We study the potential of neutralino dark matter searches and SUSY particle production at colliders in the framework of the Minimal Supersymmetric Standard Model. We show the effects of a non universal gluino mass parameter. The future experiments will be a stringent probe of the low energy MSSM and neutralino dark matter scenario. The deeper informations on both supersymmetry and astrophysics hypothesis will be obtained by correlation of the different signals or absence of signal.

1 Introduction

Several astrophysics indications point that matter in the universe is dominated by an unidentified and undiscovered dark matter (see e.g.\cite{1,2,3} for a review). The WMAP results lead to a flat $\Lambda CDM$ universe with $\Omega_{CDM}h^2 = 0.1126 \pm 0.0161$. An interesting possibility for the dark matter enigma is a bath of Weakly–Interacting Massive Particle (WIMP).

In high energy physics, the most popular extension of the Standard Model is achieved through the supersymmetry (SUSY) suggested by theoretical aspects and string theory. The Minimal Supersymmetric Standard Model (MSSM),\cite{4,5,6}, predicts the existence of several new particles, the superpartners of known particles. Those particles should be discovered in future collider experiments. Furthermore the Lightest Supersymmetric Particle (LSP) is for most of the MSSM parameters a stable (assuming R-parity conservation), massive, neutral and weakly interacting particle : the lightest neutralino being so an interesting and well motivated candidate for dark matter.

The neutralinos ($\chi_1^0 \equiv \chi, \chi_2^0, \chi_3^0, \chi_4^0$) are the masses eigenstates coming from mixing of neutral gauge and (Brout-Englert-)Higgs boson superpartners: $\tilde{B}, \tilde{W}^3, \tilde{H}^0_1, \tilde{H}^0_2$ respectively the B–ino, W–ino and up, down–Higgsinos fields. In the ($\tilde{B}, \tilde{W}^3, \tilde{H}^0_1, \tilde{H}^0_2$) basis, the neutralino mass
matrix is

\[
M_N = \begin{pmatrix}
M_1 & 0 & -m_Z \cos \beta \sin \theta_W & m_Z \sin \beta \sin \theta_W \\
0 & M_2 & m_Z \cos \beta \cos \theta_W & -m_Z \sin \beta \cos \theta_W \\
-m_Z \cos \beta \sin \theta_W & m_Z \cos \beta \cos \theta_W & 0 & -\mu \\
m_Z \sin \beta \sin \theta_W & -m_Z \sin \beta \cos \theta_W & -\mu & 0
\end{pmatrix}.
\] (1)

\(M_1, M_2\) and \(\mu\) are the bino, wino, and Higgs–Higgsino mass parameters respectively after Renormalization Group Equation (RGE) running from GUT scale down to electroweak symmetry breaking (EWSB) scale. \(\tan \beta\) is the ratio of the vev of the two Higgs doublet fields. This matrix can be diagonalized by a single unitary matrix \(z\) such that we can express the LSP \(\chi\) (the neutralino in the following) as

\[
\chi = z_{11} \tilde{B} + z_{12} \tilde{W} + z_{13} \tilde{H}_1 + z_{14} \tilde{H}_2.
\] (2)

This combination determines the nature, the couplings and the phenomenology of the neutralino.

In this talk, we will consider neutralino dark matter searches and SUSY particles production in future colliders. Related works in a variety of framework models treating relic density aspect, present accelerator constraints and/or DM searches and/or SUSY searches in future colliders can be found in e.g. references 7 - 43.

2 Dark matter searches

2.1 Dark matter distribution

The dark matter distribution is an important point for detections. If there is an agreement concerning the behavior at large radii, the shape of the innermost region of the galaxy is quite uncertain if we consider the discrepancies between simulation results of various groups. Further, the observation of systems like low surface brightness seem to favor flat cores. On top of that the small radius region behavior can differ strongly depending on physics assumptions considered like effects of the baryons, supermassive black hole induced spike, dark matter particle scatterings by stars. On the contrary, the local density \(\rho_0\) is more under control and should be in the range \(0.2 - 0.8\ \text{GeV.cm}^{-3}\). Finally possible inhomogeneities and substructures could be present giving a possible clumpyness of the halo.

2.2 Direct detection

The presence of dark matter particles can be signed by the collision with the nuclei of a detector. The astrophysical dependence is weak and comes from the knowledge of local dark matter density \(\rho_0\). From the particle physics point of view, depending on the spin of the target nuclei, the detection is driven by the spin dependent or scalar neutralino proton(nucleon) elastic cross section \(\sigma\) processes in \(\sigma_{\chi-p}\).

