Some phenomenological analyses in string theory and M-theory

David G. Cerdeño

Departamento de Física Teórica C-XI and Instituto de Física Teórica C-XVI
Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

Abstract

In these notes I will report some phenomenological analyses performed in two scenarios where the search of realistic models is giving fruitful results: the D-brane constructions in type I string theory and the Hořava-Witten scenario in M-theory. In particular, after summarizing the structure of the soft supersymmetry-breaking terms and the scales in these setups, the implications for direct detection of supersymmetric dark matter will be reviewed.

1 Introduction

The analysis of the phenomenological implications of string constructions might give us some insight on the way the low energy description in terms of the Standard Model can be recovered from them. Two of the most promising setups in this sense are the D-brane scenarios in type I string theory [1] and the Hořava-Witten construction [2] in M-theory, where realistic models have been built. Among the different analyses that can be performed, I will review here the implications of these constructions for direct detection of supersymmetric dark matter.

The lightest neutralino, χ_1^0, in supersymmetric theories might play the role of dark matter when it is the lightest supersymmetric particle. It is the leading candidate within the class of long-lived or stable weakly-interactive massive particles (WIMPs). Direct detection of neutralinos is possible through nuclear recoils after their elastic scattering on target nuclei. Therefore, evaluating the theoretical predictions for the neutralino-nucleon cross-section [3], $\sigma_{\tilde{\chi}_1^0-p}$, allows to determine the feasibility of such a detection by comparison with the sensitivities of dark matter detectors. Among these, the DAMA collaboration reported data favouring the detection of a WIMP signal in their search for annual modulation [4], although other experiments (CDMS [5], IGEX [6], EDELWEISS [7], and HDMS [8]) have already excluded a large part of its parameter space.

As a first step, the structure of the soft supersymmetry-breaking terms and the value of the initial scale for their running will be reviewed for each specific model. The scenarios considered here present qualitative differences in these parameters that will affect the theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$. Along this work, the experimental lower bounds on the masses of the supersymmetric particles [9] have been included, as well as the bounds on the $b \to s\gamma$ branching ratio [10] ($2 \times 10^{-4} \leq BR(b \to s\gamma) \leq 4.1 \times 10^{-4}$) and on a possible supersymmetric contribution to the muon anomalous magnetic moment [11], $a_\mu^{\rm SUSY}$(we will use $51 \times 10^{-10} > a_\mu^{\rm SUSY} > 7 \times 10^{-10}$, which is derived from a recent measurement [12]). The constraints due to the lower bound on the Higgs mass, $m_h < 114.1$ GeV [13, 14], will also be explicitely shown.

2 D-brane scenarios in type I string theory

There exist the interesting possibility that the supersymmetric standard model might be built using D-brane configurations from type I string vacua. In these scenarios the SM gauge group is constructed from the $U(N)$ gauge groups arising from sets of N parallel branes. Realistic models have been explicitely built in this way with three generations of particles [15]. For example, let us consider an scenario [16] where the gauge group $U(3) \times U(2) \times U(1)$, which gives rise to $SU(3) \times SU(2) \times U(1)^3$, arises from different stacks of parallel D-branes (obviously, there must be some overlap of their worldvolumes since otherwise there would be no massless modes corresponding to the exchange of open strings which could give rise to those particles transforming simultaneously under, e.g., $SU(3)$ and $SU(2)$). Here $U(1)_Y$ is a linear combination of the three $U(1)$ gauge groups arising from $U(3)$, $U(2)$, and $U(1)$ (with charges $Q_{1,2,3}$, respectively) so that:

$$Y = -\frac{1}{3}Q_3 - \frac{1}{2}Q_2 + Q_1 \ . \tag{2.1}$$

From this expression we can work out the relation of the gauge couplings associated to each of the gauge groups at the type I string scale, M_I:

$$\frac{1}{\alpha_Y(M_I)} = \frac{2}{\alpha_1(M_I)} + \frac{1}{\alpha_2(M_I)} + \frac{1}{3\alpha_3(M_I)} \ . \tag{2.2}$$

