Return of the Light Higgsino

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Abstract

It is pointed out that loop corrections involving heavy quarks and their superpartners can re-introduce a state with 99.5\% higgsino purity as a viable cold Dark Matter candidate. Such corrections can increase the mass splitting between the three higgsino-like states of the MSSM by several GeV, which results in a suppression of the co-annihilation rate by a factor of five or more. Related corrections to the couplings of the LSP to Z and Higgs bosons can change the predicted LSP detection rate by two orders of magnitude.

*Talk given at the 2nd International RESCEU Symposium on Dark Matter and its Direct Detection, Tokyo, November 26–28, 1995
In models with exact R-parity, the lightest supersymmetric particle (LSP) is stable, and is thus a particle physics candidate for the missing “Dark Matter” (DM) in the Universe [1]. In particular, a bino–like LSP would have the right relic density if \( m_{\tilde{\chi}^0_1} \approx (200 \text{ GeV})^2 \), where \( \tilde{l}_R \) stands for SU(2) singlet sleptons, which are the sfermions with the largest hypercharge; a similar result holds for photino–like LSP.

In contrast, higgsino–like LSPs are thought to have a very small relic density, unless their mass exceeds 0.5 TeV or so. If \( m_{\tilde{\chi}^0_1} > M_W \), this is due to the very large cross sections for \( \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow W^+W^-, \ Z \bar{Z} \) [1]. For \( m_{\tilde{\chi}^0_1} < M_W \), the annihilation cross section becomes quite small if the LSP is a nearly pure higgsino. However, the LSP is then close in mass to the lightest chargino and next–to–lightest neutralino. In such a situation co–annihilation processes between the LSP and the only slightly heavier higgsino–like states have to be included in the estimate of the relic density. As pointed out in ref.[3], these processes greatly reduce the predicted relic density of higgsino–like LSPs, making them uninteresting as DM candidates unless the gaugino fraction, defined as the sum of the squares of the gaugino components of the LSP eigenvector, is at least several percent.

However, very recently it was shown [4] that loop corrections [5] can change the mass splitting between the higgsino–like states of the minimal supersymmetric standard model (MSSM) by several GeV. The authors of ref.[4] were interested in the impact of such corrections on sparticle searches at LEP. However, since the rate for co–annihilation processes depends exponentially on the mass differences, these corrections can also change the prediction for the LSP relic density quite dramatically [6]. This prediction is also altered by corrections to the coupling of the LSP to the Z and, in some cases, to Higgs bosons; these couplings also largely determine the LSP–nucleon scattering cross section, and hence the LSP detection rate.

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\begin{align*}
\text{Fig. 1: Quark–squark loop corrections to the coupling of a pair of LSPs to a Z or Higgs boson.} \\
&\text{The LSP momenta } k_1 \text{ and } k_2 \text{ point towards the vertex. Note that both senses of the “Dirac arrow” (flow of fermion number) have to be added, since the LSP is a Majorana fermion. There is also a diagram of type c) with a quark–squark bubble on the other neutralino line. There are two squark mass eigenstate with a given flavor.} \\
&\text{We therefore computed [6] the vertex corrections of Figs. 1 in addition to the corrections to the masses given in refs.[4, 5]. Note that the off–diagonal wave function renormalization}
\end{align*}
\]
Figure 2: The chargino–LSP mass difference (solid), the axial–vector \( Z\tilde{\chi}^0_1\tilde{\chi}^0_1 \) coupling (long dashed), and the \( h^0\tilde{\chi}^0_1\tilde{\chi}^0_1 \) coupling (short dashed) are shown as a function of the soft breaking \( A \) parameter, including one–loop corrections involving Yukawa couplings.

diagram of Fig. 1c, which only contributes to the \( Z\tilde{\chi}^0_1\tilde{\chi}^0_1 \) coupling, is closely related to the corrections to the neutralino mass matrix; we found that this contribution usually dominates the correction to this coupling. In contrast, the potentially largest contribution to the couplings of the scalar Higgs bosons to the LSP comes from Fig. 1b; this contribution depends sensitively on the soft SUSY breaking \( A \) parameters that also appear in the off–diagonal entries of the squark mass matrices [1]. This is also true for the corrections to the mass splittings, which vanish if the two squarks of a given flavour are mass–degenerate or if the \( \tilde{q}_L – \tilde{q}_R \) mixing angle goes to zero.

