CERN-TH.6042/91

SUPERSYMMETRIC DARK MATTER BELOW THE W MASS

LESZEK ROSZKOWSKI*

Theory Division, CERN, CH-1211 Geneva 23, Switzerland

ABSTRACT

A light neutralino, with mass below m_W , is considered as a candidate for dark matter. It is found that, in minimal supersymmetry, for predominantly gaugino-like and higgsino-like neutralinos the relic mass density is naturally close to the critical density, while for a general superposition of both gauginos and higgsinos it is typically very small. If at least one light sfermion exists, then a light gaugino-like neutralino also becomes cosmologically less attractive.

CERN-TH.6042/91

March 1991

* Talk given at the UCLA International Conference on Trends in Astroparticle Physics, Nov. 28- Dec. 1, 1990.

Introduction

Supersymmetry^[1] provides a natural candidate for dark matter^[2](DM) in the Universe. It predicts that the lightest supersymmetric particle (LSP) is absolutely stable. In principle such a stable massive particle could account for most matter in the Universe, which is believed to be dark. A favorite choice^[3,4] for both the LSP and DM has become the lightest neutralino^[5] $\tilde{\chi}$, a linear combination of the fermionic partners of the neutral gauge and Higgs bosons. Other candidates for DM, like heavy neutrinos and sneutrinos,^[6] have been excluded^[7] by LEP^[8] and ⁷⁶Ge data.^[9] In contrast, the lightest neutralino has been only mildly constrained^[10] to be heavier than about 13 GeV .[†] In addition, its relic mass density left after the Big Bang is typically comparable to the critical density.^[11–13]

Cosmological consequences of the LSP have been mainly studied within the framework of the Minimal Supersymmetric Standard Model^[13,14] (MSSM), the simplest supersymmetric model of phenomenological interest. The photino, considered originally,^[3] has by now been experimentally excluded in the context of the MSSM. Subsequent studies^[4,11] considered a general neutralino case. The case of a heavy, or even ultra-heavy, LSP was extensively studied in the approximation of the LSP being the bino or the (anti)symmetric higgsino^[12] and in general,^[13] and relatively mild cosmological upper limits of several TeV were set on the LSP mass. Naturalness, on the other hand, suggests^[17] that the LSP should not be much heavier than m_W , the neutralino mass range to be also directly explored by LEP 200. In this report, I summarize the main results of a recent study^[18,19] that has focused primarily on the case of a light neutralino, with $m_{\tilde{\chi}} < m_W$, being a general superposition of both gauginos and higgsinos. I also take into account the recent experimental limits from LEP, UA2, and CDF. In the considered region, in addition to the channel $\tilde{\chi}\tilde{\chi} \rightarrow \tilde{f}\tilde{f}$ which typically dominates the annihilation cross-section, other possible LSP annihilation channels, i.e., $\tilde{\chi}\tilde{\chi} \rightarrow \text{Higgs pairs}$ (also considered in Ref. 20), and $\tilde{\chi}\tilde{\chi} \rightarrow Z\text{--Higgs}$, can become kinematically allowed. It has been found^[18,19] that

[†] Strictly speaking this bound has been obtained in the context of the most restrictive version of minimal supersymmetry, and in general does not hold.

these additional channels may in certain cases have a significant effect on the LSP relic density.

