Search for Supersymmetry at the LHC

P. G. Mercadante
Instituto de Física, Universidade de São Paulo, CP:66.318
São Paulo, SP, CEP:05389-970, Brazil

Received on 18 December, 2003

It is generally accepted that the LHC is the accelerator facility at which weak scale supersymmetry will either be discovered or definitely excluded. I give a brief introduction to weak scale supersymmetry presenting the general argument that limit the supersymmetrical spectrum to be below TeV energies. We will see that the LHC is able to search for supersymmetry in several of its realization far above the expected spectrum masses. However, in the last section we will see some well motivated scenarios where supersymmetric sparticles might be very heavy, thus beyond the LHC reach. Such scenarios deserve a more detailed study to push the LHC reach.

1 Introduction

Weak scale supersymmetry (SUSY) [1] provides a highly motivated framework for physics beyond the standard model (SM). The search for its predicted new particles is one of the primary tasks for collider experiments. In particular the large hadron collider (LHC), which is going to operate at the large electron positron collider (LEP) ring, is going to improve considerably the reach. In fact, it is common lore that the LHC is going to discover supersymmetry if it is relevant to electroweak (EW) interaction [2]. In this paper we are going to put in perspective this last statement reviewing the motivations for SUSY at the electroweak scale and some of the strategies for SUSY search at the LHC.

The particular signature of SUSY at hadron colliders are model dependent; in fact the minimal supersymmetric extension of the standard model (MSSM) has more than 100 new free parameters. Before we continue in this task that seems hopeless (looking for a particular signature in a model with more than 100 free parameters), let us review the motivation for Supersymmetry, the construction of the MSSM and the frameworks that make it possible to constrain the parameters.

2 Motivation for Supersymmetry

There are many excellent reviews for the motivation of SUSY at electroweak scale and the building of the MSSM [1]. In this work I will just point some few points that are more relevant for what we are going to see.

The standard model is able to explain all experimental results in high energy physics so far, with the exception of neutrino masses. In this talk I am not going to investigate neutrino physics, it is sufficient to mention that neutrino masses can be accommodated extending the SM [1]. The only sector that still need experimental confirmation is the Higgs scalar sector, which is responsible for breaking the EW symmetry and generating mass.

Despite its enormous success the SM of the electroweak interactions has many features that lead us to believe it is not the ultimate fundamental theory: we don't know why there are three families, we don't know why the mixing and the masses of all fermions are the way they are, in resume, it has too many input parameters which is not very attractive in a fundamental theory. Besides all this features, the SM does not include gravity, thus we know that it can not describe nature at such high scales as the Planck scale. In this way we view the SM as an effective theory good only up to some energy scale (maybe the Planck scale?).

If we believe the SM is valid up to the Planck scale [2] one first problem arises: there is an enormous mass hierarchy between the electroweak scale (TeV) and the Planck scale (10^{19} GeV). The problem that motivates SUSY at electroweak scale is the fine tuning problem that is a consequence of this big hierarchy: if we treat the SM as an effective theory and extrapolate it to very high energy the Higgs mass receives quadratic corrections. In order to keep its mass at the EW scale an enormous fine tuning would be required, making the theory very sensitive to the high energy theory. It is very suggestive that the scalar sector which presents this sensitivity to the high energy theory is also the one that still lacks experimental confirmation.

To solve this problem there are two possibilities: a) The existence of a fundamental scale near the EW scale; b) A theory that contains a fundamental Higgs boson but can be

---

[1] The neutrino sector might provide some clues to the physics beyond the standard model, including SUSY motivated frameworks, but we will not explore this avenue here.

[2] The incredible success of the standard model in predicting the electroweak phenomena with high precision makes it very attractive to extrapolate to energies far above the TeV scale.

extrapolated perturbatively to very high energy. In such a theory there is the need to cancel the quadratic divergences that appears in the Higgs boson mass corrections. Supersymmetry provides a way to ensure such cancellation: it has been noted that fermions and bosons contributes with opposite sign in the loop diagrams; if the theory predicts that each fermion has its boson partner the quadratic divergences is canceled out. This is exactly what supersymmetry does.

In order to build a supersymmetric theory for the fundamental interactions the first thing is to note that at the scale where we have experiments, nature is not supersymmetric (we do not see the supersymmetric partner of the electron, for example). Thus, if supersymmetry exist it must be broken. The mechanism for SUSY breaking is not yet fully understood, the best we can do is to parametrize the effects of SUSY-breaking. In order to do that we are guided by the principle that the breaking terms should not destabilize the scalar sector by reintroducing quadratic divergences. This is done by the introduction of the so called soft supersymmetric breaking (SSB) terms.

3 The MSSM

The MSSM is the most direct phenomenologically viable supersymmetric extension of the SM. It contains all SM particles plus its supersymmetric partners, which has spin differing by $1/2$ but with same internal quantum numbers. The only sector of the SM that need to be extended (besides, of course, introducing superpartners) is the Higgs scalar sector: to give mass to both up and down type of quarks we need to introduce two Higgs doublets. In the SM the Higgs doublet gives mass to the up fermions while its complex conjugates gives mass to down type fermions, however in a supersymmetric theory Yukawa interactions comes from a superpotential that cannot depend on a field as well as its complex conjugates, thus the need for two doublets. It is remarkable that the two Higgs doublets is also necessary for a different reason: it keeps the supersymmetric theory anomaly free.

The interactions of matter and Higgs fields (and their superpartners) with gauge bosons (and their superpartners) are determined by the gauge symmetry, being model-independent. Given the particle content of the MSSM, model dependence arises in the choice of the superpotential, which is taken to be:

$$\begin{aligned} W &= \mu H_d H_u + f_l L H_d \bar{E} + f_d Q H_d \bar{D} + f_u Q H_u \bar{U} \\ &+ \lambda L L \bar{E} + \lambda' L Q \bar{D} + \lambda'' \bar{U}\bar{D}\bar{D} + \epsilon L H_u . \end{aligned} \quad (1)$$

The objects H_d, H_u, L and Q are left-chiral superfields which are doublets under $SU(2)_L$, while $\bar{U}, \bar{D}, \bar{E}$ are singlets under $SU(2)_L$. The Yukawa coupling parameters f_l, f_u, f_d are 3×3 matrix in family space.

