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How light can the lightest neutralino be?

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We show that in the Minimal Supersymmetric Standard Model, the mass of the lightest neutralino is experimentally unconstrained if the GUT relation between the gaugino mass parameters M_1 and M_2 is dropped. We discuss what the impact of light or massless neutralinos would be on their production at LEP, as well as on electroweak precision data and rare decays.

1 Introduction

In the Minimal Supersymmetric Standard Model (MSSM) [2], the masses and mixings of the neutralinos and charginos are given by their mass matrices [2, 3]

$$\mathcal{M}_0 = M_Z \begin{pmatrix} M_1/M_Z & 0 & -s_\theta c_\beta & s_\theta s_\beta \\ 0 & M_2/M_Z & c_\theta c_\beta & -c_\theta s_\beta \\ -s_\theta c_\beta & c_\theta c_\beta & 0 & -\mu/M_Z \\ s_\theta s_\beta & -c_\theta s_\beta & -\mu/M_Z & 0 \end{pmatrix}, \mathcal{M}_\pm = M_W \begin{pmatrix} M_2/M_W & \sqrt{2}s_\beta \\ \sqrt{2}c_\beta & \mu/M_W \end{pmatrix}, \tag{1}$$

respectively, with $c_\beta = \cos\beta$, $s_\beta = \sin\beta$ and $c_\theta = \cos\theta_w$, $s_\theta = \sin\theta_w$, with the weak mixing angle θ_w. Besides the masses of the W and Z boson, M_W and M_Z, respectively, the neutralino and chargino sectors at tree level only depend on the $U(1)_Y$ and $SU(2)_L$ gaugino masses M_1 and M_2, respectively, the higgsino mass parameter μ, and the ratio $\tan\beta = v_2/v_1$ of the vacuum expectation values of the two Higgs fields. The neutralino (chargino) masses are the square roots of the eigenvalues of $\mathcal{M}_0\mathcal{M}_0^\dagger$ ($\mathcal{M}_\pm\mathcal{M}_\pm^\dagger$) [3]. The LEP limit on the chargino mass is $m_{\tilde\chi_1^\pm} \gtrsim 100$ GeV [3], from which follows that $M_2, |\mu| \gtrsim 100$ GeV. If the GUT relation $M_1 = 5/3\tan^2(\theta_w)M_2 \approx 0.5\,M_2$ is assumed, then $M_1 \gtrsim 50$ GeV, such that the lightest neutralino mass is constrained to $m_{\tilde\chi_1^0} \gtrsim 50$ GeV [3]. However, if one drops the GUT relation, M_1 is an independent parameter, allowing to tune the neutralino mass determined from the lowest-order mass matrix $\mathcal{M}_0$ freely [4–8]. The neutralino mass is identically zero for [5]

$$\det(\mathcal{M}_0) = 0 \quad \Rightarrow M_1 = \frac{M_Z^2 M_2 \sin^2\theta_w \sin(2\beta)}{\mu M_2 - M_Z^2\cos^2\theta_w\sin(2\beta)} \approx 0.05\frac{M_Z^2}{\mu} = \mathcal{O}(1\,\text{GeV}). \tag{2}$$

For $M_1 \ll M_2, |\mu|$, the neutralino $\tilde\chi_1^0$ is mainly a bino, i.e., it couples to hypercharge, and

