Probing neutrino masses in the Baryon Triality cMSSM with 1 fb^{-1} LHC data

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based on work with B. Allanach, H.K. Dreiner, S. Grab, J.S. Kim and C. Kom
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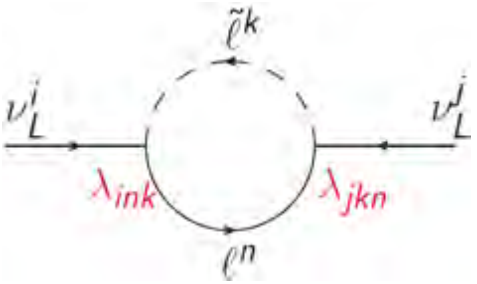
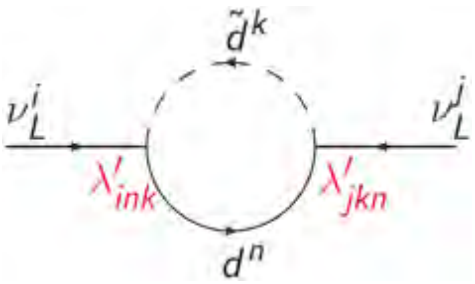
Neutrino masses

- in R-parity violating supersymmetric models, ν masses can be naturally generated without introducing new particles
- impose the discrete symmetry Baryon Triality (B_3) to ensure proton stability
- superpotential of the B_3 MSSM:

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

- we obtain one massive ν at tree-level through neutralino-neutrino mixing
- the other neutrino masses are generated at one–loop level:





Baryon Triality cMSSM

- for simplicity, we work in the **constrained MSSM:**

5 R_P-conserving parameters:

M_0	universal scalar mass at M_X
$M_{1/2}$	universal gaugino mass at M_X
A_0	universal trilinear scalar coupling at M_X
$\tan\beta$	ratio of the Higgs vevs
$\mathrm{sgn}(\mu)$	sign of the Higgs mixing parameter μ

- it turns out that A_0 needs to be fixed to $\sim 2M_{1/2}$ in order to obtain a neutrino mass hierarchy in agreement with experimental data

- additionally, 39 L-violating couplings in Baryon Triality

$$\Lambda_{ijk} = \left\{\lambda_{ijk},\ \lambda'_{ijk}\right\},\ \kappa_i \qquad + \text{corresponding SUSY breaking terms}$$

- κ_i and the corresponding SUSY breaking terms are rotated away at M_X (note that RGEs re-generate κ_i at lower scales)

Hierarchical B_3 Ansatz

- note that each SM Yukawa coupling has corresponding L-violating couplings

$$\mathcal{W}_{R_p} = Y^E_{jk} H_d L_j \bar{E}_k + Y^D_{jk} H_d Q_j \bar{D}_k$$
$$\mathcal{W}_{\not{R}_p} = \frac{1}{2}\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k$$

- we make the following 'hierarchical' ansatz at the unification scale

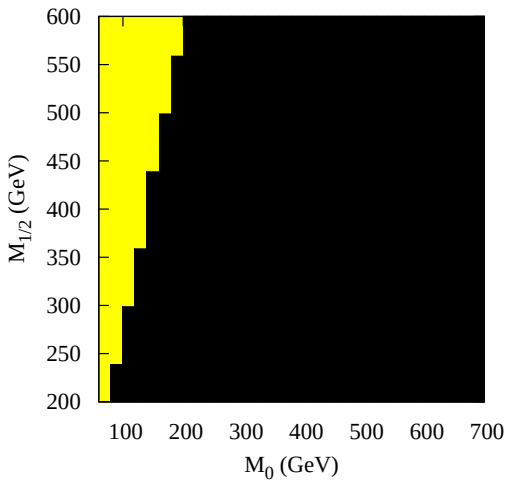
$$\begin{aligned} \lambda'_{ijk} &= \ell'_i \times Y^D_{jk} \\ \lambda_{ijk} &= \ell_i \times Y^E_{jk} - \ell_j \times Y^E_{ik} \end{aligned}$$

antisymmetric in (i, j)

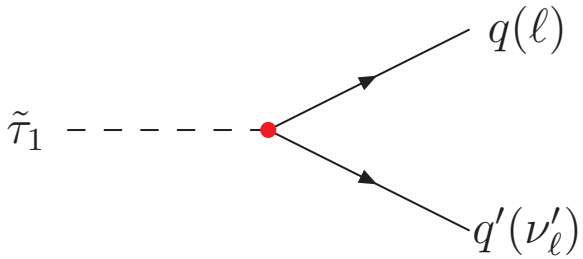
- arises naturally in the framework of **Frogatt-Nielsen models** [Thormeier et al., 2007]
- number of free L-violating parameters reduced to 6 $[\ell_i, \ell'_j]$
- results in **5 dominant couplings** λ'_{i33}, λ_{i33}
- from neutrino data, there are 5 constraints on the L-violating sector
  $\Rightarrow$ L-violating sector is quasi completely determined by ν data!
- it turns out that only the **Normal Hierarchy** neutrino mass scenario ($m_{\nu_1} \approx 0$) can be successfully fitted with these 5 couplings
  (tools: spectrum calculator Softsusy3.1 and Minuit2 to fit neutrino data)

