Neutrino masses, Dark Matter and B-L symmetry at the LHC

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1 - New Physics from the observational point of view

- Neutrino masses and mixings (Daya Bay, T2K, Icecube...)
- Dark matter particle (DAMA, XENON, CDMS...)
- Matter-antimatter asymmetry

Do they have anything to do with TeV scale physics?

2 - Neutrino Masses and Heavy Majoranas: Type I seesaw

- Type I seesaw: singlet right-handed neutrinos $N_R \sim (1,1,0)$

$$\mathcal{L}_\nu^I = -Y_D \bar{l}_L \widetilde{H} N_R - \frac{M_R}{2} \overline{N_L^c} N_R + h.c.$$

$$= -\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{N_L^c} \end{pmatrix} \begin{pmatrix} 0 & Y_D v/\sqrt{2} \\ Y_D^T v/\sqrt{2} & M_R \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \end{pmatrix} + h.c.$$

$$\Longrightarrow m_\nu \sim \frac{v_0^2}{2} Y_D \frac{1}{M_R} Y_D^T$$

M_R is defined by the L/B-L symmetry breaking scale

- In the context of SM, production channel of TeV scale heavy Majorana neutrino is $pp \to W^* \to N\ell$, but highly suppressed to the order $\mathcal{O}(m_\nu/M_R)$ Han et al. 06, 09

3 - Testability of $U(1)_{B-L}$ extended Type I seesaw at the LHC

$B-L$ extension of the SM $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

$$\mathcal{L}_{kin} = i\bar{Q}_L\gamma^\mu D_\mu Q_L + i\bar{u}_R\gamma^\mu D_\mu u_R + i\bar{d}_R\gamma^\mu D_\mu d_R + i\bar{l}_L\gamma^\mu D_\mu l_L$$

$$+i\bar{e}_R\gamma^\mu D_\mu e_R + i\bar{N}_R\gamma^\mu D_\mu N_R$$

$$D_\mu N_R = \partial_\mu N_R - ig_{BL}B'_\mu N_R$$

$$\mathcal{L}_{scalar} = (D_\mu H)^\dagger(D^\mu H) + (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(H,\Phi)$$

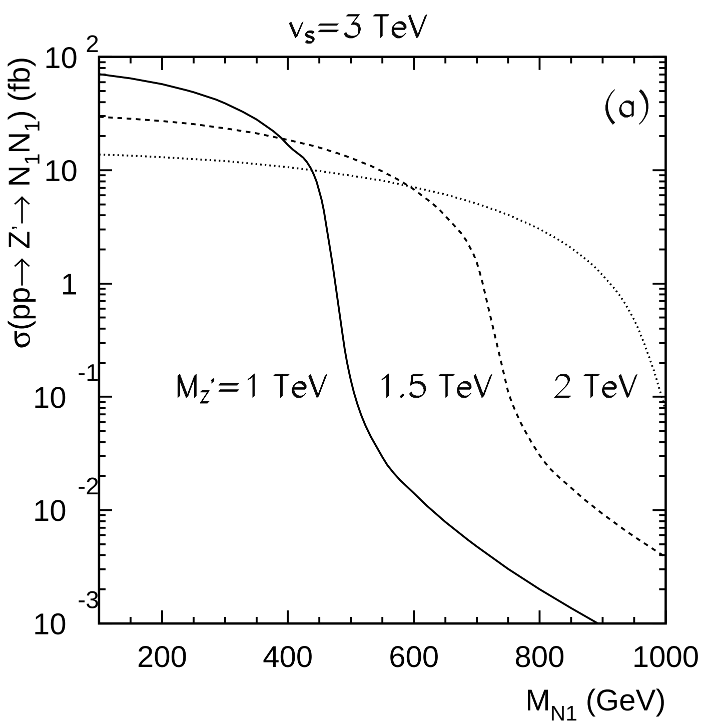
$$D_\mu\Phi = \partial_\mu\Phi + i2g_{BL}B'_\mu\Phi$$