Current experiments like EDELWEISS and CDMS are sensible to WIMP–proton cross section \(\lesssim 10^{-6}\ \text{pb}\) which is slightly not enough to probe SUSY model including RGE and radiative EWSB if one requires experimental constraints and near WMAP relic density. The next step of experiments (e.g EDELWEISS II and CDMS II) will lead to a minimum of the valley sensitivity around \(10^{-8}\ \text{pb}\) for \(m_\chi\) of order 100 GeV. Though challenging from the experimental point of view, a ton-size detector (ZEPLIN, SuperCDMS) should be able to reach \(\sigma_{\chi-p} \lesssim 10^{-10}\ \text{pb}\) which would be a conclusive tool to probe WIMP dark matter models especially for the MSSM neutralino scenario.
2.3 Gamma Indirect detection

Dark matter can annihilate in the halo, especially in the Galactic Center where the DM density is high. This can lead to important gamma fluxes and promising signals despite of the strong uncertainty coming from the unknown distribution in the innermost region. The particle physics dependence comes from neutralino annihilation cross section. There are several existing signals (INTEGRAL, EGRET, CANGAROO, HESS) from the Galactic Center region extending on very different energy ranges. Though possible explanation in term of neutralino (see e.g.33,34) are possible for each signal (except maybe for INTEGRAL, see 44 for the light dark matter proposition), those measurements are not compatible with each other and can not be explained by a single scenario. Nevertheless, the Egret signal ($\sim 4 \times 10^{-8} \gamma \text{cm}^{-2}\cdot\text{s}^{-1}$) can represent an upper bound. We will consider the HESS and GLAST experiment sensitivities (respectively $\sim 10^{-12}$-$13 \gamma \text{cm}^{-2}\cdot\text{s}^{-1}$ with 60 GeV threshold and $\sim 10^{-10} \gamma \text{cm}^{-2}\cdot\text{s}^{-1}$ with 1 GeV threshold) as a probing test of SUSY models.

2.4 Neutrino Indirect detection

Dark matter particles of the halo can also be trapped in the Sun by successive elastic diffusion on its nuclei (Hydrogen). This lead to a captured population which can annihilate. The annihilation products then decay producing neutrino fluxes which can be detected by a neutrino telescopes signing the presence of dark matter in the Sun.

The local dark matter density is the weak astrophysical dependence for this possible detection and it is shared with direct detection. Concerning particle physics dependence, the main aspect is the capture rate driven by $\sigma_{\chi-q}$ and neutralino annihilation cross section.

Present experiments like MACRO, BAKSAN, SUPER K and AMANDA give limits on possible fluxes around $10^4 \mu \text{km}^{-2}\cdot\text{yr}^{-1}$. Future neutrino telescopes like ANTARES or a km$^3$ size like ICECUBE will be able to probe respectively around $10^3$ and $10^2 \mu \text{km}^{-2}\cdot\text{yr}^{-1}$.

2.5 Positron and Antiproton Indirect detection

Neutralino annihilations in the halo can also give rise to measurable positron and antiproton fluxes. Being charged particles, they interact during their propagation such that the directional information is lost. The variability at the production level due the density profile is quite weak, indeed the understanding of the propagation and the resolution of diffusion equation is the most relevant issue. The particle physics dependence enters in the source term by the annihilation cross section.

The HEAT experiment has measured an excess of positron (peaked around 10 GeV) which can be accommodated by neutralino but requires a boost factor$^{22,23}$. We will probe SUSY models with regard to the future experiments AMS-02 and PAMELA. Considering the positron spectra being peaked around $M_\chi/2$, a benchmark condition can be $\phi_{\phi}(R_0,T) > 2 \times 10^{-7} \bar{p} \text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$. The antiproton flux is measured by experiments like BESS and CAPRICE and is accommodated by astrophysical processes. This flux is peaked at 1.76 GeV around $2 \times 10^{-6} \bar{p} \text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$. We will show as benchmark the region where $\phi_{\bar{p}}(R_0,T) > 2 \times 10^{-7} \bar{p} \text{cm}^{-2}\cdot\text{s}^{-1}\cdot\text{sr}^{-1}$.

