COSMOLOGY AND DARK MATTER AT THE LHC

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We examine the question of whether neutralinos produced at the LHC can be shown to be the particles making up the astronomically observed dark matter. If the WIMP alllowed region lies in the SUGRA coannihilation region, then a strong signal for this would be the unexpected near degeneracy of the stau and neutralino i.e., a mass difference $\Delta M \simeq (5-15)$ GeV. For the mSUGRA model we show such a small mass difference can be measured at the LHC using the signal 3τ+jet+$E_T^{\rm miss}$. Two observables, opposite sign minus like sign pairs and the peak of the $\tau\tau$ mass distribution allows the simultaneous determination of ΔM to 15% and the gluino mass $M_{\tilde{g}}$ to be 6% at the benchmark point of $M_{\tilde{g}}$=850 GeV, A_0=0, μ >0 with 30 fb^{-1}. With 10 fb^{-1}, ΔM can be determined to 22% and one can probe the parameter space up to $m_{1/2}$=700 GeV with 100 fb^{-1}.

1. Introduction

Supersymmetry (SUSY) offers the possibility of solving a number of theoretical problems of the Standard Model (SM). Thus the cancelations implied by the bose-fermi symmetry resolves the gauge hierarchy problem, allowing one to consider models at energies all the way up to the GUT or Planck scale. Further, using the SUSY SM particle spectrum with one pair of Higgs doublets. (pairs of Higgs doublets are needed on theoretical grounds to cancel anomalies and on phenomenological grounds to give rise to both u and d quark masses) the renormalization group equations (RGE) show that grand unification of the SM gauge coupling constants occurs at $M_G \simeq 10^{16}$ GeV opening up the possibility of SUSY GUT models. However, none of this can actually occur unless a natural way of spontaneously breaking SUSY occurs, and this very difficult to do with global supersymmetry. The problem was resolved by promoting supersymmetry to a gauge symmetry, supergravity (SUGRA),[1] where spontaneous breaking of supersymmetry can easily occur. One can then build SUGRA GUT models[2,3] with gravity playing a key role in the construction. A positive consequence of this promotion was that the RGE then show that the breaking of supersymmetry at the GUT scale naturally leads to the required $SU(2) \times U(1)$ breaking at the electroweak scale, thus incorporating all the successes of the SM, without any prior assumptions of negative $(\text{mass})^2$ terms.

In spite of the theoretical successes of SUGRA GUTs, there has been no experimental evidence for its validity except for the verification of grand unification (which has in fact withstood the test of time for over a decade). However, one expects SUSY particles to be copiously produced at the LHC. Further, models with R parity invariance predict the lightest neutralino $\tilde{\chi}_1^0$ to be a candidate for the astronomically observed dark matter (DM) and models exist[4] consistent with the amount of dark matter observed by WMAP,[5] and being searched for in the Milky Way by dark matter detectors. Thus it is possible to build models that both cover the entire energy range from the electroweak scale to the GUT scale and go back in time to $\sim 10^{-7}$ seconds after the Big Bang when the current relic dark matter was created.

The question then arises can we verify if the dark matter particles in the galaxy is the neutralino expected to be produced at the LHC? In principle this is doable. Thus assuming the DM detectors eventually detect the dark matter particle, they will measure the mass and cross sections, and these can be compared with those measured at the LHC. However, this may take a long time to achieve. More immediately, can we look for a signal at the LHC that is reasonably direct consequence of the assumption that the neutralino is the astronomical DM particle and in this way experimentally unify particle phenomena with early universe cosmology? To investigate this question it is necessary to choose a specific SUSY model, and for simplicity we consider here the minimal mSUGRA (though a similar analysis could be done for a wide range of other SUGRA models).

2. The mSUGRA model

The mSUGRA model depends on four soft breaking parameters and one sign. These are; $m_{1/2}$ (the universal gaugino soft breaking mass at M_G); m_0 (the universal scalar soft breaking mass at M_G); A_0 (the universal cubic soft breaking mass at M_G); $\tan\beta =< H_2 > / < H_1 >$ at the electroweak scale (where $< H_2 >$ gives rise to u quark masses and $< H_1 >$ to d quark masses); and the sign of μ parameter (where μ appears in the quadratic part of the superpotential $W^{(2)} = \mu H_1 H_2$).

