PRODUCTION OF A HIGGS PSEUDOSCALAR PLUS TWO JETS IN HADRONIC COLLISIONS

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ABSTRACT

We consider the production of a Higgs pseudoscalar accompanied by two jets in hadronic collisions. We work in the limit that the top quark is much heavier than the Higgs pseudoscalar and use an effective Lagrangian for the interactions of gluons with the pseudoscalar. We compute the amplitudes involving: 1) four gluons and the pseudoscalar, 2) two quarks, two gluons and the pseudoscalar and 3) four quarks and the pseudoscalar. We find that the pseudoscalar amplitudes are nearly identical to those for the scalar case, the only differences being the overall size and the relative signs between terms. We present numerical cross sections for proton-proton collisions with center-of-mass energy 14 TeV.

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1 Introduction

The minimal model of electroweak symmetry breaking contains one complex scalar doublet, three components of which become the longitudinal degrees of freedom of the $W^\pm$ and $Z$. The remaining component of the doublet is the so-called Higgs boson. However, the minimal model with one doublet has no a priori justification and there are several motivations for considering models with enlarged Higgs sectors, either containing more doublets, singlets or more exotic representations. For example, supersymmetric models require at least two doublets. Likewise, at least two doublets are required to produce CP violation in the Higgs sector [1].

Models with enlarged Higgs sectors have richer particle content than the minimal model; in general, neutral pseudoscalars (with respect to their fermion couplings) and charged scalars as well as extra neutral scalars are present. In this paper we will study the production of a Higgs pseudoscalar ($A$) accompanied by two jets. Study of such processes gives information about the environment in which the Higgs pseudoscalar is produced: additional jets may be used as tags or be confused with decay products. The production of additional jets also influences the transverse momentum spectrum of the pseudoscalar.

Production of a Higgs pseudoscalar in hadronic collisions proceeds primarily via gluon fusion through a top-quark loop (unless the coupling to bottom quarks is greatly enhanced). We will focus on the case of a light pseudoscalar and work in the heavy-top-quark limit: $m_t \gg M_A$. In this limit, one can use an effective Lagrangian to couple the pseudoscalar to gluons. The production of a Higgs pseudoscalar plus one jet has been considered previously [2, 3]. We compute all the contributions to the cross section for production of a pseudoscalar plus two jets: $gg \rightarrow ggA$, $gg \rightarrow qqA$, $gg \rightarrow qgA$, $qq \rightarrow ggA$, $qq \rightarrow qqA$, where ‘$q$’ stands generically for a quark or anti-quark of undetermined flavor.

The organization of the paper is as follows. The effective Lagrangian is discussed in Section 2. Section 3 contains the spinor product formalism in which the amplitudes will be computed. The Higgs pseudoscalar plus four gluon amplitude is presented in Section 4. Sections 5 and 6 contain the calculations of the amplitude involving a Higgs boson plus a quark anti-quark pair and two gluons and the amplitude for a Higgs boson plus two quark anti-quark pairs, respectively. Section 7 contains our numerical results.
2 The Effective Lagrangian

We write the generic coupling of a quark to the Higgs pseudoscalar as $R_q m_q \gamma_5 / v$, where $R_q$ is a flavor/model dependent factor which we will henceforth set equal to 1, $m_q$ is the mass of the quark, and $v = 246$ GeV is the vacuum expectation value parameter. The production mechanism in which we are interested is $gg \rightarrow A$ which occurs through a quark loop where the only contribution which we will consider is that of the top quark. In the limit in which the top quark is heavy, $m_{\text{top}} \gg M_A$, the cross section can be computed via the following effective Lagrangian \[2, 3\]

$$\mathcal{L}_{\text{eff}} = g_A C^a_{\mu\nu} \tilde{G}^a_{\mu\nu} A,$$  

(1)

where $C^a_{\mu\nu}$ is the field strength of the SU(3) color gluon field, $\tilde{G}^a_{\mu\nu}$ is its dual, $\tilde{G}^a_{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} G^a_{\rho\sigma}$, and $A$ is the pseudoscalar field. The effective coupling is given by $g_A = \frac{\alpha_s}{(8\pi v)}$. The effective Lagrangian generates vertices involving the Higgs boson and two or three gluons:

$$V_2(k^a_{1\mu}, k^b_{2\nu}) = -ig_A \delta^{ab} \epsilon^{\mu\nu\rho\sigma} k^\rho_1 k^\sigma_2,$$

$$V_3(k^a_{1\mu}, k^b_{2\nu}, k^c_{3\rho}) = -gg_A f^{abc} \epsilon^{\mu\nu\rho\sigma} (k^\rho_1 + k^\nu_2 + k^\sigma_3),$$  

