Neutrino Masses from TeV Scale

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Introduction

- **The SM, based on the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$, is in excellent agreement with almost of all current experimental results.**

- **However, New Physics beyond SM is strongly suggested by both experimental & theoretical point of view**

- Three firm observational evidences of new physics beyond the Standard Model :

    1. Neutrino Masses.
    2. Dark Matter.
    3. Baryon Asymmetry.

- These three problems may be solved by introducing right-handed neutrinos.

Neutrino masses and mixings

<u>Oscillation data</u>

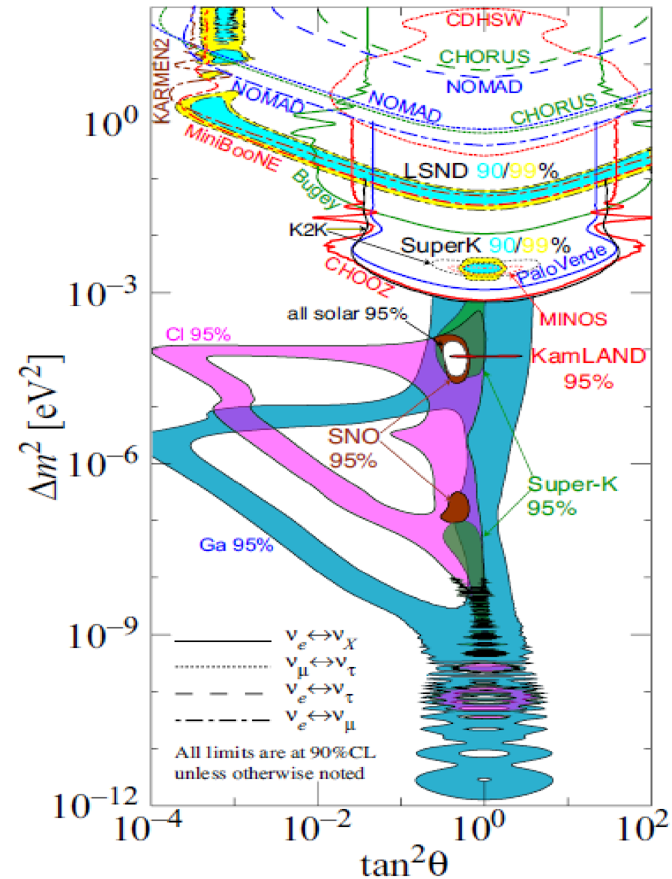
$$\Delta m^2_{21} = (7.59 \pm 0.20) \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(2\theta_{12}) = 0.87 \pm 0.03$$

$$\sin^2(2\theta_{23} > 0.92$$

$$\sin^2(2\theta_{13}) < 0.19.$$



Very small mass scale
Large mixing angle

Scale of New Physics for Seesaw Mechanism

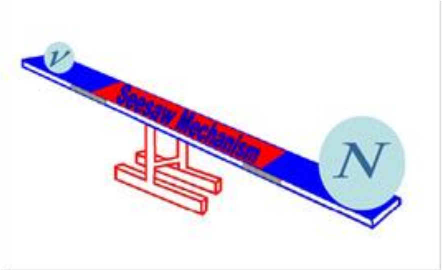
- If neutrinos are Majorana particles, their mass at low energy is described by a dimension-5 operator:

$$\mathcal{L} = \frac{f}{\Lambda}(HL)(HL) \Rightarrow m_v = \frac{fv^2}{\Lambda}$$

- Naturally

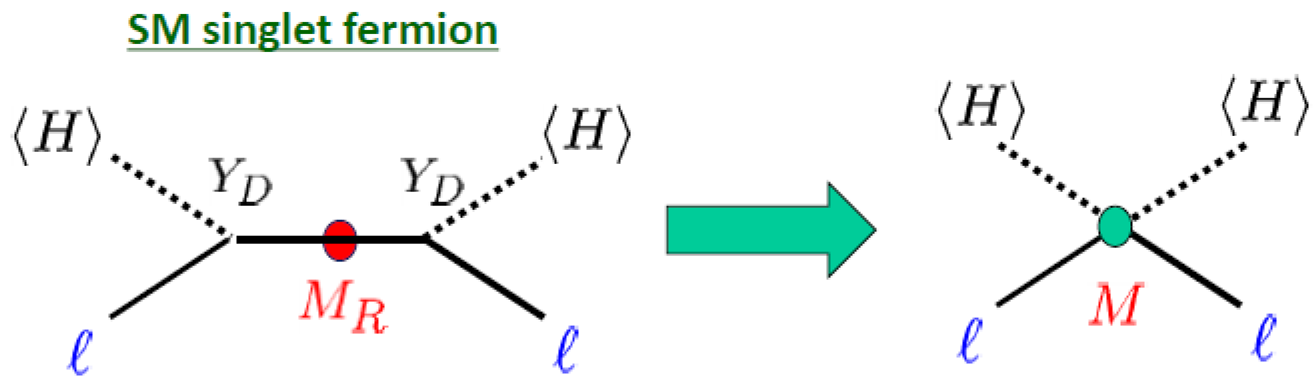
$$m_\nu \sim \mathcal{O}(\sqrt{\Delta m_{12}^2}) - \mathcal{O}(\sqrt{\Delta m_{23}^2}) = 0.01 - 0.1 \text{ eV}$$

- Therefore $\Lambda \lesssim 10^{14} \ll M_{GUT}$



- The seesaw scale lies in the intermediate scale or lower
- With such a large scale, there is no hope of direct observation of heavy neutrino or O(1/ Λ^2) effects. No signatures at LHC.

