Effects of the CP Odd Dipole Operators on Gluino Production at Hadron Colliders

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Abstract

We present the cross sections for the hadroproduction of gluinos by taking into account the CP odd dipole operators in supersymmetric QCD. The dependence of the cross sections on these operators is analyzed for the hadron colliders the Tevatron ($\sqrt{S}=1.8$ TeV) and the Cern LHC ($\sqrt{S}=14$ TeV). The enhancement of the hadronic cross section is obviously mass dependent and for a 500 GeV gluino, is up to 16 % (over 73 pb) at the LHC while it is 8 % (over 0.63 fb) at the Tevatron.

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I. INTRODUCTION

Supersymmetric QCD (SUSY-QCD) is based on the colored particles of the Minimal Supersymmetric Standard Model (MSSM) \[1, 2\] spectrum; quarks, gluons and their superpartners squarks and gluinos. Since supersymmetry is a broken one rather than an exact symmetry, the masses of the superparticles extremely exceed the masses of their SM partners \[3\]. Upper bound limits of \(\mathcal{O}(1 \text{ TeV})\) are set to these masses for the sake of the solution of the hierarchy problem. In most of the analysis the scalar partners of the five light quarks are assumed mass degenerate \[4\].

Searching for supersymmetric particles will be one of the main goals of the future experimental program of high energy physics. The particles in the strong interaction sector can be searched for most efficiently at hadron colliders. As they are presently searched at the Tevatron \((\sqrt{s} = 1.8 \text{ TeV})\) the Large Hadron Collider (LHC) with center of mass energy of \(\sqrt{s} = 14 \text{ TeV}\) will in a sense be a gluino factory.

At the fundamental level SUSY receives some additional effects from the existent particles predicted by high energy models so called GUT or String Theory. As these effect are quite general we consider them in gluino pair production. At this level we know the interaction vertices in supersymmetric QCD. After the prediction of Kane and Leville \[5\] for the tree level hadronic production of gluinos several improvements for this process have been performed \[4\]. The production of gluino pairs in electron-positron annihilation is analyzed in ref 4. In the present analysis we reconsider the productions of gluino pairs in hadron-hadron collisions and generalize to include the CP odd terms to investigate the effects of these CP violating operators in these processes. We assumed an updated range of 300-500 GeV for the gluino masses.

II. GLUINO PRODUCTION WITH THE CP VIOLATING TERMS

The dominant contributions to the production cross sections of gluino pairs in \(pp\) or \(p\bar{p}\) collisions come from the subprocesses \(q\bar{q} \to \tilde{g}\tilde{g}\) and \(gg \to \tilde{g}\tilde{g}\). The relevant Feynman diagrams are displayed in Figures 1 and 2 and the differential cross sections are calculated in the Appendix. In the first subprocess \(q\bar{q} \to \tilde{g}\tilde{g}\), in principle \(t\) and \(u\)-channel squark exchanges have also contributions in addition to the annihilation \(s\) channel gluon exchange. But these
contributions are almost always negligible since squarks of first and second generations must be nearly degenerate and they are heavy to satisfy the Electric Dipole Moment bounds. Therefore we will consider only the s-channel via gluon exchange for the reaction \( q\bar{q} \to \tilde{g}\tilde{g} \).

In calculations of the differential cross sections we use the standard structure of the effective CP-odd lagrangian including the Weinberg operator and color EDMs of quarks \[7, 8, 9\] and the interaction lagrangian of the gluinos with the gauge field gluons \[1\] to obtain the following three interaction vertices:

i) Quark-quark-gluon

\[
\Gamma_{qqg}^\mu = f^{abc} \left[ -ig_s \gamma^\mu + i \frac{d_q}{2\Lambda} \gamma_5 \sigma^\mu\nu q^\nu \right] T_{ji}^a
\]

