Testing the 2-TeV Resonance with Trileptons

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In collaboration with Natsumi Nagata(University of Minnesota) and Nobuchika Okada (University of Alabama), Journal reference :

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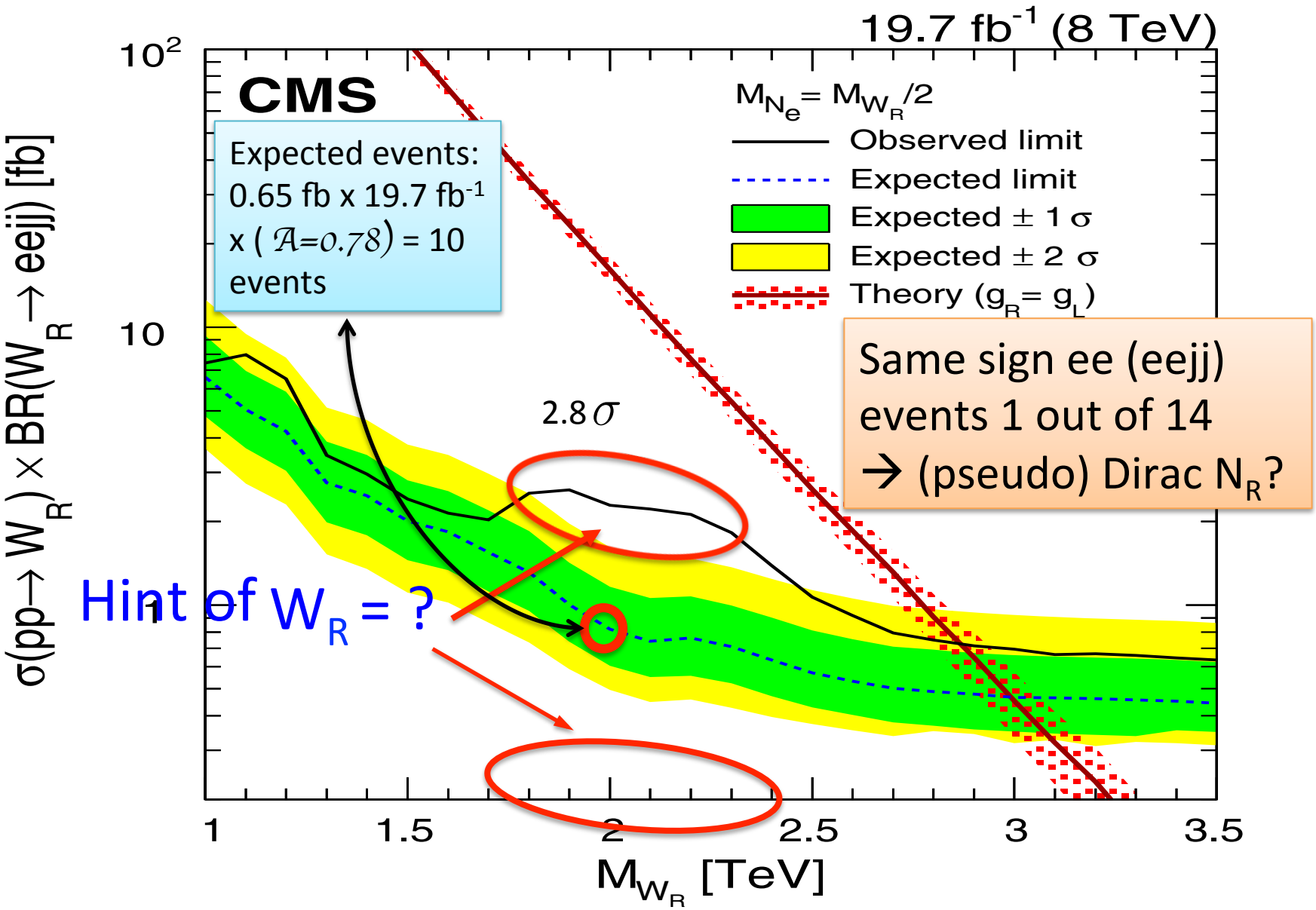
Right Handed W Boson Search at CMS (arXiv:1407.3683)

$p\,p \rightarrow W_R \rightarrow N_R(\ell = e),\ N_R \rightarrow (\ell = e)\,W,\ W \rightarrow j\,j$



