WMAPing out Supersymmetric Dark Matter and Phenomenology

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Abstract

The recent WMAP data provide a rather restricted range of the Cold Dark Matter (CDM) density $\Omega_{CDM} h^2$ of unprecedented accuracy. We combine these new data along with data from BNL E821 experiment measuring $(g_{\mu} - 2)$, the $b \rightarrow s \gamma$ branching ratio and the light Higgs boson mass bound from LEP, to update our analysis of the allowed boundaries in the parameter space of the Constrained Minimal Supersymmetric Standard Model (CMSSM). The prospects of measuring Supersymmetry at LHC look like a very safe bet, and the potential of discovering SUSY particles at a $\sqrt{s} = 1.1$ TeV linear collider is enhanced considerably. The implications for Dark Matter direct searches are also discussed.
1 Introduction

As promised, the recent WMAP satellite data provide estimates of the relevant parameters characterizing the Standard Cosmological Model with unprecedented accuracy. The WMAP satellite becomes the LEP of the Sky! The current energy density of the Universe is found to be about 73% Dark Energy and 27% Matter. Most of the matter density is in the form of Cold Dark Matter (CDM) as only a very tiny component may be due to hot neutrino dark matter and warm dark matter is ruled out due to the detected early re-ionization of the Universe at a redshift \( z \approx 0.20 \). According to WMAP the total Dark Matter density is \( \Omega_m h^2 = 0.135^{+0.008}_{-0.009} \) while the baryon density is \( \Omega_b h^2 = 0.0224 \pm 0.0009 \). We thus deduce the value for the CDM density, allowing \( 2\sigma \), to be

\[
\Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181} \tag{1}
\]

not in disagreement with similar recent observations but dramatically more precise. These new data should sound like music to the ears of the Supersymmetry practitioners that have envisioned such a state of affairs for some time now. Let us see why? One of the major and rather unexpected predictions of Supersymmetry (SUSY), broken at low energies \( M_{SUSY} \approx \mathcal{O}(1 \text{ TeV}) \), while \( R \)-parity is conserved, is the existence of a stable, neutral particle, the lightest neutralino (\( \tilde{\chi} \)), referred to as the LSP. Such particle is an ideal candidate for the Cold Dark Matter in the Universe, and much in need now. Such a prediction fits well with the fact that SUSY is not only indispensable in constructing consistent string theories, but it also seems unavoidable at low energies (\( \sim 1 \text{ TeV} \)) if the gauge hierarchy problem is to be resolved. Such a resolution provides a measure of the SUSY breaking scale \( M_{SUSY} \approx \mathcal{O}(1 \text{ TeV}) \). There is indirect evidence for such a low-energy supersymmetry breaking scale, from the unification of the gauge couplings and from the apparent lightness of the Higgs boson as determined from precise electroweak measurements, mainly at LEP. In addition, the BNL E821 experiment delivered a more precise measurement for the anomalous magnetic moment of the muon

\[
\alpha_{\mu}^{\exp} = 11659203(8) \times 10^{-10} \tag{2}
\]

where \( \alpha_{\mu} = (g_{\mu} - 2)/2 \), and a detailed calculation of the hadronic vacuum polarization contribution to this moment appeared while a similar calculation based on low-energy \( e^+e^- \) data drew similar conclusions. This calculation, especially using inclusive
data, favours smaller values of the hadronic vacuum polarization. As a result, the discrepancy between the the Standard Model (SM) theoretical prediction and the experimental value for the anomalous magnetic moment of the muon, becomes significant \[7\]

\[\delta \alpha_\mu = (361 \pm 106) \times 10^{-11}, \tag{3}\]

which corresponds to a \(3.3\sigma\) deviation. Combining this with the new WMAP value \[1\] for supesymmetric dark matter density \[1\] one restricts considerably the parameter space of the Constrained Minimal Supersymmetric Standard Model (CMSSM). In our analysis we take into account some other important constraints: the branching ratio for the \(b \to s \gamma\) transition and the light Higgs mass bound \(m_h \geq 113.5\) GeV provided by LEP \[9,10\]. Concerning the \(b \to s \gamma\) branching ratio the \(2\sigma\) bound \(1.8 \times 10^{-4} < BR(b \to s \gamma) < 4.5 \times 10^{-4}\) is used \[10\].

