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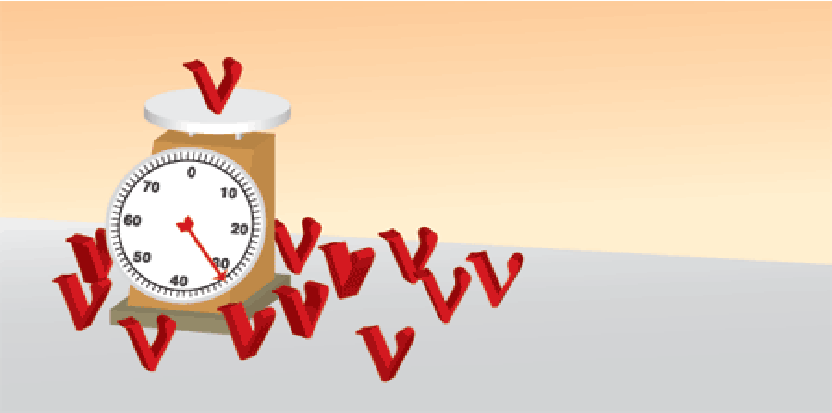
Neutrino masses in RPV models with extra pairs of Higgs doublets



arXiv:1401.1818
JHEP04(2014)033
work in collaboration with Y. Grossman

SUSY 2014, Manchester, 22th July 2014

Clara Peset

Outline

- Motivation for the model
  - supersymmetry
  - RPV
  - neutrinos
  - extra pairs of Higgs doublets
- Neutrinos in RPV models: tree level contribution
  - bounds on small RPV
  - contributions to the mass matrix
- Neutrinos in RPV models: loop level
  - small RPV
  - possible new effects
- Conclusions

NEUTRINOS-SUSY-RPV-EXTRA HD

Neutrino experimental data:

$$\Delta m^2_{32} = \left(2.32^{+0.12}_{-0.08}\right) \times 10^{-3}\,\mathrm{eV}^2, \qquad \Delta m^2_{21} = (7.5 \pm 0.20) \times 10^{-5}\,\mathrm{eV}^2,$$
$$\sin^2(2\theta_{32}) > 0.95, \quad \sin^2(2\theta_{12}) = 0.857 \pm 0.024, \quad \sin^2(2\theta_{13}) = 0.095 \pm 0.010$$

From: solar, detector & atmospheric neutrino experiments

mild mass hierarchy 2 large mixing angles + 1 smaller angle	⇔	Matrix determinant >> Matrix elements	⇒	Naturally if masses come from different sources

Opposite to flavor mixing in quarks!

NEUTRINOS-SUSY-RPV-EXTRA HD

Standard model is NOT the theory of everything

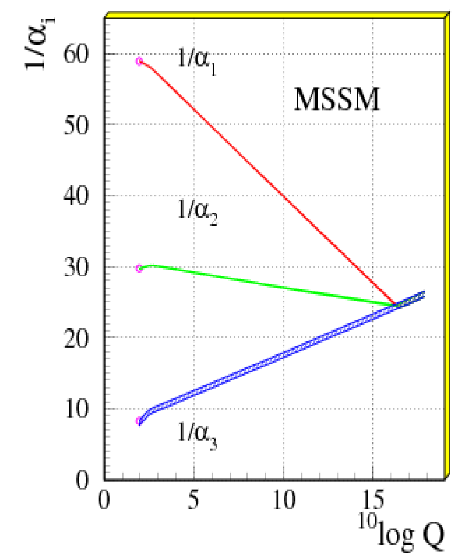
Cannot account for gravity, neutrino masses...

The mass of the Higgs is UV sensitive: $m_H^2 \approx \frac{\Lambda_{NP}^2}{16\pi^2}$

SUPERSYMMETRY

no UV sensitivity $\longrightarrow$ scalar masses protected
mass of the Higgs boson arises naturally

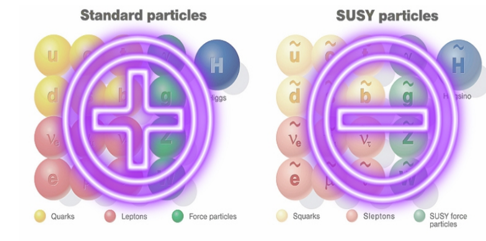
Other benefits: unification of couplings, string theory...



Simplest models should have been/be detected at LHC!