It is convenient to express the relic mass density in terms of the relic abundance $\Omega_{\tilde{\chi}} h_0^2 \equiv \rho_{\tilde{\chi}}/\rho_{\text{crit}}$, where h_0 is the Hubble parameter in units of 100 km/s/Mpc . If $\Omega_{\text{tot}} = 1$ and the Universe is at least 10 billion years old, then $0.5 \lesssim h_0 \lesssim 0.7$.^[21] Since DM is expected to account for most matter in the Universe (perhaps as much as 90 %),^[21] the range $0.25 \lesssim \Omega_{\tilde{\chi}} h_0^2 \lesssim 0.5$ is of most interest as it corresponds to the relic density close to the critical density. Conservatively, however, one excludes on cosmological grounds only the range $\Omega_{\tilde{\chi}} h_0^2 \gtrsim 1$ (unless the Universe is younger than expected). On the other side, small values of $\Omega_{\tilde{\chi}} h_0^2$ ($\lesssim 0.025$) are not interesting cosmologically, as they do not account even for enough dark matter in galactic halos. One goal of the presented study^[18] has been to point out regions of the neutralino parameter space where the relic density is persistently either too large ($\Omega_{\tilde{\chi}} h_0^2 \gtrsim 1$), causing the Universe to overclose; or too small ($\Omega_{\tilde{\chi}} h_0^2 \lesssim 0.025$). A priori, this is not simple given the fact that even in the simplest approach, at least six independent parameters have to be considered. It has been found that generally the LSP consisting of comparable fractions of both gaugino and higgsino components gives a rather small ($\lesssim 0.1$) relic abundance. This is true also for $m_{\tilde{\chi}} > m_W$ even if the LSPs annihilate only to the partial final states that have been taken into account. It is obvious that after including other final states, like WW and ZZ , the relic density will become even smaller. In the region below m_W , asymptotically large values of the mass parameters μ and M_2 of a few TeV are excluded as they correspond to too much DM. The second main goal of the presented work has been to re-examine in detail the dependence of the relic density of LSPs on the independent parameters. Here, I would like to stress a particular sensitivity to sfermion masses. It is found that even one light sfermion ($m_{\tilde{f}} \approx m_{\tilde{\chi}}$), e.g., the selectron $\tilde{e}$, causes the LSP relic mass density to be greatly reduced and strongly disfavors gaugino-like regions of $m_{\tilde{\chi}} < m_W$ on cosmological grounds for natural values of the parameters μ and M_2 .

I will first briefly review the neutralino/chargino sector of the MSSM, and list

the relevant experimental constraints that are now available. Next, I will present and discuss the relic mass density of the LSPs. Finally, I will summarize main implications for future prospects for both LSP and DM searches.

Neutralinos and Charginos

In the MSSM, the lightest neutralino χ is one of the four mass states resulting from mixing of the neutral wino $\tilde{W}^3$, the bino $\tilde{B}$, and the two neutral higgsinos $\tilde{H}_1^0$ and $\tilde{H}_2^0$

$$\chi_1^0 = N_{11}\tilde{W}^3 + N_{12}\tilde{B} + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0. \quad (1)$$

Hence $\chi \equiv \chi_1^0$. The neutralino mass spectrum can be described in terms of just three parameters: $\tan\beta \equiv v_2/v_1$, μ and M_2 , when the usual GUT relationship between the soft masses M_1 and M_2 of the bino and the wino, respectively, and the mass $m_{\tilde{g}}$ of the gluino, is assumed:

$$M_1 = \frac{5}{3} \tan^2 \theta_W M_2 \approx 0.5 M_2 \quad (2)$$

as well as

$$M_2 = \frac{g_2^2}{g_s^2} m_{\tilde{g}} \approx 0.3 m_{\tilde{g}}. \quad (3)$$

It is not restrictive to assume that $M_2 > 0$, in which case μ can be both negative and positive. Charginos $\chi_1^\pm$ and $\chi_2^\pm$, with $m_{\chi_1^\pm} < m_{\chi_2^\pm}$, are the mass states of the charged winos $\tilde{W}^\pm$ and the charged higgsinos $\tilde{H}_1^\pm$ and $\tilde{H}_2^\pm$. Expressions for the neutralino mass matrix and chargino masses can be found in Ref. 19, or in standard references.^[9,16]

I present in Figs. 1 and 2 the LSP mass contours in the (μ, M_2) plane for two representative values of $\tan\beta$: $\tan\beta = 2$ and 8. Several experimental constraints have limited the allowed parameter space considerably. First, LEP^[6] tells us that the lightest chargino $\chi_1^\pm$ is heavier than about 45 GeV. Second, UA2^[21] provides us with a lower bound on the gluino mass, $m_{\tilde{g}} > 79$ GeV, which implies, via (3),

