WMAP Data and Recent Developments in Supersymmetric Dark Matter

Utpal Chattopadhyay\textsuperscript{1(a)}, Achille Corsetti\textsuperscript{2(b)} and Pran Nath\textsuperscript{3(b)}

\textsuperscript{(a)} Department of Theoretical Physics, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India

\textsuperscript{(b)} Department of Physics, Northeastern University, Boston, MA 02115-5005, USA

Abstract

A brief review is given of the recent developments in the analyses of supersymmetric dark matter. Chief among these is the very accurate determination of the amount of cold dark matter in the universe from analyses using WMAP data. The implications of this data for the mSUGRA parameter space are analyzed. It is shown that the data admits solutions on the hyperbolic branch (HB) of the radiative breaking of the electroweak symmetry. A part of the hyperbolic branch lies in the so called inversion region where the LSP neutralino $\chi^0_1$ becomes essentially a pure Higgsino and degenerate with the next to the lightest neutralino $\chi^0_2$ and the light chargino $\chi^\pm_1$. Thus some of the conventional signals for the observation of supersymmetry at colliders (e.g., the missing energy signals) do not operate in this region. On the other hand the inversion region contains a high degree of degeneracy of $\chi^0_1, \chi^0_2, \chi^\pm_1$ leading to coannihilations which allow for the satisfaction of the WMAP relic density constraints deep on the hyperbolic branch. Further, an analysis of the neutralino-proton cross sections in this region reveals that this region can still be accessible to dark matter experiments in the future. Constraints from $g_\mu - 2$ and from $B^0_s \to \mu^+\mu^-$ are discussed. Future prospects are also discussed.

1 Introduction

Very recently the data from the Wilkinson Microwave Anisotropy Probe (WMAP) has allowed analyses of the cosmological parameters to a high degree of accuracy\cite{1, 2}. These analyses also indicate unambiguously the existence of cold dark matter (CDM) and put sharp limits on it. At the same time over the past decade experiments for the direct detection of dark matter have made enormous progress\cite{3, 4, 5, 6} with reliable limits emerging on the CDM component in direct laboratory experiments. Further, experiments are planned which in the future will be able to

\textsuperscript{1}\textsuperscript{E-mail: tpuc@iacs.res.in}
\textsuperscript{2}\textsuperscript{E-mail: corsetti@neu.edu}
\textsuperscript{3}\textsuperscript{E-mail: nath@neu.edu}
improve the sensitivities by several orders of magnitude[7, 8, 9]. In this talk we will give a brief review of the recent developments in supersymmetric dark matter (For a sample of other recent reviews see Ref.[10]). We will review the constraints on the analyses of dark matter from $g_{\mu} - 2$ and from $B_{s,d}^0 \rightarrow \mu^+\mu^-$. We will also discuss the effects of nonuniversalities and the effects of the constraints of Yukawa coupling unification. One of the main focus of our analysis will be the study of dark matter on the hyperbolic branch[11] (and focus point region[12] which is a subpiece of the hyperbolic branch) and its implications for the discovery of supersymmetry[13]. As is well known SUGRA models with R parity provide a candidate for supersymmetric dark matter. This is so because in SUGRA unified models[14, 15] one finds that over a large part of the parameter space the lightest supersymmetric particle (LSP) is the lightest neutralino which with R parity conservation becomes a candidate for cold dark matter (CDM). (An interesting alternate possibility discussed recently is that of axionic dark matter[16]). In the simplest version of SUGRA models[14, 15], mSUGRA, which is based on a flat Kähler potential the soft sector of the theory is parameterized by $m_0, m_2, A_0, \tan \beta$, where $m_0$ is the universal scalar mass, $m_2$ is the universal gaugino mass, $A_0$ is universal trilinear coupling and $\tan \beta = <H_2>/ <H_1>$ where $H_2$ gives mass to the up quark and $H_1$ gives mass to the down quark and the lepton. The minimal model can be extended by considering a curved Kähler manifold and also a curved gauge kinetic energy function. Specifically these allow one to include nonuniversalities in the Higgs sector, in the third generation sector and in the gaugino sector consistent with flavor changing neutral currents[17, 18, 19, 20, 21].

