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Right-handed sneutrino-antisneutrino oscillations in TeV scale BLSSM

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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 experimental results.

- Three firm observational evidences of new physics beyond the SM :

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

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

- The minimal extension is based on the gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$

- The scale of B- L symmetry breaking is unknown, ranging from TeV to GUT or Planck .

- In SUSY, the electroweak and SUSY breaking scale are nicely correlated through the mechanism of radiative breaking of the EW symmetry.

SUSY B – L Extension of the SM

- **BLSSM is an extension of the MSSM by extending its gauge group to be**

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

- **The particle content of BLSSM includes:**
  - **Three SM-singlet chiral superfields, N_i^c (RH neutrinos).**
  - **The Z′ vector superfield necessary to gauge the $U(1)_{B-L}$ symmetry.**
  - **Two SM-singlet chiral Higgs superfields $\chi_{1,2}$.**

- **As in MSSM, a second Higgs singlet, χ_2, is necessary to cancel $U(1)_{B-L}$ anomalies produced by the fermionic member of χ_1.**

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{\ell}_i$	$\hat{E}_i^c$	$\hat{N}_i^c$	$\hat{H}_1$	$\hat{H}_2$	$\hat{\chi}_1$	$\hat{\chi}_2$
$SU(3)_c$	3	$\bar{3}$	$\bar{3}$	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1
$U(1)_Y$	1/6	−2/3	1/3	−1/2	1	0	−1/2	1/2	0	0
$U(1)_{B-L}$	1/6	1/6	1/6	−1/2	1/2	1/2	0	0	−1	1

- **The BLSSM superpotential:**

$$\hat{W} = Y_u \hat{Q}\hat{H}_2\hat{U}^c + Y_d \hat{Q}\hat{H}_1\hat{D}^c + Y_e \hat{L}\hat{H}_1\hat{E}^c + Y_\nu \hat{L}\hat{H}_2\hat{N}^c + Y_N \hat{N}^c\hat{\chi}_1\hat{N}^c + \mu\hat{H}_1\hat{H}_2 + \mu'\hat{\chi}_1\hat{\chi}_2,$$

- **The SUSY soft breaking Lagrangian:**

$$\begin{aligned} -\mathcal{L}_{soft} &= -\mathcal{L}_{soft}^{MSSM} + \widetilde{m}^2_{Nij}\widetilde{N}_i^{c*}\widetilde{N}_j^c + m^2_{\chi_1}|\chi_1|^2 + m^2_{\chi_2}|\chi_2|^2 \\ &+ \left[Y^A_{\nu ij}\widetilde{L}_i\widetilde{N}_j^c H_u + Y^A_{Nij}\widetilde{N}_i^c\widetilde{N}_j^c\chi_1 + B\mu'\chi_1\chi_2 + \frac{1}{2}M_{B-L}\widetilde{Z}_{B-L}\widetilde{Z}_{B-L} + M'_{B-L}\widetilde{Z}\widetilde{Z}_{B-L} + h.c \right], \end{aligned}$$

- **The $U(1)_Y$ and $U(1)_{B-L}$ gauge mixing can be absorbed in the covariant derivative redefinition. In this basis**

$$\begin{aligned} M_Z^2 &= \frac{1}{4}(g_1^2 + g_2^2)v^2, \\ M_{Z'}^2 &= g_{B-L}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2, \end{aligned}$$

- **With mixing angle between Z and Z':**

$$\tan 2\theta' = \frac{2\tilde{g}\sqrt{g_1^2 + g_2^2}}{\tilde{g}^2 + 16(\frac{v'}{v})^2 g_{B-L}^2 - g_2^2 - g_1^2}.$$

- **The BLSSM scalar potential can be written as:**

$$\mathcal{V}(H_1, H_2, \chi_1, \chi_2) = V_1(H_1, H_2) + V_2(\chi_1, \chi_2),$$

With

$$V(\chi_1, \chi_2) = \mu_1^2|\chi_1|^2 + \mu_2^2|\chi_2|^2 - \mu_3^2(\chi_1\chi_2 + h.c.) + \frac{1}{2}g_{BL}^2\left(|\chi_2|^2 - |\chi_1|^2\right)^2,$$

- **The stability condition implies** $2\mu_3^2 < \mu_1^2 + \mu_2^2.$

- **Also to avoid a vanishing minimum** $\mu_1^2\mu_2^2 < \mu_3^4$.

