Direct Bounds on Electroweak Scale Pseudo-Dirac Neutrinos from $\sqrt{s} = 8$ TeV LHC Data

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Introduction

•In Standard Model (SM) the neutrinos are considered to be massless.

•The current experimants on the neutrino oscillation phenomena indicate the existance of a tiny neutrino mass.

•Extend the SM.

• Seesaw mechanism → right handed singlet massive Majorana neutrino (N_R) to extend the SM

•$\mathcal{L}_{Seesaw} \supset -m_D \bar{\nu}_L N_R - \frac{1}{2} M \bar{N}_R^C N_R + h.c$:$m_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}$

• $m_\nu = m_D \boxed{\frac{m_D}{M}}$.

• If $M_N \leq 1$ TeV, N_R could be produced at high energy colliders.

• N_R couples with W and Z through the mass mixing with the light neutrino($\sim \frac{m_D}{M}$)

$$\mathcal{L}_{int} = -\frac{g}{\sqrt{2}} W^{\mu} \bar{e} \gamma^{\mu} P_L N \times \boxed{\frac{m_D}{M}} \nearrow SuppressionFactor \qquad (1)$$

• If $M \sim 100$GeV, $m_\nu = \frac{m_D^2}{M} \sim \sqrt{\Delta m_{23}} \sim 0.05eV$, $\frac{m_D}{M} \sim \sqrt{\frac{0.05eV}{100GeV}} \sim 10^{-6}$.

• The production cross section through the weak boson is very small, $\sigma \propto (\frac{m_D}{M})^2$

Inverse seesaw Mechanism

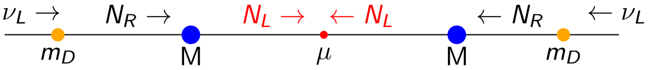
	SU(2)	$U(1)_Y$
ℓ_L	$\mathbf{2}$	$-1/2$
H	$\mathbf{2}$	$-1/2$
N_R^j	$\mathbf{1}$	0
N_L^j	$\mathbf{1}$	0

The particle content of the extended model

$$\mathcal{L}_{mass} \supset -\mu_{ij}\overline{((N_L)^c)^i}N_L^j - m_{ij}\overline{N_R^i}N_L^j - Y_{D_{ij}}\overline{\ell_L^i}HN_R^j + H.c. \quad (2)$$

i, j are the generation indices.

$$H = \begin{pmatrix} H^0 \\ H^- \end{pmatrix}. \quad (3)$$



The neutrino mass matrix is

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix} \quad (4)$$

Assuming $m_D M^{-1} \ll 1$, $m_\nu = (m_D \mathbf{M}^{-1})\mu(m_D \mathbf{M}^{-1})^T$

• μ is very small, $\mathcal{O}\,(m_\nu)$, the mixing $m_D \mathbf{M}^{-1} \sim \mathcal{O}(1)$

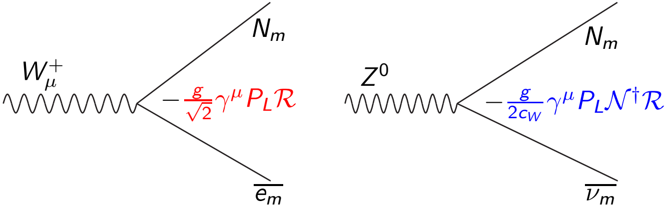
→Large mixing between light and heavy (Pseudo-Dirac)neutrinos

→Heavy (Pseudo-Dirac) neutrino can be produced at high energy colliders

• The production cross section of the heavy neutrino is sizable under all the phenomenological constraints. (A. D. and N. Okada, PRD 88 (2013) 113001)

• The flavour eigenstate (ν) in terms of the mass eigenstates

$$\nu \simeq \mathcal{N}\nu_m + \mathcal{R}N_m, \quad \mathcal{N} = (1 - \frac{1}{2}\mathcal{R}^*\mathcal{R}^T)U_{MNS} \tag{5}$$