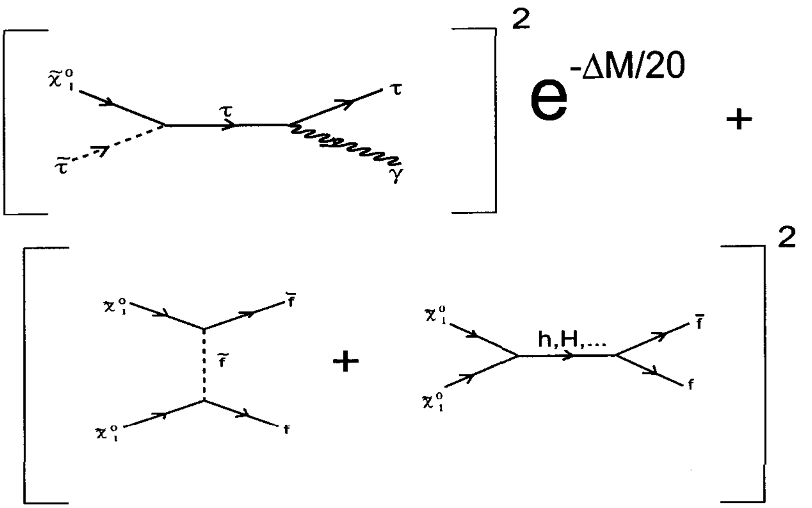

Fig. 1. The feynman diagrams for annihilation of neutralino dark matter in the early universe

Current experimental data significantly constrains these parameters. the main accelerator constraints are: The Higgs mass $m_H > 114$ GeV;[6] the lightest chargino mass $M_{\tilde{\chi}_1^\pm} > 104$ GeV; the $b \to s\gamma$ branching ratio $2.2 \times 10^{-4} < Br(b \to s\gamma) < 4.5 \times 10^{-4}$;[7] and the muon g-2 anomaly[8] which now deviates from the SM prediction by 3.4 σ. The astronomical constraint is the WMAP determination of the amount of dark matter and we use here a 2 σ range:[5]

$$0.094 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.129. \tag{1}$$

The WMAP constraint limits the parameter space to three main regions arising from the diagrams of Fig.1. (1) The stau-neutralino ($\tilde{\tau}_1 - \tilde{\chi}_1^0$) coannihilation region. Here m_0 is small and $m_{1/2} \leq 1.5$ TeV. (2)The focus region where the neutralino has a large Higgsino component. Here $m_{1/2}$ is small and $m_0 \geq 1$ TeV. (3) The funnel region where annihilation proceeds through heavy Higgs bosons which have become relatively light. Here both m_0 and $m_{1/2}$ are large.

(In addition there is a small bulk region) Note that a key element in the coannihilation region is the Boltzman factor from the annihilation in the early universe at $kT \sim 20$ GeV: $\exp[-\Delta M/20]$ where $\Delta M = M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0}$. Thus significant coannihilation occurs provided $\Delta M \leq 20$ GeV.

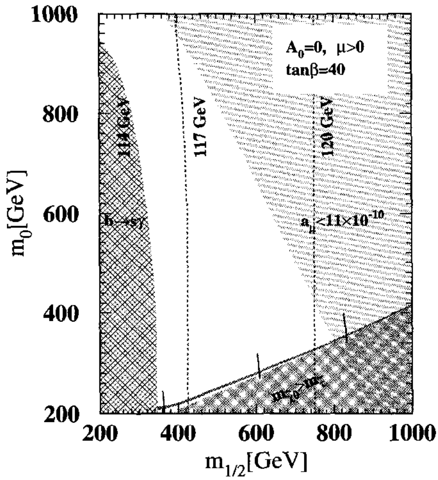

Fig. 2. Allowed parameter space for $\tan\beta = 40$ with $A_0 = 0$ and $\mu > 0$.

