The MSSM with Large Gluino Mass

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Abstract

We study the Minimal Supersymmetric Standard Model (MSSM) with large gluino mass $m_{\tilde{g}} \gg 1 \text{ TeV}$. In particular, we discuss the LHC supersymmetry discovery signatures with $n \text{ leptons} + \text{jets} + E_T^{\text{miss}}$, $n \geq 0$ for the MSSM with large gluino mass. We show that for some relations among squark and neutralino masses leptonic signatures with $n \text{ leptons} + \text{jets} + E_T^{\text{miss}}$, $n \geq 1$ do not allow to discover supersymmetry at the LHC and the only supersymmetry discovery signature remains the signature with $\text{no leptons} + \text{jets} + E_T^{\text{miss}}$. Moreover, for LSP mass close to squark masses the LHC discovery potential for this signature is strongly reduced.
One of the supergoals of the Large Hadron Collider (LHC) \[1\] is the discovery of supersymmetry \[2\]. The simplest supersymmetric generalization of the Standard Model (SM) \[3\] is the Minimal Supersymmetric Standard Model (MSSM) \[4\]. In the MSSM all sparticle masses are arbitrary that complicates the analysis. In the Minimal Supergravity model (mSUGRA) \[4\] the universality of the different soft mass parameters at the Grand Unified Theory (GUT) scale $M_{GUT} \approx 2 \cdot 10^{16}$ GeV is postulated. The renormalization group equations are used to relate GUT and electroweak scales. The equations for the determination of nontrivial minimum of the electroweak potential are used to decrease the number of unknown parameters by two. So mSUGRA model depends on five unknown parameters. Despite the simplicity of the mSUGRA model it is a very particular model. Moreover at present there are some string inspired models with nonuniversal sfermion and gaugino masses \[5\]. One loop quadratic correction to the Higgs boson mass at the SM is given by the formula \[7\]
\[\delta m^2_h = \alpha_t \Lambda^2_t + \alpha_g \Lambda^2_g + \alpha_h \Lambda^2_h,\]
where
\[\alpha_t = \frac{3m^2_t}{4\pi^2 v^2}, \quad \alpha_g = -\frac{6m^2_W + 3m^2_Z}{16\pi^2 v^2}, \quad \alpha_h = -\frac{3m^2_h}{16\pi^2 v^2}\]
and $\Lambda_i$ are the ultraviolet cutoffs of the momenta of virtual top quarks, gauge bosons, and the Higgs boson itself. From the naturalness condition $\delta m^2_h \leq m^2_h$ one can find that $\Lambda_i \leq O(1)$ TeV. One loop naturalness condition (1) predicts that the masses of stop quarks and supersymmetric analogs of electroweak gauge bosons $W$ and $Z$ have to be lighter than $O(1)$ TeV. It should be stressed that gluon corrections to the Higgs boson mass arise only at two loop level and as a consequence from the naturalness condition gluino mass has to be lighter than $O(10)$ TeV, i.e. it could be much higher than 1 TeV. Also from the naturalness point of view supersymmetric analogs of the first and the second generation quarks and leptons can have masses $O(10)$ TeV since the corresponding Yukawa couplings are small.

In this note we study the MSSM with large gluino mass $m_{\tilde{g}} \gg m_{\tilde{q}}$ \[4\]. Namely, we study the LHC supersymmetry discovery signatures with $n \geq 0$ leptons + jets + $E^\text{miss}_T$ for the MSSM model with large gluino mass. We show that for some relations among squark and gluino masses, the LHC signatures with $n \geq 1$ leptons + jets + $E^\text{miss}_T$ do not allow to discover supersymmetry and the only supersymmetry discovery signature remains the signature with no leptons + jets + $E^\text{miss}_T$. Moreover, for LSP mass close to squark masses, LHC supersymmetry discovery potential for this signature is strongly reduced.

The gluino and squark production cross sections are the biggest ones compared to slepton or gaugino cross sections. Therefore gluinos and squarks production at the LHC are the most interesting reactions from the supersymmetry discovery point of view with the cross sections around 1 pb for squark and gluino masses around 1 TeV. The squark and gluino decays produce missing transverse energy from the LSP plus multiple jets and varying numbers of leptons from the intermediate gauginos. It is natural to divide the signatures used for the squark and gluino detections into the following two groups:

1 Phenomenological consequences of the MSSM with non mSUGRA spectrum were studied in Refs \[9\], \[10\], \[11\].

2 Note that the MSSM with large gluino mass is an opposite case to the ‘focus point’ mSUGRA scenario \[5\] with $m_\theta \gg m_{1/2}$ (squark and slepton masses are large).
Following modifications in mass spectrum of the point LM1

4 leptons do not allow to discover supersymmetry.