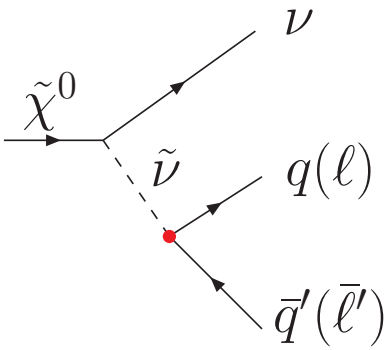
LHC collider signatures

- typical size of the L-violating couplings is small: $\Lambda_{i33} \sim 10^{-5}$
- in good approximation, we have R_p cascade decays into two LSPs
  (direct L-violating slepton decays possible, but BRs below 2%)
- LSP in hierarchical B_3 cMSSM is typically either lightest neutralino or stau:



- LSP decays via L-violating couplings:

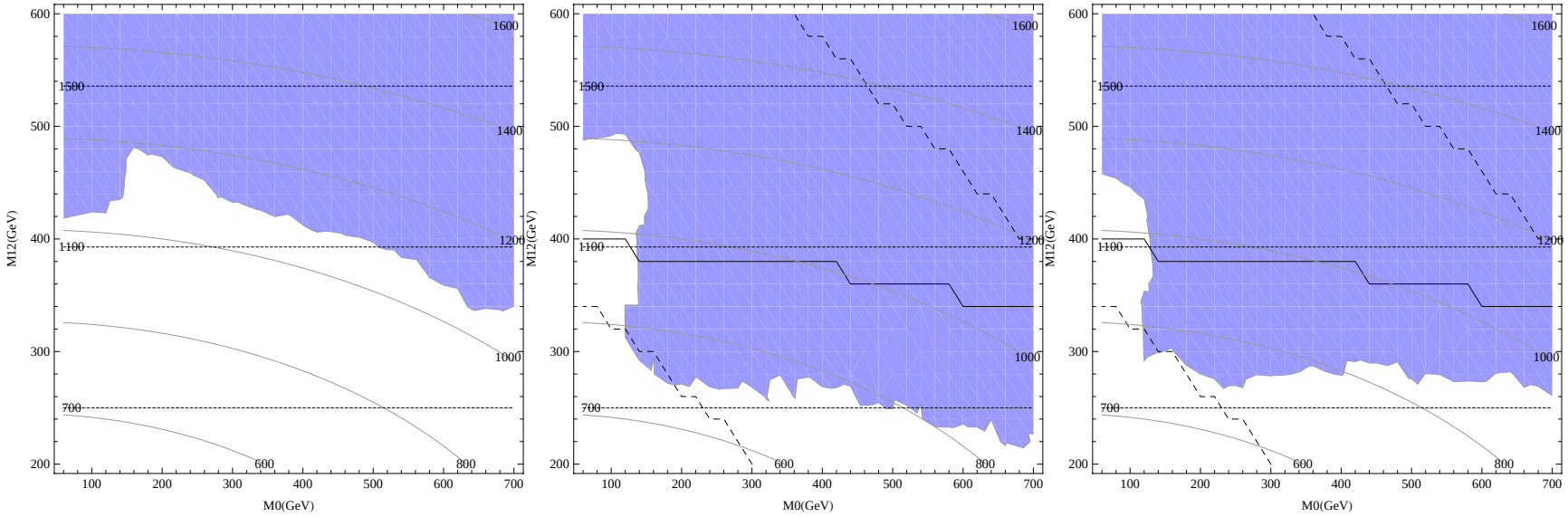




- for large M_0, $\tilde{\chi}_1^0$ decays via gauge bosons also become relevant
  ($\tilde{\chi}_1^0 \to \ell^\pm W^\mp, \nu Z$)

Exclusion limits with 1 fb^{-1} at $\sqrt{s} = 7$ TeV

- we derive exclusion limits on the hierarchical baryon triality model in $M_{1/2}$–M_0 plane, fixing $\tan\beta = 20$, $\mathrm{sgn}(\mu) > 0$
- we generate events with herwig 6.510 and perform detector simulation delphes 1.9
- we use ATLAS studies arXiv:1109.6606 (0 lept, 4 jets, MET), arXiv:1109.6572 (1 lept, 3 jets, MET) and arXiv:1110.6189 (2 lept, 2 jets, MET)



0 lept 1 lept 2 lept

- squark and gluino masses excluded up to ∼1100 GeV and ∼800 GeV

Summary

- The L-violating sector in the hierarchical B_3 cMSSM is quasi completely determined by neutrino data
- The hierarchical B_3 cMSSM predicts neutrino masses in Normal Hierarchy
- 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
- Showed scans in the $M_{1/2}$–M_0 plane with exclusion limits from early LHC data, for ATLAS studies with MET, jets and 0-3 leptons
- Squark and gluino masses excluded up to 1100 GeV and 800 GeV, respectively