(2)

where the $k_i$ are the gluon momenta directed outward and $a, b, c$ are their color indices. The four-gluon vertex vanishes as it is proportional to the completely antisymmetric combination of structure constants:

$$f^{abc} f^{cde} - f^{ace} f^{bde} + f^{ade} f^{bce} =$$

$$-2 \text{tr} \{ [T^a, T^b][T^c, T^d] - [T^a, T^c][T^b, T^d] + [T^a, T^d][T^b, T^c] \} = 0,$$  

(3)

where the $T^i$ are the SU(3) generators. It is straightforward to use this Lagrangian to obtain the $\mathcal{O}(\alpha_s^3)$ contributions to the process $gg \rightarrow A$ \[2, 3\]. These radiative corrections increase the lowest order rate by a factor of 1.5 to 2. Part of the calculation of the $\mathcal{O}(\alpha_s^3)$ radiative corrections to $gg \rightarrow A$ is the computation of the cross sections for $gg \rightarrow Ag$ and $gq \rightarrow Aq$ summed over spins. One finds that these cross sections are identical to their counterparts for Higgs scalars, up to an overall factor. Calculation of the
helicity amplitudes for these processes (using the spinor product formalism
to be discussed below) yields the expected result that they too are equal to
their counterparts, up to overall factors which include phases.

One might conjecture that the amplitudes for a Higgs pseudoscalar plus
four light partons would follow the same pattern. However, the amplitudes
involving the Higgs pseudoscalar must vanish in the limit that the momentum
of the Higgs pseudoscalar goes to zero. This is readily seen from the structure
of the three- and four-point vertices in Eq. (2). They each can be rewritten to
be explicitly proportional to the momentum of the Higgs pseudoscalar. The
amplitudes for Higgs scalars can have non-zero limits when the momentum
of the Higgs scalar vanishes and so the pseudoscalar amplitudes must have a
different form.

3 Spinor Product Formalism

We are interested in processes in which all the particles except the Higgs
pseudoscalar are massless. Each amplitude can be expressed in terms of
spinors in a Weyl basis. For light-like momentum $p$ we introduce spinors

\[ |p\pm\rangle = \frac{1}{2}(1 \pm \gamma_5)u(p) = \frac{1}{2}(1 \mp \gamma_5)v(p) \]

\[ \langle p|\pm\rangle = \bar{u}(p)\frac{1}{2}(1 \mp \gamma_5) = \bar{v}(p)\frac{1}{2}(1 \mp \gamma_5). \]  

(4)

Polarization vectors for massless vector bosons can be written in terms of
these spinors. For a gluon of momentum $k$ and positive or negative helicity

\[ e^\mu_\pm = \frac{\langle q|\gamma^\mu|k\pm\rangle}{\sqrt{2}\langle q|\mp|k\pm\rangle}, \]  

(5)

where the reference momentum $q$ satisfies $q^2 = 0$ and $q \cdot k \neq 0$ but is otherwise
arbitrary. Each helicity amplitude can be expressed in terms of products of
these spinors:

\[ \langle p-|q+\rangle = -\langle q-|p+\rangle \equiv \langle pq\rangle, \]

\[ \langle p+|q-\rangle = -\langle q+|p-\rangle \equiv [pq]. \]  

(6)
The identities
\[ \hat{p} = |p+\rangle\langle p+| + |p-\rangle\langle p-| \] (7)
and
\[ \langle p\pm|\gamma_{\mu}|q\pm\rangle\gamma_{\mu} = 2(|q\pm\rangle\langle p\pm| + |p\mp\rangle\langle q\mp|) \] (8)
allow products of spinors and Dirac matrices to be written in terms of spinor products.