The main conclusion [8] is that for the mSUGRA model the LHC (CMS) will be able to discover cascade decay

\[ \bar{g} \to q' \bar{q} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to W^\pm \tilde{\chi}_1^0 \to l^\pm \nu \tilde{\chi}_1^0, \]  

where \( l \) stands for both \( e \) and \( \mu \). Opposite sign dilepton events can arise also as a result of cascade decay

\[ \bar{g} \to q \bar{q} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to Z \tilde{\chi}_1^0 \to l^+ l^- \tilde{\chi}_1^0. \]  

The main conclusion [8] is that for the mSUGRA model the LHC (CMS) will be able to discover supersymmetry with squark or gluino masses up to \( (2-2.5) \text{ TeV} \) for \( L_{tot} = 30 \text{ fb}^{-1} \). The most powerful signature for squark and gluino detection in the mSUGRA model is the signature with multijets and \( E_T^{miss} \) (signature a).

Note that the branchings of the decays \( \tilde{\chi}_2^0 \to l^+ l^- \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to l^\pm \nu \tilde{\chi}_1^0 \) leading to the signatures with leptons depend on the relation among \( m_{\tilde{\chi}_2^0} \) and \( m_{\tilde{\chi}_1^0} \). For some relations among supersymmetry masses the branchings into leptons are suppressed and as a consequence the signatures with leptons do not allow to discover supersymmetry.

In this note we considered the modified CMS test point LM1 [3]. Namely, we considered the following modifications in mass spectrum of the point LM1 [4]:

a. no leptons + jets + \( E_T^{miss} \) events,
b. \( n \) leptons + jets + \( E_T^{miss} \), \( n \geq 1 \).

Multileptons arise as a result of the cascade decays of neutralinos and charginos into \( W^- \) and \( Z \)-bosons with subsequent decays of \( W^- \) and \( Z \)-bosons into leptonic modes. For instance, the same sign and opposite sign dilepton events arise as a result of the cascade decay

\[ \bar{g} \to q' \bar{q} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to W^\pm \tilde{\chi}_1^0 \to l^\pm \nu \tilde{\chi}_1^0, \]  

where \( l \) stands for both \( e \) and \( \mu \). Opposite sign dilepton events can arise also as a result of cascade decay

\[ \bar{g} \to q \bar{q} \tilde{\chi}_1^0, \tilde{\chi}_1^0 \to Z \tilde{\chi}_1^0 \to l^+ l^- \tilde{\chi}_1^0. \]  

The coupling constants and cross sections for SUSY processes were calculated with PYTHIA code [13]. We used the full simulation results of Ref.[8] for the estimation of background events. The CMS simulation codes CMSSW [13] in fast mode were used.

For the signature with two opposite charge and the same flavour leptons: \( l^+ l^- + E_T^{miss} \) we have used the following selection cuts [8]:
cut on leptons: \( p_T^{lep} > 20 \text{ GeV}, |\eta| < 2.4 \), lepton isolation within \( \Delta R < 0.3 \) cone,

\footnote{For mSUGRA test point LM1 \( m_0 = 60 \text{ GeV}, m_{1/2} = 250 \text{ GeV}, \tan \beta = 10, A = 0, sign \mu = +. \)}

\footnote{For test point LM1 the masses of some supersymmetric particles are: \( m_{\tilde{\chi}_1^0} = 99.6 \text{ GeV}, m_{\tilde{\chi}_2^0} = 186.4 \text{ GeV}, m_{\tilde{g}} = 579.5 \text{ GeV}, m_{\tilde{\chi}_L} = 195.7 \text{ GeV}, m_{\tilde{\chi}_R} = 122 \text{ GeV}, m_{\tilde{U}_L} = 554 \text{ GeV}, m_{\tilde{D}_R} = 530 \text{ GeV}. \)
cut on missing transverse energy: $E_{\text{T}}^{\text{miss}} > 300$ GeV.