Fig. 1: Contours of the LSP mass (short-dashed: 25 GeV, long-dashed: 40 GeV, dot-dashed: 60 GeV, solid: m_W) in the (μ, M_2) plane for $\tan\beta = 2$. Also shown are the regions of the LSP being an almost pure gaugino ($N_{11}^2 + N_{12}^2 \geq 0.99$) and higgsino ($N_{13}^2 + N_{14}^2 \geq 0.99$) (solid), as well as an almost pure bino $\tilde{B}$ and (anti)symmetric higgsino $\tilde{H}_{A,S}$ (short-dashed), as defined in the text. Other regions are marked as 'MIXED'. The allowed region is constrained by several experimental data. The results from ALEPH and CDF are preliminary.

that $M_2 > 23.5$ GeV. (A new preliminary bound of $m_{\tilde{g}} \gtrsim 150$ GeV from CDF^[23] is now also available.) Finally, very recently, ALEPH^[24] has excluded significant fractions of the (μ, M_2) plane on the basis of an unsuccessful search for neutralinos.

(For a more comprehensive discussion of current experimental constraints, see e.g., Ref. 25.)

Fig. 2: Same as Fig. 1 but for $\tan \beta = 8$. Only the most restrictive constraints (from LEP and ALEPH) are shown.

In addition, recent Higgs searches at LEP imply that $\tan \beta > 1.6$. By combining all the experimental constraints listed above, one obtains^[9] a lower bound of about 13 GeV on the mass of the lightest neutralino.^{*} This limit is improved to

^{*} After the publication of Ref. 10, it has been shown^[10] that radiative corrections again allow $\tan \beta$ as small as one. At the same time, however, ALEPH^[10] has enlarged excluded regions in the (μ, M_2) plane for smaller values of $\tan \beta$, so that the bound of about 10 – 13 GeV is still expected to hold.

about 20 GeV by the CDF preliminary limit on the gluino mass.^[10]

Note the asymptotic behaviour of the contours: for large $|\mu|$, $m_\chi \approx M_1$ and the LSP is a nearly pure bino; while for large M_2 , $m_\chi \approx |\mu|$ and χ is a nearly pure (anti)symmetric higgsino ($\tilde{H}_S$, defined as $\tilde{H}_{A,S} \equiv [\mp \tilde{H}_1 + \tilde{H}_2]/\sqrt{2}$. In Figs. 1 and 2, I delineate domains where the LSP is gaugino-like ($N_1^2 + N_2^2 \geq 0.99$) or higgsino-like ($N_3^2 + N_4^2 \geq 0.99$), as well as the (sub)regions where the LSP is a nearly pure bino $\tilde{B}$ or (anti)symmetric higgsino $\tilde{H}_{A,S}$ with the same 99 % purity.^{*} It is clear that outside the nearly pure regions there is still a large portion of the allowed region of the (μ, M_2) plane where the LSP may consist of significant fractions of both gauginos and higgsinos. I will call such regions 'mixed'.

Let me also briefly mention the Higgs sector^[10] of the MSSM. It consists of five physical scalars: two charged fields $H^\pm$, with mass $m_{H^\pm} > m_W$; two neutral scalar fields h, H , with masses m_h, m_H ($m_h \leq |\cos 2\beta| m_Z < m_Z < m_H$); and a pseudoscalar field A , with mass $m_A < m_h < m_H$. All these masses are strongly constrained by supersymmetry and can be given in terms of just two free parameters, which I take to be m_A and $\tan \beta$.

