Neutrino masses in RPV models with extra pairs of Higgs doublets

arXiv:1401.1818
work in collaboration with Y. Grossman

Joint Particle Seminar, UC Irvine

Clara Peset
11th April, 2014
Outline

- Motivation for the model
  - why supersymmetry?
  - why RPV?
  - why neutrinos?
  - why 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
NEUTRINO MASSES

SUSY

with

R-parity violation

and

extra pairs of Higgs doublets
Why SUSY?

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 $\quad$ scalar masses protected $\quad$ mass of the Higgs boson arises naturally

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

Simplest models should have been/be detected at LHC!
I. The Model: SUSY

MSSM: \[ m_H^2 \approx m_Z^2 + \text{loop corrections} \]

\[ m_{\tilde{t}} \approx 400 \ GeV, \ m_{\tilde{g}} \approx 800 \ GeV, \ m_{\tilde{W}} \approx 1 \ TeV \]

size of tree level!
I. The Model: SUSY

**SUSY @ LHC**

**ATLAS SUSY Searches** - 95% CL Lower Limits

Status: Moriond 2014

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**ATLAS** Preliminary

$\sqrt{s} = 7, 8$ TeV

**$\sqrt{s} = 7$ TeV full data**

$\sqrt{s} = 8$ TeV partial data

$\sqrt{s} = 8$ TeV full data
I. The Model: SUSY

**MSSM:**

\[ m_H^2 \approx m_Z^2 + \text{loop corrections} \]

\[ m_{\tilde{t}} \approx 400 \text{ GeV}, \ m_{\tilde{g}} \approx 800 \text{ GeV}, \ m_{\tilde{W}} \approx 1 \text{ TeV} \]

size of tree level!

**No panic!**

still large amount of data to analyze

&

second round of LHC

&

other models to explore

(RPV, non-minimal models...)

**KEEP CALM AND LOOK FOR SUSY**
Why RPV?

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

- Proton decay @ dim 5
- Neutral stable fermion \(\rightarrow\) cold DM candidate \(\chi^0\)

**NOT NECESSARY FOR NATURALNESS!**

**R-Parity violation:**

\(\chi^0 \rightarrow\) SM particles \(\rightarrow\) NO need for MET @ LHC searches!

**RPV searches:** distinctive final states with many particle states

\[\text{high jet or lepton activity}\]
### RPV SUSY @ LHC

#### ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** Moriond 2014  
**ATLAS Preliminary**  
**$\mathcal{L} dt = (4.6 - 22.9)$ fb$^{-1}$**  
**$\sqrt{s} = 7, 8$ TeV**

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*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus $1\sigma$ theoretical signal cross section uncertainty.*
I. The Model: RPV

Why RPV?

New RPV terms in the superpotential:

\[ W = -\mu \hat{L}_I \hat{H}_U + \frac{1}{2} \lambda_{IJm} \hat{L}_I \hat{L}_J \hat{E}_m + \chi'_{Imn} \hat{L}_I \hat{Q}_n \hat{D}_m + \frac{1}{2} \chi''_{Imn} \hat{D}_I \hat{D}_m \hat{Q}_n \]

L-number violation

B-number violation

Plus soft SUSY breaking

Lots of new parameters! general predictions become difficult

Generally allows for proton decay! ONLY lepton RPV or ONLY baryon RPV

Other constrains from constrains from:

- $n \rightarrow \bar{n}$
- $\mu \rightarrow e$

Small RPV parameters

Leptonic RPV majorana neutrino masses arise naturally! $\Delta L = 2$
Why neutrinos?

I. The Model: neutrinos

Neutrinos' small masses are a BIG enigma

- Sun neutrinos reaching the Earth
  \[ 7 \times 10^9 \text{ cm}^{-2} \text{s}^{-1} \]
- Contribute to the total energy of the universe as much as all the stars combined

Neutrino masses **not** within SM

Neutrinos oscillate:

- Flavor basis \( \neq \) mass basis

Majorana neutrinos:

\[ \overline{\nu} \equiv \nu \]

- dim 5 op in SM \( \rightarrow \) probe for GUT scales
- leptogenesis...
- detection double \( \beta \)-decays
  
  yet to be achieved

Cowen, Reines '56
Why neutrinos?