We note that the second line in eq. (1) represents interactions that violates lepton or baryon number. In the MSSM all terms in the second line are set to zero, in this framework we assume that there are no renormalizable baryon or lepton number violating operators in the superpotential.

Instead of postulating that the MSSM should respect baryon and lepton number conservation we can add a new symmetry, R-parity, defined as,

$$P_R = (-1)^{3B+L+2s}, \quad (2)$$

where B and L are the baryonic and leptonic numbers and s is the spin of each particle. With this assignment, each particle in the SM has $P_R = 1$ while its supersymmetric partner has $P_R = -1$. One can verify that terms in the second line of eq. (1) violate this symmetry, while those from the first line don't [3].

The advantage of introducing this new symmetry is that we know that baryon and lepton number are violated by non perturbative electroweak effects, so it can hardly be considered a fundamental symmetry. On the other hand, if the MSSM respect exact R-parity conservation it does not have renormalizable interactions that violate B or L but those symmetries can, in principle, be violated in a small amount by non renormalizable interactions. For the model phenomenology the assumption of R-parity conservation has a profound impact: supersymmetric particles (the ones with $R_P = -1$) are produced in pairs and the lightest supersymmetric particle (LSP) is stable!

With these assumptions and the particle content chosen to be the SM with a two doublet Higgs, the Superpotential is completely defined by the SM measured parameters with the exception of the mass term μ for the Higgs fields. However, we need to introduce soft breaking terms that parametrize SUSY breaking. The most general soft SUSY breaking operators consist of,

- Explicit masses for the scalar members of chiral multiplet: In the MSSM this represents soft masses for the squarks, sleptons and Higgs bosons.

- Independent gaugino masses for each gauge group: In the MSSM this corresponds to M_1, M_2, M_3 given to the $U(1)_Y$, $SU(2)_L$, and $SU(3)_C$.

- For each term allowed in the superpotential we can assign a correspondent soft term: In the MSSM this corresponds to trilinear A terms corresponding to each Yukawa interaction (see first line of eq. (1)) and a bilinear B term corresponding to the Higgs boson mass term.

With this field content the MSSM has 30 new parameters if we ignore inter-generation mixing for the soft terms and more than 100 parameters if we allow mixing. In the next section we are going to see what assumptions can be made to reduce the number of free parameters.

Before we go on, let us comment on the EW symmetry breaking sector of the two Higgs doublet model. After the Higgs mechanism there are five physical spin zero Higgs particle: two neutral CP even (h and H), one neutral CP odd A, and a pair of charged particles $H^{\pm}$. Supersymmetry requires that the lightest Higgs (h) should be very light, $M_h < 130 - 180$ GeV (in fact the bound is much more

---

[3] To see this we can treat the superfields in eq. (1) as the fields in the scalar potential.

strict at tree level: $M_h < M_Z$) [1, 3]. The existence of a light Higgs boson is favored by EW data and is possible to be confirmed at the LHC [2].

4 Mechanisms for SUSY breaking: The SUGRA paradigm

In the last section we noted that supersymmetry (actually, supersymmetry breaking) introduces more than a 100 new free parameters in the MSSM. In a hadron collider as the LHC, there are many particles being produced and the decay pattern can be very complicated: it is possible that the signal will depend on many of those free parameters! It is not just desirable but almost necessary to have a way in reducing the number of parameters in order to be able to predict anything at the LHC.

Almost all free parameters come from our ignorance of how SUSY is broken, in the form of soft breaking terms. We are going to see that some assumptions on how SUSY breaking is transmitted to the EW sector constrains the soft parameters, providing very predictive frameworks. But first let us see how some experimental constraints give us some hints of how to implement this program.

One thing that we note from the soft terms is that most of them introduces new sources of flavor neutral currents (FCNC) and charge parity (CP) violation process. For example, if the mass matrix for the right handed slepton soft term (m_e^2) is not diagonal in a basis of sleptons whose superpartners are mass eigenstates of standard model leptons, slepton mixing occurs and it can lead to dangerous contributions, via loop diagrams, to process like $\mu \to e\gamma$. The same arguments can be made to the squark masses.

All of this potentially dangerous FCNC effects in the MSSM can be evaded if one assumes that the soft breaking terms are universal. In particular, we can suppose that the soft terms are flavor blind, ie, they are each proportional to the 3×3 identity matrix in flavor space. One should note that this program implicit assumes that there is some mechanism that naturally would explain the pattern for the soft breaking terms. The new physics that gives rise to such terms can be assumed to reside in a high energy scale.

The particle content of the MSSM by itself provides a very nice hint for the scale of new physics: the unification of gauge couplings. Grand unification theories (GUT) emerged in the supposition that the three gauge couplings of the SM unifies when extrapolated to very high energy. Fig. 1 shows the running of gauge couplings using ISAJET [4], which includes two loop corrections to the RGE. The solid line shows the SM running. The supersymmetric content of the model is turned on once an arbitrary threshold is reached: we take it to be 0.45 (11) TeV for the dashed (dotted) line.

There are two basic problems with GUT theory within the SM: the unification scale is not high enough to prevent proton decay and the coupling does not really unifies in the SM context. As we can see from Fig. 1, in the MSSM context both of this problems are solved: the couplings unifies with a much better degree and at a higher energy scale when compared with the SM. It is important to emphasize that the unification of couplings is a quite general feature of the MSSM, does not depend much at which scale we include the superpartners or the details of the superpartners masses. It depends only on the particle content of the model. (A more refined discussion can be found in the SUGRA working group [5].)

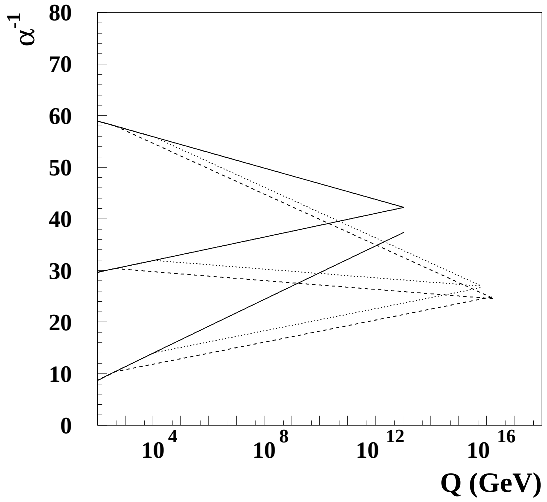

Figure 1. Gauge coupling running as a function of energy. The solid line is the SM, the dotted (dashed) line is for MSSM with 1 TeV (10 TeV) SUSY mass scale.

