Outside the mSUGRA Box

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Abstract

Most studies of the potential for discovery of superpartners at the Fermilab Tevatron or CERN LHC have focused on the so-called mSUGRA (minimal supergravity mediated supersymmetry breaking) model, not because it is well motivated but because it has a minimal number of parameters. If signals are seen that could be superpartners, most analyses will attempt to interpret them in the mSUGRA framework since the needed software and computational tools exist. With only a few signal channels, and initially large statistical and systematic errors, it is very likely that an mSUGRA interpretation will look all right even if it is not. We present an approach to studying any potential signals of new physics in “inclusive signature space” that sensitively tests any proposed interpretation, and apply it to the mSUGRA case. The approach also has significant experimental advantages, reducing the sensitivity to jet energy corrections, dependence on beam luminosity, and other systematics. Basically, if one (or more) instances of reported data lies outside certain bounded regions of inclusive signature space characteristic of the physics being tested, that physics is excluded for any parameters. The approach can be used to study supersymmetry breaking and to point to the form of the underlying theory even without detailed measurements of a number of important parameters which will be difficult or impossible to measure at hadron colliders.

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1 Introduction

It is exciting that we are getting closer to the time when direct signals of new particles or interactions at hadron colliders may give us data that will start to point toward how the foundations of the Standard Model are strengthened, and how the SM is extended. Such information could come from the Fermilab Tevatron collider as it accumulates data. If the indirect clues we have today are not very misleading such effects are very likely to come at the LHC. For simplicity in this paper we will focus on the LHC.

We will assume that the new physics is supersymmetry at the weak scale, which is well motivated. However, the approach we advocate would also be relevant if some other new physics were discovered. The experimental discovery of supersymmetry would be manifest by signals interpretable as the superpartners of the SM particles. Since supersymmetry is a broken symmetry, the masses of the superpartners are not known. But otherwise the full Lagrangian for the MSSM is known, and for a given set of masses all superpartner production and decays can be calculated. For this paper we also assume the lightest superpartner (LSP) is stable and escapes the detector; a similar analysis could be done if the LSP is unstable. One of the main goals once there is data will be learning how supersymmetry is broken. Even if that is not known, the theory is very constraining, and it is known how to write the general form of the Lagrangian. Ideally data would allow us to measure the terms of the so-called general “soft-breaking” Lagrangian. But if we only have data from hadron colliders, the number of observables is always less than the number of mass parameters in the Lagrangian, so in general data cannot be inverted to deduce the Lagrangian parameters. It is dangerous to “solve” this problem by making assumptions that reduce the number of parameters since any wrong assumption could result in very misleading implications. One important issue is that most of the Lagrangian masses are complex, leading not only to possibly large CP violating effects at colliders, but also shifting the values of superpartner masses and branching ratios. So, if the Lagrangian masses are assumed to be real the results could be unrealistic.

In order to learn how to interpret signals it is important to pay attention to what experimenters actually measure. These are first cross sections times branching ratios for production and decay of superpartners, and some kinematical distributions. That is all that can be measured at colliders. The soft-breaking Lagrangian on the other hand depends on “soft masses”. The soft masses in general are not physical mass eigenstate masses, which usually result from diagonalizing mass matrices that depend on the soft masses in complicated ways. A top-down approach would go from an underlying theory to a superpotential and a Kähler potential and
a gauge kinetic function, from which the soft-breaking Lagrangian can be calculated. Then the mass matrices for the various sectors of the theory would be written, and the mass eigenstate masses and their production and decay rates calculated. These would imply certain experimental distributions. The mass eigenstates themselves are only measurable in certain special cases for a few eigenstates. Thus in general experimenters will present a dozen or so rates, and a few kinematical distributions. How can one interpret such information to deduce the Lagrangian and study its patterns and properties in order to learn about how supersymmetry is broken and about the underlying theory?

