Production of long-lived charginos at the LHC

M G Paucar
Instituto de Física, Universidad Nacional Autónoma de México, Apdo. Postal 20-364, México 01000
E-mail: mgerardo@fisica.unam.mx

Abstract. We performed a study on the probable existence of long-lived charginos in the focus point region of parameter space in the framework of the MSSM with supergravity inspired soft SUSY breaking. The mass degeneracy of higgsino-like chargino and two higgsino-like neutralinos is the necessary condition for a long lifetime. In this region the chargino are long lived and may go through the detector or produce a secondary vertex when they decay inside the detector. We analyze the production and co-production cross section of long-lived charginos at LHC via electroweak interaction and found that, for light long-lived charginos, the production cross section may reach a few percent of pb.

1. Introduction
The discovery of supersymmetry is one of the main goals in the proposed experiments at the LHC.[1, 2]. However, search for supersymmetric particles at colliders usually proceeds from the assumption that all of them are relatively heavy (few hundreds of GeV) and short-lived which are created in strong and weak interactions and then decay (almost immediately) to usual Standard Model particles with additional missing energy taken away by the Lightest Supersymmetric Particle (LSP). Almost everywhere in the parameter space of the Constrained MSSM (CMSSM) (or also known as the minimal Supergravity model, mSUGRA) [3, 4], the LSP is the lightest neutralino (other, SUSY breaking scenarios lead to different experimental signatures and different LSP [5, 6]).

There are, however, some regions in mSUGRA conventions where the LSP is not the lightest neutralino $\tilde{\chi}_1^0$, but is a stau $\tilde{\tau}$, or a stop $\tilde{t}$, or the first chargino $\tilde{\chi}_1^\pm$ [7, 8, 9, 10]. These regions are obviously considered as forbidden ones. At the border of these regions when masses of superpartners are degenerate with the neutralino mass and hence the decay rate is suppressed, the staus, stops, and charginos become long-lived superparticles. As one departs from the border line, superpartners are slightly heavier than the neutralino and thus unstable, then they decay very fast.

Here, we explore the narrow band along the line where the radiative electroweak symmetry breaking fails. This region is consistent with the neutralino relic density constraint (the WMAP restriction on the amount of the dark matter). On the border of this region the Higgs mixing parameter $\mu$, which is determined from the requirement of electroweak symmetry breaking via radiative corrections, tends to zero. This leads to existence of light and degenerate states: one chargino and two neutralinos, all of them being essentially higgsinos. Below we discuss their properties and possible creation at the LHC.
2. Focus-point Region and Long-lived Charginos

In mSUGRA models with $R$-parity conservation, the only available set of parameters space is $[m_0, m_{1/2}, A_0, \text{sign}(\mu), \tan\beta]$. Fixing $A_0$, $\text{sign}(\mu)$, $\tan\beta$ and varying $m_0$ and $m_{1/2}$, we can get regions in parameter space for which the cross section for $\chi^+_1$ LSP annihilation and co-annihilation corresponds to the dark matter density measured by WMAP. We have imposed on the mSUGRA parameter space the following constraints: i) the gauge couplings unification [11, 12, 13], ii) neutrality of the LSP [14, 15], iii) the Higgs boson and SUSY mass experimental limits [16, 17, 18], iv) radiative electroweak symmetry breaking [19, 20]. We take the sign of $\mu$ to be positive, motivated by the contribution to the anomalous magnetic moment of muon [21].

We are interested in the region of small $\mu$ (less than $M_Z$), which takes place in the so-called focus point region near the border line of radiative electroweak symmetry breaking. In this scenario the lightest chargino ($\chi^+_1$) and two lightest neutralinos ($\chi^0_{1,2}$) are almost degenerate and have a mass of the order of $\mu$. The mass terms are nondiagonal and look like

$$L_{\text{Gaugino-Higgsino}} = -\frac{1}{2} M_3 \lambda_a \lambda_a - \frac{1}{2} \bar{\chi} M^{(0)} \chi - \bar{\psi} M^{(c)} \psi + h.c.,$$

where $\lambda_a, a = 1, 2, \ldots, 8$, are the Majorana gluino fields and $\chi, \psi$ are, respectively, the Majorana neutralino and Dirac chargino fields.

