"Mass spectrum in Supersymmetric Scheme of Gelmini-Roncadelli"

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Plan

- Standard Model
- Scheme Gelmini-Roncadelli
- Majoron
- Possible Solution
- Supersymmetric Scheme of Gelmini-Roncadelli
- Mass Spectrum

Standard Model

- We introduce only left-handed neutrinos

$$L_{iL} = \begin{pmatrix} \nu_{iL} \\ l_{iL} \end{pmatrix} \sim \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$$

$$l_{iR} \sim (\mathbf{1}, \mathbf{1}, -1) \quad i = 1, 2, 3$$

$$Q_{iL} = \begin{pmatrix} u_{iL} \\ d_{iL} \end{pmatrix} \sim \left(\mathbf{3}, \mathbf{2}, +\frac{1}{6}\right)$$

$$u_{iR} \sim \left(\mathbf{3}, \mathbf{1}, +\frac{2}{3}\right) \quad d_{iR} \sim \left(\mathbf{3}, \mathbf{1}, -\frac{1}{3}\right)$$

- One Scalar in doublet representation

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} \sim \left(\mathbf{1}, \mathbf{2}, +\frac{1}{2}\right)$$

$$\tilde{\phi} \equiv [(i\sigma_2)\, \phi^{*}] = \begin{pmatrix} \left(\phi^{0}\right)^{*} \\ -\phi^{-} \end{pmatrix} \sim \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}\right)$$

- vacuum expectation value (VEV)

$$\langle \phi \rangle \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \langle \tilde{\phi} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

- Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_{SM}^{Y} - V(\phi) + \mathcal{L}_{SM}^{kin}$$

- Yukawa Couplings

$$\begin{aligned} \mathcal{L}_{SM}^{Y} &= \left[g_{ij}^{l}\left(\bar{L}_{iL}\phi\right) l_{jR} + g_{ij}^{d}\left(\bar{Q}_{iL}\phi\right) d_{jR}\right. \\ &+ \left. g_{ij}^{u}\left(\bar{Q}_{iL}\tilde{\phi}\right) u_{jR} + hc\right] \end{aligned}$$

- All the charged leptons get mass at tree level

- Top quark mass (CMS Collaboration- LHC)

  $m_t = 172.25 \pm 0.08(\text{stat.}) \pm 0.62(\text{syst.})$ GeV

- Neutrinos massless any order in perturbation theory

- Scalar Potential

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

- Condition of Extremes

$$\left.\frac{\partial V(\phi)}{\partial \phi}\right|_{\langle\phi\rangle = v} = 0$$

- Shift in the neutral scalar field

$$\phi^0 \equiv \frac{1}{\sqrt{2}}\left(v + h^0 + iG^0\right)$$

- One Goldstone boson (CP-odd)

- One massive boson (CP-even)

$$M_{h^0}^2 = -2\mu^2$$

- Discovered in LHC

$$M_{h^0} = (125.20 \pm 0.11) \quad GeV$$

- Mass for Gauge Bosons

$$\mathcal{L}_{SM}^{kin} = (D_m\phi)^\dagger (D^m\phi)$$

$$D_m\phi = \left[\partial_m - ig\sum_{i=1}^{3}\left(\frac{\sigma^i}{2}\right)W_m^i - ig'\left(\frac{1}{2}\right)B_m\right]\phi$$

- Two Massive Gauge Bosons

$$M_{W^\pm}^2 = \frac{g^2v^2}{4} = [(80.3505 \pm 0.0077) \quad GeV]^2$$

$$W^\pm = \frac{1}{\sqrt{2}}\left(W_m^1 \mp iW_m^2\right)$$

$$M_{Z^0}^2 = \left(\frac{g^2+(g')^2}{4}\right)v^2 = \frac{M_{W^\pm}^2}{\cos^2\theta_W}$$

$$\begin{pmatrix} Z_m^0 \\ A_m \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix}\begin{pmatrix} W_m^3 \\ B_m \end{pmatrix}$$

$$\tan\theta_W \equiv \frac{g'}{g}$$

- Average Experimental Values

$$(M_{W^\pm})_{ave} = (80.4133 \pm 0.0080)\, GeV$$

$$\left(M_{Z^0}\right)_{ave} = (91.1875 \pm 0.0021)\, GeV$$

$$\sin^2\theta_W = 0.2324 \pm 0.0012$$

- Scheme Gelmini-Roncadelli PLB99, 411, (1981); S. M. Bilenky, hep-ph/1210.3065 (Neutrnos are massive)

$$\overline{L^c_{iL}} L_{jL} \sim (\mathbf{1}, \mathbf{1} \oplus \mathbf{3}, -1)$$