- **The minimization of V(χ_1, χ_2) leads to the conditions:**

$$v'^2 = (v_1'^2 + v_2'^2) = \frac{(\mu_1^2 - \mu_2^2) - (\mu_1^2 + \mu_2^2)\cos 2\beta'}{2g''^2 \cos 2\beta'},$$

$$\sin 2\beta' = \frac{2\mu_3^2}{\mu_1^2 + \mu_2^2},$$

where $\langle\chi_1\rangle = v_1$ and $\langle\chi_2\rangle = v_2$. The angle β' is defined as $\tan\beta' = v_1/v_2$.

Radiative B – L symmetry breaking

S.K., A. Masiero, 2007

$$16\pi^2 \frac{dm^2_{\chi_1}}{dt} = -12 g^2_{BL} M^2_{BL} + 12 Y^2_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right),$$

$$16\pi^2 \frac{dm^2_{\chi_2}}{dt} = -12 g^2_{BL} M^2_{BL},$$

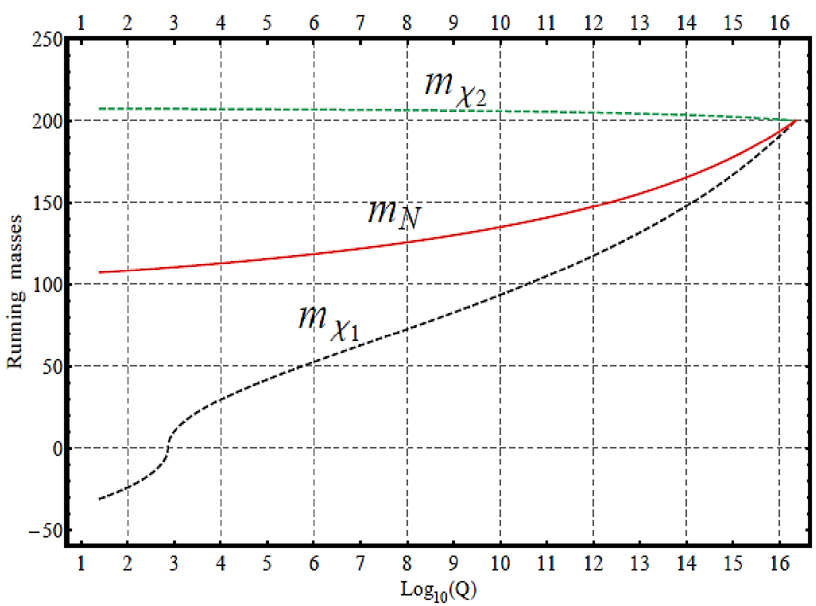
$$16\pi^2 \frac{dm^2_{N_3}}{dt} = -3 g^2_{BL} M^2_{BL} + 8 Y^2_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right),$$

$$16\pi^2 \frac{dA_{N_3}}{dt} = 28 Y^2_{N_3} A_{N_3} + 9 g^2_{BL} M_{BL}.$$

The evolution of the B-L scalar masses from GUT to TeV scalar, for m_0=200 GeV, $M_{1/2}$=A_0=100 GeV and $Y_{N3} \sim O(1)$.

