Hadronic production of doubly charmed baryons via charm excitation in the proton

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(Received 19 February 2001; published 2 July 2001)

The production of baryons containing two charmed quarks (Ξ^*_{cc}or Ξ_{cc}) in hadronic interactions at high energies and large transverse momenta is considered. It is supposed that the Ξ_{cc} baryon is formed during a nonperturbative fragmentation of the (cc) diquark, which was produced in the hard process of c-quark scattering from the colliding protons: $c+c\to(cc)+g$. It is shown that such a mechanism enhances the expected doubly charmed baryon production cross section at the Fermilab Tevatron and CERN LHC colliders approximately 2 times in contrast with predictions, obtained in the model of gluon-gluon production of (cc) diquarks in the leading order of perturbative QCD.

DOI: 10.1103/PhysRevD.64.034006 PACS number(s): 14.20.Lq, 12.38.Bx, 13.30.−a, 13.60.Rj

I. INTRODUCTION

Doubly heavy baryons take a special place among baryons which contain heavy quarks. The existence of two heavy quarks causes the brightly expressed quark-diquark structure of the Ξ_{cc} baryon, in a wave function in which the configuration with the compact heavy (QQ) diquark dominates. Regularity in a spectrum of mass of doubly heavy baryons appears similar in many respects to a case of mesons containing one heavy quark [1–4]. Production mechanisms for (QQq) baryons and $(Q\bar{q})$ mesons also have common features. At the first stage a compact heavy (QQ) diquark is formed, then it fragments in a final (QQq) baryon, picking up a light quark. The calculations of production cross sections for doubly heavy baryons in ep and pp interactions were made recently as in the model of a hard fragmentation of a heavy quark in a doubly heavy diquark [5–7] as within the framework of the model of precise calculation of the cross section of a gluon-gluon fusion into doubly heavy diquarks and two heavy antiquarks in the leading order of the perturbation theory of QCD [8–10].

The mechanism of production of hadrons containing charmed quarks, based on consideration of hard parton subprocesses with one c quark in an initial state, was discussed earlier in other papers [11–13]. It was shown that in the region of a large transferred momentum ($Q^2 \gg m_c^2$, where m_c is the charmed quark mass) the concept of a charm excitation in a hadron does not contradict the parton model and allows us to effectively take into account the contribution of the high orders of the perturbative QCD theory to the Born approximation. However, there is an open problem of the ‘‘double score,’’ which is determined by the fact that the part of the Born diagram with the birth of two heavy quarks in a gluon-gluon fusion can be interpreted the same as the diagram with the charm excitation in one of the initial protons. These diagrams give leading in α_s contribution in the c-quark perturbative, so-called pointlike structure function (SF) of a proton. As to the nonperturbative contribution in the c-quark SF of a proton [14] it does not depend upon Q^2 and becomes very small at $Q^2 \gg m_c^2$.

For example, Fig. 1 shows one of 36 Born diagrams, which have the order α_s^4, describing the production of the (cc) diquark in the gluon-gluon fusion subprocess. The experience in the calculation of heavy quark production cross sections in a gluon-gluon fusion demonstrates that the contribution of the next order of the perturbative QCD in α_s can be comparable with the contribution of the Born diagrams. In the case of gluon-gluon production of the two pairs of heavy quarks there will be more than three hundred diagrams with additional gluons in the final state, which have the order α_s^5, and their direct calculation is now considered difficult.