2nd round LHC,
other models,
large amount of
data to analyze...

NEUTRINOS-SUSY-RPV-EXTRA HD



R-Parity: $(-1)^R \quad , R = 2S + 3B + L$

- Proton decay @ dim 5
- Neutral stabe fermion ⇨ cold DM candidate χ^0

NOT NECESSARY FOR NATURALNESS!

R-Parity violation:

$\chi^0 \longrightarrow$ SM particles   NO need for MET @ LHC searches!

RPV searches: distinctive final states with many particle states: high jet or lepton activity

New RPV terms in the superpotential:

$$W = \underbrace{-\mu \hat{L}_I \hat{H}_U + \frac{1}{2}\lambda_{IJm}\hat{L}_I\hat{L}_J\hat{E}_m + \lambda'_{Inm}\hat{L}_I\hat{Q}_n\hat{D}_m}_{\not{L}} + \underbrace{\cancel{\frac{1}{2}\lambda''_{lmn}\hat{D}_l\hat{D}_m\hat{Q}_n}}_{\not{B}}$$

Plus soft SUSY breaking terms

Generally allows for proton decay!

Leptonic RPV ⇨ majorana neutrino masses arise naturally! $\Delta L = 2$

NEUTRINOS-SUSY-RPV-EXTRA HD

Breaking the spectrum:

- more possibilities for s-partners mass spectrum $\longrightarrow$ detection @ LHC
- rise Higgs mass without fine tuning $\longrightarrow$ Sister Higgs

Alves, Fox '12
arXiv:1207.5499
arXiv:1207.5522

General Issues:

- FCNC arise $\cancel{\lambda'_{Inm}\hat{L}_I\hat{Q}_n\hat{D}_m}$

- New RPV term $\boxed{\frac{\tilde{\lambda}_m}{2}\epsilon_{ij}\left(\hat{H}^i_{D_1}\hat{H}^j_{D_2}-\hat{H}^i_{D_2}\hat{H}^j_{D_1}\right)\hat{E}_m}$

Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons ⟹ Indistinguishable!

MSSM: $\hat{L}_\mu = (\hat{H}_D, \hat{L}_1, \hat{L}_2, \hat{L}_3)$

RPV terms:

$$W = \epsilon_{ij}\left[-\mu_\alpha \hat{L}^i_\alpha \hat{H}^j_U + \frac{1}{2}\lambda_{\alpha\beta m}\hat{L}^i_\alpha \hat{L}^j_\beta \hat{E}_m + \lambda'_{\alpha nm}\hat{L}^i_\alpha \hat{Q}^j_n \hat{D}_m\right]$$

$$V_{\text{soft}} = \left(M^2_{\tilde{L}}\right)_{\alpha\beta}\tilde{L}^{i*}_\alpha \tilde{L}^i_\beta - \left(\epsilon_{ij}B_\alpha \tilde{L}^i_\alpha H^j_U + \text{ h.c.}\right) + \epsilon_{ij}\left[\frac{1}{2}A_{\alpha\beta m}\tilde{L}^i_\alpha \tilde{L}^j_\beta \tilde{E}_m + A'_{\alpha nm}\tilde{L}^i_\alpha \tilde{Q}^j_n \tilde{D}_m + \text{ h.c.}\right]$$

EWSB characterized by:

$$v_u, \qquad v_d = \left(\sum v^2_\alpha\right)^{1/2}, \qquad \mu = \left(\sum \mu^2_\alpha\right)^{1/2}$$

$$v \equiv \left(|v_u|^2 + |v_d|^2\right)^{1/2} = \frac{2m_W}{g} = 246\,\text{GeV}$$

Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons ⟹ Indistinguishable!

SUSY with extra pair of Higgses: $\hat{L}_I = (\hat{H}_{D_1}, \hat{H}_{D_2}, \hat{L}_1, \hat{L}_2, \hat{L}_3)$

RPV terms:

$$W = \epsilon_{ij}\left[-\mu_{1I}\hat{L}_I^i\hat{H}_{U_1}^j - \mu_{2I}\hat{L}_I^i\hat{H}_{U_2}^j + \frac{1}{2}\lambda_{IJm}\hat{L}_I^i\hat{L}_J^j\hat{E}_m + \lambda'_{Inm}\hat{L}_I^i\hat{Q}_n^j\hat{D}_m\right]$$