At O(1)TeV, m2χ1 becomes negative, the minimization condition is satisfied and the B-L gauge symmetry is broken.

$$\mu'^2 = \frac{m^2_{\chi_2} - m^2_{\chi_1}\tan^2\theta}{\tan^2\theta - 1} - \frac{1}{4}M^2_{Z_{B-L}}.$$



Right-handed neutrinos

- We now consider the neutrino/sneutrino sector.
- After the TeV scale B–L breaking, the neutrino mass matrix is given by

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^\dagger & M_N \end{pmatrix},$$

- With $m_D = Y_\nu v^2$, $M_N = Y_N v_1'$. The neutrino masses are

$$\begin{aligned} m_{\nu_\ell} &\simeq -m_D M_N^{-1} m_D^\dagger, \\ m_{\nu_H} &\simeq M_N. \end{aligned}$$

- Therefore, if $M_N \sim O(1)$ TeV, the light neutrinos ν_ℓ mass can be of order one eV if the Yukawa coupling $Y_\nu \sim 10^{-6.}$
- This small coupling is of order the electron Yukawa coupling, so it is not quite unnatural.

Right-handed sneutrinos

- The sneutrino mass matrix, for one generation in the basis , , , , is given by

$$\mathcal{M}^2 = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ (M^2_{LR})^\dagger & M^2_{RR} \end{pmatrix},$$

where

$$M^2_{LL} = \begin{pmatrix} m^2_{\tilde{L}} + m^2_D + \frac{1}{2}M^2_Z \cos 2\beta - \frac{1}{2}M^2_{Z'} \cos 2\beta' & 0 \\ 0 & m^2_{\tilde{L}} + m^2_D + \frac{1}{2}M^2_Z \cos 2\beta - \frac{1}{2}M^2_{Z'} \cos 2\beta' \end{pmatrix},$$

$$M^2_{LR} = \begin{pmatrix} m_D(A_\nu - \mu \cot\beta + M_N) & 0 \\ 0 & m_D(A_\nu - \mu \cot\beta + M_N) \end{pmatrix},$$

$$M^2_{RR} = \begin{pmatrix} M^2_N + m^2_{\tilde{N}} + m^2_D + \frac{1}{2}M^2_{Z'} \cos 2\beta' & M_N(A_N - \mu' \cot\beta') \\ M_N(A_N - \mu' \cot\beta') & M^2_N + m^2_{\tilde{N}} + m^2_D + \frac{1}{2}M^2_{Z'} \cos 2\beta' \end{pmatrix}.$$

- A large mixing between the right-handed sneutrinos & right-handed antisneutrinos is quite plausible ($Y_N \sim O(1)$).

- The eigenvalues of the matrix M^2_{RR} are given by

$$m^2_{\tilde{\nu}_{R_{1,2}}} = m^2_{\tilde{\nu}_R} \mp \Delta m^2_{\tilde{\nu}_R},$$

where $m^2_{\tilde{\nu}_R} = \frac{1}{2}(m^2_{\tilde{\nu}_{R_1}} + m^2_{\tilde{\nu}_{R_2}})$

$$m^2_{\tilde{\nu}_R} = M^2_N + m^2_{\tilde{N}} + m^2_D + \frac{1}{2}M^2_{Z'}\cos 2\beta'.$$

While $\Delta m^2_{\tilde{\nu}_R}$ is the mass-splitting in the heavy right-handed sneutrinos, which is given by

$$\Delta m^2_{\tilde{\nu}_R} = M_N \Big| A_N - \mu' \cot\beta' \Big|.$$

- Therefore , $\tilde{\nu}_R$ and $\tilde{\nu}^*{}_R$ are no longer mass eignestates. The mass eigenstates are