Left-Right Model in Inverse Seesaw Framework

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
Q_{L_i}	3	2	1	$\frac{1}{3}$
Q_{R_i}	3	1	2	$\frac{1}{3}$
L_{L_i}	1	2	1	-1
L_{R_i}	1	1	2	-1
Φ	1	2	2	0
H_R	1	1	2	+1
S_{L_i}	1	1	1	0

See also Bhupal dev & Ravi Mohapatra, **Phys.Rev.Lett. 115 (2015) no.18, 181803**

$$\mathcal{L}_{\rm int} = - y^Q_{ij}\overline{Q}_{R_i}\Phi Q_{L_j} - \widetilde{y}^Q_{ij}\overline{Q}_{R_i}\widetilde{\Phi} Q_{L_j} - y^L_{ij}\overline{L}_{R_i}\Phi L_{L_j} - \widetilde{y}^L_{ij}\overline{L}_{R_i}\widetilde{\Phi} L_{L_j}$$
$$- f_{ij}\overline{L}_{R_i} i\sigma_2 H^*_R S_{L_j} - \frac{1}{2}\mu_{ij}\overline{S^c_{L_i}} S_{L_j} + \text{h.c.}\,,$$

$$\widetilde{\Phi} \equiv \sigma_2 \Phi^* \sigma_2 \qquad \langle \Phi \rangle = \begin{pmatrix} v_u & 0 \\ 0 & v_d \end{pmatrix} \qquad \langle H_R \rangle = \begin{pmatrix} 0 \\ v_R \end{pmatrix}$$

$\mu_{ij} \ll M_W \rightarrow$ Pseudo-Dirac Heavy neutrino

After the symmetry breaking

$$\mathcal{L}_{\rm mass} = -\frac{1}{2}\overline{\psi_i^c}\mathcal{M}_{ij}\psi_j + {\rm h.c.}$$

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

$$\left(M_D^T\right)_{ij} = y_{ij}^L v_u + \widetilde{y}_{ij}^L v_d \,,$$

$$\left(M_N^T\right)_{ij} = f_{ij} v_R \,.$$

Inverse seesaw mechanism

$$M_\nu \simeq \quad M_D M_N^{-1} \mu \left(M_N^T\right)^{-1} M_D^T$$

Mass Matrix of W-W_R Bosons

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

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

$$\tan 2\phi_{LR}^W = \frac{2 g_L g_R v^2 \sin 2\beta}{g_R^2 v_R^2 - (g_L^2 - g_R^2) v^2} \simeq 2 \sin 2\beta \left(\frac{g_R}{g_L}\right) \frac{m_W^2}{m_{W_R}^2}$$

W-W_R couplings with fermions(f), Z and Higgs(h)

