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Connecting the Direct Detection of Dark Matter with Observation of Sparticles at the LHC

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An analysis is given connecting event rates for the direct detection of neutralino dark matter with the possible signatures of supersymmetry at the LHC. It is shown that if an effect is seen in the direct detection experiments at a level of $O(10^{-44})~\rm cm^2$ for the neutralino-proton cross section, then within the mSUGRA model the next heavier particle above the neutralino is either a stau, a chargino, or a CP odd/CP even (A/H) Higgs boson. Further, the collider analysis shows that models with a neutralino-proton cross section at the level of $(1-5)\times 10^{-44}~\rm cm^2$ could be probed with as little as 1 fb⁻¹ of integrated luminosity at the LHC at $\sqrt{s}=7,10$ TeV. The most recent limit from the five tower CDMS II result on WIMP-nucleon cross section is discussed in this context. It is argued that the conclusions of the analysis given here are more broadly applicable with inclusion of non-universalities in the SUGRA models.

Introduction: Experiments for the direct detection of cold dark matter have made very significant progress recently [1-3] and are now exploring the spin independent WIMP (weakly interacting massive particle)nucleon cross sections in the region between $10^{-44}-10^{-43}$ cm². Further, the most recent five tower CDMS II result [4] has reached the sensitivity of $3.8 \times 10^{-44} \text{ cm}^2$ at a mass of 70 GeV. Since the LHC has now started its runs it is interesting to connect the direct detection of dark matter with the possible observation of sparticles at the LHC. In this paper we give such an analysis within the minimal supergravity grand unified model (mSUGRA) [5] and its extensions. In supersymmetric (SUSY) theories with R parity the lightest supersymmetric particle (LSP) is absolutely stable and if neutral it could be a candidate for dark matter [6]. This turns out to be the case when the full renormalization group analysis is carried out and one finds that the neutralino is indeed the LSP in most of the parameter space of the model [7] and thus a candidate for dark matter. The satisfaction of the relic density for the LSP neutralino can occur in a variety of ways. It can occur via coannihilation [8], on the hyperbolic branch/focus point region (HB/FP) [9], in the vicinity of a pole (alternately known as the funnel region) [8, 10], or in the bulk region. The coannihilation region may involve charginos, staus, stops, gluinos as well as other sparticles depending on the model. The pole region is typically in the vicinity of the Z boson mass or the neutral CP odd/CP even (A/H) Higgs boson mass.

Many works have analyzed the direct detection of dark matter [11–13] and the predicted cross section falls within a range, which in large measure, is observable in the direct detection experiments (for a review see [14]). Recently, a landscape approach to the analysis of SUGRA models was proposed [15] and detailed analyses were given in several works [16, 17]. In this approach, models that pass the WMAP relic density constraints, and

all the other experimental constraints, can be classified according to their mass hierarchies which for practical reasons are chosen to be the first four sparticles excluding the lightest Higgs boson. In general there can be as many as $O(10^4)$ sparticle mass patterns for the four particle hierarchies. However, under the WMAP relic density and other experimental constraints only 16 such patterns survive for $\mu > 0$, where μ is the Higgs mixing parameter in the minimal supersymmetric standard model, and these are labeled mSP1-mSP16 (see [15] for the corresponding sparticle hierarchies). Further, these patterns can be put into just a few broad classes according to their next to the lightest supersymmetric particle (NLSP). Thus model points where the NLSP is a chargino are Chargino Patterns [mSP1-4], and similarly other models are labeled Stau Patterns [mSP5-10], Stop Patterns [mSP11-13], and Higgs Patterns [mSP14-16] according to their NLSPs.

The landscape approach is also very useful in the analysis of dark matter. Thus different patterns often generate significantly different spin independent neutralino-proton cross sections with the Stau, Chargino and Higgs patterns producing relatively large cross sections while other patterns, for example, the Stop Patterns give much smaller cross sections. We explain this later in the paper.

