Neutrino Masses in the Hierarchical Baryon Triality cSSM and interplay with the LHC

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based on work with H.K. Dreiner, J.S. Kim, C. Kom (arXiv:1106.4338)
and H.K. Dreiner, J.S. Kim (preliminary)

December 8, 2011

Deutsche Telekom Stiftung

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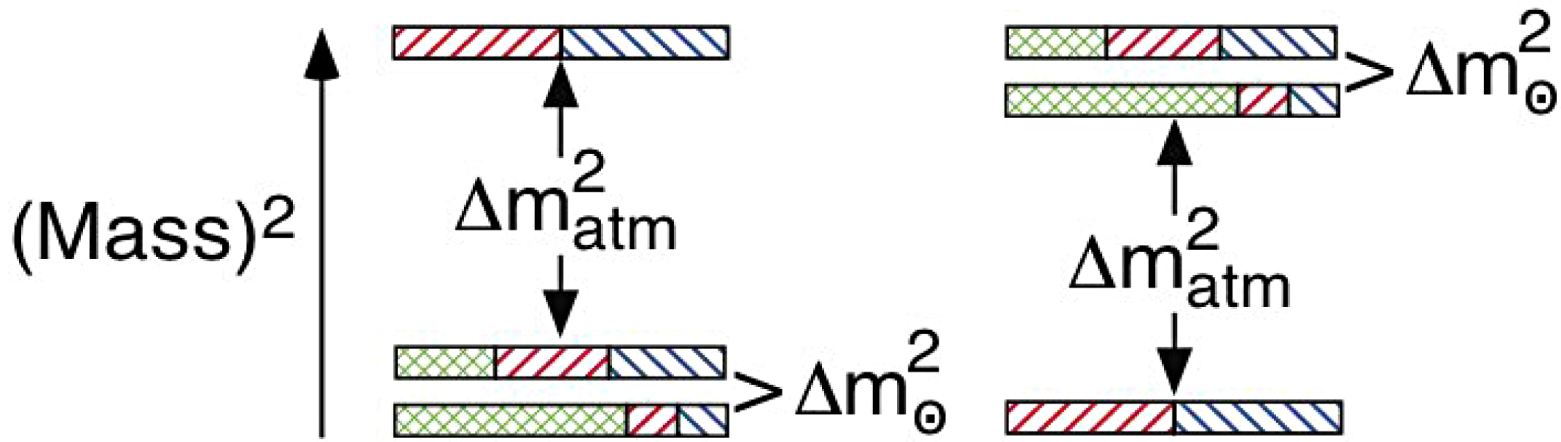
Experimental evidence for neutrino masses

- Neutrino oscillation data shows that at least 2 neutrinos are massive:

  [Schwetz et al., 2011;T2K, 2011]

$$\Delta m^2_{21} = (7.6 \pm 0.2) \cdot 10^{-5}\ \mathrm{eV}^2\ , \qquad |\Delta m^2_{31}| = (2.4 \pm 0.1) \cdot 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.31 \pm 0.02\ , \qquad \sin^2\theta_{23} = 0.51 \pm 0.06\ , \qquad \sin^2\theta_{13} \lesssim 0.03$$



Normal Hierarchy Inverted Hierarchy

- Neutrino masses in the Baryon Triality SSM are generated via lepton number (L) violating couplings

Baryon Triality Supersymmetric Standard Model

- Write down all gauge invariant and renormalizable interactions in the minimal supersymmetric extension of the SM:

$$\mathcal{W} = (\mathbf{Y_U})_{ij}\ Q_j H_u \bar{U}_k + (\mathbf{Y_D})_{ij}\ H_d Q_j \bar{D}_k + (\mathbf{Y_E})_{ij}\ H_d L_j \bar{E}_k + \mu\ H_u H_d$$
$$+ \underbrace{\frac{1}{2}\lambda''_{ijk}\ \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{B-violating}} + \underbrace{\lambda'_{ijk}\ L_i Q_j \bar{D}_k\ +\ \frac{1}{2}\lambda_{ijk}\ L_i L_j \bar{E}_k\ +\ \kappa_i H_u L_i}_{\text{L-violating}}$$

- If both L- and B-violating terms are present, the proton will decay rapidly
- The discrete gauge symmetry Baryon Triality allows for L-violating terms, but not B-violation