- **Using only renormalizable interactions, there are three tree-level models leading to this operator:**
  - **Exchange of a heavy fermionic singlet (right-handed neutrino) - see-saw type I**
  - **Exchange of a scalar $SU(2)_L$ triplet - see-saw type II.**
  - **Exchange of fermionic triplets - see-saw type III**



- **Broad range of Majorana mass is possible, depending on Dirac mass scale**

$$Y_D v \sim m_e \to M_R \sim 1\text{TeV}$$

- **What is the origin of M_R? So far, We added M_R by hand.**

Neutrino Mass Matrix

- **The most general mass matrix combining left-handed neutrino *(L)*, right-handed neutrino *(R)* and additional singlet fields carrying lepton number *(S)*:**

$$\begin{pmatrix} m_{LL} & m_{LR} & m_{LS} \\ m_{LR}^T & m_{RR} & m_{RS} \\ m_{LS}^T & m_{RS}^T & m_{SS} \end{pmatrix}$$

- **$m_{LL} = m_{LS} = m_{RS} = 0$ leads to type I.**
- **Type III is obtained in the same limit but with m_{RR} stemming from $SU(2)_L$ triplets.**
- **$m_{LL} = m_{RR} = m_{LS} = 0$ is the characteristic matrix for inverse see-saw .**
- **$m_{LL} = m_{RR} = m_{SS} = 0$ is the standard parametrization of the linear seesaw .**
- **The see-saw mechanism provides a rationale for the observed smallness of neutrino masses, by the introduction of the inverse of some large scale Λ.**

Minimal Gauged B-L Extension of the SM

- **The model is based on the gauge group**

$$G_{B\text{-}L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B\text{-}L}$$

- **Simple extension of the SM**
- **Gauge of an anomaly free global B-L symmetry in the SM.**
- **<u>Particle Contents</u>**

	l	ν_R	e_R	q	u_R	d_R	ϕ	χ
$SU(1)_L \times U(1)_Y$	(2,-1/2)	(1,0)	(1,-1)	(2,1/6)	(1,2/3)	(1,1/3)	(2,1/2)	(1,0)
$U(1)_{B\text{-}L}$	-1	-1	-1	1/3	1/3	1/3	0	2

- ***BLSM*** **can be generated from SO(10) → $SU(4)_C \times SU(2)_L \times SU(2)_R$ which is broken to $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B\text{-}L}$ through the adjoint (15,1,3) Higgs.**

- **Also $U(1)_R \times U(1)_{B-L}$ from SO(10) GUT through the breaking pattern:**

$$SO(10) \to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \to SU(3)_C \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \,.$$

- **B-LSM predicts the following new particles:**
  - **Three SM singlet fermions (right handed neutrinos) to cancel gauge anomaly.**
  - **Extra gauge boson corresponding to B−L gauge symmetry**
  - **Extra SM singlet scalar (heavy Higgs)**
- **The *$U(1)_{B-L}$* gauge symmetry can be spontaneously broken by a SM singlet complex scalar field χ:** $|\langle \chi \rangle| = v'/\sqrt{2}$

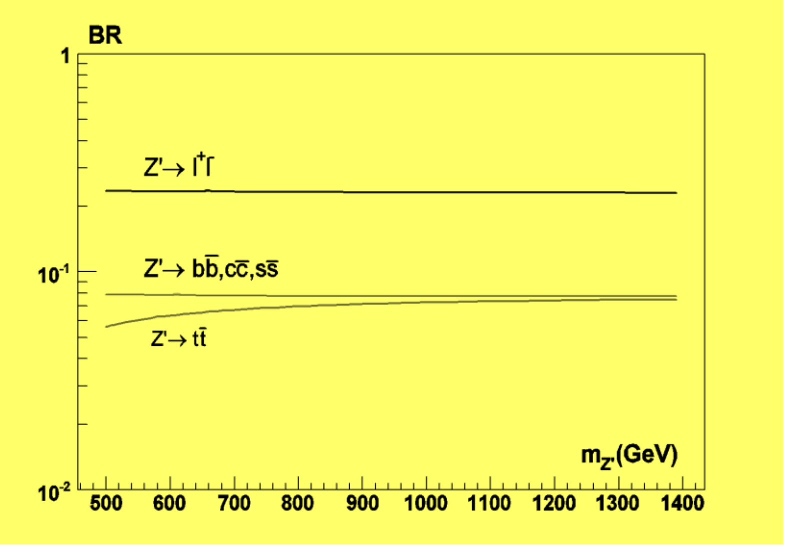
$$\Longrightarrow M_{Z'} = 2 g_{B-L} v'$$

- Branching ratios of *$Z' \to l^+l^-$* are relatively high compared to *$Z' \to q\bar{q}$*.

$$Z' \to l^+l^- \quad \mathrm{BR} = 30\%$$

$$Z' \to q\bar{q} \quad \mathrm{BR} = 10\%$$

- Search for Z' at LHC via dilepton channels are accessible at LHC.



