IRis

Northeastern University

Physics Faculty Publications

Department of Physics

December 18, 2007

# Landscape of supersymmetric particle mass hierarchies and their signature space at the CERN large hadron collider

Daniel Feldman
*Northeastern University*

Zuowei Liu
*Northeastern University*

Pran Nath
*Northeastern University*

Recommended Citation

Feldman, Daniel; Liu, Zuowei; and Nath, Pran, "Landscape of supersymmetric particle mass hierarchies and their signature space at the CERN large hadron collider" (2007). *Physics Faculty Publications.* Paper 456.

This work is available open access, hosted by Northeastern University.

# Landscape of Supersymmetric Particle Mass Hierarchies and their Signature Space at the CERN Large Hadron Collider

Daniel Feldman, Zuowei Liu, and Pran Nath

*Department of Physics, Northeastern University, Boston, Massachusetts 02115, USA*

(Received 13 July 2007; published 18 December 2007)

The minimal supersymmetric standard model with soft breaking has a large landscape of supersymmetric particle mass hierarchies. This number is reduced significantly in well-motivated scenarios such as minimal supergravity and alternatives. We carry out an analysis of the landscape for the first four lightest particles and identify at least 16 mass patterns, and provide benchmarks for each. We study the signature space for the patterns at the CERN Large Hadron Collider by analyzing the lepton+ (jet $\geq 2$) + missing $P_T$ signals with 0, 1, 2, and 3 leptons. Correlations in missing $P_T$ are also analyzed. It is found that even with 10 $\mathrm{fb}^{-1}$ of data a significant discrimination among patterns emerges.

DOI: 10.1103/PhysRevLett.99.251802 PACS numbers: 12.60.Jv, 13.85.Qk, 14.80.Ly

*Introduction.*—The search for supersymmetric particles (sparticles) is one of the major goals of the current experiments at the Fermilab Tevatron collider and at the CERN Large Hadron Collider (LHC) which will come on line in the very near future. Central to the discovery of sparticles is the way their masses align in a hierarchical mass pattern as such alignment has strong influences on the ability of experiments to probe signatures emerging from sparticle production at colliders. There are 32 supersymmetric masses in the minimal supersymmetric standard model (MSSM) including the Higgs bosons. With the sum rule constraints in the gaugino and Higgs sectors but without any phenomenological constraints the number of mass parameters is 27. Using Stirling's formula [$n! \sim \sqrt{2\pi n}(n/e)^n$] one finds at least $O(10^{28})$ possibilities for hierarchical patterns. Although this number does not rise to the level of $O(10^{1000})$ as in string landscapes, it is still an impressive number and can be construed as a mini landscape in this context. The number of possibilities is drastically reduced in the minimal supergravity grand unified model mSUGRA [1,2] although no classification has ever been made and the precise number of possibilities is not known. In this Letter we undertake this cartography. To keep the analysis under control we focus on mass hierarchies for the first four sparticles excluding the lightest Higgs particle. Such a cartography is important for devising strategies for analyzing data from the LHC.

Our analysis, based on a large scan of the mSUGRA parameter space, reveals at least 16 hierarchical patterns for the first four sparticles, of which a significant number do not appear in conventional benchmarks such as Snowmass points [3] (these are a representative sample of points in the MSSM parameter space called benchmarks which are used for theoretical predictions of supersymmetry at present and future colliders) and Post-WMAP benchmarks [4] [which is an updated version of previous benchmarks taking account of the relic density constraints from data from the Wilkinson microwave anisotropy probe (WMAP)].

The analysis is carried out in the mSUGRA model (for recent works see [5–7]). mSUGRA is an effective theory below the grand unification scale $M_G$ and its parameter space is defined by the parameters ($m_0$, $m_{1/2}$, $A_0$, $\tan\beta$, $\mathrm{sgn}\mu$) where ($m_0$, $m_{1/2}$) are the universal scalar and gaugino masses, $A_0$ is the universal trilinear coupling, and $\tan\beta$ is the ratio of the vacuum expectation values (VEVs) of the two neutral Higgs fields in MSSM, and $\mathrm{sgn}\mu$ is the sign of $\mu$, where $\mu$ is the Higgs mixing parameter. In the analysis we impose the relic density constraints on the abundance of the lightest neutralino ($\tilde{\chi}_1^0$) consistent with the WMAP: $0.0855 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.1189$ [8], and other experimental constraints as follows: $2.83 \times 10^{-4} < \mathrm{BR}(b \to s\gamma) < 4.63 \times 10^{-4}$ [where the SUSY loop contributions to this decay can be comparable to the corrections in the standard model (SM)], $m_h > 100$ GeV, $m_{\tilde{\chi}_1^\pm} > 104.5$ GeV, $m_{\tilde{t}_1} > 101.5$ GeV, $m_{\tilde{\tau}_1} > 98.8$ GeV, where $h$, $\tilde{\chi}_1^\pm$, $\tilde{t}_1$, $\tilde{\tau}_1$ are the lightest Higgs boson, chargino, top squark, and stau, respectively.