At the tree level the neutralino mass matrix is

$$M^{(0)} = \begin{pmatrix}
M_1 & 0 & -M_Z c_\beta s_\theta & M_Z s_\beta c_\theta \\
0 & M_2 & M_Z c_\beta c_\theta & -M_Z s_\beta s_\theta \\
-M_Z c_\beta s_\theta & M_Z c_\beta c_\theta & 0 & -\mu \\
M_Z s_\beta s_\theta & -M_Z s_\beta c_\theta & -\mu & 0
\end{pmatrix},$$

where $s_\beta = \sin \beta, c_\beta = \cos \beta$ and $s_\theta = \sin \theta_W$ is the usual sinus of the Weinberg weak mixing angle ($c_{W} = \cos \beta$). The physical neutralino masses $m_{\chi^0_i}$ are obtained as eigenvalues of this matrix after diagonalization.

For charginos one has

$$M^{(c)} = \begin{pmatrix}
M_2 & \sqrt{2} M_W c_\beta \\
\sqrt{2} M_W c_\beta & \mu
\end{pmatrix}. $$
This matrix has two chargino eigenstates $\tilde{\chi}^\pm_{1,2}$ with mass eigenvalues

$$M^2_{1,2} = \frac{1}{2} \left[ M_2^2 + \mu^2 + 2M_W^2 \right]$$
$$\mp \sqrt{(M_2^2 - \mu^2)^2 + 4M_W^4 \cos^2 2\beta + 4M_2^2M_W^2(m_1^2 + \mu^2 + 2M_2\mu \sin 2\beta)}$$

These matrices receive radiative corrections which are known in the leading order [22]. Typically they are of the order of a few per cent.

In Fig. 1, it is shown how the mass of the lightest neutralino and the mass of the lightest chargino obtained from Eqs. (2) and (4) depend on $\mu$.

The degeneracy of masses masses $(m_{\chi_0^0}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm})$ takes place for any choice of the other parameters since the tree level formulae weakly depend on them and the one-loop corrections are usually small. However, since the value of $\mu$ is not arbitrary in this approach but is taken from the requirement of electroweak symmetry breaking, one has to find the region of parameter space where it is small.

In Fig. 1, this region is just above the chargino LEP limit in the left bottom corner of the plots. One can see that masses are degenerate, and there the value of $\mu$ is of the order of 150–200 GeV depending on the value of $\tan \beta$. There is also a slight dependence on $M_2$ (that is on $m_{1/2}$); however, this dependence only shows how far we may go along the lines having masses degenerate. It is clearly seen that the bigger $M_2$ the larger values of $\mu$ are allowed. The mass of $\chi_2^0$ is not shown, it almost coincides with the $\chi_1^0$ mass.

In Fig. 2, we show the projection of SUSY parameter space onto the $m_0, m_{1/2}$ plane for $A_0=-800, -3500$ GeV and $\tan \beta=10, 50$. To calculate it, we use the SuSpect v2.3.4 code [23]¹. The relic density was calculated with the help of the MicrOmegas package [24].

One can see that for small value of $A_0$ the Dark matter line does not go along the electroweak symmetry breaking border but deviates from it, thus not allowing the small value of $\mu$. For large and negative $A_0$, on the contrary, these two lines almost coincide, the bigger the value of $\tan \beta$ the better.

¹ We have set the following input values at $M_W$; $\alpha^{-1}_{em} = 127.934$, $\alpha_s = 0.1172$, $m_{\nu}^{pole} = 172.7$ GeV, $m_b(m_b)^MS = 4.25$ GeV, $m_E^{pole} = 1.777$ GeV.
In Fig. 3, we show the lifetime of the lightest chargino as a function of the mass difference between the lightest chargino (NLSP) and the lightest neutralino (LSP). It appears that in order to get reasonable "large" lifetimes one has to go very far along the focus point region. Then keeping $\mu$ small one can get lifetimes of the order of $10^{-10}$ s for practically degenerate LSP and NLSP. When the mass difference increases the lifetime falls down. However, if the degeneracy is within a few GeV, charginos are long-lived.

3. Production cross-section of long-lived charginos at LHC
In the previous sections, there appeared the possibility of obtaining charginos with very long-lifetime. Now we study the production cross-section of these long-lived sparticles at LHC and analyze the possible situation when they could go through the detector.