Neutrino experimental data:

\[ \Delta m_{32}^2 = (2.32^{+0.12}_{-0.08}) \times 10^{-3} \text{ eV}^2, \quad \Delta m_{21}^2 = (7.5 \pm 0.20) \times 10^{-5} \text{ eV}^2, \]

\[ \sin^2(2\theta_{32}) > 0.95, \quad \sin^2(2\theta_{12}) = 0.857 \pm 0.024, \quad \sin^2(2\theta_{13}) = 0.095 \pm 0.010 \]

From: solar, detector & atmospheric neutrino experiments

Opposite to flavor mixing in quarks!

Exhibits:
- mild mass hierarchy
- 2 large mixing angles
+ 1 smaller angle

Matrix determinant

>>

Matrix elements

Naturally if masses come from different sources
Extra Higgs doublets

Breaking the spectrum:
- more possibilities for s-partners mass spectrum  → detection @ LHC
- rise Higgs mass without fine tuning  → Sister Higgs

General Issues:
- FCNC arise
\[
\chi_{Imm} \hat{l}_i \hat{Q}_j \hat{D}_m
\]
- New RPV term
\[
\frac{\lambda_m}{2} \epsilon_{ij} \left( \hat{H}^i_{D_1} \hat{H}^j_{D_2} - \hat{H}^i_{D_2} \hat{H}^j_{D_1} \right) E_m
\]
Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons \rightarrow \text{Indistinguishable!}

MSSM:

\[ \hat{L}_\mu = (\hat{H}_D, \hat{L}_1, \hat{L}_2, \hat{L}_3) \]

RPV terms:

\[ W = \epsilon_{ij} \left[-\mu_\alpha \hat{L}_\alpha^i \hat{H}_U^j + \frac{1}{2} \lambda_{\alpha \beta m} \hat{L}_\alpha^i \hat{L}_\beta^j \hat{E}_m + \lambda'_{\alpha mn} \hat{L}_\alpha^i \hat{Q}_n^j \hat{D}_m \right] \]

\[ V_{\text{soft}} = (M^2_L)_{\alpha \beta} \hat{L}_\alpha^i \hat{L}_\beta^i - \left(\epsilon_{ij} B_{\alpha} \hat{L}_\alpha^i \hat{H}_U^j + \text{h.c.}\right) + \epsilon_{ij} \left[\frac{1}{2} \lambda_{\alpha \beta m} \hat{L}_\alpha^i \hat{L}_\beta^j \hat{E}_m + \lambda'_{\alpha mn} \hat{L}_\alpha^i \hat{Q}_n^j \hat{D}_m + \text{h.c.}\right] \]

EWSB characterized by:

\[ v_u, \quad v_d = \left(\sum v_{\alpha}^2\right)^{1/2}, \quad \mu = \left(\sum \mu_{\alpha}^2\right)^{1/2} \]

\[ v \equiv (|v_u|^2 + |v_d|^2)^{1/2} = \frac{2m_W}{g} = 246 \text{ GeV} \]
Neutrinos in RPV SUSY

Higgs down has the same quantum numbers as leptons \[ \hat{L}_I = (\hat{H}_{D_1}, \hat{H}_{D_2}, \hat{L}_1, \hat{L}_2, \hat{L}_3) \]

Indistinguishable!

