Exploring neutrino masses and mixing in R-Parity Violating supersymmetric models

Arpita Mondal

Department of Physics, Indian Institute of Technology Patna, 801106, India

Frontiers in Particle Physics

9 August, 2024

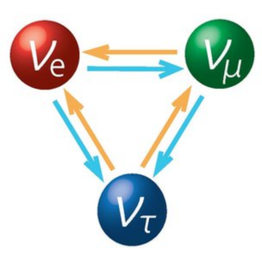
Outline

- Introduction of Model
- Bilinear RPV SUSY model
  - Neutrino mass generation
  - Observables and constraints
  - Parameters
  - Analysis details
  - Results and discussion
- Trilinear RPV model
  - Parameters
  - Results

Existence of neutrino mass

- Neutrino oscillation $\rightarrow$ one of the most robust indications towards the existence of physics BSM
- Within Standard Model (SM) framework neutrino is massless $\rightarrow$ no right handed neutrino
- No neutrino mass from RPC MSSM $\rightarrow$ leads to RPV MSSM
- R-parity, $R_p = (-1)^{(3B-2L+S)}$

Neutrino oscillation



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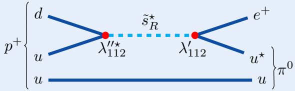


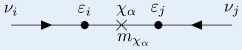
- $W_{\not{R}_p} = \varepsilon_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j \overline{e}_k + \lambda'_{ijk} L_i Q_j \overline{d}_k + \frac{1}{2}\lambda''_{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$
- Two separate analyses - lepton number violating Bilinear RPV model and Trilinear RPV model

Bilinear Model definition

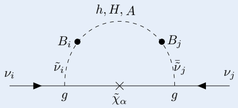
Bilinear R-Parity violating Superpotential

$$W_{\not{R}_p} = \varepsilon_i L_i H_u; \quad \mathcal{L}_{\not{R}_p} = [\varepsilon_i(\tilde{H}_u^0 \nu_{iL} - \tilde{H}_u^+ l_{iL})]; \quad \mathcal{L}_{soft} = B_i \tilde{L}_i H_u$$

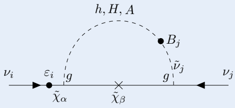
Tree and loop level diagrams



Tree level



BB loop



ϵB loop

- Only one neutrino becomes massive at tree level $\rightarrow$ The highest neutrino mass eigenstate
- BB loop is the dominant one
- Second mass becomes heavy mainly from BB loop
- Lowest mass eigenstate will become heavy from ϵB loop

Grossman and Rakshit, Phys.Rev.D 69 (2004) 093002

Observables

Neutrino observables

- Two mass square splitting values (Δm^2_{21} and Δm^2_{31})
- Three mixing angles (θ_{12}, θ_{13}, θ_{23})

Source: JHEP 02 (2021) 071.

Constraints from Higgs

- Higgs Mass: We have considered ± 3 GeV as theoretical uncertainty around 125 GeV. Phys. Rev. Lett. 114 191803 (2015)
- Higgs coupling strength data from LHC at $\sqrt{s} = 13$ TeV $\rightarrow$ Higgs coupling to Z, W, b, t, μ, τ, and γ particle. CMS-PAS-HIG-19-005, 2020

Constraints from flavor physics

- rare b-hadron decays as $\mathcal{B}(B \rightarrow X_s + \gamma)$ and $\mathcal{B}(B_s^0 \rightarrow \mu^+ + \mu^-)$ Eur. Phys. J. C 81 226 (2021) and Phys. Rev. Lett. 128 041801 (2022)

- Total 15 observables

Parameters

- Considered minimal set of parameters

List of fixed parameters

M_1 = 300 GeV
M_2 = 1.2 TeV
M_3 = 3 TeV
M_A = 3 TeV

$M_{\tilde{q}}$ = 3 TeV
$M_{\tilde{l}}$ = 2 TeV
A_t = -3.5 TeV

Range of input parameters for scanning

From literature study we came up with some exhaustive range of each parameter such as

