CERN-TH-5705/90
ACT-2

DARK MATTER IN THE LIGHT OF LEP

John Ellis
CERN - Geneva

D.V. Nanopoulos and L. Roszkowski
Astro-Particle Physics Group, Houston Advanced Research Center (HARC)
The Woodlands, TX 77381, U.S.A.
and
Texas A&M University, College Station, TX 77843, U.S.A.

and

D.N. Schramm*
CERN - Geneva

ABSTRACT

LEP constraints suggest that cold dark matter particle candidates must be heavier than previously favoured. The LEP limit on $Z^0 \rightarrow$ invisible neutrals implies that any Majorana fermions annihilating via the Z^0 to give the critical closure density must weigh more than about 14 GeV, if the present Hubble expansion rate is $50 km\ s^{-1}\ Mpc^{-1}$, a limit which can rise to about 19 GeV for Dirac fermions when underground ^{76}Ge experiments are taken into account. It is pointed out that in both the Dirac and Majorana cases the Z^0 couplings must be weaker than those of neutrinos, unless the masses exceed $\sim m_Z/2$. These arguments on mass and interaction strength should be considered in future dark matter searches. We exemplify these generic arguments by identifying regions of parameter space in the minimal supersymmetric extension of the standard model where the lightest supersymmetric particle (LSP) can have the critical density. In some of these regions the LSP is mainly a higgsino and its mass much larger than the Majorana fermion bound mentioned above. In other regions the LSP is mainly a gaugino, in which case $m_{LSP} \gtrsim 20 GeV$.

CERN-TH-5705/90
ACT-2
April 1990

⋆ On leave of absence from University of Chicago, Chicago, IL 60637, U.S.A. and NASA/Fermilab Astrophysics Center, Batavia, IL 60510, U.S.A.

Detailed measurements of the Z^0 peak in e^+e^-annihilation at LEP are giving us new precision determinations of the parameters of the Standard Model and stringent new constraints on models going beyond it. In particular, the total decay width for Z^0 decays into invisible neutral particles has been measured with unprecedented accuracy,[1] which not only determines the number of light neutrino species, verifying the GUT[2] and cosmological[3] predictions, but also constrains massive cold dark matter particle candidates[4]. The latter are also constrained indirectly by the unsuccessful LEP searches for Z^0 decays into new visible particles, which are related to invisible particles in some models such as supersymmetry.

The main purposes of this letter are twofold. The first is to inform astrophysicists and dark matter hunters of the new lower limits that LEP imposes on cold dark matter particle masses, which now must be considerably heavier than had been considered previously and have Z^0 interactions somewhat weaker than those of neutrino. The second purpose is to inform LEP experimentatists of the regions of parameter space in which they should expect a supersymmetic theory to lie, if the cold dark matter particle is the lightest supersymmetric particle (LSP).

Our analysis proceeds in three steps. First we consider cold dark matter particles that annihilate through some effective coupling to the Z^0 alone, *i.e.* if no other new particles are invented. LEP measurements[1] of $Z^0 \to$ invisible neutrals place a mass-dependent restriction on the coupling of such a dark matter particle to the Z^0, so that it can have the critical density only if the mass is above a certain value: about 14 GeV for Majorana fermions, and about 10 GeV for Dirac fermions if the present Hubble expansion rate is 50 $km/s/Mpc$. In the Dirac case, upper limits[5] on dark matter particle interactions with ^{76}Ge impose another important mass-dependent upper limit on its Z^0 couplings, which combined with LEP suggests strongly that a Dirac fermion mass would exceed about 19 GeV. This conclusion could be confirmed and strengthened by a modest improvement on the present ^{76}Ge data. It should be noted that these limits are significantly higher than the traditional Zel'dovich-Lee-Weinberg bounds,[6] and also imply weaker interactions.

As for generic dark matter interactions, we note that most couplings through vector bosons Z' beyond the Z^0 are also restricted to be very weak, since the CDF collaboration has established[7] the lower bound $m_{Z'} \gtrsim 400\ GeV$ for any Z' with couplings to quarks similar to those of the Z^0. This limit further supports the point that dark matter couplings to matter must be weaker than those of conventional neutrinos.

Next we consider the minimal supersymmetric extension of the Standard Model (MSSM), in which the cold dark matter particle is the LSP, which is probably some gaugino/higgsino fermion mixture.[8] We show that there are three or four seperate regions where the critical cosmological closure density can be attained, in which the LSP is either mainly a higgsino, or mainly a gaugino. The higgsino cases are close to the case discussed above of the Majorana fermion coupling only to the Z^0 but in these cases the mass greatly exceeds the previous bound of 14 GeV and is above $m_Z/2$. In the gaugino cases most of the annihilation is via squarks and sleptons, and the lower bound on the LSP mass is about 20 GeV. This is because the squark masses are now known to be larger than m_Z, whilst their couplings to the LSP are smaller than those of the Z^0 to neutrinos. We illustrate our supersymmetric results with curves showing the relic LSP density along favourable rays in parameter space, demonstrating that the critical density can in general be obtained only if the LSP is considerably heavier than would have been required for a massive relic Dirac or Majorana neutrino.

We start by considering the idealized case of annihilation via effective interaction through the Z^0 alone. The LEP constraint on Z^0 decays into invisible neutrals is[1]

$$N_\nu \equiv \frac{\Gamma(Z^0 \to \text{ invisible neutrals})}{\Gamma(Z^0 \to \bar{\nu}\nu)} = 3.09 \pm 0.11 \qquad (1)$$

if the Standard Model is assumed for all visible Z^0 decays, and[1]

$$N_\nu = 2.98 \pm 0.12 \qquad (2)$$

if no Standard Model assumption is made other than the ratio between $\Gamma_{\bar{\nu}\nu}$ and

$\Gamma_{e^+e^-}$. We interpret the bounds (1), (2) as implying that $N_\nu < 3.22$.

$$0.22 > N_\nu - 3 = \sin^2\phi_Z \begin{cases} \beta^{-3} & \text{(Majorana fermions)} \\ 4/\beta(3+\beta^2) & \text{(Dirac fermions)} \end{cases} , \tag{3}$$

where $\sin\phi_Z$ is the suppression of the Z^0-relic particle coupling relative to the Z^0-$\bar{\nu}\nu$ coupling and $\beta = v/c$. The LEP upper limits on $\sin^2\phi_Z$ as functions of the relic particle mass are shown in Fig. 1a for Majorana fermions and Fig. 1b for Dirac fermions.

