Unitarity constraints for Yukawa couplings in the $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model

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Abstract

Constraints from perturbative unitarity are studied in the Yukawa sector of a $SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ model. In this scenario, besides three right handed neutrinos which are included to cancel chiral anomalies, it is also postulated a complex scalar singlet for the spontaneous symmetry breaking of the extended gauge sector $U(1)_{B-L}$ and to give mass to the associated Z' boson. From different scattering processes involved neutrinos and Higgs states, exclusion regions are obtained for neutrino masses and mixing angles.

The $B-L$ model

The gauge principle for this model is based on

$$SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

It could be motivated since the following properties [1]:

- A natural explanation for the observed pattern of neutrino masses (with respect to charged leptons and quarks).
- The gauge origin of a global and not anomalous accidental $U(1)$ symmetry in the SM (related to the baryon minus lepton $(B-L)$ quantum numbers)
- The model contains a natural explanation for Leptogenesis mechanism compatible with the baryon assymetry of the universe.
- Another theoretical motivation is related to higher gauge theories could end up in a $B-L$ model. For instance the Left-Right mirror models, since they incorporate full quark lepton-symmetry for the weak interactions and give the $U(1)$ generator of electrowek symmetry a new meaning in terms of the $B-L$ quantum number.

Scalar sector

The Spontaneous symmetry breaking is achieved under the following scheme

$$SU(2)_L \times U(1)_Y \times U(1)_{B-L} \to SU(2)_L \times U(1)_Y \to U(1)_Q$$

With Vacuum Expectation Values w and v respectively. The scalar Lagrangian is

$$\mathcal{L}_S = (D_\mu \Phi)^\dagger (D^\mu \Phi) + (D_\mu \chi)^\dagger (D^\mu \chi) - V(\Phi, \chi)$$

χ is a complex singlet for SSB of $U(1)_{B-L}$ in TEV scale. Φ is the traditional $SU(2)$ doublet that generates the SSB in the electroweak SM. Accordingly, the first and second terms are the kinetic sectors for doublet and singlet. The Higgs potential is given by

$$V(\Phi, \chi) = \mu_H^2 \left(\Phi^\dagger \Phi\right) + \mu_\chi^2 \left(\chi^\dagger \chi\right) + \lambda_H \left(\Phi^\dagger \Phi\right)^2 + \lambda_\chi \left(\chi^\dagger \chi\right)^2 + \lambda_{H\chi} \left(\chi^\dagger \chi\right)\left(\Phi^\dagger \Phi\right)$$

And finally the Yukawa lagrangian

$$-\mathcal{L}_Y = \eta_{jk}^D \bar{Q}_{jL} \Phi D_{kR} + \eta_{jk}^U \bar{Q}_{jL} \tilde{\Phi} U_{kR} + \eta_{jk}^E \bar{L}_{jL} \Phi E_{kR} + \eta_{jk}^\nu \bar{L}_{jL} \tilde{\Phi} \nu_{kR} + \eta_{jk}^M \overline{(\nu_R)^c} \chi \nu_{kR} + h.c.$$

here $\tilde{\Phi} = i\sigma_2 \Phi^*$ and i, j, k take the values 1 to 3, in addition the last term is the Majorana contribution and the others are the usual Dirac ones. Q and L are the quark and leptons doublets of left chirality and D and U, E are the right handed singlets for quarks up, down and charged leptons respectively.