For the calculations of the relic density of $\tilde{\chi}_1^0$ we use MICROMEGAS version 2.0.1 [9] with sparticle and Higgs boson masses calculated using the package SUSPECT 2.3 of Ref. [10]. We have investigated other softwares [11–17] and find significant agreement among them. For each mSUGRA model point that survives the constraints mentioned above, we compute the sparticle spectrum, mixing angles, etc., The resultant SUSY Les Houches accord [18] file is called by the PGS4 olympics main Fortran file, which simulates the LHC detector effects and event reconstruction (see [19] for detailed discussion). For the computation of SUSY production cross sections and branching fractions we employ PYTHIA 6.4.11 [20], which simulates hadronization and event generation from the fundamental SUSY Lagrangian. SUSY cross section and events were generated using all 32 sparticles in this analysis. We have cross checked sample points with PROSPINO [21] which computes the next-to-leading order cross sections for the production of supersymmetric particles at hadron colliders,

 © 2007 The American Physical Society

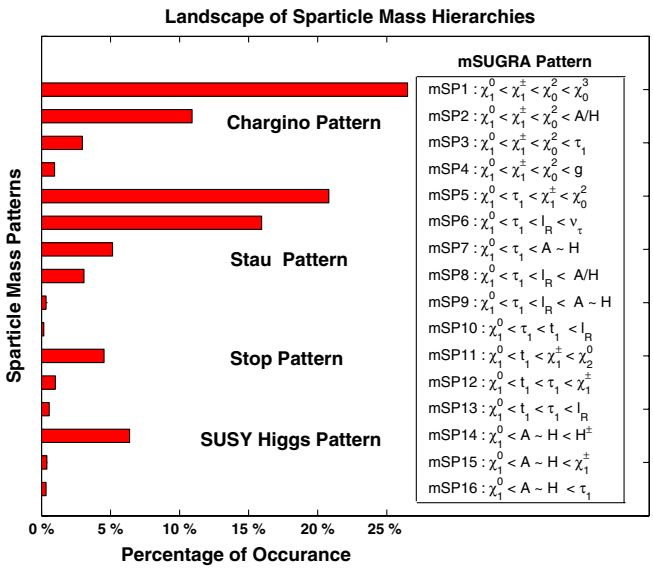


FIG. 1 (color online). The surviving hierarchical patterns in the mSUGRA landscape with constraints as discussed in the text. In mSP14,15,16 the $\tilde{\chi}_1^0$ and the Higgs bosons ($A$, $H$) are sometimes seen to switch.

and TAUOLA [22] is called by PGS4 for the calculation of tau branching fractions. With PGS4 we use the Level 1 ($L1$) triggers based on the compact muon solenoid detector (CMS) specifications [23] and the LHC detector card.