II. SUBPROCESS $c+c\to(cc)+g$

In this paper the model of (cc)-diquark production in proton-proton interactions, based on the mechanism of the charm excitation in a proton is considered. It is supposed that the (cc) diquark is formed during scattering of c quarks from colliding protons with radiation of a hard gluon, i.e., in the parton subprocess

$$c+c\to(cc)+g. \tag{2.1}$$

The Feynman diagrams of the parton subprocess (2.1) are shown in Fig. 2, where q_1 and q_2 are the four momenta of the initial c quarks, k is the four momentum of the final gluon, and p is the four-momentum of the diquark, which is divided equally between the final c quarks. The doubly heavy diquark is considered as the bound state of two c

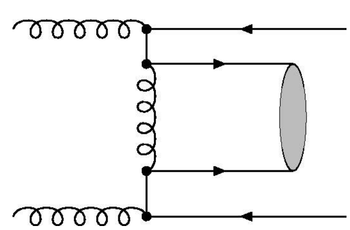

FIG. 1. One of the Born diagrams used for description subprocess $g+g\to(cc)+\bar{c}+\bar{c}$.

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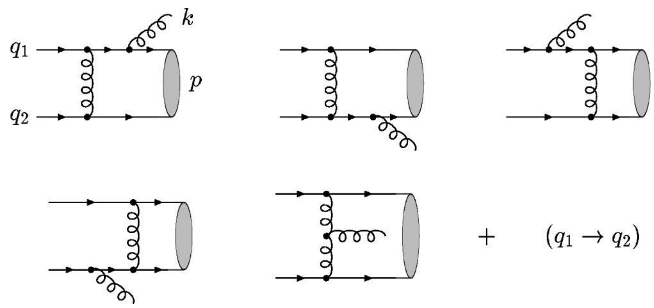

FIG. 2. Diagrams used for description subprocess $c+c\to(cc)+g$.

quarks in the antitriplet color state and in the vector spin state. If i and j are color indexes of initial quarks, and m is the color index of a final diquark, the amplitude of production of the (cc) diquark $M_{ijm}[c+c\to(cc)+g]$ is connected with the amplitude of production of two c quarks with four-momenta $p_1=p_2=p/2$ as follows:

$$\begin{aligned} M_{ijm}&[c+c\to(cc)+g,p] \\ &=K_0\frac{\varepsilon^{nmk}}{\sqrt{2}}M_{ijnk}(c+c\to c+c+g,p_1=p_2=p/2), \end{aligned} \tag{2.2}$$

where $K_0=\sqrt{(2/m_{cc})}\Psi_{cc}(0)$, $m_{cc}=2m_c$ is the diquark mass, $\Psi_{cc}(0)$ is the diquark wave function in zero point, $\varepsilon^{nmk}/\sqrt{2}$ is the color part of a diquark wave function. Considering the spin degrees of freedom of c quarks and the (cc) diquark, we have the following conformity between amplitudes of the birth of free quarks and a diquark with fixed spin projections (without color indexes and common factor K_0):

$$\begin{aligned} &M[c+c\to(cc)+g,s_z=+1] \\ &\quad\sim M(c+c\to c+c+g,s_{1z}=+\tfrac{1}{2},s_{2z}=+\tfrac{1}{2}) \end{aligned} \tag{2.3}$$

$$\begin{aligned} &M[c+c\to(cc)+g,s_z=-1] \\ &\quad\sim M(c+c\to c+c+g,s_1z=-\tfrac{1}{2},s_{2z}=-\tfrac{1}{2}) \end{aligned} \tag{2.4}$$

$$\begin{aligned} &M[c+c\to(cc)+g,s_z=0] \\ &\quad\sim\frac{1}{\sqrt{2}}[M(c+c\to c+c+g,s_1z=+\tfrac{1}{2},s_{2z}=-\tfrac{1}{2}) \\ &\qquad+M(c+c\to c+c+g,s_{1z}=-\tfrac{1}{2},s_{2z}=+\tfrac{1}{2})]. \end{aligned} \tag{2.5}$$

Because the wave function of the (cc) diquark is antisymmetric on the color index and symmetric on remaining indexes, the production of the scalar (cc) diquark is forbidden, i.e.,

$$\begin{aligned} &M(c+c\to c+c+g,s_{1z}=+\tfrac{1}{2},s_{2z}=-\tfrac{1}{2}) \\ &\quad-M(c+c\to c+c+g,s_{1z}=-\tfrac{1}{2},s_{2z}=+\tfrac{1}{2})=0. \end{aligned} \tag{2.6}$$