μ: 1 to 3 TeV
$\tan\beta$: 1 to 60
$\varepsilon_i(i = 1, 2, 3)$: -1.0 to 1.0 GeV
$B_i(i = 1, 2, 3)$: 0.1 GeV to 10 TeV
$v_i(i = 1, 2, 3)$: 10^{-8} to 0.1 GeV

- So we have total 11 free parameters

Analysis details

- For scanning we use Markov Chain Monte Carlo (MCMC) based likelihood analysis → `emcee` (Publications of the Astronomical Society of the Pacific, 125 306 (2013))

- We find the maximum likelihood function $L \propto \exp(-\mathcal{L})$

- Log likelihood $\mathcal{L} = \frac{\chi^2}{2} = \frac{1}{2}\sum_{i=1}^{n_{\rm obs}} \left[\frac{\Gamma_i^{\rm obs} - \Gamma_i^{\rm th}}{\sigma_i}\right]^2$

- Maximum likelihood means we find the minimum χ^2

- Degrees of freedom(D.O.F) = 15 independent observables - 11 free parameters = 4

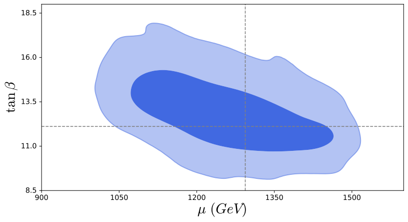
- We use a flat prior on all the parameters

- We use 500 walkers and 400 steps for each walker. Total sample generated = $500 \times 400 \times n_{core} = 200000 \times n_{core}$

Results - Normal Hierarchy ($\nu_3 > \nu_2 > \nu_1$)

- We have got χ^2_{min} = 3.46
- $\sum m_{\nu_i} = 0.059$ eV $\rightarrow$ satisfies $\rightarrow \sum m_{\nu_i} < 0.12$ eV

$\mu - \tan\beta$ contour

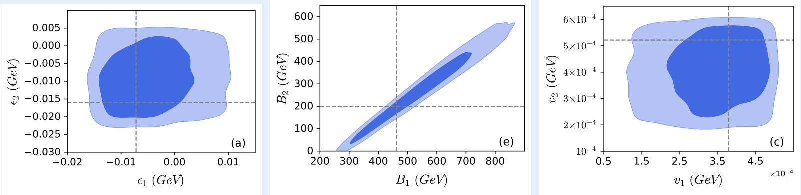


- $[m_\nu]_{ij}^{(\varepsilon\varepsilon)} \propto \frac{1}{\mu \tan^2\beta}$
- $[m_\nu]_{ij}^{(BB)} \propto \tan^2\beta$
- $[m_\nu]_{ij}^{(\varepsilon B)} \propto \tan\beta$

- Tree level $\rightarrow$ only third neutrino
- BB loop $\rightarrow$ second neutrino
- ϵB loop $\rightarrow$ first neutrino
- From theory $\tan\beta$ should not be large or very low
- It also depends on the choice of M_A and A_t parameters
- Most stringent limit comes from neutrino oscillation data

Results - Normal Hierarchy ($\nu_3 > \nu_2 > \nu_1$)

Contour plots



- $m_{highest} \propto \left(\epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2\right) \sin^2 \xi$, ξ represents alignment between ϵ_i and υ_i (JHEP 02 (2024) 004)
- Heaviest one is τ flavored $\rightarrow$ ϵ_3 and υ_3 should be largest one
- Also it has next to zero admixture of electron neutrino $\rightarrow$ ϵ_1 and υ_1 should be lowest one
- $m_2 \propto B_i B_j$ and $m_1 \propto \epsilon_i B_j + \epsilon_j B_i$
- Second one has comparable admixture of all three neutrino flavors $\rightarrow$ nice correlations among B_i parameters

Results - Normal Hierarchy ($\nu_3 > \nu_2 > \nu_1$)

- Loop contributions are already suppressed and $\tan\beta$ is already restricted by tree level mass
- For these contributions to neutrino masses to be significant, the B_i parameters have to be much larger compared to ϵ_i parameters
- ϵB loop contribution is further suppressed due to their dependence on ϵ_i
- As a result, B_1 is expected to be relatively larger than B_2 since the lightest state is dominantly electron neutrino-like
- B_3 will have larger value compared to others