After the symmetry breaking we can write the interaction terms

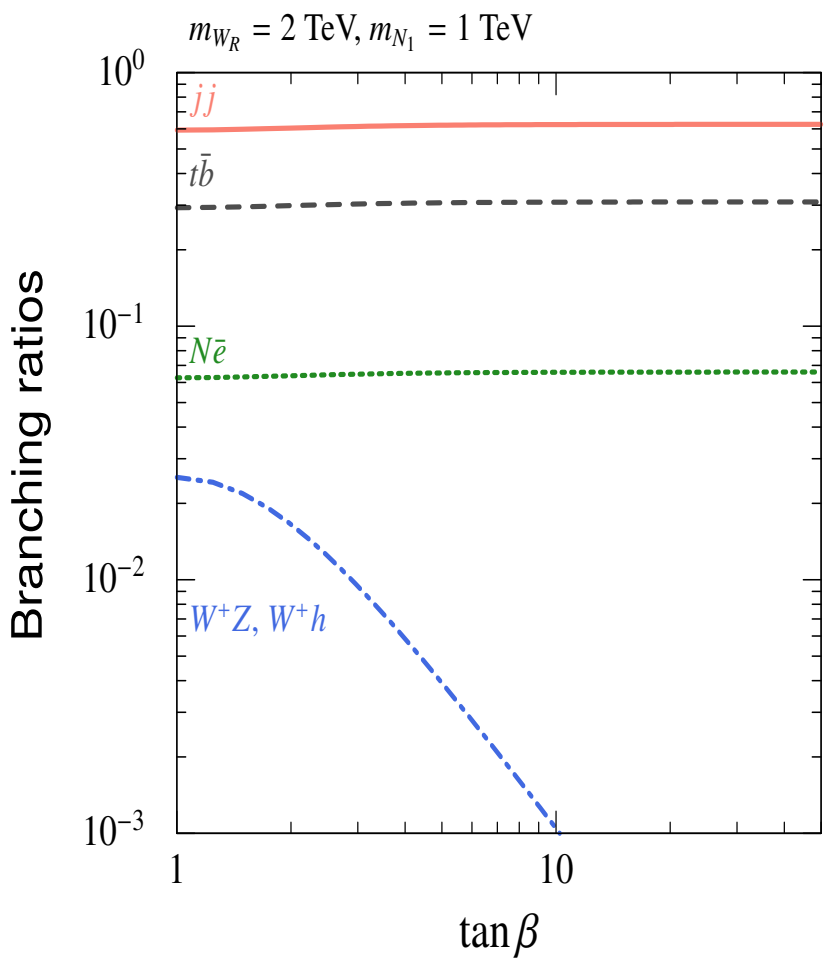
$$\mathcal{L}_{W_R ff} = \frac{g_L}{\sqrt{2}}\bar{u}\left(\cos\phi^W_{LR}\not{W}^+ - \sin\phi^W_{LR}\not{W}^+_R\right)P_L d + \frac{g_R}{\sqrt{2}}\bar{u}\left(\sin\phi^W_{LR}\not{W}^+ + \cos\phi^W_{LR}\not{W}^+_R\right)P_R d$$
$$+ \frac{g_L}{\sqrt{2}}\bar{\nu}\left(\cos\phi^W_{LR}\not{W}^+ - \sin\phi^W_{LR}\not{W}^+_R\right)P_L