*Landscape of mass hierarchies.*—We focus on the patterns for the four lightest particles (discounting the lightest Higgs particle) as they would to a great degree influence the discovery of SUSY while keeping the size of the landscape in check. We have carried out a mapping of the mSUGRA parameter space with $2 \times 10^6$ models with $\mu > 0$ and the parameter range given in Fig. 2 via Monte Carlo scan with flat priors under the constraint of radiative breaking of the electroweak symmetry. 55 hierarchical patterns for the first four particles were seen which are reduced to 16 with relic density and collider constraints. We label these as mSUGRA pattern 1 (mSP1) through mSUGRA pattern 16 (mSP16) as shown in Fig. 2. The frequency of their occurrence is exhibited in Fig. 1. A significant set of the mSP1 points lie in the region $|A_0/m_0| < 1$ and correspond to the hyperbolic branch/ focus point (HB/FP) region [24]. In Table I we also give illustrative, mass pattern motivated, benchmark points, for each of the mass patterns mSP1-mSP16 chosen with a moderate to light SUSY scale ($Q = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$) and to show the effects of scanning over the parameter space. Most of the mSP patterns do not appear in previous works. Thus all the Snowmass mSUGRA points (labeled SPS) [3] are only of types mSP(1,3,5,7) as follows: (SPS1a, SPS1b, SPS5) $\rightarrow$ mSP7, SPS2 $\rightarrow$ mSP1, SPS3 $\rightarrow$ mSP5, and (SPS4, SPS6) $\rightarrow$ mSP3. Regarding the Post-WMAP points [4] one has the following mapping ($A'$, $B'$, $C'$, $D'$, $G'$, $H'$, $J'$, $M'$) $\rightarrow$ mSP5, ($I'$, $L'$) $\rightarrow$ mSP7, $E' \rightarrow$ mSP1, $K' \rightarrow$ mSP6. We observe more patterns owing to the sampling of larger regions of the parameter space especially in $A_0$.

*Mass hierarchies and their signatures.*—We have carried out analyses of the lepton + jet signals to determine if such signals can discriminate among the patterns. We have analyzed 0, 1, 2 and 3 leptonic events (lepton $= L, \tau$; $L = e, \mu$) with and without jets. Our Standard Model backgrounds are checked against two CMS notes [25] and our results lie within the error bars of these analyses. Some analyses of this type exist [26–29] but not in the context of mass hierarchies analyzed here. We give now the details of the analysis. In Fig. 3, we use 902 sample models from Fig. 2 (corresponding to a scan of $10^6$ points as it contains all the essential features of the larger scan and is visually clearer) to generate SUSY signals through PGS4 using 10 fb$^{-1}$ of integrated luminosity. In Fig. 3(a) an analysis of the 1 L + (jets $\geq 2$) vs 0 L + (jets $\geq 2$) events is given along with the discovery limit for each of these model points. Here one is beginning to see discrimination among patterns. Specifically the signals of mSP11-mSP13 lie sig-

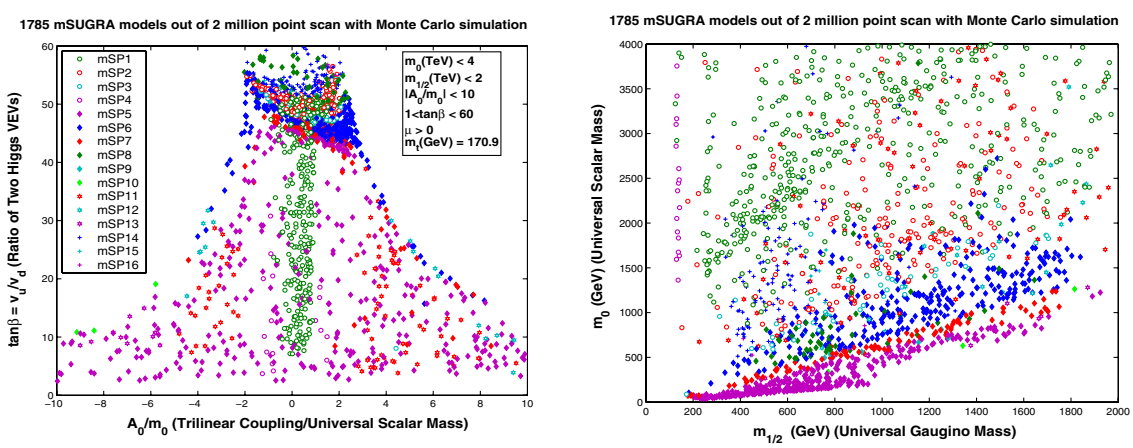


FIG. 2 (color online). The plots exhibit the 16 mass patterns (see Fig. 1) in $\tan\beta - A_0/m_0$ and $m_0 - m_{1/2}$ planes among the 1785 surviving points out of a random scan using $2 \times 10^6$ models with flat priors in the ranges indicated in the left figure panel consistent with the constraints discussed in the text.