Best-fit point

ϵ_1 = -0.0072	υ_1 = 0.00038	B_1 = 461	μ = 1293
ϵ_2 = -0.0160	υ_2 = 0.00052	B_2 = 198	$\tan\beta$ = 12
ϵ_3 = -0.0279	υ_3 = 0.00091	B_3 = 1760	

All are in GeV unit except $\tan\beta$ (JHEP 02 (2024) 004)

Results - Inverted Hierarchy ($\nu_2 > \nu_1 > \nu_3$)

- χ^2_{min} =3.38 and $\sum m_{\nu_i} = 0.1$ eV $\rightarrow$ satisfies $\rightarrow$ $\sum m_{\nu_i} < 0.15$ eV
- Second one is heaviest $\rightarrow$ an almost equal admixture of all three neutrino flavors
- ϵ_2 and υ_2 have largest values
- ν_1 is the second heaviest one and have larger values than NH scenario $\rightarrow$ larger B_1 and B_2 values required
- As neutrino oscillation parameters are more constraint in IH scenario $\rightarrow$ allowed parameter space is also more constraint

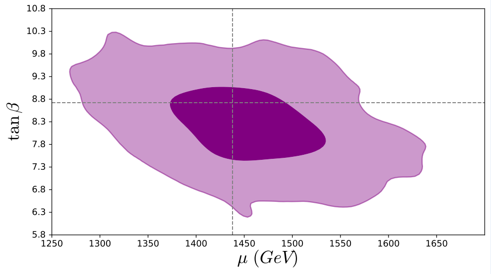
Best-fit point

ϵ_1 = -0.0216	υ_1 = 0.00086	B_1 = 894	μ = 1437
ϵ_2 = -0.0833	υ_2 = 0.00140	B_2 = 982	$\tan\beta$ = 8
ϵ_3 = -0.0499	υ_3 = 0.00110	B_3 = 1609	

All are in GeV unit except $\tan\beta$ (JHEP 02 (2024) 004)

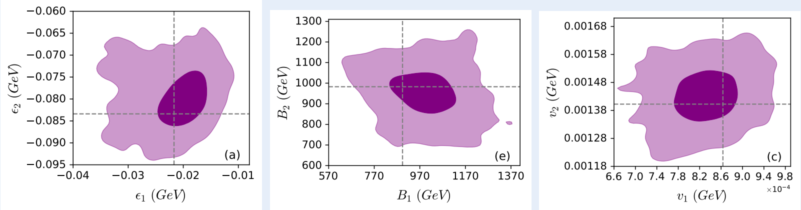
Results - Inverted Hierarchy ($\nu_2 > \nu_1 > \nu_3$)

$\mu - \tan\beta$ contour



- $[m_\nu]_{ij}^{(\varepsilon\varepsilon)} \propto \frac{1}{\mu \tan^2\beta}$
- ν_3 has lowest mass $\rightarrow$ μ must have larger value than NH scenario

Contour plots



(JHEP 02 (2024) 004)

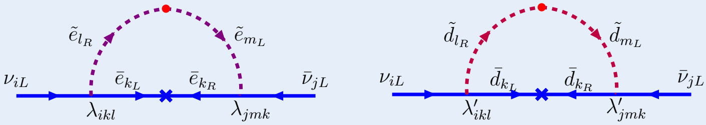
Trilinear Model

Superpotential

$$W_{\not{L}} = \frac{1}{2}\lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k$$

λ_{ijk} is antisymmetric $\rightarrow$ 9 λ_{ijk} + 27 λ'_{ijk} parameters

Loop diagrams



- Due to fermion mass hierarchy, we consider only third generation couplings λ_{i33} and λ'_{i33}
- $M_\nu = \frac{1}{8\pi^2 \tilde{m}}[\lambda_{i33}\lambda_{j33}\ m_\tau^2 + 3\lambda'_{i33}\lambda'_{j33}\ m_b^2]$
- Leading contribution to heaviest neutrino $m_{\nu_3} = \frac{3m_b^2}{8\pi^2 \tilde{m}} \sum_i \lambda'^2_{i33}$

