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# Neutrino Masses, Baryogenesis and R-parity violation

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# 1 Motivation

Majorana neutrino masses require $L$ violation

Standard Model violates $B+L$ through $SU(2)_W$ sphaleron interaction which is effective at high temperature $T > M_{EW}$

$L$ and $B+L$ violation in the early universe — Fukugita, Yanagida

1. A primordial lepton asymmetry can turn into baryon asymmetry :

$$L = \frac{(B+L)}{2} - \frac{(B-L)}{2}$$ LEPTOGENESIS

**High scale neutrino mass generation – Seesaw mechanism**

2. $L$ and $B+L$ both in thermal equilibrium :

erases a pre-existing baryon/lepton asymmetry — CONSTRAINTS on $L$ violating couplings

**Low scale neutrino mass generation – R-parity violation**

$\longrightarrow$ readily testable in future colliders

## Our conclusion will be

- The observed atmospheric and solar neutrino masses and mixing can be well accommodated in the supersymmetric standard model with broken R-parity either by bilinear or by trilinear terms.

9 bilinear or 5 trilinear parameters

$$W = \epsilon_i \mu L_i H_2 + \lambda_{i33} L_i L_3 E_3^c + \lambda'_{i33} L_i Q_3 D_3^c$$
$$V_{soft} = m^2_{L_i H_1} L_i H_1^\dagger + \epsilon_i \mu B_i L_i H_2 + h.c.$$

$\Longrightarrow$ $\Delta m^2_{12} = m_2^2 - m_1^2 \approx 7 \times 10^{-5}\text{eV}^2$ (solar)
$\Delta m^2_{13} = m_3^2 - m_1^2 \approx 3 \times 10^{-3}\text{eV}^2$ (atmospheric)

$\theta_{12} \approx 33^o$ (solar), $\theta_{23} \approx 45^o$ (atmospheric),
$\theta_{13} < 12^o$ (reactor)

- It is possible to suppress the electron number violating parameters so that a pre-existing baryon/lepton asymmetry is not erased in the bilinear model with non-universal soft terms, satisfying $\lambda'_{i33}, \epsilon_i h_b < 10^{-7}$.

● In our scheme, the observed baryon asymmetry can arise through the Affleck-Dine mechanism with a flat direction $\Phi$ lifted by $W = \frac{\Phi^{n+1}}{M_p^n}$ :

$$\frac{n_B}{s} \sim \frac{T_R}{m_\Phi}\frac{\Phi_0^2}{H^2} \sim \frac{T_R}{m_\Phi}\left(\frac{m_\Phi}{M_p}\right)^{\frac{2}{n+1}}$$
$$\sim 10^{-10}\left(\frac{T_R}{10^9\ \text{GeV}}\right)\left(\frac{M_p}{m_\Phi}\right)^{\frac{n-1}{n+1}}$$

Prime candidate of flat direction: $\Phi = L = H_2, n = 1$

$$W = \frac{LH_2LH_2}{M_p} = \frac{\Phi^4}{M_p}$$

● If the electroweak baryogenesis is operative, none of our current consideration is relevant.

## 2 Baryogenesis constraints on R-parity violation

Before the electroweak symmetry breaking, $B+L$ violating sphaleron interaction is in thermal equilibrium, so some of $B-L_i$ violating interactions should be suppressed in order not to wash out the baryon asymmetry of the universe :

$$\Gamma_{B-L_i} < H = 0.33\sqrt{g_*}\frac{T^2}{M_P} \quad \text{for} \quad T \sim M_{EW}$$

for any $i = e, \mu, \tau$.

$$\begin{aligned} W &= \epsilon_i \mu L_i H_2 + \lambda_{i33} L_i L_3 E_3^c + \lambda'_{i33} L_i Q_3 D_3^c \\ V_{soft} &= m^2_{L_i H_1} L_i H_1^\dagger + \epsilon_i \mu B_i L_i H_2 + h.c. \end{aligned}$$

- Bounds on trilinear couplings from the 1-2 interactions; sfermions $\leftrightarrow$ fermions

$$\Gamma_{12} = \frac{\pi \lambda_{i33}^{(\prime)2}}{192\zeta(3)} \frac{\tilde{m}^2}{T} \quad \text{for} \quad T > \tilde{m}$$

$$\Longrightarrow \quad \lambda'_{i33},\ \lambda_{i33} < 2 \times 10^{-7} \left( \frac{\tilde{m}}{300\ \text{GeV}} \right)^{1/2}$$