If we had a large amount of precise data, particularly from a linear collider, in principle one could take a bottom up approach from the data to the theory. But for at least a decade after LHC begins to take data, and perhaps much longer, we will only have hadron collider data, which does not generally permit going from observables to the full Lagrangian. For the first few years the signals will have significant statistical and systematic errors. Under those conditions one will be able to describe the data with a variety of models, each of which has a few parameters. In practice almost all studies so far have been done in the mSUGRA framework [1, 2], not because it is well motivated but because it has only a few parameters. Because historically it was a sensible approach to study early-on, it is by far the best studied approach. In practice, it is likely that some pieces of initial data will be describable by an mSUGRA model even if mSUGRA is not the actual theory.

In this paper we want to advocate a sensitive and systematic approach to interpreting a limited amount of data. We will see that the method is potentially very powerful in answering questions that are difficult or impossible with the usual methods. Here we will focus on the issue of deciding whether mSUGRA can be a valid extension of the SM when new data is available.

While mSUGRA is indeed a simple parametrization of the soft Lagrangian, it is not truly a model because it does not contain an explanation for its various assumptions. mSUGRA corresponds to a situation in which minimal kinetic terms are assumed for the Kähler potential in the supergravity lagrangian. It turns out that these assumptions are hard to realize in a fundamental microscopic theory like string theory. Therefore, from a theoretical point of view, mSUGRA should be extended. For example, the origin of the auxiliary field vacuum expectation values and the assumed reality of the soft terms should be explained, the neutrino sector should be added, and the smallness of $\mu$ should be explained dynamically, just to mention a few things.

On the other hand, from the phenomenological point of view, mSUGRA is sometimes con-
considered to be attractive due to its simplicity and most phenomenological studies of collider as well as non-collider (flavor physics, CP physics, cosmology) observables are based on the framework of mSUGRA. However, even in this special case, although a lot of work has been done to learn how to measure properties of new physics at the LHC, most of it relies on implicit assumptions. There are many obstacles to determining the relevant properties in a general case. Let us try to analyze some of these obstacles closely.

2 Obstacles

One major obstacle is that experiments measure cross-section times branching ratios ($\sigma \times BR$), and masses of mass eigenstates (mostly only mass differences). None of these quantities appear in the Lagrangian. The chargino, neutralino and stop masses for example, are related to the complex soft parameters $M_1, M_2, \mu$ and the stop left and right handed mass parameters in an indirect way, by being the eigenvalues of the appropriate mass matrix. Even though the gluino doesn’t mix with others in a mass matrix, it gets appreciable radiative SQCD corrections. Therefore, it is not straightforward to learn the implications of these measured quantities.

A second obstacle is that at a hadron collider there are always more Lagrangian parameters than observables. Hence in general it is not possible to solve for all Lagrangian parameters such as $\tan \beta, \mu$, gaugino masses, scalar masses, trilinear couplings, etc. This general problem has been largely overlooked and was first studied in [3, 4]. The usual approach to this problem is to keep making ad hoc assumptions until there are fewer parameters than observables to “solve” for the parameters. However, unless those assumptions are correct, this approach may not give the right answers.

A third obstacle arises due to techniques usually employed to analyze data. In order to measure masses and production cross-sections times branching ratios, selections and cuts are imposed on data to reduce backgrounds and isolate signals. In many cases, the statistics is limited and this may reduce the signal so much that little can be learned. Also, the available channels are mostly analyzed separately, one at a time. In such a situation, issues about absolute measurements, beam luminosity, etc. have to be taken into account. For example, jet energy corrections that affect missing transverse energy become quite important. In addition, at the LHC, the large number of channels may make separation of states very difficult.

Taking mSUGRA as an example, suppose a signal is found at the LHC in some channel, using cuts imposed on data. A traditional “single channel analysis” would mean that the statistics are very limited and there are large errors due to both theoretical and experimental
uncertainties. In such a situation, it would most likely be possible to find a point from the mSUGRA parameter space which fits the data (with large uncertainties) even if it were not the correct theory.

Therefore, a new innovative approach is needed to overcome these obstacles and to devise ways to favor a particular class of models while weeding out most of the others, once there is data. The philosophy of one such approach was spelled out in [5]. We implement it in detail in the following sections.