1-) Extra fermions in singlet N type I See-saw mechanism

2-) Extra scalars Δ in triplets type II

3-) Extra fermions Σ in triplets type III

- New scalar

$$\begin{aligned} \Delta &\sim (\mathbf{1}, \mathbf{3}, \mathbf{1}) \\ \Delta &= \begin{pmatrix} \Delta^0 & \frac{h^+}{\sqrt{2}} \\ \frac{h^+}{\sqrt{2}} & H^{++} \end{pmatrix} \\ \langle \Delta \rangle &= \frac{1}{\sqrt{2}} \begin{pmatrix} V_\Delta & 0 \\ 0 & 0 \end{pmatrix} \end{aligned}$$

- Fermilab's CDF

$$(M_W)_{\text{CDF}} = (80.4335 \pm 0.0094) \quad GeV$$

- Masses for neutrinos

$$\begin{aligned}\mathcal{L}^{\nu}_{\Delta,L} &= g^{\nu}_{ij}\left[\left(\overline{L^c_{iL}}\Delta L_{jL}\right) + hc\right] \\ &= g^{\nu}_{ij}\left[\overline{\nu^c_{iL}}\nu_{jL}\Delta^0\right. \\ &+ \left(\overline{\nu^c_{iL}}l_{jL} - \overline{l^c_{iL}}\nu_{jL}\right)\frac{h^+}{\sqrt{2}} \\ &+ \left.\overline{l^c_{iL}}l_{jL}H^{++} + hc\right]\end{aligned}$$

- Neutrinos are Majorana Particles

$$(A, Z) \to (A, Z+2) + 2e^-$$

- A. S. Barabash nucl-ex/1107.5663

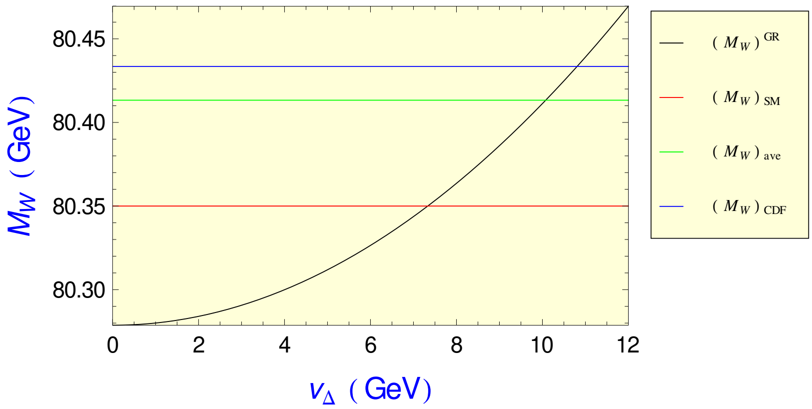
- Experiments CUORE, GERDA, MAJORANA

- Masses in Gauge Bosons

$$
\begin{aligned}
M_W^2 &= \frac{g^2 v^2}{4}(1+2R) \\
M_Z^2 &= \frac{g^2 v^2}{4\cos^2\theta_W}(1+4R) \\
\rho &\equiv \left(\frac{M_W^2}{M_Z^2 \cos^2\theta_W}\right) = \frac{1+2R}{1+4R} \simeq 1-2R \\
R &= \left(\frac{v_\Delta}{v}\right)^2 \\
\rho^{SM} &= 1 \\
\rho_{\mathrm{EXP}} &= 0.9998 \pm 0.0008
\end{aligned}
$$