3 Collider searches

3.1 LHC

As a probe of supersymmetric parameter space, we consider sparticles production in which strong interaction is relevant i.e squarks and gluinos production: parton $\rightarrow$ squarks and gluinos lead to multi-jets + isolated leptons + missing $E_T$ signals.
We consider the exclusion limits of reference [45] which establishes that squarks and gluinos could be detected up to $m_{\tilde{q}-\tilde{q}} \sim 2 - 2.5$ TeV.

### 3.2 LC

We also probe supersymmetric models with regard to a possible Linear Collider with an energy of 1 TeV, $L = 500fb^{-1}/yr$ and require 50 events.

We consider the following processes: $e^+e^- \rightarrow \tilde{\ell}\tilde{\ell}$, $\tilde{\chi}^\pm\tilde{\chi}^\mp$, $\tilde{\chi}\tilde{\chi}^0_2$, HA.

### 4 Prospection

We will now show the regions in supersymmetric parameter space which are accessible for typical experiments (red and green) of the different kinds of detection. The areas excluded by the experimental constraints (Higgs and chargino mass, $B_s \rightarrow s\gamma$, muon anomalous magnetic moment, $B_s \rightarrow \mu^+\mu^-$) are also shown (grey). Considering possible alternatives in cosmology to the standard thermal DM scenario and particle physics uncertainties in the calculation of the MSSSM spectrum and the relic density, we show the conservative range $0.03 < \Omega\chi^2 < 0.3$ (yellow with external black lines), as well as the WMAP range (internal black lines of the yellow areas).

Our starting parameter space is the Universal mSugra/CMSSM plane, where one assumes a unified gaugino mass at GUT scale ($m_1/2$) and a unified scalar mass at GUT scale ($m_0$). As a benchmark, we choose $A_0 = 0, \tan\beta = 35, \mu > 0$. In this proceeding we will only illustrate the effect of non universal gluino mass term $M_3|_{GUT}$. The effects of non universal wino mass $M_2|_{GUT}$, up-type Higgs mass $MH_u|_{GUT}$ and down-type Higgs mass $MH_d|_{GUT}$ which have been shown in the conference will be found in a shortly upcoming paper [46].

#### 4.1 Universal case

For intermediate values of $\tan\beta$, there are essentially 2 regions leading to interesting neutralino relic abundance. The first one is near the stau LSP boundary (low $m_0$) thanks to the $\tilde{\tau}\tilde{\chi}$ coannihilation processes. The second one is along the boundary where the electroweak symmetry breaking cannot be achieved radiatively (Hyperbolic Branch/Focus Point : high $m_0$, low $\mu$) and where the neutralino is mixed bino-higgsino enhancing $\chi\chi$ annihilation through $Z$ exchange and $\chi\chi^+_1, \chi\chi^0_2$ coannihilations. Those two regions are generically thin.

Direct detection is then favored for light heavy Higgs scalar $H$ (mainly low $m_0, m_{1/2}$) or when the higgsino fraction is not negligible (high $m_0$) enhancing the neutralino-Higgs coupling (see Fig. 1a)).

Concerning indirect detection with neutrino telescopes, a significant signal from the Sun requires a relevant higgsino fraction to enhance the capture rate through the spin dependent interaction $\chi q \rightarrow \chi q$. This takes place only in the HB/FP branch (high $m_0$, low $\mu$) where especially a km$^3$ size detector is able to probe models satisfying the WMAP constraint (see Fig. 1b)).

Gamma indirect detection of neutralino annihilation in the Galactic Center requires high annihilation cross section. The possible processes are either $\chi\chi \rightarrow b\bar{b}$ which needs low $A$ (low $m_0, m_{1/2}$) and/or coupling ($\propto z_{11(2)} z_{13(4)}$) enhancement through higgsino fraction (high $m_0$) or $\chi\chi \rightarrow t\bar{t}$ annihilation which requires an higgsino amount as the coupling is $\propto z_{13(4)}$ (this is located near the EWSB boundary i.e high $m_0$). This is shown on Fig. 1c) for a NFW halo profile ($\rho(r) \propto 1/r$ at small $r$).

The positron and antiproton fluxes have essentially the same particle physics dependence ($\langle\sigma v\rangle$) as gamma fluxes. The favored regions for positron and antiproton are also where the neutralino annihilation is strong (see Figs. 1d) and f) ).
Collider production situation is shown on Fig. (1d). LHC is favored for low \( \tilde{q} \) masses ("low" \( m_0 \) values \( \lesssim 2 \text{ -- } 2.5 \text{ TeV} \) and/or light \( \tilde{g} \) (small \( M_{3|_{\text{low energy}}} \), i.e \( m_{1/2} \lesssim 1000 \)).