e + \frac{g_R}{\sqrt{2}}\overline{N_1}\left(\sin\phi^W_{LR}\not{W}^+ + \cos\phi^W_{LR}\not{W}^+_R\right)P_R e$$

+ h. c.

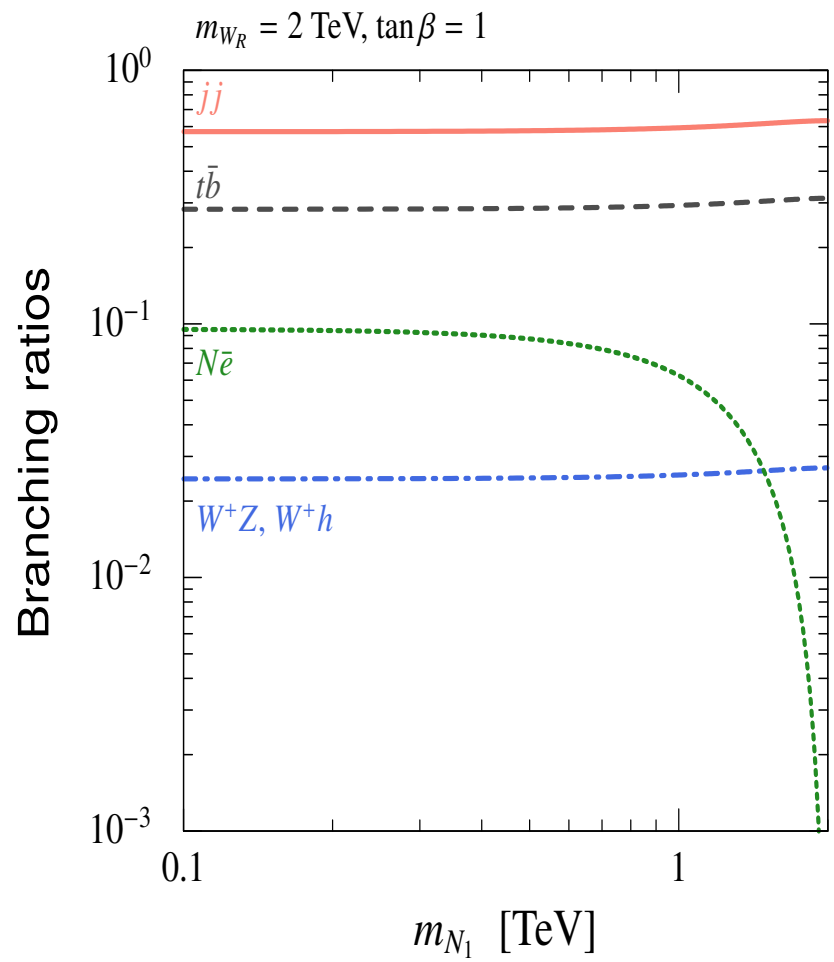
$$\mathcal{L}_{W_R WZ} = -ig_Z \sin\phi^W_{LR}\cos\phi^W_{LR}(W^+_{\mu\nu}W^{-\mu}_R + W^+_{R\mu\nu}W^{-\mu} - W^-_{\mu\nu}W^{+\mu}_R - W^-_{R\mu\nu}W^{+\mu})Z^\nu$$
$$- ig_Z \sin\phi^W_{LR}\cos\phi^W_{LR}(W^+_\mu W^-_{R\nu} + W^+_{R\mu}W^-_\nu)Z^{\mu\nu}$$