Radiative B-L symmetry Breaking

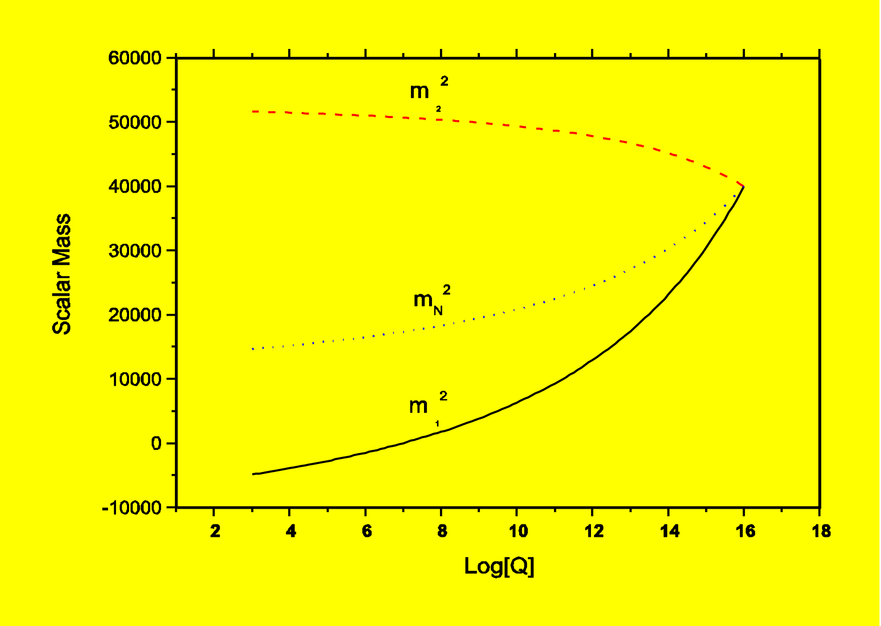
- **In MSSM, EW symmetry is broken via radiative corrections due to interplay between the large top quark Yukawa coupling and SUSY breaking mass terms**

- **In SUSY extension of Minimal Gauged B-L SM**

$$
\begin{aligned}
W &= (h_U)_{ij} Q_i H_2 U_j^c + (h_D)_{ij} Q_i H_1 D_j^c + (h_L)_{ij} L_i H_1 E_j^c + (h_\nu)_{ij} L_i H_2 N_j^c \\
&+ (h_N)_{ij} N_i^c N_j^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2 .
\end{aligned}
$$

$$
\begin{aligned}
\frac{dm^2_{\chi_1}}{dt} &= 6\tilde{\alpha}_{B-L} M^2_{B-L} - 2\tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right), \\
\frac{dm^2_{N_3}}{dt} &= \frac{3}{2}\tilde{\alpha}_{B-L} M^2_{B-L} - \tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right).
\end{aligned}
$$

❖ B-L and SUSY breaking scale are nicely correlated through radiative symmetry breaking, i.e, v' = O(1) TeV.



Neutrino masses in BLSM

- **The BLSM Yukawa Lagrangian is given by:**

$$L_{\text{Higgs}+\text{Yukawa}} = (D_\mu \phi)(D^\mu \phi) + (D_\mu \chi)(D^\mu \chi) - V(\phi,\chi) - (\lambda_e \bar{l}\,\phi e_R + \lambda_\nu \bar{l}\,\tilde{\phi}\,\nu_R + \frac{1}{2}\lambda_{\nu_R}\bar{\nu}_R^c \chi \nu_R + h.c.)$$

- **Left and right-handed neutrino form 2x2 mass matrix:**

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

- ***M_R* Majorana mass:** $M_R = \lambda_{\nu_R} v'$ $\quad v' \sim O(TeV),\ \lambda_{\nu_R} \sim O(1) \Rightarrow M_R \approx O(TeV)$

- ***m_D* Dirac mass:** $m_D = h_\nu v$ $\quad m_{\nu_L} = -m_D M_R^{-1} m_D^T,$

$$h_\nu \sim O(1) \Rightarrow m_D \approx O(100) GeV, h_\nu \sim h_e \Rightarrow m_D \approx O(10^{-4}) GeV$$

Higgs Sector

- One complex $SU(2)_L$ doublet and one complex scalar singlet
  - Six scalar degrees of freedom
  - Four are eaten by $C, Z^0, W^\pm$ after symmetry breaking
  - Two physical degrees of freedom: φ, χ
- Mass matrix:

$$\frac{1}{2}M^2(\phi,\chi) = \begin{pmatrix} \lambda_1 v^2 & \lambda_3 v v'/2 \\ \lambda_3 v v'/2 & \lambda_2 v'^2 \end{pmatrix}$$

- Mass eigenstates:

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi \\ \chi \end{pmatrix}, \qquad \tan 2\theta = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}$$

- Masses:

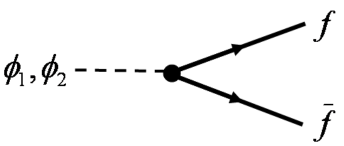
$$m_{1,2}^2 = \lambda_1 v^2 + \lambda_2 v'^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v^2 v'^2}$$

- Mixing is controlled by λ_3:

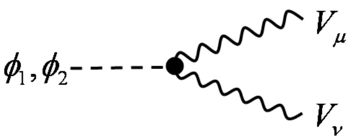
$$\lambda_3 = 0 \rightarrow m_\phi = \sqrt{\lambda_1}\, v, \quad m_\psi = \sqrt{\lambda_2}\, v'$$

Higgs Sector (Cont.)

