Neutrino masses and mixing angles in the context of bilinear R-parity violating supersymmetry

Arpita Mondal

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

Work done in collaboration with A. Choudhury, S. Mitra and S. Mondal

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Outline

- Model definition
- Motivation of this model
- Neutrino mass generation
- Observables and constraints
- Parameters
- Analysis details
- Results and discussion

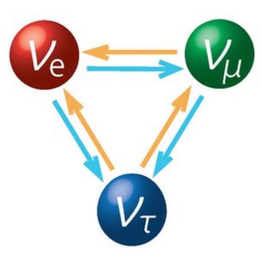
Existence of neutrino mass

- Neutrino oscillation $\rightarrow$ one of the most robust indications towards the existence of physics BSM

- Neutrino oscillation experiments $\rightarrow$ Super-Kamiokande, KamLAND, RENO

- Accelerator experiments like T2K, K2K, MINOS etc.

Neutrino oscillation



- Neutrino oscillation $\rightarrow$ tiny mass of neutrino and mixing

- 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 violating MSSM

R-Parity violating superpotential

$$W_{\not R_p} = \varepsilon_i L_i H_u + \lambda_{ijk} L_i L_j \overline{e}_k + \lambda'_{ijk} L_i Q_j \overline{d}_k + \lambda''_{ijk} \overline{u}_i \overline{d}_j \overline{d}_k$$

Motivation of considering only bilinear term

- We can generate neutrino mass by considering λ and λ' couplings
- They can generate neutrino mass at loop level only not at tree level
- Also their contribution to neutrino mass are Yukawa suppressed compared to contribution from bilinear term
- That's why we consider only bilinear term for our analysis

Model definition

Bilinear R-Parity violating Superpotential

$$W_{\not R_p} = \varepsilon_i L_i H_u$$

- $\varepsilon_i \rightarrow$ Bilinear R-parity violating coupling parameter
- L_i is lepton multiplet
- H_u is Higgs supermultiplet

Lagrangian and corresponding soft term

$$\mathcal{L}_{\not R_p} = [\varepsilon_i(\tilde{H}_u^0 \nu_{iL} - \tilde{H}_u^+ l_{iL})] + h.c$$

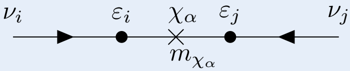
Corresponding soft terms

$$\mathcal{L}_{soft} = B_i \tilde{L}_i H_u + h.c$$

B_i is soft BRPV coupling

Tree level contribution

Tree level diagram

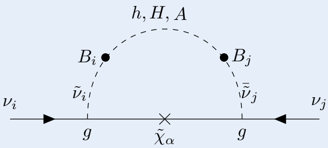


Tree level contribution to neutrino mass

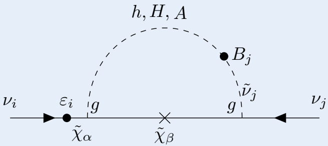
- Coupling between neutrino and up-type Higgsino
- 7×7 neutralino and neutrino mass matrix
- From the see-saw mechanism $\rightarrow$ From high mass of neutralino neutrinos get some tiny mass
- **Only one neutrino becomes massive at tree level**

Loop Contributions

Loop diagrams



a)BB loop generated neutrino mass



b)εB loop generated neutrino mass

- Sneutrino mix with different Higgs $\rightarrow$ produce splitting of sneutrino masses
- BB loop is the dominant one
- m_1 and m_2 become massive at loop level
- $[m_\nu]_{ij}^{(\varepsilon\varepsilon)} \propto \cos^2\beta \propto \frac{1}{\tan^2\beta}$
- $[m_\nu]_{ij}^{(BB)} \propto \frac{1}{\cos^2\beta} \propto \tan^2\beta$
- $[m_\nu]_{ij}^{(\varepsilon B)} \propto \frac{1}{\cos\beta} \propto \tan\beta$