The relic cosmological density is approximately inversely proportional to the annihilation cross-section:

$$\Omega h_0^2 \propto 1/\sigma \qquad : \qquad \sigma \propto \sin^2\phi_Z. \tag{4}$$

where h_0 is the present-day Hubble constant in units of 100 $km/s/Mpc$. Massive fermions with neutrino-like couplings: $\sin^2\phi_Z = 1$ would have the critical closure density[9] only if $m \sim 6$ to 8 GeV for Majorana fermions or $m \sim 3$ to 4 GeV for Dirac fermions, for $h_0 \sim 0.7$ to 0.5^*. Somewhat heavier neutrino-like relic particles would have less than the closure density[11]. However, the relic particle density could be critical if $\sin^2\phi_Z$ were suppressed by the appropriate mass-dependent factor. Fig. 1 also shows the appropriate closure values of $\sin^2\phi_Z$ for larger relic masses. We see that the two constraints of LEP and closure are only compatible for

$$m_{\nu_M} \gtrsim 14\ GeV \tag{5}$$

for Majorana fermions, and

$$m_{\nu_D} \gtrsim 10\ GeV \tag{6}$$

for Dirac fermions, if $h_0 \sim 0.5$. These bounds are somewhat weaker, $m_{\nu_M} \gtrsim 10 GeV$ and $m_{\nu_D} \gtrsim 6 GeV$, when $h_0 = 0.7$.

$\star$ Although direct observations cannot rule out $h_0 = 1$, values beyond 0.7 are inconsistent with lower limits on the age of an $\Omega = 1$ universe[10].

Another constraint on the Dirac case is imposed by the searches[5] for relic particle interactions with underground ^{76}Ge detectors, assuming that the relic particles provide a galactic halo density of 0.3 GeV/cm^3. These experiments exclude Dirac neutrinos weighing between about 10 GeV and several TeV, and can also be used to give an upper bound on the Z coupling to other Dirac fermions. This ^{76}Ge constraint on $\sin^2\phi_Z$ is also shown in Fig. 1b. We see that it excludes a range of Dirac fermion masses between about 13 GeV and 19 GeV if $h_0 = 0.5$, but not if $h_0 = 0.7$. We see that the small gap between 10 GeV and 13 GeV for $h_0 = 0.5$ and the range between about 7 GeV and 20 GeV for $h_0 = 0.7$ could be excluded by a modest improvement in the present ^{76}Ge limits,[5] which we await eagerly. Notice that, for both the Dirac and Majorana cases, the allowed couplings are weaker than the conventional electroweak coupling to neutrinos: $\sin^2\phi_Z \lesssim 0.3$ for Majorana fermions and $\lesssim 0.03$ for Dirac fermions.

We note that Ωh_0^2 rises again for relic masses beyond $m_Z/2$[11], reflecting the possibility that particles with neutrino-like couplings to the Z^0 and masses ~ 1 TeV could have the closure density. This high-mass range comes down to lower masses if the relic couplings to the Z^0 are reduced.

To go further, we restrict our analysis to the LSP in the MSSM,[8] which we take to be a neutral gaugino/higgsino mixture, sneutrinos[12] being excluded[4] by the LEP data[1] and the ^{76}Ge data[5]. The neutral gaugino/higgsino mass matrix is characterized by 3 parameters, a gaugino mass M_2, a higgsino mass mixing parameter μ, and the ratio of Higgs vacuum expectation values $\tan\beta \equiv v_t/v_b$:

$$\begin{pmatrix} M_2 & 0 & -m_Z\cos\theta_W\sin\beta & m_Z\cos\theta_W\cos\beta \\ 0 & \frac{5}{3}M_2\tan^2\theta_W & m_Z\sin\theta_W\sin\beta & -m_Z\sin\theta_W\cos\beta \\ -m_Z\cos\theta_W\sin\beta & m_Z\sin\theta_W\sin\beta & 0 & -\mu \\ m_Z\cos\theta_W\cos\beta & -m_Z\sin\theta_W\cos\beta & -\mu & 0 \end{pmatrix} \tag{7}$$

where we have assumed the normal GUT relation between the $SU(2)$ and $U(1)$ gaugino masses.

The rest of the supersymmetric particle mass spectrum is characterized by several more parameters of which the most important for our purposes are the squark and Higgs masses. We assume for simplicity that all the squark masses $m_{\tilde{q}}$ are equal, and characterize the Higgs masses by the pseudoscalar Higgs mass m_A and by $\tan\beta$. The CDF experiment at Fermilab suggests[7] that $m_{\tilde{q}} \gtrsim 120\ GeV$, whilst naturalness suggest that $m_{\tilde{q}} \lesssim 1\ TeV$ and LEP experiments[13] suggest that $m_A \gtrsim 40\ GeV$ and $\tan\beta \gtrsim 1.3$. We have explored the (μ, M_2) plane, varying $m_{\tilde{q}}$ between 120 GeV and 1 TeV, m_A between 39 GeV and 1 TeV and $\tan\beta$ between 1.5 and 10, to determine the regions of (μ, M_2) where the critical density, computed as in Ref. 14, could be attained for some h_0 between 0.5 and 0.7. These regions are shown in Fig. 2. Four regions can be distinguished: (1) μ large with $M_2 \sim m_W$, (2) M_2 large with $\mu \sim m_W$, (3) M_2 large with $\mu \sim -m_W$, and (4) μ large and negative with $M_2 \sim m_W$. In regions (1) and (4) the LSP is mainly a gaugino, whilst in regions (2) and (3) it is mainly a higgsino. The regions (1) and (2) are in fact connected when $m_{\tilde{q}} \gtrsim 200\ GeV$, by an increase in the preferred range of "gaugino" masses (1), and when $\tan\beta \lesssim 3$, by an expansion of the "higgsino" region (2), but the other regions are always disconnected. LEP and other experiments exclude[15] intersecting strips of parameter space around $\mu = 0$ and $M_2 = 0$, providing non-trivial lower bounds on the LSP mass. We note that we have restricted our attention to regions of the (μ, M_2) plane where $m_{LSP} < m_W$.