The neutralino relic mass density

Our task is to compute the relic abundance $\Omega_\chi h_0^2$ of LSPs. The input from particle physics is contained in the invariant amplitude square for the annihilation process $\chi\chi \rightarrow \text{final states}$, and in the quantity $\langle \sigma v_{rel} \rangle$, which is the thermally averaged product of the total annihilation cross section and the relative velocity of the LSPs, in the regime where the photon temperature T is much smaller than the LSP mass, $x \equiv T/m_\chi \ll 1$,

$$\langle \sigma v_{rel} \rangle \simeq a + bx. \quad (4)$$

I follow the method of Ref. 27 in computing a and b . Once these are obtained,

^{*} An almost pure bino $\tilde{B}$ with purity p satisfies $N_1^2 \geq p$, and analogously, nearly pure symmetric and antisymmetric higgsinos with purity p are those higgsino-like states with purity p (i.e., satisfying $N_3^2 + N_4^2 \geq p$) for which $(|N_3| + |N_4|)^2/2 \geq p$. Note that this definition of purity is more stringent than the one given by Olive and Stenlund.^[10]

one numerically solves the Boltzmann equation with the initial condition of the LSPs being in thermal equilibrium with photons at $x \gg 1$. Several procedures of computing the relic mass density are used in the literature. For the present purpose, it is enough to use an early approximate method^[9] of solving the Boltzmann equation, which is accurate to about 10 % (except near poles and thresholds).

I will first consider the channels $XX \rightarrow \bar{f}f$, where f is a conventional quark or lepton. These are always kinematically allowed, and occur through the Z -boson exchange in the s -channel, the exchange of scalar partners $\tilde{f}_{L,R}$ of conventional fermions in both t -channel and u -channels, and the exchange of Higgs bosons in the s -channel. These LSP annihilation channels are typically dominant for $m_\chi < m_W$. A complete calculation of the annihilation cross section has been performed for this process, including all possible exchanges of virtual particles in all three (s, t, u) channels, for the LSP χ being a general superposition of gauginos and higgsinos. These results can be found in Refs. 19 and 29. Below, I will merely briefly summarize the main points pertaining to this process:

1. The Z -boson exchange is important primarily in the ‘mixed’ and the higgsino-like regions. This is due to the $Z\chi\chi$ coupling which is proportional to $(N_{13}^2 - N_{14}^2)$. Note, however, that in the limit of the LSP being almost pure (anti)symmetric higgsinos $\tilde{H}_{A,S}$ the Z -exchange again becomes suppressed.
2. In general, LSP annihilation through sfermion exchanges is dominant in the gaugino-like regions, where the relevant Feynman couplings are comparable to the gauge coupling. On the other hand, sfermion couplings to higgsino-like LSPs are suppressed by a factor m_f/m_W , and in this case the sfermion exchange is relatively much less important below the top threshold. (For $m_\chi > m_t$ it becomes dominant.)
3. The Higgs exchange contribution^[14] to the LSP annihilation into $\bar{f}f$ is never dominant (except around the poles), but it can have significant impact on the relic density by shifting the locations and magnitude of the domains of its favored range. The relative importance of the Higgs exchange is bigger

for larger m_f and smaller Higgs masses. It is suppressed by the Higgs boson couplings to fermions ($\sim m_f/m_W$) and vanishes in the pure gaugino and higgsino limits.

In addition, I have included the Higgs-pair final states: hh, AA, hH, hA , and HA , as well as Z -Higgs final states: Zh and ZA , which may become kinematically allowed below m_W . They are of a relatively lesser importance, unless all the sfermions are rather heavy.^[19]

In the region $m_\chi > m_W$ LSPs can in addition annihilate into several new important final states: $WW, ZZ, H^+H^-, HH, W^\mp H^\pm, ZH$, and $t\bar{t}$. Out of these, I have considered only the following LSP annihilation channels: $XX \rightarrow HH, ZH, t\bar{t}$, and evaluated the relic density in the region above m_W . Obviously, this results in greatly overestimating the relic density in this region, as the neglected channels (especially WW and ZZ) will dramatically diminish the regions above m_W where the indicative results show enough, or too much, dark matter. My goal has been, however, to point out those regions in the parameter space where LSP annihilation into the final states that have been included in the analysis, already gives unacceptably small relic abundance.