Connecting the direct detection of dark matter with SUSY events at the LHC: LHC analyses including constraints from the relic density of cold dark matter have previously been investigated by many authors (see, e.g., [16, 18–22] [23] [24]). Here we investigate the relationship of event rates in the direct detection experiments with the detection of sparticles at the LHC. Our analysis is done using 2 million candidate model points which are then subject to the radiative electroweak symmetry breaking constraints, the WMAP relic density constraints, as well as other experimental constraints which are listed in [15]. The parameter set that passes these constraints is the

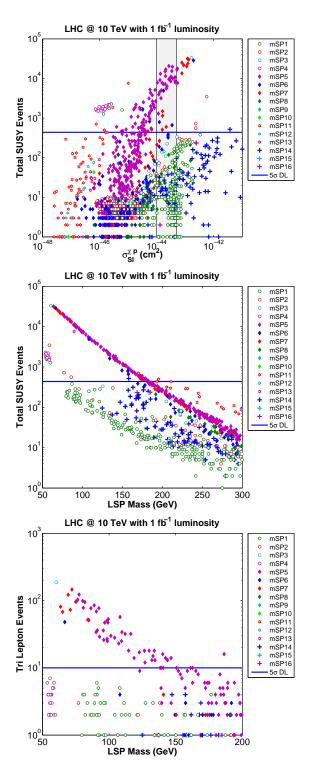


FIG. 1: (Color Online) LHC analysis at 10 TeV with 1 fb⁻¹ luminosity. Top panel: The total number of SUSY events vs the spin independent neutralino-proton cross section $\sigma_{\rm SI}^{\tilde{\chi}p}$. The shaded area is the region $\sigma_{\rm SI}^{\tilde{\chi}p}=(1-5)\times 10^{-44}~{\rm cm}^2$. Middle panel: The total number of SUSY events vs the LSP mass. Bottom panel: The number of trileptonic events [27] vs the LSP mass. To suppress the background and improve the 5σ discovery reach of the SUSY signals (indicated by horizontal lines) we select events that have $P_T > 200~{\rm GeV}$ and contain at least 2 jets with $P_T > 60~{\rm GeV}$.

sample set on which the analysis is based. In the analysis we use micrOMEGAs [25] for the relic abundance and dark matter direct detection calculations, and PGS4 [26] for detector simulations.

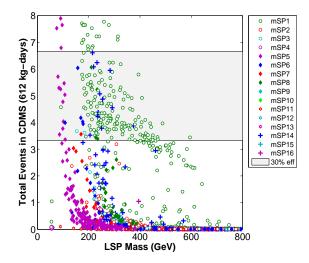


FIG. 2: (Color Online) An exhibition of the number of events predicted in the CDMS detector with 612 kg-d of data assuming 100% efficiency. The lower (upper) horizontal lines make the assumption that one (both) events in the CDMS detector are signal events and in drawing the lines we have assumed 30% detector efficiency.

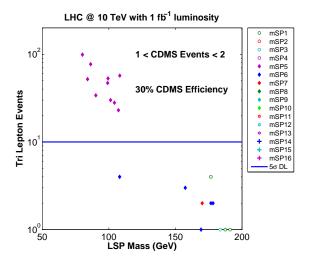


FIG. 3: (Color Online) The total number of trileptonic events at the LHC for model points that lie in the corridor between the two horizontal lines in Fig.(2) vs the LSP mass. The horizontal line indicates the 5σ discovery limit.

Fig.(1) gives the analysis at $\sqrt{s} = 10$ TeV and 1 fb⁻¹ of integrated luminosity. To reduce the background the following cuts were imposed: $P_T > 200$ GeV and at least 2 jets with $P_T > 60$ GeV. We discuss now the result of the analysis presented in Fig.(1). The top panel of Fig.(1)

gives the total number of SUSY events vs $\sigma_{\rm SI}^{\tilde{\chi}p}$, while the middle panel gives the total number of SUSY events vs the LSP mass, and the bottom panel gives an analysis of the supersymmetric trileptonic signal [27]. The 5σ discovery limit based on the Standard Model background is exhibited in each case. One finds that a significant number of model points pass the cut and lie above the discovery limit. Further, most of the model points that lie in the discovery region and give rise to strong WIMP-proton cross sections are those where the NLSP is either a stau, a chargino, or a CP odd/CP even (A/H) Higgs boson.