3 A Constructive Approach

The approach is two pronged. The first is consistency. If an approach to Beyond-the-Standard Model physics (like mSUGRA) producing a particular set of masses can reproduce a particular signal, it implies a variety of other constraints since different processes involving the same masses have to be consistent with each other. The more data one adds from other processes, the more one constrains the parameters. Therefore, a “multi-channel analysis” is called for.

The second is to use information obtained from the pattern of inclusive signatures in various channels to learn more about the theory. By an ‘inclusive signature’, we mean any signature observable in experiments indicating the existence of physics beyond the standard model, summed over all possible ways that such a signature may arise. The basic idea is that even though a single signature will not tell us much about supersymmetry breaking or the underlying theory, patterns of several inclusive signatures will. The list of inclusive signatures [5] should be expanded to get more and more information about the theory.

Our approach also has implications for experimental issues. By comparing inclusive signatures, issues that affect individual absolute measurements, such as beam luminosity, jet energy corrections, etc. drop out or become less important if one is only comparing collider event rates. It may not even be necessary to determine actual cross-sections. Therefore, it is possible to add all the ways to get a given signature, with very few cuts, to get large statistics. The Standard Model (SM) contributions to the signal can and probably should be included in the comparison prediction.

4 Application to mSUGRA

In this section, we illustrate our approach by applying it to mSUGRA — the most popular framework for phenomenological studies. The procedure is the following:
First, a sufficient number of models are generated so as to approximately cover the parameter space of mSUGRA. Of these, only some will be consistent with all the current bounds for superpartner masses, the higgs mass, constraints from flavor and CP physics, as well as the latest relic density upper bound from WMAP. Considering only those models consistent with current constraints, we then compute the spectrum of particles at the electroweak scale and inclusive signatures for each. These collider inclusive signatures denote number of events expected in excess of the standard model. All the signatures used are real observables. With inclusive signatures computed for thousands of models, we then make scatter plots between different combinations of inclusive signatures. Since the parameter space of mSUGRA is a bounded region, it is expected that scatter plots of different combinations of inclusive signatures also occupy a bounded region in the “space of inclusive signatures”. This is confirmed by our procedure, as our plots will explicitly show. Therefore, there is a precise sense in which the complete set of bounded regions obtained for different combinations of inclusive signatures can be thought of as the “footprint” of mSUGRA.

This analysis has the potential to rule out mSUGRA almost immediately with limited data. In the event of a discovery, signals will appear as isolated points in the relevant inclusive signature plots. If even a single point lies well outside the mSUGRA region in the inclusive signature plots, then mSUGRA has to be ruled out. On the other hand, even if all the points lie within the mSUGRA region, it does not imply that mSUGRA is confirmed. These issues will be explained in better detail in the following sections.

For the present paper, for simplicity, we do not include the SM contributions to the inclusive signatures. They are small since the transverse missing energy ($E_T$) cuts are designed to minimize them. For the full analysis in future that deals with real data, the SM contributions should of course be included, and the simulations run through the detectors too. A complete study can only be done with the actual parameters and cuts used to measure the inclusive signatures.

## 5 Procedural Details

We first generated a sufficient number of points so as to cover the parameter space of mSUGRA, not already excluded by experiment. An mSUGRA “point” is defined by five parameters at the high scale — $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$ and sign $\mu$. The high scale was chosen to be the unification scale $\sim 2 \times 10^{16}$ GeV. Since $\mu < 0$ is disfavored for mSUGRA [3], only $\mu > 0$ was considered.

A set of about ten thousand mSUGRA models was used to map out the region occupied
by mSUGRA in inclusive signature space and estimate its boundary. These were found by randomly sampling mSUGRA parameter space for models consistent with experimental and cosmological constraints using the framework of the most recent version of the DarkSUSY code \cite{8}. Each model is consistent with constraints on $b \rightarrow s\gamma$, $(g_{\mu} - 2)$, and particle spectra. Importantly, it was also required that the thermally produced component of the LSP relic density be no more than that of all the dark matter in the universe, $\Omega_{\text{LSP}} h^2 \leq 0.15$ \cite{7}. Because the cosmological evidence for the relic abundance of cold dark matter is largely insensitive to its composition and the mechanism by which dark matter was produced in the universe, there is no lower bound on the thermal relic density of the LSP; and using a lower bound could be very misleading. It must be kept in mind that even in cases where the thermal relic density of the LSP is low, it could still provide a good dark matter candidate if mechanisms for non-thermal production of the LSP are operative. In recent years, many non-thermal mechanisms have been noticed in literature.