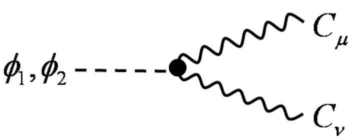
- **Couplings to fermions and gauge bosons**



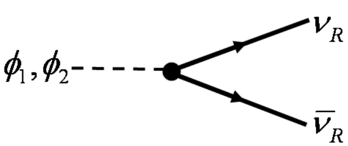
$$g_{\phi_1 ff} = i\frac{m_f}{v}\cos\theta, \qquad g_{\phi_2 ff} = i\frac{m_f}{v}\sin\theta$$



$$g_{\phi_1 VV} = -2i\frac{m_V^2}{v}\cos\theta, \qquad g_{\phi_2 VV} = -2i\frac{m_V^2}{v}\sin\theta$$



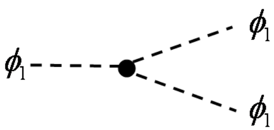
$$g_{\phi_1 CC} = 2i\frac{m_C^2}{v'}\sin\theta, \qquad g_{\phi_2 CC} = -2i\frac{m_C^2}{v'}\cos\theta$$



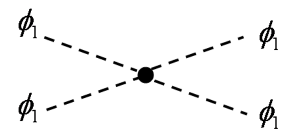
$$g_{\phi_1 \nu_R \nu_R} = -i\frac{m_{\nu_R}}{v'}\sin\theta, \qquad g_{\phi_2 \nu_R \nu_R} = i\frac{m_{\nu_R}}{v'}\cos\theta$$

Higgs Sector (Cont.)

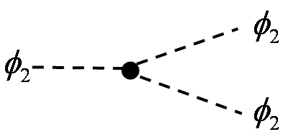
- **Self-couplings**



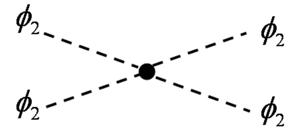
$$g_{\phi_1^3} = 6i(\lambda_1 v\cos^3\theta - \lambda_3 v'\cos^2\theta\sin\theta/2)$$



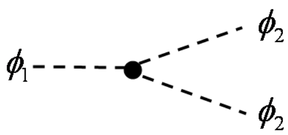
$$g_{\phi_1^4} = 6i\lambda_1\cos^4\theta$$



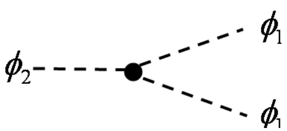
$$g_{\phi_2^3} = 6i(\lambda_2 v'\cos^3\theta + \lambda_3 v\cos^2\theta\sin\theta/2)$$



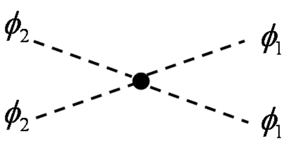
$$g_{\phi_2^4} = 6i\lambda_2\cos^4\theta$$



$$g_{\phi_1\phi_2^2} = 2i(\lambda_3 v\cos^3\theta/2 + \lambda_3 v'\cos^2\theta\sin\theta - 3\lambda_2 v'\cos^2\theta\sin\theta)$$



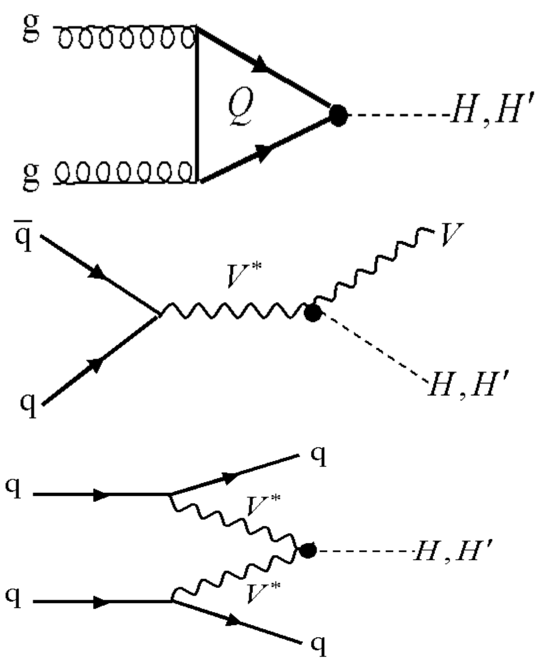
$$g_{\phi_1^2\phi_2^1} = 2i(\lambda_3 v'\cos^3\theta/2 - \lambda_3 v\cos^2\theta\sin\theta + 3\lambda_1 v\cos^2\theta\sin\theta)$$