## 2 Neutralino relic density

We have repeatedly pointed out in the past \[12,13,14\] the importance of the smallness of the Dark Matter (DM) relic density in constraining supersymmetric predictions and at the same time we have paid special attention to the large \(\tan \beta\) regime. In this region the neutralino \((\tilde{\chi})\) pair annihilation through \(s\)-channel pseudo-scalar Higgs boson \((A)\) exchange, leads to an enhanced annihilation cross sections reducing significantly the relic density \[11\]. The importance of this mechanism, in conjunction with the cosmological data which favour small values of the DM relic density, has been stressed in \[12,13\]. As mentioned above for large \(\tan \beta\) the \(\tilde{\chi} \tilde{\chi} \rightarrow b \bar{b}\) or \(\tau \bar{\tau}\) channel becomes the dominant annihilation mechanism. In fact by increasing \(\tan \beta\) the mass \(m_A\) decreases, while the neutralino mass remains almost constant, if the other parameters are kept fixed. Thus \(m_A\) is expected eventually to enter into the regime in which it is close to the pole value \(m_A = 2m_\chi\), and the pseudo-scalar Higgs exchange dominates. In previous analyses regarding DM direct searches \[13\], we had stressed that the contribution of the \(C P\)-even Higgs bosons exchange to the LSP-nucleon scattering cross sections increases with \(\tan \beta\). Therefore in the large \(\tan \beta\) region one obtains the highest possible rates for the direct DM searches and the smallest LSP relic densities. Similar results are presented in Ref. \[15\]. As mentioned before in view of the recent WMAP cosmological data, which point towards even smaller and more accurate values of the CDM abundance, the updating of the supersymmetric restrictions imposed is highly demanding. In conjunction with the \((g_\mu - 2)\) E821 data, which has been the subject of intense phenomenological study the last couple of years \[17,16,18,14,19,20,21\], it may considerably limit the bounds
of sparticle masses which is of paramount importance for the next run experiments at LHC or other accelerators [22].

For the correct calculation of the neutralino relic density in the large tan $\beta$ region, an unambiguous and reliable determination of the $A$-mass is required. The details of the procedure in calculating the spectrum of the CMSSM can be found elsewhere [18, 14]. Here we shall only briefly refer to some subtleties which turn out to be essential for a correct determination of $m_A$. In the CMSSM, $m_A$ is not a free parameter but is determined once the other parameters are given. $m_A$ depends sensitively on the Higgs mixing parameter, $m_3^2$, which is determined from minimizing the one-loop corrected effective potential. For large tan $\beta$ the derivatives of the effective potential with respect to the Higgs fields, which enter into the minimization conditions, are plagued by terms which are large and hence potentially dangerous, making the perturbative treatment untrustworthy. In order to minimize the large tan $\beta$ corrections we had better calculate the effective potential using as reference scale the average stop scale $Q_t \simeq \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} [23]$. At this scale these terms are small and hence perturbatively valid. Also for the calculation of the pseudo-scalar Higgs boson mass all the one-loop corrections must be taken into account. In particular, the inclusion of those of the neutralinos and charginos yields a result for $m_A$ that is scale independent and approximates the pole mass to better than 2% [24]. A more significant correction, which drastically affects the pseudo-scalar mass arises from the gluino–sbottom and chargino–stop corrections to the bottom quark Yukawa coupling $h_b$ [25, 26, 27, 28]. The proper resummation of these corrections is important for a correct determination of $h_b$ [29, 30], and accordingly of the $m_A$. Seeking a precise determination of the Higgs boson mass the dominant two-loop corrections to this have been included [31]. Concerning the calculation of the $b \rightarrow s \gamma$ branching ratio, the important contributions beyond the leading order, especially for large tan $\beta$ have been taken into account [32].

In calculating the $\tilde{\chi}$ relic abundance, we solve the Boltzmann equation numerically using the machinery outlined in Ref. [12]. In this calculation the coannihilation effects, in regions where $\tilde{\tau}_R$ approaches in mass the LSP, which is a high purity Bino, are properly taken into account.