Phys.Rev.D 69 (2004) 093002

Observables

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

Neutrino Observables

Observable	best fit value $\pm 1\sigma$
$\Delta m^2_{21}(10^{-5}\text{eV}^2)$	$7.50^{+0.22}_{-0.20}$
$\lvert\Delta m^2_{31}\rvert(10^{-3}\text{eV}^2)$(NH) $\lvert\Delta m^2_{31}\rvert(10^{-3}\text{eV}^2)$(IH)	$2.55^{+0.02}_{-0.03}$ $2.45^{+0.02}_{-0.03}$
$\theta_{12}/^\circ$	34.3 ± 1.0
$\theta_{13}/^\circ$(NH) $\theta_{13}/^\circ$(IH)	$8.53^{+0.13}_{-0.12}$ $8.58^{+0.12}_{-0.14}$
$\theta_{23}/^\circ$(NH) $\theta_{23}/^\circ$(IH)	49.26 ± 0.79 $49.46^{+0.60}_{-0.97}$

Source: JHEP 02 (2021) 071.

Constraints

Constraints from Higgs

- Higgs Mass: From experiment mass close to 125 GeV. Considered ± 3 GeV as theoretical uncertainty.

  Phys. Rev. Lett. 114 191803 (2015)

- Higgs coupling strength data at $\sqrt{s} = 13$ TeV collected with CMS experiment $\rightarrow$ 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

- Using these observables and constraints $\rightarrow$ try to constrain the parameter space of BRPV
- Also considered the recent collider constraints also
- Considered minimal set of parameters

List of fixed parameters

M_1 = 300 GeV
M_2 = 1.1 TeV
M_3 = 3 TeV
M_A = 3 TeV

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

- Now we have 2 MSSM parameters (μ and $\tan\beta$)
- 3 BRPV coupling parameters ($\varepsilon_1, \varepsilon_2, \varepsilon_3$)
- 3 soft coupling parameters (B_1, B_2, B_3)
- 3 vev parameters ($\upsilon_1, \upsilon_2, \upsilon_3$)
- So we have total 11 free parameters

Analysis details

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

Analysis details

- Generated model by using SARAH-4.14.5
- Output masses and mixing matrix generated by SPheno-4.0.4
- For scanning we use Markov Chain Monte Carlo(MCMC) based liklihood analysis
- Publicly available code which is a Python implementation of the ensemble sampler

  Publications of the Astronomical Society of the Pacific, 125 306 (2013)

- We use a flat prior on all the parameters
- We use 500 walkers and 400 steps for each walker

Analysis details

- We find the maximum liklihood function $L \propto \exp(-\mathcal{L})$
- Log liklihood $\mathcal{L} = \frac{\chi^2}{2} = \frac{1}{2}\sum_{i=1}^{n_{\rm obs}} \left[\frac{\Gamma_i^{\rm obs} - \Gamma_i^{\rm th}}{\sigma_i}\right]^2$
- $\Gamma_i^{\rm obs}$ represents the set of $n_{\rm obs}$ observed data points
- The corresponding errors σ_i for each data
- $\Gamma_i^{\rm th}$ is the calculated value of each observable using our theoretical model
- Maximum liklihood means we find the minimum χ^2 here
- Degrees of freedom(D.O.F) = 15 independent observables - 11 free parameters = 4

Results and discussion for NH scenario

Parameters at best-fit point

υ_1 = 3.37 $\times 10^{-4}$ GeV
υ_2 = 4.00 $\times 10^{-4}$ GeV
υ_3 = 9.66 $\times 10^{-4}$ GeV
ε_1 = -4.55 $\times 10^{-3}$ GeV
ε_2 = -8.86 $\times 10^{-3}$ GeV
ε_3 = -3.06 $\times 10^{-2}$ GeV

B_1 = 546.42 GeV
B_2 = 268.79 GeV
B_3 = 1932.49 GeV
μ = 1248.78 GeV
$\tan\beta$ = 12.48