Effectively, $\lambda'_{i33} \ni \epsilon_i h_b$

$$\Longrightarrow \quad \epsilon_i < 1.2 \times 10^{-5} c_\beta \left( \frac{\tilde{m}}{300\ \text{GeV}} \right)^{1/2}$$

- Bounds on bilinear parameters inducing trilinear couplings though slepton–Higgs mixing

Approximate diagonalization of the slepton–Higgs sector : $\tilde{L}_i,\ H_1$ and $H'_2 \equiv i\tau_2 H_2^\dagger$

$$\begin{aligned} \tilde{L}_i &\to \tilde{L}_i - \varepsilon_{i1} H_1 - \varepsilon_{i2} H'_2 \\ H_1 &\to H_1 + \varepsilon_{i1} \tilde{L}_i \\ H'_2 &\to H'_2 + \varepsilon_{i2} \tilde{L}_i \end{aligned}$$

where

$$\varepsilon_{i1} = \frac{(m^2_{H_2} + \mu^2 - m^2_{L_i})(\epsilon_i \Delta m^2_i - m^2_{L_i H_1}) - \epsilon_i \mu^2 B \Delta B_i}{(m^2_{H_1} + \mu^2 - m^2_{L_i})(m^2_{H_2} + \mu^2 - m^2_{L_i}) - \mu^2 B^2}$$

$$\varepsilon_{i2} = \frac{(m^2_{H_1} + \mu^2 - m^2_{L_i})\epsilon_i \mu \Delta B_i - \mu B(\epsilon_i \Delta m^2_i - m^2_{L_i H_1})}{(m^2_{H_1} + \mu^2 - m^2_{L_i})(m^2_{H_2} + \mu^2 - m^2_{L_i}) - \mu^2 B^2}$$

$\Delta m^2_i \equiv m^2_{H_1} - m^2_{L_i}$ and $\Delta B_i \equiv B - B_i$

$\Longrightarrow$ Lepton number violating interactions arise from the misalignment between the scalars, $\tilde{L}_i$ and $H_{1,2}$, and fermions, $L_i$ and $\tilde{H}_{1,2}$ (i.e.,$\Delta m^2_i - m^2_{L_i H_1}, \Delta B_i \neq 0$)

$$\mathcal{L}_{eff} = h_\tau \varepsilon_{i1} \tilde{L}_i L_3 E^c_3 + h_b \varepsilon_{i1} \tilde{L}_i Q_3 D^c_3 + h_t \varepsilon_{i2} \tilde{L}'_i Q_3 U^c_3$$
$$+ \frac{g' \varepsilon_{i1}}{\sqrt{2}} [H^\dagger_1 L_i \tilde{B} + \tilde{L}^\dagger_i \tilde{H}_1 \tilde{B}] + \frac{g' \varepsilon_{i2}}{\sqrt{2}} \tilde{L}^\dagger_i \tilde{H}'_2 \tilde{B}$$
$$+ \frac{g \varepsilon_{i1}}{\sqrt{2}} [H^\dagger_1 \tau^a L_i \lambda^a + \tilde{L}^\dagger_i \tau^a \tilde{H}_1 \lambda^a] + \frac{g \varepsilon_{i2}}{\sqrt{2}} \tilde{L}^\dagger_i \tau^a \tilde{H}'_2 \lambda^a + h.c.$$

$$\Longrightarrow \quad \varepsilon_{i1} < 3 \times 10^{-7} \left( \frac{m_{\chi^0}}{300 \text{ GeV}} \right)^{1/2}$$

$$\varepsilon_{i2} < 2 \times 10^{-7} s_\beta \left( \frac{m_{L_i}}{300 \text{ GeV}} \right)^{1/2}$$

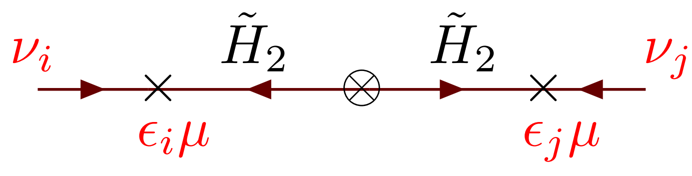
To remember,

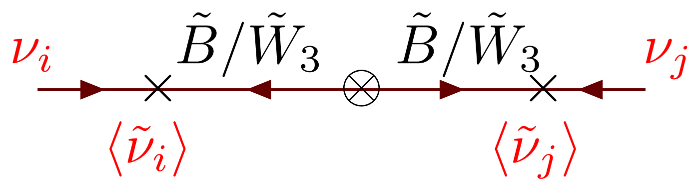
$$\epsilon_i < 1.2 \times 10^{-5} c_\beta \left( \frac{\tilde{m}}{300 \text{ GeV}} \right)^{1/2}$$

$$\lambda'_{i33},\ \lambda_{i33} < 2 \times 10^{-7} \left( \frac{\tilde{m}}{300 \text{ GeV}} \right)^{1/2}$$