Back–up slides

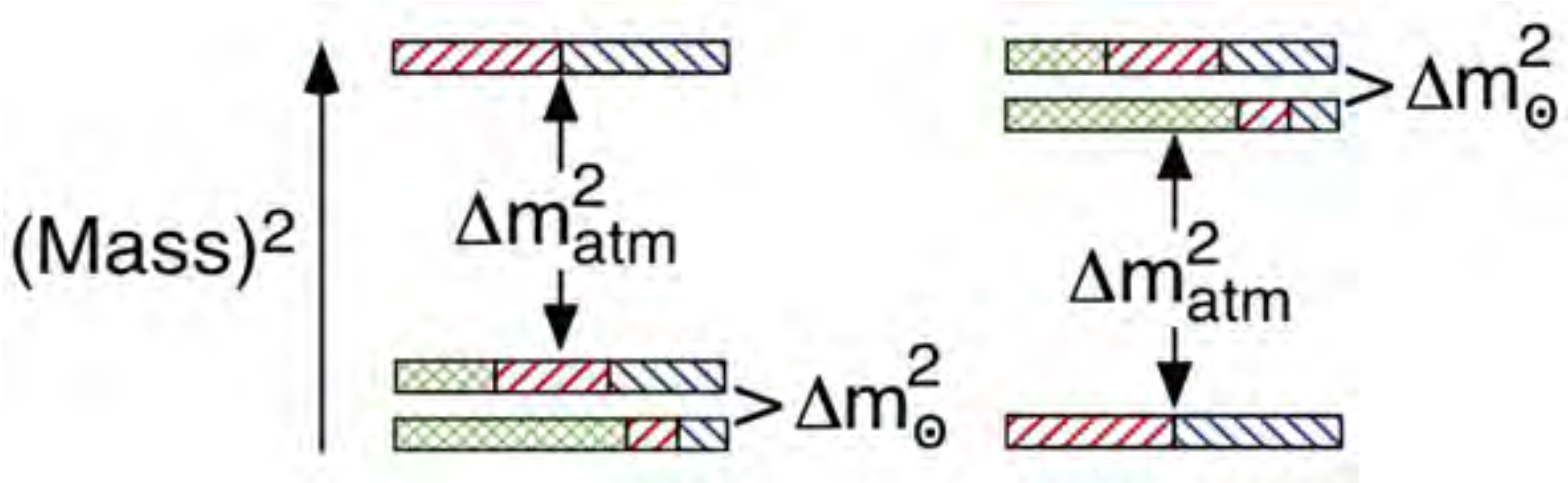
Experimental neutrino data

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

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

$$\Delta m_{21}^2 = (7.6\pm0.2)\cdot10^{-5}\ \mathrm{eV}^2\ , \qquad |\Delta m_{31}^2| = (2.4\pm0.1)\cdot10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.31\pm0.02\ , \qquad \sin^2\theta_{23} = 0.51\pm0.06\ , \qquad \sin^2\theta_{13} \lesssim 0.03$$



Normal Ordering Inverted Ordering

Trilinear B_3 cMSSM

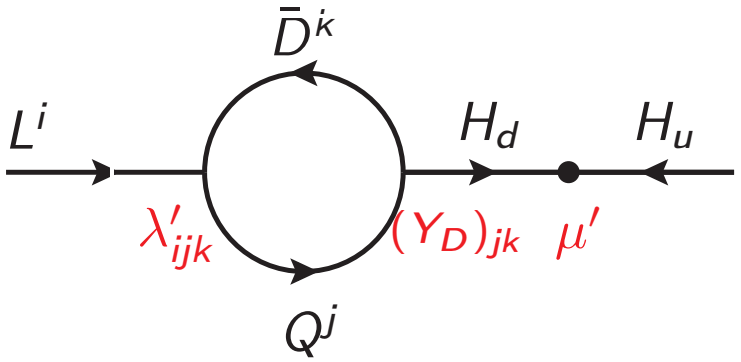
- Can we reduce the number of L-violating parameters?
- L_i and H_d superfields have the same gauge quantum numbers $(1, 2, -1)$
- The bilinear L-violating parameters κ_i can be rotated away at M_X

$$\mathcal{W} \supset \mu H_u H_d + \kappa_i H_u L_i$$

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

- 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
- <u>but</u> non-zero κ_i, $\tilde{D}_i$ will be generated at lower energies via the RGEs

$$\frac{d\kappa_i}{d(lnQ)} \sim \mu' \cdot \left[\lambda_{ijk}(Y_E)_{jk} + 3\lambda'_{ijk}(Y_D)_{jk}\right]$$



$\Rightarrow$ κ_i are present but not free parameters!

