{ij} L_R^i i\sigma_2 H_R^* S_{L_j} - \frac{1}{2} \mu_{ij} S_{Li}^c S_{L_j} + \text{h.c.},\]

\[
\tilde{\Phi} \equiv \sigma_2 \Phi^* \sigma_2 \\
\langle \Phi \rangle = \begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix} \\
\langle H_R \rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}
\]

\[\mu_{ij} \ll M_W \rightarrow \text{Pseudo-Dirac Heavy neutrino}\]
After the symmetry breaking

\[ \mathcal{L}_{\text{mass}} = -\frac{1}{2} \bar{\psi}_i^c \mathcal{M}_{ij} \psi_j + \text{h.c.} \]

\[ \mathcal{M}_{ij} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N^T \\ 0 & M_N & \mu \end{pmatrix}_{ij} \]

\[ (M_D^T)_{ij} = y_{ij}^L \nu_u + \tilde{y}_{ij}^L \nu_d, \]

\[ (M_N^T)_{ij} = f_{ij} \nu_R. \]

**Inverse seesaw mechanism**

\[ M_\nu \simeq M_D M_N^{-1} \mu (M_N^T)^{-1} M_D^T \]
Mass Matrix of $W-W_R$ Bosons

\[
\mathcal{L}_{\text{mass}} = \begin{pmatrix} W_L^- & W_R^- \end{pmatrix} \begin{pmatrix} \frac{g_L^2 v^2}{2} & -\frac{g_L g_R v^2 \sin 2\beta}{2} \\ -\frac{g_L g_R v^2 \sin 2\beta}{2} & \frac{g_R^2}{2} \{v_R^2 + v^2\} \end{pmatrix} \begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix}
\]

\[
\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} \cos \phi_{LR}^W & -\sin \phi_{LR}^W \\ \sin \phi_{LR}^W & \cos \phi_{LR}^W \end{pmatrix} \begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix}
\]

\[
\tan 2\phi_{LR}^W = \frac{2g_L g_R v^2 \sin 2\beta}{g_R^2 v_R^2 - (g_L^2 - g_R^2)v^2} \sim 2\sin 2\beta \left( \frac{g_R}{g_L} \right) \frac{m_W^2}{m_{W_R}^2}
\]
$W-W_R$ couplings with fermions (f), Z and Higgs (h)

After the symmetry breaking we can write the interaction terms

$$L_{W_{ff}} = \frac{g_L}{\sqrt{2}} \bar{u}(\cos \phi_{LR} W^+ - \sin \phi_{LR} W_R^+) P_L d + \frac{g_R}{\sqrt{2}} \bar{u}(\sin \phi_{LR} W^+ + \cos \phi_{LR} W_R^+) P_R d$$

$$+ \frac{g_L}{\sqrt{2}} \bar{\nu}(\cos \phi_{LR} W^+ - \sin \phi_{LR} W_R^+) P_L e + \frac{g_R}{\sqrt{2}} \bar{\nu}(\sin \phi_{LR} W^+ + \cos \phi_{LR} W_R^+) P_R e$$

$$+ h. c.$$ 

$$L_{W_{WZ}} = -ig_Z \sin \phi_{LR} \cos \phi_{LR} (W^+_{\mu} W^-_{\mu} + W^+_{R_{\mu\nu}} W^-_{\mu} - W^-_{\mu} W^+_{\mu} - W^-_{R_{\mu\nu}} W^+_{\mu}) Z^\nu$$

$$- ig_Z \sin \phi_{LR} \cos \phi_{LR} (W^+_{\mu} W^-_{R_{\mu\nu}} + W^+_{R_{\mu\nu}} W^-_{\nu}) Z^{\mu\nu}$$

$$L_{W_{Wh}} = -\frac{1}{2\sqrt{2}} [(g_L^2 - g_R^2) \sin 2\phi_{LR} + 2gLg_R \sin 2\beta \cos 2\phi_{LR}] v h (W^- W^+ + W^- R W^+)$$
Branching Ratios of $W_R$

(a) $\tan \beta$ dependence

$m_{W_R} = 2$ TeV, $m_{N_1} = 1$ TeV

(b) $m_{N_1}$ dependence

$m_{W_R} = 2$ TeV, $\tan \beta = 1$
Branching Ratios of $N_R$ as

Function of mixing angle

Function of mass

$eW$ decay mode is dominating
This state can subsequently decay into the three charged leptons plus a light neutrino final state. In this case, the dominant decay mode of this acceptance is estimated for the three-body decay of this acceptance. Considering these possible uncertainties, we conclude that at present any values of the range of $m_{N1}$, $m_{WR} = 2 \text{ TeV}$, $g_R = 0.4$, $\tan \beta = 1$.