Results

The results are presented as contours of constant relic abundance $\Omega_\chi h_0^2$ in the plane (μ, M_2) for two representative choices of $\tan\beta$: $\tan\beta = 2$ (Figs. 3 and 4) and 8 (Fig. 5 and 6). As mentioned in the Introduction, the primary goal of this report has been twofold: (a) to display those regions in the parameter space where the relic abundance is always either too large ($\Omega_\chi h_0^2 \gtrsim 1$), or unacceptably small ($\lesssim 0.025$); and (b) to point out the dramatic role of even one light sfermion in reducing the relic density of the gaugino-like LSPs. I will illustrate both points by considering two extreme choices for the sfermion masses: in Figs. 3 and 5 I set all the sfermion masses at 1 TeV (which is effectively equivalent to neglecting all the sfermion contributions altogether); and in Figs. 4 and 6 I allow one sfermion

(I choose the selectron $\tilde{e}$) to be as light as possible. The experimental lower bound on the mass of the selectron of about 40 GeV comes from LEP^[9] (for other sleptons the limits are similar). Experimental lower limits on the masses of squarks are, on the other hand, much more stringent. Preliminary results from CDF indicate that $m_{\tilde{q}} \gtrsim 150\text{ GeV}$ ^[23]. In order to maximize the role of one light fermion I thus set $m_{\tilde{e}} = 40\text{ GeV}$, whichever is larger. Finally, I take typical values of $m_h = 50\text{ GeV}$ for the Higgs mass and $m_t = 150\text{ GeV}$ for the mass of the top quark. A more thorough discussion of these results can be found in Ref 19.

Several distinct domains of different relic abundance are present in the allowed regions of the (μ, M_2) plane in Figs. 3–6. Their size and location strongly depend on the values of external parameters, like $\tan\beta$ and the masses of sfermions and Higgs bosons. A number of common features can nevertheless be noticed. Firstly, in the ‘mixed’ regions, both below and above m_W , the relic density is typically rather small ($\Omega_\chi h_0^2 \lesssim 0.1$), often even too small to provide enough DM in galactic halos ($\Omega_\chi h_0^2 \lesssim 0.025$). This deficit of DM in the ‘mixed’ regions is caused by the fact that a general neutralino annihilates very efficiently into several final states. Notice that those regions of very small relic abundance are likely to be actually somewhat larger since the relic density for $m_\chi > m_W$ has been underestimated. Thus I conclude that the ‘mixed’ regions, although not excluded, are cosmologically not very interesting.^[24]

In Figs. 3 and 5, all the sfermion masses have been assumed very large ($m_{\tilde{f}} = 1\text{ TeV}$). This has a relatively small effect in the higgsino-like regions, where the corresponding Feynman couplings are suppressed by a ratio m_f/m_W , but in the gaugino-like regions the relic density comes out to be typically very large (even by several orders of magnitude larger than the critical density, as in Fig. 3). By comparing Fig. 3 with Fig. 4, and Fig. 5 with Fig. 6, one can easily notice a dramatic effect that the existence of even one light sfermion, with $m_{\tilde{f}} \gtrsim m_\chi$, has on reducing the relic abundance of a gaugino-like LSP. Note that while I have chosen the selectron, any sfermion would have had a comparable effect since the gaugino-like LSP coupling to sfermions is not suppressed by the corresponding

Fig. 3: Contours of the LSP relic abundance $\Omega_\chi h_0^2$ in the allowed regions of the (μ, M_2) plane for $\tan\beta = 2$ and $m_f = 1\text{ TeV}$. The areas recently excluded by ALEPH are marked by a thick long-dashed line. For reference, the regions where the LSP is an almost pure gaugino or higgsino are marked by thick short-dashed lines, and the contour $m_\chi = m_W$ by a thick solid line (compare Fig. 1). Thin solid lines in the blank areas correspond to $\Omega_\chi h_0^2 = 0.025$, and thin long-dashed lines to $\Omega_\chi h_0^2 = 0.1$. Dense-dotted lines delimit the theoretically preferred regions where $0.25 < \Omega_\chi h_0^2 < 0.5$. Finally, grey areas encircled by thin solid lines correspond to $\Omega_\chi h_0^2 > 1$ and are cosmologically excluded. The relic abundance above m_W is significantly overestimated, as discussed in the text. In particular, grey areas in the almost pure gaugino and higgsino regions are expected to disappear once all final states are taken into account.