Sleptons productions at the Linear Collider can be probe for low \( \tilde{l} \) masses \( (m_0 \lesssim 700 \text{ GeV}, m_0 \lesssim 1000 \text{ GeV}) \). The \( \chi \chi_0^2 \) (mainly bino and wino respectively) production is also favored for low \( m_0 \) through selectron exchange but decreases when \( m_{\tilde{e}} \) (mainly \( m_0 \)) increase up to \( m_0 \sim 2000 \text{ GeV} \) where the higgsino fraction of the neutralinos allows the \( Z \) exchange along the EWSB boundary. The chargino production follows first the kinematic limit of wino chargino production \( (m_{1/2} \sim 600 \text{ GeV}, 2 * m_{\chi_1^+} \simeq 2 * 0.8 \text{ } \text{m}_{1/2} \simeq 1 \text{ TeV}) \) and then reaches higher \( m_{1/2} \) values thanks to the higgsino component of \( \chi_1^+ \) along the EWSB boundary at high \( m_0 \). The region favorable to \( HA \) production is restricted to the low-left corner of the plane as \( m_{A(H)} \) increase with both \( m_0 \) and \( m_{1/2} \).

4.2 The gluino mass : \( M_{3|_{\text{GUT}}} \)

The gluino mass parameter has the main influence on MSSM spectrum through \( \alpha_s \) in RGEs. It decreases squark masses, increases the up-type Higgs mass \( M^2_{H_u} \) at low energy (less negative) and decreases the down-type Higgs mass \( M^2_{H_d} \) which implies lighter \( m_{A,H} \) and an increasing of higgsino content of neutralinos and charginos as can be understood by tree level relations:

\[
\mu^2 \simeq -M^2_{H_u} - 1/2M^2_Z \quad \text{and} \quad \chi H^+ \simeq M^2_{H_d} - M^2_{H_u} - M^2_Z.
\]

As a result, relic density constraints are more easily satisfied than in the universal case: both \( \chi \chi \to \tilde{b}\tilde{b} \) annihilation (thanks to higher coupling and lighter \( A \) which can open the \( A \) funnel) and focus point region with \( \chi \chi \to t\bar{t} \) annihilation are enhanced. Direct detection get advantage of better couplings \( z_{11} z_{13} \) and lighter \( H \). The higher higgsino fraction favors neutrino indirect detection in the coupling in \( \chi q \) of the capture rate. Gamma,positron and antiproton indirect detection are favored by the annihilation enhancement. The \( \chi \chi \to b\bar{b} \) process is favored by the higgsino fraction and the resulting better couplings \( z_{11} z_{13} \) as well as a lighter pseudoscalar \( A \). The \( \chi \chi \to t\bar{t} \) process couplings, \( \propto z^2_{13(4)} \), are favored by the higgsino fraction as well as \( \chi \chi \to W^+W^- \). LHC gets strong potentiality enhancement thanks to lighter squarks \( (\tilde{t}) \) and lighter gluinos. For the Linear Collider, the \( HA \) production is favored (lighter \( H, A \)) as well as \( \chi^+ \chi^- \chi \chi_0^2 \) favored by the lower \( \mu \) values. The non universal \( M_{3|_{\text{GUT}}} \) situation is illustrated on Fig. (2) (compare panels with those of Fig. (1)).

This kind of models with light gluino mass at GUT scale are very favorable for SUSY detection in colliders as well as all neutralino dark matter searches and can be found in some effective string inspired scenarios.

5 Conclusion

Dark matter experiments and collider searches will be a quite conclusive step to probe the possibility of low energy supersymmetry and neutralino dark matter in the Minimal Supersymmetric Standard Model. The possible correlation between (non) signals of different kinds of detection will bring the maximum of information on models and scenarios both for supersymmetry and astrophysics.