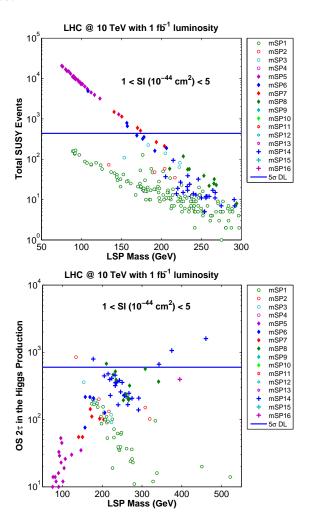


FIG. 4: (Color Online) Top panel: The total number of SUSY events at the LHC for model points that lie in the corridor $\sigma_{\rm SI}^{\tilde{\chi}p} = (1-5)\times 10^{-44}~{\rm cm}^2$ vs the LSP mass. The detector cuts are the same as in the analysis of Fig.(1). Bottom panel: Opposite sign (OS) two tau signal arising from Higgs production where only trigger level cuts are employed. The horizontal line indicates the 5σ discovery limit in each case.

We turn now to a discussion of events in the CDMS detector for the models we consider in Fig.(1). The CDMS detector has accumulated 612 kg-day of data after qual-

ity selection cuts are made [4]. CDMS II has observed two candidate events but there is a possibility that both events could be background [4]. However, the opposite possibility that one or both of these events could be signal is not excluded. It is then interesting to ask what the implications at the LHC would be if this were the case. Fig.(2) gives the total number of events in the CDMS detector vs the LSP mass for various points in the parameter space of the mSUGRA model. The lower (upper) horizontal lines in Fig.(2) correspond to one (both) CDMS II events being signal where we have drawn these lines assuming 30% efficiency. We note that the model points in the corridor enclosed by the two horizontal lines have an NLSP which is either a stau, a chargino or an A/H Higgs boson. This is also true in the region slightly below or above the corridor. Specifically we note that the patterns where the NLSP is a stop are not favored.

Regarding the stop NLSP, its spin independent cross section $\sigma_{\rm SI}^{\bar{\chi}p}$ is highly suppressed since the models that have stop NLSPs are effectively 100 percent bino. The vanishing of the Higgsino component, therefore, suppresses $\sigma_{\rm SI}^{\tilde{\chi}p}$. Removing the constraint of REWSB may allow one to circumvent the above feature. However, we work in the framework of REWSB, which is a key prediction of high scale models. There are several driving factors which generate large $\sigma_{\mathrm{SI}}^{\tilde{\chi}p}$ and predict large event rates at the LHC. First, the size of the LHC signals is determined by the scale of the sparticle spectra with a lighter spectrum generally leading to larger size signals. For the $\sigma_{\rm SI}^{\bar{\chi}p}$, its largeness is dictated by the relative mass scale of the mediating t-channel Higgses and s-channel squarks, and the relative size of the LSP Higgsino component $(H_{i=1,2})$ and the size of tan β . For the models we study, it is the t-channel Higgs exchange and the Higgsino component of the LSP that govern the spin independent cross sections. Thus the models that predict the largest $\sigma_{\rm SI}^{\tilde{\chi}p}$ are generally the Higgs Patterns (HPs), the Chargino Patterns (CPs) and the very lightest of the stau patterns.

The HPs tend to occur in the bulk of the $m_0 - m_{1/2}$ plane (and are a relatively new discovery [15, 17]; see [15] for the large parameter space investigated in this work and complete set of constraints). The HPs have large LSP $H_{i=1,2}$ components and the SUSY Higgses can be quite light and $\tan \beta$ is large. For the CPs, these generally occur on the Hyperbolic Branch/Focus Point region of REWSB. This is the region where the scalar masses get large, but the gauginos are relatively light. Here it is the large Higgsino component and generally a largish $\tan \beta$ which gives rise to the largeness of the $\sigma_{\rm SI}^{\chi p}$, while, for example, the chargino LSP coannihilation can reduce the relic abundance to lie in the WMAP preferred region. Lastly, for very light stau mass patterns, it is the stau coannihilation regions that give rise to WMAP preferred region, and for models where the LSP is light, these models can have a non-negligible $H_{i=1,2}$ components, as