2 Constraints on dark matter analyses

There are a number of constraints that must be imposed in the theoretical analyses of supersymmetric dark matter. These include the constraints from $g_{\mu} - 2$, the flavor changing neutral current (FCNC) constraints, constraints from $B_{s,d}^0 \rightarrow \mu^+\mu^-$ limits, and constraints from the currents limits on the relic density for cold dark matter. Here we discuss some of these. We begin with a discussion of the $g_{\mu} - 2$ constraint. The analysis of $g_{\mu} - 2$ has been under scrutiny for a considerable period of time. In supersymmetry it is predicted that the effects of supersymmetric electroweak corrections to $g_{\mu} - 2$ can be of the same size as the standard model electroweak effects[22]. Furthermore, the sign of the supersymmetric electroweak correction is correlated with the sign of the Higgs mixing parameter $\mu[23, 24]$. 

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It is also known that the effects of extra dimensions on \( g_\mu - 2 \) are substantially smaller than the effects from supersymmetric loop corrections[25]. Experimentally the situation is still somewhat unsettled due to the ambiguity in the errors of the hadronic corrections. A recent estimate of the difference between experiment and the standard model gives[26] a \( \sim 3\sigma \) effect. Further, the sign of the difference in these analyses is positive indicating a positive \( \mu \). In Fig.1 we give a numerical analysis of neutralino-proton cross section \( \sigma_{\chi p} \) which enters in the direct detection of dark matter. The results are taken from the analysis of Ref.[27]. The analysis shows that the \( g_\mu - 2 \) constraint is very strong and eliminates a large part of the parameters space consistent with the relic density constraints. The analysis also shows that a very substantial part of the parameter space consistent with \( g_\mu - 2 \) and relic density constraints will be accessible to future dark matter detectors.

We turn now to the implications of a positive \( \mu \) for Yukawa coupling unification and the implications of the Yukawa unification constraint on supersymmetric dark matter analyses. It is known that \( b - \tau \) unification prefers \( \mu < 0 \)[28]. The above arises from the fact that a negative correction to the b-quark mass is desired for \( b - \tau \) unification and a negative correction is most readily manufactured if \( \mu \) is negative. However, a closer scrutiny shows that the sign of the loop correction to the b quark mass is not rigidly tied to the sign of \( \mu \). Thus the dominant correction to the b quark mass arises from the gluino exchange diagram and the sign of this correction is determined by the sign of \( \mu M_3 \) (see Ref.[29] and the references quoted therein). At same time the supersymmetric correction to \( g_\mu - 2 \) is governed mainly by the chargino exchange and the sign of that contribution is determined by the term \( \mu \tilde{m}_2 \)[30]. Thus it is possible to relax the rigid relationship between the \( \mu \) sign and the sign of the loop correction to the b quark mass while maintaining the usual connection between the sign of \( \mu \) and the sign of the supersymmetric loop correction to \( g_\mu - 2 \). The solution to this relaxation is provided by nonuniversalities which allow one to switch the sign of \( M_3 \) relative to the sign of \( \tilde{m}_2 \). This switch in sign can be seen to arise group theoretically when the gaugino mass terms has nontrivial group transformations. Thus, for example, in \( SU(5) \) the gaugino masses in general tranform like the \((24 \times 24)_s\) representation of \( SU(5) \). Now \((24 \times 24)_s = 1 + 24 + 75 + 200 \) and for the 24 plet on the right hand side one has that the \( SU(3) \times SU(2) \times U(1) \) gaugino masses are in the ratio \( M_3 : M_2 : M_1 = 2 : -3 : -1 \) and there is a relative sign between the \( M_3 \) and the \( M_2 \). Similarly for \( SO(10) \) the gaugino masses transform like the \((45 \times 45)_{sym} \) representations of \( SO(10) \) where
(45 \times 45)_{sym} = 1 + 54 + 210 + 770. Here the 54 plet representation on the right hand gives\[31\] \( M_3 : M_2 : M_1 = 1 : -3/2 : -1 \) and one finds once again that \( M_3 \) and \( M_2 \) have opposite signs. The above possibilities allow for\[32, 33\] (see also\[34\]) \( \mu > 0, \Delta a_\mu > 0, \Delta 有点符号 < 0 \) allowing for \( b-\tau \) unification for a positive \( \mu \). Detailed analyses of these can be found in\[32, 33\] where the implications of Yukawa unification on supersymmetric dark matter are also discussed.

