How light can the lightest neutralino be?

Olaf Kittel
Departamento de Física Teórica y del Cosmos and CAFPE,
Universidad de Granada, E-18071 Granada, Spain
E-mail: kittel@th.physik.uni-bonn.de

Abstract. In this talk we summarize previous work on mass bounds of a light neutralino in the Minimal Supersymmetric Standard Model. We show that without the GUT relation between the gaugino mass parameters $M_1$ and $M_2$, the mass of the lightest neutralino is essentially unconstrained by collider bounds and precision observables. We conclude by considering also the astrophysics and cosmology of a light neutralino.

1. Introduction

The lightest supersymmetric particle, the LSP, plays a special role in the search for Supersymmetry (SUSY) [1] at colliders. For conserved R-parity or proton hexality [2,3], the LSP is stable and thus the end product of cascade decays of any produced SUSY particle. Thus the nature of the LSP is decisive for all supersymmetric signatures at the LHC and ILC. Here we ask the question ‘How light can the lightest neutralino be?’, and discuss bounds from collider physics and precision observables, to summarize previous works [4–9]. Note that over the last decade there has been tremendous interest to derive bounds on the neutralino mass mainly from its relic density to explain the dark matter of the universe [10–13].

2. Neutralino framework

In the Minimal Supersymmetric Standard Model (MSSM) [1], the masses and mixings of the neutralinos and charginos are given by their mass matrices [1,14]

$$ M_0 = M_Z \begin{pmatrix} M_1/M_Z & 0 & -s_\theta c_\beta & s_\theta s_\beta \\ 0 & M_2/M_Z & c_\theta c_\beta & -c_\theta s_\beta \\ -s_\theta c_\beta & c_\theta c_\beta & 0 & -\mu/M_Z \\ s_\theta s_\beta & -c_\theta s_\beta & -\mu/M_Z & 0 \end{pmatrix}, \quad M_\pm = M_W \begin{pmatrix} M_2/M_W & \sqrt{2}s_\beta \\ \sqrt{2}c_\beta & \mu/M_W \end{pmatrix},$$

(1)

respectively, with $c_\beta = \cos \beta$, $s_\beta = \sin \beta$ and $c_\theta = \cos \theta_w$, $s_\theta = \sin \theta_w$, and the weak mixing angle $\theta_w$. 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 $\mu$, 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 $M_0 M_0^\dagger$ ($M_\pm M_\pm^\dagger$) [14].
The PDG cites as the laboratory bound on the lightest neutralino mass \[ m_{\tilde{\chi}_1^0} > 46 \text{ GeV} \] (2) at 95% C.L., which is based on the chargino searches at LEP, \( m_{\tilde{\chi}_\pm} \gtrsim 100 \text{ GeV} \) \[14\]. These yield lower limits on \( M_2, |\mu| \gtrsim 100 \text{ GeV} \). Furthermore, this bound assumes an underlying SUSY GUT, i.e., \( M_1 = 5/3 \tan^2(\theta_w)M_2 \approx 0.5M_2 \). The experimental bound on \( M_2 \) then implies the lower bound on \( M_1 \), which give rise to the lower bound in Eq. (2).

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 \( M_0 \) freely \[4, 8, 10, 15\]. This choice can be made stable against radiative corrections \[8\]. The neutralino mass is identically zero for \[ |\mu| \approx \frac{1}{2} M_Z, \theta_w \approx 0 \] (3) and \( \theta_w \approx \frac{\pi}{2} \). This will automatically reduce the contribution to the invisible \( Z \) width, \( Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \). The masses of the other neutralinos and charginos are then 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. Finally, we summarize bounds from astrophysics and cosmology.

3. Collider bounds

Neutralino production at LEP: If we assume \( m_{\tilde{\chi}_1^0} = 0 \), the associated production \( e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \) would be accessible at LEP up to the kinematical limit of \( \sqrt{s} = m_{\tilde{\chi}_1^0} = 208 \text{ GeV} \). In order to compare with the results of the LEP searches we make use of the model-independent upper bounds on the topological neutralino production cross section obtained by OPAL with \( \sqrt{s} = 208 \text{ GeV} \) \[16\],

\[
\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \times \text{BR}(\tilde{\chi}_1^0 \to Z\tilde{\chi}_1^0) \times \text{BR}(Z \to q\bar{q}).
\] (4)

Taking into account \( \text{BR}(Z \to q\bar{q}) \approx 70\% \), one can roughly read off from the OPAL plots \[16\],

\[
\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0) \times \text{BR}(\tilde{\chi}_1^0 \to Z\tilde{\chi}_1^0) < 70 \text{ fb}.
\] (5)