## 3 Neutrino masses and mixing from R-parity violation

TREE MASS :




$$M_{ij}^{tree} = -\frac{M_Z^2}{F_N} \xi_i \xi_j c_\beta^2$$

where $F_N = M_1 M_2/(c_W^2 M_1 + s_W^2 M_2) + (M_Z^2/\mu) c_{2\beta}$ and

$$\xi_i \equiv \frac{\langle \tilde{\nu}_i \rangle}{\langle H_1^0 \rangle} - \epsilon_i = \frac{\left(m^2_{L_i H_1} + \epsilon_i \Delta m^2_{L_i}\right) + \epsilon_i \mu \Delta B_i \tan\beta}{m^2_{L_i} + \frac{1}{2} M_Z^2 \cos 2\beta}$$

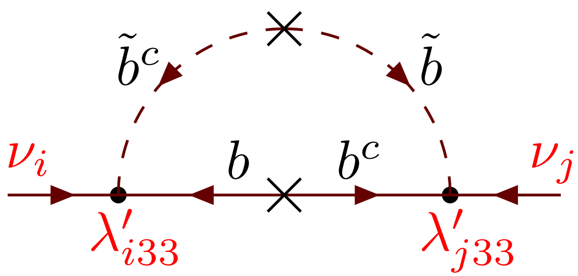
* $\xi$ measures non-universality in a basis-independent way.

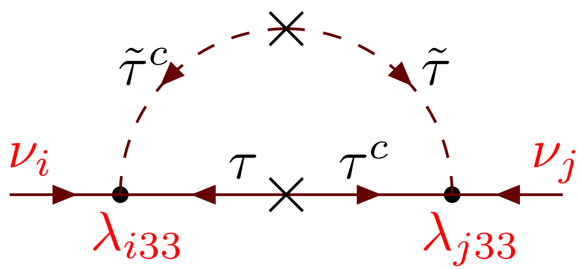
**Sneutrino VEVs :**

$$\frac{\langle \tilde\nu_i \rangle}{\langle H_1^0 \rangle} = \frac{\left(m^2_{L_i H_1} + \epsilon_i \mu^2\right) + \epsilon_i \mu B_i \tan\beta}{m^2_{L_i} + \frac{1}{2} M_Z^2 \cos 2\beta}$$

LOOP MASS :

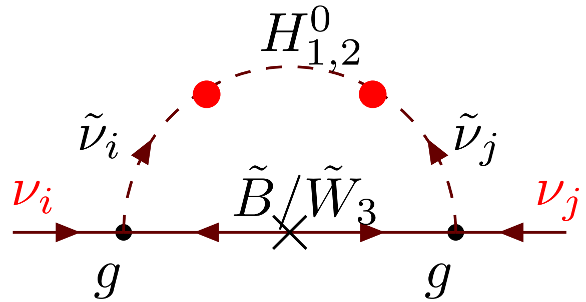
**Sbottom–bottom / stau–tau loop**




$$M_{ij}^{loop} = 3\frac{\lambda'_{i33}\lambda'_{j33}}{8\pi^2}\frac{m_b^2(A_b + \mu\tan\beta)}{m^2_{\tilde b_1} - m^2_{\tilde b_2}}\ln\frac{m^2_{\tilde b_1}}{m^2_{\tilde b_2}} + \frac{\lambda_{i33}\lambda_{j33}}{8\pi^2}\frac{m_\tau^2(A_\tau + \mu\tan\beta)}{m^2_{\tilde\tau_1} - m^2_{\tilde\tau_2}}\ln\frac{m^2_{\tilde\tau_1}}{m^2_{\tilde\tau_2}}.$$