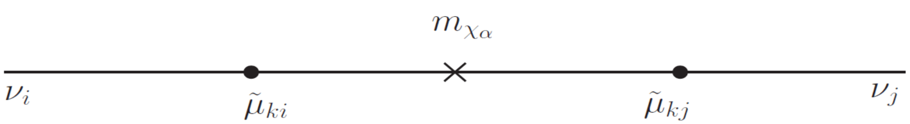
$$V_{\mathrm{soft}} = \left(M_{\tilde{L}}^2\right)_{IJ}\tilde{L}_I^{i*}\tilde{L}_J^i - \left(\epsilon_{ij}B_{1I}\tilde{L}_I^iH_{U_1}^j + \mathrm{h.c.}\right) - \left(\epsilon_{ij}B_{2I}\tilde{L}_I^iH_{U_2}^j + \mathrm{h.c.}\right)$$
$$+\epsilon_{ij}\left[\frac{1}{2}A_{IJm}\tilde{L}_I^i\tilde{L}_J^j\tilde{E}_m + A'_{Inm}\tilde{L}_I^i\tilde{Q}_n^j\tilde{D}_m + \mathrm{h.c.}\right]$$

EWSB characterized by:

$$v_u = \left(v_{u_1}^2 + v_{u_2}^2\right)^{1/2}, \qquad v_d = \left(\sum v_I^2\right)^{1/2}, \qquad \mu_1 = \left(\sum \mu_{1I}^2\right)^{1/2}, \qquad \mu_2 = \left(\sum \mu_{2I}^2\right)^{1/2}$$

$$v \equiv \left(|v_u|^2 + |v_d|^2\right)^{1/2} = \frac{2m_W}{g} = 246\,\mathrm{GeV}$$

TL Neutrino mixing matrix



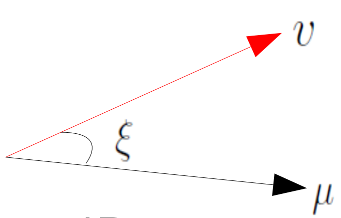
Neutrino – neutralino mixing

MSSM:

Mixing matrix basis $\{\tilde{B}, \tilde{W}^3, \tilde{H}_U, \nu_\alpha\}$

Product of non-zero eigenvalues

$$\boxed{\det{}' M^N = \mu^2 v_d^2 \sin^2 \xi}$$



4D-vectors

$$\boxed{\xi^2 \lesssim \frac{m_3}{\tilde{m}}}$$

small RPV

Diagoalize M to obtain the neutrino mass matrix:

$$M^N = \begin{pmatrix} M_{4\times4} & \mu_{4\times3} \\ \mu^T_{3\times4} & 0_{3\times3} \end{pmatrix} \Longrightarrow U M^N U^+ = \begin{pmatrix} M'_{4\times4} & 0_{4\times3} \\ 0_{3\times4} & m_{\nu\,3\times3} \end{pmatrix}$$

$$\boxed{m_{\nu\,3\times3} = \mu^T M^{-1} \mu}$$

light neutrinos

heavy neutralinos

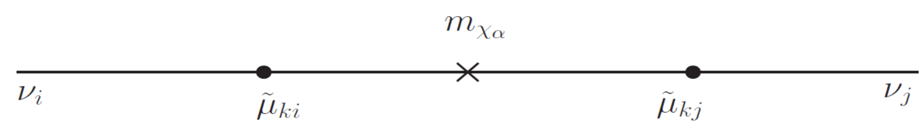
$$(m_\nu)_{ij} = X \mu_i \mu_j$$

rank 1 matrix

$$X \equiv \frac{m_{\tilde{\gamma}} m_Z^2 \cos^2\beta}{\mu(m_Z^2 m_{\tilde{\gamma}} \sin 2\beta - M_1 M_2 \mu)} \sim \frac{\cos^2\beta}{\tilde{m}}$$

$$\boxed{m_3 = X \vec{\mu}^2, \qquad m_1 = m_2 = 0}$$

TL Neutrino mixing matrix



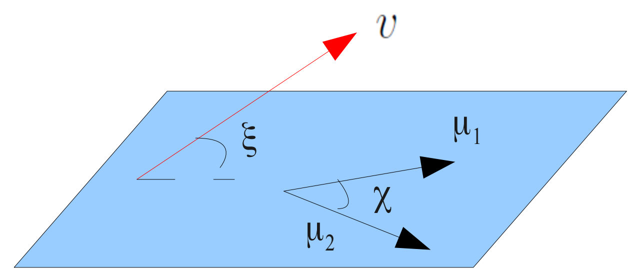
Neutrino – neutralino mixing

SUSY with extra pair of Higgses:

Mixing matrix basis $\{\tilde{B}, \tilde{W}^3, \tilde{H}_{U_1}, \tilde{H}_{U_2}, \nu_I\}$

Product of non-zero eigenvalues

$$\boxed{\det{}' M^N = 2\frac{m_Z^2\, m_{\tilde{\gamma}}}{v^2}\, v_d^2\, \mu_1^2\, \mu_2^2 \sin^2\chi \sin^2\xi}$$



5D-vectors

$$\boxed{\xi^2 \lesssim \frac{m_3}{\tilde{m}}}$$

small RPV

Diagoalize M to obtain the neutrino mass matrix:

$$M^N = \begin{pmatrix} M_{6\times6} & \mu_{6\times3} \\ \mu^T_{3\times6} & 0_{3\times3} \end{pmatrix} \Longrightarrow U M^N U^+ = \begin{pmatrix} M'_{6\times6} & 0_{6\times3} \\ 0_{3\times6} & m_{\nu\ 3\times3} \end{pmatrix}$$

$$\boxed{m_{\nu\ 3\times3} = \mu^T M^{-1} \mu}$$

light neutrinos

$$(m_\nu)_{ij} = \frac{X}{\Delta\mu^2}\left[\mu_{1i}\tilde{\mu}_2 - \mu_{2i}\tilde{\mu}_1\right]\left[\mu_{1j}\tilde{\mu}_2 - \mu_{2j}\tilde{\mu}_1\right]$$

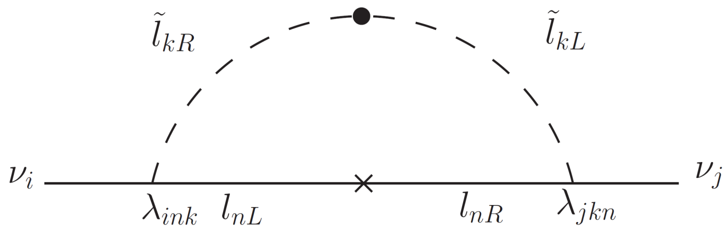
$$X \equiv \frac{m_{\tilde{\gamma}} m_Z^2 \cos^2\beta}{M_1 M_2 \Delta\mu^2 + m_{\tilde{\gamma}} m_Z^2 \sin(2\beta)(\tilde{\mu}_1 \sin\beta_2 - \tilde{\mu}_2 \cos\beta_2)} \sim \frac{\cos^2\beta}{\tilde{m}}$$

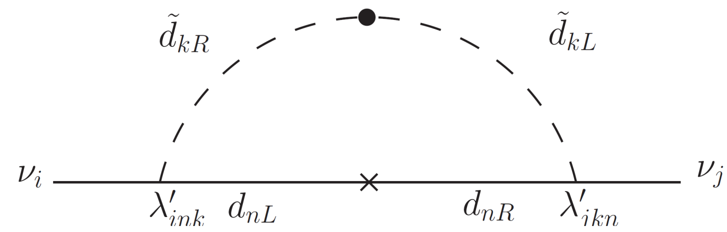
rank 1 matrix

$$\boxed{m_3 = \frac{X}{\Delta\mu^2}\mu_1^2\mu_2^2 \sin^2\chi \sin^2\xi, \qquad m_1 = m_2 = 0}$$

heavy neutralinos

Loop contributions: λλ loops





MSSM:

$$[m_\nu]_{ij}^{(\lambda'\lambda')} \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk}\,\lambda'_{jkl}\,\frac{m_{d_l}\,\Delta m^2_{\tilde{d}_k}}{m^2_{\tilde{d}_k}} \sim \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{ilk}\lambda'_{jkl}\frac{m_{d_l} m_{d_k}}{\tilde{m}}$$