ii) Gluon-gluino-gluino

\[
\Gamma_{g\tilde{g}\tilde{g}}^\mu = f^{abc} \left[ -g_s \gamma^\mu + i \frac{d_{\tilde{g}}}{4\Lambda} \gamma_5 \sigma^\mu\nu q^\nu \right]
\]

iii) Three gluon

\[
\Gamma_{gg\tilde{g}}^\mu \epsilon_{1\mu} \epsilon_{2\nu} = f^{abc} \left[ -g_s C^\mu\nu_{\rho}(p_1, p_2, -q) - i \frac{C\mu\nu_{\rho}(p_1, p_2, q)}{4\Lambda} \epsilon_{1\mu} \epsilon_{2\nu} \right]
\]

where \( g_s \) is the strong coupling constant, \( q \) is the momentum carried by the mediator, \( d_q \) and \( \tilde{d}_q \) are effective color EDMs couplings of quarks and gluinos respectively. \( \Lambda \) denotes the scale up to which the effective theory is assumed to hold. \( C^\mu\nu_{\rho}(p_1, p_2, q) \) is the standard
three gluon vertex with all momenta incoming \( C^{\mu\nu\rho}(p_1, p_2, q) = g^{\mu\nu}(p_1 - p_2)^\rho + g^{\nu\rho}(p_2 - q)^\mu + g^{\mu\rho}(q - p_1)^\nu \). \( C_W \) is the coefficient of the Weinberg operator and the term with this coefficient is the result of a straightforward calculation of the dimension-6 Weinberg operator 6:

\[
O_W = -\frac{C_W}{6} f_{abc} \epsilon^{\mu\lambda\nu\rho} G_{a}^{\mu\lambda} G_{b}^{\nu \sigma} G_{c}^{\rho \sigma}
\]

where \( G_{a}^{\mu\lambda} \) is gluon field strength tensor.

The differential cross sections are presented in the Appendix. Integrating them over \( \hat{t} \) leads to the total partonic cross sections:

\[
\hat{\sigma}(q_i q_i \rightarrow \tilde{g}\tilde{g}) = \frac{1}{12 \pi s^3} \left\{ J(d^2 d_1^2 J^2 \hat{s}^2 - g_s^2 \hat{s}(d^2 + d_1^2) J^2 - 12 d^2 m^2 \hat{s} + 3(d^2 + d_1^2) \hat{s}^2) + d^2 g_s^4 (J^2 + 3 \hat{s}(4 m^2 + \hat{s})) \right\}
\]

where \( \hat{s} = x_1 x_2 S \) is the partonic CM energy, \( J = s \beta, \beta = \sqrt{1 - \frac{4m^2}{s}} \) being gluino velocity in the partonic center of mass system, \( m \) denotes mass of the produced gluinos, and \( d_1 = d_q/2 \Lambda, d = d_q/4 \Lambda \). In obtaining Eq.1 only the s-channel of Fig.1 was considered.

For the second subprocess \( gg \rightarrow \tilde{g}\tilde{g} \) contributions of all the three diagrams in Fig.2 are considered, and the integrated cross section in this case is obtained as