4.1 mSUGRA

The first successfully economic framework for SUSY phenomenology, which have incorporated this idea of unification, is the so called SUGRA (or mSUGRA) framework [6]. In this picture SUSY is supposed to be broken in a hidden sector and the information of this breaking is transmitted via gravity interaction to the MSSM at the Planck scale. If supersymmetry is broken in the hidden sector by a VEV $< F >$ the soft terms in the visible sector are typically of order $m_{soft} \sim \frac{<F>}{M_P}$. To have $m_{soft} \sim 300$ GeV as required to stabilize the scalar sector we need $\sqrt{< F >} \sim 10^{11}$ GeV. In this picture the gravitino (graviton's superpartner) gets a mass at the order of soft terms, $m_{3/2} \sim \frac{<F>}{\sqrt{3}M_P}$, and does not play any role in collider physics.

With some special assumptions (hence the m for minimal SUGRA) the scalar masses and the trilinear couplings are all unified at this high scale. To be consistent with GUT unification the gauginos masses are also unified at this scale. The soft terms are completed determined by just four parameters: the gauginos mass, $m_{1/2}$; the scalars mass m_0; the trilinear term A_0 and the bilinear term B_0. The other free parameter of the model is the supersymmetric mass term μ.

The above unification relations are valid at the scale where SUSY breaking is communicated to the MSSM sector which, for practical purpose, we take as the GUT scale in

SUGRA models [4]. In order to compute process at the TeV scale the best thing to do is to evolve this parameters to the EW scale using the RGE equation. Once we get the soft breaking terms at the EW scale we can generate all the MSSM spectrum and verify if it is consistent phenomenologically. In particular the Higgs sector should give the right pattern of EW breaking, which means that we should have, at tree level:

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2, \tag{3}$$

where m_{H_d} and m_{H_u} are soft breaking terms of down and up Higgs doublets and μ is the (supersymmetric) Higgs mass term, evaluated at the EW scale. We have eliminated B_0 in favor of $\tan\beta = \frac{v_u}{v_d}$, the ratio of vacuum expected values of the two Higgs doublets. Considering soft terms as input values at GUT scale and m_Z fixed by its measured value we can adjust $|\mu|$ to satisfy this relation, fixing its absolute value.

A more detailed look at eq. (3) tells us that it is not always possible to satisfy it. This looks like a very strong constraint: we need to choose the soft parameters m_{H_d} and m_{H_u} very carefully in order to be consistent to EW data. In particular, for positive values of $m_{H_d}^2$, the unified choice of $m_{H_d} = m_{H_u}$ is not valid.

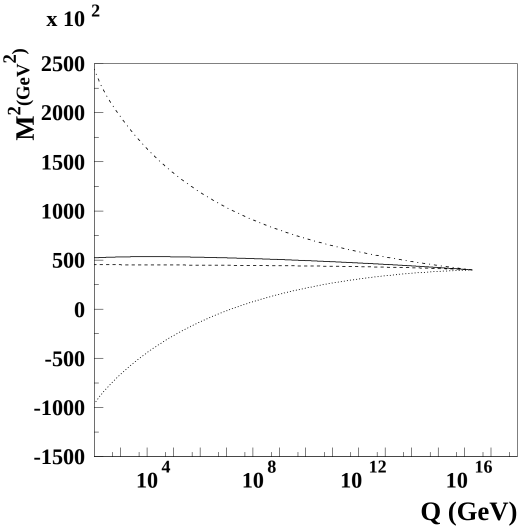

Figure 2. Running of soft scalar masses as a function of energy. The solid (dotted) line is for $m_{H_d}^2$ ($m_{H_u}^2$). The dashed (dot-dashed) line shows m_{er}^2 (m_{dr}^2).

Fortunately, the unification relation is valid at the GUT scale, we need to run down the soft parameters to the EW scale in order to use eq. (3). More generally, one can check that if $m_{H_d}^2 > 0$ the requirement of $m_{H_u} < 0$ is sufficient to satisfy eq. (3). In Fig. 2 we show the running of the scalar soft masses using the RGE equation. The solid curve is for m_{H_d} while the dotted curve is for m_{H_u}. The dashed (dot-dashed) line shows m_{er} (m_{dr}) for reference. Because of the large Yukawa top coupling, m_{H_u} is pushed to negative values which is just what is necessary to trigger EW symmetry. This mechanism is called radiatively electroweak symmetry breaking. The fact that a large top mass is needed for this mechanism to work is very suggestive.

Another important issue that could have consequences on the phenomenology is the nature of the lightest supersymmetric particle. In models where R-parity is conserved this particle is stable and should be neutral for cosmological reasons [7]. Within the MSSM the only candidates would be the lightest neutralino, the sneutrino or (in a supergravity theory) the gravitino (the supersymmetric partner of the graviton) if it is extremely light (as it happens in gauge mediated models with a low SUSY breaking scale). Again, mSUGRA provides a large region of parameter space where the neutralino is the LSP. Gauge interactions give positive contribution for the soft terms when they are run down to EW scale. Starting with universal soft terms for gaugino masses the gluino mass m_3 gets the higher value because of the stronger $SU(3)$ interaction while m_1 (the mass terms corresponding to the $U(1)$ group) gets the smaller value, in the ratio $\frac{3m_1}{5\alpha_1} = \frac{m_2}{\alpha_2} = \frac{m_3}{\alpha_3}$. After diagonalizing the neutral mass matrix and the charged matrix the lightest neutralino is usually the LSP. This neutralino LSP is a good candidate for Dark Matter, which is now strongly constrained by the Wilkinson Microwave Anisotropy Probe (WMAP) data.

In brief, mSUGRA provides a very predictive model for Supersymmetry: the model is completely specified by the sign of μ plus the four parameter set,

$$m_0, m_{1/2}, A_0, \tan\beta. \tag{4}$$

4.2 Gauge Mediated Models

Although mSUGRA is a very attractive model it is hard to believe that it is the only possible answer and that nature should be described by its minimal version. If we want to explore SUSY phenomenology we need to consider alternative scenarios. One of the weakest points of the mSUGRA is the fact that unification of scalar masses (thus a mechanism for solving the FCNC problem that arises if we allow arbitrary soft terms) is an assumption without a strong justification (from the theoretical point of view, of course).