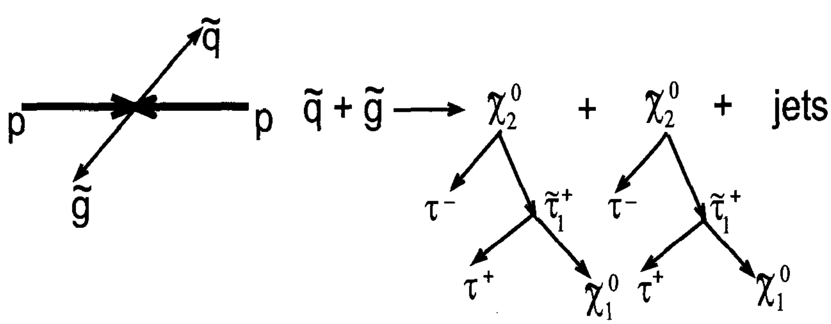

Fig. 3. SUSY production and decay channels

The accelerator constraints further restrict the parameter space and if the muon g-2 anomaly maintains, $\mu > 0$ is prefereed and there remains mainly the coannihilation region. This is illustrated in Fig.2 which shows the allowed narrow coannihilation band (for the case $\tan\beta = 40$, $A_0 = 0$, $\mu > 0$) where $\Delta M = (5 - 15)$ GeV and $m_{1/2} \leq 800$ GeV. (There is a small focus region for small $m_{1/2}$ and $m_0 > 1$ TeV since the $b \to s\gamma$ constraint ceases to opperate at $m_0 > 1$ TeV.)

The coannihilation band is narrow ($\Delta M = 5-15$ GeV) due to the Boltzman factor in Fig.1, the range in ΔM corresponding to the allowed WMAP range for $\Omega_{\tilde{\chi}_1^0} h^2$. The dashed verticle lines are possible Higgs masses.

One may ask two questions; (1) Can such a small stau-neutralino mass difference (5-15 GeV) arise in mSUGRA, i.e. one would naturally expect these SUSY particles to be hundreds of GeV apart and (2) Can such a small mass difference be measured at the LHC? If the answers to both these questions are affirmative, the observation of such a small mass difference would be a strong indication that the neutralino is the astronomical DM particle since it is the cosmological constraint on the amount of DM that forces the near mass degeneracy with the stau, and it is the accelerator constraints that suggests that the coannihilation region is the allowed region.

3. Can ΔM be Small in SUGRA models?

At the GUT scale $m_{1/2}$ governs the gaugino masses, while m_0 the slepton masses. Thus, at M_G one would not expect any degeneracies between the two classes of particles. However, at the electroweak scale the RGE can modify this result. To see analytically this possibility , consider the lightest selectron $\tilde{e}^c$ which at the electroweak scale has mass

$$m^2_{\tilde{e}^c} = m^2_0 + 0.15 m^2_{1/2} + (37\text{GeV})^2 \tag{2}$$

while the $\tilde{\chi}^0_1$ has mass

$$m^2_{\tilde{\chi}^0_1} = 0.16 m^2_{1/2} \tag{3}$$

The numerical accident that the coefficients of $m^2_{1/2}$ is nearly the same for both cases allows a near degeneracy. Thus for $m_0 = 0$, the $\tilde{e}^c$ and $\tilde{\chi}^0_1$ become degenerate at $m_{1/2}$=(370-400) GeV. For larger $m_{1/2}$, the near degeneracy is maintained by increasing m_0, so that one can get the narrow corridor in the m_0-$m_{1/2}$ plane seen in Fig.2. Actually the case of the stau $\tilde{\tau}_1$ is more complicated since the large t-quark mass causes left-right mixing in the stau mass matrix and results in the $\tilde{\tau}_1$ being the lightest slepton (not the selectron). However, a result similar to Eqs. (1,2) occurs, with a $\tilde{\tau}_1 - \tilde{\chi}^0_1$ coannihilation corridor resulting.

We note that the results of Eqs.(1,2) depend only on the U(1) gauge group and so coannihilation can occur even if there were non-universal scalar mass soft-breaking or non-universal gaugino mass soft breaking at M_G. Thus, coannihilation can occur in a wide class of SUGRA models, and is not just a feature of mSUGRA.