The parameters of the viable mSUGRA models obtained at the high scale were used as an input to the Renormalization Group (RG) evolution and superpartner spectrum calculating program — SUSPECT2 \cite{9}. The collider simulation for LHC was done by calling the Monte-Carlo simulation program PYTHIA \cite{11}. A luminosity of 10 $fb^{-1}$ was assumed for the analysis. Standard cuts from \cite{12, 13} were applied to the output obtained from PYTHIA to minimize the Standard Model (SM) background. Thus, a list of the number of events in excess of the standard model, which passed the imposed cuts, for all relevant collider signatures was obtained. The precise nature of cuts and the list of signatures used is described in the following subsection.

\section{5.1 Cuts}

For cuts, two basic entities must be defined: jets and leptons. A region $|\eta| \leq 3$ was picked using fixed cones of size $R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.7$, where $\eta$ is the pseudorapidity and $\phi$ is the azimuthal angle. Clusters in this region with $E_T \geq 100$ GeV were labelled as jets. Leptons were defined as electrons or muons with $|\eta| < 5$ and $p_T \geq 20$ GeV. We also required leptons to be isolated from jets by imposing that the visible activity within a cone of $R = 0.3$ about the lepton direction is less than $E_T(\text{cone}) = 5$ GeV. These definitions are similar to that used by Baer et al in \cite{12, 13}.

Once jets and leptons are defined, a generic signature can be characterized as $(m\text{-jet}) + (n\text{-lepton})$.

\footnote{Only points which were compatible with both programs — ISAJET \cite{10} (used in DARKSUSY) and SUSPECT2 — were used for collider simulation.}
lepton) + $E_T$, where $m$ takes 0, 1, 2, 3, and $\geq 4$ and $n$ takes 0, 1, 2 and $\geq 3$. The transverse missing energy was required to satisfy $E_T \geq 100$ GeV. We also require the angle between jets and $E_T$ in the transverse plane to be greater than $15^\circ$. For $n = 2$, the signature can be further classified as an opposite-sign (OS) dilepton or a same-sign (SS) dilepton signature, depending on the relative charges of the two leptons. Thus different combinations of jet and lepton configurations give 20 (= $5 \times 4$) different signatures in total.

However, as already emphasized in Section 3, it is good to use very inclusive signatures. Here, by inclusive signatures we mean that for a given leptonic configuration, different jet configurations are summed over. For example, the “inclusive same-sign dilepton with $m \geq 2$ jets” signature refers to events with two same sign leptons and number of jets greater or equal to two. The inclusive signatures we include in this study are listed below:

1. 0 leptons + $\geq 2$ jets + $E_T$
2. 1 lepton + $\geq 2$ jets + $E_T$
3. Opposite Sign (OS) dileptons + $\geq 2$ jets + $E_T$
4. Same Sign (SS) dileptons + $\geq 2$ jets + $E_T$
5. Trileptons + $\geq 2$ jets + $E_T$

Inclusive signatures with $\geq 2$ jets were used in our analysis, since SM backgrounds are well known for such cases [12, 13]. In some cases, certain signatures with definite number of jets can also be useful to probe physics. Additional signatures can be added when the analysis is done for real data. The most important point is to only use fully observable quantities.

6 Plots and Analysis

A few important plots are shown in the next few pages. The remaining plots can be seen at the website: http://feynman.physics.lsa.umich.edu/~signaturespace.

The blue area in these plots denotes the experimentally allowed region occupied by mSUGRA for any possible parameters. The “stars” denote other models of supersymmetry breaking and are present only to illustrate that it is easy to be ‘outside the mSUGRA box’. It should be kept in mind that while theory predicts the cross-section for a given process, experiments only
Number of events are stated for 10 fb$^{-1}$ of data, approximately the first year of data from the LHC.