Gauge mediated supersymmetry breaking models (GMSB) [8] solve this problem from start. The assumption here is that there is a intermediate sector that shares gauge interactions with the MSSM and also knows of SUSY breaking from the Hidden sector. The information of SUSY breaking is thus transmitted to the MSSM sector by means of ordinary $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge interaction. There is still gravitational communication between the MSSM and the hidden sector but it is much smaller compared with the gauge communication in theories where the intermediate scale is much smaller than the Planck scale. Because soft terms are proportional to gauge quantum num-

---

[4] It could be argued that this scale should be the Planck scale. In this case there would be a small effect of running from Planck to GUT scale that could change a little the soft relations.

bers, squarks and sleptons with same quantum numbers are degenerate in mass leading to a suppression of FCNC effects.

In this picture there is an intermediate mass scale M_{mess} where the boundary conditions for the soft terms must be fixed. Soft mass terms are proportional to a mass scale Λ which signalizes the breakdown of SUSY. Considering that the messenger sector consists of n_5 sets of quark and lepton superfields in a $5 + \bar{5}$ representation of SU(5) (having the messenger sector in a complete representation of SU(5) keeps the successful prediction for the gauge coupling unification) the gaugino masses are determined by,

$$m_i = n_5 \Lambda \frac{\alpha_i}{4\pi}, \tag{5}$$

while soft scalar masses are given by,

$$m^2_{scalar} = 2 n_5 \Lambda^2 \left[C_3 (\frac{\alpha_3}{4\pi}) + C_2 (\frac{\alpha_2}{4\pi}) + \frac{3}{5} (\frac{Y}{2})^2 (\frac{\alpha_1}{4\pi}) \right] , \tag{6}$$

with $C_3 = \frac{4}{3}$ for color triplet and zero for color singlet, $C_2 = \frac{3}{4}$ for weak doublets and zero for singlets and Y is the hypercharge. The A terms and B terms are induced only at two loop order and are negligible. The model is thus determined by just few parameters:

$$M_{mess}, \Lambda, n_5, \tan\beta, sgn(\mu), C_{grav}, \tag{7}$$

where C_{grav} is a constant larger than 1 which will set the gravitino mass. As $\tan\beta$ is interchangeable with B_0 and we have argued that B_0 should be small one might consider that $\tan\beta$ should be fixed, however details in the generation of μ would change this relation, thus it is common to have $\tan\beta$ as an input parameter.

The general implementation of this model is very similar to mSUGRA: There is a set of boundary conditions for the soft terms at some high scale, RGE equations are used to run down this terms to the EW scale where the complete MSSM spectrum is calculated. In particular, the Higgs mechanism should be triggered by this evolution.

It is clear that the different assumptions for soft breaking terms will give different relations for sparticle masses. But the most important difference from mSUGRA models is that in GMSB the gravitino can be very light. Generically, the gravitino mass is given by,

$$m_{3/2} \sim \frac{< F >}{\sqrt{3} M_P} , \tag{8}$$

where $< F >$ is a supersymmetric breaking VEV. In order to give soft terms at the EW scale order $\sqrt{< F >} \sim 10^{11}$ GeV is required in SUGRA models leading to $m_{3/2} \sim$ TeV. However, in gauge mediated models the soft terms are estimated to be $m_{soft} \sim \frac{<F>}{M_{mess}}$. As M_{mess} can be much smaller than M_P, it is possible to have $\sqrt{< F >} \sim 10^4$ GeV in this scenario. As we can see from eq. (8) this would give a very light gravitino; this gravitino would be the LSP and if it is really light (order of eV) the next lightest supersymmetric particle (NLSP) decays in a gravitino plus its SM partner within the detector. This very light gravitino does not make a good candidate for cold dark matter which is a definite disadvantage of this model when compared with SUGRA.

Direct decay of other supersymmetric particles to the gravitino has a very small BR, in this picture there is going to be at least two NLSP particle in each event. The nature of the NLSP is thus very important for phenomenology. We note that the NLSP does not have the same constraints that the LSP have, in particular, it is possible for the NLSP to be a slepton and, indeed, in a large region of parameter space this is the case.

5 Search for Supersymmetry at the LHC

We have seen that the MSSM provides a quite general framework for supersymmetry. However, it has too many free parameters and most of its parameter space gives rise to process that violated FCNC, being ruled out by experiment. With some assumptions on the nature of the soft SUSY breaking terms, consistent frameworks are developed with few parameters and very predictive power. In this section we are going to see the predicted reach of the LHC in this frameworks.

5.1 mSUGRA

In the mSUGRA framework the complete supersymmetric spectrum is determined by the parameter set,

$$m_0, m_{1/2}, A_0, \tan\beta, sign(\mu).$$

From this parameters, m_0 and $m_{1/2}$ set the scale for scalars and gaugino masses while A_0 is relevant mostly for the third generation sfermions. We expect that $\tan\beta$ and $sign(\mu)$ are relevant to the decay patterns. It is very common to present the reach in mSUGRA framework in the plane $m_0 \times m_{1/2}$, fixing the other parameters.

At the Tevatron $p\bar{p}$ collider, in most of mSUGRA relevant parameter space (and not already ruled out by LEP constraint on the lightest chargino) the gluinos are too heavy, so charginos pair and charginos/neutralinos associated productions dominates. The golden plate channel would be the trilepton signal from charginos product decay [5]. In a recent evaluation [9] the reach of Tevatron RUN 2 was estimated in about $m_{1/2} < 190$ GeV, depending on the others parameters, which represents a gluino mass of about 575 GeV.

At the LHC gluino pair production dominates in a large fraction of space parameter. For low m_0 values squarks are also light so that $\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$ all have large rates. For very high $m_{1/2}$ gluinos are too heavy and chargino-neutralino associated production dominates. It is usual to classify the signal in several channels containing many hard jets and leptons plus missing E_T. The reach of the LHC has been evaluated in mSUGRA [10]. In Fig. 3, taken from ref. [11], it is shown the reach for $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ in several channels. We can see that the best reach is given by the inclusive $jets + E_T^{miss}$ and extend to $m_{1/2}$ as large as 1400 GeV for small values of m_0 and 700 GeV for $m_0 \sim 4000$

TeV. We also see that it covers gluino mass of 2 TeV up to $m_0 = 3000$ GeV. As a comparison, the Tevatron reach lies below the $m_{1/2} = 200$ GeV line, it is clear that the LHC will extend considerably the reach!