Parameters space

- we have 2 λ_{i33} $(i = 1, 2)$ and 3 λ'_{i33} $(i = 1, 2, 3)$ parameters
- We also consider μ and $\tan\beta$ as before
- Total 7 parameters
- We have added one other observable $B \to \tau\nu$
- we have 16 observables $\rightarrow$ d.o.f = 9

Range of parameters

$|\lambda_{i33}|(i = 1, 2)$: 0 - 0.001 GeV

$|\lambda'_{i33}|(i = 1, 2, 3)$: 0 - 0.001 GeV

μ = 1000 - 3000 GeV

$\tan\beta$ = 1 - 60

- only LLE coupling $\rightarrow$ Δm^2_{31} and θ_{12}
- only LQD coupling $\rightarrow$ can satisfy all except Δm^2_{21}

Results - Normal hierarchy ($\nu_3 > \nu_2 > \nu_1$)

- The minimum χ^2 we obtained 4.14 for d.o.f 9
- It also satisfies the cosmological bound
- Here $m_{\nu_3} = \frac{3m_b^2}{8\pi^2\tilde{m}} \sum_i \lambda'^2_{i33}$
- λ'_{333} must have higher value than others
- Second and first neutrinos get masses mostly from λ_{i33} couplings $\rightarrow$ λ_{233} coupling must have larger value than λ_{133}

Best-fit point

$\lambda_{133} = 1.71 \times 10^{-4}$
$\lambda_{233} = 2.52 \times 10^{-4}$
$\mu = 1996$
$\tan\beta$ = 6.68

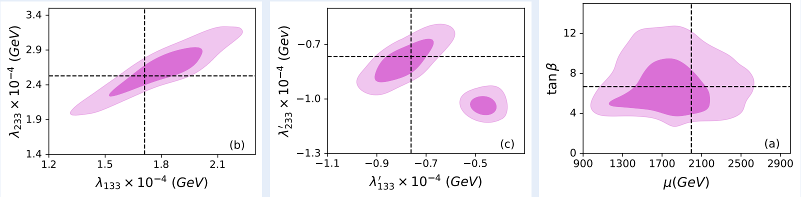
$\lambda'_{133} = -7.61 \times 10^{-5}$
$\lambda'_{233} = -7.65 \times 10^{-5}$
$\lambda'_{333} = -1.34 \times 10^{-4}$

All parameters are in GeV unit except $\tan\beta$

Results - Normal hierarchy

- With the λ_{i33} $(i = 1, 2)$, the bino-type LSP $(\widetilde{\chi}_1^0)$ decay final states $\rightarrow \tau^{\pm}e^{\mp}\nu$, $\tau^{\pm}\tau^{\mp}\nu$, and $\tau^{\pm}\mu^{\mp}\nu$
- λ'_{i33} $(i = 1, 2, 3) \rightarrow l + b + j$ and $2b + \not{E}_T$
- At the best-fit point branching fraction corresponding to λ_{i33} and λ'_{i33} coupling $\sim$ 83% and 17% respectively
- As the coupling values of λ_{i33} are larger than the values of λ'_{i33}, the branching ratio corresponding to the λ_{i33} coupling is also comparatively higher

contour plot



Results - Inverted hierarchy

- Minimum χ^2 obtained 4.56 for d.o.f 9
- Second one is the heaviest one $\rightarrow \lambda_{233}$ has the largest value than others
- Third neutrino gets mass from $\lambda'_{i33} \rightarrow \lambda'_{333}$ must have higher value and it is lower than NH scenario
- Lowest neutrino eigenstate has mass very close to second one and to get that higher mass we need contribution from both couplings $\rightarrow \lambda_{133}$ must have larger value as well as λ'_{133}
- the total branching ratio corresponding to λ_{i33} and λ'_{i33} couplings are 93% and 7% respectively due the larger values of LLE type RPV couplings than LQD type couplings.