Neutrino masses in Baryon Triality: tree level

- In the B_3 cMSSM, neutrinos mix with neutralinos

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

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

$\Rightarrow$ analogous to standard seesaw mechanism

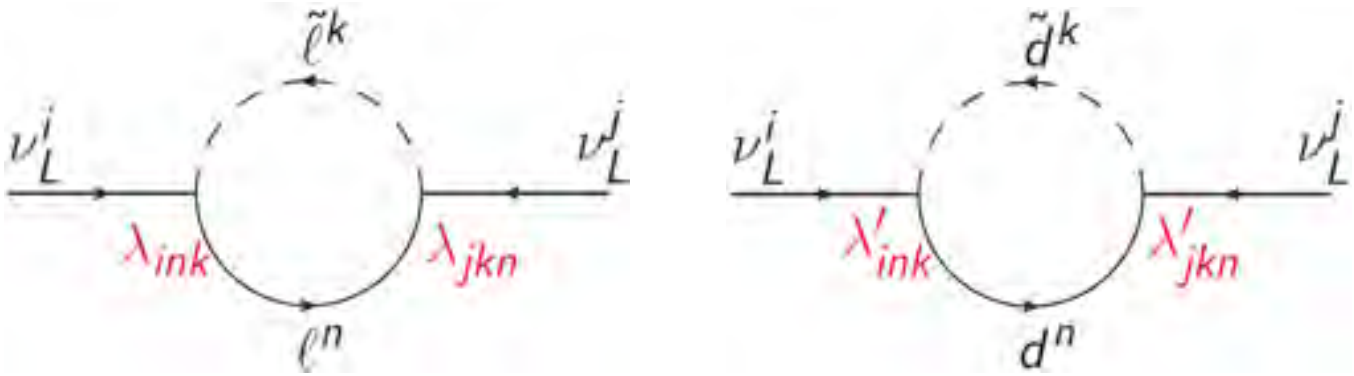
- effective neutrino mass matrix

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

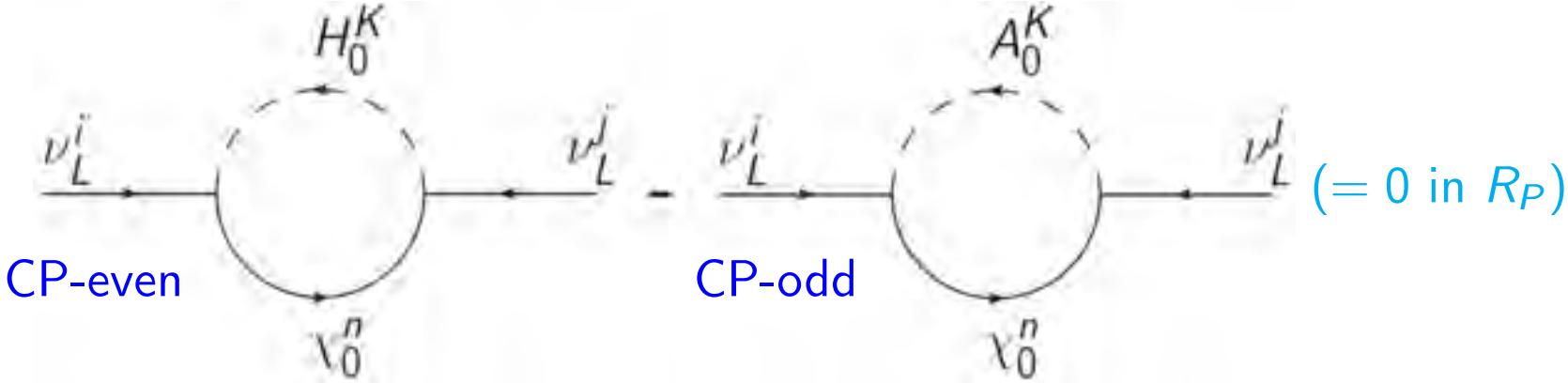
- one non-zero eigenvalue $m_\nu^{\text{tree}} \sim \sum(\frac{v_d}{\mu}\kappa_i - v_i)^2$.

Neutrino masses in Baryon Triality: 1–loop level

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



Neutral Scalar - Neutralino loops



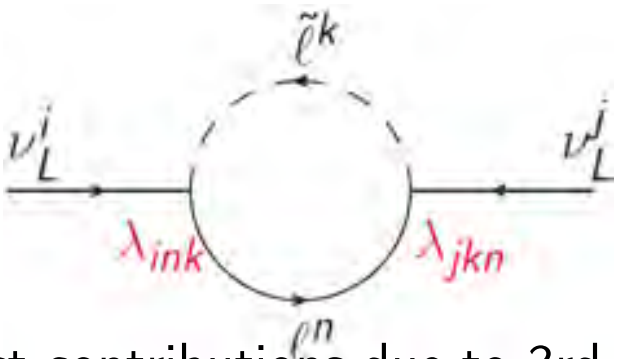
Dependence of neutrino masses on B_3 cMSSM parameters

- Dependence of tree–level mass on L-violating parameters:

$$
\begin{aligned}
m_\nu^{\text{tree}} &\sim \sum_i \left(\frac{v_d}{\mu}\kappa_i - v_i\right)^2 \\
&\sim \sum_i \left(\lambda_{ijk}(\mathbf{Y_E})_{jk} + 3\lambda'_{ijk}(\mathbf{Y_D})_{jk}\right)^2 \cdot \mathcal{F}_{soft}
\end{aligned}
$$