Figure 1. Bino admixture of \( \tilde{\chi}_1^0 \) (left plot) and masses of charginos and neutralinos (right plot) for \( M_2 = 200 \text{ GeV}, \tan \beta = 10, \text{ and } M_1 \) as given in Eq. \[3\], such that \( m_{\tilde{\chi}_1^0} = 0 \text{ GeV} \) \[8\]. Left to the vertical lines at \( \mu \approx 135 \text{ GeV} \), the chargino mass is \( m_{\tilde{\chi}_1^0} < 94 \text{ GeV} \). In the right panel, the dotted line indicates the reach of LEP2 (\( \sqrt{s} = 208 \text{ GeV} \)) for \( e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 \) production, and the dashed line indicates the mass of the \( Z \) boson, \( M_Z \approx 91 \text{ GeV} \).

We analyze this bound assuming conservatively that \( \text{BR}(\tilde{\chi}_1^0 \to Z\tilde{\chi}_1^0) = 1 \). Note that OPAL has only considered the hadronic \( Z \) decay channel, \( Z \to q\bar{q} \). If other leptonic neutralino decays open, for example 2-body (or 3-body) decays via sleptons, see the dot-dashed line in Fig. 1(b), this would lead to a reduction of the hadronic signal OPAL searched for, and thus would allow for higher neutralino production cross sections. In that sense our bounds on these production cross sections are conservative.

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such that $m\tilde{e}_R = m\tilde{e}_L = m_{\tilde{e}}$, such that $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0) =$ 70 fb for $m\chi_1^0 = 0$ with $\tan \beta = 10$. In (a), (b), the dashed lines indicate the kinematical limit $m\tilde{\chi}_2^0 = \sqrt{s} = 208$ GeV, in the gray shaded areas the chargino mass is $m_{\tilde{\chi}_1^\pm} < 94$ GeV. Along the dot-dashed contour in (b) the relation $m_{\tilde{\chi}} = m\chi_2^0$ holds.

This is already a very tight bound, since typical neutralino production cross sections can be of the order of 100 fb, see Fig. 2(a). For bino-like neutralinos, the main contribution to the cross section is due to $\tilde{e}_R$ exchange. Thus, the bound on the neutralino production cross section can be translated into lower bounds on the selectron mass $m_{\tilde{e}}$, for $m\chi_1^0 = 0$. In Fig. 2(b), we show lower bounds of the selectron mass, such that along the contours the bound $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0) =$ 70 fb is fulfilled.

**Radiative neutralino production:** Another search channel at LEP is radiative neutralino production, $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_2^0\gamma$. However, due to the large SM background from radiative neutrino production $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, we find that the significance is always $S < 0.1$ for $L = 100$ pb$^{-1}$ and $\sqrt{s} = 208$ GeV [6][7]. Cuts on the photon energy or angle do not help, due to similar distributions of signal and background. At the ILC however, radiative neutralino production will be measurable, due to a higher luminosity and the option of polarized beams [6][7][17].

### 4. Bounds from precision observables and rare decays

In the following we study the impact of a light or massless neutralino on electroweak precision physics. As an example, we focus on the invisible $Z$ width, $\Gamma_{\text{inv}}$, which is potentially very sensitive to a light or massless neutralino, due to the contribution $Z \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$, which involves the higgsino contribution of the neutralino. However, a light neutralino is mainly bino-like for $|\mu| \gtrsim 125$ GeV, see Fig. 1. In Fig. 3 we show the difference $\Delta \Gamma = (\Gamma_{\text{inv}} - \Gamma_{\text{inv}}^{\text{exp}})/\Delta \Gamma$ from the measured invisible width $\Gamma_{\text{inv}}^{\text{exp}} = 499.0 \pm 1.5$ MeV [14][18], in units of the experimental error $\Delta \Gamma = 1.5$ MeV, to the theoretical prediction $\Gamma_{\text{inv}}$. The calculations of $\Gamma_{\text{inv}}$ include the full $O(\alpha)$ SM and MSSM contributions, supplemented with leading higher-order terms [12]. The deviation from the measured width $\Gamma_{\text{inv}}^{\text{exp}}$ is larger than 5$\sigma$ only for $|\mu| \lesssim 125$ GeV, where an increasing higgsino admixture leads to a non-negligible neutralino coupling to the $Z$. However those parts of the $\mu$-$M_h$ planes are mostly already excluded by direct chargino searches at LEP. Note also that already the SM contribution to $\Gamma_{\text{inv}}$ is more than 1$\sigma$ larger than the experimental value $\Gamma_{\text{inv}}^{\text{exp}}$ [18][19].
Figure 3. Contour lines in the $\mu - M_2$ plane for the difference $\delta\Gamma = (\Gamma_{\text{inv}} - \Gamma_{\text{exp}})/\Delta \Gamma$ of theory prediction and experimental value of the invisible $Z$ width in units of the experimental error $\Delta \Gamma = 1.5$ MeV, for $m_{\tilde{\chi}^0_1} = 0$ GeV, $\tan \beta = 10$, and (a) $A_\tau = A_t = A_b = m_3 = M_A = 2M_f = 500$ GeV, (b) $A_\tau = A_t = A_b = m_3 = M_A = M_f = 600$ GeV. Along the dashed line $m_{\tilde{\chi}^\pm_1} = 94$ GeV.