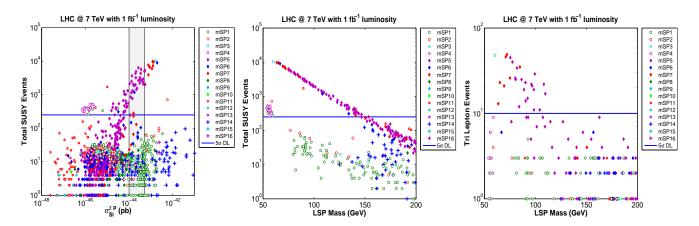


FIG. 5: (Color Online) LHC analysis at 7 TeV with 1 fb⁻¹ luminosity. Left panel: The total number of SUSY events vs the spin independent neutralino-proton cross section $\sigma_{\rm SI}^{\tilde{\chi}p}$. The shaded area is the region $\sigma_{\rm SI}^{\tilde{\chi}p} = (1-5) \times 10^{-44}$ cm². Middle panel: The total number of SUSY events vs the LSP mass. Right panel: The number of trileptonic events [27] vs the LSP mass. To suppress the background and improve the 5σ discovery reach of the SUSY signals (indicated by horizontal lines) we select events that have $P_T > 200$ GeV and contain at least 2 jets with $P_T > 60$ GeV. These parameter points exhibited above which are discoverable at the LHC at 7 TeV via the trileptonic signal are yet to be constrained by the Tevatron.

well as relatively light CP-Even Higgs, both of which lead to an enhanced $\sigma_{\text{NI}}^{\tilde{\chi}p}$.

Now, these model classes reside in different mass hierarchies [15]. It is the mass hierarchies which largely dictate the type of signal that is visible at the LHC (provided the mass scale is low enough to produce visible signals) through kinematically allowed decay chains which are different for the different mass hierarchies. The stop patterns produce lots of jets, but are rather void of leptons. They are also undetectable with present direct detection experiments as discussed above. The HPs, CPs and staus, can also produce large lepton, jet and missing energy signals, the largest missing energy coming from the HPs and the stau patterns over the CPs (see Refs. Thus in summary, if the model has a low SUSY mass scale of spectra it will produce a discoverable signal at the LHC. If such a light model has enhanced $\hat{H}_{i=1,2}$ and/or light scalars, it will produce a large number of events rates in the CDMS and Xenon detectors [28]. The type of LHC signal is governed by the sparticle mass hierarchy which dictates the decay chains allowed and thus the multiplicity of final observable states. The above conclusions also holds more broadly in nonuniversal SUGRA models.

Fig.(3) gives the number of trileptonic events vs the LSP mass for the model points that lie in the corridor enclosed by the two horizontal lines in Fig.(2). The signature analysis is done at $\sqrt{s} = 10$ at 1 fb⁻¹ with detector cuts as in Fig.(1). One finds that with 1 fb⁻¹ of integrated luminosity there is a significant number of model points that lie above the discovery limit and will be probed by the LHC. We also note that in Fig.(3) all the models that lie above the discovery limit are those with stau as the NLSP with mass splittings be-

tween the stau and the LSP being O(10%) of the LSP mass. The relic density of these models would have arisen from neutralino-stau coannihilations in the early universe. With larger luminosity other models where the chargino or possibly the CP odd/CP even Higgs is the NLSP will begin to be probed.