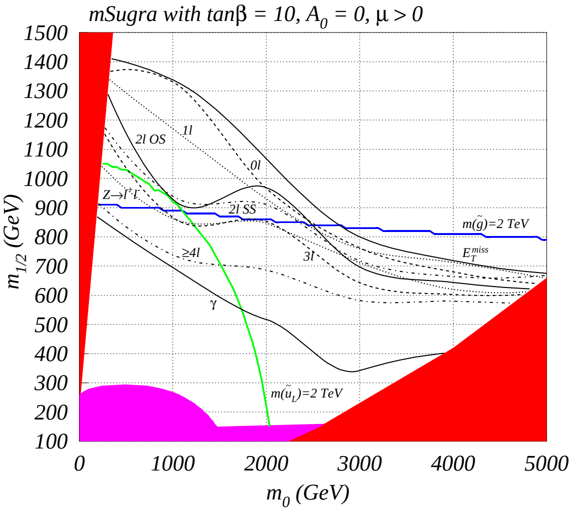

Figure 3. LHC reach for several channels extract from ref. [11]. The E_T missing inclusive channel is the upper solid line. Also shown is gluino mass contour of 2 TeV.

5.2 GMSB

In the GMSB framework the complete supersymmetric spectrum is determined by the parameter set, given at eq.(7):

$$M_{mess}, \Lambda, n_5, \tan\beta, sgn(\mu), C_{grav}.$$

From this parameter the most important is Λ which set the scale for the soft mass terms. M_{mess} just set the scale where the boundary condition is valid, in other words it just tells how much it is needed to run down to the EW scale. In GMSB the search strategy depends on the nature of the NLSP. It is common to define regions of parameter space according to the nature of the NLSP [12]. n_5 alters the relations of gauginos and scalar soft masses being important to determine the identity of the NLSP. $\tan\beta$ is also important to determine the nature of the NLSP. In the studies of reference [13, 14] C_{grav} is set to 1, which permits the prompt decay of the NLSP, neglecting possible handles coming from tracks or displaced vertices, so this reach projections are conservatives.

In a given region the studies can be presented as a function of Λ, which sets the mass scale of the model. Several cases have been studied: A $U(1)$ gaugino like NLSP (which gives two photons in the final state), a stau NLSP (which gives two taus in the final state), a co-NLSP scenario (which gives a signal with several isolated leptons), a Higgsino NLSP (which might give Z bosons or Higgs boson in the final state).

The most difficult scenario is the stau NLSP where Tevatron reach would correspond to a gluino mass of about 800 GeV while in the most favorable scenario (co-NLSP) the reach will extend up to gluino mass of 1000 GeV [13]. In similar studies for the LHC [14] it was found that the LHC will have a reach of $m_{\tilde{g}} \sim 3$ TeV in the favorable scenario of co-NLSP and $m_{\tilde{g}} \sim 2$ TeV in the stau NLSP scenarios. Generally the LHC reach is better then in mSUGRA framework.

5.3 Anomaly Mediated, Gaugino Mediated

There are other compelling models for SUSY breaking, including anomaly mediated supersymmetry breaking [15] and gaugino mediation models [16], but it is beyond the scope of this work to introduce them here. The LHC reach was also evaluated for such models [17, 18], given a reach of about 2 TeV for the gluino mass.

6 The flavor problem and the decoupling solution: is the LHC going to see it?

We come back here to the central point for SUSY at the electroweak scale. As it was pointed out, supersymmetry provides a way to protect the scalar sector against quadratic divergences which permits the supersymmetric version of the SM to be extended to very high energy scale without the need for large cancellation. In order to remain coherent with this view, it is supposed that sparticles should have their masses at the EW scale, otherwise the need for fine tuning reappear in the scalar sector. (In particular, looking at eq. (3), if the Higgs mass parameters and μ are very large it is evident that a large fine tuning is needed to keep m_Z at its measured value.) In the previous section we saw that the LHC is able to find supersymmetry, in many of its realizations, for gluinos as heavy as 2 TeV, so if supersymmetry solves the fine tuning problem it will be found at the LHC.

This last statement should be taken with a grain of salt, however. Trying to quantify fine tuning is very subjective, some of the measurements of fine tuning might indicate that supersymmetry should have been found already [19]! This should mean that EW supersymmetry is ruled out? It does not seem to be the mainstream feeling. Are we sure to find supersymmetry at the LHC? In other words, should we rule out supersymmetry (at least low energy supersymmetry) if it is not found at LHC? This is what such strong statement as "If supersymmetry is relevant to electroweak interactions, it will be discovered ..." [2] suggest. On the other hand, may am I suggesting here that EW supersymmetry will be a possibility for ever, even if it is not found at the LHC? Where to draw the line? It is not my purpose here to answer this question but rather to take the view that we should explore all possibilities and try to push the LHC reach to its maximum.

In contrast to fine tuning arguments, lower bounds from LEP II and Tevatron on sparticles masses tends to push the spectrum to higher values. In the following we are going to explore possible signals at the LHC in some scenarios where the superpartners are very heavy. The main motivation for these scenarios is the so called decoupling solution for the flavor problem: high masses for the superpartners helps to avoid constraints from low energy process such as FCNC, rare decays and CP violation.

We are going to explore two scenarios with large sfermions masses: inverted mass hierarchy models and focus point models. In both scenarios we are guided by the construction of models with large scalar masses trying, at the same time, to address the fine tuning problem.

6.1 Inverted Mass Hierarchy

The problem posed above, sub-TeV particles required by naturalness arguments and multi-TeV particles required by FCNC and CP violation low energy experimental constraints, can be reconciled by the following consideration: low energy constraints comes mainly from processes involving first and second generation of fermions, while the Higgs scalar sector couples mainly to the third generation [20]. Thus, an inverted mass hierarchy (IMH) spectrum is desirable: third generation sfermions with sub-TeV masses while first and second generations gets multi-TeV masses.

