PRAMANA
— journal of
physics

Vol. 79, No. 4
October 2012
pp. 849–852

Flavoured co-annihilation

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Abstract. In minimal supergravity (mSUGRA) or CMSSM, one of the main co-annihilating partners of the neutralino is the lightest stau, $\tilde{\tau}_1$. In the presence of flavour violation in the right-handed sector, the co-annihilating partner would be a flavour mixed state. The flavour effect is two-fold: (a) It changes the mass of $\tilde{\tau}_1$, thus modifying the parameter space of the co-annihilation and (b) flavour violating scatterings could now contribute to the cross-sections in the early Universe. In fact, it is shown that for large enough $\delta \sim 0.2$, these processes would constitute the dominant channels in co-annihilation regions. The amount of flavour mixing permissible is constrained by flavour violating $\tau \to \mu$ or $\tau \to e$ processes. For Δ_{RR} mass insertions, the constraints from flavour violation are not strong enough in some regions of the parameter space due to partial cancellations in the amplitudes. In mSUGRA, the regions with cancelations within LFV amplitudes do not overlap with the regions of co-annihilations. In non-universal Higgs model (NUHM), however, these regions do overlap leading to significant flavoured co-annihilations. At the LHC and other colliders, these regions can constitute for interesting signals.

Keywords. Minimal supergravity; non-universal Higgs model; lepton flavour violation.

PACS Nos 04.65.+e; 12.60.Jv; 14.80.Ly; 95.35.+d; 95.30.Cq

1. Introduction

Supersymmetric Standard Models have a natural dark matter candidate namely, the lightest supersymmetric particle (LSP) if R-parity is conserved [1]. In mSUGRA/CMSSM models, the LSP typically is the lightest neutralino [2]. In most of the parameter space of these models, the lightest neutralino is mostly a bino ($\tilde{B}^0$); the bino component being close to 99%. The bino cross-section being small, in most of the parameter space, the neutralinos are overproduced resulting in a larger relic density compared to WMAP [3] bounds. However, there are special regions in the mSUGRA parameter space where the neutralino is able to satisfy the relic density limits [4]. These are: (i) bulk region, (ii) stop ($\tilde{t}$) co-annihilation region, (iii) stau ($\tilde{\tau}$) co-annihilation region, (iv) A-pole funnel region and (v) focus point/hyperbolic branch regions. The stau co-annihilation region requires the mass of the lightest $\tilde{\tau}$ to be close to the mass of the LSP. Among the above depicted regions, the stau co-annihilation and focus point regions get modified due to pre-GUT effects and the see-saw mechanism.

DOI: 10.1007/s12043-012-0388-0; ***e*Publication: 6 October 2012**

In the present work [5], we study the effects of considering flavour violation in the co-annihilation region. The co-annihilating partner of the neutralino LSP is no longer a pure $\tilde{\tau}$ state, but can have significant amount of flavour mixing in the RR sector. In supersymmetric grand unified theories due to RGE running from the Planck scale to the GUT scale generates RR flavour violating entries in the sleptonic sector. Typically in SUSY GUT theories these RG-generated flavour violating entries are ($\mathcal{O}(10^{-3}$–$10^{-5})$) too tiny to make any considerable effects in the co-annihilation region, while flavour symmetries at the high scale or SUSY left–right symmetric models can generate flavour violating entry ($\sim\mathcal{O}(10^{-1})$). Thus in this work we have taken a model-independent approach and assume the presence of a single flavour violating entry $\Delta_{\mathrm{RR}}^{\mu\tau}$ and studied its implication in the co-annihilation region.

