Neutralino Dark Matter and Electroweak Baryogenesis

C. Balázs[1], M. Carena[2], A. Menon[1,3], D.E. Morrissey[4], and C.E.M. Wagner[1,3]
[1] HEP Division, Argonne National Laboratory, 9700 Cass Ave., Argonne, IL 60439, USA
[2] Fermi National Accelerator Laboratory, P.O.Box 500, Batavia, IL 60510, USA
[3] Enrico Fermi Institute, Univ. of Chicago, 5640 S. Ellis Ave., Chicago, IL 60637, USA and
[4] Department of Physics, University of Michigan, 3444B Randall Lab., Ann Arbor, MI 48109, USA

This review summarizes the viability that the minimal supersymmetric extension of the standard model (MSSM) can simultaneously provide the correct neutralino relic abundance and baryon number asymmetry of the Universe.

From the observations of the Wilkinson Microwave Anisotropy Probe (WMAP) [1], in agreement with the Sloan Digital Sky Survey (SDSS) [2], the dark matter density of the Universe can be deduced, in critical units, as

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

at 95% CL ($h = 0.71^{+0.04}_{-0.03}$). Since the standard model of particle physics (SM) cannot account for this, new physics has to be invoked to explain dark matter. This new physics has to accommodate non-standard, non-baryonic, massive, weakly interacting particles that make up the observable dark matter. Low energy supersymmetry provides an excellent solution to the origin of dark matter and it has been extensively studied in the literature in different scenarios of supersymmetry breaking [3–10]. In this summary, we limit ourselves to the case when the lightest neutralinos make up all or part of the observed dark matter and we only consider the MSSM.

In order to assess the viability of simultaneous generation of the observed baryon–anti-baryon asymmetry and dark matter, we focus on the narrow parameter region of the MSSM defined by the equations of the previous section. As we established earlier, in this parameter region electroweak baryogenesis is expected to yield the observed amount of baryon density of the Universe. We also assume that the lightest neutralino is lighter than the light stop so that it is stable. To further simplify the analysis, we assume that the gaugino mass parameters M_1 and M_2 are related by the standard unification relation, $M_2 = (g_2^2/g_1^2)\, M_1 \simeq 2\, M_1$. The first and second generation sfermion soft masses are taken to be very large, $m_{\tilde{f}} \gtrsim 10$ TeV, to avoid the electron electric dipole moment (EDM) constraints in the presence of sizable phases. The only phase that we introduce is the one directly related to electroweak baryogenesis (EWBG), namely $Arg(\mu)$ and for convenience we set the phases of A_f equal and opposite to it. For simplicity, we neglect the mixing between CP-even and CP-odd Higgs bosons due to these phases.

We compute the relic abundance of neutralinos as described in [11], and display the main result in Figure 1. This plot shows the typical dependence of the neutralino relic density on $|\mu|$ and M_1 for value of the ratio of the Higgs vacuum expectation values $\tan\beta = 7$, pseudoscalar mass $M_A = 1000$ GeV, and $Arg(\mu) = \pi/2$. The green (medium gray) bands show the region of parameter space where the neutralino relic density is consistent with the 95% CL limits set by WMAP data. The regions in which the relic density is above the experimental bound and excluded by more than two standard deviations are indicated by the red (dark gray) areas. The yellow (light gray) areas show the regions of parameter space in which the neutralino relic density is less than the WMAP value. An additional source of dark matter, unrelated to the neutralino relic density, would be needed in these regions. Finally, in the (medium-light) gray region at the upper right the lightest stop becomes the LSP, while in the hatched area at the lower left corner the mass of the lightest chargino is lower than is allowed by LEP data [1].