It is possible that the IMH is generated already at the GUT scale (GSIMH). Because sfermions soft terms from first and second generations are very large and they contribute to the evolution of third generation at two loop order, it is very important to consider two loop contributions to the renormalization group. This contributions tends to drive third generation masses to negative values, breaking color or electric charge symmetry, unless the GUT scale third generation mass is very high, so there is a limited range of parameter space where a viable spectrum is generated [21]. Regions of parameter space where first and second generation scalar masses are in the 5-20 TeV range and third generation in the sub-TeV range are mapped out in ref. [22].

An intriguing feature of this type of models is that it is going to be very hard to find it at the LHC. In ref. [22] our preliminar study with a particular point where this IMH is achieved shows that the general search strategy is not going to work. A more dedicated search, perhaps looking for third generation fermions, is needed.

In resume, in GSIMH type of models it is possible to achieve a significant hierarchy which poses challenges in the search for this models. The task in theoretical developments would be to explain the origin of the peculiar choice of SSB parameters at the GUT scale.

An attractive alternative where IMH can occur has been suggested in a series of papers [23]. The idea is to start with multi-TeV masses for all scalar particles at the GUT scale and generate the IMH radiatively. It has been noted that for simple forms of the soft breaking terms, third generations soft terms is driven to small values while first and second generation soft terms remain at the multi-TeV range. The beauty of this scenario is that the boundary conditions that soft terms need to satisfy is consistent with $SO(10)$ grand unification.

In order to have a realistic spectrum from this model we have to implement Yukawa unification as expected in $SO(10)$ grand unified models. Yukawa unification occurs only at a very high value of $\tan\beta$, a region of parameter space where it is very difficult to implement REWSB. It has been noted, however, that the introduction of $D - term$, that occur when spontaneous gauge symmetry breaking leads to a reduction in rank of the gauge group [24] (in this case from $SO(10)$ to the $SU(3) \times SU(2) \times U(1)$), can help to get the REWSB mechanism [25]. A second problem arises: the introduction of D-term and the full implementation of the RGE equations (with two loop effects, TeV masses contributions, non unification of Yukawa couplings below GUT scale) perturb the simple exact solution that drives the third generation masses to small values. Moreover, the Yukawa coupling values allowed by the top quark mass measurements is not as large as the ones used in ref. [23]. As a result the amount of hierarchy obtained is rather limited.

In reference [26] realistic models were generated in this scenario. It is possible to get sub TeV third generation masses while keeping first and second generation at the order of 3-5 TeV. This is enough to decouple the first and second generation from the LHC searches. In this scenario the mSUGRA strategy has a limited reach in the LHC. This preliminary study shows that b-tag jets can help to improve the reach [26].

In both scenarios of IMH it is clear that the LHC capacity to find it must be explored in more detail. In particular, the capacity for $b - tag$ would be crucial in this scenarios. A more detailed study for scenarios where third generation squarks might be the only sparticle produced at the LHC with particular emphasis on $b - tag$ is in order.

6.2 Focus Point

An intriguing region in the mSUGRA parameter space is the large m_0 region. In this region all scalar sparticles are heavy, which helps to ameliorate the FCNC and CP violation problems. Naively, large scalar masses would require very large cancellations in the scalar potential to keep the EW scale at its experimental value, rendering the model unatural. For this reason, this region of parameter space have been neglected in phenomenological studies.

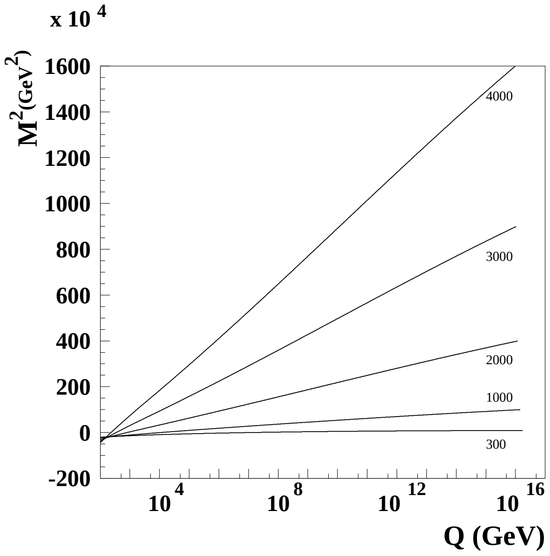

Figure 4. Running of the up Higgs soft mass (m_{H_u}) in the focus point region. In this plot, A_0=0, $\tan\beta = 10$, $m_{1/2} = 300$ GeV, $\mu > 0$ and the values of m_0 are shown in GeV for each line. This figure was inspired in ref. [27].

However, it has been noted that in the region where $m_{1/2}$ is not so large there is an interesting focus point behavior for the soft Higgs masses, as is shown in Fig. 4 the soft Higgs masses is run down to the same value at the EW scale, independently of the GUT scale value of m_0 [27]. One could say that big m_0 values are as natural as the small ones, as it naturally leads to the same EW values. In fact, from the minimization condition in the scalar potential,

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu|^2 \sim -m_{H_u}^2 - |\mu|^2, \quad (9)$$

we see that, for large $\tan\beta$ (where the last approximation is valid), the value of μ^2 is sensitive only to $m_{H_u}^2$ which, by its turn, is insensitive to the value of m_0 due to the focus point behavior.

Moreover, as it can be seen from Fig. 4, the m_{H_u} values obtained in this solutions are small, leading to a very small μ. This region of small μ happens for large m_0 and for $m_{1/2}$, just above the theoretically excluded limit where no REWSB is achieved (we should note that this region is very sensitive to the value of the top quark mass). We will refer to it by the focus point (FP) region. The main consequence of the small value of μ is that the lightest two neutralinos and the lightest chargino are mainly a Higgsino, which enhances its coupling to third generation fermions. This has important consequences in dark matter prediction as well as direct searches in collider.

This FP region has received renewed attention due to experimental data on CDM as well improved neutralino relic density evaluations [28]. As we have pointed out, a very attractive feature of R-parity conserving models is that the LSP is stable, providing a natural candidate for dark matter. In mSUGRA the LSP is the lightest neutralino and its contribution to dark matter is calculable.

Recent analyses from the WMAP and other experiments set the physical matter and baryon densities to be [29] $\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$ and $\Omega_b h^2 = 0.0224 \pm 0.0009$, respectively, where h is the Hubble constant in units of 100 km/s/Mpc. The excess of non-baryonic matter results in $\Omega_{CDM} h^2 = 0.1126^{+0.008}_{-0.009}$. The upper limit derived from this is a true constraint on any stable relic from the Big Bang, such as the NLSP of the mSUGRA model [5], while the lower limit does not present a true constraint as there could be other sources of cold dark matter in the model.