Applying the usual RGE's for the gauge couplings $\alpha_{Y,2,3}$ (assuming the matter content of the MSSM) and using their experimental values at the electroweak scale, as well as the value of M_Z, the following relation is obtained:

$$\ln\frac{M_I}{M_s} = 33.09 - \frac{1.05}{\alpha_1(M_I)} - 1.22\ln\frac{M_s}{M_Z} \ , \tag{2.3}$$

where 200 GeV $\lesssim M_S \lesssim$ 1 TeV is the supersymmetric threshold. For $0.07 \lesssim \alpha_1(M_I) \lesssim 0.1$, intermediate values for the string scale, $M_I \approx 10^{10-12}$ GeV, are obtained. Other examples arising from different D-brane configurations can be found where intermediate scales appear naturally in order to reproduce the low energy data on the coupling constants.

Regarding the soft supersymmetry-breaking terms in these constructions, general formulae were obtained in [17], under the assumption of dilaton/moduli supersymmetry-breaking. The resulting soft parameters are generally non-universal, and the particular example we are considering here also displays this feature [16].

The theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$ are very sensitive to the aforementioned properties: intermediate scales [18] as well as non-universal soft terms [19] might induce an enhancement of $\sigma_{\tilde{\chi}_1^0-p}$ [20]. The first attempts to study dark matter within these constructions were carried out in scenarios with M_{GUT} as the initial scale [21] and dilaton-dominated scenario with an intermediate scale [22]. However, the crucial issue of the D-brane origin of the $U(1)_Y$ gauge group was not included in these analyses. When this is taken into account, as in the the example above, interesting results are obtained. The theoretical predictions for $\sigma_{\tilde{\chi}_1^0-p}$ as a function of the resulting neutralino mass are depicted in Fig. 1 for a complete scan of the parameters, as described in [16], and for two different values of $\tan\beta$. All the points represented satisfy the experimental constraints on the

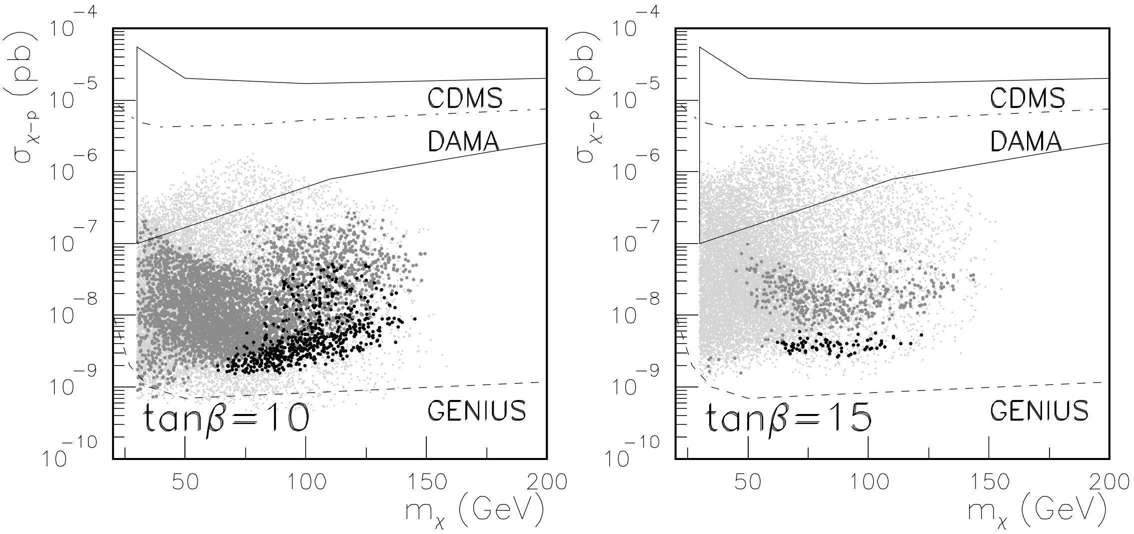

Figure 1: $\sigma_{\tilde{\chi}_1^0-p}$ versus $m_{\tilde{\chi}_1^0}$ in the D-brane scenario discussed in the text. Only dark grey and black dots fulfill $b \to s\gamma$ and $a_\mu^{\rm SUSY}$ constraints. Dark grey dots correspond to points with $91 < m_h < 114.1$ GeV, whereas black dots fulfill $m_h > 114.1$ GeV. The region compatible with DAMA results, as well as the CDMS and the projected GENIUS [23] sensitivities are also depicted.