**Neutral scalar–neutralino loop** : important if $\xi_i \not\propto \eta_i$




$$M^{loop}_{ij} = -\frac{g^2}{32\pi^2}\sum_a (t_W N_{1a} - N_{2a})^2 m_{\tilde\chi^0_a}\left(\sum_\phi \frac{1}{2}\theta_{i\phi}\theta_{j\phi}B_0(m^2_{\tilde\chi^0_a}, m^2_\phi) + \frac{Z_{ij}}{m^2_{\tilde\nu_i} - m^2_{\tilde\nu_j}}[B_0(m^2_{\tilde\chi^0_a}, m^2_{\tilde\nu_i}) - B_0(m^2_{\tilde\chi^0_a}, m^2_{\tilde\nu_j})]\right)$$

$$\theta_{ih} = +\xi_i s_\alpha + \eta_i s_\beta m_A^2 \frac{m^2_{\tilde\nu_i} c_{\alpha-\beta} - M_Z^2 c_{2\beta} c_{\alpha+\beta}}{(m^2_{\tilde\nu_i} - m_h^2)(m^2_{\tilde\nu_i} - m_H^2)}$$

$$\theta_{iH} = -\xi_i c_\alpha + \eta_i s_\beta m_A^2 \frac{m^2_{\tilde\nu_i} s_{\alpha-\beta} - M_Z^2 c_{2\beta} s_{\alpha+\beta}}{(m^2_{\tilde\nu_i} - m_h^2)(m^2_{\tilde\nu_i} - m_H^2)}$$

$$\theta_{iA} = -i\xi_i s_\beta + i\eta_i s_\beta \frac{m_A^2}{m_A^2 - m^2_{\tilde\nu_i}}$$

$$Z_{ij} = \eta_i \eta_j m_A^4 M_Z^2 c_\beta^2 s_\beta^4 \left[ \frac{m^2_{\tilde\nu_i}}{F_S^i} + \frac{m^2_{\tilde\nu_j}}{F_S^j} \right],$$

where $F_S^i \equiv (m^2_{\tilde\nu_i} - m_A^2)(m^2_{\tilde\nu_i} - m_h^2)(m^2_{\tilde\nu_i} - m_H^2)$

$$c_{2\alpha} = c_{2\beta} \frac{(m_A^2 - M_Z^2)}{(m_h^2 - m_H^2)}, \qquad s_{2\alpha} = s_{2\beta} \frac{(m_A^2 + M_Z^2)}{(m_h^2 - m_H^2)}$$

and $\eta_i \equiv \frac{\langle \tilde\nu_i \rangle}{\langle H_1^0 \rangle} - \epsilon_i \frac{B_i}{B} = \xi_i - \epsilon_i \frac{\Delta B_i}{B}$

* $\eta_i$ : another measure of non-universality.

Convenient to rewrite $\varepsilon_{i1,i2}$ using the Higgs/sneutrino minimization condition

$$\varepsilon_{i1} = -\xi_i - \eta_i \frac{m_A^2 s_\beta^2 (m_{\tilde{\nu}_i}^2 - M_Z^2 c_{2\beta})}{m_{\tilde{\nu}_i}^2 (m_{\tilde{\nu}_i}^2 - m_A^2) - (m_{\tilde{\nu}_i}^2 - m_A^2 s_\beta^2) M_Z^2 c_{2\beta}}$$

$$\varepsilon_{i2} = \frac{\eta_i}{t_\beta} \frac{m_A^2 s_\beta^2 m_{\tilde{\nu}_i}^2}{m_{\tilde{\nu}_i}^2 (m_{\tilde{\nu}_i}^2 - m_A^2) - (m_{\tilde{\nu}_i}^2 - m_A^2 s_\beta^2) M_Z^2 c_{2\beta}}$$

## Schemes accounting for the observed neutrino masses and mixing

- Trilinear couplings with universal soft terms :

Lepton flavour violation only from $\lambda'_{i33}$ and $\lambda_{i33}$
Non-vanishing $\xi_i$ and $\eta_i$ induced through RGE: $\xi_i \approx \eta_i \sim c'_i \lambda'_{i33} + c_i \lambda_{i33}$

$$M^\nu_{ij} \approx C' \lambda'_i \lambda'_j + C \lambda_i \lambda_j$$

Essentially, $C',\ C \sim 10^7 - 10^9\,\mathrm{eV}$ $\qquad C' > \frac{3}{8\pi^2} \frac{m_b^2 (A_b + \mu t_\beta)}{m^2_{\tilde{b}}} \sim 10^7$ eV.