Results - Inverted hierarchy

Best-fit point

$\lambda_{133} = 2.21 \times 10^{-4}$

$\lambda_{233} = 4.88 \times 10^{-4}$

$\mu = 1676$

$\tan\beta$ = 8.38

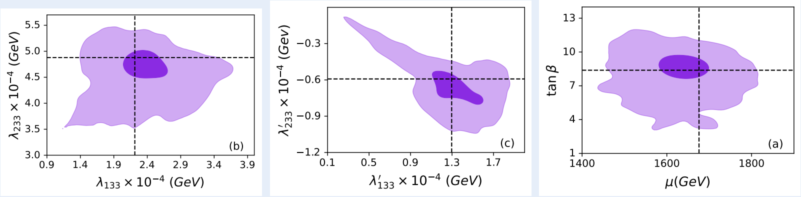
$\lambda'_{133} = 1.29 \times 10^{-4}$

$\lambda'_{233} = -5.92 \times 10^{-5}$

$\lambda'_{333} = -1.25 \times 10^{-4}$

All parameters are in GeV unit except $\tan\beta$

contour plot



The allowed parameter space for IH scenario is more constraint than NH scenario as BRPV model

Conclusion

- We have considered neutrino observables along with recent higgs data and flavor physics data
- We have done two separate analyses for Bilinear RPV and Trilinear RPV model
- To scan the parameter space we have used MCMC based likelihood analysis
- We obtained that the both the models can explain neutrino and other experimental data.
- We have also shown the allowed 1σ and 2σ region for each parameter space along with their correlation
- But the allowed parameter space is tightly constrained

THANK YOU

Collider constraints

Gluino search

- Limit is 2.0-2.5 TeV for various couplings $\rightarrow m_{\tilde{g}}$ = 3 TeV

Squark search

Limit is 0.8-1.9 TeV for different couplings $\rightarrow m_{\tilde{q}} = 3$ TeV (fixed)

Slepton search

- Limit is 0.86-1.2 TeV depending on couplings $\rightarrow$ all the slepton masses fixed at 3 TeV

Chargino search

- We have considered a scenario with bino-type LSP and wino-type NLSP
- $m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^\pm}$ excluded upto 1.14 TeV for λ_{i33} coupling
- We consider $m_{\tilde{\chi}_2^0}/m_{\tilde{\chi}_1^\pm}$ masses fixed at 1.2 TeV and $m_{\tilde{\chi}_1^0}$ = 300 GeV

Results with only LLE coupling

- Mass matrix for this model is $M_\nu|_\lambda = \frac{1}{8\pi^2\tilde{m}}\ \lambda_{i33}\lambda_{j33}\ m_\tau^2$
- After diagonalization only third neutrino becomes heavy, $m_{\nu_3} = \frac{m_\tau^2}{8\pi^2\tilde{m}} \sum_{i=1,2} \lambda_{i33}^2$
- $\sin\theta_{12} = \frac{\lambda_{133}}{\sqrt{\lambda_{133}^2+\lambda_{233}^2}}$
- This model can satisfy only Δm_{31}^2 and $\sin\theta_{12}$

Parameter	Value	Observable	Value	χ^2 contribution
λ_{133}	2.76×10^{-4}	Δm_{21}^2	4.15×10^{-13}	1162
λ_{233}	4.06×10^{-4}	Δm_{31}^2	2.56×10^{-3}	0.11
μ	2151	θ_{13}	7.67×10^{-25}	4305
$\tan\beta$	8.02	θ_{12}	34.27	0.001
		θ_{23}	90.0	2659

Results with only LQD couplings

- Mass matrix for this model $M_\nu|_{\lambda'} = \frac{3}{8\pi^2\tilde{m}} \lambda'_{i33}\lambda'_{j33}\, m_b^2$
- After diagonalization only third neutrino becomes heavy which is already mentioned before
- $\sin\theta_{13} = \frac{\lambda'_{133}}{\sum_{i=1,2,3}\lambda'^2_{i33}}$ and $\sin\theta_{23} = \frac{\lambda'_{233}}{\sum_{i=2,3}\lambda'^2_{i33}}$
- It can satisfy all the observables except Δm^2_{21} which is reflected in the result