\[
\hat{\sigma}(gg \rightarrow \tilde{g}\tilde{g}) = \frac{1}{2512 \pi s^4 (J^2 - \hat{s}^2)} \left\{ 3J(d^4 \hat{s}^2 (-5J^4 + 6912 m^8 + 3354 m^4 \hat{s}^2 - 480 m^2 \hat{s}^3 + 9 \hat{s}^4 + J^2 (-3354 m^4 + 480 m^2 \hat{s} - 4 \hat{s}^2)) - 4g_s^4 (J^4 + 2J^2 \hat{s} (-12 m^2 + 7 \hat{s}) - 3 \hat{s}^2 (64 m^4 - 8 m^2 \hat{s} + 5 \hat{s}^2)) - 2d^2 g_s^2 \hat{s} (J^4 + J^2 (144 m^4 + 210 m^2 \hat{s} - 25 \hat{s}^2) + 6 \hat{s} (384 m^6 - 56 m^4 \hat{s} - 35 m^2 \hat{s}^2 + 4 \hat{s}^3))
+ 12 d m (4g_s^2 + d^2 (20 m^2 - 3 \hat{s})) \hat{s}^3 (\hat{s}^2 - J^2) \right\} w
+ 12 \hat{s}^3 (J^2 - \hat{s}^2) (d^2 \hat{s} (-4 m^2 + \hat{s}) + 2g_s^2 (2m^2 + \hat{s}) w^2)
- 12 \hat{s} (\hat{s}^2 - J^2) (4g_s^4 (-4 m^4 + 2 m^2 \hat{s} + \hat{s}^2)
+ d^2 m^4 (d (48 m^4 + 316 m^2 \hat{s} + 3 \hat{s}^2) + 16 m \hat{s}^2 w)
+ 2d g_s^2 m (4m (12^m^4 - 12 m^2 \hat{s} + \hat{s}^2) + \hat{s}^3 w)) \log(\frac{J + \hat{s}}{J - \hat{s}}) \right\}
\]

with and \( w = C_W/6 \Lambda^2 \). Since the gluinos are Majorana fermions the statistical factor of 1/2 is implied to avoid double counting.
TABLE I: The hadronic cross sections in pb for the $q\bar{q}$ initial states at the Tevatron ($\sqrt{s}=1.8$ TeV)

| $\Lambda$ (GeV) | $m=300$ GeV | $m=400$ GeV | $m=500$ GeV |
|-----------------|-------------|-------------|-------------|
| 800             | 0.227689    | 0.0136852   | 0.000536575 |
| 1000            | 0.221508    | 0.0131209   | 0.000506254 |
| 2000            | 0.2133299   | 0.0123716   | 0.000465985 |
| 4000            | 0.211253    | 0.0121849   | 0.000455946 |
| 6000            | 0.210874    | 0.0121503   | 0.000454088 |
| 8000            | 0.210741    | 0.0121382   | 0.000453438 |

The total cross section $pp(p\bar{p}) \to g\tilde{g}X$ is calculated as a function of the hadronic CM energy $S$ and gluino mass $m$, by convoluting the cross sections of subprocesses and parton densities through the factorization theorem

$$\sigma_{\text{tot}}(s, m) = \int_{\tau_0}^{1} d\tau \int_{1}^{1} \frac{dx}{x_1} \frac{1}{1+\delta_{ij}} \sum_{ij} \left[ f_i(x)f_j(\frac{\tau}{x}) + f_i(\frac{\tau}{x})f_j(x) \right] \hat{\sigma}(m, \hat{s}, \hat{u})$$

where $(i,j) = (g,g), (q_\alpha, \bar{q}_\alpha)$, $\alpha = u, d, s$. In performing the calculations we used the Feynman gauge for the internal gluon propagators. We have also used $-g^{\mu\nu}$ for the polarization sum of the external gluons by adding the ghost term. In Tables I-IV we have presented the cross sections for the gluino masses of 300, 400 and 500 GeV to see the $\Lambda$ and mass dependence. The calculated cross sections are not very sensitive to the $\Lambda$ values but drop fast with the increasing mass values. The $gg$ initial state is always dominant at the LHC. At the Tevatron for $m=300$ GeV the $q\bar{q}$ cross sections are grater than the $gg$ cases, but the situation is reversed for the masses of 400 or 500 GeV.