ATM : $\lambda'_{133} \ll \lambda'_{233} \approx \lambda'_{333} \approx 10^{-4} - 10^{-5}$, $\qquad \tan\theta_{23} \sim \lambda'_{233}/\lambda'_{333}$
SOL : $\lambda_{133} \approx \lambda_{233} \approx 10^{-4} - 10^{-5}$, $\qquad \tan\theta_{12} \sim \lambda_{133}/\lambda_{233}$

$\Longrightarrow$ Too large to avoid the baryogenesis constraints

- Bilinears with non-universal soft terms : no trilinear couplings

**Option 1 : Small deviation from universality**

**ATM** due to large sbottom–bottom loop mass

$$M_{ij}^{loop} = \frac{3h_b^2}{8\pi^2}\epsilon_i\epsilon_j \frac{m_b^2(A_b + \mu \tan\beta)}{m_{\tilde{b}_1}^2 - m_{\tilde{b}_2}^2} \ln \frac{m_{\tilde{b}_1}^2}{m_{\tilde{b}_2}^2} .$$

$$\Longrightarrow \quad \epsilon_1 \ll \epsilon_2 \approx \epsilon_3 \approx 8 \times 10^{-3} \cos\beta \left(\frac{\tilde{m}}{300\ \text{GeV}}\right)^{1/2} \left(\frac{m_3}{0.05\,\text{eV}}\right)^{1/2}$$

$$\tan\theta_{23} \sim \epsilon_2/\epsilon_3, \quad \tan\theta_{13} \sim \epsilon_1/\epsilon_2$$

**SOL** due to tree mass requiring very small deviation of universality

$$M_{ij}^{tree} = -\frac{M_Z^2}{F_N}\xi_i\xi_j \cos^2\beta$$

$$\Longrightarrow \quad \xi_1 \sim \xi_2 \sim 3 \times 10^{-7} \frac{1}{\cos\beta} \left(\frac{F_N}{M_Z}\right)^{1/2} \left(\frac{m_2}{8\,\text{meV}}\right)^{1/2}$$

$$\tan\theta_{12} \sim \xi_1/\xi_2$$

Expect $\xi_1 \simeq \eta_1 (= \xi_i - \epsilon_i \Delta B_i / B)$ and thus

$$\varepsilon_{11} \approx -\xi_1 \frac{m^2_{\tilde{\nu}_1} - m^2_A c^2_\beta}{m^2_{\tilde{\nu}_1} - m^2_A}\,, \quad \varepsilon_{12} \approx -\frac{\xi_1}{t_\beta} \frac{m^2_A s^2_\beta}{m^2_{\tilde{\nu}_1} - m^2_A}$$

The baryogenesis constraints can be satisfied *if*

$$1 < \tan\beta < \frac{m^2_A}{m^2_{\tilde{\nu}_1}}$$

## Option 2 : Large deviation of universality

**ATM** by tree mass

$$M_{ij}^{tree} = -\frac{M_Z^2}{F_N}\xi_i\xi_j\cos^2\beta$$

$$\Longrightarrow \quad \xi_1 \ll \xi_2 \approx \xi_3 \approx 5.2\times 10^{-7}\frac{1}{c_\beta}\left(\frac{F_N}{M_Z}\right)^{1/2}\left(\frac{m_3}{0.05\text{ eV}}\right)^{1/2}$$

$$\tan\theta_{23} \sim \xi_2/\xi_3, \quad \tan\theta_{13} \sim \xi_1/\xi_2$$

**SOL** by neutral scalar–neutralino loops

$$M_{ij}^{loop} \approx \frac{g^2}{64\pi^2} m_{\chi^0}\theta_{i\phi}\theta_{j\phi}B_0(m_{\chi^0}^2, m_\phi^2)$$

$$\theta_{ih} \quad \approx \quad \eta_i s_\beta m_A^2 \frac{m_{\tilde\nu_i}^2 c_{\alpha-\beta} - M_Z^2 c_{2\beta}c_{\alpha+\beta}}{(m_{\tilde\nu_i}^2 - m_h^2)(m_{\tilde\nu_i}^2 - m_H^2)}$$

$$\theta_{iH} \approx \eta_i s_\beta m_A^2 \frac{m^2_{\tilde\nu_i} s_{\alpha-\beta} - M_Z^2 c_{2\beta} s_{\alpha+\beta}}{(m^2_{\tilde\nu_i} - m_h^2)(m^2_{\tilde\nu_i} - m_H^2)}$$