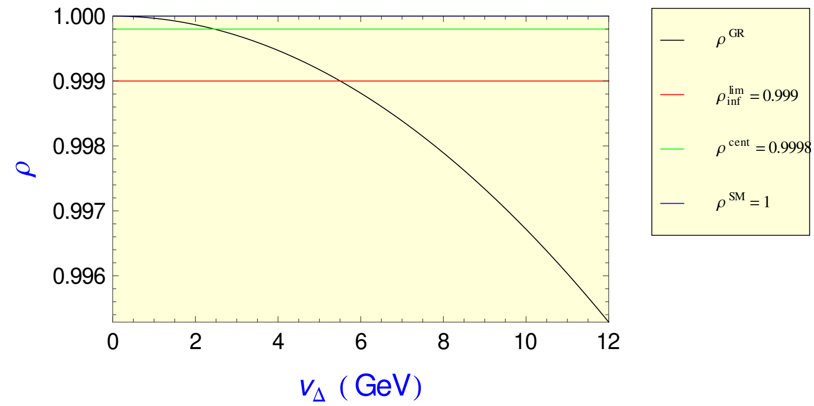
- Some Numerical Results

- M_W



80.45
80.40
80.35
80.30
0
2
4
6
8
10
12
M_W (GeV)
v_Δ (GeV)
$(M_W)^{GR}$
$(M_W)_{SM}$
$(M_W)_{ave}$
$(M_W)_{CDF}$

- ρ



1.000
0.999
0.998
0.997
0.996
0
2
4
6
8
10
12
ρ
v_Δ (GeV)
ρ^{GR}
$\rho^{lim}_{inf} = 0.999$
$\rho^{cent} = 0.9998$
$\rho^{SM} = 1$

- Scalar Potential (Majoron M^0)

$$
\begin{aligned}
V_G(\phi,\Delta) &= \mu^2(\phi^\dagger\phi) + M^2 Tr(\Delta^\dagger\Delta) \\
&+ \lambda_1(\phi^\dagger\phi)^2 + \lambda_2\left[Tr(\Delta^\dagger\Delta)\right]^2 \\
&+ \lambda_3 Tr[(\Delta^\dagger\Delta)(\Delta^\dagger\Delta)] \\
&+ \lambda_4(\phi^\dagger\phi)Tr(\Delta^\dagger\Delta) \\
&+ i\lambda_5\epsilon_{ijk}(\phi^\dagger\sigma^i\phi)(\Delta^{j\dagger}\Delta^k)
\end{aligned}
$$

- CP-even two massives states

- CP- odd two Goldstone boson

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + M^0$$

- It is excluded by experimental data

- A. S. Barabash nucl-ex/1107.5663

- Possible Solution

- We can remove Majoron; E.Ma PRL80, 5716, (1998)

$$V(\phi, \Delta) = V_G(\phi, \Delta) + \left[\mu_M \left(\phi^\dagger \Delta \tilde{\phi}\right) + hc\right]$$

- Mass Spectrum

$$\begin{aligned} M^2_{h^0} &\approx 2\lambda_1 v^2 \ \text{S}MHiggs \\ M^2_{H^0} &\approx \frac{\mu_M}{\sqrt{2}} \frac{v^2}{V_\Delta} \\ M^2_{A^0} &\approx \frac{\mu_M}{\sqrt{2}} \left(\frac{4v^2_\Delta + v^2}{V_\Delta}\right) = M^2_{H^0} + 2\sqrt{2}\mu_M V_\Delta \end{aligned}$$

- $V_\Delta \leq 3$ GeV $\mu \geq 10^0$ GeV

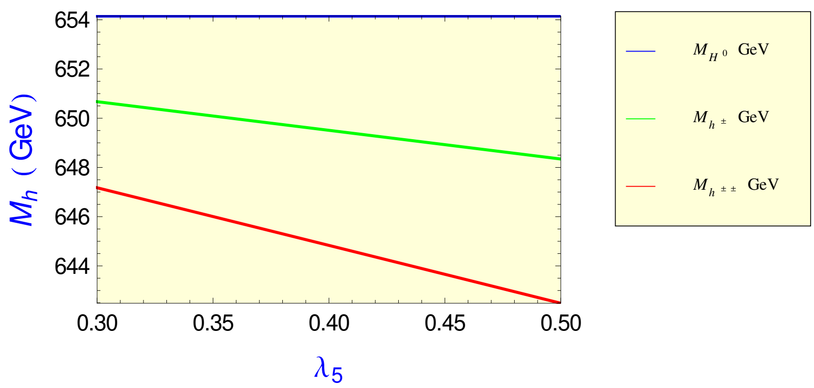
$$\begin{aligned} 400 &\leq M_{H^0} \leq 1000 \ GeV \\ 400 &\leq M_{A^0} \leq 1000 \ GeV \end{aligned}$$