Using the new WMAP value for CDM density [11] and the bound for $(g_\mu - 2)$ as described in the introduction, the parameter space is constrained significantly, as depicted in the figures. In the panels of figure [11] we display our results by drawing the cosmologically $2\sigma$ allowed region $0.094 < \Omega_{\tilde{\chi}} h_0^2 < 0.129$ (dark green), in the $m_0, M_{1/2}$

$^{1}$Similar conclusions have been also reached in Ref. [22].
Figure 1: Cosmologically allowed regions of the relic density for of $\tan \beta = 40$ and 45 in the $(M_{1/2}, m_0)$ plane. The mass of the top is taken 175 GeV. In the dark green shaded area $0.094 < \Omega_{\chi} h_0^2 < 0.129$. In the light green shaded area $0.129 < \Omega_{\chi} h_0^2 < 0.180$. The solid red lines mark the region within which the supersymmetric contribution to the anomalous magnetic moment of the muon is $\alpha_{\mu}^{\text{SUSY}} = (361 \pm 106) \times 10^{-11}$. The dashed red line is the boundary of the region for which the lower bound is moved to its $2\sigma$ limit. The dashed-dotted blue lines are the boundaries of the region $113.5 \text{ GeV} \leq m_{\text{Higgs}} \leq 117.0 \text{ GeV}$. The cyan shaded region is excluded due to $b \rightarrow s \gamma$ constraint.

plane, for values of $\tan \beta$ equal to 40 and 45 respectively. For comparison also drawn, in light green, is the region $0.129 < \Omega_{\chi} h_0^2 < 0.180$. Note that the value 0.180 was our previous upper bound [12,13,14]. In the figures shown we used for the top, tau and bottom masses the default values $M_t = 175 \text{ GeV}, M_\tau = 1.777 \text{ GeV}$ and $m_b(m_b) = 4.25 \text{ GeV}$. We have fixed $A_0 = 0$, since our results are not sensitive to the value of the common trilinear coupling. The solid red lines mark the region within which the supersymmetric contribution to the anomalous magnetic moment of the muon falls within the E821 range $\alpha_{\mu}^{\text{SUSY}} = (361 \pm 106) \times 10^{-11}$. The dashed red line marks the boundary of the region when the more relaxed $2\sigma$ value on the lower bound of the E821 range is used. Along the blue dashed-dotted contour lines the light $CP$-even Higgs mass takes values $113.5 \text{ GeV}$ (left) and $117.0 \text{ GeV}$ (right) respectively. The line on the left marks therefore the recent LEP bound on the Higgs mass [9]. Also shown is the chargino mass bound 104 GeV. The shaded area (in red) at the bottom of each figure, labelled by TH, is theoretically forbidden since the light stau is lighter than the lightest of the neutralinos. The cyan shaded region is excluded by the $b \rightarrow s \gamma$ constraint.
For large values of $\tan \beta$, see the right panel of figure 2, a region opens up within which the relic density is cosmologically allowed. This is due to the pair annihilation of the neutralinos through the pseudo-scalar Higgs exchange in the s-channel. As explained before, for such high $\tan \beta$ the ratio $m_A/2m_\tilde{\chi}$ approaches unity and the pseudo-scalar exchange dominates yielding large cross sections and hence small neutralino relic densities. It is for this reason that we give special emphasis to this particular mechanism which opens up for large $\tan \beta$ and delineates cosmologically allowed domains of small relic densities and large elastic neutralino - nucleon cross. In this case the lower bound put by the $(g_\mu - 2)$ data cuts the cosmologically allowed region which would otherwise allow for very large values of $m_0, M_{1/2}$.