2. $\tilde{\tau}$ Co-annihilation in the presence of flavour violation

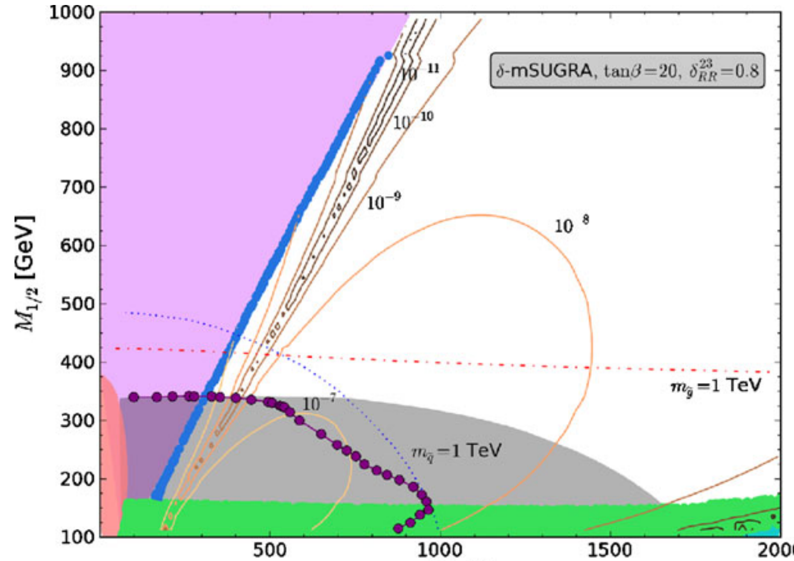
RR sector flavour violating entry in the sleptonic mass matrix will modify the lightest stau mass, and so the co-annihilation condition gets modified. At the weak scale, the sleptonic mass matrix in the presence of a single flavour violating entry ($\Delta_{\mathrm{RR}}^{\mu\tau}$) is

$$\mathcal{M}_{\tilde{l}}^2 = \begin{pmatrix} m_{\tilde{\mu}_{\mathrm{L}}}^2 & 0 & m_{\tilde{\mu}_{\mathrm{LR}}}^2 & 0 \\ 0 & m_{\tilde{\tau}_{\mathrm{L}}}^2 & 0 & m_{\tilde{\tau}_{\mathrm{LR}}}^2 \\ m_{\tilde{\mu}_{\mathrm{LR}}}^2 & 0 & m_{\tilde{\mu}_{\mathrm{R}}}^2 & \Delta_{\mathrm{RR}}^{\mu\tau} \\ 0 & m_{\tilde{\tau}_{\mathrm{LR}}}^2 & \Delta_{\mathrm{RR}}^{\mu\tau} & m_{\tilde{\tau}_{\mathrm{R}}}^2 \end{pmatrix}. \tag{1}$$

Assuming $\Delta_{\mathrm{RR}}^{\mu\tau}$ to be smaller than the flavour diagonal elements, the lightest stau mass ($m_{\tilde{\tau}_1}$) can be written as

$$m_{\tilde{\tau}_1}^2 \simeq m_{\tilde{\tau}_{\mathrm{R}}}^2(1-\delta_{\mathrm{RR}}) - m_\tau \mu \tan\beta, \tag{2}$$

where $\delta_{\mathrm{RR}} \equiv \Delta_{\mathrm{RR}}^{\mu\tau}/\sqrt{m_{\tilde{\mu}_{\mathrm{R}}^2} m_{\tilde{\tau}_{\mathrm{R}}^2}}$. From eq. (2) one can see that increasing δ_{RR} will decrease the stau mass or in other words the co-annihilation will occur at a lower neutralino mass for the fixed universal scalar mass parameter (m_0). But having large flavour violating entry in the $\tilde{\mu}_{\mathrm{R}}$–$\tilde{\tau}_{\mathrm{R}}$ sectors of the sleptonic mass matrix will also give rise to rare lepton flavour violating decays (e.g., $\tau \to \mu\gamma$, $\tau \to \mu ee$ etc.). The RR-sector δ's are unbounded compared to the LL sectors as they are from purely bino and bino-higgsino diagrams and also they come in opposite sign in the branching ratio expression [6,7]. These two contributions cancel each other in the parameter space where $|\mu|^2 \approx m_{\tilde{\tau}_{\mathrm{R}}}^2$ and this space is also called the cancellation region. In CMSSM these is no overlap between these two regions [8]. In the non-universal Higgs mass models (NUHM) one relaxes the universality in the Higgs sector compared to the case in CMSSM. Thus in NUHM the Higgsino mass parameter $|\mu|$ becomes free. With a suitable choice of the two Higgs masses at the GUT scale one will be able to overlap the cancellation region with the co-annihilation region even at a small δ_{RR}. In figure 1 we have shown the cancellation and co-annihilation regions in both CMSSM and NUHM scenario. We see that in NUHM scenario with $m_{\mathrm{H_u}} = 1.5 m_0$ and $m_{\mathrm{H_d}} = 0.5 m_0$ the co-annihilation and cancellation regions completely overlap for $\delta_{\mathrm{RR}} = 0.7$. With a different set of choice of the $m_{\mathrm{H_u}}$ and $m_{\mathrm{H_d}}$ it is possible to achieve this complete overlap at much smaller δ_{RR}.