[1] $http://lepsusy.web.cern.ch/lepsusy/www/inos\_moriond01/charginos\_pub.html$

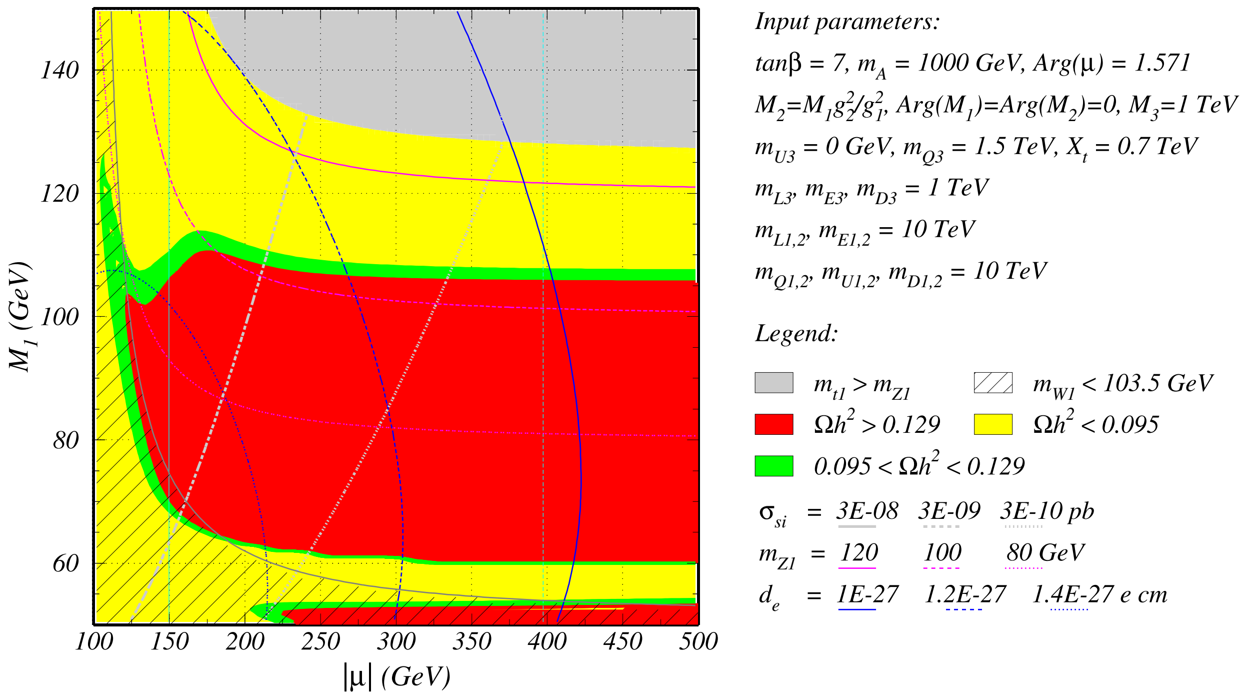

Figure 1: Neutralino relic density as a function of M_1 vs. $|\mu|$ for $M_A = 1000$ GeV and $Arg(\mu) = \pi/2$.

The region where the relic density is too high consists of a wide band in which the lightest neutralino has mass between about 60 and 105 GeV and is predominantly bino. Above this band, the mass difference between the neutralino LSP and the light stop is less than about 20-25 GeV, and stop- neutralino coannihilation as well as stop-stop annihilation are very efficient at reducing the neutralino abundance. There is an area below the disallowed band in which the neutralino mass lies in the range 40-60 GeV, and the neutralino annihilation cross-section is enhanced by resonances from s-channel h^0 and Z^0 exchanges.

The relic density is also quite low for smaller values of $|\mu|$. In these regions, the neutralino LSP acquires a significant Higgsino component allowing it to couple more strongly to the Higgs bosons and the Z^0. This is particularly important in the region near $(|\mu|, M_1) = (175, 110)$ GeV where the neutralino mass becomes large enough that annihilation into pairs of gauge bosons through s-channel Higgs and Z^0 exchange and t-channel neutralino and chargino exchange is allowed, and is the reason for the dip in the relic density near this point. Since the corresponding couplings to the gauge bosons depend on the Higgsino content of the neutralino, these decay channels turn off as $|\mu|$ increases. For higher M_1 values, the lightest neutralino and chargino masses are also close enough that chargino- neutralino coannihilation and chargino-chargino annihilation substantially increase the effective cross section.

In Figure 1, we have taken $M_2 = (g_2^2/g_1^2)M_1$, as suggested by universality. Because of this, smaller values of M_1 and μ are excluded by the lower bound on the chargino mass from LEP data [2], as indicated by the hatched regions in the figures. This constraint becomes much less severe for larger values of the ratio M_2/M_1. We also find that increasing this ratio of gaugino masses (with M_1 held fixed) has only a very small effect on the neutralino relic density.

The search for weakly interacting massive particles is already in progress via detection of their scattering off nuclei by measuring the nuclear recoil. Since neutralinos are non-relativistic they can be directly detected via the recoiling

[2] See the LEPSUSY web-page for combined LEP Chargino Results, up to 208 GeV.