For the $\tan \beta = 55$ case, close to the highest possible value, and considering the $2 \sigma$ lower bound on the muon’s anomalous magnetic moment $\alpha_{\mu}^{SUSY} \geq 149 \times 10^{-11}$ and values of $\Omega_\chi h^2$ in the range $0.1126^{+0.0161}_{-0.0181}$, we find that the allowed points are within a narrow stripe. The point with the highest value for $m_0$ is ( in GeV ) at $(m_0, M_{1/2}) = (850, 550)$ and that with the highest $M_{1/2}$ at $(m_0, M_{1/2}) = (750, 600)$. The latter marks the lower end of the line segment of the boundary $149 < 10^{-11} \alpha_{\mu}^{SUSY}$ which amputates the cosmologically allowed stripe. It should be noted that within $1\sigma$ of the E821 data only a few points survive which lie in a small region centered at $(m_0, M_{1/2}) = (725, 300)$. The bounds on $m_0, M_{1/2}$ displayed in figure 2 refer to the $A_0 = 0$ case. Allowing for $A_0 \neq 0$ values, the upper bounds put on $m_0, M_{1/2}$ increase a little and so do the corresponding bounds on sparticle masses.
Table 1: Upper bounds, in GeV, on the masses of the lightest of the neutralinos, charginos, staus, stops and Higgs bosons for various values of $\tan \beta$ if the new WMAP value $\Omega_{CDM}h^2$ for the Dark Matter and the $2\sigma$ bound $149 < 10^{-11} < \alpha_{SUSY}^{\mu} < 573 \times 10^{-11}$, is imposed.

| $\tan \beta$ | $\tilde{\chi}^0$ | $\tilde{\chi}^+$ | $\tilde{\tau}$ | $t$ | $h$ |
|-------------|-----------------|-----------------|-------------|-----|-----|
| 10          | 155             | 280             | 170         | 580 | 116 |
| 15          | 168             | 300             | 185         | 640 | 116 |
| 20          | 220             | 400             | 236         | 812 | 118 |
| 30          | 260             | 470             | 280         | 990 | 118 |
| 40          | 290             | 520             | 310         | 1080| 119 |
| 50          | 305             | 553             | 355         | 1120| 119 |
| 55          | 250             | 450             | 585         | 970 | 117 |

For the LSP, the lightest of the charginos, stops, staus and Higgses the upper bounds on their masses are displayed in Table 1 for various values of the parameter $\tan \beta$, if the new WMAP determination $\Omega_{CDM}h^2$ of the Dark Matter and the $2\sigma$ bound $149 < 10^{-11} < \alpha_{SUSY}^{\mu} < 573$ of E821 is respected. We have also taken into account the limits arising from Higgs boson searches as well as from $b \to s\gamma$ experimental constraints. In extracting these values we used a random sample of 40,000 points in the region $|A_0| < 1$ TeV, $\tan \beta < 55$, $m_0, M_{1/2} < 1.5$ TeV and $\mu > 0$. The lightest of the charginos has a mass whose upper bound is $\approx 550$ GeV, and this is smaller than the upper bounds put on the masses of the lightest of the other charged sparticles, namely the stau and stop, as is evident from Table 1. Hence the prospects of discovering CMSSM at a $e^+e^-$ collider with center of mass energy $\sqrt{s} = 800$ GeV, are not guaranteed. Thus a center of mass energy of at least $\sqrt{s} \approx 1.1$ TeV is required to discover SUSY through chargino pair production. Note that in the allowed regions the next to the lightest neutralino, $\tilde{\chi}'$, has a mass very close to the lightest of the charginos and hence the process $e^+e^- \to \tilde{\chi}\tilde{\chi}'$, with $\tilde{\chi}'$ subsequently decaying to $\tilde{\chi} + l^+l^-$ or $\tilde{\chi} + 2$ jets, is kinematically allowed for such large $\tan \beta$, provided the energy is increased to at least $\sqrt{s} = 860$ GeV. It should be noted however that this channel proceeds via the $t$-channel exchange of a selectron and it is suppressed due to the heaviness of the exchanged sfermion. Therefore only if the center of mass energy is increased to $\sqrt{s} = 1.1$ TeV supersymmetry can be discovered in a $e^+e^-$ collider provided it is based on the Constrained scenario.
Figure 3: Scatter plot of the scalar neutralino-nucleon cross section versus $m_{\tilde{\chi}}$, from a random sample of 40,000 points. On the top of the figure the CDMS excluded region and the DAMA sensitivity region are illustrated. Blue pluses (+) are points within the E821 experimental region $\alpha_{\mu}^{\text{SUSY}} = (361 \pm 106) \times 10^{-11}$ which are cosmologically acceptable $\Omega_{\chi} h^2 = 0.1126^{+0.0161}_{-0.0181}$. Green diamonds (○) are points within the 2σ E821 experimental region and also cosmologically acceptable. Crosses (×) represent the rest of the random sample. The Higgs boson mass bound $m_h > 113.5$ GeV and the $b \to s \gamma$ constraint are properly taken into account.