Some authors have recently studied[16] the case of larger m_{LSP}. They find that in the "higgsino" region LSP annihilations into vector boson pairs dominate when they are kinematically accessible, whereas in the "gaugino" regions LSP annihilation into fermions may still dominate. We find that when $m_{\tilde{q}} < 200\ GeV$, these always give $\Omega h_0^2 < 1/4$ for $m_{LSP} > m_W$ in the "gaugino" region, and therefore there can be no "bridge" between the "gaugino" and "higgsino" regions across the $m_{LSP} > m_W$ domain for $m_{\tilde{q}} \leq 200 GeV$, though one could in principle appear when $m_{\tilde{q}}$ is larger. We should also note that, both for μ positive and negative, there are regions of small $|\mu|$ and M_2 where $\frac{1}{4} < \Omega h_0^2 < \frac{1}{2}$ would appear to be possible. However, these are for values of (μ, M_2) that are already ruled out by

accelerator searches for sparticles, notably at LEP and by CDF.[7]

To explore the allowed regions (1), (2), (3) and (4) in more detail, we have probed the allowed values of Ωh_0^2 along rays in the (μ, M_2) plane which cut through them, namely (a) $\mu/M_2 = 5$, (b) $\mu/M_2 = .2$, (c) $\mu/M_2 = -.2$, (d) $\mu/M_2 = -5$. The values of Ωh_0^2 along these rays for several choices of $m_{\tilde{q}}$, m_A and $\tan\beta$ are shown in Fig. 3. We see in Fig. 3a that the relic density $\Omega h_0^2 << \frac{1}{4}$ for all values of m_{LSP} along the $\mu/M_2 = 5$ ray when $m_{\tilde{q}} = 120\ GeV$, $m_A = 40\ GeV$ and $\tan\beta = 2$. We see that the relic density is little affected by increasing m_A to 1 TeV, though there is slight increase at small m_{LSP} where the Higgs exchanges are more important. On the other hand, if $m_{\tilde{q}}$ is increased to 1 TeV, we see that the relic density increases by a large factor at large m_{LSP} - where annihilation is dominated by $\tilde{q}$ exchange - but the increase is smaller at low m_{LSP} - where Higgs exchanges also contribute. We also find (not shown) that if both m_A and $m_{\tilde{q}} = 1\ TeV$, $\Omega h_0^2 > 1/2$ for almost all values of m_{LSP} except for a small range where $m_{LSP} \sim m_Z/2$. Also not shown are relic mass density values for larger values of $\tan\beta$: we find that they are qualitatively similar to those for $\tan\beta = 2$, with the main exception being a smaller dip due to Z^0 exchange. The regions where $\frac{1}{4} < \Omega h_0^2 < \frac{1}{2}$ for $m_{LSP} > m_Z/2$ were foreshadowed in our earlier, more general discussion.[14]

Turning next to the $\mu/M_2 = .2$ ray in Fig. 3b, we see that when $m_{\tilde{q}} = 120\ GeV$, $m_A = 40\ GeV$ and $\tan\beta = 2$ the relic density is small when $m_{LSP} \lesssim 60\ GeV$, but Ωh_0^2 can be in the interesting range between 1/4 and 1/2 for $m_{LSP} \sim 70$ to 80 GeV. If $\tan\beta$ is increased to 10, with $m_{\tilde{q}}$ and m_A kept fixed, we see that always $\Omega h_0^2 < .1$. The relic density is seen to be increased at large m_{LSP} if m_A is increased to 1 TeV with $\tan\beta = 2$ and $m_{\tilde{q}} = 120\ GeV$, but decreased again for $\tan\beta = 10$, $m_A = 1\ TeV$ and $m_{\tilde{q}} = 120\ GeV$. We do not show density values for larger values of $m_{\tilde{q}}$, since along this ray they are indistinguishable from those for small $m_{\tilde{q}}$, as one might expect in this region where $\tilde{q}$ exchange is known to be much less important than Z^0 exchange. As along the previous ray, the regions where $\frac{1}{4} < \Omega h_0^2 < \frac{1}{2}$ for $m_{LSP} > m_Z/2$ were foreshadowed in our earlier, more general discussion.

Looking at the $\mu/M_2 = -.2$ ray in Fig. 3c, we see that when $\tan\beta = 2$, $m_A = 40\ GeV$ and $m_{\tilde{q}} = 120\ GeV$ the relic density Ωh_0^2 is very small for $m_{LSP} \lesssim 60\ GeV$, but then rapidly increases to become $> 1/2$ when $m_{LSP} \sim 80\ GeV$. When $\tan\beta$ is increased to 10, the relic density is decreased so that $\Omega h_0^2 < .1$ for all values of m_{LSP}. As could be expected, if m_A is increased to $1\ TeV$ the relic density is increased, and is further increased into the interesting range for $m_{LSP} \gtrsim 70 GeV$ if $m_{\tilde{q}}$ is also increased to $1\ TeV$. The relic density is almost independent of m_A and $m_{\tilde{q}}$ when $\tan\beta = 2$, so we do not show any other density curves for this choice of $\tan\beta$. Moreover, the density curves for $\tan\beta = 10$, $m_A = 40\ GeV$ and $m_{\tilde{q}} = 1\ TeV$ are essentially identical to that for $\tan\beta = 10$, $m_A = 40\ GeV$ and $m_{\tilde{q}} = 120\ GeV$, and hence also not shown. The high-mass regions with $\frac{1}{4} < \Omega h_0^2 < \frac{1}{2}$ are qualitatively similar to those along the previous ray.