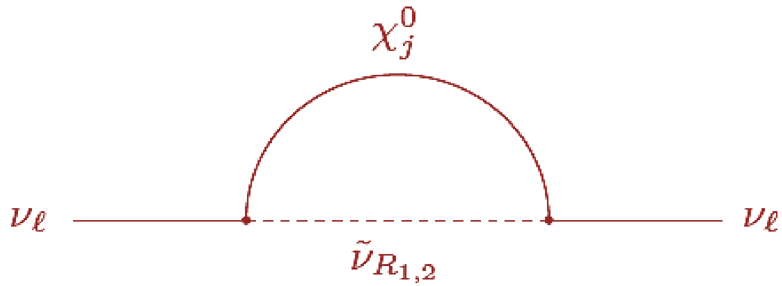
$$\tilde{\nu}_1 = \frac{1}{\sqrt{2}}\Big(\tilde{\nu}_R + \tilde{\nu}^*_R\Big), \qquad \tilde{\nu}_2 = \frac{-i}{\sqrt{2}}\Big(\tilde{\nu}_R - \tilde{\nu}^*_R\Big).$$

- $\tilde{\nu}_R$ and $\tilde{\nu}^*{}_R$ mixing is an analogue to $B^0 - \overline{B}^0$ and $K^0 - \overline{K}^0$ that are generated by $\Delta B = 2$ and $\Delta S = 2$.

Constraints on sneutrino - antisneutrino mixing

- The sneutrino mass splitting may generate one loop contribution to the neutrino mass.
- In BLSSM neutrino mass can be generated through the exchange of right-handed sneutrinos and neutral Higgsinos are running in the loop.

$$m_\nu^{(1)} = \frac{|Y_\nu|^2 \Delta m_R}{32\pi^2} \sum_j |U_{jH}|^2 f(y_j),$$



- Where $$f(x) = \frac{\sqrt{x}\,(x - 1 - \ln(x))}{(1-x)^2}$$
- Assuming that the neutrino mass, $m_\nu \sim O(10^{-9})$ → $|Y_\nu|^2 \Delta m_{\tilde{\nu}_R} \ll 10^{-9}$
- This bound can easily be satisfied for any value of $\Delta m_{\nu R} \sim O(10^3)$ GeV, since $Y_\nu \ll 10^{-6}$ $\Longrightarrow$ No constraint on the right-handed sneutrino mass splitting is imposed.

Sneutrino-antisneutrino oscillation

- Sneutrino-antisneutrino oscillation can be a very useful probe to look for signatures of lepton number violation (ΔL = 2).

- The oscillation of sneutrinos into antisneutrinos is described by

$$P_{\tilde{\nu}\to\tilde{\nu}^*} = \frac{x_{\tilde{\nu}}^2}{2(1+x_{\tilde{\nu}}^2)},$$

- Where = / It is clear that << 1 is not favored and in order to get a viable probability of oscillation 1.

- In MSSM the mass splitting can be generated by introducing the dimension-five operator: $\frac{\alpha}{M}\left(\hat{L}\hat{H}_2\right)\left(\hat{L}\hat{H}_2\right),$

- For $m_\nu \sim$ 0.1 eV one finds $\sim$ 0.1 keV. To get 1, the sneutrino decay width should be $\lesssim$ O(10−7) GeV.

- In BLSSM $x_{\nu R} = \Delta m_{\nu R}/\Gamma_{\nu R}$ can be quite large. The right-handed sneutrino-antisneutrino oscillation probability $P_{\tilde{\nu}\to\tilde{\nu}^*} \simeq 1/2$.