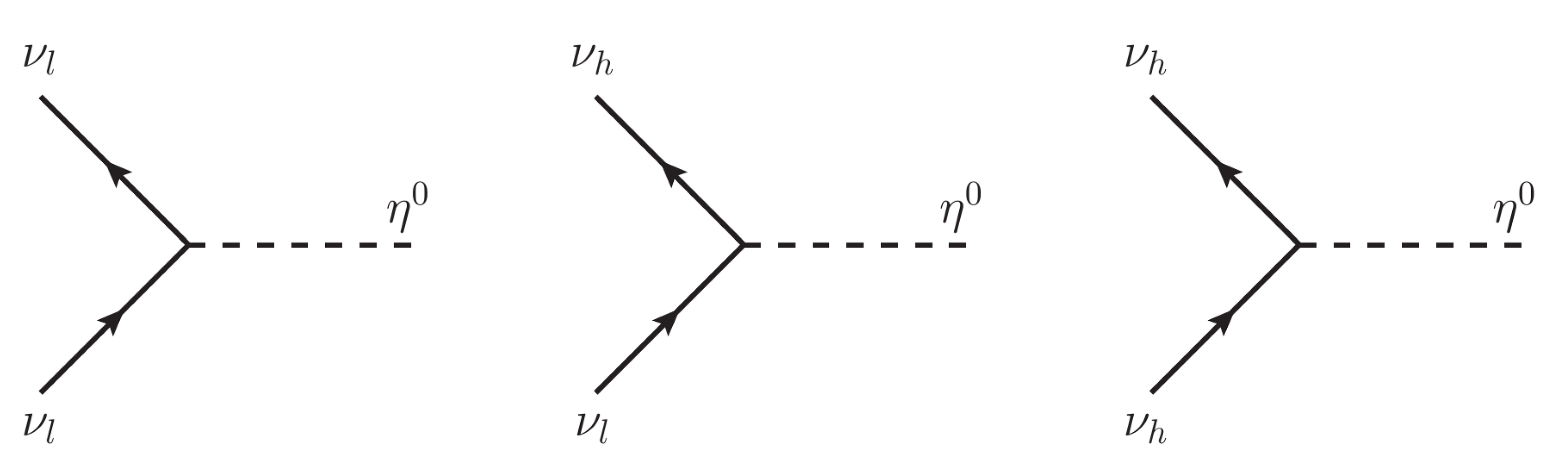
In order to implement the see saw mechanism, we choose the following texture for mass matrix

$$\boldsymbol{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}, \quad M_D = \frac{\eta^\nu}{\sqrt{2}} v, \quad M_R = \sqrt{2} \eta^M w$$

This matrix can be diagonalised by a rotation about an angle α_ν, such that:

$$\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} = \begin{pmatrix} \cos\alpha_\nu & -\sin\alpha_\nu \\ \sin\alpha_\nu & \cos\alpha_\nu \end{pmatrix} \begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix}, \; m_{\nu_l} \cong \frac{M_D^2}{M_R}, \; m_{\nu_h} \cong M_R, \; \tan 2\alpha_\nu \cong -2\sqrt{\frac{m_{\nu_l}}{m_{\nu_h}}}$$

Feynman rules for Yukawa sector



Given their importance, we list here the Feynman rules involving the heavy and light neutrinos with scalars in the pure $B-L$ model $(\tilde{g} = 0)$ (mass degenerate regime) [1]:

Coupling	Feynman Rule
$\Xi(\nu_l \nu_l h_1)$	$-\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \cos\alpha \sin 2\alpha_\nu + m_{\nu_h} \cos 2\alpha_\nu \sin\alpha - m_{\nu_h} \sin\alpha\right)$
$\Xi(\nu_l \nu_l h_2)$	$-\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \sin\alpha \sin 2\alpha_\nu - m_{\nu_h} \cos 2\alpha_\nu \cos\alpha + m_{\nu_h} \cos\alpha\right)$
$\Xi(\nu_h \nu_l h_1)$	$-\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \cos\alpha \cos 2\alpha_\nu - m_{\nu_h} \sin 2\alpha_\nu \sin\alpha\right)$
$\Xi(\nu_h \nu_l h_2)$	$-\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \sin\alpha \cos 2\alpha_\nu + m_{\nu_h} \sin 2\alpha_\nu \cos\alpha\right)$
$\Xi(\nu_h \nu_h h_1)$	$\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \cos\alpha \sin 2\alpha_\nu + m_{\nu_h} \cos 2\alpha_\nu \sin\alpha + m_{\nu_h} \sin\alpha\right)$
$\Xi(\nu_h \nu_h h_1)$	$\frac{1}{2w}\left(\sqrt{2} w \eta^\nu \sin\alpha \sin 2\alpha_\nu - m_{\nu_h} \cos 2\alpha_\nu \cos\alpha - m_{\nu_h} \cos\alpha\right)$

where the Yukawa coupling and mixing angle

$$\eta^\nu = \frac{\sqrt{2 m_h m_l}}{v}, \quad \sin 2\alpha_\nu = -2\frac{\eta^\nu \frac{v}{\sqrt{2}}}{\sqrt{4\left(\eta^\nu \frac{v}{\sqrt{2}}\right)^2 + m_{\nu_h}^2}}, \quad \cos 2\alpha_\nu = \frac{m_{\nu_h}}{\sqrt{4\left(\eta^\nu \frac{v}{\sqrt{2}}\right)^2 + m_{\nu_h}^2}}$$

Jacob-Wick formalism and Unitarity Constraints

The JWF is based on a diagonalization (at least partial) in the angular momentum basis of the $\widehat{S}$ matrix for the scattering of two particles (with initial helicities λ_a, λ_b and final helicities λ_c, λ_d) in the center of mass frame.