III. DISCUSSION AND CONCLUSION

The results for the $p\bar{p}(pp) \to g\tilde{g}X$ cross sections are presented in Fig.3 for $q\bar{q}$ annihilation and in Fig.4 for $gg$ fusion at the Tevatron by fixing $\Lambda=1000$ GeV. Similarly the corresponding results are presented in Fig.5 and Fig.6 at the LHC. The solid lines are displayed for $d=d_1=w=0$, without CP violating terms and dotted lines are displayed by taking the contributions of CP-odd terms. For illustrations all effective couplings $d_q$, $d_{\tilde{g}}$ and $C_W$ are set equal to 1. We used MRST [10] parametrization in convoluting of parton densities. We
| \( \Lambda \) (GeV) | \( m=300 \) (GeV) | \( m=400 \) (GeV) | \( m=500 \) (GeV) |
|----------------|----------------|----------------|----------------|
| 800            | 0.352658       | 0.00868101     | 0.000174379    |
| 1000           | 0.352641       | 0.0086626      | 0.000172692    |
| 2000           | 0.353933       | 0.00873083     | 0.000174725    |
| 4000           | 0.354495       | 0.0087646      | 0.000176001    |
| 6000           | 0.354610       | 0.00877161     | 0.000176271    |
| 8000           | 0.354652       | 0.00877412     | 0.000176369    |

TABLE II: The hadronic cross sections in pb for the \( gg \) initial states at the Tevatron (\( \sqrt{s} = 1.8 \) TeV)

| \( \Lambda \) (GeV) | \( m=300 \) (GeV) | \( m=400 \) (GeV) | \( m=500 \) (GeV) |
|----------------|----------------|----------------|----------------|
| 800            | 25.9082        | 12.8225        | 7.37316        |
| 1000           | 24.1935        | 11.5765        | 6.43782        |
| 2000           | 22.0388        | 10.0294        | 5.28865        |
| 4000           | 21.5236        | 9.66296        | 5.01886        |
| 6000           | 21.4292        | 9.59601        | 4.96966        |
| 8000           | 21.3963        | 9.57264        | 4.9525         |

TABLE III: The hadronic cross sections in pb for the \( q\bar{q} \) initial states at the LHC (\( \sqrt{s} = 14 \) TeV)

treated the gluon and light quark flavors as massless. From Fig.4 it is obvious that effects of the CP violating terms in lagrangian are negligible at the Tevatron for the \( gg \) fusion. The enhancements in the total hadronic cross sections at this collider for gluinos of masses 300, 400, and 500 GeV are 1.5 %, 4.2 %, and 7.9 % respectively. However the event rates are very low due to the low cross sections; for instance the number of events for 500 GeV gluinos at the Tevatron with an integrated luminosity of 2 \( fb^{-1} \) is only 1-2 per year.

At the LHC, the event rates are substantially high; for instance the number of events for 500 GeV gluinos is as high as \( 10^7 \) in each LHC detector for a high integrated luminosity of 100 \( fb^{-1} \).

In addition to the high event rates at the LHC, CP odd terms give extra contributions, for instance the enhancements in the total hadronic cross sections for 300, 400, and 500 GeV gluinos are 6 %, 10 %, and 16 % respectively. Main contribution to the enhancements comes
TABLE IV: The hadronic cross sections in pb for the $gg$ initial states at the LHC ($\sqrt{s} = 14$ TeV)

from the Weinberg term, especially at high mass values. Finally gluon-gluon fusion is always the dominant process in pp collisions such that the LHC can be treated as a gluon-gluon collider, at a first approximation.

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APPENDIX A: COLOR FACTORS

The generators of SU_{c}(3) are defined by the commutation relations

$$[T_a, T_b] = i f_{abc} T_c$$  \hspace{1cm} (A1)

The matrices defined as $F_{bc}^a = -i f_{abc}$ also satisfy similar relations $[F_a, F_b] = i f_{abc} F_c$ which means that $F_a$ form the adjoint representation of SU_{c}(3). Fundamental identities we have used in this work for the traces of color matrices in the fundamental and adjoint representations are

$$Tr T_a = 0$$
$$Tr(T^a T^b) = \frac{1}{2} \delta_{ab}$$
$$Tr(F_a F_b) = 3 \delta_{ab}$$
$$Tr(F_a F_b F_c) = i \frac{3}{2} f_{abc}$$

