Can the LHC rule out the MSSM?

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If supersymmetry (SUSY) exists in nature and is a solution to the hierarchy problem then it should be detectable at the TeV energy scale which the large hadron collider (LHC) is now exploring. One of the main goals of the LHC is the discovery or exclusion of the R-parity conserving minimal supersymmetric standard model (MSSM). So far, the SUSY search results are presented in the context of the constrained MSSM and other specific simplified SUSY models. A model-independent analysis necessarily relies on the trigger-system of the LHC detectors. By using the posterior samples of a 20-parameter MSSM, the phenomenological MSSM, from a fit to indirect collider and cosmological data we find that there is a significant volume in the MSSM parameter space that would escape the standard trigger-systems of the detectors. As such, in the absence of discovery in the current and future LHC runs, it would be difficult if not impossible to exclude the MSSM unless some dedicated and special triggers are commissioned or a Higgs boson with mass as predicted by the supersymmetric models is not found.

Introduction.

The current understanding of nature, in the form of experimentally tested knowledge about the fundamentals of particle physics, have major limitations that include the ignorance about what constitutes cold dark matter (CDM) and about the mechanism for explaining particles masses and the wide hierarchies between them. The Higgs mechanism could explain the source for particle masses but suffers the so-called hierarchy problem since the mass of the Higgs particle itself is not stable to radiative corrections.

A solution for the hierarchy problem is feasible with supersymmetry (SUSY) by which the Higgs boson mass become stable to radiative corrections. SUSY predicts that for each standard model (SM) particle there should be a corresponding equal-mass sparticle with a half-unit spin difference. The fact that no sparticle has been observed to date indicates that the symmetry, if it exists, is broken and the sparticles are much heavier than their corresponding SM particles. It is expected that sparticles would be produced at high energy colliders. For instance, from a proton-proton collision strongly interacting squarks (q) and gluinos (g) would be pair-produced which would subsequently decay into SM particles to form jets, leptons and photons. With R-parity conservation, sparticle decay chains would end with the lightest supersymmetric particle (LSP) which is cosmologically stable and hence could account for the whole or part of the CDM. It is expected that a SUSY scenario that addresses the hierarchy-problem would be manifest at O(TeV) energy-scale.

At particle colliders where sparticles could be produced, the neutralino (χ^0_1) LSP would fly out without interacting with the collider particles detection systems. Its experimental signature corresponds to final states with unbalanced total momentum in the transverse plane to the colliding particles beam axis. The magnitude of the missing transverse energy (E_T) and the transverse momentum, p_T, of the resulting jets respectively depends on the LSP mass and its difference from the lightest squark or gluino. Generically, SUSY events at colliders would have large missing E_T (LSP mass) and large jets p_T (related to the energy carried by quarks from heavy squark/gluino decay to neutralino.) However, this is not necessary always the case as it will be shown in the forthcoming paragraphs. SUSY scenarios with non-standard characteristics should not be neglected in strategic search studies.

The LHC is a proton-proton collider designed to reach up to 14 TeV centre-of-mass energy in search for the origin of particles masses and for new physics beyond the SM (BSM). During the year 2010 runs, the LHC general purpose detectors, ATLAS and CMS, have collected about 35 pb⁻¹ data at 7 TeV. No significant excess to the SM expectation has been found in their SUSY search analyses. The results are reported in the form of limits on the parameter space of some chosen model and on non-SM cross sections for the chosen SUSY search channels.

In this article we emphasis that the LHC results are detectors’ trigger-system dependent. SUSY final states with characteristics that cannot be triggered by the detectors would be lost forever as “uninteresting” event(s). Events that end up with very soft jets would be rejected as QCD background (non-SUSY) since the triggers are optimised to minimise the recording of background events. For example, the non-SM cross section limits presented in Ref. 1 would necessary not apply for the SUSY scenario where the resulting jets and missing energy would not get triggered or would escape the imposed kinematic cuts. Therefore, in the absence of SUSY discovery in the current and future LHC runs, it would be difficult, if not impossible, to rule out the MSSM. We give explicit examples of such SUSY points from the 20-parameter phenomenological MSSM (pMSSM) fits to (indirect collider and cosmological data) posterior samples, which are not possible to obtain from the constrained MSSM (CMSSM/mSUGRA) parameter space, that would escape the LHC detectors’ trigger-systems and perform a generator-level analyses on simulated SUSY events to illustrate the nature of the resulting jets and leptons p_T and of events missing E_T that could be obtained.