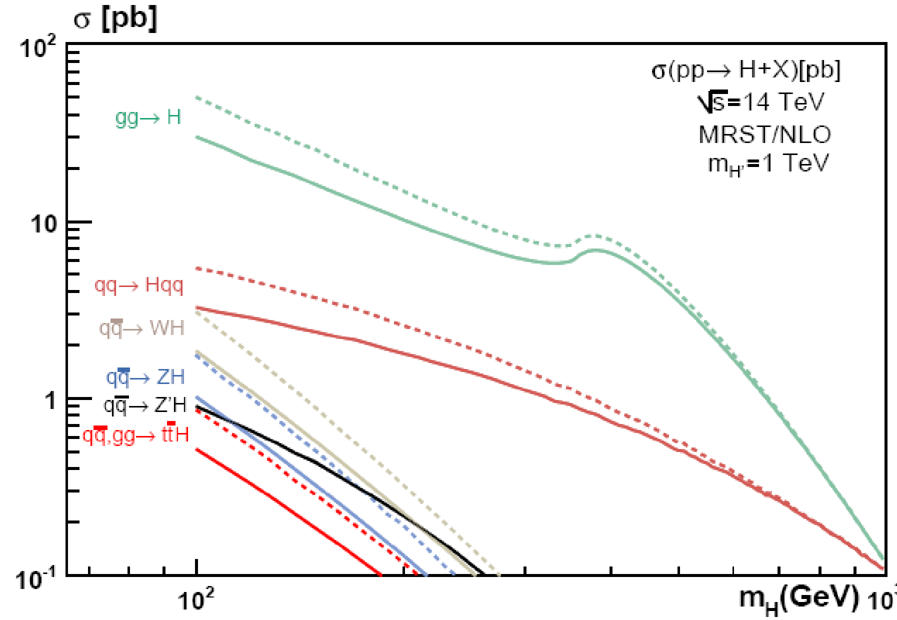


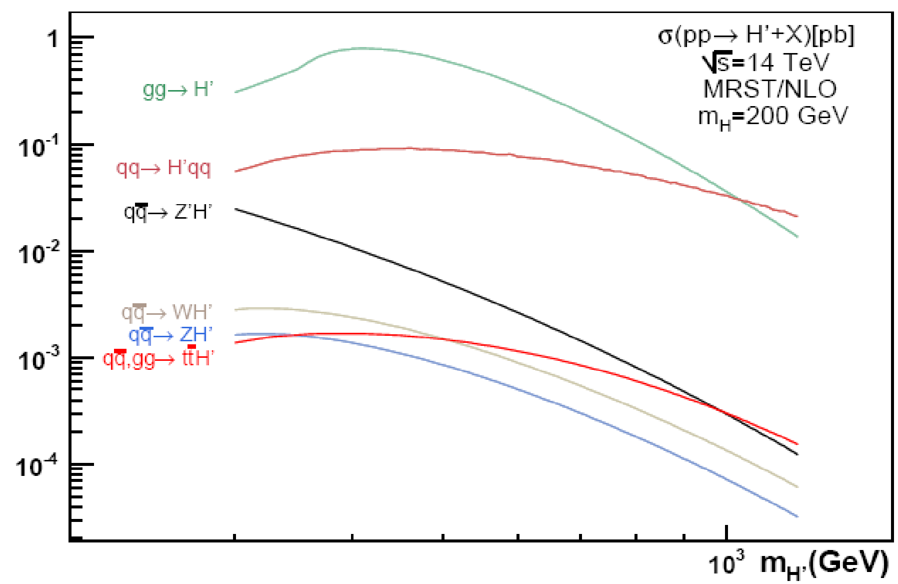
$$g_{\phi_1^2\phi_2^2} = i\lambda_3\cos^4\theta$$

Higgs Production

- **Heavy and light Higgses are produced through same processes:**
  - **gluon-gluon fusion**
  - **vector boson fusion**
  - **associated production with *W/Z/Z'***
  - **associated production with heavy quarks**







Higgs Decay

BR

- **Branching Ratios of Light Higgs are very close to those of SM**
  - **Couplings are cancelled in the ratio**
  - **Decay width of *H→Z'Z' is very tiny***
  - **Low mass range M_H < 130 GeV:**