Next we discuss the implications of the \( B^0_{s,d} \rightarrow l^+l^- \) constraint. In the Standard Model \( B(\bar{B}^0_s \rightarrow \mu^+\mu^-) = (3.1 \pm 1.4) \times 10^{-9} \). However, this branching ratio may lie beyond the reach of RUNII which may reach a sensitivity of \( 10^{-8-7} \). It turns out that in SUSY/SUGRA models the \( B(\bar{B}^0_s \rightarrow \mu^+\mu^-) \sim \tan^6 \beta \) for large \( \tan \beta \)[35]. This arises from the so called counterterm diagram. Because of the large \( \tan \beta \) factor the branching ratio in SUSY models can get much larger than in the Standard Model. Specifically in mSUGRA the branching ratio can be as large as \( O(10^{-6}) \) and within reach of RUNII[36]. Further, it was found that CP phases can provide an extra enhancement of \( \sim 10^2 \) in some cases (see Ibrahim and Nath in Ref.[36]). Thus SUSY enhancement brightens the prospect for the observation of this decay at Fermilab. Further, the observation of \( B^0_{s,d} \rightarrow l^+l^- \) will be evidence for SUSY even before the sparticles are seen directly at colliders. In Fig. (2) the implications of the constraints of various limits on \( B^0_{s,d} \rightarrow l^+l^- \) branching ratio are given. Thus, for example, a branching ratio \( BR(B^0_{s,d} \rightarrow l^+l^-) = 10^{-8} \) can probe the parameter space in \( m_{\frac{1}{2}} - m_0 \) in the range up ot 600 GeV-700 GeV for \( \tan \beta = 50, A_0 = \) and \( \mu > 0 \).

3 The Hyperbolic Branch, Supersymmetry and Dark Matter

It was shown quite sometime ago that the radiative breaking of supersymmetry has two branches: an ellipsoidal branch (EB) and a hyperbolic branch (HB). This can be exhibited easily by examining the relation for radiative breaking that determines \( \mu[11] \), i.e.,

\[
C_1 m_0^2 + C_3 m_{1/2}^2 + C'_2 A_0^2 + \Delta \mu^2_{loop} = \mu^2 + \frac{1}{2} M_Z^2
\]

where \( \Delta \mu^2_{loop} \) arise from loop corrections to the effective potential[37]. When \( \tan \beta \) is small, the loop corrections are typically small, and furthermore \( C_1, C_2', C_3 > 0 \) and the variation of these parameters with the renormalization group scale are also
Figure 1: Exhibition of the neutralino-proton scalar cross section for values of \(\tan \beta\) of 5, 10, 30, 50 and \(A_0 = 0\) and \(\mu > 0\). The blue dots are the points satisfying mSUGRA constraints and the red circles additionally satisfy the relic density constraint of \(0.1 < \Omega h^2 < 0.3\). The black squares satisfy the 2\(\sigma\) constraint on \(b \rightarrow s + \gamma\) and \(g_{\mu} = 2\). The limits of various current and future experiments are also indicated. Taken from Ref.[27].
small. In this case the radiative breaking of the electroweak symmetry is realized on the ellipsoidal branch and there is an upper limit to the soft parameters for a fixed value of $\mu$. However, for other regions of the parameter space specifically when $\tan \beta$ is large one finds that $\Delta \mu^2_{\text{loop}}$ is large and furthermore the scale dependence of some of the co-efficients $C_i$ is rather large. Specifically in this case, if one chooses a scale $Q_0$ where the loop correction $\Delta \mu^2_{\text{loop}}$ is minimized one finds that the co-efficient $C_1$ at $Q_0$ turns negative and the hyperbolic branch is realized. Thus on the hyperbolic branch $m_0, m_{1/2}$ can get very large for fixed $\mu$. A very interesting phenomenon of inversion occurs when $M_i >> |\mu|$. In this case an examination of the neutralino mass matrix and of the chargino mass matrix shows that $\chi^0_1, \chi^0_2, \chi^\pm_1$ are essentially degenerate with mass $\mu$. More specifically one finds that[13] (for other analyses that explore the implications of WMAP data see [38, 39])