TABLE I. Benchmarks using SUSPECT 2.3 with one point for each mass pattern mSP1-mSP16. Also given are the neutralino LSP [lightest SUSY ($R$ parity odd) particle], and the lightest charged particle (LCP) masses. We take $\mu > 0$, $m_b^{\overline{\rm MS}}(m_b) = 4.23$, $\alpha_s^{\overline{\rm MS}}(M_Z) = .1172$, and $m_t$(pole) = 170.9 GeV. At least five LCP from these benchmarks will be accessible at the International Linear Collider (ILC).

| mSUGRA | $m_0$ (GeV) | $m_{1/2}$ (GeV) | $A_0$ (GeV) | tan$\beta$ | $\mu(Q)$ (GeV) | LSP (GeV) | LCP (GeV) |
|---|---|---|---|---|---|---|---|
| mSP1: | 2001 | 411 | 0 | 30 | 216 | 156.1 | 202.6 |
| mSP2: | 1125 | 614 | 2000 | 50 | 673 | 256.7 | 483.1 |
| mSP3: | 741 | 551 | 0 | 50 | 632 | 230.5 | 434.7 |
| mSP4: | 1674 | 137 | 1985 | 18.6 | 533 | 54.3 | 106.9 |
| mSP5: | 111 | 531 | 0 | 5 | 679 | 217.9 | 226.3 |
| mSP6: | 245 | 370 | 945 | 31 | 427 | 148.6 | 156.8 |
| mSP7: | 75 | 201 | 230 | 14 | 246 | 74.8 | 100.2 |
| mSP8: | 1880 | 877 | 4075 | 54.8 | 1141 | 373.1 | 379.6 |
| mSP9: | 667 | 1154 | −125 | 51 | 1257 | 499.2 | 501.8 |
| mSP10: | 336 | 772 | −3074 | 10.8 | 1695 | 329.2 | 331.7 |
| mSP11: | 871 | 1031 | −4355 | 10 | 2306 | 447.1 | 491.5 |
| mSP12: | 1371 | 1671 | −6855 | 10 | 3593 | 741.2 | 791.8 |
| mSP13: | 524 | 800 | −3315 | 15 | 1782 | 342.7 | 383.8 |
| mSP14: | 1036 | 562 | 500 | 53.5 | 560 | 236.2 | 399.1 |
| mSP15: | 1113 | 758 | 1097 | 51.6 | 724 | 321.1 | 595.9 |
| mSP16: | 525 | 450 | 641 | 56 | 484 | 184.6 | 257.9 |

nificantly lower than the others. In Fig. 3(b) we give an analysis of $1\tau + 1$ L + (jets $\geq 2$) vs 2 L + (jets $\geq 2$). We see that relative to Fig. 3(a) there is now more dispersion among the patterns and furthermore the SM background is also significantly smaller in this case. Finally, in Fig. 4(a) we have a plot of OS(opposite sign)$2\tau$ + (jets $\geq 2$) vs 3 L + (jets $\geq 2$). Here we see that the dispersion among models is even larger and the SM background is even smaller. Thus, we can see visually the effect of the SM background shrinking, the signal relative to the background getting stronger and the discrimination among the patterns increasing as we move from Fig. 3(a) to 4(a). As expected the trileptonic signal [30] is the strongest with the least background. The missing $P_T$ cuts can also help discriminate among models. In Fig. 4(b) we give an analysis of OS $2\tau$ + (jets $\geq 2$) vs missing $P_T$ cut. One may note the very significant dispersion among the patterns with missing $P_T$ cut.

*Conclusion.*—The discovery of supersymmetry is one of the major goals of the current effort at the Tevatron and in experiments with the CMS and the ATLAS detectors in the very near future at the LHC. When sparticles are produced the signatures of their production will be determined by their hierarchical mass patterns. In this Letter we have investigated hierarchical mass patterns for the four lightest sparticles within one of the leading candidate theories—the mSUGRA model. The analysis shows 16 such patterns consistent with all the current experimental constraints and