$$H \to b\bar{b} \quad \mathrm{BR} = 60\text{-}90\%$$

$$H \to \tau^+\tau^-, c\bar{c}, gg \quad \mathrm{BR} = \text{a few }\%$$

$$H \to \gamma\gamma, \gamma Z \quad \mathrm{BR} = \text{a few }\%$$

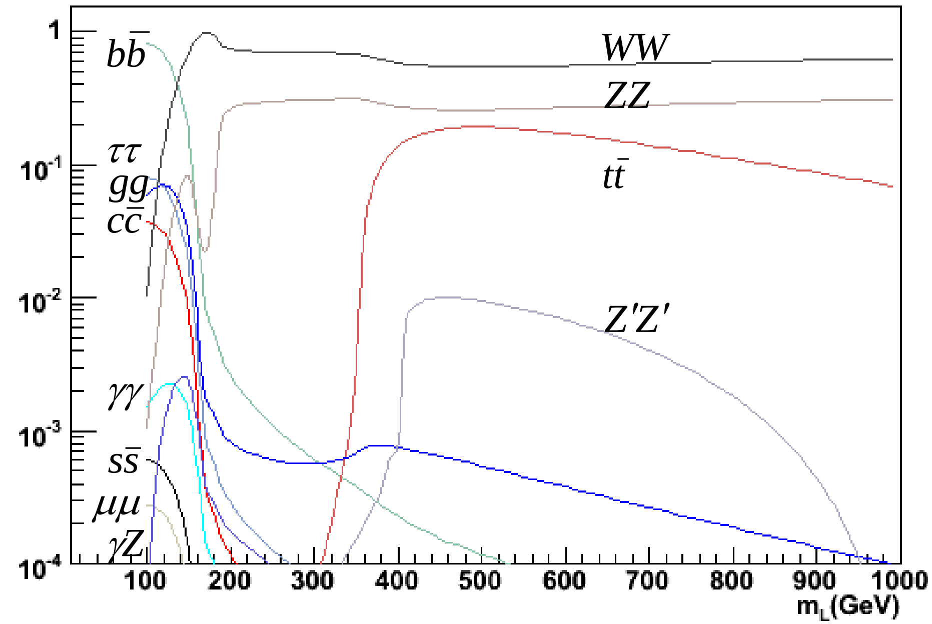
  - **High mass range M_H > 130 GeV:**

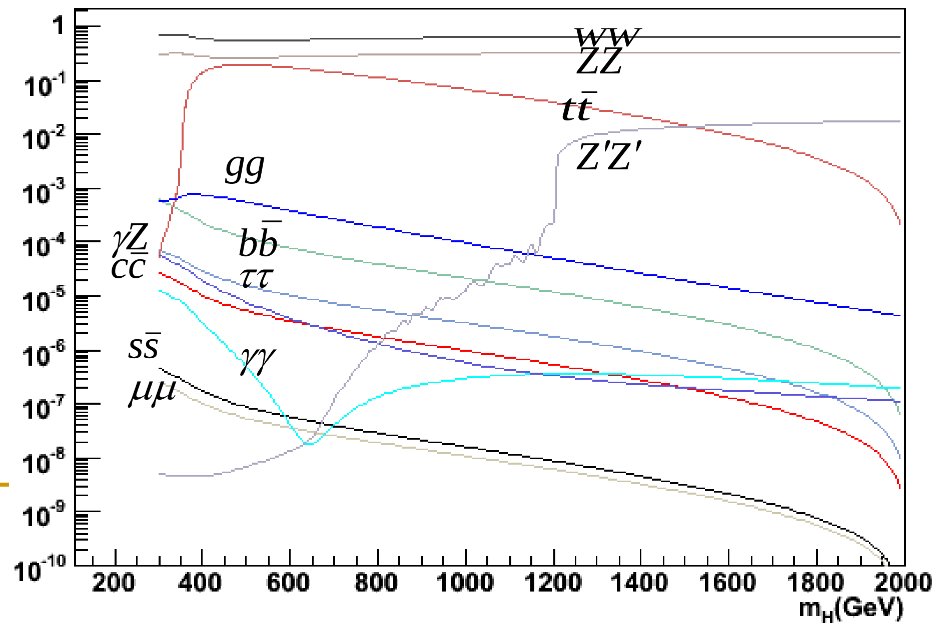
$$H \to WW, ZZ \ \ (\mathrm{BR} = \frac{2}{3}, \frac{1}{3})$$

$$H \to t\bar{t} \quad \mathrm{BR} \le 20\%$$

Interesting mass range of Heavy Higgs (200<$m_{H'}$):

  - ***H'→WW/ZZ* channel is dominant**





TeV Scale Gauged B-L With Inverse Seesaw Mechanism

- **Type-I seesaw mechanism implies $\lambda_\nu \sim 10^{-6}$, which is unnatural fine-tuning.**

- **A new modification for TeV scale B-L model, based on the inverse seesaw mechanism, has been recently proposed.**

- **In the new model $U(1)_{B-L}$ is spontaneously broken by a SM singlet scalar χ with B-L charge =+1. Z'_{B-L} and three ν_R with B-L =-1 are introduced.**

- **Three SM singlet fermions S_1 with B-L =+2 and three singlet fermions S_2 with B-L=-2 are considered to implement the inverse seesaw mechanism.**

- **The Lagrangian of the leptonic sector in this model is given by**

$$\begin{aligned}\mathcal{L}_{B-L} \;=\; & -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + i\,\bar{L}D_\mu\gamma^\mu L + i\,\bar{e}_R D_\mu\gamma^\mu e_R + i\,\bar{\nu}_R D_\mu\gamma^\mu \nu_R + i\,\bar{S}_1 D_\mu\gamma^\mu S_1 + i\,\bar{S}_2 D_\mu\gamma^\mu S_2 \\ & + (D^\mu\phi)(D_\mu\phi) + (D^\mu\chi)(D_\mu\chi) - V(\phi,\chi) - \Big(\lambda_e \bar{L}\phi e_R + \lambda_\nu \bar{L}\tilde{\phi}\nu_R + \lambda_S \bar{S}_2\chi\nu_R + h.c.\Big),\end{aligned}$$

- **After B-L and EW symmetry breaking, the neutrino Yukawa interaction terms lead to the following mass terms:**

$$\mathcal{L}_m^\nu = m_D \bar{\nu}_L \nu_R + M_N \bar{\nu}_R^c S_2 + h.c.,$$

- **Small Majorana masses for $S_{1,2}$ may be generated through possible non-renormalizable terms like: $\bar{S}^c{}_2 \chi^4 S_2$/M^3**

- **Thus, the Lagrangian of neutrino masses is given by**

$$\mathcal{L}_m^\nu = \mu_s \bar{S}_2^c S_2 + (m_D \bar{\nu}_L \nu_R + M_N \bar{\nu}_R^c S_2 + h.c.),$$

- $\mu_s = \frac{v'^4}{4M^3} \lesssim 10^{-6}\ \text{GeV}.$

- **The 9x9 neutrino mass matrix takes the form:** $\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_N \\ 0 & M_N^T & \mu_s \end{pmatrix}.$

- **The light and heavy**

$$m_{\nu_l} = m_D M_N^{-1} \mu_s (M_N^T)^{-1} m_D^T,$$
$$m_{\nu_H}^2 = m_{\nu_{H'}}^2 = M_N^2 + m_D^2.$$

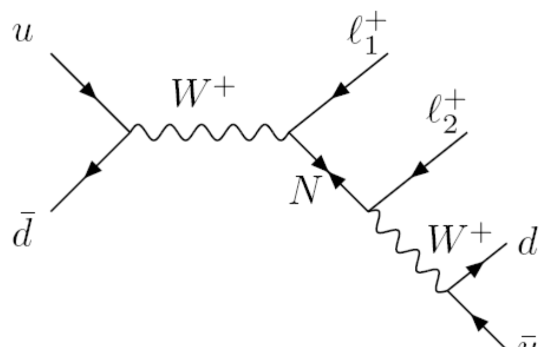
- **Light neutrino mass ~ eV is obtained for a TeV scale M_N, if μ_S << M_N. No restriction imposed on the m_D.**

Signatures for ν_R at the LHC

- In *BLSM*, ν_R production at LHC can happen through:

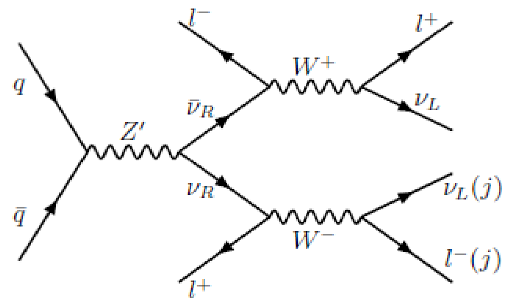
i. If ν_L - ν_R mixing is > 10^{-2} (Inverse Seesaw)

$$q\overline{q'} \longrightarrow W^+ \longrightarrow l^+ \nu_R \longrightarrow l^+ l^+ \text{ + jets.}$$

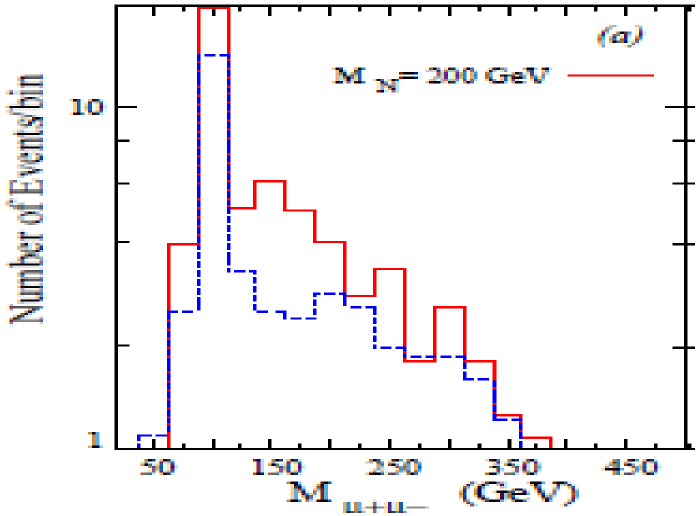


ii. In pair via Z' production

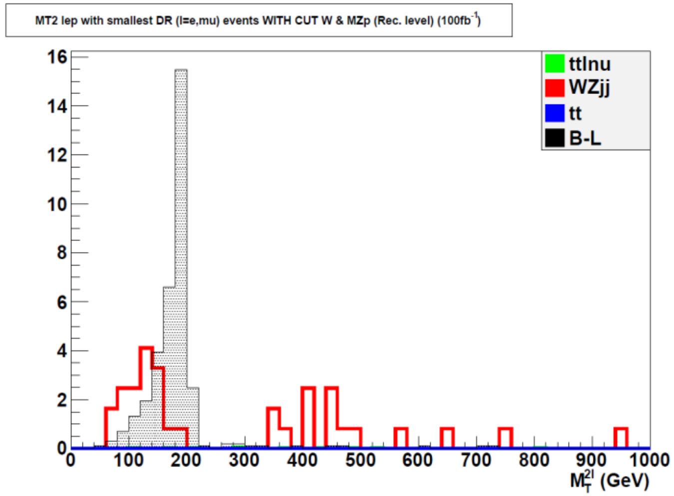
$$q\bar{q} \longrightarrow Z' \longrightarrow \nu_R \nu_R \longrightarrow 2(l^+ l^-) + ET$$



❖ These decays are very clean with four hard leptons in the final states and large missing energy due to the associated neutrinos.



K.Huitu, S.K., H.Okada,S. K. Rai, PRL101, 2008

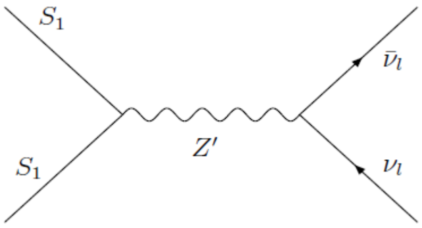


L.Basso, S.Moretti, G.Pruna, PRD83, 2011

- **Extraction of a right-handed neutrino signal at the 14 TeV LHC, for a mass of 200 GeV, in the fully leptonic (left, assuming 300 inverse fb) and semi-leptonic (right, assuming 100 inverse fb) decay mode of ν_R pairs produced from a Z'_{B-L} decay.**
- **If ν_L - ν_R mixing < 10^{-7} (type I Seesaw), ν_R appears as long lived particle.. Final states embedding then distinctive displaced vertices**
- **These signatures can provide a powerful insight in the whole leptonic sector of the B-L mode**

Warm Dark Matter in BLSM

- **WDM is an interesting candidate for solving the typical CDM problem of predicting many more small dwarf galaxies than observed.**
- **In BLSM with Inverse seesaw, the second SM-singlet fermion, S_1, remains light with mass:** $m_{S_1} = \mu_s \simeq \mathcal{O}(1)$ keV.
- **S_1 is a kind of sterile neutrinos that has no mixing with active neutrinos.**
- **Therefore, it is free from all constrained imposed on sterile neutrinos due to their mixing with the active neutrinos, like X-rays constraints.**
- **It only interacts with the gauge boson Z′.**
- **The thermal average annihilation cross section of S_1 $S_1 \longrightarrow \nu_L \nu_L$ is given by**



$$\langle \sigma_{S_1}^{ann} v \rangle = \frac{\int_0^\infty dp\; p^2 W_{S_1 S_1}(s) K_1(\frac{s}{T})}{m_{S_1}^4 T \left[K_2(\frac{m_{S_1}}{T})\right]^2},$$

$$W_{S_1 S_1}(s) = \frac{1}{32\pi} \int \frac{d\cos}{2} \sqrt{\frac{s - 4m_{S_1}^2}{s}} |\mathcal{M}(S_1 S_1 \to \nu_l \nu_l)|^2,$$

$$\int \frac{d\cos\theta}{2} |\mathcal{M}(S_1 S_1 \to \nu_l \nu_l)|^2 = \frac{2}{3} \frac{|g_{B-L}^2 q_{S_1} q_\nu|^2}{(s - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2} (s - 4m_{S_1}^2) s.$$