Fig. 4: Same as in Fig. 3, except the selectron mass is taken to be equal to m_χ , but not less than 40 GeV .

fermion mass.

Secondly, for large M_2 and $|\mu| \approx m_W$ (higgsino regions) the relic abundance $\Omega_\chi h_0^2$ increases with increasing M_2 , and eventually becomes larger than one (grey areas in the graphs), except for narrow bands of small $\Omega_\chi h_0^2$ due to Z - and Higgs poles. This growth of the relic abundance is caused by the fact that the process $\chi\chi \rightarrow \bar{f}f$ is considerably suppressed in the higgsino-like region roughly around $m_\chi \sim m_W$, while other kinematically allowed annihilation channels are rather subdominant for higgsino-like LSPs.

Of course, once the vector boson final states (WW and ZZ) are taken into

Fig. 5: Same as in Fig. 3, except for $\tan \beta = 8$.

account, the relic density will decrease dramatically in the higgsino regions above m_W , but not below. Asymptotically large values of M_2 are thus cosmologically excluded for m_χ below m_W . Qualitatively similar conclusions have been obtained in Ref. 12 in the limit of a pure higgsino but the quantitative pattern of relic density contours below m_W is in this approximation considerably oversimplified, mainly due to neglecting the s -channel exchanges of the Z and the Higgs bosons. Their effect is clearly visible in the presented figures. Note that in the higgsino-like regions below m_W there always exist some domains where the relic abundance is neither excessively large (to overclose the Universe) nor too small to provide a solution to the DM problem. Those theoretically preferred domains are bigger and

located at smaller (and more natural) values of M_2 when $\tan \beta$ is smaller. Their dependence on the sfermion masses is negligible. The regions of a light higgsino-like neutralino should be thus of primary interest to both supersymmetry and dark matter hunters.

Fig. 6: Same as in Fig. 4, except for $\tan \beta = 8$.

Finally, above m_W for large values of $|\mu|$ and M_2 , the relic density grows again due to the increase of m_χ , as expected, and cosmological limits^[12,13] can be placed on the ultra-heavy LSPs. I note also that the new final states involving Higgs bosons which at some point become kinematically allowed, are of relatively small significance below m_W but can be quite important for larger values of m_χ . A more

detailed discussion of the relative contribution of the various annihilation channels to reducing the relic abundance of the LSPs can be found in Ref. 19.

Conclusions

I conclude by re-emphasizing that, in the context of minimal supersymmetry, a light neutralino, with the mass below m_W , may be an attractive DM candidate. Several regions of the neutralino parameter space have been identified where the relic density of the LSPs is always naturally close to the critical density. In these domains the LSP is predominantly gaugino- or higgsino-like. Conversely, the neutralinos consisting of comparable fractions of both gaugino and higgsino components generally annihilate very effectively and their relic density is typically rather small ($\Omega_\chi h^2 \lesssim 0.1$), often even too small to account for DM in galactic halos ($\Omega_\chi h^2 \lesssim 0.025$). If one or more light sfermions ($m_{\tilde{f}} \gtrsim m_\chi$) exist, which is a rather likely possibility, then also light gauginos become much less attractive as DM candidates. Thus I conclude that a light higgsino, either $\tilde{H}_3$ or $\tilde{H}_4$, with mass somewhat smaller than m_W (60 to 80 GeV) emerges as a likely candidate for both the LSP and DM. Future accelerator searches as well as cold DM searches should seriously contemplate focusing on the higgsino case with mass considerably bigger than previously thought but still below the mass of the W .