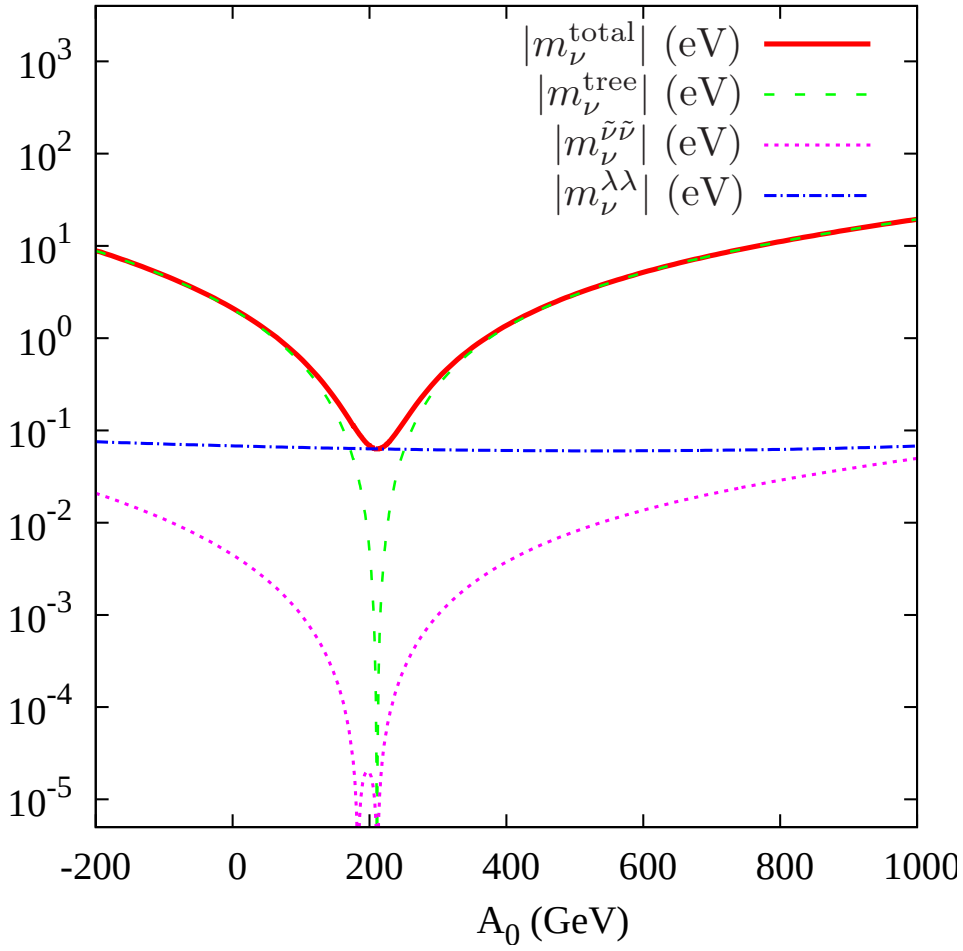
- Dependence of $\lambda\lambda$–loops on L-violating parameters: *(similar for $\lambda'\lambda'$–loops)*

$$(M_\nu)_{ij} \sim \lambda_{ink}\lambda_{jkn}\, m_n^\ell m_k^\ell \cdot \mathcal{F}'_{soft}$$



- 3rd generation couplings (Λ_{i33}) generate the largest contributions due to 3rd generation dominance in Higgs-Yukawa sector
- Dependence on soft breaking parameters ($\mathcal{F}$, $\mathcal{F}'$) is very different!
  One particularly strong effect: A_0 dependence

Dependence of neutrino masses on A_0



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

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

$$A_0 \approx 2M_{1/2} \qquad \text{(for } \lambda'_{ijk} \text{ couplings)}$$
$$A_0 \approx \tfrac{1}{2}M_{1/2} \qquad \text{(for } \lambda_{ijk} \text{ couplings)}$$

Obtaining phenomenologically viable ν masses

- The experimentally determined ν mass hierarchy is

$$\frac{m_{\nu_3}}{m_{\nu_2}} \lesssim 5,$$

(largest for NH and smallest (~ 1) for degenerate ν masses)

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

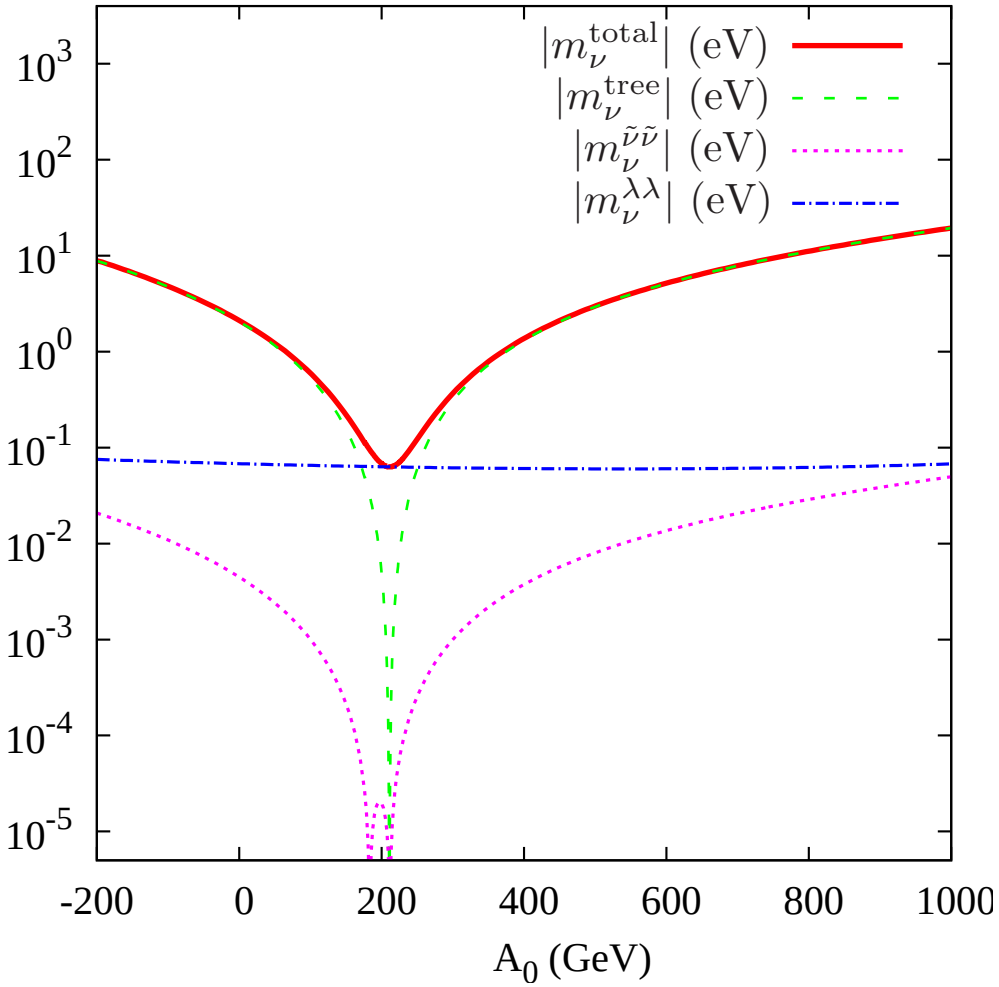
$$m_{\nu_3} \sim m_\nu^{\text{tree}}$$
$$m_{\nu_2} \sim m_\nu^{\text{loop}}$$