Figure 1: Number of events for Trilepton (3L) with ≥ 2 jets vs Number of events for Opposite Sign dilepton (OS) with ≥ 2 jets. The blue area denotes the region occupied by mSUGRA, while the red, green and black “stars” correspond to other supersymmetry breaking models.
Figure 2: Number of events for Same Sign (SS) Dilepton with $\geq 2$ jets vs Number of events for Opposite Sign Dilepton (0S) with $\geq 2$ jets. The blue area denotes the region occupied by mSUGRA, while the red, green and black “stars” correspond to other supersymmetry breaking models.
Figure 3: Number of events for Trilepton (3L) with $\geq 2$ jets vs Number of events for Single Lepton (1L) with $\geq 2$ jets. The blue area denotes the region occupied by mSUGRA, while the red, green and black “stars” correspond to other supersymmetry breaking models.
Figure 4: Number of events for Trilepton (3L) with ≥ 2 jets vs Number of events for No lepton (0L) with ≥ 2 jets. The blue area denotes the region occupied by mSUGRA, while the red, green and black “stars” correspond to other supersymmetry breaking models.
measure the number of events\(^2\). Therefore, to compare explicit theoretical predictions with experimental measurements, the luminosity for the process has to be known precisely. This is quite hard to do in practice and luminosity determination is accompanied by large uncertainties. Our approach is useful even if the luminosity is not known. One way to implement this is to normalize the number of events for all signatures with respect to a reference signature, thus plotting ratios of the number of events with respect to that of the reference signature, for both experiment and theory. This will help in reducing the dependence of the inclusive signatures on the luminosity. This has not been done in our analysis for simplicity, but should be done in more sophisticated analyses.

From the plots, it is clear that the mSUGRA region occupies a bounded region in inclusive signature space. This confirms our expectation, as was already mentioned in section 4. Since the mSUGRA parameter space is a smooth region, it is reasonable to expect that it would map to a smooth region in inclusive signature space. Therefore, even though in practice a set of about ten thousand “discrete” points was used for the simulation, the mSUGRA regions have been represented as a smooth continuous “blobs”. In general, there is statistical error since we have sampled a finite number of mSUGRA models. In addition, even though we have imposed a minimal set of cuts, the shape and size of the regions may depend somewhat on the cuts imposed. The blobs have been drawn such that they overestimate the regions occupied by mSUGRA, to make results more robust. Overestimating the set of points as smooth blobs helps us to get a rough idea of the “size” of the mSUGRA region in each plot. For real data with experimental cuts, the relevant region can be determined as precisely as desired.

We should emphasize again that our goal is to illustrate the advocated approach by a simple example. Of course, more sophisticated analysis can (and should) be done, once we get a better understanding of the basics. For example, more sophisticated cuts which take into account the actual detector environment can be imposed. However, even a simplified analysis can teach us many things. First, in each of the plots, three points are shown which lie “far away” from mSUGRA. These points correspond to other models of supersymmetry breaking. The precise nature of these models is unimportant for this analysis. They have been shown here merely as “existence proofs” of models which occupy a different region in inclusive signature space. It is undoubtedly important to understand the reasons why other supersymmetry breaking approaches (models), such as those represented by the “stars” in the plots, lie outside the mSUGRA region. However, that is not the emphasis of the present paper and will be analyzed

\(^2\)An integrated luminosity of 10 \(fb^{-1}\) has been assumed for the analysis; this corresponds roughly to a luminosity of \(10^{33}\) \(cm^{-2}s^{-1}\) for one collider year (\(\sim 10^7\) s).
in future work.

Second, as has been mentioned before, in the event of a discovery at the LHC, this method could rule out mSUGRA. Signals observed will appear as isolated points in each of the plots. If even a single point lies outside the mSUGRA region in any of the plots, then mSUGRA has to be ruled out. This is quite clear. However, the situation is not so simple if all the points lie within the mSUGRA regions. It does not imply that mSUGRA has been confirmed. This is because, in general, there could be an overlap in the regions occupied by different models. In such a situation, further analysis needs to be done. One possibility is to better define the concept of “distance” — to a particular model from an experimental data point or between two models, in inclusive signature space. It would then seem reasonable to postulate that models which are closer in “distance” to the experimental data point than others in inclusive signature space, are more favorable than others. However, sufficient care has to be taken in defining such a concept so that subtle effects involving different types of uncertainties and errors are properly taken into account. A preliminary study of these kinds of issues has been done in [14].