$$\mathcal{L}_{W_R Wh} = -\frac{1}{2\sqrt{2}}[(g_L^2 - g_R^2)\sin 2\phi^W_{LR} + 2g_L g_R \sin 2\beta\cos 2\phi^W_{LR}]vh(W^-W^+_R + W^-_R W^+)$$

Branching Rations of W_R



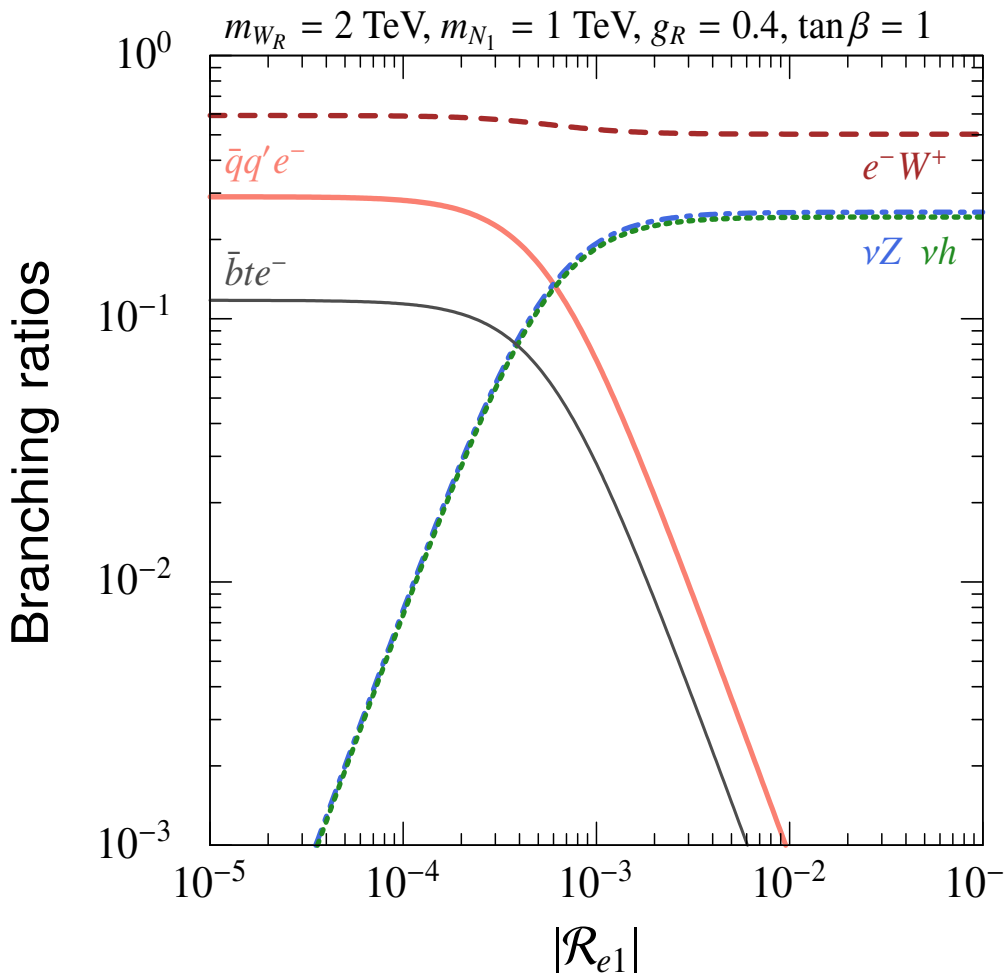
(a) $\tan\beta$ dependence



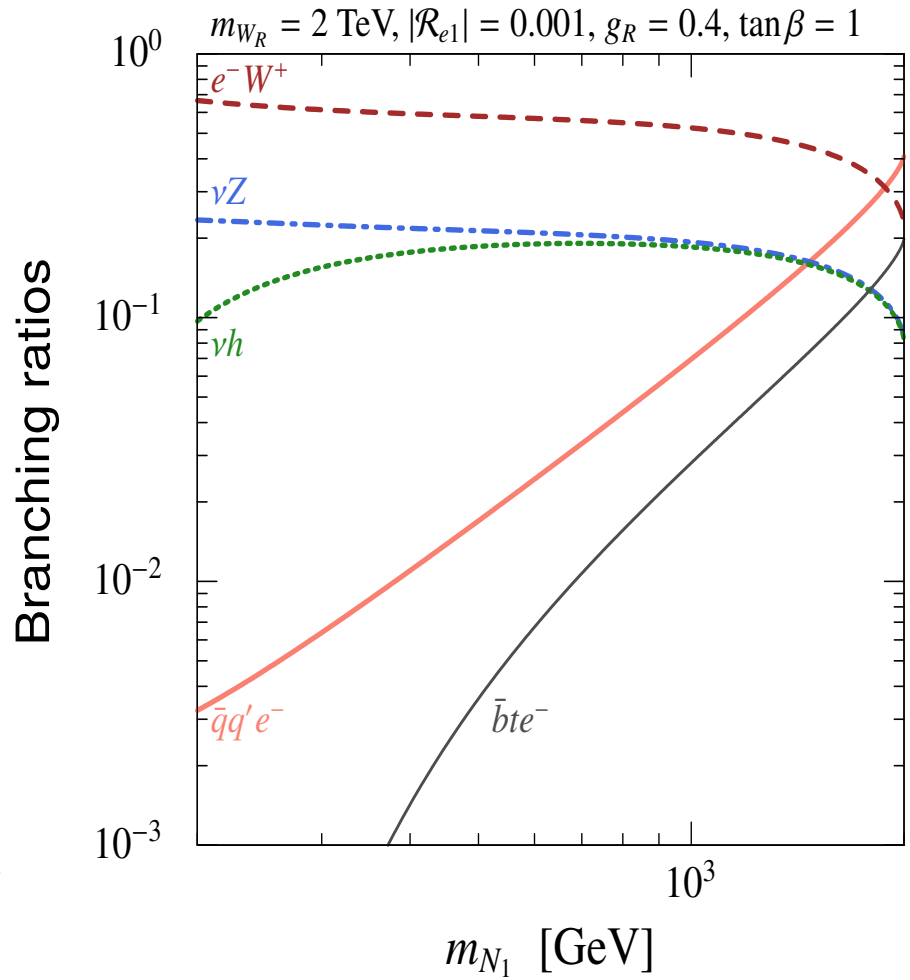