- Agree with Atlas results

- There are also charged scalars

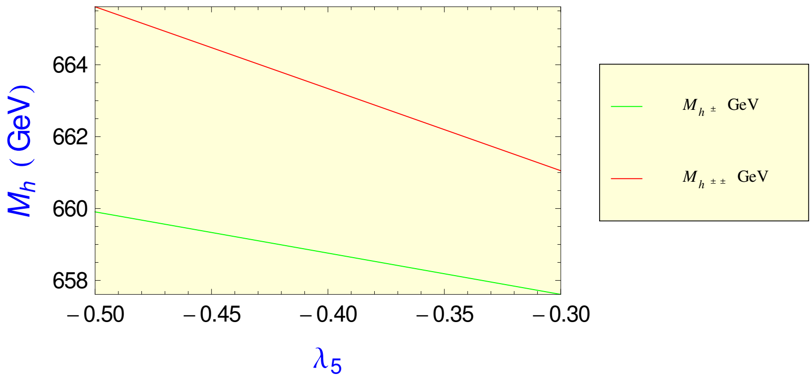
$$
\begin{aligned}
M_{h^\pm}^2 &= M_{H^0}^2 - \frac{\lambda_5}{4} v^2 \\
M_{h^{\pm\pm}}^2 &= M_{H^0}^2 - \frac{\lambda_5}{2} v^2
\end{aligned}
$$

- $\lambda_5 > 0$



$$M_{H^0} > M_{h^\pm} > M_{h^{\pm\pm}}$$

- $\lambda_5 < 0$



$$M_{h^{\pm\pm}} > M_{h^\pm} > M_{H^0}$$

- Some decays channels

$$\begin{aligned} H^{\pm\pm} &\rightarrow l^\pm l^\pm \\ H^{\pm\pm} &\rightarrow W^\pm W^\pm \\ H^{\pm\pm} &\rightarrow H^\pm W^\pm \rightarrow \bar{b}bW^\pm W^\pm \end{aligned}$$

- contain source of L and CP violation at high scale

- can not induce Leptogenesis Ambrosio PLB604, 199, (2004)

- It is simple to introduce it in SUSY

- A. V. Gladyshev and D. I. Kazakov [arXiv:1212.2548 [hep-ph]]

- Usual fermions Chiral Superfield

- Scalars Chiral Superfield

$$H_1 = \begin{pmatrix} h_1^0 \\ h_1^- \end{pmatrix} \quad \langle H_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 \\ 0 \end{pmatrix}$$
$$H_2 = \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix} \quad \langle H_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- Gauge bosons SM Vector Superfields

a-) Gluons g, superpartners gluinos $\tilde{g}$

b-) $SU(2)$ gauge W_i, superpartnes $\tilde{W}_i$ $i = 1, 2, 3$

c-) $U(1)$ gauge B_m, superpartner $\tilde{B}$

- Superpotential

$$
\begin{aligned}
W_{RC}^{MSSM} &= \mu\left(\hat{H}_1\hat{H}_2\right) + f^l_{ij}\left(\hat{H}_1\hat{L}_i\right)\hat{E}_j \\
&+ f^d_{ij}\left(\hat{H}_1\hat{Q}_i\right)\hat{D}_j + f^u_{ij}\left(\hat{H}_2\hat{Q}_i\right)\hat{U}_j
\end{aligned}
$$

- Some Problems in the MSSM

a-) Neutrinos are massless

b-) μ Problem

b1-) Singlet N

$$t_N\hat{N} + \mu_N\hat{N}\hat{N} + \kappa\hat{N}\hat{N}\hat{N} + \lambda\hat{N}\left(\hat{H}_1\hat{H}_2\right)$$

b2-) Triplet T $Y = 0$

$$\mu_T Tr\left[\hat{T}\hat{T}\right] + \lambda Tr\left[\left(\hat{H}_1\hat{T}\hat{H}_2\right)\right]$$

c-) Strong CP Problem

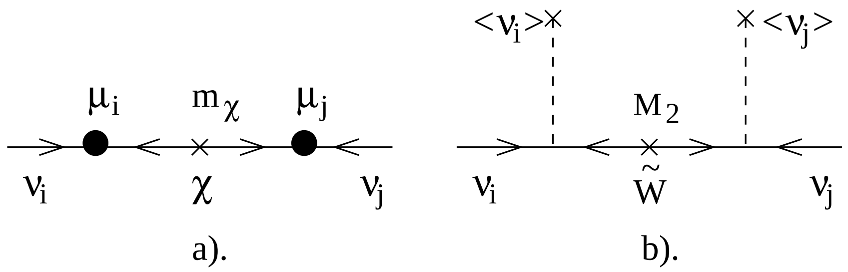
- Generate mass to neutrinos break R-Parity