$$
M_{\chi^0_1} = \mu - \frac{M_Z^2}{2} (1 - \sin 2\beta) [\frac{\sin^2 \theta_W}{M_1 - \mu} + \frac{\cos^2 \theta_W}{M_2 - \mu}]
$$

$$
M_{\chi^0_2} = \mu + \frac{M_Z^2}{2} (1 + \sin 2\beta) [\frac{\sin^2 \theta_W}{M_1 + \mu} + \frac{\cos^2 \theta_W}{M_2 + \mu}]
$$

$$
M_{\chi^\pm_1} = \mu + \frac{M_W^2 \cos^2 \beta}{\mu} - \frac{M_W^2}{\mu} (\frac{M_2 \cos \beta + \mu \sin \beta}{M_2^2 - \mu^2})^2
$$

(2)

In the inversion region the squarks and sleptons and the gluino may lie in the several TeV region and thus may not be easily observable at accelerators. Here
the lightest particles are $h^0, \chi^0_1, \chi^0_2, \chi^{\pm}_1$ where $m_{\chi^0_1} \simeq m_{\chi^{\pm}_1} \simeq m_{\chi^0_2} \simeq \mu$. We note that the mass relations here are in gross violation of the scaling laws[40]. Further, the quantities relevant for the observation of the lightest supersymmetric particles in this case are the mass differences $\Delta M^\pm = m_{\chi^{\pm}_1} - m_{\chi^0_1}$, and $\Delta M^0 = m_{\chi^0_2} - m_{\chi^0_1}$. While $m_{\chi^0_1}, m_{\chi^+_1}, m_{\chi^-_1}$ may lie in the several hundred GeV region, $\Delta M^\pm$ and $\Delta M^0$ lies in the 1-10 GeV region. The smallness of the mass differences makes the observation of these particles rather difficult since the decay of the NLSP and also of the light chargino will result in rather soft particles which may not be observable at the LHC. Situations of this type have been discussed in other contexts in the literature[41, 42]. However, quite surprisingly the satisfaction of the relic density constraints can occur easily in the inversion region. This is so because as pointed out already that in the inversion region there is a near degeneracy of $m_{\chi^0_1}, m_{\chi^+_1}, m_{\chi^-_1}$ which implies a lot of coannihilation. Specifically one has coannihilations[43] involving the processes[13]

$$\chi^+_1\chi^-_1, \chi^0_1\chi^0_2 \rightarrow u_i\bar{u}_i, d_i\bar{d}_i, W^+W^-$$
$$\chi^0_1\chi^+_1, \chi^0_2\chi^0_1 \rightarrow u_i\bar{d}_i, \bar{e}_i\nu_i, AW^+, ZW^+, W^+h$$

(3)

Because of coannihilation relic density constraints can be easily satisfied even though the squark and slepton masses may lie in the several TeV region. Detailed analyses show that in the HB region $\sigma_{\chi^0_1\rightarrow p}$ may still be accessible to dark matter experiment. Thus observation of dark matter may be the only means of observing SUSY effects if the inversion region of HB is realized in nature. We note in passing that the so called focus point region[12] is a part of the hyperbolic branch and corresponds to low values of $m_{\chi^+_1}$. For further discussion see Ref.[11, 13, 38, 39].