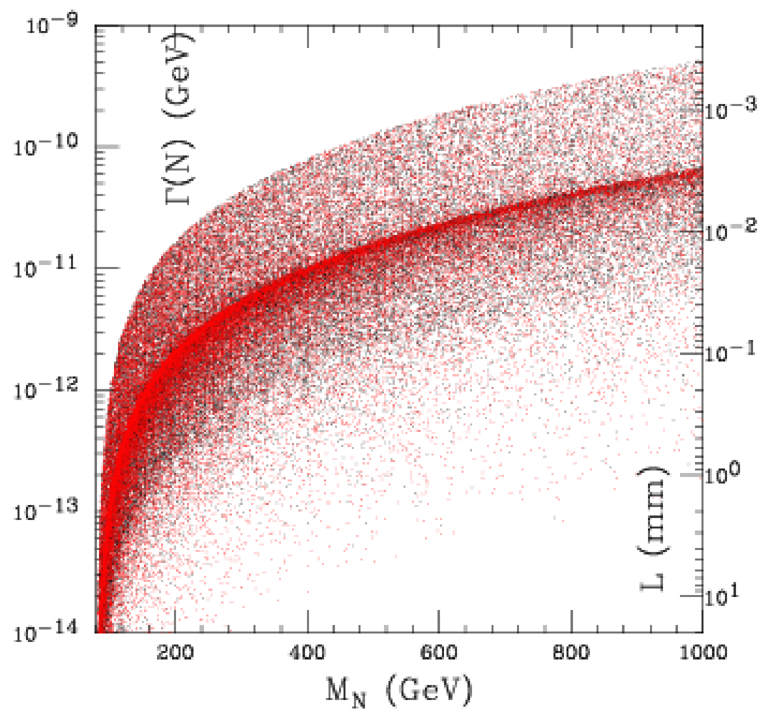
$$\mathcal{L}_\nu = -Y_D\bar{l}_L\tilde{H}N_R - \frac{Y_M}{2}\bar{N_L^C}N_R\Phi + h.c.$$

Once additional scalar singlet $\Phi \sim (1,1,0,2)$ gets vev $\langle\Phi\rangle = v_\Phi/\sqrt{2}$, one gets $Z' = Z_{BL}$ with $M_{Z'} = 2g_{BL}v_\Phi$ and mass matrix of right-handed neutrino with $M_N = Y_M v_\Phi/\sqrt{2}$

The typical signature of this model is to search Z' resonance in purely leptonic final states.

Leading production channel of N pair $pp \to Z' \to NN$ has large production rate (P.F. Perez, T. Han, TL, PRD80:073015, 2009)





$\Delta L = 2$ **signal for** N **decay:** $NN \to \ell^\pm \ell^\pm W^\mp W^\mp \to \ell^\pm \ell^\pm + 4jets$