- However, the ratio between tree–level and 1–loop contributions is typically (*c.f.* next slide)

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

- we need a mechanism to suppress (some) tree–level contributions
  $\Rightarrow A_0$ dependence of the tree–level mass

Tree–level to 1–loop ratio



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

$\Rightarrow$ Ratio between tree–level and 1–loop masses is typically large, except for tree–level minimum region!

Neutrino masses in TBM approximation

- In the tri-bi-maximal mixing approximation ($\sin^2[\theta_{12}] = \frac{1}{3}$, $\sin^2[\theta_{23}] = \frac{1}{2}$, $\sin^2[\theta_{13}] = 0$), 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 $U^\dagger_{PMNS} M_\nu U_{PMNS} = diag(m_{\nu_i})$

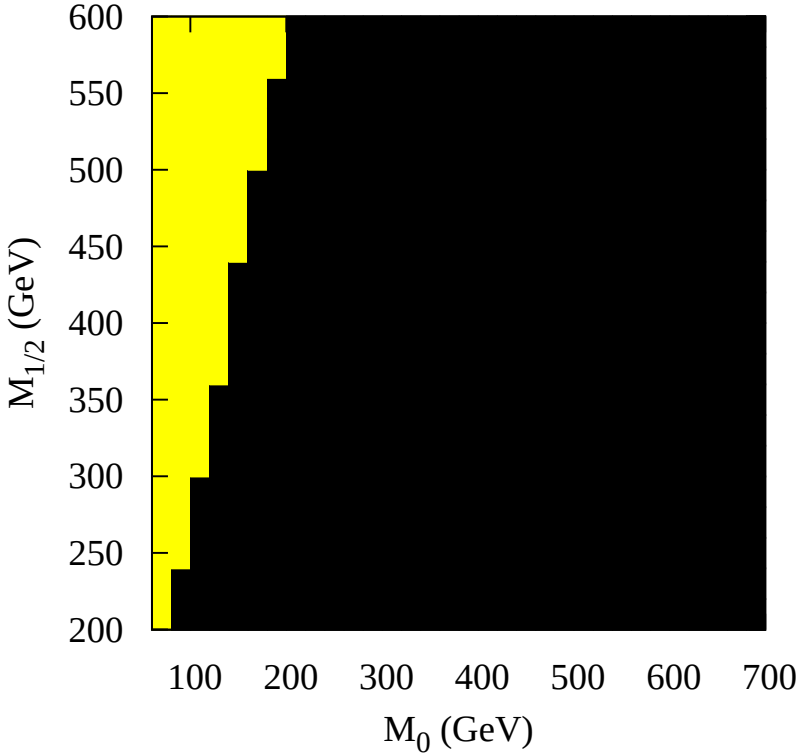
- each contribution can be fitted by an independent set of L-violating couplings

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

- 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_{ν_2} and m_{ν_3}, while $m_{\nu_1} = 0$ (NH)
- Small deviations from TBM (including θ_{13}) can be explained via RG effects

LSP type

- In Baryon Triality models, the LSP is unstable and can in principle be any sparticle.
- If $M_0 \ll M_{1/2}$, some sleptons can become lighter than the lightest neutralino.
- The lightest slepton is typically the right-handed stau (due to largest L-R mixing)
- LSPs in our scan: $\tilde{\chi}_0^1$ and $\tilde{\tau}_1$