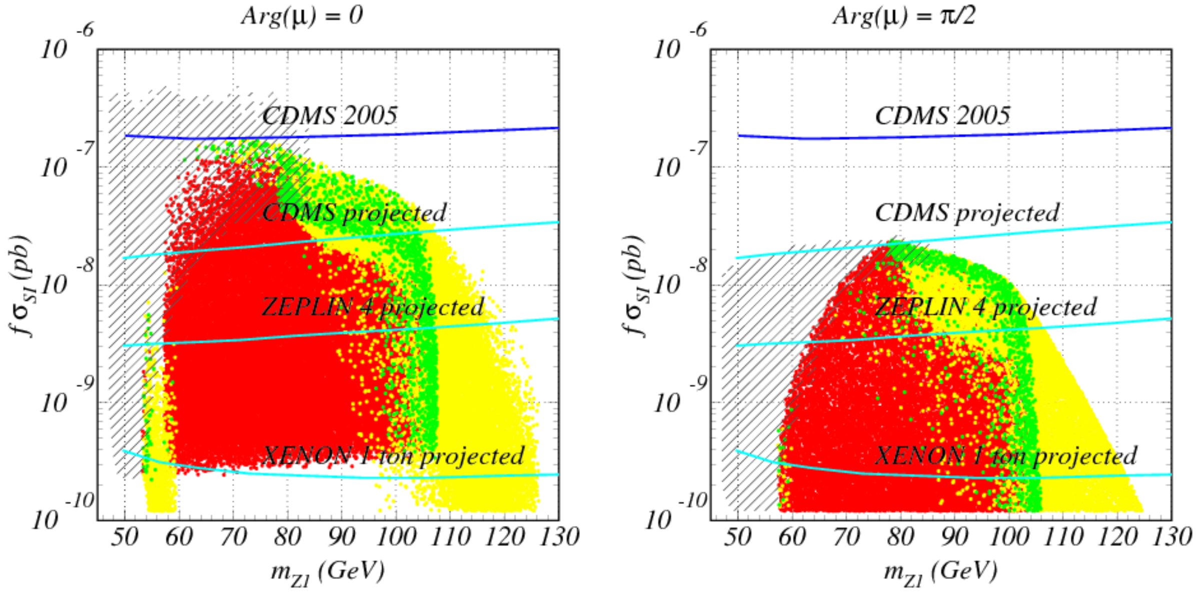

Figure 2: Spin independent neutralino-proton elastic scattering cross sections as a function of the neutralino mass for $Arg(\mu) = 0$ (left) and $Arg(\mu) = \pi/2$ (right). The lower solid (cyan) lines indicate the projected sensitivity of CDMS, ZEPLIN and XENON, respectively.

off a nucleus in elastic scattering. There are several existing and future experiments engaged in this search. In Figure 2, we examine the dependence of the neutralino- proton scattering cross section on the phase of μ. In order to do this, we conduct a random scan over the following range of MSSM parameters:

$$-(80 \text{ GeV})^2 < m^2_{\tilde{U}_3} < 0, \quad 100 \text{ GeV} < |\mu| < 500 \text{ GeV}, \quad 50 \text{ GeV} < M_1 < 150 \text{ GeV},$$
$$200 \text{ GeV} < M_A < 1000 \text{ GeV}, \quad 5 < \tan\beta < 10. \tag{2}$$

Parameters which are not scanned over are fixed as in [11]. The result of the scan, projected on the stop mass versus neutralino mass plane, is shown by Figure 2. Here we plot $f\sigma_{SI}$ as the function of the lightest neutralino mass, where f accounts for the diminishing flux of neutralinos with their decreasing density [12].

For models marked by yellow (light gray) dots the neutralino relic density is below the 2 σ WMAP bound, while models represented by green (medium gray) dots comply with WMAP within 2 σ. Models that are above the WMAP value by more than 2 σ are indicated by red (dark gray) dots. The hatched area is excluded by the LEP chargino mass limit of 103.5 GeV. The top solid (blue) line represents the 2005 exclusion limit by CDMS [13]. The lower solid (cyan) lines indicate the projected sensitivity of the CDMS, ZEPLIN [14] and XENON [15] experiments.

Presently, the region above the (blue) top solid line is excluded by CDMS. In the near future, for $Arg(\mu) = 0$, CDMS will probe part of the region of the parameter space where the WMAP dark matter bound is satisfied. The ZEPLIN experiment will start probing the stop-neutralino coannihilation region together with the annihilation region enhanced by s-channel A^0 resonances. Finally, XENON will cover most of the relevant parameter space for small phases. Prospects for direct detection of dark matter tend to be worse for large values of the phase of μ, $Arg(\mu) \simeq \pi/2$.