A massless or light neutralino has low impact 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 $(g - 2)_\mu$. We thus refer the reader to the original paper [8]. Rare meson decays into a light bino-like neutralino have also been analyzed [20], but no constraints on the neutralino mass could be set.

5. Bounds from astrophysics and cosmology

**Supernova cooling:** Light neutralinos of masses of order 100 MeV could be thermally produced inside a Supernova. If their mean free path is of the order of the Supernova core size or larger, the neutralinos escape freely and lead to an additional cooling of the Supernova [5, 21, 22]. To be in agreement with observations of the Kamiokande and IMB Collaborations from SN 1987A, see Ref. [5], 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 $m_{\tilde{\chi}^0_1} > \sim 200$ MeV [5], with $m_{\tilde{e}} = 500$ GeV. For heavy sleptons, $m_{\tilde{e}} > \sim 1200$ GeV, however, no bound on the neutralino mass can be set [5].

**Hot dark matter:** We consider the case of a nearly massless neutralino, $m_{\tilde{\chi}^0_1} \lesssim O(1 \text{ eV})$. Since the very light bino contributes to the hot dark matter of the universe, we assume here implicitly that the cold dark matter originates from another source. The bino relic energy density, $\rho_{\tilde{B}}$, divided by the critical energy density of the universe, $\rho_c$, is given by [23]

$$\Omega_{\tilde{B}} \equiv \frac{\rho_{\tilde{B}}}{\rho_c} = \frac{43}{11} \zeta(3) \frac{8\pi G_N}{3H_0^2} \frac{g_{\text{eff}}(T)}{g_{\ast}(T)} \frac{T^3}{m_{\tilde{B}}^2}. \quad (6)$$

In order for the bino hot dark matter not to disturb the large structure formation, we assume its contribution to be less than the upper bound on the energy density of the neutrinos, as determined by the WMAP data [24]

$$\Omega_{\tilde{B}} h^2 \leq [\Omega_\nu h^2]_{\text{max}} = 0.0076. \quad (7)$$

From Eqs. (6) and (7), we find the conservative upper bound

$$m_{\tilde{B}} \leq 0.7 \text{ eV}. \quad (8)$$
Thus a very light bino with mass below about 1 eV is consistent with structure formation. This line of argument was originally used by Gershtein and Zel’dovich [25] and Cowik and McClelland [26] to derive a neutrino upper mass bound, by requiring $\Omega_\nu \leq 1$. We have here obtained an upper mass bound for a hot dark matter bino.

**Cold dark matter:** The impact of a light neutralino on its thermal relic density has widely been studied [10]. If the neutralino accounts for the dark matter, its mass has to be $m_{\tilde{\chi}} > 3 \ldots 20$ GeV. Although seeming theoretically unmotivated, those bounds could in principle be evaded by allowing a small amount of R-parity violation [4], and/or additional dark matter candidates.

Note that many authors have revisited the case of a light WIMP in the sub 10 GeV mass range, to explain recent results from the DAMA/LIBRA, CDMS and/or CoGeNT experiments [11]. In the MSSM, to ensure their effective annihilation, such particles must exchange a light $O(\text{GeV})$ pseudoscalar Higgs at large values of $\tan \beta$. Since this is however ruled out by recent TEVATRON results on SUSY Higgs searches, the authors of Ref. [12] recently concluded that a light MSSM neutralino of $m_{\tilde{\chi}} < 15$ GeV should be excluded. In Ref. [13] it was pointed out that also improved measurements on $B_s \to \mu \mu$ exclude neutralinos with such light masses to accommodate the CoGeNT preferred region.

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