Non-Thermal WDM Production During Reheating in BLSM

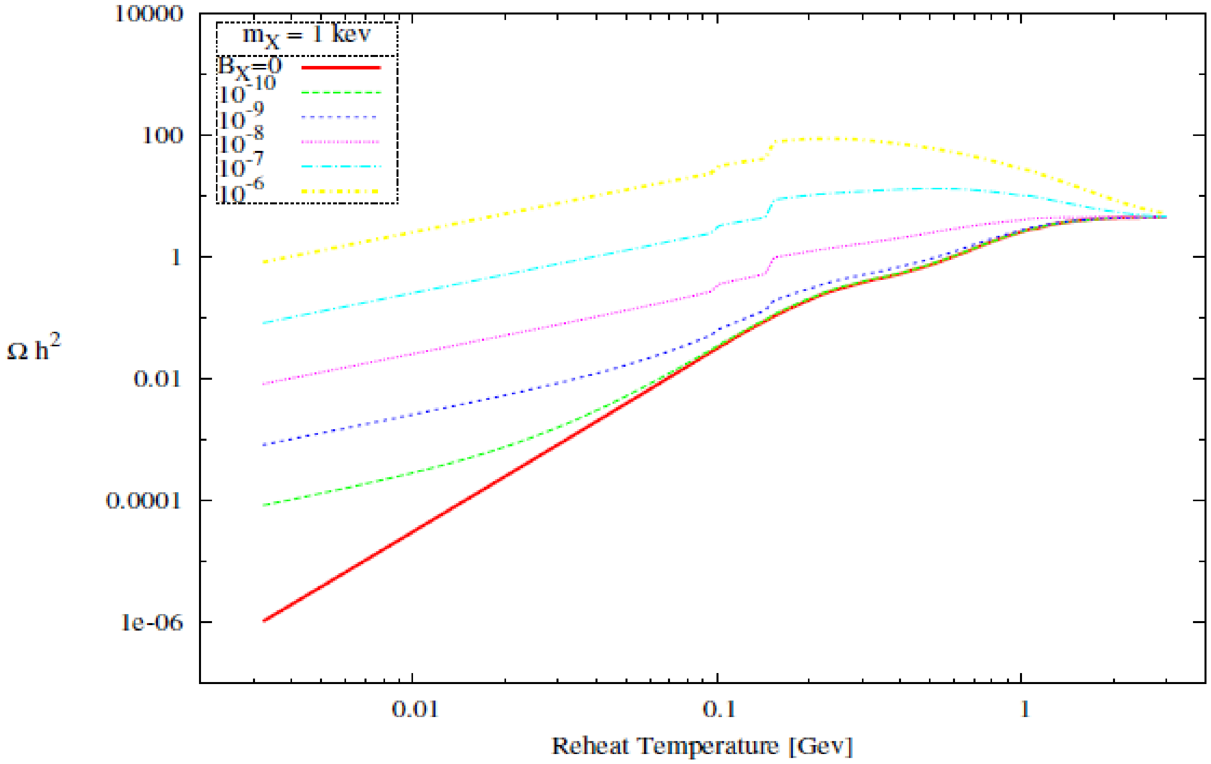
- We consider that our universe may have gone through one or more inflationary phases, which are followed by a reheating stage where a scalar field ϕ field decays into radiation and DM

- We consider the case where our WDM candidate χ is produced in this reheating era

$$\begin{aligned}
\dot{\rho_\phi} &= -3H\rho_\phi - \Gamma_\phi \rho_\phi, \\
\dot{\rho_R} &= -4H\rho_R + (1 - B_\chi)\Gamma_\phi \rho_\phi, \\
\dot{n_\chi} &= -3Hn_\chi + \frac{B_\chi}{m_\chi}\Gamma_\phi \rho_\phi - \langle \sigma_\chi^{ann} v \rangle \left[(n_\chi)^2 - (n_\chi^{eq})^2 \right],
\end{aligned}$$

- The reheating temperature in terms of the decay width (Γ_ϕ) of ϕ can be obtained through

$$T_{RH} = \left(\frac{90}{\pi^2 g_*(T_{RH})} \right)^{1/4} (\Gamma_\phi M_P)^{1/2} .$$



- **Thermal (B = 0) and non-thermal relic abundance for B-L light sterile neutrino S_1 as function of the reheating temperature and different branching ratios of decay of the ϕ field into WDM particles.**
- **First thing to note is that with $B_\chi \lesssim 10^{-7}$ and low reheating, $T_{RH} \lesssim O(0.01)$ GeV, one can easily account for the observed relic abundance and get $\Omega h^2 \simeq 0.1$. While with $B_\chi = 0$, a larger reheating temperature, $T_{RH} \sim O(1)$ GeV is required.**

Conclusions

- **A symmetry structure deeply rooted in the SM could well be the key to extend it into a credible new physics scenario.**
- **BLSM embeds naturally the neutrino mass patterns measured by experiment and at the same time offers a wealth of new physics signals.**
- **The dynamics generating the new states occurring in the model can emerge at the TeV scale (and particularly so in its SUSY version).**
- **Therefore, they are within the reach of the CERN collider.**

Thank you