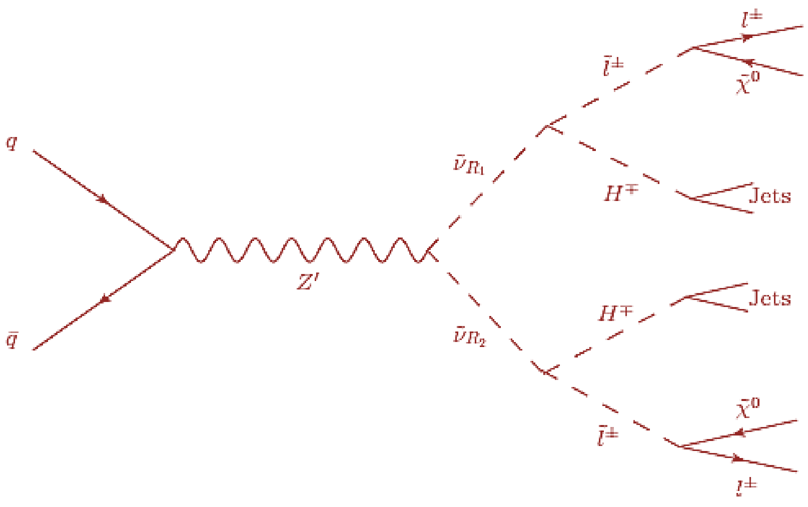
Right-handed sneutrinio at the LHC

- In BLSSM, the relevant interactions for the right-handed sneutrino are given by

$$\begin{aligned}\mathcal{L}_{int}^{\tilde{\nu}_R} &= (Y_\nu)_{ij}\bar{l}_i P_R (V_{k2}\tilde{\chi}_k^+)^\dagger (\Gamma_{\nu R})_{\alpha j}\tilde{\nu}_{R_\alpha} + (Y_\nu)_{ij}(U_{\rm MNS})_{il}\bar{\nu}_l P_R (N_{k1}^* \tilde{\chi}_k^0)(\Gamma_{\nu_R})_{j\alpha}\tilde{\nu}_{R_\alpha} \\ &+ (Y_\nu)_{ij}(M_N)_j \cos\beta \left[(\Gamma_{L_L})_{\beta i}\bar{l}_\beta H^+ (\Gamma_{\nu R})_{\alpha j}\tilde{\nu}_{R_\alpha}\right].\end{aligned}$$

- If right-handed sneutrino is heavier than slepton, then it decays into the slepton and a charged Higgs boson, which in turn decay into SM particles.

- The coupling right-handed sneutrino-slepton-charged Higgs boson is proportional to MN, So the associated decay rate may not be suppressed.



Production of sneutrino pairs at the LHC and its decay to a same-sign di-lepton pair, missing transverse energy and jets.

- **The total cross section of such a same-sign di-lepton signal at the LHC is given by**

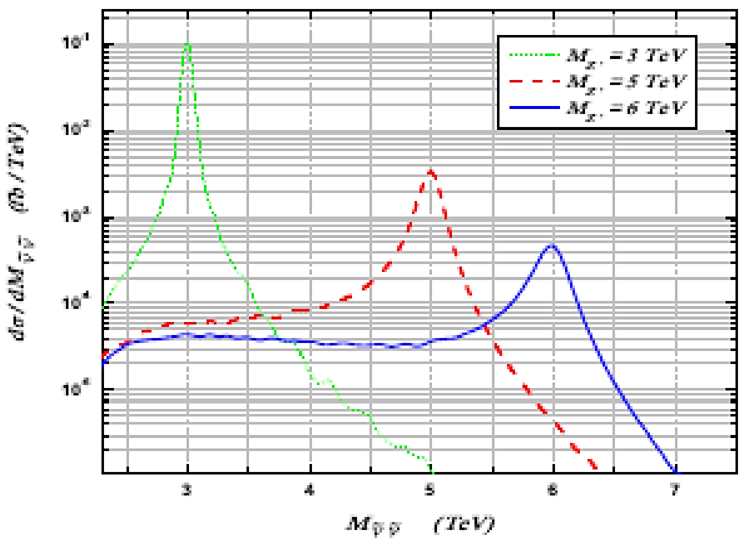
$$\sigma(q\bar{q} \to Z' \to \tilde{\nu}_{R_1}\tilde{\nu}_{R_2} \to l^{\pm}l^{\pm} + E_T^{miss} + \text{jets})$$
$$\simeq \sigma(q\bar{q} \to Z' \to \tilde{\nu}_{R_1}\tilde{\nu}_{R_2})\, \text{BR}(\tilde{\nu}_{R_1}\tilde{\nu}_{R_2} \to \tilde{l}^{\pm}\tilde{l}^{\pm}H^{\mp}H^{\mp} \to l^{\pm}l^{\pm} + E_T^{\text{miss}} + \text{jets}).$$