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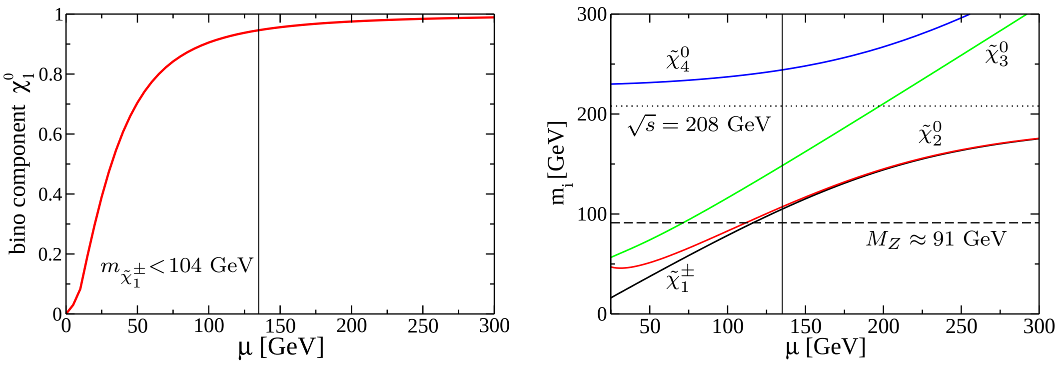


Figure 1: Bino admixture of $\tilde{\chi}_1^0$ (left plot) and masses of charginos and neutralinos (right plot) for $M_2 = 200$ GeV, $\tan\beta = 10$, and M_1 as given in Eq. (2), such that $m_{\tilde{\chi}_1^0} = 0$ GeV [7]. Left to the vertical lines at $\mu \approx 135$ GeV, the chargino mass is $m_{\tilde{\chi}_1^\pm} < 104$ GeV. In the right panel, the dotted line indicates the reach of LEP2 ($\sqrt{s} = 208$ GeV) for $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_i^0$ production, and the dashed line indicates the mass of the Z boson, $M_Z \approx 91$ GeV.

the masses of the other neutralinos and charginos are of the order of M_2 and $|\mu|$, see Fig. 1. In the following, we discuss bounds on the neutralino mass from production at LEP and from precision observables [7, 8], as well as bounds from rare meson decays [9]. Finally, we summarize bounds from cosmology and astrophysics [6–8].

2 Neutralino production at LEP

The OPAL collaboration [10] has derived upper bounds on the topological neutralino production cross section $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) \times \mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) \times \mathrm{BR}(Z \to q\bar{q})$ at LEP with $\sqrt{s} = 208$ GeV, normalized such that $\mathrm{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$. Their observed limit at 95% confidence level in the $m_{\tilde{\chi}_1^0}$–$m_{\tilde{\chi}_2^0}$ plane is shown in Fig. 2(a). For $m_{\tilde{\chi}_1^0} = 0$ GeV, one can roughly read off the upper limit $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 q\bar{q}) < 50$ fb, or equivalently, since $\mathrm{BR}(Z \to q\bar{q}) \approx 70\%$, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) < 70$ fb. This is already a very tight bound, since typical neutralino production cross sections can be of the order of 100 fb. For bino-like neutralinos, the main contribution to the cross section is due to $\tilde{e}_R$ exchange. Thus one can translate the OPAL bound on the neutralino production cross section into lower bounds on the selectron mass $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{e}}$, for $m_{\tilde{\chi}_1^0} = 0$. In Fig. 2(b) we show the contours of $m_{\tilde{e}}$ in the μ–M_2 plane, such that along the contours $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) = 70$ fb. For example, for a fixed selectron mass of $m_{\tilde{e}} = 300$ GeV, the area below the 300 GeV contour in Fig. 2(b) is excluded by LEP.

Another search channel at LEP is radiative neutralino production, $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0\gamma$. Due to the large background from radiative neutrino production $e^+e^- \to \nu\bar{\nu}\gamma$, we find that the significance is always $S < 0.1$ for $\mathcal{L} = 100\ \mathrm{pb}^{-1}$ and $\sqrt{s} = 208$ GeV [11, 12]. At the ILC however, radiative neutralino production will be measurable, due to the significant higher luminosity and the option of polarized beams [11–13].