- We have got χ^2_{min} = 3.47 and $\frac{\chi^2_{min}}{D.O.F}$ = 0.87
- Neutrino masses at the best-fit point are $m_{\nu_1} = 3.41 \times 10^{-6}$ eV, $m_{\nu_2} = 8.67 \times 10^{-3}$ eV and $m_{\nu_3} = 5.05 \times 10^{-2}$ eV
- $\sum m_\nu = 0.059$ eV $\rightarrow$ satisfies upper limit on the sum of neutrino masses coming from the cosmological data $\rightarrow$ $\sum m_\nu < 0.12$ eV

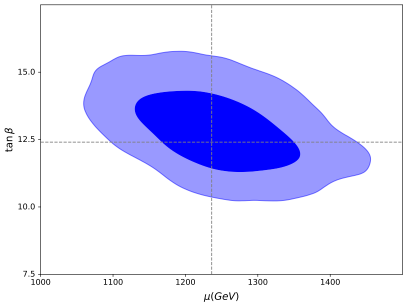
Results and discussion

Contribution to χ^2_{min} from each observable

	Observable	Best-fit value	χ^2 contribution	Total contribution
Neutrino observables	Δm^2_{21}	7.51×10^{-5}	2.1×10^{-3}	8.1×10^{-2}
	Δm^2_{31}	2.55×10^{-3}	2.45×10^{-2}	
	θ_{13}	8.54	7.29×10^{-3}	
	θ_{12}	34.40	1.06×10^{-2}	
	θ_{23}	49.10	3.43×10^{-2}	
Higgs Mass	m_h	124.70	9.5×10^{-3}	9.5×10^{-3}
Flavor Observales	$B \rightarrow X_s + \gamma$	3.14×10^{-4}	1.43	1.50
	$B_s \rightarrow \mu^+ + \mu^-$	3.21×10^{-9}	6.9×10^{-2}	
Higgs coupling	k_z	1.0	0.32	1.87
	k_w	1.0	0.61	
	k_b	1.001856	0.43	
	k_τ	1.001856	0.26	
	k_μ	1.001856	8.8×10^{-3}	
	k_t	0.9999882	8.2×10^{-3}	
	k_γ	1.074519	0.21	

Results and discussion

$\mu - \tan\beta$ contour plot



The dashed line corresponds to the best-fit point

- Both are tightly constrained

- $[m_\nu]^{(\varepsilon\varepsilon)}_{ij} \propto \frac{1}{\tan^2\beta}$
- $[m_\nu]^{(BB)}_{ij} \propto \tan^2\beta$
- $[m_\nu]^{(\varepsilon B)}_{ij} \propto \tan\beta$
- Without loop contributions $\rightarrow$ no mixing of neutrinos
- From theory $\tan\beta$ should not be very large or small
- 2σ allowed region for $\mu \rightarrow$ 1078-1423 GeV
- 2σ allowed region for $\tan\beta$ $\rightarrow$ 10.5-15

Results and discussion

- 2σ region are:

  ε_1: -1.7$\times 10^{-2}$ to 4.0$\times 10^{-3}$ GeV

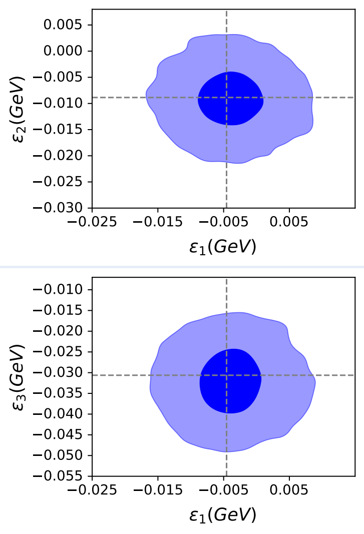
  ε_2: -2.1$\times 10^{-2}$ to 3.2$\times 10^{-3}$ GeV

  ε_3: -4.9$\times 10^{-2}$ to -1.5$\times 10^{-2}$ GeV

- $\varepsilon_1 - \varepsilon_2 - \varepsilon_3$ parameter space is tightly constrained