(b) m_{N_1} dependence

Branching Ratios of N_R *as*

Function of mixing angle



Function of mass

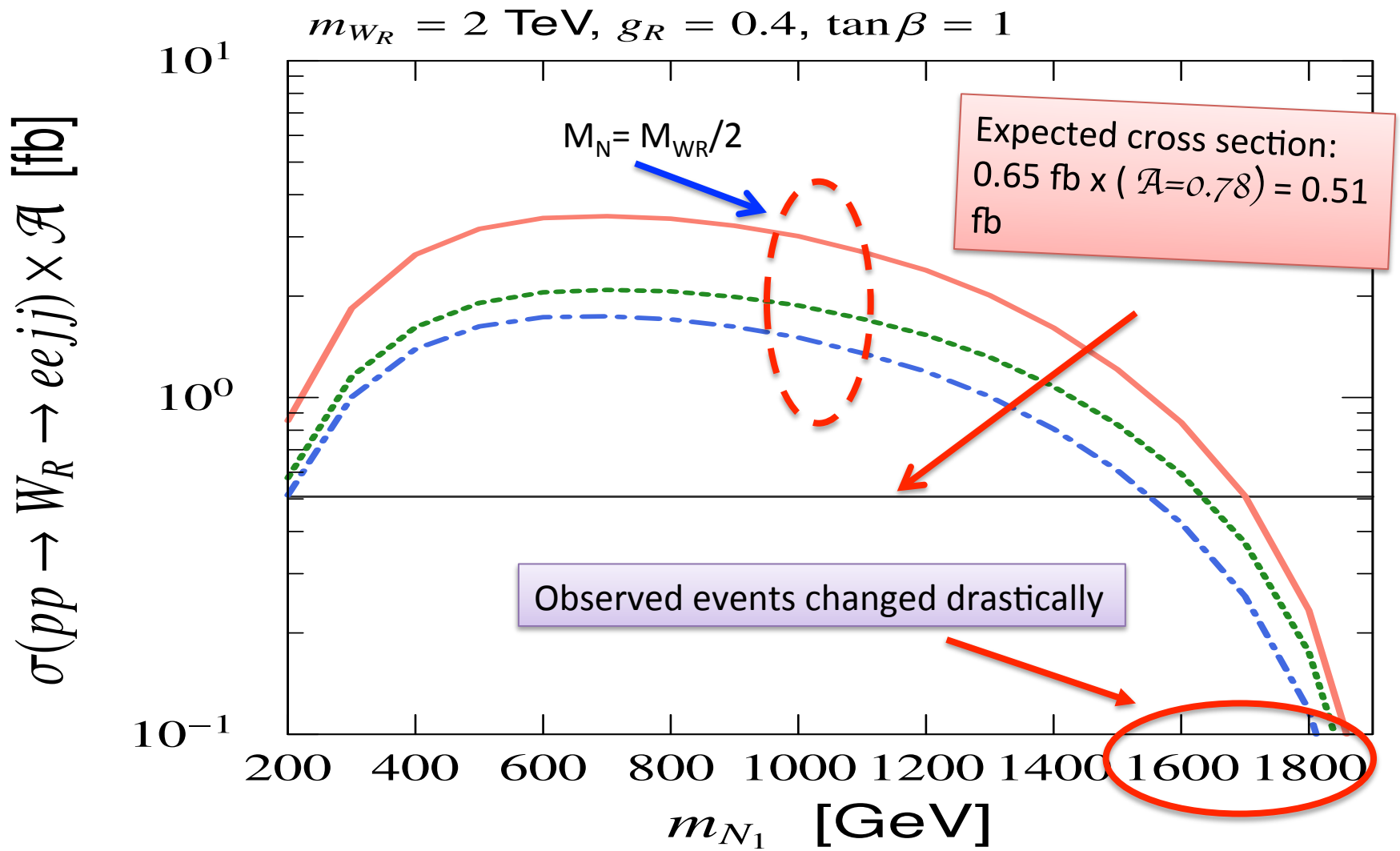


eW decay mode is dominating

Production Cross Sections at LHC in *eejj* channel

$|\mathcal{R}_{e1}| = 10^{-4}$, 10^{-3}, and 10^{-2} (from outer to inner)