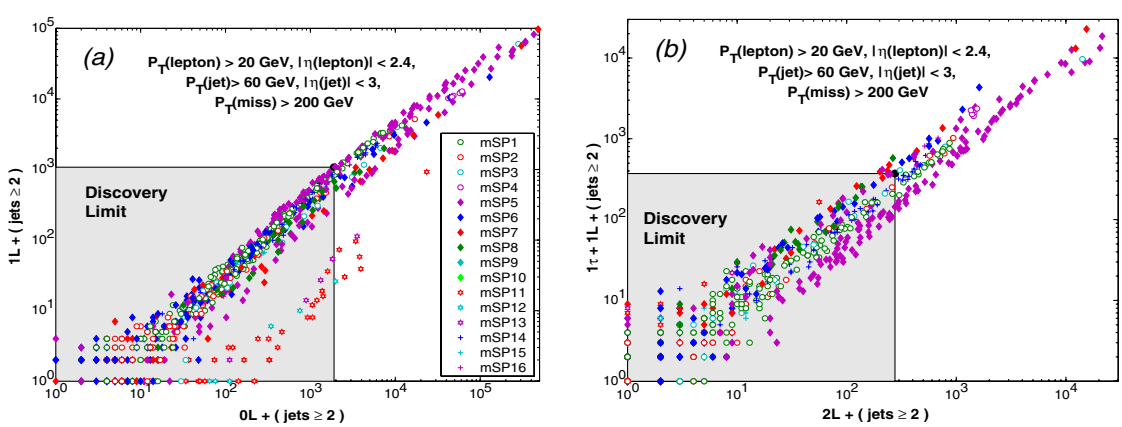


FIG. 3 (color online). Leptons + $n$ jets ($n \geq 2$) signatures originating from 16 patterns with $P_T$ and rapidity $\eta$ cuts as shown where (a) single-lepton vs no-lepton; (b) single-lepton plus single-$\tau$ vs dilepton. the shaded regions in (a)–(b) are due to SM backgrounds $t\bar{t}$, $b\bar{b}$, DiJets, Drell-Yan, and $Z$, $W$ production. The discovery limits are max$\{5\sqrt{N_{\rm SM}}, 10\}$, where $N_{\rm SM}$ is the standard model background.

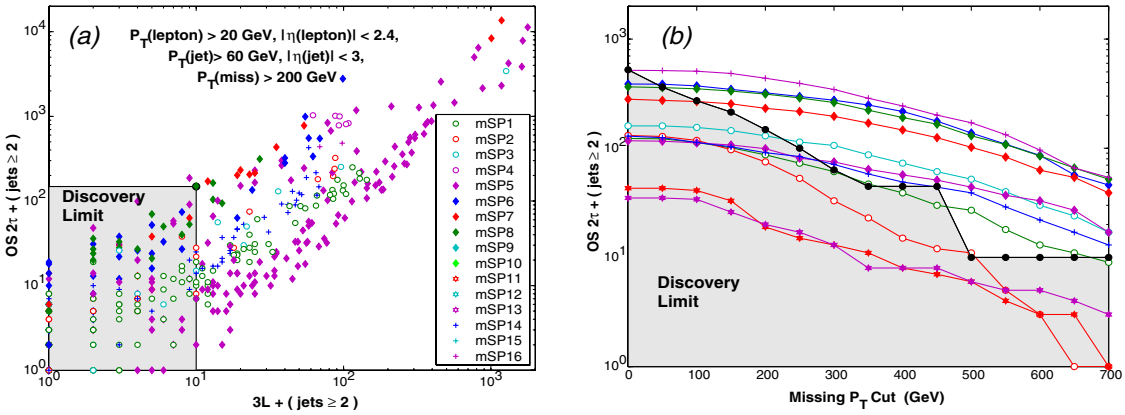


FIG. 4 (color online). The number of $\tau^+\tau^-$ events vs (a) trilepton events, and vs (b) $P_T^{\rm miss}$ cut. In (b) the post trigger level cuts are as in Figs. 3 and 4(a) except for the $P_T^{\rm miss}$ cut. Each curve is for one point for each mSP, chosen such that their PGS4 data files are nearly of the same (5MB) size.

most of these patterns are new not discussed in the previous literature. We also carried out an analysis of signatures of these patterns which include (0,1,2,3) leptons + $n$ jets ($n \geq 2$) signals and also missing transverse momentum ($P_T$) signals. We conclude that even with 10 fb$^{-1}$ of luminosity significant dispersion can be seen among many mSP signatures and thus discrimination among patterns is possible. Similar analyses are desirable for other plausible soft breaking scenarios beyond mSUGRA.

We thank Brent Nelson and George Alverson for discussions. This work is supported in part by NSF Grant No. PHY-0456568.