- **The scattering Matrix Element for sneutrino pair production is given by**

$$|\mathcal{M}(q\bar{q} \to Z' \to \tilde{\nu}_{R_1}\tilde{\nu}_{R_2})|^2 = C_q (Y^q_{B-L})^2 (Y^{\nu_R}_{B-L})^2 \frac{8 g^4_{B-L}\, s |\vec{k}|^2}{(s - M^2_{Z'})^2 + (M_{Z'}\Gamma_{Z'})^2}(1 - \cos^2\theta),$$

- **The differential cross section of right-handed sneutrino pair production at the LHC with √s = 14 TeV as CM energy for three choices of M_Z' = 3, 5 and 6 TeV, and g_{B-L}= 1/2, 5/6, 1,**

- **The corresponding values of the integrated cross sections are 11, 1 and 0.3 fb, for $m_{\tilde{\nu}R1}$ = 0.8 TeV and $m_{\tilde{\nu}R2}$ = 1.2 TeV.**



- If the mass of the right-handed sneutrino is smaller than the mass of the slepton, then the only available decay channels for the right-handed sneutrino are:

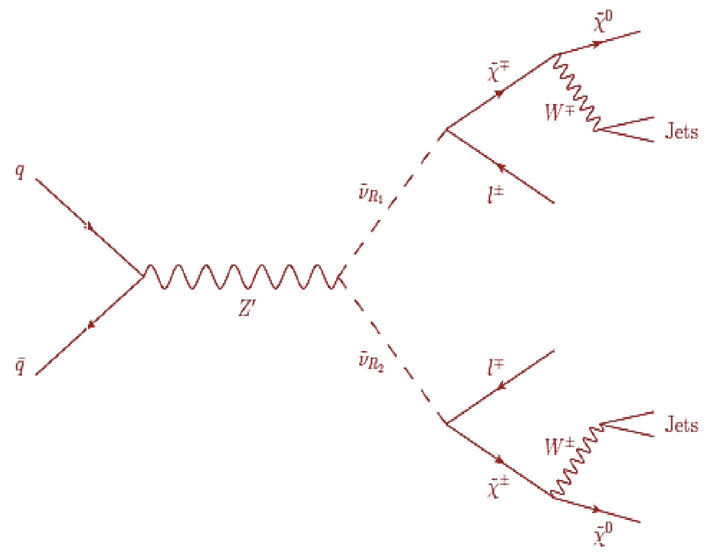
$$\tilde{\nu}_{R_{1,2}} \to l^{\pm}\tilde{\chi}^{\mp} \text{ or } \tilde{\nu}_{R_{1,2}} \to \nu_L \tilde{\chi}^0$$

- The chargino may decay to $W^{\mp}$ and the lightest neutralino. An opposite-sign di-lepton (OS) pair, missing transverse energy and jets, is a possible signal.

- Due to the oscillation between the right-handed sneutrino and antisneutrino, it is possible for $\tilde{\nu}_{R1}$ to decay to l^{-} whilst $\tilde{\nu}_{R2}$ decays to l^{+}.

- The difference between SS and OS outgoing di-leptons implies lepton charge asymmetry.

- a smoking gun signal for right-handed sneutrino oscillation.