lower masses of the supersymmetric particles and $m_h \geq 91$ GeV. Small (light grey) dots represent points not fulfilling the $b \to s\gamma$ and $a_\mu^{\rm SUSY}$ constraints. Large dots do satisfy these, and among them, dark grey points have 91 GeV$\leq m_h \leq 114.1$ GeV, while black dots are consistent with the stronger lower bound for the Higgs mass $m_h > 114.1$ GeV. This constraint on the Higgs mass can be lowered for some non-universal cases [14], and therefore we have preferred to show it explicitely.

These predictions for $\sigma_{\tilde{\chi}_1^0-p}$ are larger than those obtained for the minimal supergravity scenario. However, they are still below the sensitivities of the present dark matter detectors due to the experimental constraints, among which, the bound on the Higgs mass is the most important one. Due to the effect of the intermediate scale and the non-universal soft terms, values for the cross-section as large as $\sigma_{\tilde{\chi}_1^0-p} \sim 5 \times 10^{-8}$ can be obtained for $\tan\beta = 10$. Although in principle increasing the value of $\tan\beta$ leads to an enhancement of $\sigma_{\tilde{\chi}_1^0-p}$, the constraints on $b \to s\gamma$ and $a_\mu^{\rm SUSY}$ become more stringent (e.g., the value of $a_\mu^{\rm SUSY}$ turns out to be larger and exceeds the experimental bound more easily). Thus extensive regions of the parameter space are excluded, mainly those with larger values for the cross-section, as it can be seen in the right-hand side of Fig. 1.

3 Heterotic M-theory

The 11-dimensional Hořava-Witten scenario [2], also named heterotic M-theory after its relation to the strong coupling limit of the $E_8 \times E_8$ heterotic string theory, is also an interesting framework where the search of realistic models is giving fruitful results. In this construction the eleventh dimension is compactified on an orbifold S^1/Z_2 and therefore

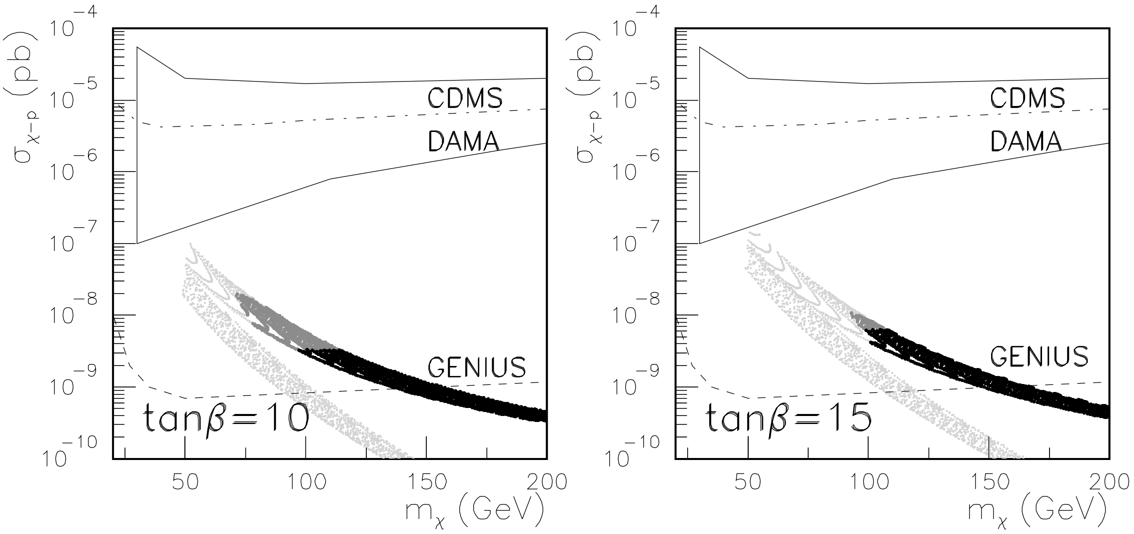

Figure 2: $\sigma_{\tilde{\chi}_1^0-p}$ versus $m_{\tilde{\chi}_1^0}$ for an example of the parameter space of M-theory with one five-brane. The same convention for colours as in Fig. 1 has been used .

there exist two 10-dimensional fixed hyperplanes. The matter fields are confined to these, whereas gravity can propagate along the eleventh dimension. The six remaining extra dimensions can be compactified on a Calabi-Yau threefold in order to obtain an effective $N = 1$, 4-dimensional supergravity.