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Because of different color factors, it is convenient to express the square of the matrix element in the form

\[
|M(gg \rightarrow \tilde{g}\tilde{g})|^2 = C_{ss}|M_s|^2 + C_{tt}|M_t|^2 + C_{uu}|M_u|^2 + 2C_{st}M_s\bar{M}_t - 2C_{su}M_s\bar{M}_u \tag{A3}
\]

where the obtained values of color factors are

\[
C_{ss} = C_{tt} = C_{uu} = 72 \\
C_{st} = C_{su} = -C_{tu} = 36 \tag{A4}
\]

The color factor of \( |M(q\bar{q} \rightarrow \tilde{g}\tilde{g})|^2 \) is obtained to be 12.

**APPENDIX B: DIFFERENTIAL CROSS SECTIONS**

The differential cross sections to produce gluino pairs are determined from the Feynman diagrams of Figures 1 and 2 via the subprocesses \( q\bar{q} \rightarrow \tilde{g}\tilde{g} \) and \( gg \rightarrow \tilde{g}\tilde{g} \) respectively and obtained as

\[
\frac{d\hat{\sigma}(q\bar{q} \rightarrow \tilde{g}\tilde{g})}{dt} = \frac{1}{12\pi\hat{s}}[d^2d_1^2(\hat{t} - \hat{u})^2(-2m^2 + \hat{t} + \hat{u})^2 \\
+ 2g_s^4(6m^4 + \hat{t}^2 + \hat{u}^2 - 4m^2(\hat{t} + \hat{u})) \\
- 4g_s^2(2m^2 - \hat{t} - \hat{u})((d_1^2(m^2 - \hat{t})(m^2 - \hat{u})) + d^2(m^4 - \hat{t}\hat{u}))]
\]

by considering only s-channel of Fig.1, and

\[
\frac{d\hat{\sigma}(gg \rightarrow \tilde{g}\tilde{g})}{dt} = \frac{9}{512\pi\hat{s}^2}[M_s^2 + M_t^2 + M_u^2 + M_{st} + M_{su} + M_{tu}]
\]

with
\[ M_s^2 = \frac{4}{s^2} \left[ 4 g_s^4 \left( m^2 - \hat{t} \right) (m^2 - \hat{u}) - w^2 d^2 \left( -2 m^2 + \hat{t} + \hat{u} \right)^4 \left( 2 m^2 + \hat{t} + \hat{u} \right) + g_s^2 \left( 2 m^2 - \hat{t} - \hat{u} \right) \left( d^2 (\hat{t} - \hat{u})^2 + 2 w^2 (4 m^2 - \hat{t} - \hat{u}) (2 m^2 + \hat{t} + \hat{u})^2 \right) \right] \]

\[ M_t^2 = \frac{-2}{(\hat{t} - m^2)^2} \left[ 4 g_s^4 (m^4 - \hat{t} \hat{u} + m^2 (3 \hat{t} + \hat{u})) + 2 g_s^2 d^2 (5 m^6 - 59 m^4 \hat{t} + 3 \hat{t}^3 + m^2 \hat{t} (7 \hat{t} - 4 \hat{u})) + d^4 \hat{t} (4 m^6 + 67 m^4 \hat{t} + \hat{t}^2 (4 \hat{t} - \hat{u}) + m^2 \hat{t} (69 \hat{t} + \hat{u})) \right] \]

\[ M_u^2 = \frac{-2}{(\hat{u} - m^2)^2} \left[ 4 g_s^4 (m^4 - \hat{t} \hat{u} + m^2 (\hat{t} + 3 \hat{u})) + 2 g_s^2 d^2 (5 m^6 - 59 m^4 \hat{u} + 3 \hat{u}^3 + m^2 \hat{u} (7 \hat{u} - 4 \hat{t})) + d^4 \hat{u} (4 m^6 + 67 m^4 \hat{u} + \hat{u}^2 (4 \hat{u} - \hat{t}) + m^2 \hat{u} (69 \hat{u} + \hat{t})) \right] \]

\[ M_{st} = \frac{4}{s (\hat{t} - m^2)} \left[ 2 g_s^4 (m^4 - 2 m^2 \hat{t} + \hat{u}) - w d^3 m (m^4 + 4 m^2 \hat{t} + 3 \hat{t}^2) \left( -2 m^2 + \hat{t} + \hat{u} \right)^2 + g_s^2 d (3 d \hat{t} (m^4 + \hat{t} \hat{u} + m^2 (3 \hat{t} + \hat{u})) - m (\hat{t} - \hat{u}) (2 m^2 + \hat{t} + \hat{u})^2 w) \right] \]

\[ M_{su} = \frac{4}{s (\hat{u} - m^2)} \left[ 2 g_s^4 (m^4 - 2 m^2 \hat{t} + \hat{u}) - w d^3 m (-2 m^2 + \hat{t} + \hat{u})^2 (m^4 + 4 m^2 \hat{u} + 3 \hat{u}^2) + g_s^2 d (3 d \hat{u} (m^4 + \hat{t} \hat{u} + m^2 (\hat{t} - 3 \hat{u}) + m \hat{u} (2 m^2 + \hat{t} + \hat{u})^2) \right] \]

\[ M_{tu} = \frac{2}{(\hat{t} - m^2) (\hat{u} - m^2)} \left[ 4 g_s^4 m^2 (\hat{s} - 4 m^2) + d^4 m^2 (13 m^6 - 7 m^4 (\hat{s} - 10 \hat{u}) + 2 \hat{u} \hat{s} (\hat{s} + \hat{u}) - m^2 \hat{u} (39 \hat{s} + 35 \hat{u}) + d^2 g_s^2 (-140 m^6 + 2 \hat{s} \hat{u} (\hat{s} + \hat{u}) + m^4 (49 \hat{s} + 88 \hat{u}) - m^2 (\hat{s}^2 + 46 \hat{s} \hat{u} + 44 \hat{u}^2)) \right] \]

where \( d_1 = d_q / 2 \Lambda, d = d_{\tilde{q}} / 4 \Lambda \) and \( w = C_W / 6 \Lambda^2 \).

In the special case of \( d_1 = d = w = 0 \) we obtain the following result for the differential cross section for the gluino production which agrees with references [11, 12]:

\[
\frac{d \hat{\sigma} (gg \rightarrow \tilde{g}\tilde{g})}{d \hat{t}} = \frac{9 \pi \alpha_s^2}{4 s^2} \left[ \frac{2 \left( m^2 - t \right) \left( m^2 - u \right)}{s^2} - \frac{m^4 - t u + m^2 \left( 3 t + u \right)}{(m^2 - t)^2} - \frac{m^4 - t u + m^2 \left( t + 3 u \right)}{(m^2 - u)^2} + \frac{m^4 - 2 m^2 t + t u}{s (u - m^2)} + \frac{m^4 - 2 m^2 u + t u}{s (t - m^2)} + \frac{m^2 \left( s - 4 m^2 \right)}{(m^2 - t) (m^2 - u)} \right]
\] (B3)

but we should note that the denominators (or numerators) of \( s - t \) and \( s - u \) terms should
be exchanged in Eq.(3.10) of ref. 12 and Eq.(3.1) of ref. 11.

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FIG. 1: $qq \rightarrow \tilde{g}\tilde{g}$

FIG. 2: $gg \rightarrow \tilde{g}\tilde{g}$
FIG. 3: The total cross sections for the $qq$ initial states for the Tevatron with $\Lambda=1$ TeV.

FIG. 4: The total cross sections for the $gg$ initial states for the Tevatron with $\Lambda=1$ TeV.
FIG. 5: The total cross sections for the $qq$ initial states for the LHC with $\Lambda=1$ TeV.

FIG. 6: The total cross sections for the $gg$ initial states for the LHC with $\Lambda=1$ TeV.