Parameter	Value	Observable	Value	χ^2 contribution
λ'_{133}	-6.66$\times 10^{-5}$	Δm^2_{21}	6.55$\times 10^{-11}$	1162
λ'_{233}	-1.25$\times 10^{-4}$	Δm^2_{31}	2.61$\times 10^{-3}$	4.0
λ'_{333}	-1.21$\times 10^{-4}$	θ_{13}	8.74	2.60
μ	1867	θ_{12}	35.66	1.85
$\tan\beta$	7.73	θ_{23}	48.86	0.25

Trilinear mass matrix

$$M^{\nu}_{ij}|_{\lambda} = \frac{1}{16\pi^2}\sum_{k,l,m}\lambda_{ikl}\lambda_{jmk}\; m_{e_k}\,\frac{(\tilde{m}^{e^2}_{LR})_{ml}}{m^2_{\tilde{e}_{Rl}} - m^2_{\tilde{e}_{Lm}}}\; ln\left(\frac{m^2_{\tilde{e}_{Rl}}}{m^2\tilde{e}_{Lm}}\right) + (i \leftrightarrow j)$$

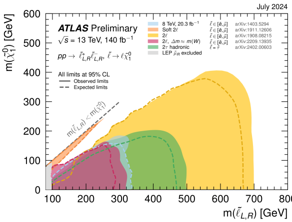
$$M^{\nu}_{ij}|_{\lambda'} = \frac{3}{16\pi^2}\sum_{k,l,m}\lambda'_{ikl}\lambda'_{jmk}\; m_{d_k}\,\frac{(\tilde{m}^{d^2}_{LR})_{ml}}{m^2_{\tilde{d}_{Rl}} - m^2_{\tilde{d}_{Lm}}}\; ln\left(\frac{m^2_{\tilde{d}_{Rl}}}{m^2\tilde{d}_{Lm}}\right) + (i \leftrightarrow j) \tag{1}$$

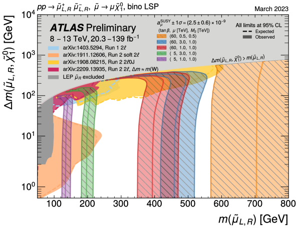
$$M^{\nu}_{ij}|_{\lambda} \simeq \frac{1}{8\pi^2}\,\frac{A^e - \mu\tan\beta}{\bar{m}^2_{\tilde{e}}}\sum_{k,l}\lambda_{ikl}\lambda_{jkl}\; m_{e_k}m_{e_l}$$

$$M^{\nu}_{ij}|_{\lambda'} \simeq \frac{3}{8\pi^2}\,\frac{A^d - \mu\tan\beta}{\bar{m}^2_{\tilde{d}}}\sum_{k,l}\lambda'_{ikl}\lambda'_{jkl}\; m_{d_k}m_{d_l} \tag{2}$$

Result - Anomalous muon magnetic moment

- $\Delta a_\mu = a_\mu^{Exp} - a_\mu^{SM} = (25.1 \pm 5.9) \times 10^{-10}$
- Sneutrino-chargino and slepton-neutralino loops contribution
- Lower the smuon masses keeping all other slepton masses decoupled





Input parameters			Output observables		
Parameters	BP-I	BP-II	Output	BP-I	BP-II
M_1 (GeV)	128	183	$m_{\tilde{\chi}_1^0}$ (GeV)	125	180
M_2 (GeV)	1200	1200	$m_{\tilde{\chi}_1^\pm}$ (GeV)	1198	1192
$m_{\tilde{\mu}_L}$ (GeV)	120	200	$m_{\tilde{\mu}_1}$ (GeV)	164	224
$m_{\tilde{\mu}_R}$ (GeV)	190	240	$m_{\tilde{\mu}_2}$ (GeV)	175	235
$\tan\beta$	13.75	11.94	Δa_μ ($\times 10^{-10}$)	**25.41**	**13.52**

Table: (JHEP 02 (2024) 004)