Basic Cuts

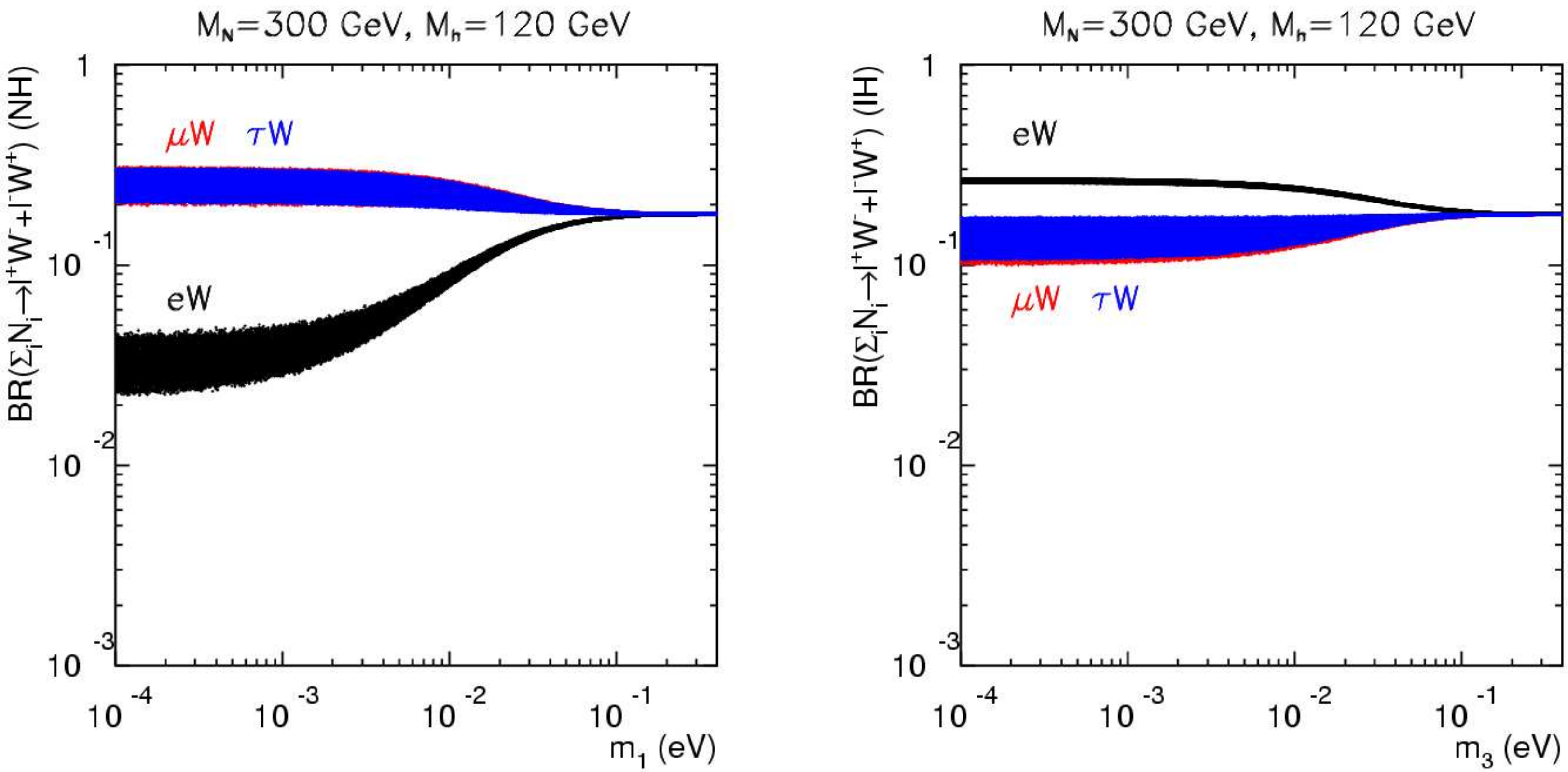
- $p_T(\ell_{min}) > 15$ GeV, $p_T(j_{min}) > 25$ GeV
- $|\eta(\ell)| < 2.5$, $|\eta(j)| < 3.0$
- $\Delta R_{jj} > 0.3$, $\Delta R_{j\ell}, \Delta R_{\ell\ell} > 0.4$

SM Background: same-sign W's leptonic decay

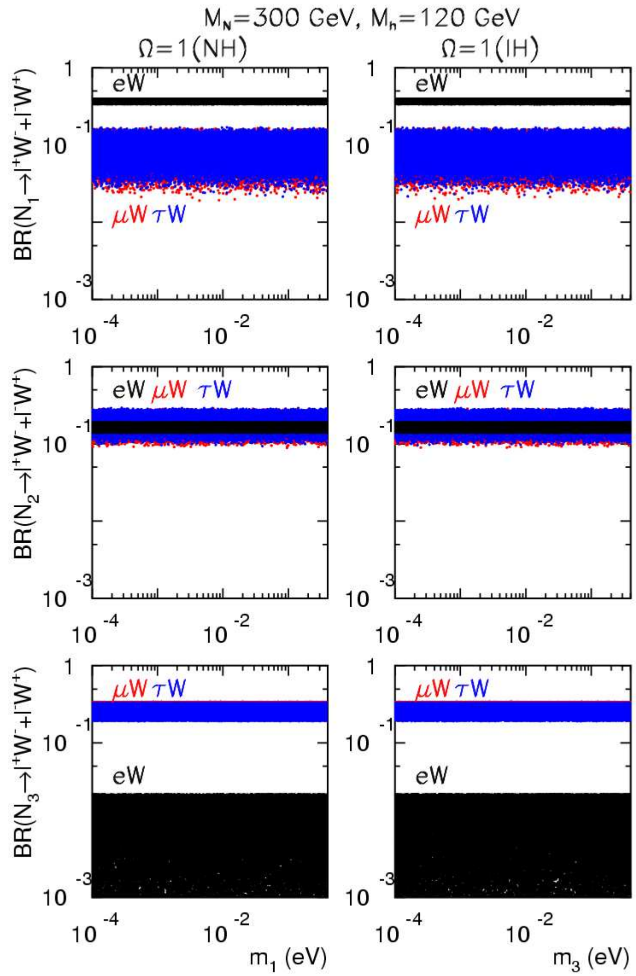
- leading bkg: $t\bar{t}W^\pm \to W^\pm W^\pm jjb\bar{b}$
- veto SM bkg events with large missing energy $\not{E}_T < 20$ GeV; hadronic W boson reconstruction; the two heavy neutrinos have equal masses