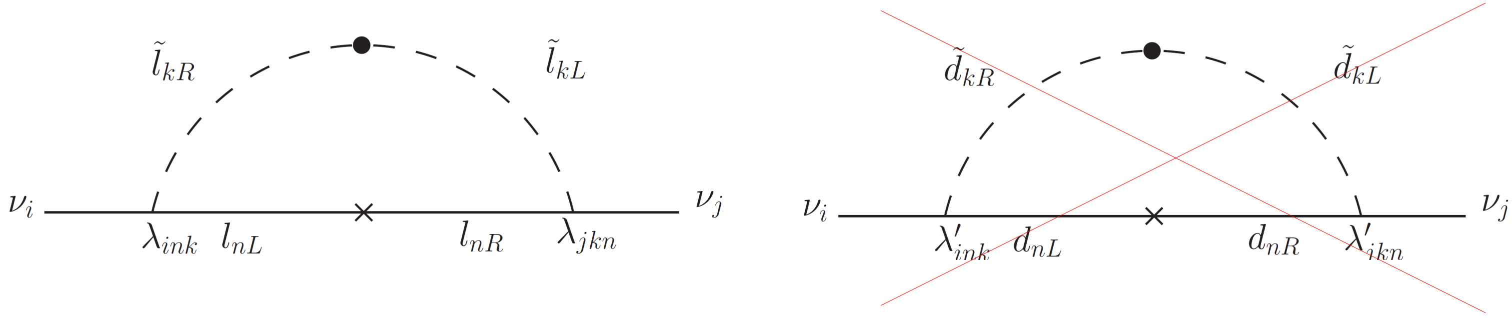
neglecting quark/lepton mixings

Supression factors:

$\boxed{\text{2RPV COUPLINGS+LOOP FACTOR+2 QUARK MASSES}}$

Irrelevant in most cases

Loop contributions: λλ loops



SUSY with extra
pair of Higgses:

$$\delta m_{\nu_{ij}}^{\lambda\lambda} \approx \frac{1}{8\pi^2} \sum_{n,k} \lambda_{ink}\lambda_{jkn} \frac{m_{l_n} \Delta m^2_{\tilde{l}_k}}{m^2_{\tilde{l}_k}}$$

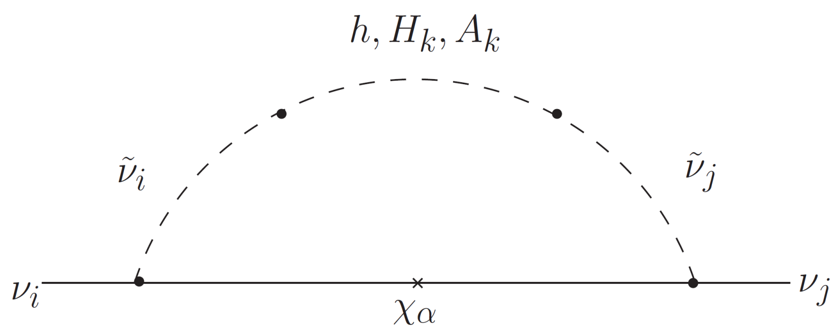
neglecting quark/lepton mixings

Supression factors:

$$\boxed{\text{2RPV COUPLINGS+LOOP FACTOR+2 LEPTON MASSES}}$$

Irrelevant in most cases

Loop contributions: BB loops



MSSM:

$$[m_\nu]_{ij}^{(BB)} = \sum_{\alpha,i,j} \frac{g^2 B_i B_j}{4\cos^2\beta}(Z_{\alpha 2} - Z_{\alpha 1} g'/g)^2 m_{\chi_\alpha} \Big\{ I_4(m_h, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \cos^2(\alpha - \beta) + I_4(m_H, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \sin^2(\alpha - \beta) - I_4(m_A, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \Big\} ,$$

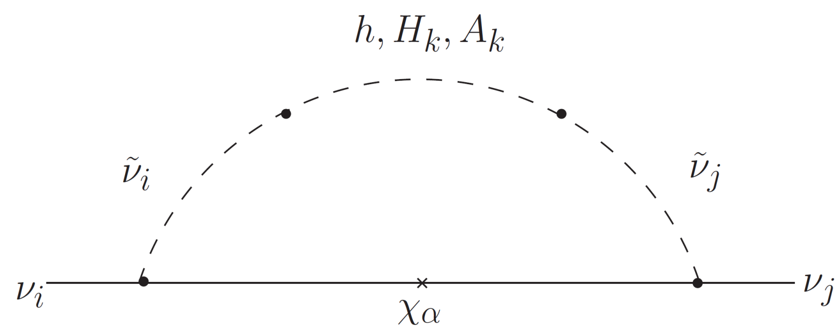
Supression factors:

Grossman, Rakshit '04

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

$$\cos^2(\alpha - \beta) = \frac{m_h^2(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)}, \qquad m_Z^2 - m_h^2 = m_H^2 - m_A^2$$

Loop contributions: BB loops



SUSY with extra pair of Higgses:

$$\delta m_{\nu_{ij}}^{BB} = \sum_\alpha \frac{g^2}{4}\left(Z_N^{0\alpha} - \frac{g'}{g} Z_N^{1\alpha}\right)^2 \Big[\tilde{B}_{ih}\tilde{B}_{jh} I_4(m_h, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha})$$
$$+ \sum_k \tilde{B}_{iH_k}\tilde{B}_{jH_k} I_4(m_{H_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) + \sum_k \tilde{B}_{iA_k}\tilde{B}_{jA_k} I_4(m_{A_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha})\Big]$$

Enlarged Higgs-like spectrum:

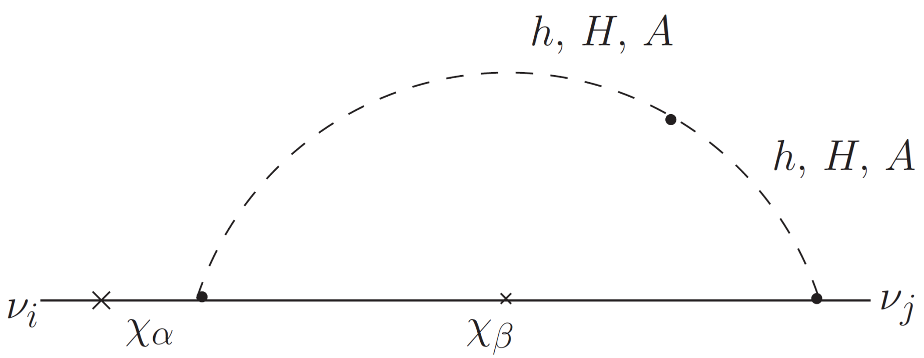
$$\frac{i}{\sqrt{2}}\tilde{B}_{i\{h,H_j,A_j\}} \equiv \frac{i}{\sqrt{2}}\Big[B_{1i}\{Z_R^{00}, Z_R^{0j}, iZ_H^{0j}\} + B_{2i}\{Z_R^{10}, Z_R^{1j}, iZ_H^{1j}\}$$
$$+(M_{\tilde{L}}^2)_{0(1+i)}\{Z_R^{20}, Z_R^{2j}, iZ_H^{2j}\} + (M_{\tilde{L}}^2)_{1(1+i)}\{Z_R^{30}, Z_R^{3j}, iZ_H^{3j}\}\Big]$$

larger number of diagrams!

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

Loop contributions: μB loops



MSSM:

$$[m_\nu]_{ij}^{(\mu B)} \sim \frac{g^2}{64\pi^2 \cos\beta} \frac{\mu_i B_j + \mu_j B_i}{\tilde{m}^2}$$

(approximate expression)

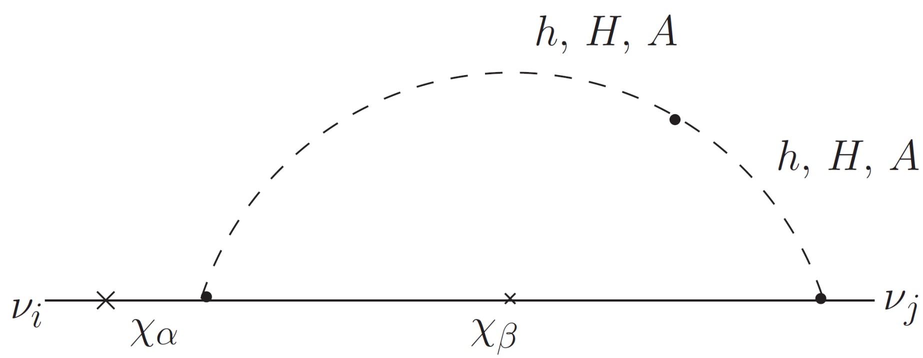
- subleading in μ with respect to the tree level (if tree level is dominant)