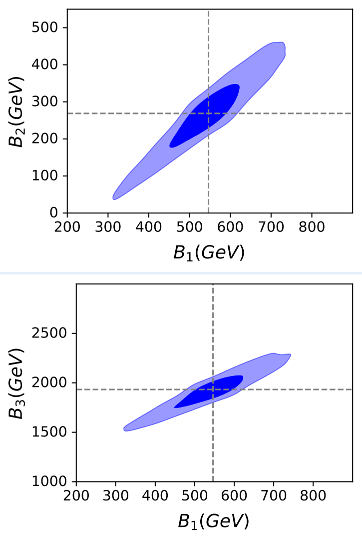
- ε_3 is loosely constrained as compared to other two ε

$\varepsilon_1 - \varepsilon_2 - \varepsilon_3$ contour plot



Results and discussion

$B_1 - B_2 - B_3$ contour plot



- 2σ region are:

  B_1: 310 - 730 GeV

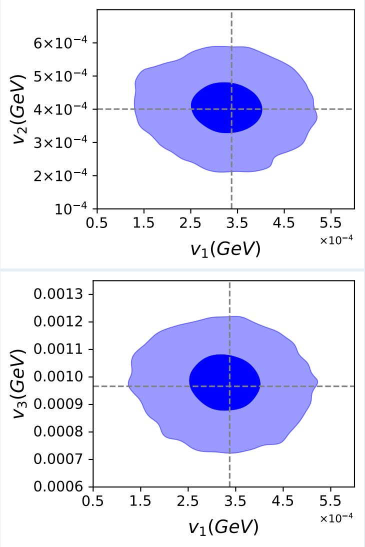
  B_2: 35 - 460 GeV

  B_3: 1530 - 2285 GeV

- B_1 and B_2 have almost same allowed parameter space
- B_3 has large allowed parameter space
- They all are highly correlated and for large value of B_1, B_2 and B_3 are also large

Results and discussion

$\upsilon_1 - \upsilon_2 - \upsilon_3$ contour plot



- 2σ region are:

  υ_1: 1.2×10^{-4} - 5.2×10^{-3} GeV

  υ_2: 2.1×10^{-4} - 5.9×10^{-4} GeV

  υ_3: 7.2×10^{-4} - 1.2×10^{-3} GeV

- υ_3 parameter space is loosely constrained as compared to υ_1 and υ_2

Results for IH scenario

The MCMC run for this scenario is still going on

Contribution to χ^2_{min} from each observable

	Observable	Best-fit value	χ^2 contribution	Total contribution
Neutrino observables	Δm^2_{21}	7.49×10^{-5}	6.82×10^{-4}	4.85×10^{-3}
	Δm^2_{31}	2.45×10^{-3}	2.07×10^{-3}	
	θ_{13}	8.56	8.23×10^{-3}	
	θ_{12}	34.42	1.03×10^{-2}	
	θ_{23}	49.33	2.72×10^{-2}	
Higgs Mass	m_h	123.98	0.11	0.11
Flavor Observales	$B \to X_s + \gamma$	3.16×10^{-4}	1.15	1.22
	$B_s \to \mu^+ + \mu^-$	3.21×10^{-9}	0.07	
Higgs coupling	k_z	1.0	0.32	1.89
	k_w	1.0	0.61	
	k_b	1.001822	0.43	
	k_τ	1.001822	0.26	
	k_μ	1.001822	8.84×10^{-3}	
	k_t	0.9999762	8.30×10^{-3}	
	k_γ	1.077167	0.23	
Total $\chi^2_{min} = 3.28$				
$\frac{\chi^2_{min}}{D.O.F}$ = 0.82				

Conclusion

- We have considered neutrino observables along with recent higgs data and flavor physics data
- We have considered minimal set of parameter including 9 BRPV prameters along with 2 MSSM parameters(μ and $\tan\beta$)
- Scanned the parameter space using MCMC
- We obtained that the BRPV model 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