Neutrino Masses & Bounds on L-violating couplings in Baryon Triality mSUGRA

Marja Hanussek

Physikalisches Institut, Universität Bonn

in collaboration with H. Dreiner, S. Grab (ArXiv:1005.3309)
and J.S. Kim, C. Kom (work in progress)

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Overview

Neutrino oscillations

- Neutrino oscillation data shows that neutrinos are massive:

  (Gonzalez-Garcia et al., 2010)

$$\Delta m^2_{21} = 7.59 \pm 0.20 \times 10^{-5}\ \mathrm{eV}^2$$

$$|\Delta m^2_{31}| = 2.46 \pm 0.12\, 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.32 \pm 0.02 \quad \sin^2\theta_{23} = 0.46 \pm 0.02 \quad \sin^2\theta_{23} < 0.05$$

- Cosmological bound from a combination of WMAP and LSS data:

  (Cirellia et al, 2006)

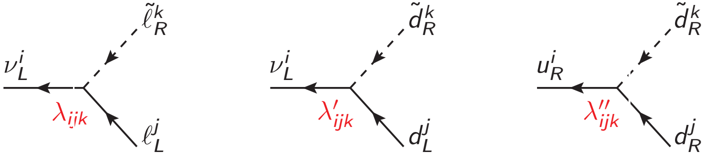
$$\sum m_{\nu_i} < \mathcal{O}(1\ \mathrm{eV})$$

- In the R-parity conserving MSSM neutrinos are massless. An extension is required to generate neutrino masses.
- Small neutrino masses arise naturally in a lepton number violating ('B_3') MSSM, without introducing new fields or a new mass scale.

Baryon triality mSUGRA

Full gauge invariant and renormalizable superpotential:

$$W = W_{MSSM} + \frac{1}{2}\lambda_{ijk}\ L_i L_j \bar{E}_k + \lambda'_{ijk}\ L_i Q_j \bar{D}_k - \ \kappa_i L_i H_u + \frac{1}{2}\lambda''_{ijk}\ \bar{U}_i \bar{D}_j \bar{D}_k$$



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- MSSM: R-Parity forbids all the above additional terms to prevent rapid proton decay
- However, there is another symmetry which ensures proton stability and also forbids potentially dangerous dimension-five operators:
- **Baryon Triality** (B_3)
  - forbids BNV terms: λ''_{ijk} + dim.-5 operators
  - allows LNV terms: λ_{ijk}, λ'_{ijk}, κ_i

B_3 mSUGRA model

- For simplification, we work in the framework of mSUGRA: scalar and gaugino masses arising from SUSY breaking are taken to be universal at the gauge coupling unification scale M_X
- 5 free R_P conserving parameters at M_X

$$M_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$$

- trilinear LNV couplings λ_{ijk}, λ'_{ijk} constitute 36 additional parameters (+ same number of soft-breaking terms)
- in principle there are also three bilinear LNV couplings κ_i + softies

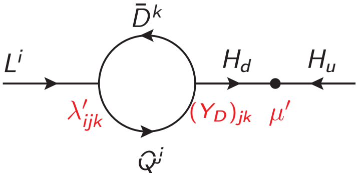
B_3 mSUGRA model

- The bilinear LNV parameters κ_i can be rotated away at M_X

$$W \supset \mu H_u H_d + \kappa_i H_u L_i$$

$$\begin{pmatrix} \mu \\ \kappa_i \end{pmatrix} \to \begin{pmatrix} \mu' \\ 0 \end{pmatrix} \quad \text{for} \quad \begin{pmatrix} H_d \\ L_i \end{pmatrix} \to \begin{pmatrix} \mathcal{L}_0 \\ \mathcal{L}_i \end{pmatrix} = \mathcal{O}_{4\times4} \begin{pmatrix} H_d \\ L_i \end{pmatrix}$$

- assuming universal SUSY breaking the corresponding soft-breaking terms $\tilde{D}_i H_u \tilde{L}_i$ can be rotated away simultaneously at M_X
- running from M_X to M_Z, non-zero κ_i will be generated



Neutrino masses at tree level

- In the B_3 mSUGRA model, neutrinos mix with neutralinos

$$\mathcal{L} = -\frac{1}{2}\left(-i\widetilde{\mathcal{B}} \quad -i\widetilde{\mathcal{W}}^3 \quad \tilde{h}_u^0 \quad \tilde{h}_d^0 \quad \nu_i \right)\mathcal{M}_N \begin{pmatrix} -i\widetilde{\mathcal{B}} \\ -i\widetilde{\mathcal{W}}^3 \\ \tilde{h}_u^0 \\ \tilde{h}_d^0 \\ \nu_j \end{pmatrix},$$

$$\mathcal{M}_N = \begin{pmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{pmatrix}$$

$\Rightarrow$ analogous to standard seesaw mechanism

- effective neutrino mass matrix

$$\mathcal{M}^\nu_{\text{eff}} = -m\mathcal{M}^{-1}_{\chi^0} m^T$$

- one non-zero eigenvalue $m_\nu^{\text{tree}} \sim \sum(\frac{v_d}{\mu}\kappa_i - v_i)^2$.