The pMSSM. The pMSSM is set up such that the physics behind SUSY breaking, mediation mechanism and renormalisation group (RG) running of the parameters from the SUSY-breaking scale is not relevant for, and
hence decoupled from, the SUSY-breaking terms parameterisation procedure. The soft SUSY-breaking parameters (20 and a sign choice) are derived from the parent 105-parameters MSSM by imposing phenomenological constraints to suppress CP-violation sources and constraints from the observed absence of FCNC:

\[ M_{1,2,3}; m_{3rd\,gen}^{3rd\,gen}, m_{1st/2nd\,gen}^{1st/2nd\,gen}; A_{t,b,\tau,\mu=e}, m_{H_u,d}^2, \tan \beta \]

where the first 3 parameters, \(M_1, M_2\) and \(M_3\) are the gaugino mass parameters. The next 10 parameters represent 3rd and degenerate 1st and 2nd generation sfermion masses. \(A_{t,b,\tau,\mu=e}\) represent the trilinear scalar couplings. An alternative choice of parameters would be to replace the Higgs doublets mass terms \(m_{H_u}^2\) and \(m_{H_d}^2\) with the CP-odd neutral Higgs mass parameter, \(M_A\) and the Higgs doublets mixing parameter, \(\mu\). As illustrated in Ref. [7, 11] the technology to simultaneously vary and explore the parameters for making a statistically convergent global fit is well within reach. However in the absence of direct SUSY data the pMSSM parameter space is weakly constrained and most, but not all, posterior inference would be necessarily prior dependent. A Bayesian comparison/selection analyses between GUT-scaled models for SUSY-breaking is performed in Ref. [13] and pMSSM discovery prospects were studied in Ref. [14].

The squark and gluino mass posterior probability distributions from the pMSSM fits to indirect collider and cosmological data are shown in Fig. 1. For both log and flat prior cases the region with \(m_{\tilde{g}} > m_{\tilde{q}}\) is preferred. A contour approximating the experimental exclusion limits [6, 15] on the CMSSM/mSUGRA squark-gluino plane is also placed on top of the pMSSM posterior distribution for reference purpose.

![Fig. 1: pMSSM posterior probability map for gluino and lightest squark masses based on fits to indirect collider and cosmological data [7, 11]. The inner and outer contours represent 68% and 95% probability regions respectively. For reference purpose a contour line approximating the LHC limits [6, 15] for CMSSM/mSUGRA is also shown (dotted line). Points below the contour are excluded at 95% CL for the CMSSM/mSUGRA models but not necessarily so for the pMSSM.](image)

There are various SUSY spectrum topologies in the pMSSM posterior points which are difficult to obtained from constrained versions of the MSSM. In particular an approximately neutralino degenerate squarks in the CMSSM/mSUGRA parameter space is difficult to obtain. That is mainly due to the nature of the RG running boundary conditions at the GUT-scale: the ratio \(M_1 : M_2 : M_3 = 1 : 2 : 6\) is fixed at the electroweak (EW) scale and to leading order, \(M_i / g_i\) do not RG run [2]. Here \(g_i, i = 1, 2, 3\) represents the electromagnetic, weak or strong interaction couplings respectively; \(M_1, M_2,\) and \(M_3\) are the gaugino soft mass parameters at the EW scale. For a predominantly bino neutralino the gluino-neutralino mass ratio is fixed. Next, the gluino mass scales as \(m_{\tilde{g}} \sim M_3\) correct to subleading corrections after RG running from the GUT scale to the EW scale. On the other hand, squark mass \(m_{\tilde{q}}^2 \sim m_0^2 + K_3 + \ldots\), where \(K_3 \sim 6.0 m_{\tilde{g}}^2 / 2\), where \(m_{\tilde{g}} / 2\) is the common gaugino soft mass term at the GUT scale. Squarks would therefore be mostly heavier than the gluino, so obtaining a compact spectrum \(m_{\tilde{g}} >> m_{\tilde{q}} \gtrsim m_{\chi_1}\), such as the one shown in Fig. 1(b), would be very rare/impossible.
For the pMSSM, the scenario is different. All SUSY-breaking parameters are freely varied at the EW scale so constraints on the parameters from RG running is minimal. The pMSSM fits prefer \( m_\tilde{g} > m_\tilde{\chi}_1^0 \) as shown in Fig. 1. Moreover there is a significant number of pMSSM parameter points where the mass difference between the lightest sneutrino and the LSP is small, compared to the top-quark mass, that would lead to soft jets in collider (SUSY event) final states. About 17% of the 116931 pMSSM posterior points considered have lightest squarks quasi-degenerate with the neutralino LSP. These model points are concentrated around the \( \Delta M_{\text{min}} = m_{\text{min}(\tilde{q})} - m_{\tilde{\chi}_1^0} \) equals 10 to 25 GeV narrow-peak region shown in Fig. 2(a) and have various squark masses and decay patterns. For instance, only 81 points remain if both \( \Delta M_{\text{min}} = m_{\text{min}(\tilde{q})_{1st/2nd\, \text{gen}}} - m_{\tilde{\chi}_1^0} \) are required to be within the top-quark mass, \( m_t \), and that \( m_{\tilde{q}_{1st/2nd\, \text{gen}}} \sim m_{\tilde{\chi}_1^0} \) \( \ll m_{\tilde{\gamma}_{3rd\, \text{gen}}} \geq 2 \) TeV; see the example point shown in Fig. 2(b) whose sparticle and Higgs boson masses are given in Tab. II (spectrum Z). These would be difficult to exclude at the LHC due to the fact that SUSY events from such a scenario would be mainly buried under the huge QCD background and would, as a result of the trigger system design to suppress QCD background, not be captured by the detectors.