$$\theta_{iA} \approx i\eta_i s_\beta \frac{m_A^2}{m_A^2 - m^2_{\tilde\nu_i}}$$

$$\Longrightarrow \quad \theta_{1\phi} \sim \theta_{2\phi} \sim 6 \times 10^{-6} \left(\frac{300\text{ GeV}}{m_{\chi^0}}\right)^{1/2} \left(\frac{m_\phi}{m_{\chi^0}}\right) \left(\frac{m_2}{8\text{ meV}}\right)^{1/2}$$

$$\tan\theta_{12} \sim \eta_1/\eta_2$$

Having small $\xi_1$, possible to suppress $\varepsilon_{11,12}$ *if* $m_h \approx m_{\tilde\nu_1}$

* $m_h$ is a tree-level mass.

$$(\theta_{ih}, \theta_{iH}, \theta_{iA}; \varepsilon_{i1} + \xi_i, \varepsilon_{i2})$$

Case 1 $\quad t_\beta = 3,\ m_A = 100$ GeV $(m_h = 60$ GeV$)$

$(+77, +64, -9.1; -3.6, 1)$ for $m_{\tilde{\nu}_e} = 55$ GeV

$(-22, -21, -6.5; -0.96, 1)$ for $m_{\tilde{\nu}_e} = 71$ GeV

Case 2 $t_\beta = 30,\ m_A = 100$ GeV $(m_h = 90$ GeV$)$

$(-113, +342, -77; -17,\ 1)$ for $m_{\tilde{\nu}_e} = 73$ GeV

$(-66, -210, -49; +11,\ 1)$ for $m_{\tilde{\nu}_e} = 115$ GeV

Case 3 $t_\beta = 3,\ m_A = 300$ GeV $(m_h = 72$ GeV$)$

$(+29, +53, -8.4; -1.5,\ 1)$ for $m_{\tilde{\nu}_e} = 60$ GeV

$(-10, -26, -5.5; +0.54,\ 1)$ for $m_{\tilde{\nu}_e} = 90$ GeV

Case 4 $t_\beta = 30,\ m_A = 300$ GeV $(m_h = 91$ GeV$)$

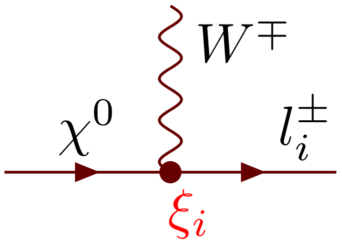
$(+18, +289, -74; -14,\ 1)$ for $m_{\tilde{\nu}_e} = 75$ GeV

$(-6.9, -212, -49; +11,\ 1)$ for $m_{\tilde{\nu}_e} = 115$ GeV

## Collider test of the schemes

**clean same-sign dilepton signals :** $e^+e^- \to \chi^0\chi^0 \to l_i^- l_j^- W^+W^+$

**Lepton flavour violating decay of the LSP measures the neutrino mixing angles :**




$$\Gamma(\chi^0 \to l_i W) \sim \frac{G_F m_{\chi^0}^3}{4\pi} |\xi_i|^2 c_\beta^2$$

$$\tau_{\chi^0} \sim 0.2\ cm \quad \text{for} \quad m_{\chi^0} = 100\ \text{GeV}$$

$$B(eW) : B(\mu W) : B(\tau W) = |\xi_1|^2 : |\xi_2|^2 : |\xi_3|^2$$

**Bilinear model, Option I :** $B(eW) \sim B(\mu W)$

**Bilinear model, Option II :** $B(eW) \ll B(\mu W) \approx B(\tau W)$

# 4 Conclusion

• **Low energy models for neutrino mass generation have a difficulty of washing out the baryon asymmetry of the universe.**

• **Reconciliation of such a cosmological consideration with the observed neutrino masses and mixing can be made in the supersymmetric standard model with the bilinear R-parity violation and non-universal soft masses** *accepting a certain degree of fine-tuning.*

**1. Small violation of universality :**
**ATM from the sbottom–bottom loop**
**SOL from the tree-level**

$$1 < \tan\beta < m_A^2/m_{\tilde{\nu}_e}^2$$

**2. Large violation of universality :**
**ATM from the tree-level**
**SOL from the sneutrino/Higgs loops**

$$m_{\tilde{\nu}_e}^2 \approx m_h^2$$

• **The electron number violation can only be suppressed : small $\theta_{13}$.**

• **The Affleck-Dine mechanism is a viable option of baryogenesis in our scheme.**