Hierarchical B_3 Ansatz

- L_i and H_d superfields have the same gauge quantum numbers $(1, 2, -1)$
- each SM Yukawa coupling has corresponding L-violating couplings

$$\mathcal{W}_{R_p} = Y^E_{jk} H_d L_j \bar{E}_k + Y^D_{jk} H_d Q_j \bar{D}_k$$

$$\mathcal{W}_{\not{R}_p} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$$

- κ_i and the corresponding SUSY breaking terms are rotated away at M_X
  $\rightarrow$ 36 L-violating parameters $\Lambda_{ijk} = \left\{\lambda'_{ijk},\ \lambda_{ijk}\right\}$ at M_X
- we propose the following ansatz

$$\begin{aligned} \lambda'_{ijk} &= \ell'_i \times Y^D_{jk} \\ \lambda_{ijk} &= \ell_i \times Y^E_{jk} - \ell_j \times Y^E_{ik} \qquad \text{antisymmetric in (i, j)} \end{aligned}$$

- arises naturally in the framework of **Frogatt-Nielsen models** [Thormeier et al., 2007]
- number of free L-violating parameters reduced to 6 $[\ell_i,\ \ell'_j]$
- results in 5 dominant couplings $\lambda'_{i33},\ \lambda_{i33}$
- From experiments, there are 5 $(\Delta m^2_{21},\ \Delta m^2_{31},\ \theta_{12},\ \theta_{23},\ \theta_{13})$ + 1 $(\sum_i m_{\nu_i})$ neutrino constraints on the L-violating sector
- L-violating sector is almost completely determined by ν data!

Neutrino masses in Baryon Triality: 1–loop contributions

- In the B_3 cMSSM model, neutrinos mix with neutralinos

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

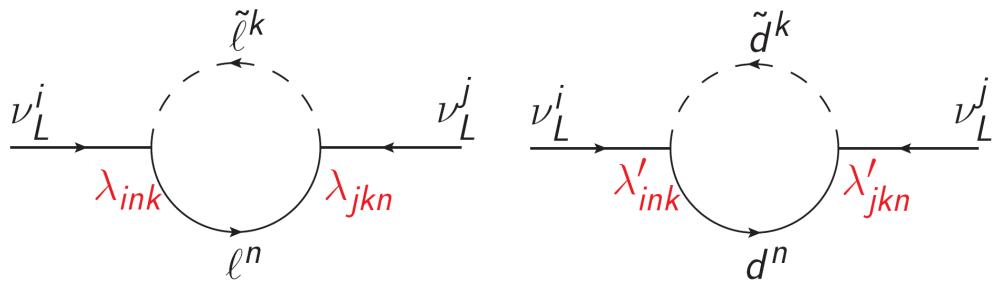
$$\mathcal{M}'_N = \begin{pmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & m_\nu^{\text{loops}} \end{pmatrix} \qquad \text{(full 7x7 matrix at 1–loop level)}$$

$\Rightarrow$ analogous to standard seesaw mechanism

- effective neutrino mass matrix

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

- dominant 1–loop contributions:



Fitting the experimental data

- The experimentally determined ν mass hierarchy is

$$\frac{m_3}{m_2} \lesssim 5,$$

(largest for NH [$m_1 \approx 0$] and smallest [~ 1] for degenerate ν masses)

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

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

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

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

- the right hierarchy can be obtained by fixing $A_0 \approx 2M_{1/2}$
(due to RGE behavior of L-violating couplings)

Neutrino masses in TBM approximation

- In the tri-bi-maximal mixing aproximation ($\sin^2[\theta_{12}] = \frac{1}{3}$, $\sin^2[\theta_{23}] = \frac{1}{2}$, $\sin^2[\theta_{13}] = 0$), the neutrino mass matrix can be brought into following form

$$M_\nu = \underbrace{\frac{m_{\nu_1}}{3}\begin{pmatrix} 2 & -1 & 1 \\ -1 & 0.5 & -0.5 \\ 1 & -0.5 & 0.5 \end{pmatrix}}_{M_\nu^{(1)}} + \underbrace{\frac{m_{\nu_2}}{3}\begin{pmatrix} 1 & 1 & -1 \\ 1 & 1 & -1 \\ -1 & -1 & 1 \end{pmatrix}}_{M_\nu^{(2)}} + \underbrace{\frac{m_{\nu_3}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}}_{M_\nu^{(3)}}$$