It is expected that by the summer of 2010 the CDMS will have 3 times more Germanium in their detector and thus in the near future we may reach a sensitivity in $\sigma_{SI}^{\bar{\chi}p}$ of $\sim 1 \times 10^{-44}$ cm². Anticipating this reach we display in Fig.(1) (see the shaded region in the top panel) and in Fig.(4) the SUSY signatures at the LHC in the region of the parameter space with $\sigma_{\rm SI}^{\tilde{\chi}p}$ in the range $(1-5)\times 10^{-44}$ cm². Specifically, the top panel of Fig.(4) shows that a significant part of the parameter space in this region can be probed with the total number of SUSY events above the 5σ discovery limit at the LHC with as little as 1 fb⁻¹ of integrated luminosity. The bottom panel gives a parallel analysis for a signal from OS 2τ events arising in the Higgs boson production modes. We note that the models probed using the OS 2τ from Higgs productions are different from the models being probed in the SUSY events. One also has the inverse possibility, in that if the LHC sees a signal in this region, one can extrapolate to estimate $\sigma_{\text{SI}}^{\tilde{\chi}p}$ using the top panel of Fig.(1).

LHC Signatures at 7 TeV: It has recently been announced that the LHC will begin its early physics analysis with a center of mass energy of 7 TeV and will likely operate at this energy till the end of 2011 or till it has accumulated 1 fb $^{-1}$ of data. In light of this possibility we extend the analysis to include a center of mass energy of 7 TeV. The analysis is shown in Fig.(5). The results of the analysis mimic the 10 and 14 TeV results with less events and lower discovery limits. Finally, one may wish to ask

what more the LHC at 1 fb^{-1} of integrated luminosity can discover that the Tevatron would not. First since the LHC energy in the first run at 7 TeV is significantly larger than the Tevatron center of mass energy of 1.96 TeV, the LHC would have a larger mass reach for sparticles simply on the basis of kinematics. Further, even for model points which may also be accessible at the Tevatron, the LHC gives significantly larger cross sections for sparticle productions. Thus, for example, for the mSUGRA parameter point $m_0/\text{GeV} = 60, m_{1/2}/\text{GeV} = 250, A_0/\text{GeV} =$ $-50, \tan \beta = 10$, with sign(μ) positive, which sits in mSP5, a branch of the stau coannihilation region, one finds that for the LHC the SUSY production cross section is $\sigma_{\rm SUSY}(\sqrt{s}=7~{\rm TeV})\sim 5000~{\rm fb}$ while for the Tevatron, $\sigma_{\rm SUSY}(\sqrt{s}=1.96~{\rm TeV})\sim 160~{\rm fb}$ which indicates that the cross section at the LHC is 30 times larger than at the Tevatron for this parameter point. Thus even taking account of the present larger luminosity of the Tevatron (although the timeline for the full analysis of the data at the Tevatron relative to the LHC early runs remains unclear), and particular cuts, the LHC should produce a larger number of events in this case. At the same time it produces a spin independent cross section of $\sim 10^{-44} \text{ cm}^2$ with an LSP mass of 95 GeV. Similar conclusions can be drawn for other SUGRA mass patterns.

Conclusion: In this work we have given an analysis which connects the direct detection of dark matter with potential signals of supersymmetry at the LHC. Recently the sensitivities of experiments for the detection of dark matter have increased significantly and the current experiments are probing spin independent WIMP-nucleon cross sections well below the level of 10^{-43} cm². Thus the most recent five tower result from CDMS II gives an upper bound on the spin independent WIMP-nucleon cross section of $3.8 \times 10^{-44} \text{ cm}^2$ at a WIMP mass of 70 GeV. Further, a new generation of dark matter experiments will in the near future begin to probe these cross sections at the level of 10^{-44} cm². It is then interesting to ask within the framework of supersymmetry, with neutralino as the LSP, what the correspondence is of a possible observation of events in a dark matter detector and the possible observation of SUSY signatures at the LHC. First an analysis of the sparticle landscape for models that lead to spin independent neutralino-nucleon cross section in the range $10^{-44} - 10^{-43}$ cm² shows that the parameter space of mSUGRA in this range produces the NLSP which is either a stau, a chargino or a CP odd/CP even Higgs. Further, we have carried out an analysis of distinct LHC signatures for this part of the parameter space in the early runs. Our analysis shows that a part of the parameter space which gives rise to spin-independent neutralino-proton cross section in the range $(1-5) \times 10^{-44}$ cm² can produce observable signals at the LHC with as little as 1 fb⁻¹ of data at $\sqrt{s} = 7,10$ TeV.

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