Decoding the Origin of Dark Matter

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Abstract. We discuss the interplay between LHC signatures and the mechanism by which dark matter is generated in the early universe in supersymmetric theories. The LHC signatures of two of the major mechanisms for such generation of dark matter which are known to be the Stau Coannihilation (Stau-Co) region and annihilation on the Hyperbolic Branch (HB) are exhibited in detail. By analyzing the various LHC signatures, including multi leptons, hadronic jets, b-tagging, and missing transverse momentum, one can discriminate between the Stau-Co region and the HB region for the mSUGRA model. Interestingly, there are some regions of the parameter space which are beyond the current and near future reach of the dark matter direct detection experiments but will be accessible at the LHC, and vice versa.

Keywords: Dark Matter, LHC, mSUGRA

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INTRODUCTION

Supersymmetry, and more specifically supergravity grand unified models, provide a well motivated framework for the exploration of new physics. Supergravity grand unified models also lead to the lightest neutralino as the lightest SUSY particle (LSP) which is a candidate for dark matter with $R$ parity preserved.

There are three broad regions in the parameter space of supergravity models that satisfy the relic density measured by the WMAP experiment [1]. These include (i) the Hyperbolic Branch (HB) where multi TeV scalars can appear consistent with small fine tuning (this region is alternatively referred as the Focus Point region) [2, 3], (ii) The coannihilation regions where the coannihilation cross section between the LSP and the next lightest supersymmetric particle (NLSP) plays a significant role in satisfying the relic density, (iii) the Higgs pole region where dark matter annihilation cross section occurs near a Higgs boson pole. The coannihilation regions contain stau coannihilation [4, 5], stop coannihilation, gluino coannihilation [6, 7, 8], etc. We focus our discussion on the stau coannihilation region (Stau-Co) and the HB region as these two are the more generic and also are the more probable models as suggested by the recent landscape analysis for different hierarchical mass patterns in mSUGRA [9, 10, 11].

LHC SIGNATURES

As mentioned above we focus our attention on the LHC signatures of the two major mechanisms for the generation of dark matter in the early universe, i.e., HB and Stau-Co. One of the most important LHC signatures of SUSY models is the missing transverse...
momentum, $p_T$. A detailed analysis regarding the $p_T$ signature and of the total number of SUSY events is given in Fig.(1) where the average of the $p_T$ is obtained for the events passing the post trigger detector cuts. Here one finds that $\langle p_T \rangle$ extends over a large range of energy scale for the Stau-Co models, while for the HB models this quantity lies within a much narrower band. Thus $\langle p_T \rangle$ can be viewed as a smoking gun signature to discriminate between the two mechanisms [12].

A complete quantitative analysis of the $p_T$ in an event is complicated due to the fact that it involves many particles and their decay chains [13, 14, 15]. Here we give a qualitative discussion about this phenomenon. In the HB region, usually the gauginos are relatively lighter than squarks, and thus the SUSY productions at the LHC are dominated by gaugino production. The copiously produced gluino then decays via an off-shell squark due to the hierarchical relations which results in a three body decay with two fermions and one gaugino. The other gauginos can also have dominant three body decay branching ratios which together make the cascade decay chains very lengthy. Thus the longer decay chains tend to produce a much reduced $\langle p_T \rangle$ in the HB region. However, for the Stau-Co regions, the scalar mass is usually light and the squark production in the hadron collider becomes important. Because the squarks are usually lighter than the gluino in Stau-Co, the electroweak decay process with charginos or neutralinos as the final states can dominate the gluino final state. Further, $\tilde{q}_R$ can decay directly to the LSP and a quark, due to the gauge content of the neutralinos. Therefore, the decay chains of the Stau-Co models are much shorter which give rise to a relatively larger $\langle p_T \rangle$.

We note that the HB models can also have many more jets in their LHC events than the Stau-Co models because of the difference in their cascade decays. Thus one can impose a large jet number cut for the purpose of optimizing the signal over the background in the HB region, while the same technique would overkill the signal in the Stau-Co region. A detailed analysis regarding this aspect is displayed in the Fig.(1). This in turn also gives us a good discriminator between the two dark matter generation mechanisms.

Further, since in the HB region, the relatively lighter gluino has to undergo a three body decay via an off shell squark, the dominant modes are the ones with smaller
virtuality which happen to be the lighter stop and the lighter sbottom. Thus the gluino decays are very rich in bottom quarks. This is again a remarkable signature for SUSY discovery using b-tagging and a great discriminator between the HB and the Stau-Co.

**DARK MATTER DIRECT DETECTION**

We discuss now the direct detection of dark matter. An analysis of the scalar neutralino-proton cross section $\sigma(\chi p)$ as a function of the LSP mass is given in Fig.(2). We note that the models in the HB region and the Higgs pattern models give much larger dark matter cross sections than the ones in the Stau-Co region and the Stop patterns. The separation in this dark matter signature space makes it easy to identify the HB and Stau-Co mechanisms once the dark matter is discovered [10].

![FIGURE 2. Analysis of $\sigma(\chi p)$ in mSUGRA: (left panel) the Stau-Co models (mSP5) and Higgs patterns (mSP14-16); (right panel) the HB models (mSP1) and the Stop patterns (mSP11-13). A Wall consisting of models in the HB region with a $\sigma(\chi p)$ in the range $10^{-44} \pm 5$ cm$^2$ enhancing the prospects for the observation of dark matter by SuperCDMS [16], ZEPLIN-MAX[17] or LUX[18]. Figure taken from [10].](image)

Another interesting phenomenon is the appearance of the Wall which runs horizontally to high LSP masses. The large neutralino-proton cross section arising from the Wall enhances the prospects for the discovery of dark matter for a broad range of energy scale. Although it is known that a large Higgsino component can give rise to strong neutralino-proton cross section, the finding that the Wall is composed of models arising mostly from the HB region is new and has not been observed before the work of [10].

**DUAL PROBES**

Additional information regarding the discrimination between the HB and the Stau-Co regions can be obtained combining the LHC signature and the neutralino-proton cross section in the dark matter direct detection experiments. One finds that dark matter direct detection can complement the LHC search in some region of the parameter space. An example is given in Fig.(3). Here one finds that a large collection of models originating
from the HB region can be probed by the SuperCDMS experiment while they are unlikely to be discovered with 10 fb$^{-1}$ luminosity at the LHC. There are also models beyond the reach of the current and the near future dark matter experiments, but such models can be explored at the LHC. A clear separation in the plot of Fig.(3) again offers a way of distinguishing these two mechanisms, i.e., HB and Stau-Co.

FIGURE 3. An exhibition of the dual probes of SUSY by direct detection experiments and by lepton, jet and missing energy signals at the LHC. The analysis above focuses on the HB models (Chargino Pattern, mSP1) and the Stau-Co models (Stau Pattern, mSP5) for mSUGRA ($\mu > 0$). Figure taken from [19].

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