\[
\Delta M_{\text{min}} = m_{\text{min}(\tilde{q})} - m_{\tilde{\chi}_1^0}
\]

**Example pMSSM points.** For illustration, apart from the spectrum shown in Fig. 2(b), four other example spectra labelled A, B, C, and D, are shown in Fig. 2 and Tab. I. For spectrum A, SUSY production would be dominated by the light squarks production which would readily decay to the neutralino and ordinary jets. Spectrum B has an interesting feature that all produced squarks and gluinos would decay to the LSP via the the lightest squark, the sbottom, so there would be possible for b-tagging of jets. The dominant leading order(LO) and next-to-leading order(NLO) sparticle production cross sections for 7 TeV proton-proton collider and selected decay branching ratios, respectively computed using **prospino** [17] v2.1 and **SUSY-HIT** [18] packages, for the spectrum B scenario are summarised in Tab. II. Unlike A and B, spectrum C and D would have SUSY-initiated leptons in events final states.

The \( p_T \) and missing \( E_T \) features are extracted by performing a generator-level analysis on SUSY events from 7 TeV LHC simulations for each of the spectrum A, B, C and D. We use **Herwig++-2.5** [19] to generate 10000 SUSY events from each of the spectra points. The four-vectors of particles energy and three-momenta are passed on to **fastjet-2.4.2** [20] for obtaining and sorting the jets from events final states. The anti-\( k_T \) jet clustering algorithm with distance parameter \( R = 0.4 \) is used. The generator level cuts applied are: particle pseudorapidity \( |\eta| < 5.0 \), and transverse momentum \( p_T^{\text{part}} > 1.0 \) GeV. Leptons are required to have \( |\eta| < 2.5 \) and \( p_T^{\text{lep}} > 1.5 \) GeV, while for jets \( p_T^{\text{jets}} > 1.5 \) GeV. The distributions of leading jets \( p_T \) in events with 0-lepton and two or more jets are shown in
$\tilde d_L \sim \tilde s_L$
$\tilde u_L \sim \tilde c_L$
$\tilde b_1$
$\tilde t_1$
$\tilde c_L \sim \tilde \mu_L$
$\tilde \nu_e \sim \tilde \nu_\tau$
$\tilde \tau_1$

| Sparticles | A | B | C | D | Z |
|------------|---|---|---|---|---|
| $\tilde d_L \sim \tilde s_L$ | 507 | 579 | 2516 | 971 | 507 |
| $\tilde u_L \sim \tilde c_L$ | 489 | 579 | 2521 | 986 | 497 |
| $\tilde b_1$ | 1874 | 318 | 601 | 525 | 2450 |
| $\tilde t_1$ | 982 | 1466 | 555 | 498 | 2068 |
| $\tilde c_L \sim \tilde \mu_L$ | 142 | 642 | 1579 | 584 | 1091 |
| $\tilde \nu_e \sim \tilde \nu_\tau$ | 1415 | 627 | 1578 | 586 | 1091 |
| $\tilde \tau_1$ | 1778 | 926 | 1455 | 697 | 1130 |
| $\tilde \tau_2$ | 2199 | 1226 | 2753 | 1636 | 1602 |
| $\tilde \nu_e \sim \tilde \nu_\tau$ | 142 | 642 | 1579 | 584 | 1091 |
| $\tilde \tau_1$ | 1778 | 926 | 1455 | 697 | 1130 |
| $\tilde \tau_2$ | 2199 | 1226 | 2753 | 1636 | 1602 |