SUSY with extra pair of Higgses:

RPV terms:

\[
W = \epsilon_{ij} \left[ -\mu_{1I} L_I^i \hat{H}_{U_1}^i - \mu_{2I} L_I^i \hat{H}_{U_2}^i + \frac{1}{2} \lambda_{Ijm} L_I^i \hat{L}_J^j \hat{E}_m + \chi_{Imn} L_I^i \hat{Q}_n^j \hat{D}_m \right]
\]

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

EWSB characterized by:

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

\[
v \equiv \left( |v_u|^2 + |v_d|^2 \right)^{1/2} = \frac{2m_W}{g} = 246 \text{ GeV}
\]
II. Neutrinos in RPV SUSY: tree level mass

TL Neutrino mixing matrix

Neutrino – neutralino mixing

MSSM:

Mixing matrix

\[
M^N = \begin{pmatrix}
M_1 & 0 & m_Z s_W \hat{v}_u & -m_Z s_W \hat{v}_\alpha \\
0 & M_2 & -m_Z c_W \hat{v}_u & m_Z c_W \hat{v}_\alpha \\
m_Z s_W \hat{v}_u & -m_Z c_W \hat{v}_u & 0 & \mu_\alpha \\
-m_Z s_W \hat{v}_\alpha^T & m_Z c_W \hat{v}_\alpha^T & \mu_\alpha^T & 0_{3 \times 3}
\end{pmatrix}
\]

Basis: \( \{ \tilde{B}, \tilde{W}^3, \tilde{H}_U, \nu_\alpha \} \)

Product of non-zero eigenvalues

\[
\det' M^N = \mu^2 v_d^2 \sin^2 \xi
\]

4D-vectors

small RPV

\[\xi^2 \lesssim \frac{m_3}{m}\]
II. Neutrinos in RPV SUSY: tree level mass

TL Neutrino masses

Diagonalize $M$ to obtain the neutrino mass matrix:

\[ M^N = \begin{pmatrix} M_{4 \times 4} & \mu_{4 \times 3} \\ \mu_{3 \times 4}^T & 0_{3 \times 3} \end{pmatrix} \implies U M^N U^+ = \begin{pmatrix} M'_{4 \times 4} & 0_{4 \times 3} \\ 0_{3 \times 4} & m_{\nu_{3 \times 3}} \end{pmatrix} \]

Seesaw mechanism

MSSM:

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

\[ m_{\nu_{3 \times 3}} = \mu^T M^{-1} \mu \]

\[ m_3 = X \mu^2, \quad m_1 = m_2 = 0 \]

\[ X \equiv \frac{m_{\gamma} m_Z^2 \cos^2 \beta}{\mu (m_Z^2 m_{\gamma} \sin 2\beta - M_1 M_2 \mu)} \sim \frac{\cos^2 \beta}{\tilde{m}} \]
II. Neutrinos in RPV SUSY: tree level mass

TL Neutrinos mixing matrix

Neutrino – neutralino mixing

\[ M^N = \begin{pmatrix}
M_1 & 0 & m_{ZSW} \hat{\nu}_{u_1} & m_{ZSW} \hat{\nu}_{u_2} & -m_{ZSW} \hat{\nu}_{I} \\
0 & M_2 & -m_{ZCW} \hat{\nu}_{u_1} & -m_{ZCW} \hat{\nu}_{u_2} & m_{ZCW} \hat{\nu}_{I} \\
 m_{ZSW} \hat{\nu}_{u_1} & -m_{ZCW} \hat{\nu}_{u_1} & 0 & 0 & \mu_1 \\
 m_{ZSW} \hat{\nu}_{u_2} & -m_{ZCW} \hat{\nu}_{u_2} & 0 & 0 & \mu_2 \\
-m_{ZSW} \hat{\nu}_I^T & m_{ZCW} \hat{\nu}_I^T & \mu_1^T & \mu_2^T & 0_{5 \times 5}
\end{pmatrix} \]

SUSY with extra pair of Higgses:

Basis: \( \{ \tilde{B}, \tilde{W}^3, \tilde{H}_U, \tilde{H}_U, \nu_I \} \)

Product of non-zero eigenvalues

\[ \det'M^N = 2 \frac{m_{\tilde{Z}}^2}{v^2} \frac{m_{\tilde{\mu}}^2}{v_d} \mu_1^2 \mu_2^2 \sin^2 \chi \sin^2 \xi. \]
II. Neutrinos in RPV SUSY: tree level mass