due to requirement $U_{PMNS}^\dagger M_\nu U_{PMNS} = diag(m_{\nu_i})$

- each contribution can be fitted by an independent set of L-violating couplings

$$(M_\nu)_{ij}^{(\alpha)} \propto \Lambda_{ikk}\Lambda_{jll}\,(m_f)_k (m_f)_l$$

- Minimally, we need 3 couplings Λ_{ikk} to fit $M_\nu^{(1)}$ or $M_\nu^{(2)}$ and 2 for $M_\nu^{(3)}$
  $\rightarrow$ 5 parameters ℓ_i, ℓ'_j can only generate $M_\nu^{(2)}$ and $M_\nu^{(3)}$, while $m_{\nu_1} = 0$ (NH)
- Small deviations from TBM (including θ_{13}) can be explained via RG effects
- We use SOFTSUSY to calculate low energy spectrum and MINUIT2 to fit neutrino masses

Results

- benchmark point with neutralino LSP

$$M_{1/2} = 360 \text{ GeV},\ M_0 = 140 \text{ GeV},\ \tan\beta = 20,\ \text{sgn}(\mu) > 0$$

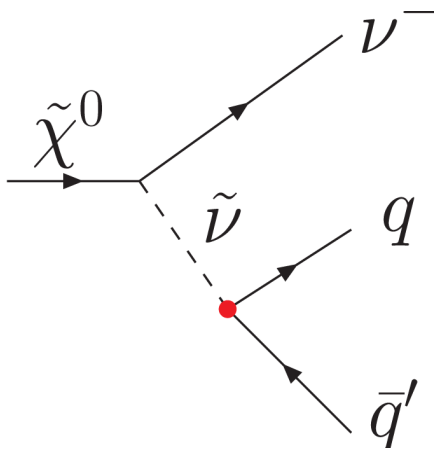
- we obtain

$$\lambda_{133} = 1.62 \times 10^{-06}, \quad \lambda_{233} = 2.66 \times 10^{-06}, \quad \lambda_{322} = 1.49 \times 10^{-07}$$

$$\lambda'_{133} = 4.66 \times 10^{-06}, \quad \lambda'_{233} = 2.78 \times 10^{-05}, \quad \lambda'_{333} = 3.53 \times 10^{-05}$$

- all remaining L-violating couplings are at least one order of magnitude smaller
- we generate events with herwig 6.510 (includes L-violating 4-body decays); detector simulation delphes 1.9
- branching ratios with isawig 7.82

LHC collider signatures - Neutralino LSP

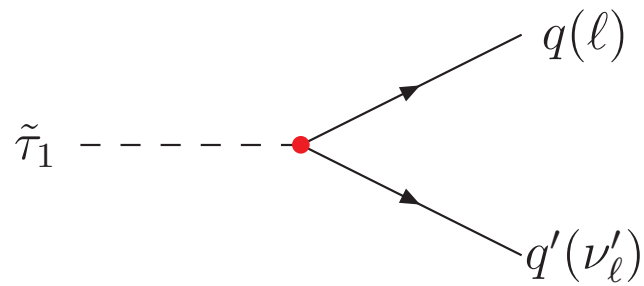


$M_{1/2} = 360$ GeV, $M_0 = 140$ GeV, $A_0 = 686$ GeV, $\tan\beta = 20$

Operator	Decay mode	Branching Ratio
$L_3 Q_3 \bar{D}_3$	$\nu_\tau b\bar{b}$	0.310
$L_3 Q_3 \bar{D}_3$	$\nu_{\bar{\tau}} b\bar{b}$	0.310
$L_2 Q_3 \bar{D}_3$	$\nu_\mu b\bar{b}$	0.170
$L_2 Q_3 \bar{D}_3$	$\nu_{\bar{\mu}} b\bar{b}$	0.170

$$\Gamma(\tilde{\chi}_1^0 \to f_1 f_2 f_3) = \Lambda^2 N_c \frac{\alpha}{128\pi^2} \frac{m^5_{\tilde{\chi}^0_1}}{m^4_{\tilde{f}}}$$