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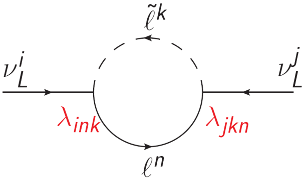
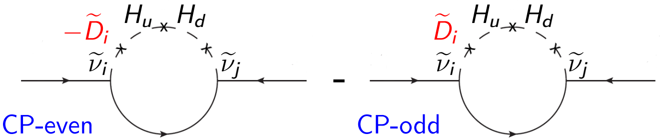
Loop contributions to neutrino masses

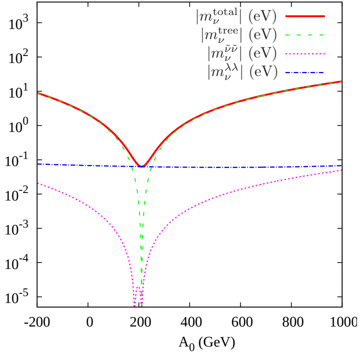
$\lambda\lambda$- and $\lambda'\lambda'$-loops



Neutral Scalar - Neutralino loops $\sim \Delta m^2_{\tilde{\nu}}$



mSUGRA dependence of the neutrino mass contributions



$\lambda'_{233} = 10^{-5}$, $M_{1/2} = 100$ GeV, $M_0 = 500$ GeV, $\tan\beta = 20$, sgn$\mu = +1$

- RGEs tell us that tree–level mass always displays this minimum, for

$$A_0 \approx 2M_{1/2} \text{ (for any } \lambda'_{ijk} \text{ coupling)}$$
$$A_0 \approx 1/2M_{1/2} \text{ (for any } \lambda_{ijk} \text{ coupling)}$$

- Further dependence on other mSUGRA parameters (see 2D scans)

Bounds on L-violating parameters

- For studying upper bounds on the trilinear LNV couplings from neutrino masses, restrict model to one (dominant) LNV coupling at a time $\Lambda \in (\lambda_{ijk}, \lambda'_{ijk})$
  $\Rightarrow$ 6 free parameters in total

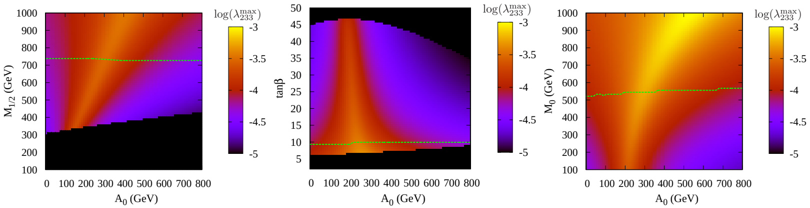
$$\Lambda,\ M_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}\mu$$

- fix these at the unification scale, use RGEs to calculate mass spectrum and couplings at M_Z
  $\Rightarrow$ SOFTSUSY-3.1.5 + own code for 1–loop neutrino masses
- We can use the cosmological bound on neutrino masses

$$\sum_i m_{\nu_i} < \mathcal{O}(1\ \mathrm{eV})$$

to obtain upper bounds on the size of Λ.

Bounds on L-violating parameters



Upper bounds on λ'_{233} around $M_{1/2} = 500$ GeV, $M_0 = 100$ GeV, tan $\beta = 20$, sgn$\mu = +1$

- approx 2 orders of magnitude variation in bounds
- shifted to higher values of A_0 for tan$\beta \lesssim 10$, and $M_0 \gtrsim 500$ GeV
- excluded regions due to tachyons and light Higgs
- contour lines showing disfavoured region from anomalous magnetic moment of the muon

Comparison to previous results

- neutrino mass minimum yields bounds that are 1-2 orders of magnitude weaker than in previous studies (e.g. Allanach et al., 2003).
- Upper bounds on λ'_{ijk} at $M_{\rm GUT}$ for SPS1a-like parameters:

	Up mixing			Down mixing		
A_0 (GeV)	-100	500	550	-100	500	550
λ'_{i11}	2×10^{-3}	3×10^{-2}	1×10^{-1}	1×10^{-3}	1×10^{-2}	7×10^{-2}
λ'_{i22}	1×10^{-4}	1×10^{-3}	7×10^{-3}	1×10^{-4}	1×10^{-3}	6×10^{-3}
λ'_{i33}	3×10^{-6}	3×10^{-5}	2×10^{-4}	3×10^{-6}	3×10^{-5}	2×10^{-4}
$\lambda'_{i21}, \lambda'_{i12}$	-	-	-	5×10^{-4}	7×10^{-3}	4×10^{-2}
$\lambda'_{i32}, \lambda'_{i23}$	2×10^{-2}	4×10^{-1}	-	8×10^{-5}	9×10^{-4}	4×10^{-3}
$\lambda'_{i31}, \lambda'_{i13}$	-, 2×10^{-2}	-, 6×10^{-2}	-, 2×10^{-1}	9×10^{-4}	9×10^{-3}	4×10^{-2}