Promising regions for CDM includes the focus point region, where the large Higgs component of the LSP allows for efficient annihilation into vector boson pairs, keeping the amount of CDM compatible with WMAP results. Others regions that might be consistent with WMAP results are the stau co-annihilation region and the axial Higgs A annihilation corridor at large $\tan\beta$. The so called bulk region at low m_0 and $m_{1/2}$ was advocated as an indication that the LHC would discover mSUGRA as it points to small $m_{1/2}$ and m_0 but now this region has been practically ruled out.

Recently Baer *et al.* [11] attempted to set bounds on the neutralino relic density constraint in mSUGRA model, along with other indirect experimental constraints, namely rare decays $b \to s\gamma$ or $B_s \to \mu^+\mu^-$ and the muon anomalous magnetic moment. These low energy data favorable regions were confronted with direct search of SUSY at the CERN LHC collider for an integrated luminosity of 100 fb^{-1}. In Fig. 5 we shown their results for $\tan\beta = 30$, $A_0 = 0$ and $\mu > 0$. We see that the bulk region is difficult to reconcile with LEP2 limits on the Higgs mass, as it extend up to only $m_{1/2} < 100$ GeV (as opposed to about 200 GeV in pre WMAP results [30]). The region very close to the left-hand side of the figure where stau mass is similar to the LSP mass is the co-annihilation region. The FP region is the narrow band just above the region labeled No REWSB in the right-hand side.

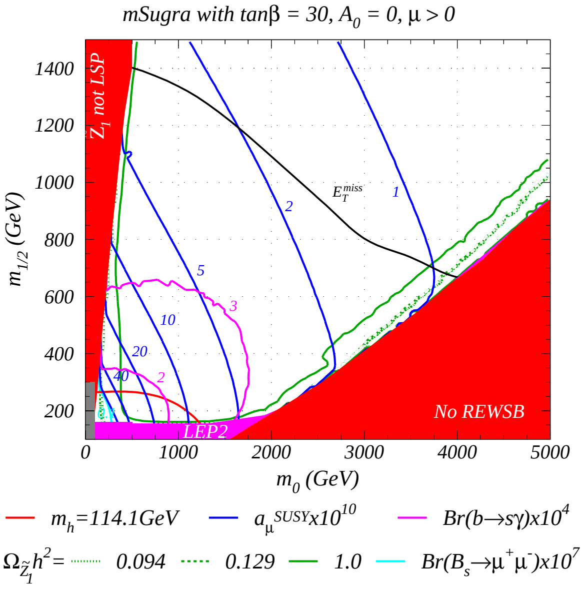

Figure 5. Neutralino relic density constraint on the mSUGRA parameter space for $\tan\beta = 30$, $A_0 = 0$ and $\mu > 0$ along with LHC maximal reach and contours of several low energy observables obtained from Ref. [11].

The very interesting feature about the FP region is that it extend far away from the expected reach of the LHC via missing ET plus jets channel (the line with the label E_T^{miss} in Fig. 5), posing a challenge to its discovery.

Motivated by the fact that in this portion of parameter space the LSP has a substantial higgsino component, thus gluino decay predominantly into third generation quarks, we expect that SUSY signature will be very rich in multiple hard b jets. Therefore an efficient b-tagging may improve the discovery reach of supersymmetry over the canonical search.

Although $\widetilde{W}_1\widetilde{Z}_1, \widetilde{W}_1\widetilde{Z}_2$ cross section dominates in this region, those particles are degenerated in mass so their visible decay are quite soft. The gluino production will be the

---

[5] It would be easy to evade such constraint, however, by allowing a small amount of R-parity violation.

main source for hard visible activity that can be singled out from the background. In Fig. 6 we present the gluino cross section as a function of its mass. Because its cross section is rather small we are going to work with rate limited signal, thus the efficiency of detectors will be crucial. In the region we are considering, gluino decays predominantly via $\widetilde{W}_1^+ b\bar{t}$, $\widetilde{W}_1^- \bar{b}t$, $\widetilde{Z}_{1,2} b\bar{b}$, $\widetilde{Z}_{1,2} t\bar{t}$, leading to a final state with many very hard b's. Our preliminary results were presented in this congress by Kenichi Mizukoshi [31].

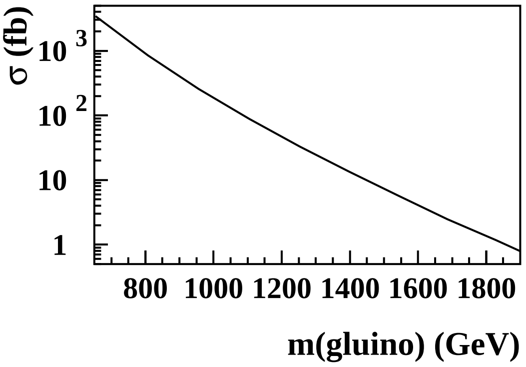

Figure 6. Gluino pair production cross section as a function of its mass at the LHC.

7 Summary and Discussions

I have presented here some of the frameworks where supersymmetry is realized and the potentiality of the LHC to find it. It is clear that the LHC is going to extend the present reach considerably. For most of the scenarios, the LHC is going to probe sparticles as heavy as 500 GeV. Even for R-parity violation models [32], not discussed here, the LHC is able to cover most of the sub-TeV region [2].

We have seen that the main motivation of electroweak supersymmetry is the solution of the fine tuning problem. This generally would require sparticles of sub-TeV masses, leading to a strong confidence that the LHC is going to find supersymmetry if it is relevant to the electroweak scale.

We have stressed here, however, that the present bounds and the success of the SM in explain all the low energy results pushes the supersymmetric masses to higher values. To reconcile the need for respecting the low energy constraint in mSUGRA we propose some scenarios with very high masses [6] for supersymmetric particles that might respect some fine tuning criteria (though we stay away from the discussion of quantifying fine tuning). The focus point region, in addition to that, is a favored region from cold dark matter constraints.

It would be a real challenge for the LHC to search for the scenarios proposed here. In particular, the capacity for the LHC to identify b jets will be crucial to extend the reach in such scenarios. A more refined work in this direction is under perform.