Grossman, Rakshit hep-ph/0311310

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

Loop contributions: μB loops



SUSY with extra pair of Higgses:

$$\delta m_{\nu_{ij}}^{\mu B} \sim \sum_{\alpha,\beta} \frac{g^2}{16\pi^2} \left(\tilde{\mu}_{i\alpha}\tilde{B}_{jh} + \sum_k \tilde{\mu}_{i\alpha}\tilde{B}_{jH_k} + \sum_k \tilde{\mu}_{i\alpha}\tilde{B}_{jA_k} \right.$$
$$\left. + \tilde{\mu}_{j\alpha}\tilde{B}_{ih} + \sum_k \tilde{\mu}_{j\alpha}\tilde{B}_{iH_k} + \sum_k \tilde{\mu}_{j\alpha}\tilde{B}_{iA_k} \right)$$

- subleading in μ with respect to the tree level (if tree level is dominant)

Supression factors:

$\boxed{\text{2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS}}$

Contributions from new term

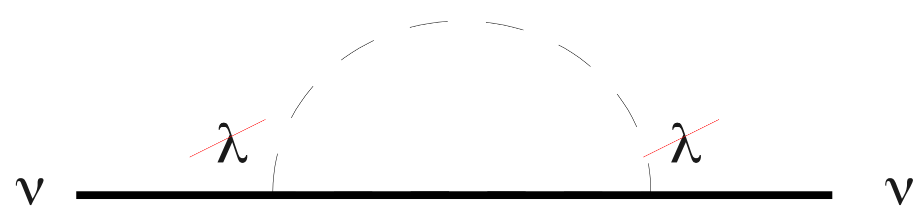
$$\boxed{\frac{\tilde{\lambda}_m}{2}\epsilon_{ij}\left(\hat{H}^i_{D_1}\hat{H}^j_{D_2}-\hat{H}^i_{D_2}\hat{H}^j_{D_1}\right)\hat{E}_m}$$

less constrained than usual RPV couplings

NO ONE LOOP EFFECTS

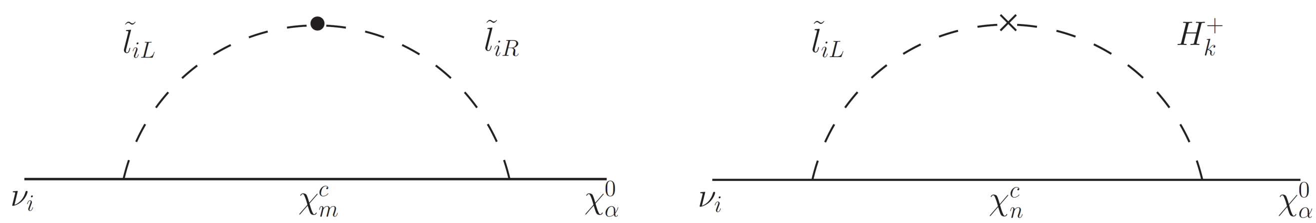
No neutrinos involved in the vertex
RPV in charged sector

Topological argument:



Contributions from new term

SEPARABLE TWO LOOP DIAGRAMS



effective μ couplings

$$[m_\nu]^{S,\tilde{\lambda}\tilde{\lambda}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{\lambda}}_{i\alpha}\mu^{\tilde{\lambda}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \frac{27}{32\pi^4} g^2 \tilde{\lambda}_i \tilde{\lambda}_j \frac{m_{l_i} m_{l_j}}{\tilde{m}}$$

$$[m_\nu]^{S,\tilde{\lambda}\tilde{B}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{\lambda}}_{i\alpha}\mu^{\tilde{B}}_{j\alpha} + \mu^{\tilde{B}}_{i\alpha}\mu^{\tilde{\lambda}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \sum_k \frac{27}{128\pi^4} g^3 \frac{\tilde{\lambda}_i \tilde{B}_{jk} m_{l_i} + \tilde{\lambda}_j \tilde{B}_{ik} m_{l_j}}{\tilde{m}^2}$$

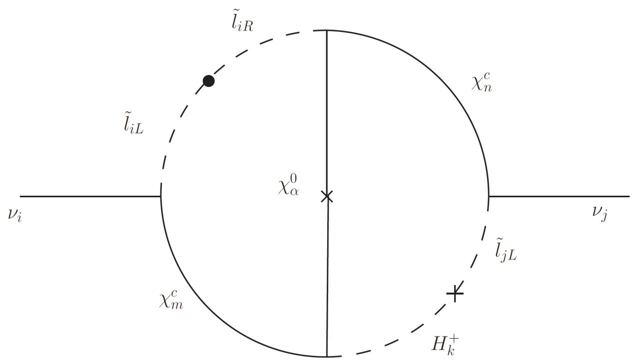
$$[m_\nu]^{S,\tilde{B}\tilde{B}}_{ij} = \sum_\alpha \frac{\mu^{\tilde{B}}_{i\alpha}\mu^{\tilde{B}}_{j\alpha}}{m_{\chi^0_\alpha}} \approx \sum_{k,k'} \frac{27}{512\pi^4} g^4 \frac{\tilde{B}_{ik}\tilde{B}_{jk'}}{\tilde{m}^3}$$