4. Coannihilation signal at the LHC

At the LHC, the major SUSY production processes are gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) e.g., $p + p \to \tilde{g} + \tilde{q}$. These then decay into lighter SUSY particles and Fig.3 shows a major decay scheme. The final states involve two $\tilde{\chi}_1^0$ giving rise to missing transverse energy $E^T_{\rm miss}$) and four τ's, two from the $\tilde{g}$ and two from the $\tilde{q}$ decay chain for the example of Fig 3. In the coannihilation region, two of the taus are high energy ("hard" taus) coming from the $\tilde{\chi}_2^0 \to \tau\tilde{\tau}_1$ decay (since $M_{\tilde{\chi}_2^0} \simeq 2M_{\tilde{\tau}_1}$) while two are low energy ("soft" taus) coming from the $\tilde{\tau}_1 \to \tau + \tilde{\chi}_1^0$ decay since ΔM is small. The signal is thus $E_T^{\rm miss}$+ jets $+\tau$'s, which should be observable at the LHC detectors.

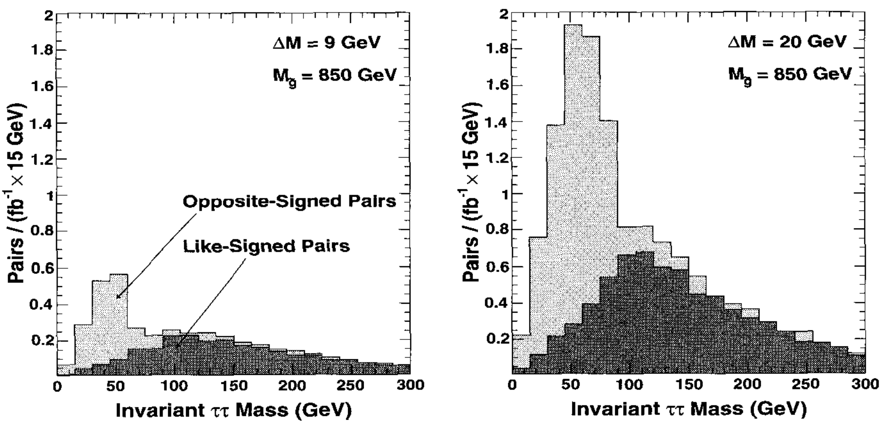

Fig. 4. Number of tau pairs as a function of invariant $\tau\tau$ mass. The difference N_{OS}-N_{LS} cancels for mass $\geq$ 100 GeV eliminating background events

As seen above we expect two pairs of taus, each pair containing one soft and one hard tau from each $\tilde{\chi}_2^0$ decay. Since $\tilde{\chi}_2^0$ is neutral, each pair should be of opposite sign(while SM and SUSY backgrounds, jets faking taus will have equal number of like sign as opposite sign events). Thus one can suppress backgrounds statistically by considering the number of oppsite sign events N_{OS} minus the like sign events N_{LS}. The four τ final state has the smallest background but the acceptance and efficiency for reconstructing all four taus is low. Thus to implement the above ideas we consider here the three τ final state of which two are hard and one is soft. (The two τ final state with higher acceptance but larger backgrounds was discussed in,[9] and an analysis of the coannhilation signal at the ILC was given in.[10]

We label three taus by their transverse energies with $E_1^T > E_2^T > E_3^T$ and form the pairs 13 and 23. For signal events one of the two pairs should be coming from a $\tilde{\chi}_2^0$ decay and have opposite sign(OS) while the other is not correlated. There are two measurables that can be formed. The number N and the mass of the pair M. To simulate the data we use ISAJET 7.64[11] and PGS detector simulator.[12] Events are chosen with $E_T^{\rm miss}$ and 1 jet and three taus with visible momenta $p_T^{\rm vis} > 40$ GeV, $p_T^{\rm vis} > 40$ GeV, $p_T^{\rm vis} > 20$ GeV. We assume here that it is possible to reconstruct taus with $p_T^{\rm vis}$ as low as 20 GeV. Standard Model background is reduced by requiring $E_T^{\rm jet1} > 100$ GeV, $E_T^{\rm miss} > 100$ GeV with tevatron results, $E_T^{\rm jet1} + E_T^{\rm miss} > 400$ GeV. We also assume rate of a jet faking a τ ($f_{j\to\tau}$) to be $f_{j\to\tau} = 1\%$ (with a 20% error in $f_{j\to\tau}$) consistent with Tevatron results.