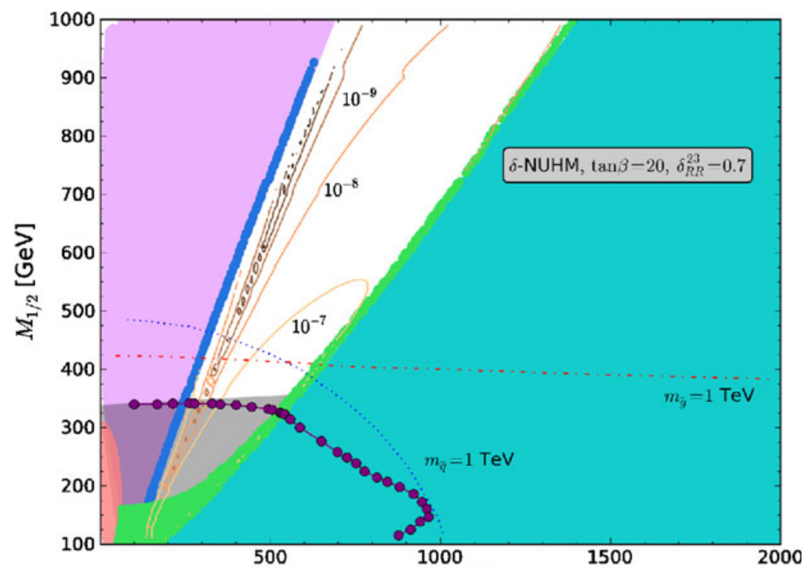


Figure 1. (**a**) The contours show branching ratio, BR($\tau \to \mu\gamma$) for $\delta_{RR} = 0.8$ and for $\tan\beta = 20$, $A_0 = 0$. The light blue line indicates WMAP bound satisfied region. The black translucent region is excluded by direct search in LEP for the Higgs boson. Region inside the dark brown contours or the *cancellation region*, the branching ratio is very much lower than the neighbouring region. In this region δ_{RR} becomes unbounded because of the cancellation between the $\tilde{B}^0$ and $\tilde{B}^0$–$\tilde{H}^0$ diagrams. (**b**) NUHM scenario with $m_{H_u} = 1.5m_0$, $m_{H_d} = 0.5m_0$ for $\tan\beta = 20$ and $\delta_{RR} = 0.7$. The darker green region indicates inefficient radiative electroweak symmetry breaking.

Having this flavour violation in the RR-sector also introduces new flavour violating couplings into the Lagrangian. Because of these flavour violating vertices, for the same initial states ($\chi_1^0 - \tilde{\tau}$, $\tilde{\tau} - \tilde{\tau}$ or $\chi_1^0 - \chi_1^0$), new final-state processes will contribute to the relic density calculation, thus reducing the neutralino relic abundances in the co-annihilation region. Neglecting these new flavour violating final states will overestimate the relic density in this region.

3. Summary and outlook

Large flavour violation if present in the RR sector can significantly modify the co-annihilation region both in spectrum and relic density calculations. Extensions of mSUGRA like NUHM, have interesting regions with flavoured co-annihilations. The flavour violation at the $\tilde{\mu}$–$\tilde{\tau}$ sector gives rise to the mass splitting in the $\tilde{e}$–$\tilde{\mu}$ sector, which are degenerate in CMSSM. Thus, measuring these mass splittings serves indirect signals of SUSY at colliders like LHC or ILC.

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[8] Having $A_0 \neq 0$ and very large $\delta_{\rm RR}$ ($\sim$0.9) might give rise to a non-zero but tiny overlap at a very large $M_{1/2}$