For integrated luminosity $L_{\text{tot}} = 10$ fb$^{-1}$ the number of background events is $N_{\text{bkg}} = 93$ [8]. For points LM1 and (a1 - f1) the number of signal events and the significance $S_{c12} = 2(\sqrt{N_{\text{sig}}} + N_{\text{bkg}} - \sqrt{N_{\text{bkg}}})$ [15] are presented in Table 1.

| Point | $N_{\text{sig}}$ | $S_{c12}$ |
|-------|-----------------|-----------|
| LM1   | 91              | 13.9      |
| a1    | 15              | 2.1       |
| b1    | 7               | 1.0       |
| c1    | 3               | 0.4       |
| d1    | 29              | 3.8       |
| e1    | 4               | 0.6       |
| f1    | 1               | 0.1       |

Table 1: The number of signal events and significance $S_{c12}$ for points LM1 and (a1 - f1) at $L_{\text{tot}} = 1$ fb$^{-1}$, dilepton signature $l^+l^- + E_{\text{T}}^{\text{miss}}$.

\[ E_{\text{T}}^{\text{miss}} \geq 200 \text{ GeV}, \ n_{\text{jet}} > 3, \]
\[ E_{Tj1} \geq 180 \text{ GeV}, \ E_{Tj2} \geq 110 \text{ GeV}, \ E_{Tj3} \geq 30 \text{ GeV}, \]
\[ E_{T}^{\text{miss}} + E_{Tj2} + E_{Tj3} + E_{Tj4} \geq 500 \text{ GeV}. \]

For points (a2 - f2) we checked that the signature with $n \geq 1$ leptons + jets + $E_{T}^{\text{miss}}$ does not allow to discover supersymmetry even at high integrated luminosity $L_{\text{tot}} = 100$ fb$^{-1}$. For instance, for point b2 the number of signal events at $L_{\text{tot}} = 1$ fb$^{-1}$ is $N_{\text{sig}} = 2$ (see Table 3).
Table 3: The number of signal events and significance $S_{c12}$ for points (a2 - f2) at $L_{tot} = 1 \, fb^{-1}$, dilepton signature $l^+l^- + E_T^{miss}$.

| Point | $N_{sig}$ | $S_{c12}$ |
|-------|-----------|-----------|
| a2    | 9.6       | 1.4       |
| b2    | 4.9       | 0.7       |
| c2    | 3.9       | 0.6       |
| d2    | 0.2       | 0.03      |
| e2    | 0         | 0         |
| f2    | 0         | 0         |

Table 4: The number of signal events and significance $S_{c12}$ for points (a2 - f2) at $L_{tot} = 1 \, fb^{-1}$, signature $\text{no leptons} + n \geq 3 \, \text{jets} + E_T^{miss}$.

| Point | $N_{sig}$ | $S_{c12}$ |
|-------|-----------|-----------|
| a2    | 185       | 10.2      |
| b2    | 145       | 8.2       |
| c2    | 141       | 8.0       |
| d2    | 68        | 4.1       |
| e2    | 23.5      | 1.5       |
| f2    | 8.5       | 0.5       |

The reason is that the supersymmetry cross section $\sigma(pp \rightarrow \text{sparticles} + ...) \approx 0.7 \, pb$ is not very big and cascade decays $\tilde{q} \rightarrow \tilde{\chi}_2^0 q \rightarrow l^+l^- \tilde{\chi}_1^0$, $\tilde{q} \rightarrow \tilde{\chi}_2^\pm q \rightarrow l^\pm \nu \tilde{\chi}_1^0$, leading to the signatures with multileptons in final state are suppressed. The main decay mode becomes decay $\tilde{q} \rightarrow q \tilde{\chi}_1^0$ that means in particular that in the signature $\text{no leptons} + \text{jets} + E_T^{miss}$ the events with two hadron jets dominate. For the signature $\text{no leptons} + \text{jets} + E_T^{miss}$ we found that it is possible to discover supersymmetry for points (a2 - f2). For point f2 we found that the use of the cuts [8] does not allow to discover supersymmetry. The reason is that for $m_{\chi_1^0}$ close to $m_{\tilde{q}}$ the decay $\tilde{q} \rightarrow q \tilde{\chi}_1^0$ leads to more soft distributions in $E_T^{miss}$ and $E_{T,jet}$ compared to the case when $m_{\tilde{q}} \gg m_{\chi_1^0}$ [9] so the number of signal events is decreased.