In Fig. 4, we show the production of long-lived charginos in annihilation channel at LHC. Since three states are almost degenerate, one has also co-production which has to be taken into account. This refers also to the annihilation process that defines the amount of the Dark matter.

To calculate the production rate of long-lived chargino, we used CALCHEP code [25] which takes into account the parton distributions inside protons. For our purposes we took the MRST2002NLO parton distribution functions [26]. We choose several benchmark points in the CMSSM parameter space which are situated in the focus point region along the border of electroweak symmetry breaking (see Fig. 2). The values of $\mu$ and $\tan \beta$ are varied. As we have already mentioned for consistency with the relic density constraint the advocated scenario prefers large negative $A_0$ and large $\tan \beta$.

For each benchmark point we have calculated the cross-sections of chargino production and co-production with the lightest and next-to-lightest neutralino. The result of the calculations are summarized in table 1.
One can see that on average the cross-sections reach a few tenth of pb and slightly vary with the change of \( \tan \beta \). The cross-sections mainly depend on \( \mu \): the bigger the value of \( \mu \) the smaller the cross-section. This is due to the fact that the cross-section mostly depends on the masses determined mostly by \( \mu \) and mixings.

**Table 1.** The cross-sections for the chargino production and co-production at the LHC in the focus point region for \( \mu = 120 \text{ GeV} \) and \( \tan \beta = 10, 30, 50 \).

| Process       | \( \tan \beta = 10 \) | \( \tan \beta = 30 \) | \( \tan \beta = 50 \) |
|---------------|------------------------|------------------------|------------------------|
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.58 0.54 0.53         |                        |                        |
| \( u\bar{u} \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.58 0.54 0.53         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.27 0.24 0.24         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.27 0.24 0.24         |                        |                        |
| \( \sigma_{p1}(pb) \) | 1.68 1.56 1.54         |                        |                        |
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) |                        |                        |                        |
| \( u\bar{d} \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) | 1.08 0.99 0.98         |                        |                        |
| \( \tilde{d}u \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) | 1.08 0.99 0.98         |                        |                        |
| \( \sigma_{p2}(pb) \) | 2.16 1.98 1.96         |                        |                        |
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) |                        |                        |                        |
| \( u\bar{u} \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) | 0.68 0.66 0.65         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) | 0.68 0.66 0.65         |                        |                        |
| \( \sigma_{p3}(pb) \) | 1.37 1.32 1.30         |                        |                        |

**Table 2.** The cross-sections for the chargino production and co-production at the LHC in the focus point region for \( \mu = 200 \text{ GeV} \) and \( \tan \beta = 10, 30, 50 \).

| Process       | \( \tan \beta = 10 \) | \( \tan \beta = 30 \) | \( \tan \beta = 50 \) |
|---------------|------------------------|------------------------|------------------------|
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.11 0.10 0.10         |                        |                        |
| \( u\bar{u} \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.11 0.10 0.10         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.05 0.04 0.04         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_1^- \) | 0.05 0.04 0.04         |                        |                        |
| \( \sigma_{p1}(pb) \) | 0.32 0.28 0.28         |                        |                        |
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) |                        |                        |                        |
| \( u\bar{d} \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) | 0.15 0.14 0.13         |                        |                        |
| \( \tilde{d}u \to \tilde{\chi}_1^+ \tilde{\chi}_1^0 \) | 0.15 0.14 0.13         |                        |                        |
| \( \sigma_{p2}(pb) \) | 0.30 0.28 0.26         |                        |                        |
| \( pp \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) |                        |                        |                        |
| \( u\bar{u} \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) | 0.12 0.12 0.12         |                        |                        |
| \( \tilde{d}d \to \tilde{\chi}_1^+ \tilde{\chi}_2^0 \) | 0.12 0.12 0.12         |                        |                        |
| \( \sigma_{p3}(pb) \) | 0.24 0.24 0.24         |                        |                        |
4. Conclusions

We have shown that within the mSUGRA framework there exists an interesting possibility to get long-lived charginos, superpartners of the charged Higgs boson (or W-boson) which might be produced at the Large Hadron Collider. In this case the lightest chargino and the lightest neutralinos are almost fully higgsinos, the higgsino content reaching 70 - 80 % depending on a particular benchmark point. The cross-sections of chargino pair production and co-production via electroweak interaction crucially depend on the chargino mass, and for light charginos it can reach a few pb. As in the case of light stops (see ref. [9]), the light chargino NLSP scenario requires large negative values of the soft trilinear SUSY breaking parameter $A_0$, and large values of $m_0$ and $m_{1/2}$. The chargino decay would have an unusual signature and produce a noticeable signal rather than pure missing energy taken away by the lightest neutralino. The two options are: charginos go through the detector, or they produce a secondary vertex when they decay inside the detector.