Benchmark point 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

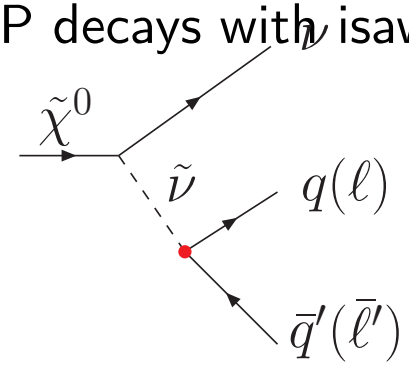
$$\lambda_{133} = 1.62 \times 10^{-06}, \quad \lambda_{233} = 2.66 \times 10^{-06}, \quad \lambda_{322} = 1.49 \times 10^{-07}$$

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

- all remaining L-violating couplings are at least one order of magnitude smaller
- we generate events with herwig 6.510 and perform detector simulation delphes 1.9

LHC collider signatures - Neutralino LSP

- Evaluated branching ratios of LSP decays with isawig 7.82



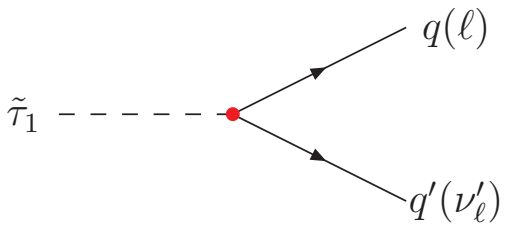
$M_{1/2} = 360$ GeV, $M_0 = 140$ GeV, $A_0 = 686$ GeV, $\tan\beta = 20$

Operator	Decay mode		Branching Ratio
$L_3 Q_3 \bar{D}_3$	$\nu_\tau b\bar{b}$	$[\bar{\nu}_\tau b\bar{b}\ ]$	0.62
$L_2 Q_3 \bar{D}_3$	$\nu_\mu b\bar{b}$	$[\bar{\nu}_\mu b\bar{b}\ ]$	0.34
$L_i L_3 E_3$	$\nu_i \tau^+ \tau^-$	$[\nu_\tau \ell_i^+ \tau^-]$	0.03

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

- $LL\bar{E}$ decay suppressed due to color factor and $\frac{\lambda_{i33}}{\lambda'_{133}} \sim 0.1$
- For larger scalar masses, decays via gauge bosons ($\tilde{\chi}_1^0 \to \ell^\pm W^\mp, \nu Z$) can also become relevant

LHC collider signatures - Stau LSP



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

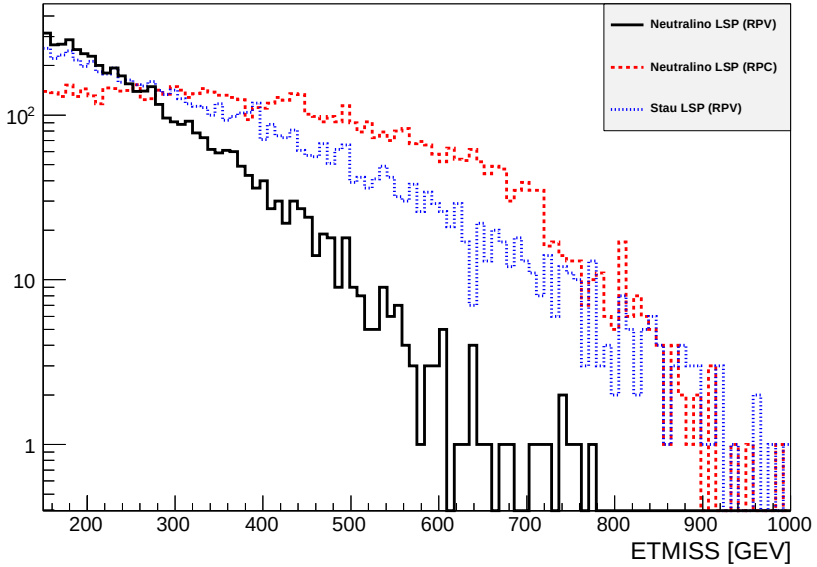
Operator	Decay mode	Branching Ratio
$L_3 Q_3 \bar{D}_3$	$t\bar{b}$	0.34
$L_2 L_3 E_3$	$\mu^+ \bar{\nu}_\tau$	0.19
$L_2 L_3 E_3$	$\tau^+ \bar{\nu}_\mu$	0.19
$L_1 L_3 E_3$	$e^+ \bar{\nu}_\tau$	0.12
$L_1 L_3 E_3$	$\tau^+ \bar{\nu}_e$	0.12

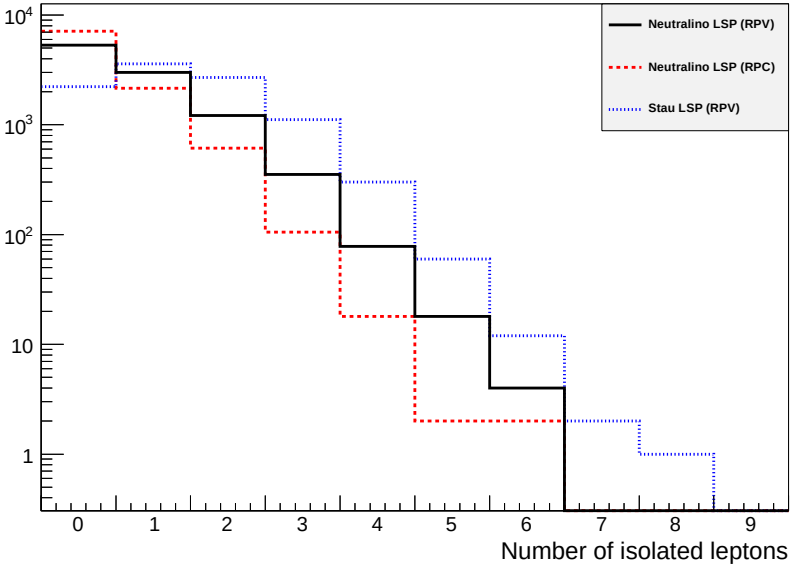
$$\Gamma(\tilde{\tau} \to f_1 + f_2) = \frac{N_c \Lambda^2 m_{\tilde{\tau}_2}}{16\pi}$$