- in vicinity of minimum, other bounds may become competitive, (checked for neutrino models on the next slides)!

e.g. two couplings bounds in Chemtob, 2008

Minimal large coupling scenario

- Can we max out the bounds which were stated on the last slides in realistic scenarios explaining neutrino masses?
- To generate two (or three) non-zero neutrino masses, we need to violate at least two lepton flavours
- We can construct a very simple scenario with degenerate neutrino masses where we have only two dominant trilinear couplings, e.g.

$$\begin{aligned} \lambda_{321} &\sim 0.41 \\ \lambda'_{121} &\sim 0.02 \qquad\qquad (A_0 \text{ minimum!}) \end{aligned}$$

- Additionally, we need some small couplings to obtain best fit, e.g.:

$$\begin{aligned} \lambda_{312} &\sim -1.3 \times 10^{-4} & \lambda_{213} &\sim -2.7 \times 10^{-6} \\ \lambda'_{332} &\sim -1.8 \times 10^{-5} & \lambda'_{232} &\sim 5.6 \times 10^{-6} \end{aligned}$$

(for $A_0 = 985$ GeV, $M_0 = 500$ GeV, $M_{1/2} = 700$ GeV, $tanb = 40$, sgn$(\mu) = -1$)

- The large λ_{321} leads to a selectron LSP!

Hierarchical scenario

- Make ansatz that trilinear LNV couplings have the same hierarchical form as the Higgs Yukawa couplings (at M_X):

$$\begin{aligned} \lambda'_{ijk} &= l'_i \times (Y_D)_{jk} \\ \lambda_{ijk} &= l_i \times (Y_E)_{jk} - l_j \times (Y_E)_{ik} \end{aligned}$$

- This ansatz can be embedded in the framework of $U(1)_X$
- The LNV sector is fully described by the 6 parameters l_i, l'_i
- Normal hierarchy (NH) neutrino sector assuming vanishing θ_{13}:

$$\begin{aligned} m_\nu &\approx (0,\ 0.009,\ 0.05)\ \mathrm{eV} \\ \sin^2(\theta_{12}) &= 0.32,\ \ \sin^2(\theta_{23}) = 0.46,\ \ \sin^2(\theta_{13}) \approx 0 \end{aligned}$$

$\Rightarrow$ 6 constraints and 6 free parameters

- We expect the LNV sector to be completely determined by neutrino data!

Obtaining solutions in the hierarchical scenario

- The experimentally determined mass hierarchy is maximally (for NH)

$$\frac{m_3}{m_2} \sim 5$$

- Recall that in B_3 mSUGRA there is only one tree–level neutrino mass, thus we would like

$$m_3 \sim m_\nu^{\mathrm{tree}}$$
$$m_2 \sim m_\nu^{\mathrm{loop}}$$

- However, the ratio between tree–level and 1–loop contributions is typically

$$\frac{m_\nu^{\mathrm{tree}}}{m_\nu^{\mathrm{loops}}} \sim \mathcal{O}(100)$$

- we need a mechanism to suppress (some) tree–level contributions
  $\Rightarrow$ use the A_0 dependence of the tree–level mass
- the tree–level minimum region ($A_0 \approx 2M_{1/2}$) seems to be preferred from neutrino data in this type of scenario!

Example solution in the hierarchical scenario

mSUGRA parameters $A_0 = 910$ **GeV**, $M_0 = 100$ **GeV**, $M_{1/2} = 500$ **GeV**, $tanb = 20$, $\mathrm{sgn}(\mu) = +1$:

$$\begin{aligned} \lambda'_1 &= -0.5 \times 10^{-4} \\ \lambda'_2 &= 3.1 \times 10^{-4} \\ \lambda'_3 &= 4.3 \times 10^{-4} \\ \lambda_1 &= 0.9 \times 10^{-5} \\ \lambda_2 &= 1.7 \times 10^{-5} \end{aligned}$$

(for best-fit normal hierarchy data)

Summary

- There are extended regions of mSUGRA parameter space where upper bounds on L-violating couplings become one to two orders of magnitude weaker than previously considered, up to $\Lambda \sim \mathcal{O}(0.1)$
- this effect is due to the A_0 influence on the tree–level neutrino mass
- typically, the tree–/1–loop hierarchy in B_3 mSUGRA is too large to explain neutrino mass hierarchy
- the A_0 dependence of the tree–level neutrino mass can be used to controll this hierarchy, making it possible to obtain NH/IH and degenerate solutions to neutrino oscillation data in a natural way.
- two example B_3 neutrino scenarios were presented:
  - *'minimal large coupling scenario'*: degenerate neutrino mass spectrum via only two dominant L-violating couplings of $\mathcal{O}(0.1)$, all other couplings suppressed by at least two orders of magnitude
  - *'hierarchical scenario'*: the L-violating couplings display the same hierarchy as the Higgs Yukawa couplings (size $\mathcal{O}(10^{-5})$) and the L-violating sector is fully determined by neutrino data if the overall neutrino mass scale is fixed

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