3 Bounds from precision observables and rare decays

The invisible Z width Γ_{inv} is potentially very sensitive to a light or massless neutralino, due to the contribution from $Z \to \tilde{\chi}_1^0\tilde{\chi}_1^0$. However, a light neutralino is mainly bino-like for $|\mu| \gtrsim 125$ GeV, see Fig. 1. For a pure bino, the coupling to the Z boson vanishes at tree level. In Fig. 3, we show the difference $\delta\Gamma = (\Gamma_{\mathrm{inv}} - \Gamma_{\mathrm{inv}}^{\mathrm{exp}})/\Delta\Gamma$ from the measured invisible

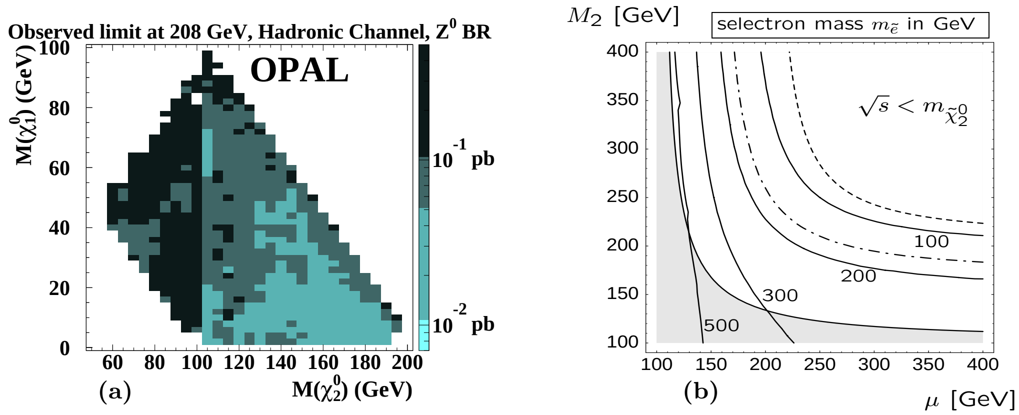


Figure 2: **(a)** 95% confidence limit on the cross section $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) \times \text{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) \times \text{BR}(Z \to q\bar{q})$ with $\text{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$ at $\sqrt{s} = 208$ GeV, OPAL collaboration [10]. **(b)** Contour lines in the μ–M_2 plane of the lower bounds on the selectron mass $m_{\tilde{e}_R} = m_{\tilde{e}_L} = m_{\tilde{e}}$, such that $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0) = 70$ fb for $m_{\tilde{\chi}_1^0} = 0$ with $\tan\beta = 10$ [7]. The dashed line in **(b)** is the kinematical limit $m_{\tilde{\chi}_2^0} = \sqrt{s} = 208$ GeV, along the dot-dashed contour the relation $m_{\tilde{e}} = m_{\tilde{\chi}_2^0}$ holds.

width $\Gamma_{\text{inv}}^{\text{exp}} = 499.0 \pm 1.5$ MeV [3, 14], in units of the experimental error $\Delta\Gamma = 1.5$ MeV, to the theoretical prediction Γ_{inv}. The calculations of Γ_{inv} include the full $\mathcal{O}(\alpha)$ SM and MSSM contributions, supplemented with leading higher-order terms [15]. The deviation from the measured width $\Gamma_{\text{inv}}^{\text{exp}}$ is larger than 5σ only for $|\mu| \lesssim 125$ GeV. For decreasing $|\mu|$, the increasing higgsino admixture leads to a non-negligible neutralino coupling to the Z boson. Note that already the SM contribution to Γ_{inv} is more than 1σ larger than the experimental value $\Gamma_{\text{inv}}^{\text{exp}}$ [14, 15].