Fig 4. shows the number of events as a function of the $\tau\tau$ mass for gluino mass $M_{\tilde{g}} = 850$ GeV and $\Delta M = 9$ GeV and 20 GeV. One sees that the difference $N_{OS} - N_{LS}$ cancels out as expected for $\tau\tau$ mass $\geq$100 GeV (consistent with the fact that the signal events are expected to lie below 100 GeV).

Fig. 5 shows the behavior of N_{OS-LS} as a function of ΔM and $M_{\tilde{g}}$. The central black line is for the assumed 1%. rate for jets faking a τ, the shaded region around it is for a 20% uncertainty in $f_{j\to\tau}$. One sees that provided this uncertainty is not large, it produces only a small effect.

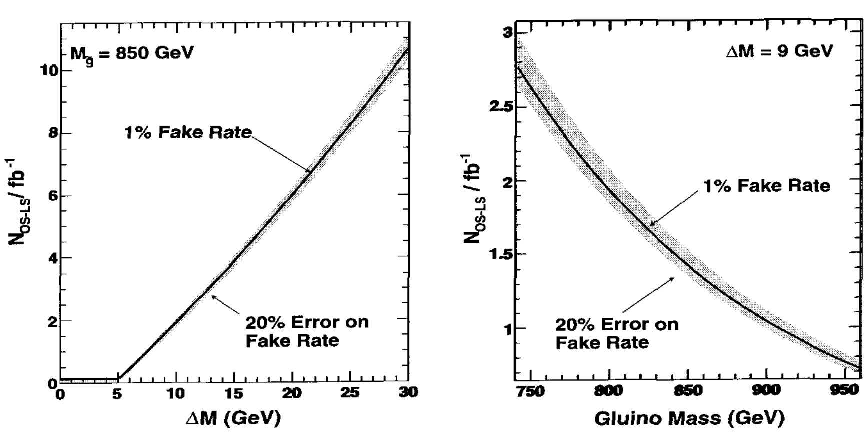

Fig. 5. N_{OS-LS} as function of ΔM (left graph) and as a function of $M_{\tilde{g}}$ (right graph). The central black line assumes a 1% fake rate, the shaded area representing the 20% error in the fake rate

Figs 4 and 5 show two important features. First, N_{OS-LS} increases with ΔM(since the τ acceptance increases) and N_{OS-LS} decreases with $M_{\tilde{g}}$(since the production cross section of gluinos and squarks decrease with $M_{\tilde{g}}$). Second, from Fig.4 one sees that N_{OS-LS} forms a peaked distribution.[9,13] The ditau peak position $M_{\tau\tau}^{\text{peak}}$ increases with both ΔM and $M_{\tilde{g}}$. This allows us to use the two measurables N_{OS-LS} and $M_{\tau\tau}^{\text{peak}}$ to determine both ΔM and $M_{\tilde{g}}$. Fig.6 shows this determination for the benchmark case of ΔM=9 GeV, $M_{\tilde{g}}$=850 GeV, A_0=0 and $\tan\beta$=40. Plotted there are constant values of N_{OS-LS} and constant values of $M_{\tau\tau}^{\text{peak}}$ in the $\Delta M - M_{\tilde{g}}$ plane which exhibit the above dependance of these quantities on ΔM and $M_{\tilde{g}}$. With luminosity of 30 fb^{-1} one determines ΔM and $M_{\tilde{g}}$ with the following accuracy:

$$\delta\Delta M/\Delta M \simeq 15\%; \; \delta M_{\tilde{g}}/M_{\tilde{g}} = 6\% \tag{4}$$

Fig. 7 shows how the accuracy of the measurement changes with luminosity. One sees that even with 10 fb^{-1} (which should be available at the LHC after about two years running)one could determine ΔM to within 22%, which should be sufficient to know whether one is in the SUGRA coannihilation region.