Large phases, however, induce sizable corrections to the electron electric dipole moment. As it was shown in [11] the EDM experiments are sensitive probes of this model. Presently the experimental upper limit is

$$|d_e| < 1.6 \times 10^{-27} \, e\, cm, \tag{3}$$

at 90% CL. One- and two-loop contributions with $\mathcal{O}(1)$ phases, containing an intermediate first generation slepton or charginos and Higgs bosons respectively, can easily be larger than this limit. The one-loop diagrams are suppressed by choosing high first and second generation sfermion masses in this work. The two-loop corrections are suppressed by large M_A or small $\tan\beta$. The range of d_e values obtained in our scan are consistent with the the current electron EDM bound and EWBG. On the other hand, for $M_A < 1000$ GeV, about an order of magnitude improvement of the electron EDM bound, $|d_e| < 0.2 \times 10^{-27}\, e\,cm$, will be sufficient to test this baryogenesis mechanism within the MSSM.

In summary, the requirement of a consistent generation of baryonic and dark matter in the MSSM leads to a well defined scenario, where, apart from a light stop and a light Higgs boson, one has light neutralinos and charginos, sizeable CP violating phases, and moderate values of $5 \lesssim \tan\beta \lesssim 10$. All these properties will be tested in a complementary fashion by the Tevatron, the LHC and a prospective ILC, as well as through direct dark-matter detection experiments in the near future. The first tests of this scenario will probably come from electron EDM measurements, stop searches at the Tevatron and Higgs searches at the LHC within the next few years.

Research at the HEP Division of ANL is supported in part by the US DOE, Division of HEP, Contract W-31-109-ENG-38. Fermilab is operated by Universities Research Association Inc. under contract no. DE-AC02-76CH02000 with the DOE.

References

[1] **WMAP** Collaboration, D. N. Spergel *et. al.*, *Astrophys. J. Suppl.* **148** (2003) 175, [astro-ph/0302209].

[2] **SDSS** Collaboration, M. Tegmark *et. al.*, *Phys. Rev.* **D69** (2004) 103501, [astro-ph/0310723].

[3] R. Arnowitt, B. Dutta, B. Hu, and Y. Santoso, *Phys. Lett.* **B505** (2001) 177–183, [hep-ph/0102344].

[4] A. Djouadi, M. Drees, and J. L. Kneur, *JHEP* **08** (2001) 055, [hep-ph/0107316].

[5] J. R. Ellis, K. A. Olive, Y. Santoso, and V. C. Spanos, *Phys. Lett.* **B588** (2004) 7–16, [hep-ph/0312262].

[6] J. R. Ellis, K. A. Olive, Y. Santoso, and V. C. Spanos, *Phys. Rev.* **D69** (2004) 095004, [hep-ph/0310356].

[7] A. B. Lahanas, N. E. Mavromatos, and D. V. Nanopoulos, *Int. J. Mod. Phys.* **D12** (2003) 1529–1591, [hep-ph/0308251].

[8] H. Baer and C. Balazs, *JCAP* **0305** (2003) 006, [hep-ph/0303114].

[9] J. L. Feng, S. Su, and F. Takayama, *Phys. Rev.* **D70** (2004) 075019, [hep-ph/0404231].

[10] J. L. Feng, S.-f. Su, and F. Takayama, *Phys. Rev.* **D70** (2004) 063514, [hep-ph/0404198].

[11] C. Balazs, M. Carena, A. Menon, D. E. Morrissey, and C. E. M. Wagner, *Phys. Rev.* **D71** (2005) 075002, [hep-ph/0412264].

[12] J. R. Ellis, A. Ferstl, and K. A. Olive, *Phys. Rev.* **D63** (2001) 065016, [hep-ph/0007113].

[13] **CDMS** Collaboration, D. S. Akerib *et. al.*, astro-ph/0509259.

[14] D. B. Cline, H.-g. Wang, and Y. Seo, *eConf* **C010630** (2001) E108, [astro-ph/0108147].

[15] **XENON** Collaboration, R. J. Gaitskell, prepared for IDM 2004: 5th International Workshop on the Identification of Dark Matter, Edinburgh, Scotland, United Kingdom, 6-10 Sep 2004.