- A. Yu. Smirnov hep-ph/0411194

- Superpotential

$$\begin{aligned} W_{RV}^{MSSM} &= W_{RC}^{MSSM} + \mu_i \hat{L}_i \hat{H}_2 + \lambda'_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k \\ &+ \lambda''_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k \end{aligned}$$

- one get mass tree-level (Majorana Particle)



- type I (gaugino $U(1)$ $\tilde{B}$)

- type III (wino $\tilde{W}_3$)

- Supersymmetric Scheme of Gelmini-Roncadelli
  A. Rossi PRD66, 075003, (2002)

- Usual fermions, Gauge bosons H_1, H_2
  $MSSM$

- Scalars

$$\Delta_1 = \begin{pmatrix} \Delta_1^0 & \frac{h_1^+}{\sqrt{2}} \\ \frac{h_1^+}{\sqrt{2}} & H_1^{++} \end{pmatrix} \quad \langle\Delta_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} V_{\Delta_1} & 0 \\ 0 & 0 \end{pmatrix}$$

$$\Delta_2 = \begin{pmatrix} \Delta_2^{--} & \frac{h_2^-}{\sqrt{2}} \\ \frac{h_2^-}{\sqrt{2}} & \Delta_2^0 \end{pmatrix} \quad \langle\Delta_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ 0 & V_{\Delta_2} \end{pmatrix}$$

- $\Delta_1 \sim (\mathbf{1}, \mathbf{3}, 1)$ $L = -2$

- $\Delta_2 \sim (\mathbf{1}, \bar{\mathbf{3}}, -1)$ $L = 2$

- Leptogenesis is possible due to finite temperatura effects

- Superpotential

$$\begin{aligned} W^{GR}_{SUSY} &= W^{MSSM}_{RC} + \mu_{\Delta} Tr\left[\left(\hat{\Delta}_1 \hat{\Delta}_2\right)\right] \\ &+ f^N_{ij} Tr\left[\hat{L}_i \hat{\Delta}_1 \hat{L}_j\right] + \lambda_1 Tr\left[\hat{H}_1 \hat{\Delta}_1 \hat{H}_1\right] \\ &+ \lambda_2 Tr\left[\hat{H}_2 \hat{\Delta}_2 \hat{H}_2\right] \end{aligned}$$

- Δ_1 and Δ_2 degenerated μ_{Δ}

- CP-violation induce Leptogenesis by SSB

$$\begin{aligned} -\mathcal{L}_{soft} &= m^2_{\Delta_1} \Delta_1^{\dagger} \Delta_1 + m^2_{\Delta_2} \Delta_2^{\dagger} \Delta_2 \\ &+ (B M_T \Delta_1 \Delta_2 + hc) + \ldots \end{aligned}$$

- B-term remove degeneracy

- T_- mass $\mu_\Delta^2 + BM_T$ (unstable)

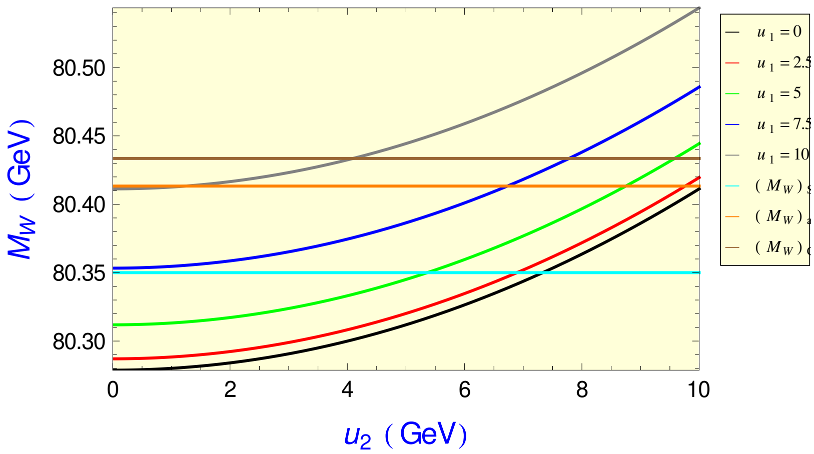
- T_+ mass $\mu_\Delta^2 - BM_T$

- T_- decay in Leptons Lepton Asymmetry
  Ambrosio PLB604, 199, (2004)