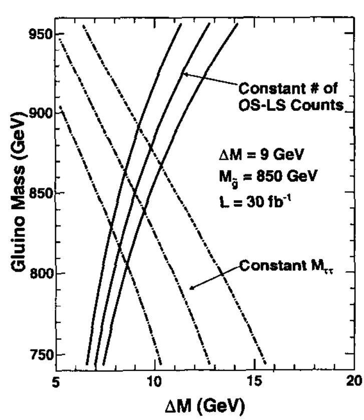

Fig. 6. Simultaneous determination of ΔM and $M_{\tilde{g}}$. The three lines plot constant N_{OS-LS} and $M_{\tau\tau}^{\text{peak}}$ (central value and 1σ deviation) in the $M_{\tilde{g}}$-ΔM plane for the benchmark point of ΔM=9 GeV and $M_{\tilde{g}}$=850 GeV assuming 30 fb^{-1} luminosity

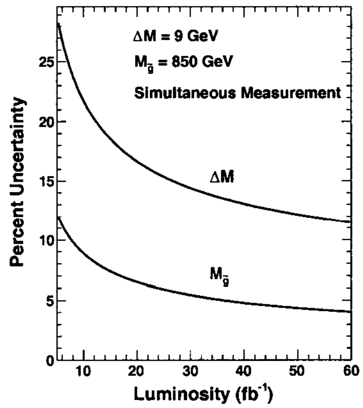

Fig. 7. Uncertainty in the determination of ΔM and $M_{\tilde{g}}$ as a function of luminosity.

5. Conclusions

We have examined here the question of how one might show that the $\tilde{\chi}_1^0$ particle produced at the LHC is the astronomically observed dark matter. If ΔM, the stau-neutralino mass difference lies in the coannihilation region of the SUGRA m_0-$m_{1/2}$ plane where $\Delta M = (5-15)$ GeV, this would be strong indication that the neutralino is the dark matter particle as otherwise the mass difference would not naturally be so small. We saw how it was possible to measure such a small mass difference at the LHC for the mSUGRA model using a signal of $E_T^{\rm miss}$+ 1 jet+3τ, and simultaneously determine the gluino mass $M_{\tilde{g}}$, provided it is possible at the LHC to reconstruct taus with $p_T^{\rm vis}$ as low as 20 GeV. With 30 fb^{-1} one could then determine ΔM with 15% accuracy and $M_{\tilde{g}}$ with 6%, at our benchmark point of ΔM=9 GeV, $M_{\tilde{g}}$=850 GeV, $\tan\beta = 40$, and A_0=0. Even with only 10fb^{-1} one would determine ΔM to within 25% accuracy, sufficient to learn whether the signal is in the coannihilation region.

While the analysis done here was within the framework of mSUGRA, similar analyses can be done for other SUGRA models provided the production of neutralinos is not suppressed. However, the determination of $M_{\tilde{g}}$ does depend on the mSUGRA universality of the gaugino masses at M_G to relate $M_{\tilde{\chi}_2^0}$ to $M_{\tilde{g}}$. Thus a model independent method of determining $M_{\tilde{g}}$ would allow one to to test the question of gaugino universality. However, it may not be easy to directly measure $M_{\tilde{g}}$ at the LHC for high $\tan\beta$ in the coannihilation region due to the large number of low energy taus, and the

ILC would require a very high energy option to see the gluino.

As mentioned above, one can also measure ΔM using the signal $E_T^{\rm miss}+$ 2 jets+2τ.[9] This signal has higher acceptance but larger backgrounds. There, with 10 fb^{-1} one finds that one can measure ΔM with 18% error at the benchmark point assuming a separate measurement of $M_{\tilde{g}}$ with 5% error has been made. While we have fixed our benchmark point at $M_{\tilde{g}}$ = 850 GeV(i.e. $m_{1/2}$ =360 GeV), higher gluino mass would require more luminosity to see the signal. One finds that with 100 fb^{-1} one can probe $m_{1/2}$ at the LHC up to $\sim$ 700 GeV (i.e., $M_{\tilde{g}}$ up to $\simeq$ 1.6 TeV).

Finally, it is interesting to compare with possible measurements of ΔM at the ILC. If we implement a very forward calorimeter to reduce the two γ background, ΔM can be determined with 10% error at the benchmark point.[10] Thus in the coannihilation region, the determination of ΔM at the LHC is not significantly worse than at the ILC.

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