Finally, we examine the $\mu/M_2 = -5$ ray in Fig. 3d. The density curve for $\tan\beta = 2$, $m_A = 40\ GeV$ and $m_{\tilde{q}} = 120\ GeV$ has a fairly classical Zel'dovich-Lee-Weinberg form, decreasing as m_{LSP} increases, with $1/4 < \Omega h_0^2 < 1/2$ for $10\ GeV \lesssim m_{LSP} \lesssim 20\ GeV$. The dips correspond to annihilations through scalar and pseudoscalar Higgs exchanges, and disappear when m_A is increased to $1\ TeV$ with $\tan\beta$ and $m_{\tilde{q}}$ kept fixed. On the other hand, if $\tan\beta$ is increased to 10 with $m_A = 40\ GeV$ and $m_{\tilde{q}} = 120\ GeV$, we see that $\Omega h_0^2 < .1$ for all values of m_{LSP}. This density is increased, but still $\Omega h_0^2 < 1/4$, if m_A is increased to $1\ TeV$ with $\tan\beta$ fixed at 10 and $m_{\tilde{q}}$ at $120\ GeV$. Finally, we see that for $\tan\beta = 10$, $m_A = 40\ GeV$ and $m_{\tilde{q}} = 1\ TeV$ the relic density increases with m_{LSP}, so that $1/4 < \Omega h_0^2 < 1/2$ for $50\ GeV \lesssim m_{LSP} \lesssim 60\ GeV$, and $\Omega h_0^2 > 1/2$ when $m_{LSP} \gtrsim 60\ GeV$. This is an example of the type of high-mass allowed region[14] advertized previously. Not shown are density curves for $\tan\beta = 2$, $m_A = 40\ GeV$ and $1\ TeV$, and $m_{\tilde{q}} = 1\ TeV$, nor that for $\tan\beta = 10$, $m_A = 1\ TeV$, $m_{\tilde{q}} = 1\ TeV$: this is because with these parameter choices $\Omega h_0^2 >> 1/2$ for essentially all values of m_{LSP}.

Fig. 3 confirms that the generic LSP mass required to obtain $1/4 < \Omega h_0^2 < 1/2$ is now considerably larger than the values frequently discussed in the past. Along ray (a) we find $m_{LSP} \gtrsim 20\ GeV$, whilst along rays (b) and (c) we find $m_{LSP} \gtrsim$

$60\ GeV$. The case of ray (d) is somewhat special: in very exceptional cases where $2m_{LSP} \sim$ the scalar Higgs mass one can get $1/4 < \Omega h_0^2 < 1/2$ for $m_{LSP} \sim 10\ GeV$, but in the absence of such a light Higgs we find $m_{LSP} \gtrsim 15\ GeV$. Even LSP masses close to $15\ GeV$ are very vulnerable to forthcoming accelerator searches for sparticles: along this ray one expects $m_{LSP} \sim 1/6 m_{\tilde{g}}$, and the CDF collaboration has sensitivity to $m_{\tilde{g}} \lesssim 150\ GeV$. Hence a negative result from the CDF gluino search would enforce $m_{LSP} \gtrsim 25\ GeV$. These results mean that cold dark matter searches for the LSP should be optimized for masses $\gtrsim 20\ GeV$. In particular, searches for nuclear recoil due to elastic LSP scattering in the laboratory should contemplate using heavier nuclei.

ACKNOWLEDGEMENTS

We would like to thank God for creating the Universe. DNS acknowledges support from NSF and NASA at the University of Chicago and the NASA/FNAL Astrophysics Center.

REFERENCES

1. For a review and references, see:
   J. Steinberger, Proc. ESO-CERN Topical Symposium on LEP and the Universe, CERN preprint TH. 5709 (1990).
2. A.J. Buras, J. Ellis, M.K. Gaillard and D.V. Nanopoulos, *Nucl.Phys.* **B139** (1978), 66;
   D.V. Nanopoulos and D.A. Ross, *Nucl. Phys.* **B157** (1979), 273, *Phys. Lett.* **108B** (1982), 351 and **118B** (1982), 99.
3. K.A. Olive, D.N. Schramm, G. Steigman and T. Walker, *Phys.Lett.* **B236** (1990), 454;
   For earlier, less refined estimates of the number of generations, see:
   G. Steigman, D.N. Schramm and J. Gunn, *Phys.Lett.* **66B** (1977), 202;
   K.A. Olive, D.N. Schramm, G. Steigman, M.S. Turner and J. Yang, *Ap.J.* **246** (1981), 557;
   J. Yang, M.S. Turner, G. Steigman, D.N. Schramm and K.A. Olive, *Ap.J.* **281** (1984), 493.
4. K. Griest and J. Silk, Center for Particle Astrophysics preprint TH-89-014 (1989);
   L. Krauss, *Phys.Rev.Lett.* **64** (1990), 999.
5. D. Caldwell et al., *Phys.Rev.Lett.* **61** (1988), 510.
6. Ya.B. Zel'dovich, *Ad. in Astr. and Astrophys.* **3** (1965), 241;
   H.Y. Chiu, *Phys.Rev.Lett.* **17** (1966), 712;
   B.W. Lee and S. Weinberg, *Phys.Rev.Lett.* **39** (1977), 165;
   P. Hut, *Phys.Lett.* **69B** (1977), 85.
7. CDF Collaboration, S. Geer, Talk presented at PASCOS-90 (1990).
8. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive and M. Srednicki, *Nucl.Phys.* **B238** (1984), 453.