4 Analysis of dark matter with WMAP constraints

In this section we discuss the implications of the WMAP constraints. We also discuss the implications for the detection of dark matter in dark matter detectors presently in operation[3, 4, 5, 6] as well as those that are planned for the future[7, 8]. We begin with the result of WMAP which gives for CDM[1, 2]

$$\Omega_\chi h^2 = 0.1126^{+0.016}_{-0.018}$$

(4)

In the theoretical analyses of the relic density coannihilation[44, 45, 46, 47, 48, 49, 50, 51] plays a central role. However, unlike the usual coannihilation phenomena
Figure 3: Regions allowed by the WMAP relic density constraints in the $m_0 - m_{1/2}$ plane for $\tan \beta = 50$ with a $2\sigma$ error corridor around the WMAP constraint. Taken from Ref.[13]

where the particles that enter in the coannihilation process are the neutralino and the stau here the particles that coannihilate are $\chi^0_1, \chi^0_2, \chi^\pm_1$. Specifically the processes are listed in Eq.(3). In the inversion region the neutralino is essentially a Higgsino as opposed to being a Bino which is what happens over the most of the rest of the parameter space of SUGRA models. In Fig.(3) a numerical analysis of the region in the parameter space of $m_0 - m_{1/2}$ allowed under the WMAP relic density constraint with a $2\sigma$ error corridor is exhibited. One finds that the region consistent with the WMAP relic density constraint can indeed stretch to rather large values in $(m_0, m_{1/2})$ extending into several TeV in each direction. In Figs.(4) a further investigation of the parameter space consistent with the relic density constraints is carried out. Thus in Fig.(4a) an analysis of the parameter space in the $m_0$ and $m_{\chi^0_1}$ consistent with the relic density constraint is given. Here one finds that $m_{\chi^0_1}$ is sharply limited while $m_0$ gets large. The vertical patch at $m_{\chi^0_1}$ around a TeV is the inversion region where the neutralino is essentially a Higgsino. A similar phenomenon is visible in Fig.(4b). A plot of the neutralino-proton scalar (spin dependent) cross section $\sigma_{\chi p}$ as a function of $m_{\chi^0_1}$ is given in Fig.(4c)(Fig.(4d)). A comparison with Fig.(1) shows that a significant part of the inversion region will be accessible to future experiments on the direct detection of dark matter.
Figure 4: (a) Plot in $m_0 - m_{\chi_1^0}$ showing the allowed region consistent with WMAP constraints; (b) Same as (a) except the plot is in $m_0 - m_{\chi_1^0}^{1/2}$; (c) Scalar $\sigma_{\chi p}$ cross section as a function of $m_{\chi_1^0}$; (d) Same as (c) except that the plot is for spin dependent $\sigma_{\chi p}$ cross section. The patches exhibit the inversion region where the neutralino is essentially a higgsino. Taken from Ref.[13].
5 Conclusion

In this paper we have given a brief summary of some of the recent developments in supersymmetric dark matter. We have discussed the constraints of $g_\mu - 2$ and of $B_s^0 \to \mu^+\mu^-$ on dark matter analyses. One of the most stringent constraints arises from the recent observation from WMAP which has measured the relic density for CDM to a high degree of accuracy. We discussed the allowed parameter space in mSUGRA satisfying the WMAP constraints. It was shown that quite surprisingly the allowed parameter space is quite large. Specifically one finds that a very significant region on the hyperbolic branch with $(m_0, m_{1/2})$ extending in several TeV still allows the satisfaction of the relic density constraints consistent with WMAP. The consistency with the WMAP data arises due to coannihilation of $\chi^0_1, \chi^0_2, \chi^\pm_1$. Further, one finds that the neutralino-proton cross section fall in range that may be accessible to dark matter detectors in the future. Thus if SUSY is realized deep on the hyperbolic branch, then direct observation of sparticles, aside from the light Higgs, may be difficult. However, degeneracy of $\chi^0_1, \chi^0_2, \chi^\pm_1$ would lead to significant coannihilation and satisfaction of relic density constraints and the direct detection of supersymmetric dark matter may still be possible. Finally, we note that in heterotic string models tan $\beta$ is a determined quantity under the constraints of radiative breaking of the electroweak symmetry[52] and thus dark matter analyses are more constrained in this framework. This constraint will be explored in further work. A similar situation may occur in models based on soft breaking in intersecting D branes[53].

Acknowledgments

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