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References

1. G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005)
2. G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996)
3. C. Muñoz, Int. J. Mod. Phys. A 19 (2004) 3093.
4. P. Fayet and S. Ferrara, Phys. Rept. 32, 249 (1977).
5. H. E. Haber and G. L. Kane, Phys. Rept. 117, 75 (1985).
6. R. Barbieri, Riv. Nuovo Cim. 11N4, 1 (1988).
7. J. R. Ellis, et al, Phys. Lett. B510 (2001) 236;
8. J. R. Ellis, K. A. Olive and Y. Santoso, New Jour. Phys. 4 (2002) 32;
9. A. Djouadi, M. Drees and J. L. Kneur, JHEP 0108 (2001) 055;
10. J.L. Feng, K.T. Matchev, F. Wilczek, Phys.Rev. D63 (2001) 045024,
11. U. Chattopadhyay, A. Corsetti, P. Nath, arXiv:hep-ph/0303201.
12. J. Ellis, K. A. Olive, Y. Santoso and V. C. Spanos, arXiv:hep-ph/0303043.
13. V. Berezinsky et al, Astropart.Phys. 5 (1996) 1-26,
14. P. Nath, R. Arnowitt, Phys.Rev. D56 (1997) 2820-2832,
15. V. Bertin, E. Nezri, J. Orloff, JHEP 02 (2003) 046
16. A. Birkedal-Hansen B. D. Nelson Phys.Rev. D67 (2003) 095006
17. A. Corsetti, P. Nath, Phys.Rev D64 (2001) 125010
18. S. Profumo, Phys. Rev. D 68, 015006 (2003)
19. P. Ullio, Nucl. Phys. Proc. Suppl. 110, 82 (2002).
20. A. Cesarini et al. Astropart. Phys. 21, 267 (2004)
21. D. Hooper and L. T. Wang, Phys. Rev. D 69, 035001 (2004)
22. E. A. Baltz, J. Edsjo, K. Freese and P. Gondolo, Phys. Rev. D 65, 063511 (2002)
23. D. Hooper and J. Silk, Phys. Rev. D 71, 083503 (2005)
24. A. Bottino, F. Donato, N. Fornengo and S. Scopel, Phys. Rev. D 70, 015005 (2004)
25. F. Donato, N. Fornengo, D. Maurin and P. Salati, Phys. Rev. D 69, 063501 (2004)
26. A. B. Lahanas et al. Int. J. Mod. Phys. D 12, 1529 (2003)
27. J. Edsjo, M. Schelke, P. Ullio and P. Gondolo, JCAP 0304, 001 (2003)
28. E. A. Baltz and J. Edsjo, Phys. Rev. D 59, 023511 (1999)
29. L. Bergstrom, J. Edsjo and P. Ullio, [arXiv:astro-ph/9902012
30. P. Ullio, L. Bergstrom, J. Edsjo and C. G. Lacey, Phys. Rev. D 66, 123502 (2002)
31. Y. Mambrini and C. Munoz, [arXiv:hep-ph/0407158.
32. S. Baek, Y. G. Kim and P. Ko, JHEP 0502, 067 (2005)
33. W. de Boer et al. [arXiv:astro-ph/0408272
34. F. Aharonian et al. [The HESS Collaboration], [arXiv:astro-ph/0408145
35. G. Belanger, S. Kraml and A. Pukhov, [arXiv:hep-ph/0502079
36. G. Belanger et al. [arXiv:hep-ph/0412309]
37. B. C. Allanach, G. Belanger, F. Boudjema and A. Pukhov, JHEP 0412, 020 (2004)
38. G. Belanger et al. Nucl. Phys. B 706, 411 (2005)
39. R. Arnowitt, B. Dutta, T. Kamon and V. Khotilovich, arXiv:hep-ph/0411102
40. L. S. Stark, P. Hafliger, A. Biland and F. Pauss, arXiv:hep-ph/0502197
41. H. Baer, A. Belyaev, T. Krupovnickas and J. O’Farrill, JCAP 0408, 005 (2004)
42. H. Baer, A. Mustafayev, S. Profumo, A. Belyaev and X. Tata, arXiv:hep-ph/0504001
43. H. Baer, A. Mustafayev, E. K. Park and S. Profumo, arXiv:hep-ph/0505227
44. C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, Phys. Rev. Lett. 92, 101301 (2004)
45. F. Charles, [arXiv:hep-ph/0105026
46. J.-B. De Vivie, Y. Mambrini, E. Nezri in preparation.
47. P. Binetruy et al. Astropart. Phys. 22, 1 (2004). G. Bertone et al. [hep-ph/0406083

Figure 1: MSUGRA Universal $A_0 = 0$, $\tan \beta = 35$, $\mu > 0$
Figure 2: MSUGRA non Universal gluino mass $M_S|_{GUT} = 0.6m_{1/2}$, $A_0 = 0$, $\tan \beta = 35$, $\mu > 0$