LHC collider signatures - Stau LSP

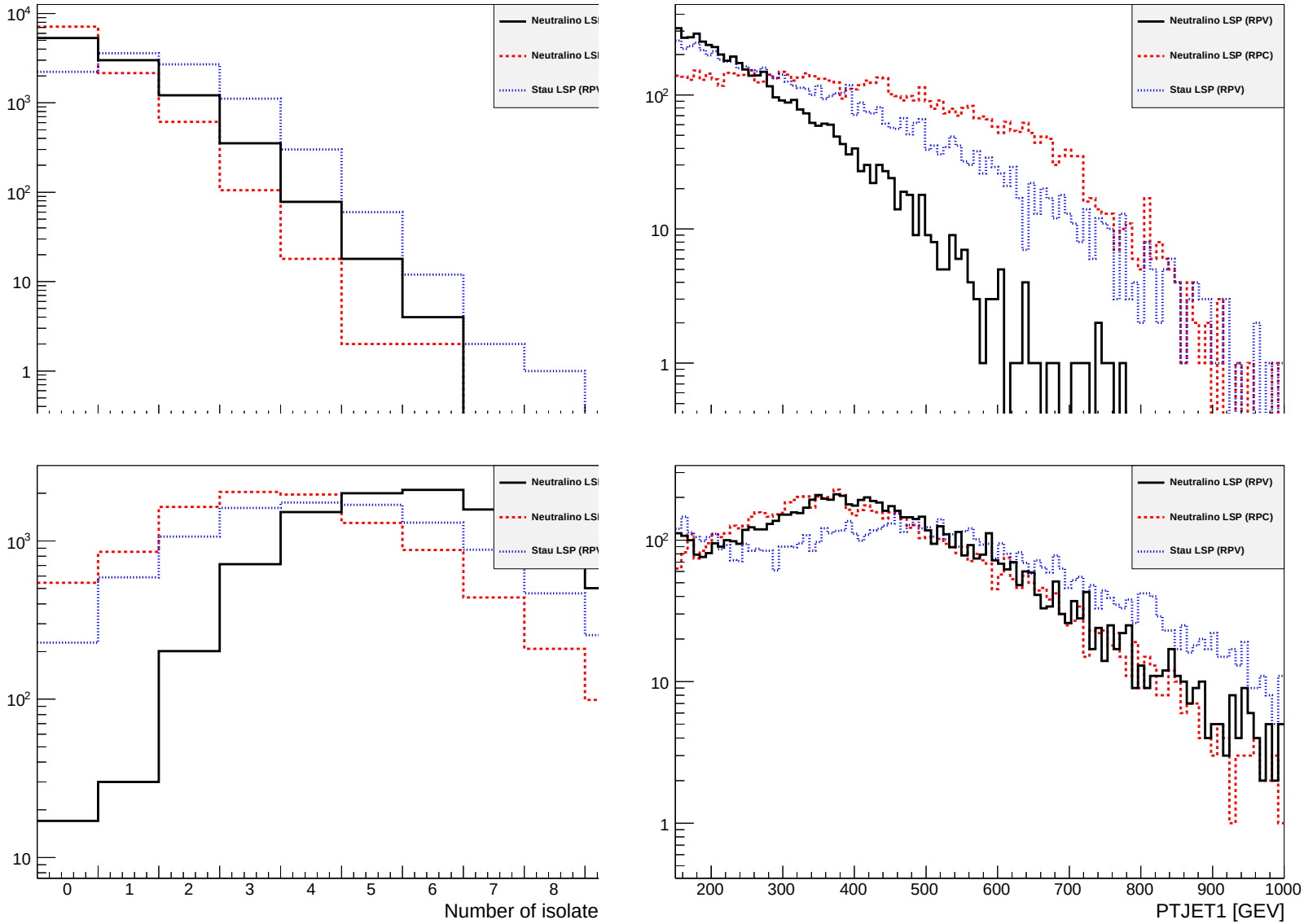


$M_{1/2} = 480$ GeV, $M_0 = 140$ GeV, $A_0 = 883$ GeV, $\tan\beta = 20$

Operator	Decay mode	Branching Ratio
$L_3 Q_3 \bar{D}_3$	$t\bar{b}$	0.335
$L_2 L_3 E_3$	$\mu^+ \nu_{\bar{\tau}}$	0.192
$L_2 L_3 E_3$	$\tau^+ \nu_{\bar{\mu}}$	0.192
$L_1 L_3 E_3$	$e^+ \nu_{\bar{\tau}}$	0.124
$L_1 L_3 E_3$	$\tau^+ \nu_{\bar{e}}$	0.124
$L_3 Q_2 D_2$	$c\bar{s}$	0.019