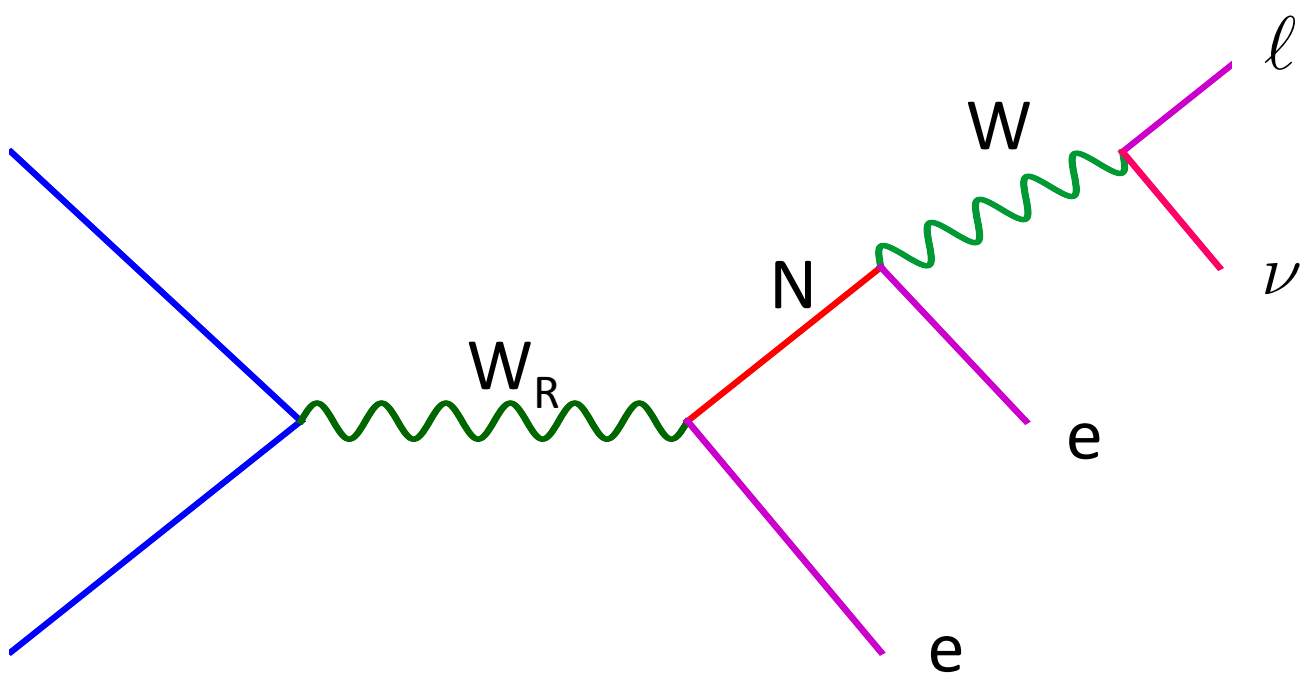
The horizontal gray line corresponds to 10 events for an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$



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

$$p\,p \rightarrow W_R \rightarrow N \rightarrow W\,e\,,\,W \rightarrow \ell\,\nu$$



We performed the simulation study using MadGraph with the same parameter sets

Selection Criteria (CMS multilepton search)

Phys. Rev. **D 90** (2014) 032006

- Electrons and muons are required to satisfy that their transverse momentum $p_{\rm T}$ be larger than 10 GeV and the magnitude of their pseudo-rapidity η 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 ϕ is the azimuthal angle.

- At least one electron or muon should have $p_{\rm T} > 20\,{\rm GeV}$.

- Jets should satisfy $p_{\rm T} > 30\,{\rm GeV}$ 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 $\geq 12\,{\rm GeV}$.

- We reject the "on-Z" events in which a pair of OSSF charged leptons yields $75 < m_{\ell^+\ell^-} < 105\,{\rm GeV}$.

Luminosity $19.5\,{\rm fb}^{-1}$

Results

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

Our results CMS results

Category	$m_{\ell^+\ell^-}$	$m_{N_1} = 1\,\text{TeV}$	1.6 TeV	Observed	Expected
$H_T > 200\,\text{GeV}$					
$E_T^{miss} > 100\,\text{GeV}$	Above-Z	4.76	1.67	5	3.6 ± 1.2
	Below-Z	0	0	7	9.7 ± 3.3
$50 < E_T^{miss} < 100\,\text{GeV}$	Above-Z	0.60	0.03	4	5.0 ± 1.6
	Below-Z	0	0	10	11.0 ± 3.8
$E_T^{miss} < 50\,\text{GeV}$	Above-Z	0	0	3	7.3 ± 2.0
	Below-Z	0	0	26	25.0 ± 6.8
$H_T < 200\,\text{GeV}$					
$E_T^{miss} > 100\,\text{GeV}$	Above-Z	5.53	1.81	18	13.0 ± 3.5
	Below-Z	0.38	0	21	24 ± 9
$50 < E_T^{miss} < 100\,\text{GeV}$	Above-Z	0.44	0	50	46.0 ± 9.7
	Below-Z	0	0	142	130 ± 27
$E_T^{miss} < 50\,\text{GeV}$	Above-Z	0.47	0	178	200 ± 35
	Below-Z	0	0	510	560 ± 87

The results are comparable

Conclusions

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

Our model can explain the CMS eejj 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.