3 Direct Dark Matter searches

We turn now to study the impact of the new WMAP data on Dark Matter, the $(g_\mu - 2)$, the $b \to s \gamma$ and the Higgs mass bounds, on the direct DM searches. The random sample used in this study is the same used in the previous section when considering the neutralino relic density. In figure 3 we plot the scalar $\tilde{\chi}$-nucleon cross section as function of the LSP mass, $m_{\tilde{\chi}}$. On the top of it the shaded region (in cyan colour) is excluded by the CDMS experiment [33]. The DAMA sensitivity region is plotted in yellow [34]. Pluses (+) (in blue colour) represent points which are both compatible with the E821 data $\alpha_{\mu}^{\text{SUSY}} = (361 \pm 106) \times 10^{-11}$ and the WMAP cosmological bounds $\Omega_{CDM} h^2 = 0.1126^{+0.0161}_{-0.0181}$. Diamonds (○) (in green colour) represent points which are compatible with the 2σ E821 data $149 \times 10^{-11} < \alpha_{\mu}^{\text{SUSY}} < 573 \times 10^{-11}$ and the cosmological bounds. The crosses (×) (in red colour) represent the rest of the points of our random sample. Here the Higgs boson mass, $m_h > 113.5$ GeV and the $b \to s \gamma$ bounds have been properly considered.
taken into account. From this figure it is seen that the points which are compatible both with the \((g_\mu - 2)\) E821 and the cosmological data can yield cross sections slightly above \(10^{-8}\) pb when \(m_{\tilde{\chi}}\) is about 120 GeV. The maximum value of \(m_{\tilde{\chi}}\) is around 200 GeV but in this case the scalar cross section drops by almost an order of magnitude \(10^{-9}\) pb. Accepting the \(2 \sigma (g_\mu - 2)\) bound the maximum value of the scalar cross section is again \(10^{-8}\) pb, for \(m_{\tilde{\chi}} \approx 120\) GeV, but the \(m_{\tilde{\chi}}\) bound is increased to about 280 GeV at the expense of having cross sections slightly smaller than \(10^{-9}\) pb. Considering the \(\mu > 0\) case, it is very important that using all available data, one can put a lower bound \(\approx 10^{-9}\) pb on the scalar cross section which is very encouraging for future DM direct detection experiments [35]. Such a lower bound cannot be imposed when \(\mu < 0\), since the scalar cross section can become very small due to accidental cancellations between the sfermion and Higgs exchange processes. However, this case is not favoured by \((g_\mu - 2)\) and \(b \rightarrow s \gamma\) data.

4 Conclusions

We have combined the new WMAP cosmological data [1] on Dark Matter with recent high energy physics experimental information including measurements of the anomalous magnetic moment of the muon, from E821 Brookhaven experiment, the \(b \rightarrow s \gamma\) branching ratio and the light Higgs boson mass bound from LEP and we studied the imposed constraints on the parameter space of the CMSSM. We have assessed the potential of discovering SUSY, if it is based on CMSSM, at future colliders and DM direct search experiments. The use of the new WMAP data in conjuction with the \(2 \sigma (g_\mu - 2)\) bound can guarantee that in LHC but also in a \(e^+e^-\) collider with center of mass energy \(\sqrt{s} \approx 1.1\) TeV CMSSM can be discovered. The effect of these constraints is also significant for the direct DM searches. For the \(\mu > 0\) case we found that the minimum value of the spin-independent \(\tilde{\chi}\)-nucleon cross section attained is of the order of \(10^{-9}\) pb.

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