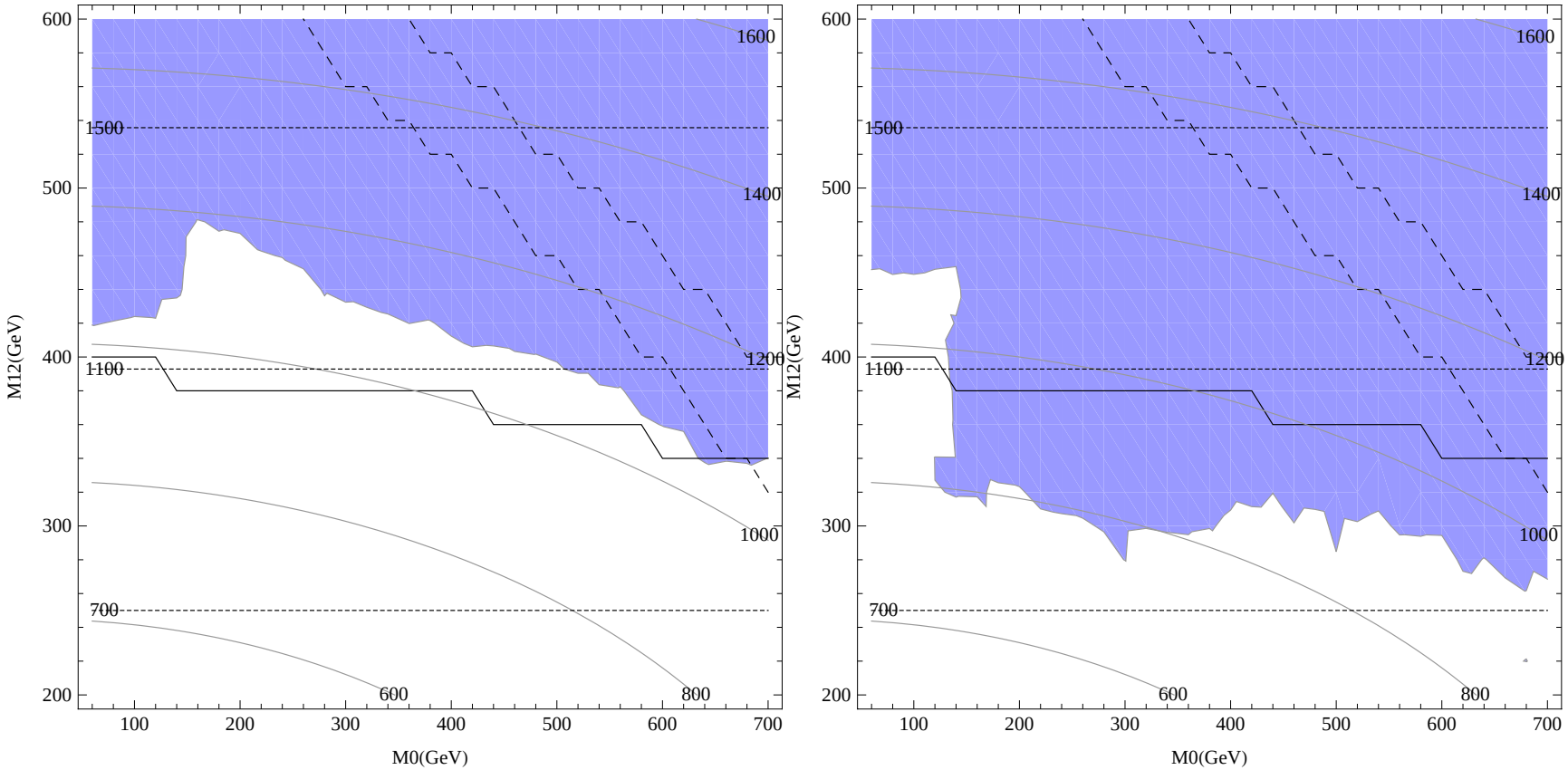
$$\Gamma(\tilde{\tau} \to f_1 + f_2) = \frac{N_c \Lambda^2 m_{\tilde{\tau}_2}}{16\pi}$$

Kinematical distributions



(Isawig 7.82, Herwig 6.510, Delphes 1.9)

Exclusion limit in 4 jets, MET and 0 or 1 isolated lepton channel with 1 fb^{-1} at $\sqrt{s} = 7$ TeV (arXiv:1109.6606, arXiv:1109.6572)



(work in progress on further studies)

Summary

- The L-violating sector in the hierarchical B_3 cMSSM is quasi completely determined by neutrino data
- In order to obtain the right neutrino mass hierarchy, the tree–level contribution to neutrino masses needs to be suppressed by fixing the value of the universal scalar coupling A_0
- Scans in the $M_{1/2}$–M_0 plane with exclusion limits from early LHC data