Decay of heavy neutrinos

All the partial decay widths of heavy neutrinos N_i are proportional to $V^2_{PMNS} m_\nu / M_N$, $BR(\sum_i N_i \to \ell^\pm W^\mp)$ under degenerate case:

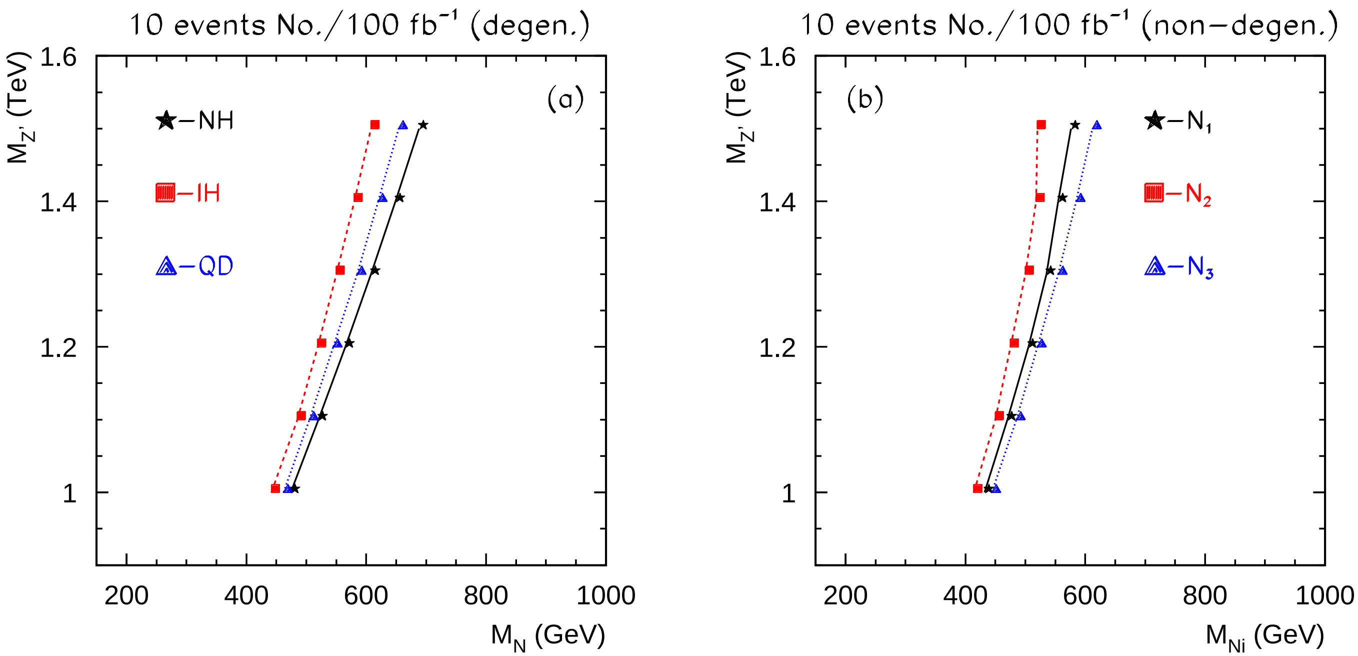


$BR(N_i \to \ell^{\pm}W^{\mp})$ under non-degenerate case:



Measuring Branching Fractions and Probing the Neutrino Mass Patterns

Event contours in the $M_{Z'} - M_N$ plane at the LHC including all cuts



The number of events is written as

$$N = L \times \sigma(pp \to N_1 N_1) \times 2\,\mathrm{BR}^2(N_1 \to \ell^+ W^-)(\tfrac{6}{9})^2$$

4 - A pessimistic case: $M_N > 1\ \mathrm{TeV}$ or $M_{Z'}/2$

How can we get detectable signatures at the LHC in B-L extension framework?