To conclude, in this note we studied the MSSM with large gluino mass $m_{\tilde{g}} \gg m_{\tilde{q}}$. Namely, we investigated the LHC supersymmetry discovery signatures with $n \geq 0 \, \text{leptons} + \text{jets} + E_T^{miss}$ for the MSSM with large gluino mass. We found that for some relations among squark and gaugino masses signatures with $n \geq 1 \, \text{leptons} + \text{jets} + E_T^{miss}$ isolated leptons do not allow to discover supersymmetry and the only supersymmetry discovery signature remains the signature $\text{no leptons} + \text{jets} + E_T^{miss}$. Moreover, for LSP mass close to squark masses the LHC supersymmetry discovery potential for this signature is strongly reduced.

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Figure 1: The distributions of $E_T^{\text{miss}}$ for points a1 - f1, dilepton signature $l^+l^- + E_T^{\text{miss}}$.

Figure 2: The distributions of $E_T^{\text{miss}}$ for points a1 - f1, signature \textit{no leptons} + $n \geq 3$ jets + $E_T^{\text{miss}}$. 
Figure 3: The distributions of $E_{T}^{\text{miss}}$ for points a2 - f2, dilepton signature $l^{+}l^{-} + E_{T}^{\text{miss}}$. 

Figure 4: The distributions of $E_{T}^{\text{miss}}$ for points a2 - f2, signature no leptons + $n \geq 3$ jets + $E_{T}^{\text{miss}}$. 
References

[1] As a review, see for example:
N.V.Krasnikov and V.A.Matveev, Phys.Usp. 47(2004)643; hep-ph/0309200.

[2] Y.A.Golfand and E.P.Likhtman, JETP Letters 13(1971)323;
D.V.Volkov and V.P.Akulov, JETP Letters 16(1972)621;
J.Wess and B.Zumino, Phys.Lett. B49(1974)52.

[3] S.L.Glashow, Nucl.Phys. 22(1961)579;
S.Weinberg, Phys.Rev.Lett. 19(1967)1264;
A.Salam, Elementary Particle Theory (ed. N.Svartholm) Almquist and Wiksells, Stockholm, 1964;
H.D.Politzer, Phys.Rev.Lett. 30(1973)1346;
D.J.Gross and F.E.Wilczek, Phys.Rev.Lett. 30(1973)1343.

[4] Reviews and original references can be found in:
R.Barbieri, Riv.Nuovo Cim. 11(1988)1;
A.B.Lahanus and D.V.Nanopoulos, Phys.Rep. 145(1987)1;
H.E.Haber and G.L.Lane, Phys.Rep. 117(1985)75;
H.P.Nilles, Phys.Rep. 110(1984)1.

[5] S.K.Soni and H.A.Weldom, Phys.Lett. 126B(1983)215;
L.E.Ibanez and D.Lust, Nucl.Phys. B382(1991)305.

[6] J.L.Feng, K.T.Matchev and T.Moroi, Phys.Rev.Lett. 84(2000)2322.

[7] R.Barbieri, L.J.Hall and V.S.Rychkov, Phys.Rev. D74(2006)015007.

[8] G.L.Bayatian et al., J.Phys.G: Nucl.Part.Phys. G34 (2007) 995-1579, Chapter 4.2.

[9] S.I.Bityukov and N.V.Krasnikov, Phys.Lett. B469(1999)149;
S.I.Bityukov and N.V.Krasnikov, Nuovo Cim. A112(1999)913;
S.I.Bityukov and N.V.Krasnikov, Nuovo Cim. A112(1999)913;
S.I.Bityukov and N.V.Krasnikov, Phys.Atom.Nucl. 65(2002)1341;
Yu.M.Andreev, N.V.Krasnikov and A.N.Toropin, arXiv:0706.2578 [hep-ph].

[10] K.Choi and H.P.Nilles, JHEP 0704(2007)006.

[11] S.Bhattacharya, A.Datta and B.Mukhopadhyaya, arXiv:0708.2427 [hep-ph].

[12] H.Baer et al., Phys.Lett. B161(1985)175;
G.Gamberini, Z.Phys. C30(1986)605;
H.Baer et al., Phys.Rev. D36(1987)96;
G.Gamberini et al., Phys.Lett. B203(1988)453;
R.M.Barnett, J.Gunion and H.Haber, Phys.Rev. D37(1988)1892;
A.Bartl et al., Z.Phys. C52(1991)477.
[13] T. Sjöstrand, S. Mrenna and P. Skands, JHEP 0605(2006)026.

[14] https://twiki.cern.ch/twiki/bin/view/CMS/SWGuide.

[15] S. I. Bityukov and N. V. Krasnikov, Mod. Phys. Lett. A13(1998)3235;
    S. I. Bityukov and N. V. Krasnikov, Nucl. Instrum. Meth. A452(2000)518.