9. E.W. Kolb and K.A. Olive, *Phys.Rev.* **D33** (1986), 1202 [**E D34** (1986) 2531].
10. D.N. Schramm, Proc. Institut d'Astrophysique, Symposium on Astrophysical Ages and Dating Methods, ed. J. Audouze, Paris (1989).
11. P. Hut and K.A. Olive, *Phys.Lett.* **87B** (1979), 144;
    K. Griest and M. Kamionkowski, *Phys.Rev.Lett.* **64** (1990), 615;
    S. Dimopoulos, R. Esmailzadeh, L. Hall and N. Tetradis, CERN preprint TH. 5704 (1990).
12. L. Ibañez, *Phys.Lett.* **137B** (1984), 160;
    S. Hagelin, G. Kane and S. Raby, *Nucl.Phys.* **B241** (1984), 638.
13. ALEPH Collaboration, CERN preprint EP/90-16 (1990).
14. J. Ellis, Z. Lalak, and L. Roszkowski, CERN preprint TH. 5470 (1989).
15. J. Ellis, G. Ridolfi and F. Zwirner, CERN preprint TH. 5596 (1989);
    J.L. Lopez and D.V. Nanopoulos, CTP-TAMU-18/90 (1990); ALEPH Collaboration, J.-F. Grivaz, Talk at PASCOS-90, Northeastern University (1990).
16. K.A. Olive and M. Srednicki, Univ. of Minnesota preprint UMN-TH-801/89 (1989);
    K. Griest, M. Kamionkowski, and M.S. Turner, Fermilab preprint Pub-89/239-A (1989).

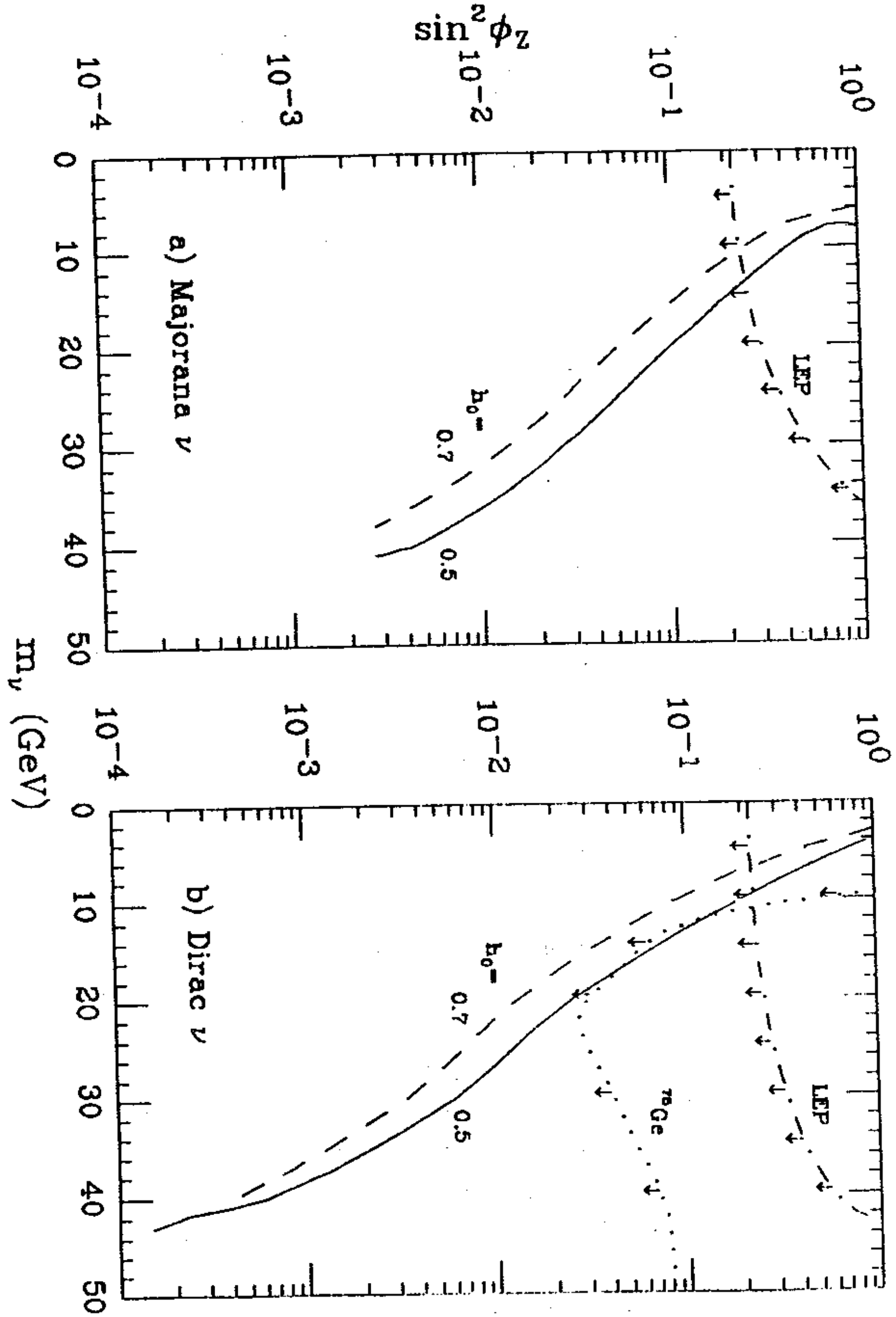


Figure 1

FIGURE CAPTIONS

1) Values of mass m and Z^0 coupling strength $\sin^2\phi_Z$ relative to a conventional neutrino consistent with LEP[1] and giving $\Omega = 1$ for $h_0 = 0.5$ or 0.7 (a) for Majorana fermions and (b) for Dirac fermions. In the latter case the constraint[5] from underground ^{76}Ge experiments is also shown.