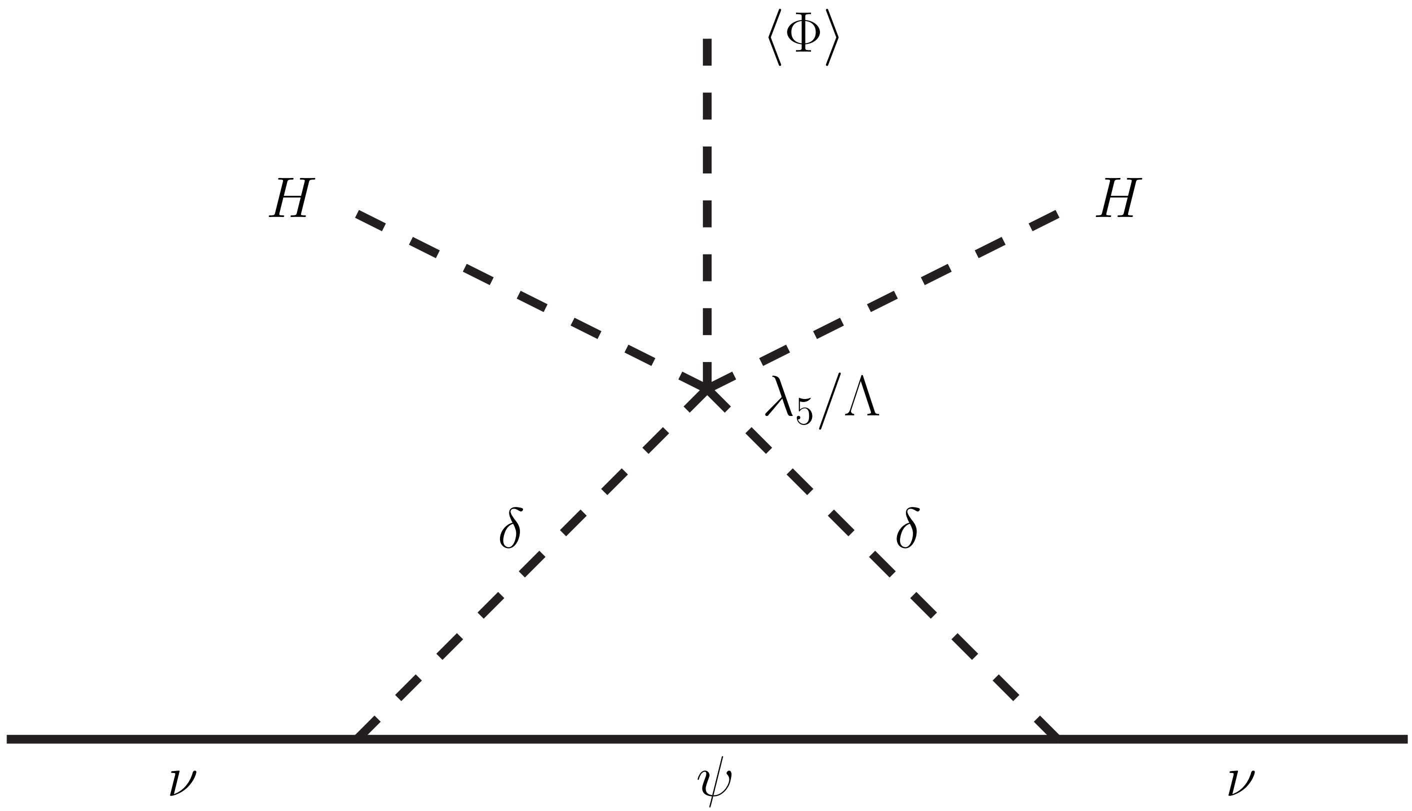
Consider a hybrid seesaw: Type I seesaw plus radiative seesaw model in which an additional $SU(2)$ scalar doublet $\eta^T = (\eta^+, \eta^0)$ and gauge singlet fermion are included beyond minimal B-L extension of SM (TL, W. Chao, arXiv: 1004.0296 [hep-ph])