$$\mathcal{M}(s,\Omega) = 16\pi\xi_I \sum_J (2J+1) \mathcal{D}^\dagger_{(J)}(\Omega)^{\lambda_a - \lambda_b}_{\lambda_c - \lambda_d} \mathcal{M}^J(s), \;\; \mathcal{M}^J(s) = \frac{1}{16\pi\xi_I} \int \mathcal{M}(s,\Omega) \mathcal{D}^{*(J)}(\Omega)^{\lambda}{}_{\lambda'} d\Omega.$$

where s is the CM energy, and $\Omega \equiv (\theta, \phi)$ defines the scattering polar and azimuthal angles, ξ_I is a indistinguibility factor. In addition, $\mathcal{D}(\Omega)^\lambda{}_{\lambda'}$ are Wigner functions. If $\lambda' = \lambda = 0$, at the high energy limit, perturbative unitarity requires that

$$|\mathrm{Re}(\mathcal{M}^J(s))| \leq \frac{1}{2}\xi_I.$$

$\nu\nu \to \nu\nu$ processes

In the following we consider the tree level matrix elements for the process $\nu_i \nu_j \to \nu_i \nu_j$ $(i, j = l$ or $h)$ for Majorana neutrinos at the high energy limit under the helicity spinors formalism. By virtue in models with Majorana neutrinos there are heavy particles (as initial and final states), this formalism shall take into account CM-energies of order $\sqrt{s} >> v, w$. The Higgs (η^0) contributions are shown in Fig. 1.