[1] A. H. Chamseddine, R. Arnowitt, and P. Nath, Phys. Rev. Lett. **49**, 970 (1982); P. Nath, R. Arnowitt, and A. H. Chamseddine, Nucl. Phys. **B227**, 121 (1983).
[2] R. Barbieri, S. Ferrara, and C. A. Savoy, Phys. Lett. B **119**, 343 (1982); L. J. Hall, J. D. Lykken, and S. Weinberg, Phys. Rev. D **27**, 2359 (1983).
[3] B. C. Allanach *et al.*, Eur. Phys. J. C **25**, 113 (2002).
[4] M. Battaglia, A. De Roeck, J. R. Ellis, F. Gianotti, K. A. Olive, and L. Pape, Eur. Phys. J. C **33**, 273 (2004).
[5] A. Djouadi, M. Drees, and J. L. Kneur, J. High Energy Phys. 03 (2006) 033; U. Chattopadhyay, D. Das, A. Datta, and S. Poddar, Phys. Rev. D **76**, 055008 (2007); M. E. Gomez, T. Ibrahim, P. Nath, and S. Skadhauge, Phys. Rev. D **72**, 095008 (2005).
[6] R. Arnowitt *et al.*, Phys. Lett. B **649**, 73 (2007); V. Khotilovich *et al.*, *ibid.* **618**, 182 (2005).
[7] J. R. Ellis, S. Heinemeyer, K. A. Olive, and G. Weiglein, J. High Energy Phys. 05 (2006) 005.
[8] D. N. Spergel *et al.*, Astrophys. J. Suppl. Ser. **170**, 377 (2007).
[9] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, Comput. Phys. Commun. **176**, 367 (2007).
[10] A. Djouadi, J. L. Kneur, and G. Moultaka, Comput. Phys. Commun. **176**, 426 (2007).
[11] F. E. Paige, S. D. Protopopescu, H. Baer, and X. Tata, arXiv:hep-ph/0312045.
[12] W. Porod, Comput. Phys. Commun. **153**, 275 (2003).
[13] B. C. Allanach, Comput. Phys. Commun. **143**, 305 (2002).
[14] H. Baer, J. Ferrandis, S. Kraml, and W. Porod, Phys. Rev. D **73**, 015010 (2006).
[15] G. Belanger *et al.*, Phys. Rev. D **72**, 015003 (2005).
[16] B. C. Allanach, A. Djouadi, J. L. Kneur, W. Porod, and P. Slavich, J. High Energy Phys. 09 (2004) 044.
[17] B. C. Allanach, S. Kraml, and W. Porod, J. High Energy Phys. 03 (2003) 016; arXiv:hep-ph/0207314.
[18] P. Skands *et al.*, J. High Energy Phys. 07 (2004) 036.
[19] http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm.
[20] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05, (2006) 026.
[21] W. Beenakker *et al.*, Phys. Rev. Lett. **83**, 3780 (1999).
[22] S. Jadach, Z. Was, R. Decker, and J. H. Kuhn, Comput. Phys. Commun. **76**, 361 (1993).
[23] CMS Collaboration, CERN/LHCC Report No. 2006-001, 2006.
[24] K. L. Chan, U. Chattopadhyay, and P. Nath, Phys. Rev. D **58**, 096004 (1998); J. L. Feng, K. T. Matchev, and T. Moroi, Phys. Rev. Lett. **84**, 2322 (2000); H. Baer, C. Balazs, A. Belyaev, T. Krupovnickas, and X. Tata, J. High Energy Phys. 06 (2003) 054.
[25] D. J. Mangeol and U. Goerlach, CMS NOTE 2006/096; M. Chiorboli, M. Galanti, and A. Tricomi, CMS NOTE 2006/133.
[26] N. Arkani-Hamed, G. L. Kane, J. Thaler, and L. T. Wang, J. High Energy Phys. 08 (2006) 070.
[27] J. P. Conlon *et al.*, J. High Energy Phys. 08 (2007) 061.
[28] G. L. Kane, P. Kumar, and J. Shao, J. Phys. G **34**, 1993 (2007).
[29] H. Baer, V. Barger, G. Shaughnessy, H. Summy, and L. t. Wang, Phys. Rev. D **75**, 095010 (2007).
[30] P. Nath and R. Arnowitt, Mod. Phys. Lett. A **2**, 331 (1987); R. Arnowitt, R. M. Barnett, P. Nath, and F. Paige, Int. J. Mod. Phys. A **2**, 1113 (1987); H. Baer, C. h. Chen, F. Paige, and X. Tata, Phys. Rev. D **50**, 4508 (1994); V. D. Barger, C. Kao, and T. j. Li, Phys. Lett. B **433**, 328 (1998).