	Q_L, u_R, d_R	l_L, ℓ_R	N_R	H	Φ		η	ψ
$B-L$	$\frac{1}{3}$	-1	-1	0	$+2$		$+1$	0

The relevant lagrangian and scalar potential are

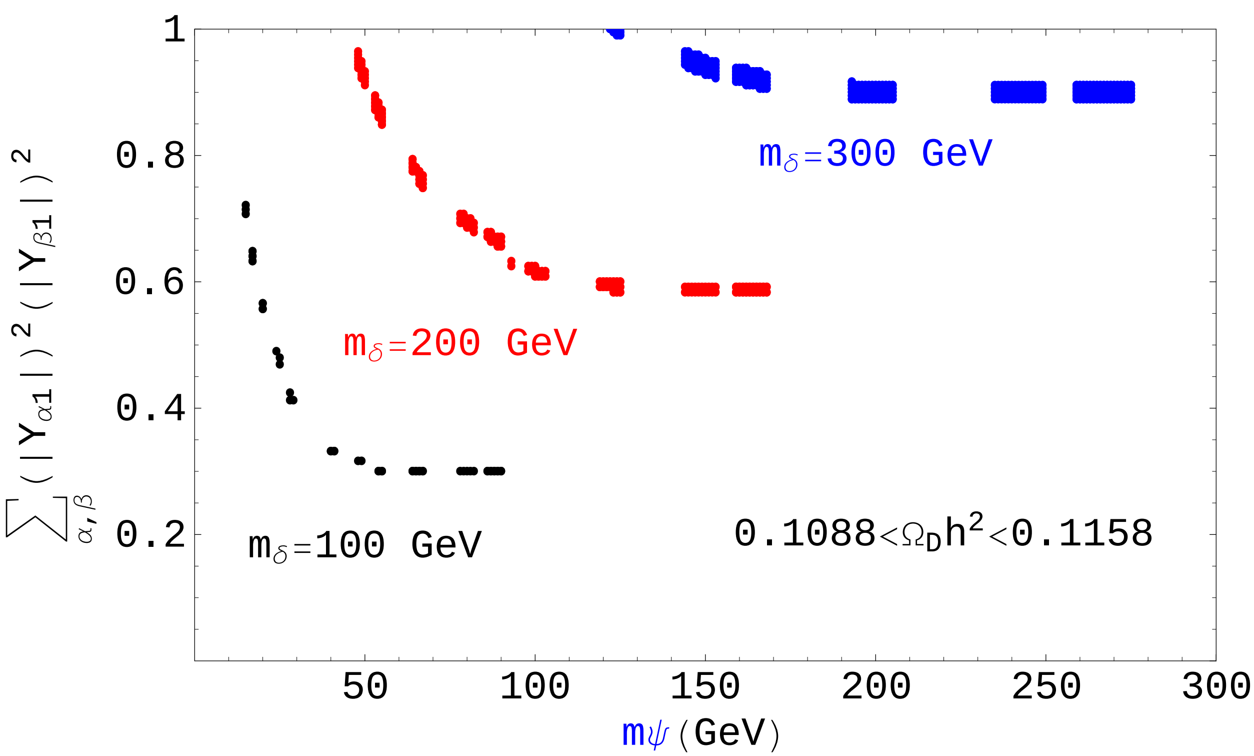
$$\mathcal{L}_{Kin} = i\overline{Q_L}\gamma^\mu D_\mu Q_L + i\overline{u_R}\gamma^\mu D_\mu u_R + i\overline{d_R}\gamma^\mu D_\mu d_R + i\overline{l_L}\gamma^\mu D_\mu l_L$$
$$+ i\overline{\ell_R}\gamma^\mu D_\mu \ell_R + i\overline{N_R}\gamma^\mu D_\mu N_R + i\overline{\psi_R}\gamma^\mu D_\mu \psi_R$$
$$-\mathcal{L}_Y = Y_\psi \overline{l_L}\widetilde{\eta}\psi_R + Y_D\overline{l_L}\widetilde{H}N_R + \frac{1}{2}m_\psi\overline{\psi^C_R}\psi_R + \frac{1}{2}Y_M\overline{N^C_R}N_R\Phi + h.c.$$
$$\mathcal{L}_{Scalar} = (D_\mu H)^\dagger(D^\mu H) + (D_\mu\eta)^\dagger(D^\mu\eta) + (D_\mu\Phi)^\dagger(D^\mu\Phi) - V$$
$$V(H,\eta,\Phi) = -m_H^2 H^\dagger H - m_\eta^2\eta^\dagger\eta - m_\Phi^2\Phi^\dagger\Phi + \lambda_H(H^\dagger H)^2$$
$$+\lambda_\eta(\eta^\dagger\eta)^2 + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \lambda_1(H^\dagger H)(\eta^\dagger\eta) + \lambda_2(H^\dagger\eta)(\eta^\dagger H)$$
$$+\lambda_3(H^\dagger H)(\Phi^\dagger\Phi) + \lambda_4(\eta^\dagger\eta)(\Phi^\dagger\Phi) + \frac{\lambda_5}{\Lambda}\left[(H\eta^\dagger)^2\Phi + h.c.\right]$$