TABLE I: Sparticle spectrum and Higgs bosons for the example pMSSM points A, B, C, D and Z. All masses are in GeV.

| Process | Branching ratio |
|---------|-----------------|
| $\tilde u_L \rightarrow \tilde g \ u$ | 0.995 |
| $\tilde d_L \rightarrow \tilde g \ d$ | 0.995 |
| $\tilde b_1$ | 1874 | 318 | 601 | 525 | 2450 |
| $\tilde t_1$ | 982 | 1466 | 555 | 498 | 2068 |
| $\tilde c_L \sim \tilde \mu_L$ | 142 | 642 | 1579 | 584 | 1091 |
| $\tilde \nu_e \sim \tilde \nu_\tau$ | 1415 | 627 | 1578 | 586 | 1091 |
| $\tilde \tau_1$ | 1778 | 926 | 1455 | 697 | 1130 |
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| $\tilde \nu_e \sim \tilde \nu_\tau$ | 142 | 642 | 1579 | 584 | 1091 |
| $\tilde \tau_1$ | 1778 | 926 | 1455 | 697 | 1130 |
| $\tilde \tau_2$ | 2199 | 1226 | 2753 | 1636 | 1602 |

TABLE II: Selected sparticle leading order (LO) and next-to-leading order (NLO) production cross sections and decay branching ratios for the example pMSSM spectrum B scenario for which b-tagging of jets can be implemented.

Fig. 4(a). The distributions of the events missing $E_T$ and leptons’ $p_T^{lep}$ are shown in Fig. 4(b).

Triggers/Cuts. It is mainly expected SUSY collider events would end with high-$p_T$ jets and large missing $E_T$. The triggers or kinematic cuts used in the SUSY search analysis [6] effectively requires reconstructed jet to have $p_T > 120$ GeV and events with more than 100 GeV of missing $p_T$. These cuts would have thrown away most of scenario A and B events as background events (see Fig. 4) if actually produced during the collider run. In the absence of discovery from the 2010 LHC data and the increase in luminosity in current runs the cuts would be increasing (perhaps to more that 400 GeV on the jets $p_T$ cuts) in order to be more conservative in events selection. As a result MSSM spectra which lead to soft jets, soft leptons and/or low, compared to what is usually assumed, missing transverse momentum would be lost forever if produced at the LHC.
FIG. 3: Plots (a) and (b) show pictures of the example pMSSM spectrum A and B respectively (see Tab. II for the mass magnitudes.) that have an LSP quasi-degeneracy with 1st/2nd generation type lightest squark and hence would be difficult to trigger by the LHC 2010 and current trigger systems. The other squarks and/or gluino are much heavier than 1 TeV so have relatively negligible production cross sections. The search for spectrum A could be via 0-lepton plus jets plus missing $E_T$ channel which is same for spectrum B but with additional possibility for b-jets. Similarly spectrum C and D, shown on plot (b) and (c) respectively, are example cases for the search channel involving b-jets and leptons. In all the plots solid, dashed and dotted lines approximately represent decays with branching ratios respectively greater or equal to 0.1, 0.01 and 0.001 obtained from Herwig v6.510 [16] interfaced with Isajet v7.72.
FIG. 4: This figure shows the missing transverse momentum $p_T$ of leading jets, plot (a), and missing $E_T$, plot (b), from generator-level analyses for the example pMSSM spectra shown in in Fig. 3. The leptons $p_T$ for spectra C and D are also shown on the second plot.

Conclusions. The pMSSM posterior samples have MSSM spectra with several distinct characteristics. A large splitting between the lightest squark and the LSP is usually assumed as the main characteristic feature of SUSY spectrum. This scenario is indeed very probable as can be seen from Fig. 2(a). However, there is a significant region where the mass difference is small (comparable to the top-quark mass) as in the peak in $\Delta M_{min}$ around 10 to 25 GeV. A SUSY scenario with the latter pattern would be difficult to exclude by the LHC experiments due to the nature of the detectors’ trigger system. One can conclude that, the LHC with current running parameters cannot rule out the MSSM unless special trigger systems are commissioned or if a Higgs boson is found with mass outside the generic MSSM prediction. In the case where a Higgs boson is found and with mass in the range valid for the MSSM points then the discovery or exclusion of models illustrated here would most likely have to await the operation of a linear collider [2].

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