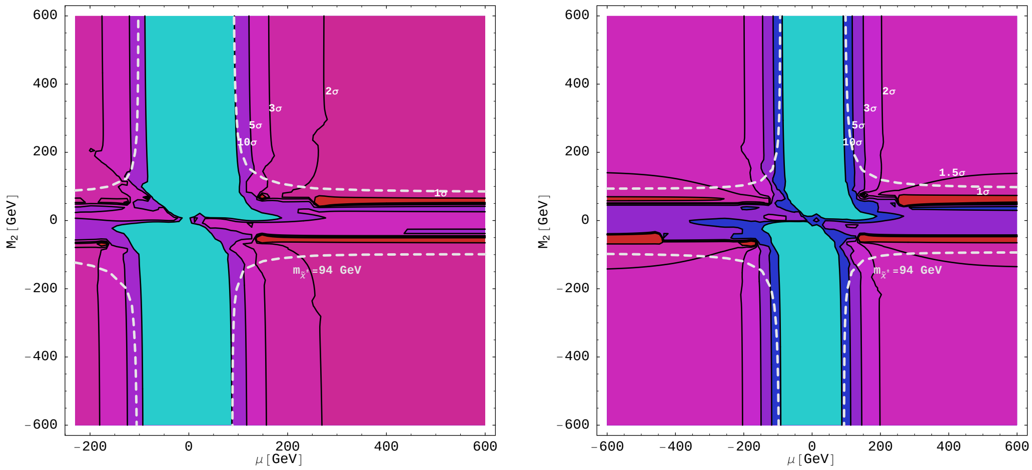
We have also studied the impact of a massless or light neutralino on the W boson mass, the effective leptonic weak mixing angle $\sin^2\theta_{\text{eff}}$, the electric dipole moments of the electron, neutron and mercury, and the anomalous magnetic moment of the muon $(g-2)_\mu$, but have found no significant constraints on the neutralino mass [7]. Also rare decays like $b \to s\gamma$, $\Upsilon(1S) \to \tilde{\chi}_1^0\tilde{\chi}_1^0$ [16], $J/\Psi(B^0) \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, $K[D,B]^+ \to \pi^+\tilde{\chi}_1^0\tilde{\chi}_1^0$, do not constrain $m_{\tilde{\chi}_1^0}$ [9].

4 Bounds from cosmology and astrophysics

The impact of a light neutralino on its thermal relic density has previously been studied [6,8]. If the neutralino accounts for the dark matter, its mass has to be $m_{\tilde{\chi}_1^0} > 3\ldots20$ GeV, in order not to over-close the universe. However, this bound can be evaded by allowing a small amount of R parity violation [4]. One would thus assume that the neutralinos are stable on the time scale of collider experiments, but are not stable on cosmological time scales.

Light neutralinos could be thermally produced inside a Supernova. If their mean free path is of the order of the Supernova core size or lager, the neutralinos escape freely and lead to an additional cooling of the Supernova. To be in agreement with observations of the Kamiokande and IMB Collaborations from SN 1987A, see Ref. [17], the cooling must not shorten the neutrino signal. The energy that is emitted by the neutralinos is much smaller than that emitted by the neutrinos if $m_{\tilde{\chi}_1^0} \gtrsim 200$ MeV [17], with $m_{\tilde{e}} = 500$ GeV. For heavy sleptons, $m_{\tilde{e}} \gtrsim 1200$ GeV, however, no bound on the neutralino mass can be set [8, 17].

A very light neutralino would be a hot dark matter candidate. The Cowsik-McClelland bound [18] gives here $m_{\tilde{\chi}_1^0} \lesssim 1$ eV [8], such that a light relativistic neutralino does not disturb the formation of large structures in the universe. Thus, a light or even massless neutralino can be in agreement with constraints from cosmology and astrophysics.



(a) **(b)**

Figure 3: Contour lines in the μ–M_2 plane for the difference $\delta\Gamma = (\Gamma_{\rm inv} - \Gamma_{\rm inv}^{\rm exp})/\Delta\Gamma$ of theory prediction and experimental value of the invisible Z width in units of the experimental error $\Delta\Gamma = 1.5$ MeV, for $m_{\tilde{\chi}_1^0} = 0$ GeV, $\tan\beta = 10$, and **(a)** $A_\tau = A_t = A_b = m_{\tilde{g}} = M_A = 2M_{\tilde{f}} = 500$ GeV, **(b)** $A_\tau = A_t = A_b = m_{\tilde{g}} = M_A = M_{\tilde{f}} = 600$ GeV. Along the dashed line $m_{\tilde{\chi}_1^\pm} = 94$ GeV.

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