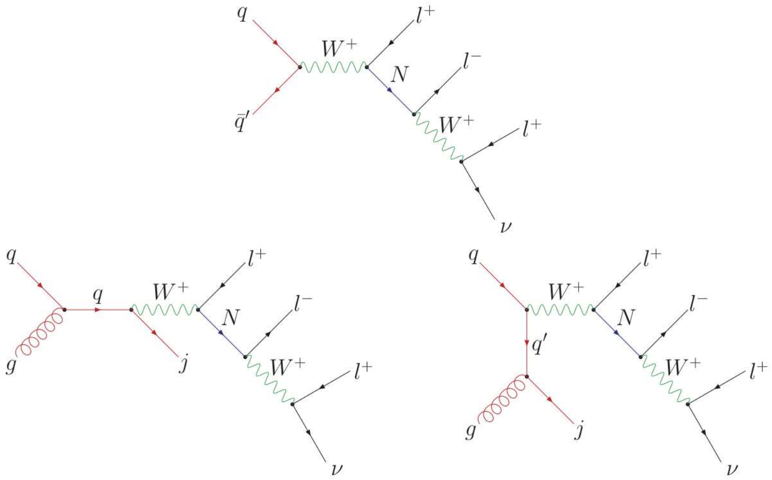


$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu \overline{e_m}\gamma^\mu P_L \left(\mathcal{N}\nu_m + \mathcal{R}N_m\right) + h.c., \tag{6}$$

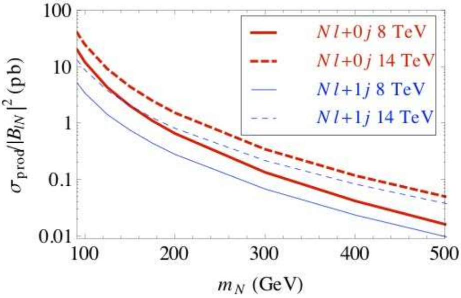
$$\begin{aligned} \mathcal{L}_{NC} &= -\frac{g}{2c_w} Z_\mu \left[\overline{\nu_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{N})\nu_m + \overline{N_m}\gamma^\mu P_L(\mathcal{R}^\dagger\mathcal{R})N_m\right] \\ &- \frac{g}{2c_w} Z_\mu \left[\overline{\nu_m}\gamma^\mu P_L(\mathcal{N}^\dagger\mathcal{R})N_m + h.c.\right] \end{aligned} \tag{7}$$

e_m, ν_m, N_m are the three generations of the leptons in the vector form.

Signal Process



Trilepton plus missing transverse energy signal of a heavy (pseudo-Dirac) Neutrino at the LHC



The inclusive parton-level cross sections for the processes $pp \to N\ell^+ + \bar{N}\ell^-$ (thick, red) and $pp \to N\ell^+ j + \bar{N}\ell^- j$ (thin, blue) at $\sqrt{s} = 8$ TeV (solid) and 14 TeV (dashed) LHC. The results are shown for the single flavor (SF) case.

LHC Constraints

• Recently CMS has presented a model independent search of anomalous production of events with at least three isolated charged leptons using 19.5 fb^{-1} data at $\sqrt{S}$ =8 TeV LHC. [arXiv:1404.5801[hep-ex]].

• The experimental results are consistent with the SM expectations.

•We utilize the CMS results to derive the first direct collider limits on the pseudo-Dirac heavy neutrino mass and their mixing with the active neutrinos.

• We perform the simulation study using MadGraph bundled with Pythia and Delphes for the collider signature of the trilepton+ missing energy from the heavy (pseudo-Dirac) neutrino with the same search criteria applied by the CMS.

• Then we compare our signal events with the CMS observed data.

• For simplicity we assume that m_D and M are diagonal.

• In the final events we have considered the Opposite Sigh Same Flavor (OSSF) leptons (like the recent CMS search).