Amplitudes adequate to the diagrams in Fig. 2, where the final c quarks are in the arbitrary spin states, are written out below, without the color factors and the common factor K_0,

$$M_1=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\mu(\hat{p}_1+\hat{k}+m_c)\gamma^\nu U(q_1)\overline{U}(p_2)\gamma_\nu U(q_2)/[(p_1+k)^2-m_c^2](p_2-q_2)^2, \tag{2.7}$$

$$M_2=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\nu U(q_1)\overline{U}(p_2)\gamma^\mu(\hat{p}_2+\hat{k}+m_c)\gamma_\nu U(q_2)/[(p_2+k)^2-m_c^2](q_1-p_1)^2, \tag{2.8}$$

$$M_3=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\nu(\hat{q}_1-\hat{k}+m_c)\gamma^\mu U(q_1)\overline{U}(p_2)\gamma_\nu U(q_2)/[(q_1-k)^2-m_c^2](p_2-q_2)^2, \tag{2.9}$$

$$M_4=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\nu U(q_1)\overline{U}(p_2)\gamma^\nu(\hat{q}_2-\hat{k}+m_c)\gamma_\mu U(q_2)/[(q_2-k)^2-m_c^2](q_1-p_1)^2, \tag{2.10}$$

$$M_5=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\nu U(q_1)\overline{U}(p_2)\gamma^\lambda U(q_2)G_{\lambda\mu\nu}(p_2-q_2,k,p_1-q_1)/(q_1-p_1)^2(p_2-q_2)^2 \tag{2.11}$$

where $g_s=\sqrt{4\pi\alpha_s}$, α_s is the strong coupling constant, $G_{\lambda\mu\nu}(p,k,q)=(p-k)_\nu g_{\lambda\mu}+(k-q)_\lambda g_{\nu\mu}+(q-p)_\mu g_{\nu\lambda}$. Let us remark that the amplitudes M_6-M_{10} are received by replacement of the initial quark momenta $q_1\leftrightarrow q_2$ in the amplitudes M_1-M_5 and are given a minus sign that allows for the antisymmetrization of the initial state of two identical c quarks. The corresponding color factors are presented by the following expressions:

$$C_1=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^c_{nl}T^b_{li})(T^b_{kj}),\quad C_6=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^c_{nl}T^b_{lj})(T^b_{ki}),$$

$$C_2=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^b_{ni})(T^c_{kl}T^b_{lj}),\quad C_7=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^c_{nj})(T^c_{kl}T^b_{li}),$$

$$C_3=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^b_{nl}T^c_{li})(T^b_{kj}),\quad C_8=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^b_{nl}T^c_{lj})(T^b_{ki}), \tag{2.12}$$

$$C_4=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^b_{ni})(T^b_{kl}T^c_{lj}),\quad C_8=\frac{\varepsilon^{nmk}}{\sqrt{2}}(T^b_{nj})(T^b_{kl}T^c_{li}),$$

$$C_5=\frac{i\varepsilon^{nmk}}{\sqrt{2}}(T^b_{ni})(T^a_{kj})f^{bac},$$

$$C_{10}=\frac{i\varepsilon^{nmk}}{\sqrt{2}}(T^b_{nj})(T^a_{ki})f^{bac}.$$

Using the known property of a completely antisymmetric tensor of the third rank

$$\varepsilon_{n'mk'}\varepsilon^{nmk}=\delta^n_{n'}\delta^k_{k'}-\delta^k_{n'}\delta^n_{k'},$$

it is easy to find products of the color factors $C_{i,j}=\Sigma_{color}C_iC_j^*$, which are presented in Appendix A.

The method of the calculation of a production amplitude of a bound nonrelativistic state of quarks in the fixed spin state is based on a formalism of the projection operator [15]. Using properties of the charge conjugation matrix $C=i\gamma_2\gamma_0$, we can link a scattering amplitude of a quark on a quark with a scattering amplitude of an antiquark on a quark, for example

$$\begin{aligned}M_1&=g_s^3\varepsilon_\mu(k)\overline{U}(p_1)\gamma^\mu(\hat{p}_1+\hat{k}+m_c)\gamma^\nu U(q_1)\overline{U}(p_2)\gamma_\nu U(q_2)/[(p_1+k)^2-m_c^2](p_2-q_2)^2\\&=g_s^3\varepsilon_\mu(k)\overline{V}(q_1)\gamma^\nu(-\hat{p}_1-\hat{k}+m_c)\gamma^\mu V(p_1)\overline{U}(p_2)\gamma_\nu U(q_2)/[(p_1+k)^2-m_c^2](p_2-q_2)^2.\end{aligned}\quad(2.13)$$

As it may be shown, at $p_1=p_2=p/2$ one has

$$V(p_1,s_{1z}=-\tfrac{1}{2})\overline{U}(p_2,s_{2z}=+\tfrac{1}{2})\sim\hat{\varepsilon}(p,s_z=+1)(\hat{p}+m_{cc}),$$

$$V(p_1,s_{1z}=+\tfrac{1}{2})\overline{U}(p_2,s_{2z}=-\tfrac{1}{2})\sim\hat{\varepsilon}(p,s_z=-1)(\hat{p}+m_{cc}),\quad(2.14)$$

$$\frac{1}{\sqrt{2}}[V(p_1,s_{1z}=-\tfrac{1}{2})\overline{U}(p_2,s_{2z}=+\tfrac{1}{2})+V(p_1,s_{1z}=+\tfrac{1}{2})\times\overline{U}(p_2,s_{2z}=-\tfrac{1}{2})]\sim\hat{\varepsilon}(p,s_z=0)(\hat{p}+m_{cc}),$$

where $\varepsilon^\mu(p)$ is the polarization four vector of a spin-1 particle. After following effective replacements

$$V(p_1)\overline{U}(p_2)\to\hat{\varepsilon}(p)(\hat{p}+m_{cc})\quad\text{and}\quad K_0\to K,\quad(2.15)$$

where $p_1=p_2=p/2$ and $K=\Psi(0)/2\sqrt{m_{cc}}$, amplitudes M_i, with corresponding color factors C_i, describe production of the (cc) diquark with fixed polarization. The square of the module of amplitude of the (cc)-diquark production after average on spin and color degrees of freedom is given by the following expression:

$$\overline{|\mathcal{M}|^2}=1/36K^2\sum_{i,j=1}^{10}\sum_{spin}M_i(p_1,p_2)M_j^*(p_1,p_2)C_{i,j},\quad(2.16)$$

where in the amplitudes M_i we have put $p_1=p_2=p/2$. The summation on vector diquark polarizations in the square of the amplitude of the process (2.1) was done using the standard formula

$$\sum_{spin}\varepsilon^\mu(p)\varepsilon^{*\nu}(p)=-g^{\mu\nu}+\frac{p^\mu p^\nu}{m_{cc}^2}.\quad(2.17)$$

The calculation of the value $F=\Sigma_{i,j}^{10}\Sigma_{spin}M_iM_j^*C_{i,j}$ has been executed using the package of analytical calculations FEYNCALC [16]. The answer is shown in Appendix B as a function of the standard Mandelstam variables $\hat{s}$ and $\hat{t}$.

III. RESULTS OF CALCULATIONS

In the parton model the cross section of a (cc)-diquark production in pp interactions is represented as follows:

$$\frac{d\sigma}{dp_\perp}[pp\to(cc)+X]=p_\perp\int_{y_{min}}^{y_{max}}dy\int_{x_{1min}}^{1}dx_1\,C_p(x_1,Q^2)C_p(x_2,Q^2)\times\frac{\overline{|\mathcal{M}|^2}}{16\pi[s(s-m_{cc}^2)]^{1/2}}\times\frac{1}{x_1s-\sqrt{s}m_\perp e^y},\quad(3.1)$$

where

$$x_2=\frac{x_1\sqrt{s}m_\perp e^{-y}-\frac{3}{2}m_{cc}^2}{x_1s-\sqrt{s}m_\perp e^y},$$

$$x_{1min}=\frac{\sqrt{s}m_\perp e^y-\frac{3}{2}m_{cc}^2}{s-\sqrt{s}m_\perp e^{-y}}.$$

$C_p(x,Q^2)$ is the c-quark distribution function in a proton at $Q^2=m_\perp^2=m_{cc}^2+p_\perp^2$, $p_\perp$ is the diquark transverse momentum, y is the rapidity of the diquark in c.m.f. of colliding protons,

$$\begin{aligned}\hat{s}&=(q_1+q_2)^2=x_1x_2s+\frac{m_{cc}^2}{2},\\\hat{t}&=(q_1-p)^2=\tfrac{3}{2}m_{cc}^2-x_1\sqrt{s}m_\perp e^{-y},\\\hat{u}&=(q_2-p)^2=\tfrac{3}{2}m_{cc}^2-x_2\sqrt{s}m_\perp e^{y}.\end{aligned}\quad(3.2)$$

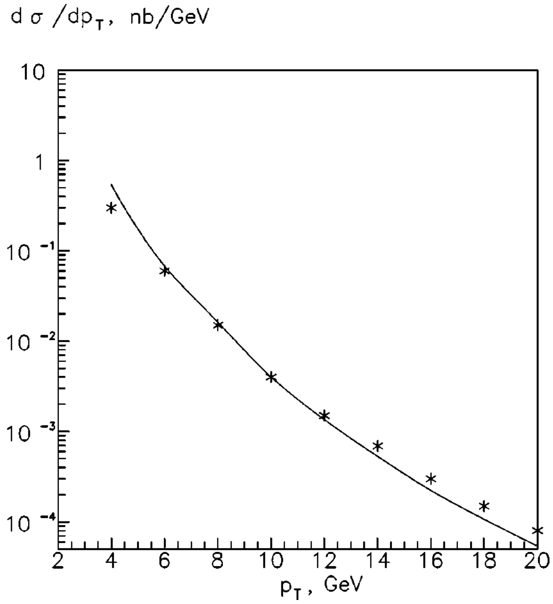

FIG. 3. Cross section of Ξ_{cc}-baryon production at $\sqrt{s}=1.8$ TeV and $|y|<1$. Stars (*) show the results of the calculation from paper [10], curve is our result obtained in the model of a charm excitation in colliding protons.

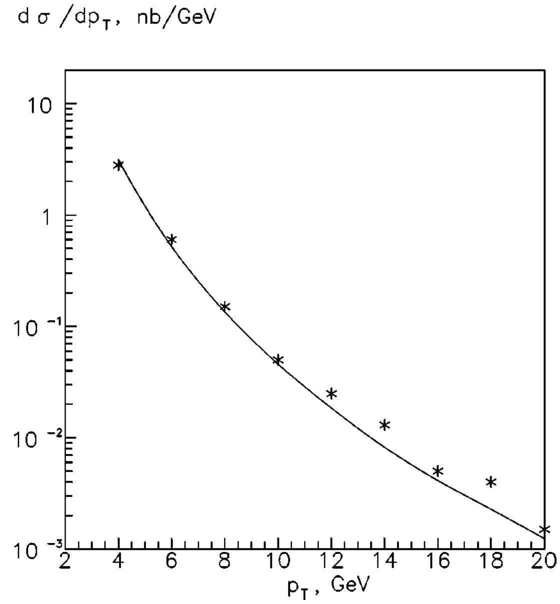

FIG. 4. Cross section of Ξ_{cc}-baryon production at $\sqrt{s}=14$ TeV and $|y|<1$. Stars (*) show the results of the calculation from paper [10], curve is our result obtained in the model of a charm excitation in colliding protons.

It is supposed that spin-$\frac{1}{2}$ and spin-$\frac{3}{2}$ Ξ_{cc} baryons' relative yield is $1:2$ as it is predicted by the simple counting rule for the spin states. The production cross section of Ξ_{cc} baryons plus Ξ_{cc}^* baryons in our approach is connected with the production cross section of the (cc) diquark within the framework of a model of a nonperturbative fragmentation as follows:

$$\frac{d\sigma}{dp_\perp}(pp\to\Xi_{cc}+X)=\int_0^1\frac{dz}{z}\,\frac{d\sigma}{dp_\perp'}\times\left[pp\to(cc)X,p_\perp'=\frac{p_\perp}{z}\right]\times D_{(cc)\to\Xi_{cc}}(z,Q^2), \qquad (3.3)$$

where $D_{(cc)\to\Xi_{cc}}(z,Q^2)$ is the phenomenological function of a fragmentation, normalized approximately on unity, as a total probability of a transition (cc) diquark in the final doubly charmed baryon. At $Q^2=m_{cc}^2$ the fragmentation function is selected in the standard form [17],

$$D_{(cc)\to\Xi_{cc}}(z,Q^2)=\frac{D_0}{z\left(m_{cc}^2-\frac{m_\Xi^2}{z}-\frac{m_q^2}{1-z}\right)^2}, \qquad (3.4)$$

where $m_\Xi=m_{cc}+m_q$ is the Ξ_{cc}-baryon mass, m_q is the light quark mass, and D_0 is the rate-fixing constant. The fragmentation function for $Q^2>Q_0^2$ can be determined by solving the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation [18]. Following Ref. [10], at numerical calculations, we have used the following values of parameters: $m_{cc}=3.4$ GeV, $\alpha_s=0.2$, $|\Psi_{cc}(0)|^2=0.03$ GeV^3, $m_q=0.3$ GeV. For a c-quark distribution function in a proton $C_p(x,Q^2)$ the parametrization CTEQ5 [19] was used. In Figs. 3 and 4 at $\sqrt{s}=1.8$ TeV and $\sqrt{s}=14$ TeV, accordingly, the curves show results of our calculations of the $p_\perp$ spectra ($|y|<1$) of Ξ_{cc} baryons, and the stars show results of the calculations from paper [10], adequate to the contribution of the gluon-gluon fusion production of Ξ_{cc} baryons in a Born approximation. Thus, our calculations demonstrate that the observed production cross section of Ξ_{cc} baryons at the Fermilab Tevatron and Large Hadron Collider (LHC) can be approximately 2 times more at the expense of the contribution of the parton subprocess $c+c\to(cc)+g$, than it was predicted earlier in Refs. [8,10].

ACKNOWLEDGMENTS

The authors thank S. P. Baranov, V. V. Kiselev, and A. K. Likhoded for useful discussions. The work is executed with the support of the Program ''Universities of Russia – Basic Researches'' (Project 02.01.03).

APPENDIX A

$$C_{1,1}=\tfrac{7}{9},\quad C_{2,3}=\tfrac{10}{9},\quad C_{3,6}=-\tfrac{10}{9},\quad C_{4,10}=-2,\quad C_{6,10}=1,$$

$$C_{1,2}=\tfrac{1}{9},\quad C_{2,4}=-\tfrac{2}{9},\quad C_{3,7}=\tfrac{2}{9},\quad C_{5,5}=3,\quad C_{7,7}=\tfrac{7}{9},$$

$$C_{1,3}=-\tfrac{2}{9},\quad C_{2,5}=1,\quad C_{3,8}=\tfrac{8}{9},\quad C_{5,6}=-1,\quad C_{7,8}=\tfrac{10}{9},$$
$$C_{1,4}=\tfrac{10}{9},\quad C_{2,6}=-\tfrac{7}{9},\quad C_{3,9}=-\tfrac{16}{9},\quad C_{5,7}=1,\quad C_{7,9}=-\tfrac{2}{9},$$
$$C_{1,5}=-1,\quad C_{2,7}=-\tfrac{1}{9},\quad C_{3,10}=2,\quad C_{5,8}=2,\quad C_{7,10}=1,$$
$$C_{1,6}=-\tfrac{1}{9},\quad C_{2,8}=\tfrac{2}{9},\quad C_{4,4}=\tfrac{16}{9},\quad C_{5,9}=-2,\quad C_{8,8}=\tfrac{16}{9},$$
$$C_{1,7}=-\tfrac{7}{9},\quad C_{2,9}=-\tfrac{10}{9},\quad C_{4,5}=-2,\quad C_{5,10}=3,\quad C_{8,9}=-\tfrac{8}{9},$$
$$C_{1,8}=-\tfrac{10}{9},\quad C_{2,10}=1,\quad C_{4,6}=\tfrac{2}{9},\quad C_{6,6}=\tfrac{7}{9},\quad C_{8,10}=2,$$
$$C_{1,9}=\tfrac{2}{9},\quad C_{3,3}=\tfrac{16}{9},\quad C_{4,7}=-\tfrac{10}{9},\quad C_{6,7}=\tfrac{1}{9},\quad C_{9,9}=\tfrac{16}{9},$$
$$C_{1,10}=-1,\quad C_{3,4}=-\tfrac{8}{9},\quad C_{4,8}=-\tfrac{16}{9},\quad C_{6,8}=-\tfrac{2}{9},\quad C_{9,10}=-2,$$
$$C_{2,2}=\tfrac{7}{9},\quad C_{3,5}=2,\quad C_{4,9}=\tfrac{8}{9},\quad C_{6,9}=\tfrac{10}{9},\quad C_{10,10}=3.$$

APPENDIX B

$$F=-(4\pi\alpha_s)^3\frac{512F_N}{9F_D}, \tag{B1}$$

$$\begin{aligned}F_N=&\,26361\,M^{18}-6\,M^{16}(20513\,s+67472\,t)+16\,M^{14}(14621\,s^2+100076\,s\,t-86020\,t^2)\\&-16\,M^{12}(14873\,s^3+122408\,s^2\,t-657280\,s\,t^2-382560\,t^3)\\&+64\,M^{10}(2101\,s^4-658\,s^3\,t-509652\,s^2\,t^2-468736\,s\,t^3-170408\,t^4)\\&+65536\,s\,t^2\,(s+t)^2\,(9\,s^4+11\,s^3\,t+13\,s^2\,t^2+4\,s\,t^3+2\,t^4)\\&-256\,M^8(120\,s^5-8749\,s^4\,t-201737\,s^3\,t^2-255896\,s^2\,t^3-149332\,s\,t^4-44640\,t^5)\\&-1024\,M^6(7\,s^6+2180\,s^5\,t+44390\,s^4\,t^2+74060\,s^3\,t^3+57876\,s^2\,t^4+28176\,s\,t^5+7184\,t^6)\\&-16384\,M^2\,t\,(10\,s^7+353\,s^6\,t+924\,s^5\,t^2+1151\,s^4\,t^3+898\,s^3\,t^4+460\,s^2\,t^5+160\,s\,t^6+28\,t^7)\\&+4096\,M^4\,(s^7+235\,s^6\,t+5484\,s^5\,t^2+11610\,s^4\,t^3+11609\,s^3\,t^4+7368\,s^2\,t^5+3056\,s\,t^6+672\,t^7),\end{aligned} \tag{B2}$$

$$F_D=(M^2-s)^2\,(M^2-4\,t)^4\,[5\,M^2-4\,(s+t)]^4. \tag{B3}$$

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