7 Generalization

It is clear that our approach can shed important light on the status of mSUGRA in the event of a discovery at the LHC. However, we wish to go beyond mSUGRA and generalize our approach in ways such that it is possible to reap its maximum benefits.

More generally, the approach can be applied to study many questions and implications of any hadron collider signal. It can also be used to systematically combine collider and non-collider information. A natural thing would be to do the same analysis for a variety of other supersymmetry breaking models. That is, one should try to carve out the parameter space of different supersymmetry breaking models and study their inclusive signatures. This in turn has the potential to distinguish and ultimately rule out entire classes of models. Different models will tend to occupy different bounded regions in the space of inclusive signatures. Even though the regions occupied by some or many of these models might overlap in some or many of the plots, they are bound to be different in at least some of them. Detected signals will appear as isolated points in the relevant inclusive signature plots. The models whose “regions” in all the relevant inclusive signature plots contain the point, are compatible with the experimental data while other models are not. From the argument of the previous section, it requires more work to differentiate models which are “compatible” with the experimental data in the above

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3We have explicitly seen this in our analysis of other models.
sense. Another way to differentiate models would be to introduce new inclusive signatures (or combinations of inclusive signatures from different types of experiments) which provide new information.

One could go even further. Our theoretical prejudice orients us towards supersymmetry breaking models which explain supersymmetry breaking from a fundamental theory (like string theory), because they have an ultraviolet completion in contrast to others. Various aspects of low energy phenomenology could crucially depend on specific string constructions (for example, the heterotic vs D-brane constructions), on specific moduli fields acquiring vacuum expectation values (the dilaton, kahler moduli or complex structure moduli) and on the values of numbers and charges that appear in string theory (modular weights, anomalous U(1) charges, anomaly cancellation coefficients, topological quantities, etc.) to name a few. Armed with our approach, trying to figure out general “rules of thumb” about how the above alternatives affect inclusive signatures would be of great value in choosing the most promising avenue for further top-down study.

In addition, from a more bottom-up perspective, one could try to study the entire parameter space of the MSSM and its effect on the pattern of inclusive signatures. Of course, a brute force analysis is a herculean computation challenge. However, once we understand different corners of the parameter space of the MSSM (mSUGRA for example) and their effect on the pattern of inclusive signatures, an intelligent intuitive approach can allow us to make important statements about the effects of a generic MSSM model on the pattern of inclusive signatures.

8 Conclusion

In this paper, we have emphasized some obstacles to determining the implications of new physics at the LHC. Proper study of the obstacles in a general theory is lacking in the literature, as most phenomenological analyses rely on explicit and implicit assumptions. In light of these obstacles and the incomplete nature of theoretical models at our disposal, an innovative and constructive approach is required. One such approach has been presented in the paper - to learn about the properties of new physics from patterns of inclusive signatures.

This approach has been applied here to the case of the minimal supergravity mediated supersymmetry breaking scenario (mSUGRA) in detail, resulting in a “footprint” of mSUGRA in “inclusive signature space”, seen from figures 1-4 in the paper. The figures clearly show that mSUGRA occupies a finite bounded region in inclusive signature space and it is possible to find models which lie outside this region. Thus, in the event of a discovery, this approach can
rule out mSUGRA if any experimental point lies outside the mSUGRA region in any inclusive signature space projection. However, confirming mSUGRA (or any particular model) requires further analysis.

The signature space approach also has major experimental advantages, allowing reduction of the effects of luminosity uncertainties, and of acceptance and jet energy corrections.

It is possible to generalize the approach to other models, distinguish between them and to get valuable insights about different approaches to supersymmetry breaking and the fundamental microscopic theory which leads to it. The main purpose of this paper was to illustrate the above approach by applying it to a particular model — mSUGRA, the most popular “model” for phenomenological studies. A more sophisticated analysis can (and should) be done when data is available, taking various effects like detector environment, errors, statistics, etc. into account.

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