• We consider the two benchmark cases : a) Single Flavor (SF) and b) Flavour Diagonal (FD)

• SF: One heavy neutrino couples with one flavor.
Signal Example: $pp \to N\mu, N \to W\mu, W \to \ell_\alpha \nu_\alpha$

• FD: Two degenerate heavy neutrinos couple with two lepton flavors individually. The cross section is twice larger than that of the SF case.

CMS Criteria

(i) The transverse momentum of each lepton: $p_T^\ell > 10$ GeV.

(ii) The transverse momentum of at least one lepton: $p_T^{\ell,\mathrm{leading}} > 20$ GeV.

(iii) The jet transverse momentum: $p_T^j > 30$ GeV.

(iv) The pseudo-rapidity of leptons: $|\eta^\ell| < 2.4$ and of jets: $|\eta^j| < 2.5$.

(v) The lepton-lepton separation: $\Delta R_{\ell\ell} > 0.1$ and the lepton-jet separation: $\Delta R_{\ell j} > 0.3$.

(vi) The invariant mass of each OSSF lepton pair: a) $m_{\ell^+\ell^-} < 75$ GeV and b) $m_{\ell^+\ell^-} > 105$ GeV.

(vii) The scalar sum of the jet transverse momenta: $H_T < 200$ GeV.

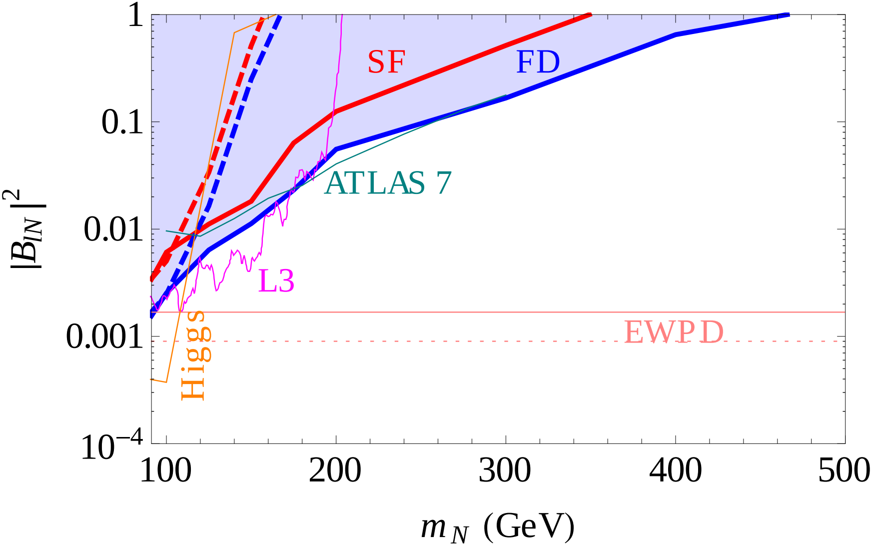
(viii) The missing transverse energy: $\not{E}_T < 50$ GeV.

•Case I : $m_{\ell^+\ell^-} < 75$: CMS has observed 510 events with the SM background expectation 560±87 events . Upper limit of $510 - (560 - 87) = 37$ events.

•Case II: $m_{\ell^+\ell^-} > 105$: CMS has observed 178 events with the SM background expectation 200±35 events. Upper limit of $178 - (200 - 35) = 13$ events.

• These set a 95 % CL on the mixing parameter as a function of the heavy neutrino mass.

• The upper bound in FD case is twice stronger than that in the SF case as it was expected.


1
0.1
0.01
0.001
10^{-4}
100
200
300
400
500
$|B_{lN}|^2$
m_N (GeV)
SF
FD
ATLAS 7
L3
Higgs
EWPD

Conclusion

•The detailed collider signature of the Pseudo-Dirac Heavy Neutrino form the Inverse Seesaw Mechanism has been studied.

•We have obtained the current direct bound from the CMS results.

•The strongest limit on the mixing parameter $|B_{\ell N}| = 0.039$ at $m_N = 91.2$ GeV in FD case. This bound is comparable to the EWPD

•Collider bound could be significantly improved at $\sqrt{s} = 14$ TeV