2) Domains of the (μ, M_2) plane consistent with LEP[15], CDF and[7] $\frac{1}{4} < \Omega h_0^2 < \frac{1}{2}$ for some choice $120GeV \leq m_{\tilde{q}} \leq 1TeV$, $39GeV \leq m_A \leq 1TeV$ and $1.5 < \tan\beta < 10$. Note the favoured regions (1), (2), (3) and (4) discussed in the text and the rays (a), (b), (c) and (d).

3) The LSP mass density Ωh_0^2 as a function of m_{LSP} along the rays $\mu/M_2 =$ (a) 5, (b) 0.2, (c) -0.2, (d) -5 shown in Fig. 3 and discussed in the text. The different lines correspond to different choices of $\tan\beta/m_A/m_{\tilde{q}}$.

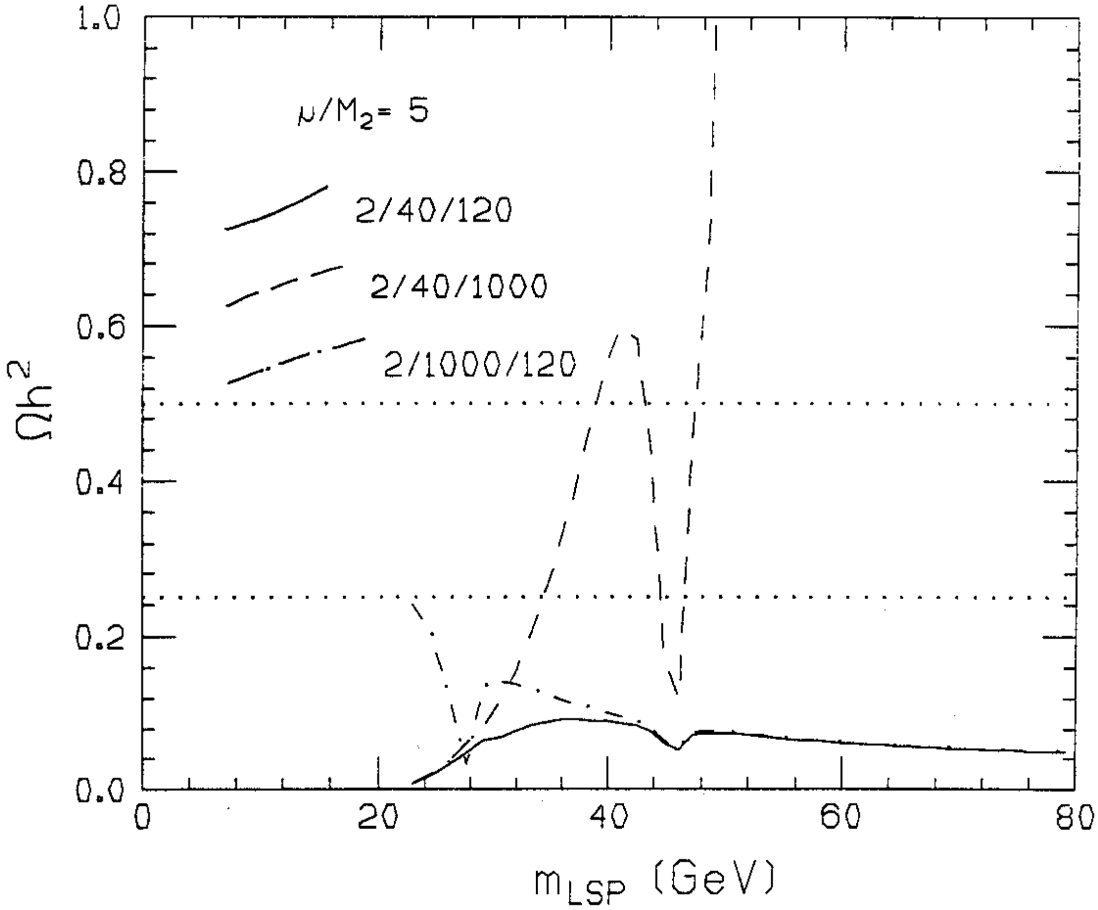