- Gauge bosons

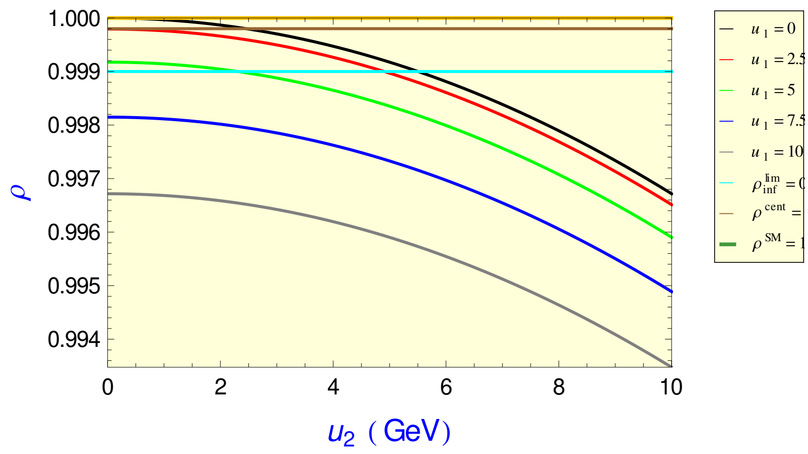
$$
\begin{aligned}
M^2_{W^\pm} &= \frac{g^2 v^2}{4}\left[1 + 2\left(u_1 + u_2\right)\right] \\
M^2_{Z^0} &= \frac{g^2 v^2}{4\cos^2\theta_W}\left[1 + 4\left(u_1 + u_2\right)\right] \\
\rho &\approx 1 - 2\left(u_1 + u_2\right) \\
u_1 &= \left(\frac{V_{\Delta_1}}{v}\right)^2, \quad u_2 = \left(\frac{V_{\Delta_2}}{v}\right)^2
\end{aligned}
$$

- M_W



80.50
80.45
80.40
80.35
80.30
M_W (GeV)
0
2
4
6
8
10
u_2 (GeV)
$u_1 = 0$
$u_1 = 2.5$
$u_1 = 5$
$u_1 = 7.5$
$u_1 = 10$

- ρ



1.000
0.999
0.998
0.997
0.996
0.995
0.994
ρ
0
2
4
6
8
10
u_2 (GeV)
$u_1 = 0$
$u_1 = 2.5$
$u_1 = 5$
$u_1 = 7.5$
$u_1 = 10$

- $\lambda_{1,2}$ explicity break L similar to μ_M

- Charginos, Neutralinos and Sleptons Production

- Singlet/ Triplet

$$
\begin{aligned}
& \lambda_T \hat{N} Tr\left[\left(\hat{\Delta}_1 \hat{\Delta}_2\right)\right] + \lambda_N \hat{N}\left(\hat{H}_1 \hat{H}_2\right) \\
+ \ & \kappa \hat{N}\hat{N}\hat{N} + \lambda_1 Tr\left[\left(\hat{H}_1 \hat{\Delta}_1 \hat{H}_2\right)\right] \\
+ \ & \lambda_2 Tr\left[\left(\hat{H}_1 \hat{\Delta}_2 \hat{H}_2\right)\right]
\end{aligned}
$$

- Both Mechanism are present in MSUSY331

1-) J. C. Montero, V. Pleitez and M. C. Rodriguez, *Phys. Rev.* **D65**, 035006, (2002);

2-) M. Capdequi-Peyranère and M.C. Rodriguez, *Phys. Rev.* **D 65**, 035001 (2002);

- M. C. Rodriguez *Int. J. Mod. Phys.* **A39**, 2440001, (2024);

- M. C. Rodriguez *Int. J. Mod. Phys.* **A40**, 2550092, (2025).

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