Acknowledgements

I acknowledge an early collaboration on the subject with J. Lopez and K. Yuan.^[16] I am grateful to J.-F. Grivaz for informing me about the most recent results from ALEPH on the neutralino searches at LEP.^[24]

REFERENCES

1. For a review, see *e.g.*, H. -P. Nilles, Phys. Rep. 110 C (1984) 1.
2. For reviews, see *e.g.*, V. Trimble, Ann. Rev. Astron. Astrophys. 25 (1987) 425; J. R. Primack, B. Sadoulet, and D. Seckel, Ann. Rev. Nucl. Part. Sci. 38 (1988) 751.
3. H. Goldberg, Phys. Rev. Lett. 50 (1983) 1419; L. M. Krauss, Nucl. Phys. B 227 (1983) 556.
4. J. Ellis, J. S. Hagelin, D. V. Nanopoulos, K. A. Olive and M. Srednicki, Nucl. Phys. B 238 (1984) 453.
5. H. E. Haber and G. L. Kane, Phys. Rep. 117 C (1985) 75.
6. J. S. Hagelin, G. L. Kane and S. Raby, Nucl. Phys. B 241 (1984) 638; L. E. Ibáñez, Phys. Lett. B 137 (1984) 160.
7. K. Griest and J. Silk, Nature 343 (1990) 26; L. Krauss, Phys. Rev. Lett. 64 (1990) 999.
8. For recent reviews, see *e.g.* G. Altarelli, CERN preprint CERN-TH-5834/90 (August 1990), E. Fernández, CERN preprint CERN-PPE/90-151 (October 1990), and F. Dydak, CERN preprint CERN-PPE/91-14 (January 1991).
9. D. Caldwell *et al.*, Phys. Rev. Lett. 61 (1988) 510.
10. L. Roszkowski, Phys. Lett. B 252 (1990) 471.
11. K. Griest, Phys. Rev. D 38 (1988) 2357; Phys. Rev. D 39 (1989) 3802(E).
12. K. A. Olive and M. Srednicki, Phys. Lett. B 230 (1989) 78; and Univ. of Minnesota preprint UMN-TH-805/90 (May 1990).
13. K. Griest, M. Kamionkowski, and M. S. Turner, Phys. Rev. D 41 (1990) 3565.
14. J. Ellis, L. Roszkowski, and Z. Lalak, Phys. Lett. B 245 (1990) 545.
15. J. Ellis, D. V. Nanopoulos, L. Roszkowski, and D. N. Schramm, Phys. Lett. B 245 (1990) 251.
16. J. F. Gunion and H. E. Haber, Nucl. Phys. B 272 (1986) 1.
17. J. Ellis, K. Enqvist, D. V. Nanopoulos, and F. Zwirner, Mod. Phys. Lett. A 1 (1986) 57; R. Barbieri and G. F. Giudice, Nucl. Phys. B 306 (1988) 63.
18. J. Lopez, L. Roszkowski, and K. Yuan, unpublished.
19. L. Roszkowski, CERN preprint CERN-TH.6041/91 (March 1991).
20. R. Barbieri, M. Frigeni and G. F. Giudice, Nucl. Phys. B 313 (1989) 725.
21. E. Kolb and M. Turner, *The Early Universe*, (Addison-Wesley, New York, 1989).
22. UA2 Collaboration, J. Alitti *et al.*, Phys. Lett. B 235 (1990) 363.
23. CDF Collaboration, presented at various recent conferences.
24. ALEPH Collaboration, D. Decamp *et al.*, Phys. Lett. B 244 (1990) 541; V. Bertin and J.-F. Grivaz, ALEPH report ALEPH 91-29 (February 1991).
25. J. Ellis, invited talk presented at the Nobel Symposium on Early Cosmology, Graftavallen, Sweden, June 11-16, 1990, CERN preprint CERN-TH.5822/90 (July 1990).
26. J. Ellis, G. Ridolfi, and F. Zwirner, CERN preprint CERN-TH.5946/90 (November 1990).
27. M. Srednicki, R. Watkins, and K. A. Olive, Nucl. Phys. B 310 (1988) 693.
28. B. Lee and S. Weinberg, Phys. Rev. Lett. 39 (1977) 165.
29. L. Roszkowski, in preparation.