Figure 3a

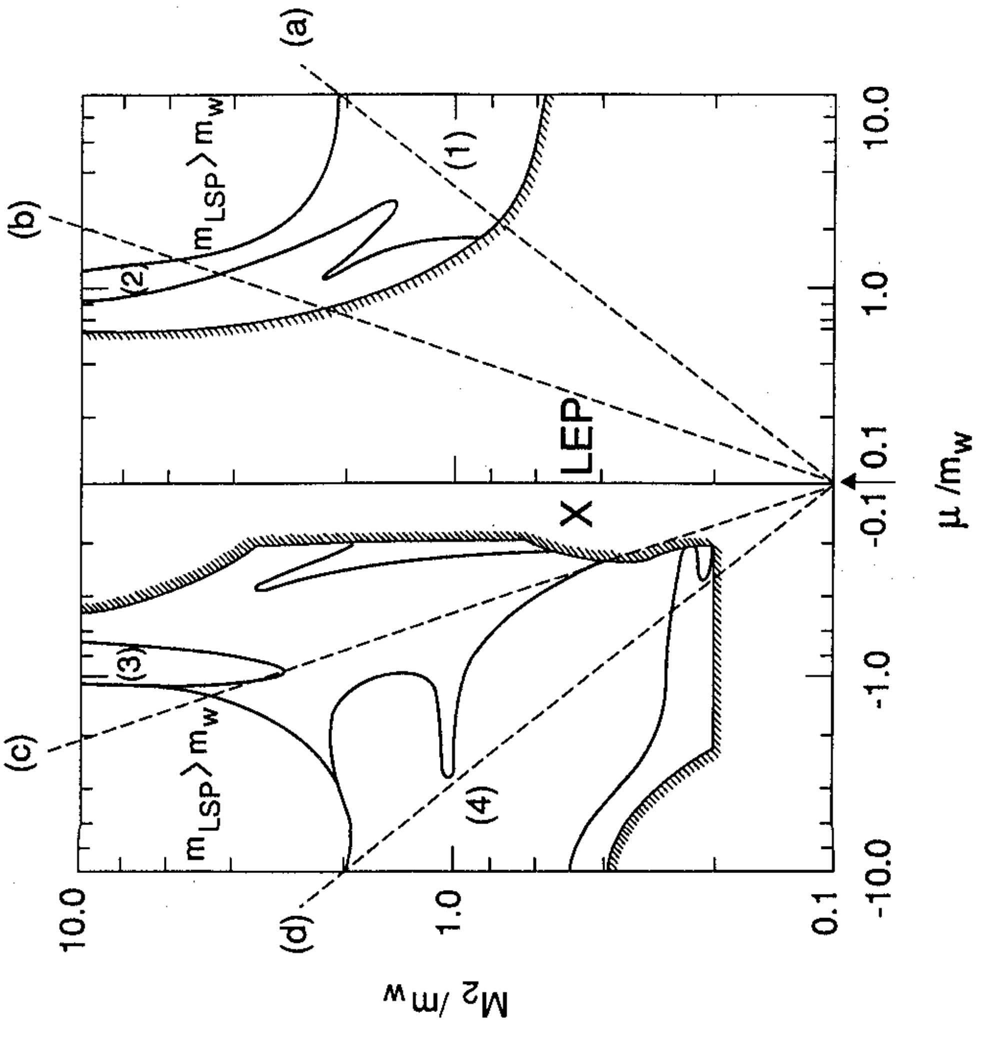


Figure 2

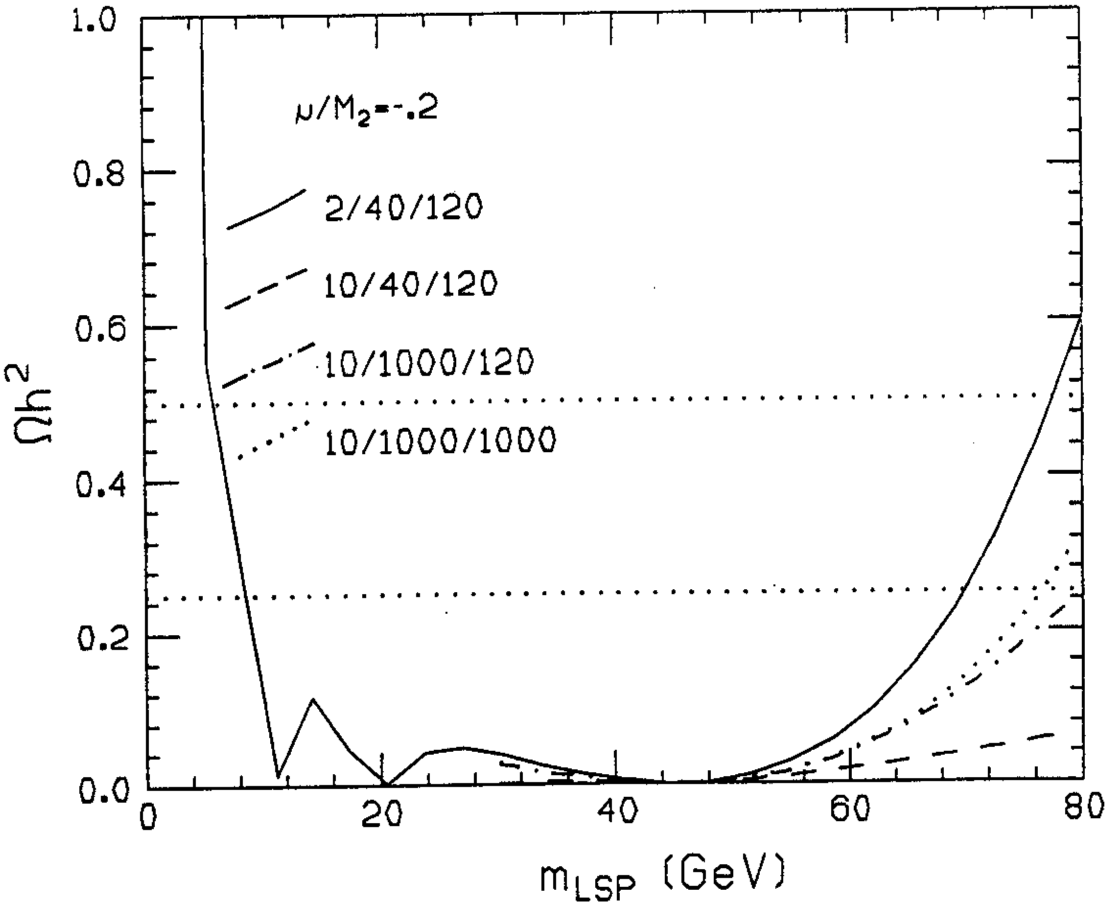


Figure 3c

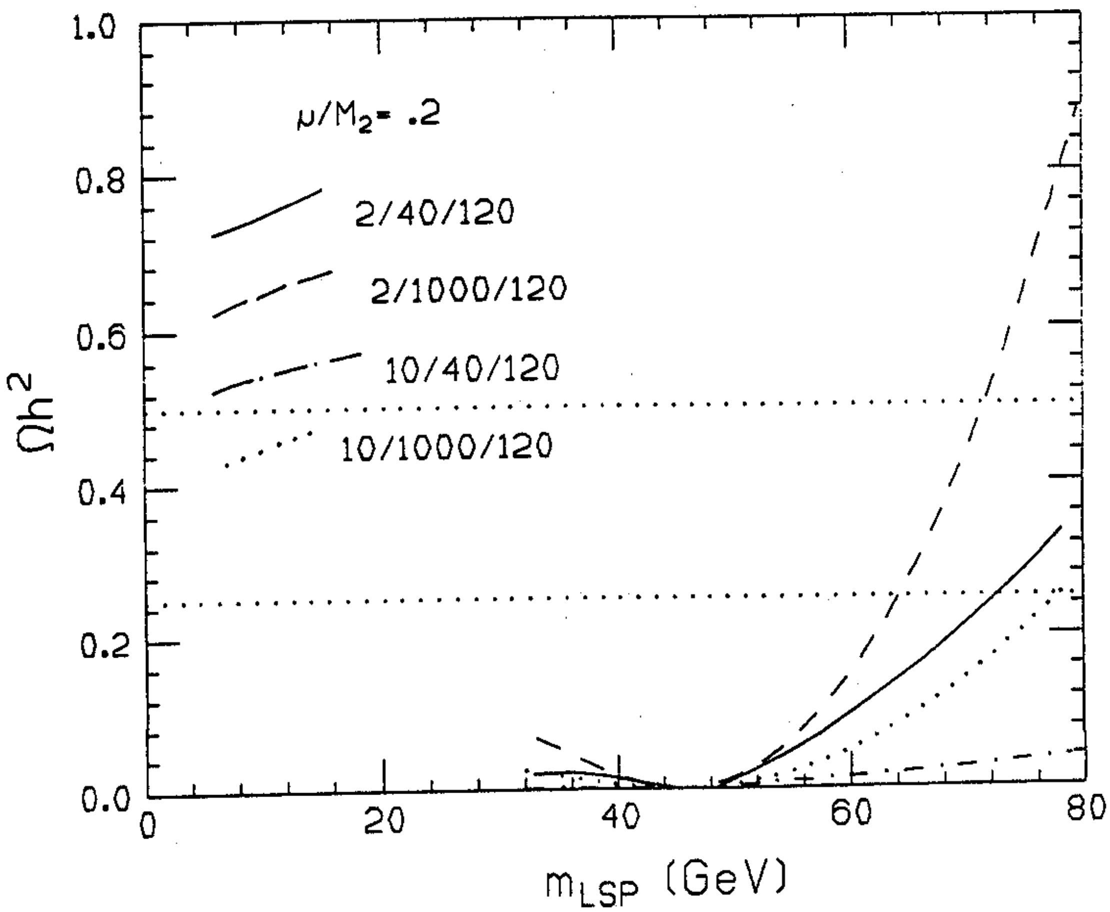
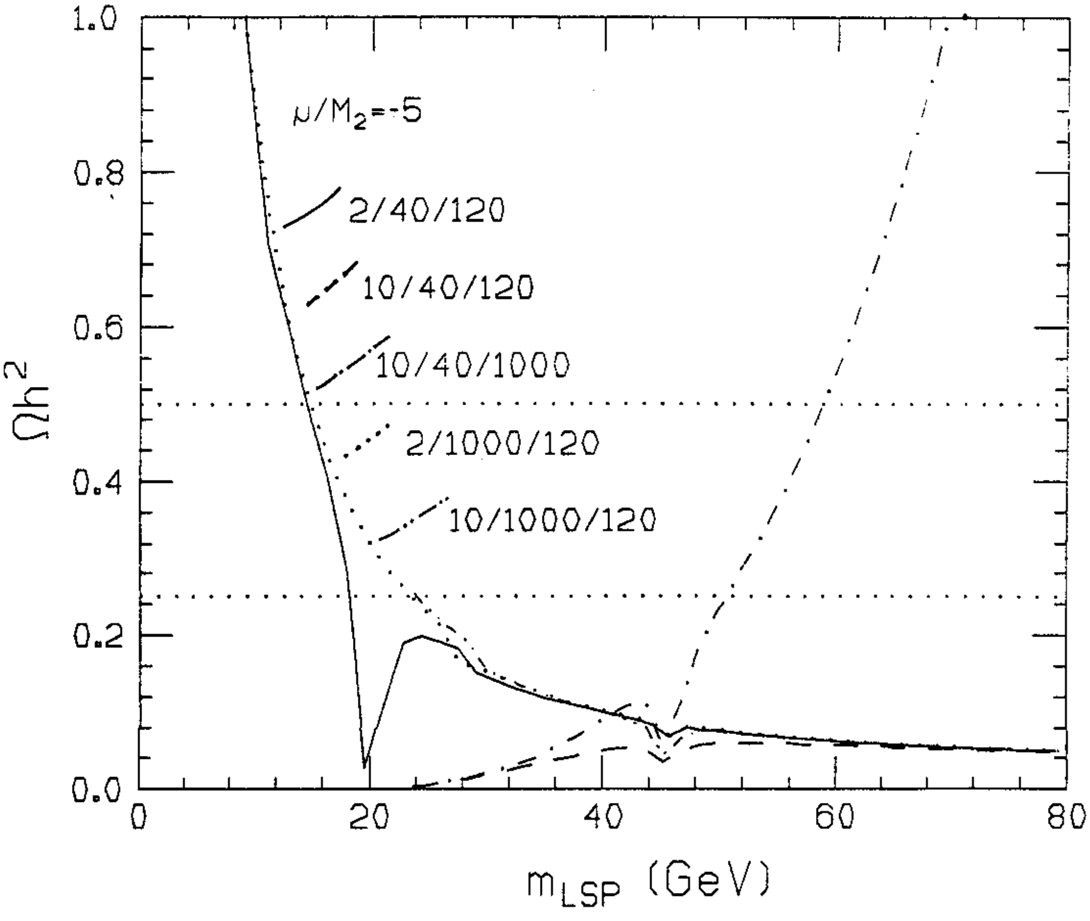


Figure 3b



μ/M₂=-5
2/40/120
10/40/120
10/40/1000
2/1000/120
10/1000/120
Ωh²
m_LSP (GeV)

Figure 3d