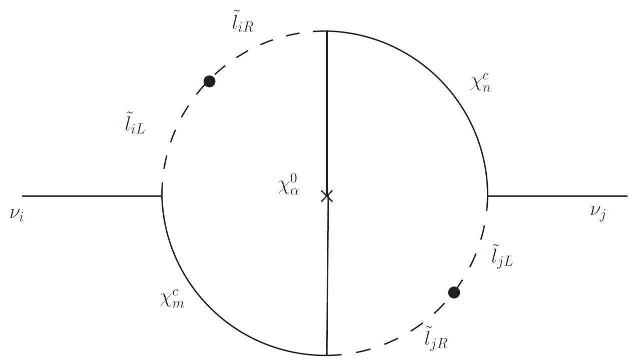
Supression factors:

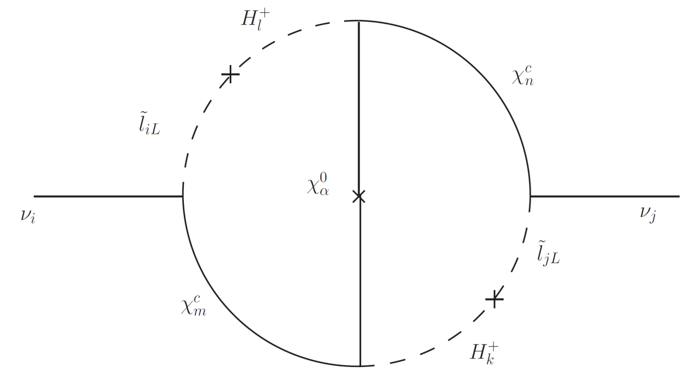
2RPV COUPLINGS+2LOOP FACTOR+ 2 lepton Yukawas / 1 lepton Yukawa / 0 lepton Yukawa

Contributions from new term

NON- SEPARABLE TWO LOOP DIAGRAMS







Complicated loop functions involving fermionic propagators → solved numerically

$$[m_\nu]^{\mathrm{NS},\tilde{\lambda}\tilde{\lambda}}_{ij} \approx \frac{60.48}{256\pi^4} g^2 \tilde{\lambda}^*_i \tilde{\lambda}^*_j \frac{m_{l_i} m_{l_j}}{\tilde{m}}$$

$$[m_\nu]^{\mathrm{NS},\tilde{\lambda}\tilde{B}}_{ij} \approx -\sum_k \frac{15.12}{256\pi^4} g^3 \tilde{\lambda}^*_i \tilde{B}_{jk} \frac{m_{l_i}}{\tilde{m}^2}$$

$$[m_\nu]^{\mathrm{NS},\tilde{B}\tilde{B}}_{ij} \approx \sum_{k,l} \frac{3.80}{256\pi^4} g^2 \frac{\tilde{B}_{il}\tilde{B}_{jk}}{\tilde{m}^3}$$

Supression factors:

2RPV COUPLINGS+2LOOP FACTOR+ 2 lepton Yukawas / 1 lepton Yukawa / 0 lepton Yukawa

Summary

Neutrino masses in RPV MSSM

- RPV SUSY models provide an alternative to usual seesaw mechanism

- Naturally generate mild hierarchichal masses with large mixing angles: only one neutrino gets mass at tree level

- Need small RPV couplings: several suppression factors
  relative importance?

Neutrino masses in RPV SUSY with extra HD

- Adding pairs of Higgs doublets makes a new term HHE: contributes at two loops

- The extra pairs of Higgs doublets do not change the fact that only one neutrino gets mass at tree level

- The lepton Yukawa coupling controls the suppression
  If the couplings are of the same order, it governs the suppression
  If λ is the only significant coupling, it always comes with a Yukawa

The results here exposed can be extended to similar models like dRPV


THANK YOU!

DOUBLE BETHA DECAY: