Effects of the *CP* odd dipole operators on gluino production at hadron colliders

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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 [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 standard model partners [3]. Upper bound limits of $\mathcal{O}$ (1 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].

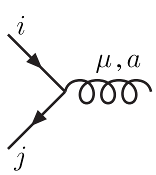
Searching for supersymmetric particles will be one of the main goals of the future experimental program of high energy physics. The particles in the strong interaction sector can be searched for most efficiently at hadron colliders. As they are presently searched at the Tevatron ($\sqrt{s} = 1.8$ TeV),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

At the fundamental level, supersymmetry receives some additional effects from the existent particles predicted by high energy models so called GUT (grand unified theory) or string theory. As these effects 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 Leveille [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. [6]. 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 Figs. 1 and 2 and the differential cross sections are calculated in the Appendices A and B In the first subprocess $q\bar{q} \to \tilde{g}\,\tilde{g}$, in principle $\hat{t}$ and $\hat{u}$-channel squark exchanges have also contributions in addition to the annihilation s-channel gluino 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. The current bounds require squarks of the first two generations to weigh around 4 TeV. 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 electric dipole moments of quarks [7–9] and the interaction Lagrangian of the gluinos with the gauge field gluons [1] to obtain the following three interaction vertices:

(i) Quark-quark-gluon



$$\Gamma^{\mu}_{qqg} = [-ig_s\gamma^{\mu} + i\tfrac{d_q}{2\Lambda}\gamma_5\sigma^{\mu\nu}\,q_{\nu}]T^{a}_{ji}$$

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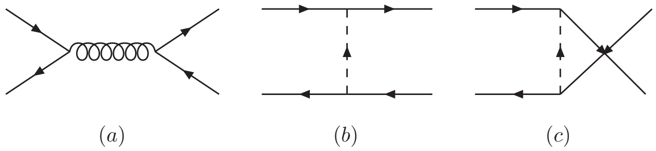


FIG. 1. Feynman diagrams for gluino production in $q\bar{q}$ scattering.

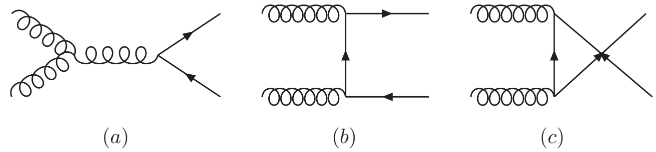
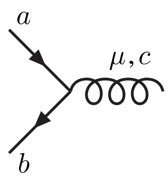


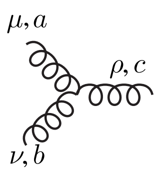
FIG. 2. Feynman diagrams for gluino production in gg scattering.

(ii) Gluon-gluino-gluino



$$\Gamma^{\mu}_{g\tilde{g}\tilde{g}} = f^{abc}[-g_s\gamma^{\mu} + i\tfrac{d_{\tilde{g}}}{4\Lambda}\gamma_5\sigma^{\mu\nu}q_{\nu}]$$

(iii) Three gluon



$$\Gamma^{\mu\nu\rho}_{ggg}\epsilon_{1\mu}\epsilon_{2\nu} = f^{abc}[-g_sC^{\mu\nu\rho}(p_1, p_2, -q) - i\tfrac{C_W}{3\Lambda^2}\epsilon^{\mu\nu\alpha\rho}p_1.p_2q_{\alpha}]\epsilon_{1\mu}\epsilon_{2\nu}$$

where g_s is the strong coupling constant, q is the momentum carried by the mediator, and d_q and $d_{\tilde{g}}$ are effective color electric dipole moment couplings of quarks and gluinos, respectively. Λ 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 [10]:

$$\mathcal{O}_W = -\frac{C_W}{6}f_{abc}\epsilon^{\mu\lambda\nu\rho}G^{\mu\lambda}_aG^b_{\nu\sigma}G^c_{\rho\sigma}, \tag{1}$$

where $G^{\mu\nu}_a$ is a gluon field strength tensor.

There is an additional gluino production channel related to squark-gluino associated production initiated by the scattering of quarks and gluons. The diagram involves gluon-gluino-gluino and quark-quark-gluon vertices and hence is sensitive to the dipole operators discussed. In the present work, we focus only on the pair production of gluinos.

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

$$\begin{aligned}\hat{\sigma}_q(q_i\bar{q}_i \to \tilde{g}\,\tilde{g}) = \left(\frac{1}{72\pi\hat{s}^4}\right)&[J(d^2{d_1}^2J^2\hat{s}^2 \\ &+ g_s^2\hat{s}(-(d^2 + {d_1}^2)J^2 - 12d^2m^2\hat{s} \\ &+ 3(d^2 + {d_1}^2)\hat{s}^2) \\ &+ g_s^4(J^2 + 3\hat{s}(4m^2 + \hat{s})))],\end{aligned} \tag{2}$$

where $\hat{s} = x_1x_2S$ is the partonic center of mass energy, $J = \hat{s}\beta$, $\beta = \sqrt{1 - \frac{4m^2}{\hat{s}}}$ being gluino velocity in the partonic center of mass system, m denotes mass of the produced gluinos, and $d_1 = d_q/2\Lambda$, $d = d_{\tilde{g}}/4\Lambda$. In obtaining Eq. (1) only the s channel of Fig. 1 was considered.

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

$$\hat{\sigma}(gg \to \tilde{g}\,\tilde{g}) = \frac{1}{2}\frac{1}{512\pi\hat{s}^4(J^2-\hat{s}^2)}\Big[3\Big(J(d^4\hat{s}^2(-5J^4+6912m^8+3354m^4\hat{s}^2-480m^2\hat{s}^3+9\hat{s}^4 + J^2(-3354m^4+480m^2\hat{s}-4\hat{s}^2))-4g_s^4(J^4+2J^2\hat{s}(-12m^2+7\hat{s})-3\hat{s}^2(64m^4-8m^2\hat{s}+5\hat{s}^2)) - 2d^2g_s^2\hat{s}(J^4+J^2(144m^4+210m^2\hat{s}-25\hat{s}^2)+6\hat{s}(384m^6-56m^4\hat{s}-35m^2\hat{s}^2+4\hat{s}^3)) + 12dm(4g_s^2+d^2(20m^2-3\hat{s}))\hat{s}^3(\hat{s}^2-J^2)w+12\hat{s}^3(J^2-\hat{s}^2)(d^2\hat{s}(-4m^2+\hat{s})+2g_s^2(2m^2+\hat{s}))w^2) - 12\hat{s}(\hat{s}^2-J^2)(4g_s^4(-4m^4+2m^2\hat{s}+\hat{s}^2)+d^3m^4(d(48m^4+316m^2\hat{s}+3\hat{s}^2)+16m\hat{s}^2w) + 2dg_s^2m(4dm(-12m^4-7m^2\hat{s}+\hat{s}^2)+\hat{s}^3w))\log\Big(\frac{J+\hat{s}}{J-\hat{s}}\Big)\Big)\Big], \quad (3)$$

with $w = C_W/6\Lambda^2$. Since the gluinos are Majarona fermions the statistical factor of 1/2 is implied to avoid double counting.

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

$$\sigma_{\rm tot}(s,m) = \int_{\tau_0}^1 d\tau \int_\tau^1 \frac{dx}{x}\frac{1}{1+\delta_{ij}}\sum_{ij}\Big[f_i(x)f_j\Big(\frac{\tau}{x}\Big) + f_i\Big(\frac{\tau}{x}\Big)f_j(x)\Big]\hat{\sigma}(m,\hat{s},\hat{u}), \quad (4)$$

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, II, III, and IV we have presented the cross sections for the gluino masses of 300, 400, and 500 GeV to see the Λ and mass dependence. The calculated cross sections are not very sensitive to the Λ 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 greater than the gg cases, but the situation is reversed for the masses of 400 or 500 GeV.

TABLE I. The hadronic cross sections in pb for the $q\bar{q}$ initial states at the Tevatron ($\sqrt{s} = 1.8$ TeV).

Λ (GeV)	$m = 300$ GeV	$m = 400$ GeV	$m = 500$ GeV
800	0.227 689	0.0 136 852	0.000 536 575
1000	0.221 508	0.0 131 209	0.000 506 254
2000	0.213 299	0.0 123 716	0.000 465 985
4000	0.211 253	0.0 121 849	0.000 455 946
6000	0.210 874	0.0 121 503	0.000 454 088
8000	0.210 741	0.0 121 382	0.000 453 438

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

Λ (GeV)	$m = 300$ (GeV)	$m = 400$ (GeV)	$m = 500$ (GeV)
800	0.352 658	0.00 868 101	0.000 174 379
1000	0.352 641	0.0 086 626	0.000 172 692
2000	0.353 933	0.00 873 083	0.000 174 725
4000	0.354 495	0.0 087 646	0.000 176 001
6000	0.354 610	0.00 877 161	0.000 176 271
8000	0.354 652	0.00 877 412	0.000 176 369

III. DISCUSSION AND CONCLUSION

The results for the $p\bar{p}(pp) \to \tilde{g}\,\tilde{g}\,X$ 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 Figs. 5 and 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. Since Eq. (2) is even in d_q and $d_{\tilde{g}}$, the choice of sign for these coefficients is immaterial for $q\bar{q} \to \tilde{g}\,\tilde{g}$ cross sections. However, the situation is a bit different for

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

Λ (GeV)	$m = 300$ (GeV)	$m = 400$ (GeV)	$m = 500$ (GeV)
800	25.9082	12.8225	7.37 316
1000	24.1935	11.5765	6.43 782
2000	22.0388	10.0294	5.28 865
4000	21.5236	9.66 296	5.01 886
6000	21.4292	9.59601	4.96 966
8000	21.3963	9.57264	4.9525

TABLE IV. The hadronic cross sections in pb for the gg initial states at the LHC ($\sqrt{s} = 14$ TeV).

Λ (GeV)	$m = 300$ (GeV)	$m = 400$ (GeV)	$m = 500$ (GeV)
800	324.288	163.190	91.125
1000	306.743	148.258	78.410
2000	293.053	137.326	69.599
4000	291.167	136.018	68.681
6000	290.884	135.837	68.565
8000	290.791	135.778	68.529

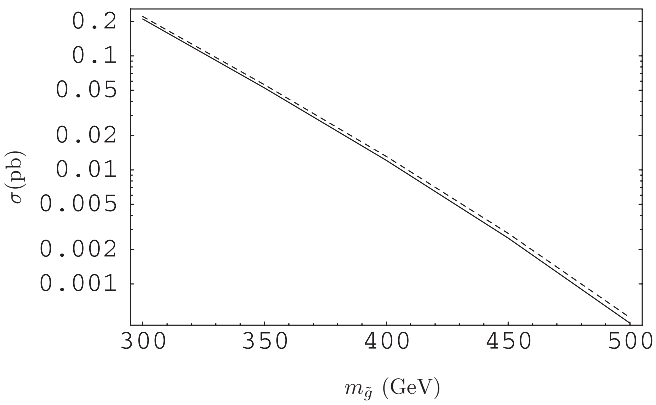


FIG. 3. The total cross sections for the $q\bar{q}$ initial states for the Tevatron with $\Lambda = 1$ TeV.

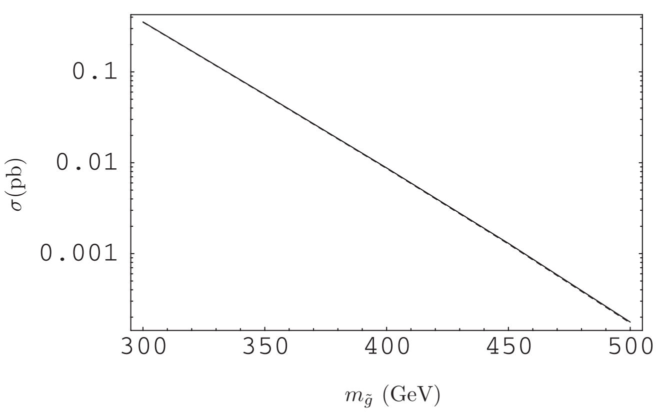


FIG. 4. The total cross sections for the gg initial states for the Tevatron with $\Lambda = 1$ TeV.

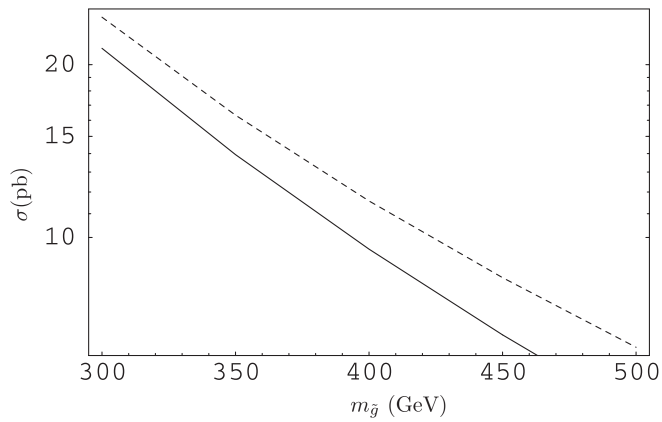


FIG. 5. The total cross sections for the $q\bar{q}$ initial states for the LHC with $\Lambda = 1$ TeV.

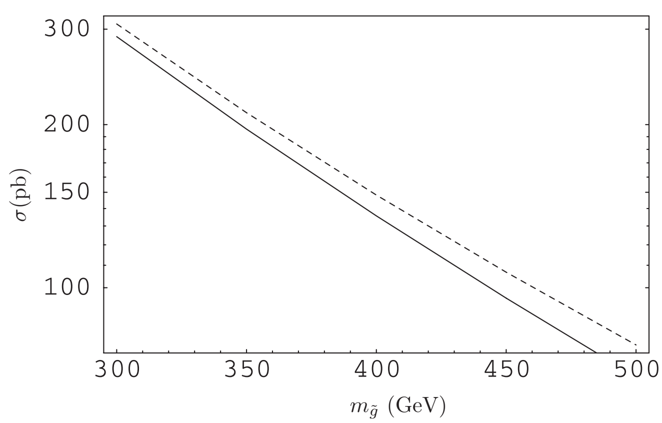


FIG. 6. The total cross sections for the gg initial states for the LHC with $\Lambda = 1$ TeV.

$gg \to \tilde{g}\,\tilde{g}$. Here, in Eq. (3) there are three terms which are odd in $d_{\tilde{g}}$ and C_W. Changing the signs of both coefficients obviously would not change the result, but changing the sign of one of these coefficients has a tiny effect on the resulting cross sections. For example for $\Lambda = 1000$ GeV, the hadronic σs in Table IV change to 303.71, 145.775, and 76.438 pb for 300, 400, and 500 GeV gluinos, respectively. We used MRST [11] parametrization in convoluting of parton densities. We 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 from the Weinberg term, especially at high mass values. 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.

The detection of dipole operators at colliders could be quite difficult first because one needs a measurement of the superpartner masses (those of gluinos and squarks) and then identification of the phase effects. In this sense, dependencies of cross sections on the phases as well as certain spin, *CP*, or left-right asymmetries could be helpful tools.

ACKNOWLEDGMENTS

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APPENDIX A: COLOR FACTORS

The generators of $SU_c(3)$ are defined by the commutation relations

$$[T_a, T_b] = i f_{abc} T_c. \quad \text{(A1)}$$

The matrices defined as $F^a_{bc} = -i f_{abc}$ 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

$$\mathrm{Tr}T_a = 0, \qquad \mathrm{Tr}(T_a T_b) = \tfrac{1}{2}\delta_{ab}, \qquad \mathrm{Tr}(F_a F_b) = 3\delta_{ab},$$
$$\mathrm{Tr}(F_a F_b F_c) = i\tfrac{3}{2} f_{abc}, \qquad \mathrm{Tr}(F_a F_b F_a F_c) = \tfrac{9}{2}\delta_{bc},$$
$$f_{acd} f_{bcd} = 3\delta_{ab}, \qquad f_{abc} f_{abc} = 24. \quad \text{(A2)}$$

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

$$|M(gg \to \tilde{g}\,\tilde{g})|^2 = C_{ss}|M_s|^2 + C_{tt}|M_t|^2 + C_{uu}|M_u|^2 + 2C_{st} M_s \bar{M}_t - 2C_{su} M_s \bar{M}_u - 2C_{tu} M_t \bar{M}_u, \quad \text{(A3)}$$

where the obtained values of color factors are

$$C_{ss} = C_{tt} = C_{uu} = 72, \qquad C_{st} = C_{su} = -C_{tu} = 36. \quad \text{(A4)}$$

The color factor of $|M(q\bar{q} \to \tilde{g}\,\tilde{g})|^2$ 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 Figs. 1 and 2 via the subprocesses $q\bar{q} \to \tilde{g}\,\tilde{g}$ and $gg \to \tilde{g}\,\tilde{g}$, respectively, and obtained as

$$\frac{d\hat{\sigma}(q\bar{q} \to \tilde{g}\,\tilde{g})}{d\hat{t}} = \frac{1}{12\pi\hat{s}^4}[d^2 d_1{}^2(\hat{t} - \hat{u})^2(-2m^2 + \hat{t} + \hat{u})^2 + 2g_s^4(6m^4 + \hat{t}^2 + \hat{u}^2 - 4m^2(\hat{t} + \hat{u})) - 4g_s^2(2m^2 - \hat{t} - \hat{u})(-(d_1{}^2(m^2 - \hat{t}) \times (m^2 - \hat{u})) + d^2(m^4 - \hat{t}\,\hat{u}))] \quad \text{(B1)}$$

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

$$\frac{d\hat{\sigma}(gg \to \tilde{g}\,\tilde{g})}{d\hat{t}} = \frac{9}{512\pi\hat{s}^2}[M_s^2 + M_t^2 + M_u^2 + M_{st} + M_{su} + M_{tu}], \quad \text{(B2)}$$

with

$$M_s^2 = \frac{4}{\hat{s}^2}[4g_s^4(m^2 - \hat{t})(m^2 - \hat{u}) - w^2 d^2(-2m^2 + \hat{t} + \hat{u})^4 \times (2m^2 + \hat{t} + \hat{u}) + g_s^2(2m^2 - \hat{t} - \hat{u})(d^2(\hat{t} - \hat{u})^2 + 2w^2(4m^2 - \hat{t} - \hat{u})(-2m^2 + \hat{t} + \hat{u})^2)],$$

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

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

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

$$M_{su} = \frac{4}{\hat{s}(\hat{u} - m^2)}[2g_s^4(m^4 - 2m^2\hat{t} + \hat{t}\,\hat{u}) - wd^3 m(-2m^2 + \hat{t} + \hat{u})^2(m^4 + 4m^2\hat{u} + 3\hat{u}^2) + g_s^2 d(3d\hat{u}(m^4 + m^2(\hat{t} - 3\hat{u}) + \hat{t}\,\hat{u}) + wm(\hat{t} - \hat{u})(-2m^2 + \hat{t} + \hat{u})^2)],$$

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

where $d_1 = d_q/2\Lambda$, $d = d_{\tilde{g}}/4\Lambda$, 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 [12,13]:

$$\frac{d\hat{\sigma}(gg \to \tilde{g}\,\tilde{g})}{d\hat{t}} = \frac{9\pi\alpha_s^2}{4\hat{s}^2}\bigg[\frac{2(m^2-\hat{t})(m^2-\hat{u})}{\hat{s}^2} - \frac{m^4-\hat{t}\,\hat{u}+m^2(3\hat{t}+\hat{u})}{(m^2-\hat{t})^2} - \frac{m^4-\hat{t}\,\hat{u}+m^2(\hat{t}+3\hat{u})}{(m^2-\hat{u})^2} + \frac{m^4-2m^2\hat{t}+\hat{t}\,\hat{u}}{\hat{s}(\hat{u}-m^2)} + \frac{m^4-2m^2\hat{u}+\hat{t}\,\hat{u}}{\hat{s}(\hat{t}-m^2)} + \frac{m^2(\hat{s}-4m^2)}{(m^2-\hat{t})(m^2-\hat{u})}\bigg], \tag{B3}$$

but we should note that the denominators (or numerators) of $\hat{s}-\hat{t}$ and $\hat{s}-\hat{u}$ terms should be exchanged in Eq. (3.10) of Ref. [13] and Eq. (3.1) of Ref. [12], which seem to be typographical errors.

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