Neutrino mass generation



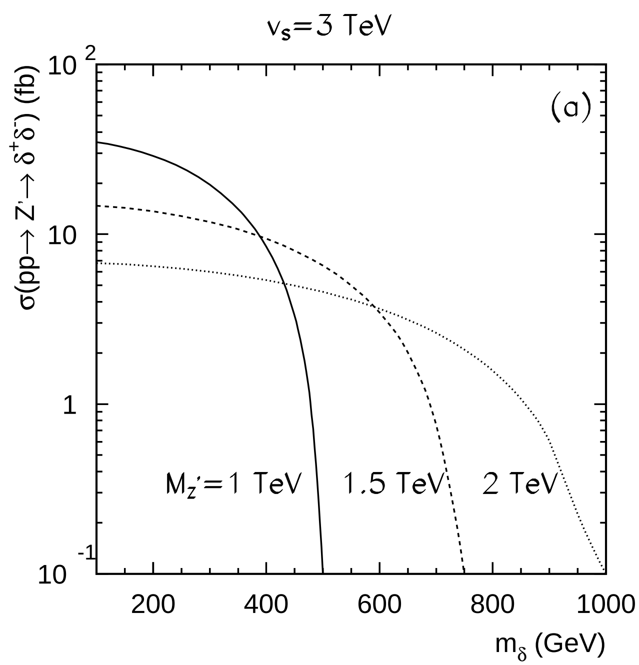
Dark Matter candidate

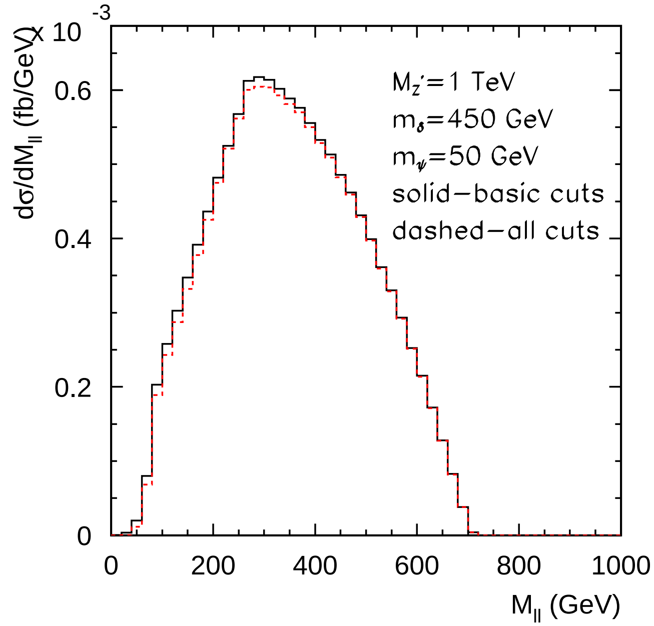
- mass hierarchy: $m_\psi < m_\eta \ll M_N \sim M_{Z'} \sim \langle \Phi \rangle \sim \mathcal{O}(\mathrm{TeV})$
- annihilation rate of ψ



Production of η and ψ at the LHC when heavy neutrinos are forbidden

$$pp \to Z' \to \eta^+\eta^- \to \ell^+\psi\ell^-\psi$$





It is appropriate to determine missing particle mass in this production topology using the invariant mass distribution $M_{\ell^+\ell^-}$ (T. Han, TL, J. Song, in progress)

5 - Summary

- The production mechanisms for the heavy neutrinos through Z' gauge boson in the $U(1)_{B-L}$ extension of SM are studied. We design different cuts to identify signal $NN \to \ell^{\pm}\ell^{\pm}jjjj$ and suppress SM backgrounds
- We find the $\Delta L = 2$ channels could provide conclusive signals at the LHC in connection with the light neutrino mass and mixing properties
- If we consider heavier Majorana neutrinos situation, radiative seesaw mechanism can give an option of getting physical light neutrino mass and provide dark matter candidate