**TL Neutrino masses**

Diagonalize $M$ to obtain the neutrino mass matrix:

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

**Seesaw mechanism**

SUSY with extra pair of Higgses:

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

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

**rank 1 matrix**

$$ m_3 = \frac{X}{\Delta \mu^2} \mu_1^2 \mu_2^2 \sin^2 \chi \sin^2 \xi, \quad m_1 = m_2 = 0 $$
III. Neutrinos in RPV SUSY: loop contributions

Loop contributions: $\lambda \lambda$ loops

MSSM:

$$[m_\nu]_{ij}^{(\lambda' \lambda')} \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda'_{il} \lambda'_{jk} \frac{m_{dl}}{m_{dk}} \frac{\Delta m^2_{dk}}{m^2_{dk}} \approx \sum_{l,k} \frac{3}{8\pi^2} \lambda_{il} \lambda_{jk} \frac{m_{dl} m_{dk}}{\tilde{m}}$$

neglecting quark/lepton mixings

Supression factors:

2RPV COUPLINGS + LOOP FACTOR + 2 QUARK MASSES

Irrelevant in most cases

Grossman, Rakshit '04
III. Neutrinos in RPV SUSY: loop contributions

Loop contributions: $\lambda \lambda$ loops

SUSY with extra pair of Higgses:

$$\delta m_{\nu_{ij}} \approx \frac{1}{8\pi^2} \sum_{n,k} \lambda_{ink} \lambda_{jkn} \frac{m_{l_n} \Delta m_{l_k}^2}{m_{l_k}^2}$$

neglecting quark/lepton mixings

Supression factors:

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

Irrelevant in most cases
III. Neutrinos in RPV SUSY: loop contributions

Loop contributions: BB loops

MSSM:

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

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS

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

\[
m_Z^2 - m_h^2 = m_H^2 - m_A^2.
\]

Grossman, Rakshit '04
Loop contributions: BB loops

\[ \delta m_{\nu_{ij}}^{BB} = \sum_{\alpha} \frac{g^2}{4} \left( Z_N^{0\alpha} - \frac{g'}{g} Z_N^{1\alpha} \right)^2 \left[ \tilde{B}_{ih} \tilde{B}_{jh} I_4(m_h, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \right] \]

\[ + \sum_k \tilde{B}_{iH_k} \tilde{B}_{jH_k} I_4(m_{H_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) + \sum_k \tilde{B}_{iA_k} \tilde{B}_{jA_k} I_4(m_{A_k}, m_{\tilde{\nu}_i}, m_{\tilde{\nu}_j}, m_{\chi_\alpha}) \]

Enlarged Higgs-like spectrum:

\[ \frac{i}{\sqrt{2}} \tilde{B}_{i}\{h, H_j, A_j\} \equiv \frac{i}{\sqrt{2}} \left[ B_{1i}\{Z_R^{00}, Z_R^{0j}, iZ_H^{0j}\} + B_{2i}\{Z_R^{10}, Z_R^{1j}, iZ_H^{1j}\} \right. \]

\[ \left. + (M_L^2)_{0(1+i)}\{Z_R^{20}, Z_R^{2j}, iZ_H^{2j}\} + (M_L^2)_{1(1+i)}\{Z_R^{30}, Z_R^{3j}, iZ_H^{3j}\} \right] \]

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS
Loop contributions: \(\mu B\) loops

MSSM:

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

(average expression)

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

\[
[m_\nu]^{(\mu\mu)} = C_{\mu i \mu j} \quad \rightarrow \quad \frac{m_1}{m_2} \sim O(\varepsilon_L^2)
\]

\[
[m_\nu]^{(V\mu)} = C_{\mu i j} \varepsilon_L(V_i U_j + V_j U_i) \quad \rightarrow \quad \frac{m_1}{m_2} \sim O(\varepsilon_L)
\]

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS
Loop contributions: $\mu B$ loops

SUSY with extra pair of Higgses:

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

$$+ \tilde{\mu}_{j\alpha} \tilde{B}_{ih} + \sum_k \tilde{\mu}_{j\alpha} \tilde{B}_{iH_k} + \sum_k \tilde{\mu}_{j\alpha} \tilde{B}_{iA_k}$$

- subleading in $\mu$ with respect to the tree level (if tree level is dominant)

Supression factors:

2RPV COUPLINGS+LOOP FACTOR+CANCELLATIONS
IV. Neutrinos in RPV SUSY: new term contributions

Contributions from new term

\[
\frac{\lambda_m}{2} \epsilon_{ij} \left( \hat{H}_D^i \hat{H}_D^j - \hat{H}_D^i \hat{H}_D^j \right) \hat{E}_m
\]

less constrained than usual RPV couplings

NO ONE LOOP EFFECTS

No neutrinos involved in the vertex
RPV in charged sector

Topological argument:
IV. Neutrinos in RPV SUSY: new term contributions

Contributions from new term

SEPARABLE TWO LOOP DIAGRAMS

\[ [m_\nu]^{S,\lambda\lambda}_{ij} = \sum_\alpha \frac{\mu_i^{\lambda} \mu_j^{\lambda}}{m_{\chi_\alpha^0}} \approx \frac{27}{32\pi^4} g^2 \tilde{\lambda}_i \tilde{\lambda}_j \frac{m_{ij} m_{ij}}{\tilde{m}} \]

\[ [m_\nu]^{S,\lambda B}_{ij} = \sum_\alpha \frac{\mu_i^{\lambda} \mu_j^{\lambda}}{m_{\chi_\alpha^0}} \approx \sum_k \frac{27}{128\pi^4} g^3 \tilde{\lambda}_i \tilde{B}_{jk} m_{ij} + \tilde{\lambda}_j \tilde{B}_{ik} m_{ij} \]

\[ [m_\nu]^{S,BB}_{ij} = \sum_\alpha \frac{\mu_i^{\lambda} \mu_j^{\lambda}}{m_{\chi_\alpha^0}} \approx \sum_{k,k'} \frac{27}{512\pi^4} g^4 \tilde{B}_{ik} \tilde{B}_{jk'} \]

Suppression factors:

- $2$ lepton Yukawas
- $1$ lepton Yukawa
- $0$ lepton Yukawa

2RPV COUPLINGS + 2LOOP FACTOR +
IV. Neutrinos in RPV SUSY: new term contributions

Contributions from new term

NON-SEPARABLE TWO LOOP DIAGRAMS

Complicated loop functions involving fermionic propagators

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

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

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

Suppression factors:

<table>
<thead>
<tr>
<th>2RPV COUPLINGS+2LOOP FACTOR+</th>
<th>2 lepton Yukawas</th>
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<tbody>
<tr>
<td></td>
<td>1 lepton Yukawa</td>
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<tr>
<td></td>
<td>0 lepton Yukawa</td>
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</tbody>
</table>
Conclusions: neutrino masses in RPV MSSM

- RPV SUSY models provide an alternative to usual seesaw mechanism
- Naturally generate mild hierarchical masses with large mixing angles
- Need small RPV couplings
- One neutrino has a tree level mass, while the other two just from loop effects
- Several suppression factors relative importance is model dependent
Conclusions: neutrino masses in RPV extra HD

- Adding pairs of Higgs doublets makes a new term HHE, which is forbidden in the MSSM arise in the superpotential

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

- The new term containing two Higgses starts contributing at two loops

- We find that there is a new parameter that controls the suppression, the lepton Yukawa coupling

  If the couplings are of the same order, it governs the suppression
  If $\lambda$ is the only significant coupling, it always comes with a Yukawa
FUTURE PERSPECTIVES

- SUSY needs to be further tested before it can be “ruled out”
  need to analyze more data, more processes, more models...

- Neutrino masses are still one of the most interesting enigmas in particle physics
  their small masses can constrain the parameters of different models

- The results here exposed can be extended to similar models, and are not only
  valid when the doublet is just a copy of the MSSM one
  for example, they could be relevant in the case of dRPV
THANK YOU!
IV. Future prospective