The horizontal gray line corresponds to 10 events for an integrated luminosity of 19.7 $\text{fb}^{-1}$. Expected cross section: $0.65 \text{ fb} \times (A=0.78) = 0.51 \text{ fb}$.

Observed events changed drastically.
Trilepton plus missing energy mode

This model can explain the eejj excess
Another possible mode is trilepton plus missing energy, which has been studied by CMS in *Phys. Rev. D* 90 (2014) 032006

We performed the simulation study using MadGraph with the same parameter sets
Selection Criteria (CMS multilepton search)


- Electrons and muons are required to satisfy that their transverse momentum \( p_T \) be larger than 10 GeV and the magnitude of their pseudo-rapidity \( \eta \) be smaller than 2.4. They should be separated from each other by \( \Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} > 0.1 \), where \( \phi \) is the azimuthal angle.

- At least one electron or muon should have \( p_T > 20 \) GeV.

- Jets should satisfy \( p_T > 30 \) GeV and \( |\eta| < 2.5 \). They are required to be separated from a lepton by \( \Delta R > 0.3 \).

- For each event, we construct OSSF charged leptons \( \ell^+ \ell^- \ (\ell = e, \mu) \) and require that the invariant mass of these charged leptons, \( m_{\ell^+\ell^-} \), should be \( \geq 12 \) GeV.

- We reject the “on-Z” events in which a pair of OSSF charged leptons yields \( 75 < m_{\ell^+\ell^-} < 105 \) GeV.

  **Luminosity** \( 19.5 \text{ fb}^{-1} \)
$m_{W_R} = 2 \text{ TeV}, \ g_R = 0.4, \ \mathcal{R}_{e1} = 10^{-5}, \ \text{and} \ \tan \beta = 1$

The results are comparable

<table>
<thead>
<tr>
<th>Category</th>
<th>$m_{\ell^+\ell^-}$</th>
<th>$m_{N_1} = 1\text{ TeV}$</th>
<th>Observed</th>
<th>Expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T &gt; 200\text{ GeV}$</td>
<td>$E_T^{\text{miss}} &gt; 100\text{ GeV}$</td>
<td>Above-Z</td>
<td>4.76</td>
<td>5</td>
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<td></td>
<td>Below-Z</td>
<td>0</td>
<td>7</td>
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<tr>
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<td>$50 &lt; E_T^{\text{miss}} &lt; 100\text{ GeV}$</td>
<td>Above-Z</td>
<td>0.60</td>
<td>4</td>
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<td></td>
<td>Below-Z</td>
<td>0</td>
<td>10</td>
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<td></td>
<td>$E_T^{\text{miss}} &lt; 50\text{ GeV}$</td>
<td>Above-Z</td>
<td>0</td>
<td>3</td>
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<tr>
<td></td>
<td></td>
<td>Below-Z</td>
<td>0</td>
<td>26</td>
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<tr>
<td>$H_T &lt; 200\text{ GeV}$</td>
<td>$E_T^{\text{miss}} &gt; 100\text{ GeV}$</td>
<td>Above-Z</td>
<td>5.53</td>
<td>18</td>
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<td>21</td>
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<td>50</td>
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<td>$E_T^{\text{miss}} &lt; 50\text{ GeV}$</td>
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<td>Below-Z</td>
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<td>510</td>
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</table>
Conclusions

We have discussed the extended gauge sector model based on $SU(2)_L \times SU(2)_R \times U(1)_{\text{B-L}}$ gauge theory introducing the inverse seesaw mechanism.

Our model can explain the CMS ee$jj$ anomaly through the sizable left-right mixing in the gauge sector.

We have considered another possible mode, trilepton plus missing energy from our model and performed the simulation study.

We have consistently probed the model through the teilepton plus missing energy signal.