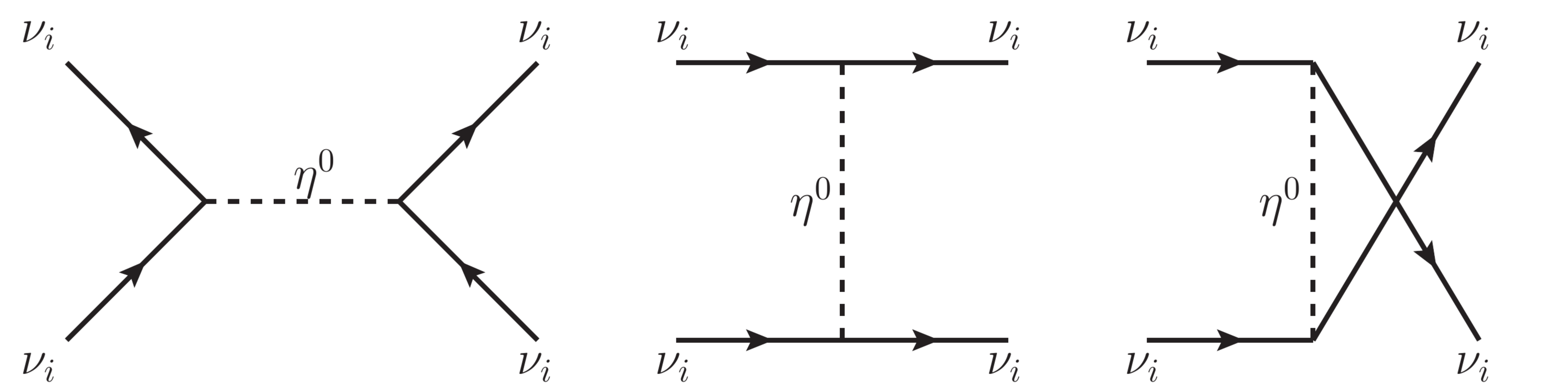


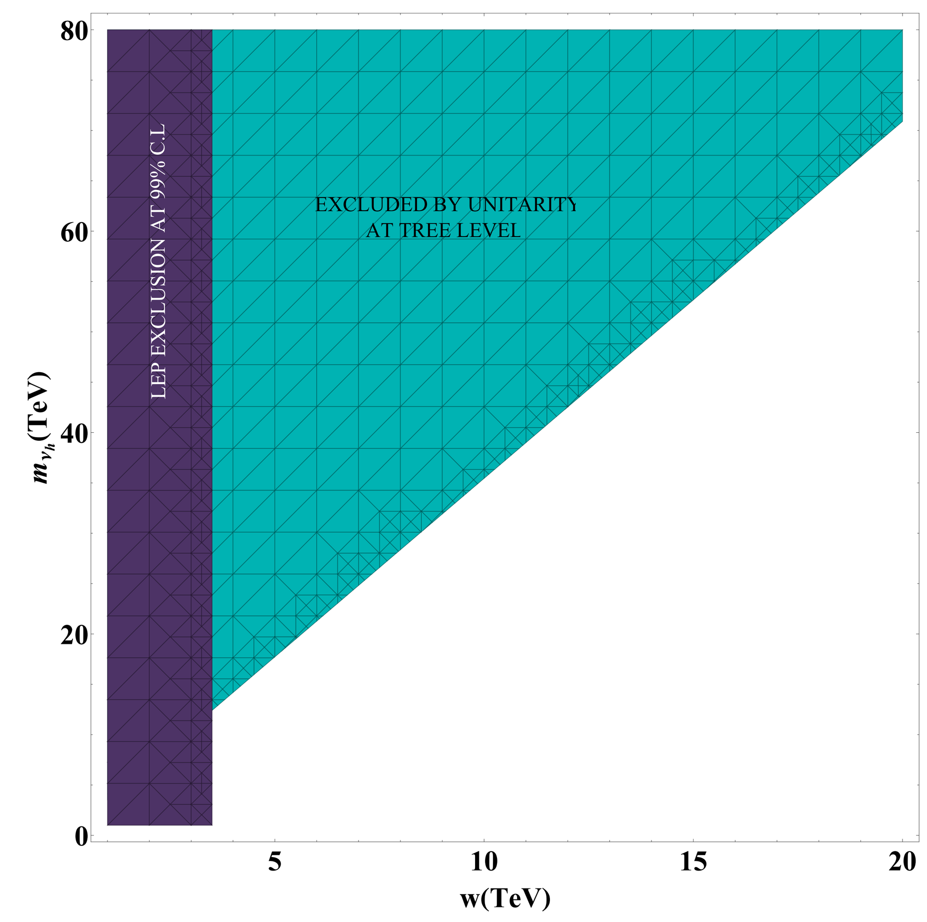
Figure : Contributions from s, t and u channels for $\nu_i \nu_i \to \nu_i \nu_i$ Majorana scattering processes (with $i = l, h$).

First, we write the invariant amplitude in a general form:

$$\mathcal{M}(\nu_i \nu_j \to \nu_i \nu_j) = -\sum_{\eta^0} \left(\Xi^{\eta^0}_{\nu\nu}\right)^2 \left[\frac{(\bar{v}_1 u_2)(\bar{u}_3 v_4)}{s - m_{\eta^0}^2} - \frac{(\bar{u}_3 u_1)(\bar{u}_4 u_2)}{t - m_{\eta^0}^2} + \frac{(\bar{u}_4 u_1)(\bar{u}_3 u_1)}{u - m_{\eta^0}^2}\right]$$

here Ξ^{η^0} are the couplings between Majorana fermions and neutral Higgs bosons. The relative minus sign of the t-channel graph relative to the s and u-channel graphs is obtained by noting that 3142 [4132] is an odd [even] permutation of 1234. From unitarity limit, we found for $\nu_{h\uparrow}\nu_{h\uparrow} \to \nu_{h\uparrow}\nu_{h\uparrow}$

$$\nu_h \nu_h \to \nu_h \nu_h : \left(\frac{16 m_{\nu_h}^2 m_{\nu_l}^2 \frac{w^2}{v^2}}{4 m_{\nu_h} m_{\nu_l} + m_{\nu_h}^2} + \frac{m_{\nu_h}^4}{4 m_{\nu_h} m_{\nu_l} + m_{\nu_h}^2} + m_{\nu_h}^2 + \frac{2 m_{\nu_h}^3}{\sqrt{4 m_{\nu_h} m_{\nu_l} + m_{\nu_h}^2}}\right) < 16\pi w^2$$



Exclusion region from perturbative unitarity (at tree level) for $\nu_h \nu_h \to \nu_h \nu_h$ Majorana neutrinos scattering (cyan). The violet region is due to exclusion region from LEP experiment at 99 % C.L. for $M_z'/g' \geq 7$ TeV. This could be translated into a limit on $w \geq 3.5$ TeV [1]

Conclusions and Remarks

Under the use of a general expansion of partial waves, unitarity constraints over neutrinos scattering processes in $B-L$ model were obtained. The main assumption for unitarity bound is that the $B-L$ model is a valid description of physics up to very high energy scales where new or non-perturbative physics of some kind must be taken into account. In the case of elastic scattering processes, diagonal Yukawa couplings constraints (coming from $\nu_h \nu_h \to \nu_h \nu_h$) are more stringent that coming from whose $\nu_l \nu_l \to \nu_l \nu_l$ or $\nu_h \nu_l \to \nu_h \nu_l$. This leads bounds over heavy mass neutrino, which depend on singlet VEV w, but it is strongly independent of light neutrino mass.

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