- signature with one or two leptons from LSP decay (if demanding MET)

Kinematical distributions

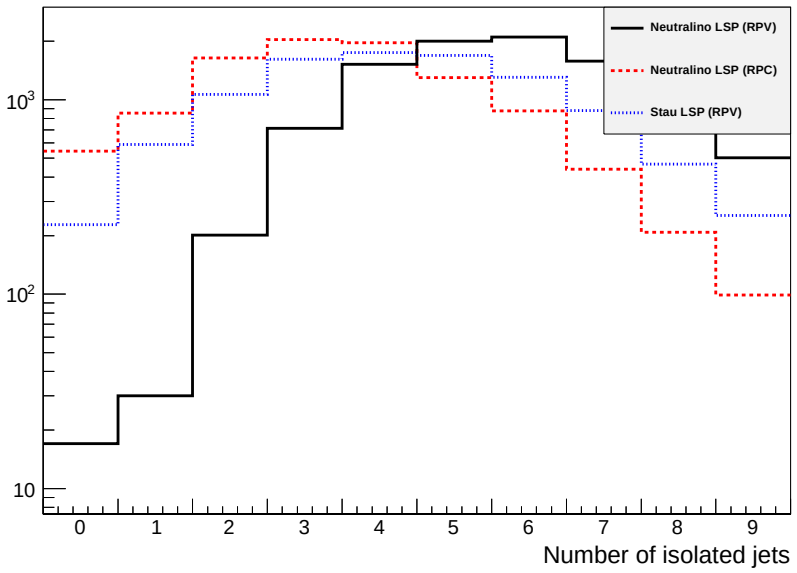
- we generate events with herwig 6.510 and perform detector simulation delphes 1.9

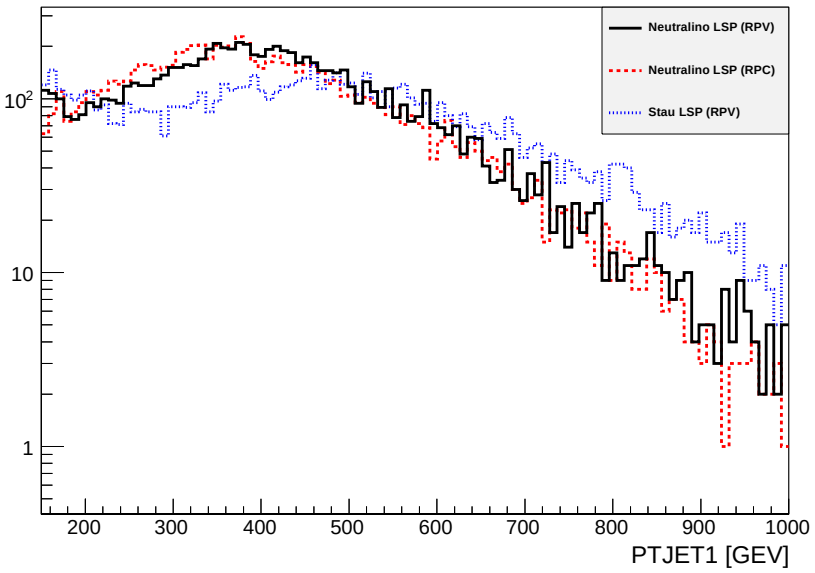




- less missing E_T than R_p scenarios, but still on the safe side for typical 7 TeV cuts
- more leptons in the final state for stau LSP scenario

Kinematical distributions





- more jets in the neutralino LSP scenario
- p_T distribution of hardest jets similar

Displaced vertices

- $\tilde{\tau}$ LSP decays via $\lambda_{i33} \sim 10^{-6}$ into $\ell\nu$ have a finite decay length

$$c\gamma\tau \approx \gamma \frac{10^{-10}}{\lambda_{i33}^2} \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{\tau}_1}} \right) \mu\mathrm{m} \sim 100\ \mu\mathrm{m},$$

  with boost factor $\gamma \approx 10$.
- potentially large enough to allow for detection at the LHC

ATLAS Cuts

- we use ATLAS studies arXiv:1109.6606 (0 lept, jets, MET), arXiv:1109.6572 (1 lept, jets, MET) and arXiv:1110.6189 (2 lept, jets, MET)

cut	0 lept, jets, MET	1 lept, jets, MET	2 lept, jets, MET (SS)
n_{lept}	0	1	2
E_T^{miss}	> 130 GeV	> 240 GeV	> 80 GeV
n_{jets}	4	3	2
p_T^{j1}	> 130	> 80 GeV	> 50 GeV