Acknowledgments

The author is much in debt with Xerxes Tata for valuable discussions. I am also in debt with Howard Baer for suggesting to explore the IHM framework in depth. Yili Wang, Csaba Baláz and Michal Brhlik have colaborated in most of the works concerned here. Kenichi Mizukoshi and Roger Kadala are collaborating in the exploration of the b-jet scenario in the LHC. Finally, I thank the organizing comitee of the Brazilian conference for inviting me and the audience of our section for lively discussion. This work is supported by FAPESP.

References

[1] For reviews in SUSY see Stephen P. Martin *A Supersymmetry Primer* hep-ph/9709356; X. Tata *What is supersymmetry and how do we find it*, presented at IX J. Swiec Summer School, hep-ph/9706307; N. Polonsky *Supersymmetry: Structure and Phenomena. Extensions of the Standard Model* Lect. Notes Phys. **M68**, 1 (2001).

[2] Scientific note: the Atlas and CMS collaborations, hep-ph/0110021

[3] J. Gunion and H. Haber, Nucl. Phys. **B278**, 449 (1986).

[4] H. Baer, F. Paige, S. Protopopescu and X. Tata, hep-ph/0001086

[5] S. Abe *et al.* (SUGRA working group collaboration), hep-ph/0003154.

[6] A. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); R. Barbieri, S. Ferrara and C. Savoy, Phys. Lett. **B**119, 343 (1982); L.J. Hall, J. Lykken and S. Weinberg, Phys. Rev. D**27**, 2359 (1983); for a review, see H. P. Nilles, Phys. Rep. **110**, 1 (1984).

[7] S. Wolfram, Phys. Lett. **B**82, 65 (1979); C. B. Dover, T. Gaisser and G. Steigman, Phys. Rev. Lett. **42**, 1117 (1979).

[8] M. Dine, A. Nelson, Y. Nir and Y. Shirman, Phys. Rev. **D53**, 2658 (1996).

[9] H. Baer, T. Krupovnickas and X. Tata, hep-ph/0305325.

[10] S. Abdullin *et al.* (CMS Collaboration), hep-ph/9806366

[11] H. Baer, C. Balázs, A. Belyaev, T. Krupovnickas and X. Tata, hep-ph/0304303.

[12] R. Culbertson *et al.* (SUSY working group collaboration), hep-ph/0008070.

[13] H. Baer, P. G. Mercadante, X. Tata and Y. Wang, Phys. Rev. D**60**, 055001 (1999).

[14] H. Baer, P. G. Mercadante, F. Paige, X. Tata and Y. Wang, Phys. Lett. **B**435, 109 (1998) ; H. Baer, P. G. Mercadante, X. Tata and Y. Wang, Phys. Rev. D**62**, 095007 (2000)

[15] L. Randall and R. Sundrum, Nucl. Phys. B**557**, 79 (1996); G. Giudice, M. Luty, H. Murayama, and R. Rattazzi, JHEP **9812**, 027 (1998).

[16] M. Schmaltz and W. Skiba, Phys. Rev. D**62**, 095005 (2000). .

---

[6] It is true, however, that the scenario studied here does not solve the flavor problem completely; there is still need of some ajustment in the soft terms.

[17] H. Baer, J. K. Mizukoshi and X. Tata, Phys. Lett. **B**488, 367 (2000).

[18] H. Baer, A. Belyaev, T. Krupovnickas, and X. Tata, Phys. Rev. D**65**, 075024 (2002).

[19] G. F. Giudice, hep-ph/9912279.

[20] M. Drees, Phys. Rev. D**33**, 1468 (1986); A. Pomarol and D. Tommasini, Nucl. Phys. **B466**, 3 (1996); A.G. Cohen, D.B. Kaplan, and A.E. Nelson, Phys. Lett. B**388**, 588 (1996); J. Hisano, K. Kurosawa, and Y. Nomura, Phys. Lett. B**445**, 316 (1999); V. Barger, C. Kao, and R-J. Zhang, Phys. Lett. B**483**, 184 (2000); for an overview, see H. Baer, M. Diaz, P. Quintana, and X. Tata, JHEP **0004**, 016 (2000).

[21] N. Arkani-Hamed and H. Murayama, Phys. Rev. D**56**, R6733 (1997); K. Agashe and M. Graesser, Phys. Rev. D**59**, 015007 (1999).

[22] H. Baer, C. Balázs, P. Mercadante, X. Tata, and Y. Wang, Phys. Rev. D**63**, 015011 (2000).

[23] J. Feng, C. Kolda, and N. Polonsky, Nucl. Phys. B**546**, 3 (1999); J. Bagger, J. Feng, and N. Polonsky, Nucl. Phys. B**563**, 3 (1999); J. Bagger, J. Feng, N. Polonsky, and R. Zhang, Phys. Lett. B**473**, 264 (2000).

[24] M. Drees, Phys. Lett. B**181**, 279 (1986); C. Kolda and S. Martin, Phys. Rev. D**53**, 3871 (1996).

[25] H. Baer, M. Diaz, J. Ferrandis, and X. Tata, Phys. Rev. D**61**, 111701 (2000); H. Baer, M. Brhlik, M. Diaz, J. Ferrandis, P. Mercadante, P. Quintana, and X. Tata, Phys. Rev. D**63**, 015007 (2001).

[26] H. Baer. P. Mercadante and X. Tata, Phys. Lett. **B475**, 289 (2000); H. Baer, C. Balázs, M. Brhlik, P. Mercadante, X. Tata, and Y. Wang, Phys. Rev. D**64**, 015002 (2001).

[27] J. Feng, K. Matchev, and T. Moroi, Phys. Rev. Lett. **84**, 2322 (2000) and Phys. Rev. D**61** 075005 (2000).

[28] J. Ellis, T. Falk, K. Olive, and M. Srednicki, Astropart. Phys. **13** 181, (2000); H. Baer and M. Brhlik, Phys. Rev. D**57**, 567 (1998); J. Feng, K. Matchev, and F. Wilczek, Phys. Lett. B**482**, 388 (2000).

[29] C. L. Bennett *et al.*, hep-ph/0302207; D. N. Spergel *et al.*, hep-ph/0302209.

[30] K. A. Olive, hep-ph/030835

[31] P. G. Mercadante and J. K. Mizukoshi, Prepared for XXIV Brazilian National meeting on Particles and Fields.

[32] B. Allanach *et al.*, hep-ph/9906224.