This is demonstrated in Fig. 2, which shows the chargino–LSP mass splitting (solid), the axial–vector \( Z\tilde{\chi}^0_1\tilde{\chi}^0_1 \) coupling (long dashed), and the coupling of the LSP to the light scalar Higgs boson \( h^0 \) (short dashed); all results have been normalized such that they can be plotted to a common scale. In all three cases the tree–level prediction is very close to the one–loop corrected estimate for \( A = 0 \). We see that the mass splitting can change by about \( \pm 4 \) GeV, while the \( Z\tilde{\chi}^0_1\tilde{\chi}^0_1 \) coupling changes by about a factor of three as \( A \) is varied across its allowed range. Since for the given choice of parameters (in particular, \( \mu < 0 \)) the tree–level prediction for \( g_{h^0\tilde{\chi}^0_1\tilde{\chi}^0_1} \) is very small, the loop corrections can even flip the sign of this coupling.

Fig. 3 shows predictions for the LSP relic density as a function of the gaugino fraction. Since the LSP mass has been kept fixed at 70 GeV, both the mass \( M_2 \) of the \( SU(2) \) gauginos[4] and the higgsino mass parameter \( \mu \) vary along the curves. The dotted curve has been obtained ignoring loop corrections to the higgsino masses and couplings; the other two curves include

\[ \text{We assume gaugino mass unification} \]
The LSP relic density $\Omega_{\tilde{\chi}}h^2$ is shown as a function of the gaugino fraction. These results are for a fixed LSP mass, so that both $M_2$ and $\mu$ vary along the text. Further, $|A|$ has been decreased from $2.7m_{\tilde{q}}$ to $2.5m_{\tilde{q}}$ as $M_2$ was increased from about 150 GeV to 1 TeV.

these corrections, with $A$ being close to its upper and lower limit, respectively. We see that in the region of high higgsino purity, the corrections can either increase or decrease the predicted LSP relic density by more than a factor of five. If $A$ is large and positive, a state with 99.9% higgsino purity can form galactic DM haloes ($\Omega_{\tilde{\chi}}h^2 \geq 0.02$), while a state with 99.5% higgsino purity can form all cold DM in the recently popular mixed DM models ($\Omega_{\tilde{\chi}}h^2 \geq 0.15$).

Finally, Fig. 4 shows the dependence of the predicted LSP detection rate in an isotopically pure $^{76}$Ge detector on the $A$ parameter. The dotted curve again holds in the absence of the loop corrections of Figs. 1. There is still some dependence on $A$, due to top–stop loop corrections to $m_{h^0}$ [7]. Clearly the $A$–dependence becomes much stronger once the corrections of Figs. 1 are included (solid curve). If $|A|$ is near its upper limit, these corrections increase the predicted counting rate by about two orders of magnitude. However, they can also lead to an exactly vanishing cross section for LSP scattering off spinless nuclei. This happens near the point where $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = 0$ (see Fig. 2).

In summary, loop corrections re–introduce a 99.5% pure higgsino state as viable CDM candidate. These corrections can also increase the expected LSP detection rate by two orders of magnitude, if $\mu < 0$. In both cases the sign of the corrections can also be opposite, however, suppressing the relic density, and perhaps even reducing the LSP scattering cross section off spinless nuclei to zero.

‡There are also small $q - \tilde{q}$ loop contributions [7] to the scattering matrix element; therefore the complete matrix element vanishes at a small positive value of $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0}$, rather than at $g_{h\tilde{\chi}_1^0\tilde{\chi}_1^0} = 0$. 

Figure 3: The LSP relic density $\Omega_{\tilde{\chi}}h^2$ is shown as a function of the gaugino fraction. These results are for a fixed LSP mass, so that both $M_2$ and $\mu$ vary along the text. Further, $|A|$ has been decreased from $2.7m_{\tilde{q}}$ to $2.5m_{\tilde{q}}$ as $M_2$ was increased from about 150 GeV to 1 TeV.
Figure 4: The expected LSP detection rate in a $^{76}\text{Ge}$ detector is plotted as a function of $A$, with (solid) and without (dotted) the corrections depicted in Figs. 1. The values of the other parameters are: $m_{\tilde{\chi}_1^0} = 70$ GeV, $m_{\tilde{q}} = 430$ GeV, $M_2 = 300$ GeV, $m_A = 1.5$ TeV, and $\tan\beta = 1.5$.

Acknowledgements I thank my collaborators Mihoko Nojiri, D.P. Roy and Youichi Yamada for an enjoyable collaboration. I also thank the members of the KEK theory division for their hospitality while this report was written.

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