Acknowledgements

I would like to express my sincere thanks to Professors D.I. Kazakov and A.V. Gladyshev for their valuable discussion and constructive criticism on this work. I would like also to thank Professor M. Mondragon for her constant encouragement and help. The work of M. G. P. is supported by ICYTDF-CLAF postdoctoral fellowship. Support from PAPITT Project IN113412 is kindly acknowledged.

References

[1] Haber H E and Kane G L 1985 Phys. Rep. 117 75
[2] Gladyshev A V and Kazakov D I 2007 Phys. Atom. Nucl. 70 1553
[3] Hall L J, Lykken J and Weinberg S 1983 Phys. Rev. D 27 2359-2378.
[4] Nath P, Arnowitt R and Chamseddine A H, 1983 Nucl. Phys. B 227 121-133.
[5] Randall L and Sundrum R 1999 Nucl. Phys. B 557 79-118.
[6] Dine M and Nelson A E 1993 Phys. Rev. D 48 1277-1287.
[7] Gladyshev A V, Kazakov D I and Paucar M G 2005 Mod. Phys. Lett. A 20 3085
[8] Paucar M G 2008 Phys. Atom. Nucl. 71 695
[9] Gladyshev A V, Kazakov D I and Paucar M G 2007 Light stops in the MSSM parameter space arXiv:0704.1429v1 [hep-ph]
[10] Gladyshev A V, Kazakov D I and Paucar M G 2008 Proc. 15th Int. Conf. on Supersymmetry and the Unification of Fundamental Interactions (Karlsruhe) ed W de Boer and I Gebauer (Brno: Librix) Vol 1, p 338
[11] Amaldi U, de Boer W and Furstenau H 1991 Phys. Lett. B 260 447
[12] Ellis J R, Kelley S and Nanopoulos D V 1991 Phys. Lett. B 260 131
[13] Giunti C, Kim C W and Lee U W 1991 Mod. Phys. Lett. A 6 1745
[14] Ellis J R et al. 1884 Nucl. Phys. B 238 453
[15] Jungman G, Kamionkowski M and Griest K 1996 Phys.Rep. 267 195
[16] LEP Higgs Working Group for Higgs boson searches, OPAL Collaboration, ALEPH Collaboration, DELPHI Collaboration and L3 Collaboration 2003 Search for the Standard Model Higgs Boson at LEP Preprint CERN-EP/2003-011, hep-ex/0306033
[17] Joint LEP2 SUSY Working Group 2001 Combined LEP Chargino Results up to 208 GeV http://lepsusy.web.cern.ch/lepsusy/ww/inos_moriond01/charginos_pub.html
[18] Combined LEP Selectron/Smuon/Stau Results, 183-208 GeV http://lepsusy.web.cern.ch/lepsusy/ww/sleptons_summer02/slep_2002.html
[19] Ibáñez L E and Ross G G 1992 Nucl. Phys. B 368 3
[20] Ross G G and Roberts R G 1992 Nucl. Phys. B 377 571
[21] Brown H N et al (Muon g-2 Collaboration) 2001 Phys. Rev. Lett. 86 2227
[22] Pierce D and Papadopoulos A 1994 Phys. Rev. D 50 565
[23] Djouadi A, Kneur J L and Moultaka G 2007 Comput. Phys. Commun. 176 426
[24] Belanger G, Boudjema F, Fukhov A and Senemon A 2002 Comput. Phys. Commun. 149 103
[25] Pukhov A 2004 Calchep 3.2: MSSM, structure functions and event generation, arXiv:hep-ph/0412191
[26] Martin A D, Roberts R G, Stirling W J and Thorne R S 2003 Eur. Phys. J. C 28 455