- The lepton charge asymmetry is defined as

$$A^{\rm asym} = \frac{\sigma(SS) - \sigma(OS)}{\sigma(SS) + \sigma(OS)} = \frac{\sigma(l^- l^- \tilde{\chi}^+ \tilde{\chi}^+) - \sigma(l^+ l^- \tilde{\chi}^+ \tilde{\chi}^-)}{\sigma(l^- l^- \tilde{\chi}^+ \tilde{\chi}^+) + \sigma(l^+ l^- \tilde{\chi}^+ \tilde{\chi}^-)},$$

- where the SS cross section s is obtained as

$$\sigma(SS) = \sigma(q\bar{q} \to Z' \to \tilde{\nu}_{R_1} \tilde{\nu}_{R_2})\, {\rm BR}(\tilde{\nu}_{R_1} \to l^+ \tilde{\chi}^-)\, {\rm BR}(\tilde{\nu}_{R_2} \to l^+ \tilde{\chi}^-),$$

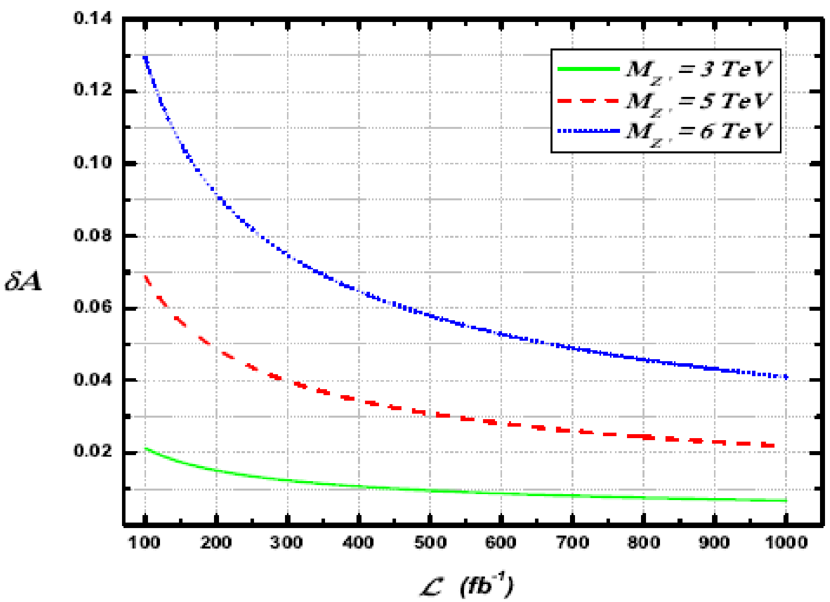
- and the OS cross section is given by

$$\sigma(OS) = \sigma(q\bar{q} \to Z' \to \tilde{\nu}_{R_1} \tilde{\nu}_{R_2})\, {\rm BR}(\tilde{\nu}_{R_1} \to l^+ \tilde{\chi}^-)\, {\rm BR}(\tilde{\nu}_{R_2} \to l^- \tilde{\chi}^+).$$

- If there is no oscillation, the lepton charge asymmetry will be given by $A^{asym} = -1$, while with maximal oscillation the asymmetry is given by $A^{asym} = 0$.

$$A_{\rm eff} = \frac{A^{\rm asym} + 1}{2},$$

- The effective lepton charge asymmetry associated to the decay of right-handed sneutrinos is given by $A_{\rm eff} = \frac{1}{2}.$



Conclusion

- We have proven that right-handed sneutrino - antisneutrino oscillations, emerging in the BLSSM in presence of a type I seesaw mechanism of light neutrino mass generation, are testable at the LHC.

- Constraints imposed on the mass splitting between heavy right-handed sneutrino and the corresponding antisneutrino by the experimental limits set on the light neutrino masses are considered.

- We have shown that pair production of such right-handed sneutrinos decaying into leptons and charginos generates a cross section which is promptly accessible at 14 TeV.

- Effective lepton charge asymmetry offer an efficient means to resolve the aforementioned
- oscillation phenomenon.

- The signature of sneutrino - antisneutrino oscillations can also be obtained from other possible extensions of the MSSM, that lead to $\Delta L = 2$ violation, like the MSSM with R - parity violation or with Higgs triplets or else a SUSY Left-Right model.

- Our analysis is quite relevant and it is not limited to the B – L extension of MSSM that we have adopted here.

Thank You!