In this construction, non-perturbative vacua involving the existence of five-branes have been shown to give rise to phenomenologically interesting gauge groups [24]. The effective low-energy theory after compactification [25, 26] is described in terms of the two model independent bulk superfields, the dilaton and the Kähler modulus[a], and a new modulus for each five-brane, which parameterizes its position along the orbifold.

In [27, 28] the parameter space of this effective theory was analyzed. The different scales and the resulting soft terms were evaluated and some phenomenological implications were investigated. The initial scale for the running of the soft parameters was found to be typically of the order of the phenomenologically favoured GUT scale, $M_{GUT} \approx 3 \times 10^{16}$ GeV. Although it is possible to obtain intermediate values for this scale, this always implies unnatural choices of the parameters. The presence of five-branes induces important corrections to the expressions of the soft-terms, and new features appear. For example, obtaining scalar masses larger than gaugino masses is possible for wide ranges of the parameters (this was impossible in the case of the standard embedding). Thus the low-energy spectrum can exhibit qualitative differences with respect to those obtained in non-perturbative vacua.

Several analyses of dark matter in M-theory were performed in non-perturbative vacua [29], as well as in vacua with one five-brane [30], in the limit of dilaton dominated supersymmetry-breaking (although in this case, the corrections of the soft terms reported

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[a] We are assuming a compactification on a Calabi-Yau manifold with only one Kähler modulus, which leads to interesting phenomenological virtues as emphasized in [25]. In particular, the soft supersymmetry-breaking terms are automatically universal, and therefore the presence of dangerous flavour changing neutral currents is avoided.

in [28] were not taken into account). Because we are dealing with universal soft terms and an initial scale of the order of M_{GUT}, the effective theory is a subset of minimal supergravity and the results are qualitatively the same for the whole parameter space. Fig. 2 represents $\sigma_{\tilde{\chi}_1^0-p}$ versus $m_{\tilde{\chi}_1^0}$ for two values of $\tan\beta$ in a representative example. In particular, it corresponds to the case where there is a five-brane located at the middle point of the orbifold interval (the particular instanton numbers in the observable and hidden hyperplane and five-brane charge are described in [28], where also the details on the scan over the different parameters can be found).

The resulting neutralino-nucleon cross-section is in general smaller than in the D-brane scenarios, and is therefore beyond the reach of present dark matter detectors (in particular, no compatibility with the DAMA region can be achieved). When all the experimental constraints are taken into account (being again the bound on the Higgs mass the most restrictive one) the cross-section lies below $\sigma_{\tilde{\chi}_1^0-p} \sim 5 \times 10^{-9}$ pb. Once more, this value cannot be increased for larger values of $\tan\beta$ due to the importance of the $b \to s\gamma$ and a_μ^{SUSY}constraints in those regimes.

4 Outlook

I have reviewed in these notes some phenomenological implications of D-brane scenarios in type I string theory and the Hořava-Witten construction in M-theory. In particular, the theoretical predictions for direct detection of supersymmetric dark matter (neutralinos) have been summarized after reviewing the structure of the scales and soft terms in both setups. On the one hand, D-brane scenarios offer the interesting possibility of having non-universal soft terms, as well as intermediate initial scales for their running. On the other hand, due to the compactification we have considered, the soft terms in the Hořava-Witten scenario are universal. Moreover, the initial scale for their running is of the order of M_{GUT}. For these reasons the predictions for $\sigma_{\tilde{\chi}_1^0-p}$ differ in both cases. In particular, the D-brane constructions predict larger results for this quantity. However, in both cases, the experimental constraints exclude all of the regions compatible with the sensitivities of the present detectors. Therefore, the results for $\sigma_{\tilde{\chi}_1^0-p}$ in these constructions would only be within the reach of future experiments.

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