Amplitudes for processes involving the Higgs pseudoscalar contain expressions of the form \( \epsilon_{\mu\nu\rho\sigma}w^{\mu}x^{\nu}y^{\rho}z^{\sigma} \) where \( w, x, y, z \) are momenta, polarization vectors, or fermion currents. These contractions can be written in terms of spinor products through the following procedure. We first write
\[ \epsilon_{\mu\nu\rho\sigma}w^{\mu}x^{\nu}y^{\rho}z^{\sigma} = \frac{1}{4i} \text{tr}\{\hat{w}\hat{x}\hat{y}\hat{z}\gamma_{5}\} = \frac{1}{4i} \text{tr}\{\hat{w}\hat{x}\hat{y}\hat{z}(P_+ - P_-)\}, \] (9)
where the projection operators are \( P_{\pm} = (1 \pm \gamma_5)/2 \). Using Eq. (7) for momenta and Eq. (8) for polarization vectors and fermion currents, each slashed vector can be written in terms of outer products of spinors:
\[ \hat{w} = w_+|w_1+\rangle\langle w_2+| + w_-|w_3-\rangle\langle w_4-|. \] (10)
Inserting Eq. (10) into Eq. (9) and expressing the trace in terms of matrix multiplication, we have
\[ \epsilon_{\mu\nu\rho\sigma}w^{\mu}x^{\nu}y^{\rho}z^{\sigma} = \frac{1}{4i}(w_+\langle w_2+|\hat{x}\hat{y}\hat{z}|w_1+\rangle - w_-\langle w_4-|\hat{x}\hat{y}\hat{z}|w_3-\rangle), \] (11)
which reduces to spinor products upon application of Eq. (10) to \( \hat{x}, \hat{y}, \) and \( \hat{z} \).

For the remainder of the paper we will use the convention that all the particles are outgoing. The amplitudes for the various processes involving two incoming massless particles and two outgoing massless particles plus a Higgs pseudoscalar can then be obtained by crossing symmetry. The momenta of the massless particles are labeled \( p_1, p_2, p_3, p_4 \) with the Higgs pseudoscalar momentum being \( p_\lambda \). Our convention is then \( p_1 + p_2 + p_3 + p_4 + p_\lambda = 0 \). We will use the shorthand notations \( \langle p_ip_j \rangle = \langle ij \rangle, [p_ip_j] = [ij], (p_i + p_j)^2 = S_{ij}, \) and \( (p_i + p_j + p_k)^2 = S_{ijk} \).
4 Agggg Amplitude

The Agggg amplitude is obtained by summing the 25 Feynman diagrams detailed in Fig. 1. (The diagrams are the same as the scalar case except for the absence of the vertex involving the pseudoscalar and four gluons [6, 7].) To facilitate the cancellations that simplify the amplitude we introduce the dual color decomposition. The scattering amplitude for a Higgs pseudoscalar and $n$ gluons with external momenta $p_1, \ldots p_n$, colors $a_1, \ldots a_n$, and helicities $\lambda_1, \ldots \lambda_n$ is written as [8, 9]

$$M = 2 g_A g^{n-2} \sum_{\text{perms}} \text{tr}(T^{a_1} \ldots T^{a_n}) m(p_1, \epsilon_1; \ldots; p_n, \epsilon_n),$$

(12)

where the sum is over the non-cyclic permutations of the momenta. The ordered sub-amplitudes $m(p_1, \epsilon_1; \ldots; p_n, \epsilon_n)$, which we abbreviate $m(1, \ldots, n)$, are invariant under cyclic permutations of the momenta, gauge transformations, and (modulo signs) reversal of the order of their arguments. They also factorize in the soft and collinear limits. For $n = 4$, the subamplitudes do not interfere in the sum over colors:

$$\sum_{\text{colors}} |M|^2 = \frac{g^2 g_A^2}{4} N^2 (N^2 - 1) \sum_{\text{perms}} |m(1, 2, 3, 4)|^2.$$

(13)

The complete set of sub-amplitudes can be obtained from the following three:

$$m(1^+, 2^+, 3^+, 4^+) = \frac{M_A^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41 \rangle}$$

(14)

$$m(1^-, 2^+, 3^+, 4^+) = -\frac{\langle 1^- | p_A | 3^- \rangle^2 \langle 24 \rangle^2}{S_{124} S_{12} S_{14}} - \frac{\langle 1^- | p_A | 4^- \rangle^2 \langle 23 \rangle^2}{S_{123} S_{12} S_{23}} - \frac{\langle 1^- | p_A | 2^- \rangle^2 \langle 34 \rangle^2}{S_{134} S_{14} S_{34}} + \frac{[24]}{[12] [23] [34] [41]} \left\{ S_{23} \langle 1^- | p_A | 2^- \rangle - S_{234} \langle 1^- | p_A | 4^- \rangle \right\}$$

(15)

$$m(1^-, 2^-, 3^+, 4^+) = -\frac{\langle 12 \rangle^4}{\langle 12 \rangle \langle 23 \rangle \langle 34 \rangle \langle 41 \rangle} + \frac{[34]^4}{[12] [23] [34] [41]}.$$

(16)

The structures containing $p_A$ can be expanded in terms of spinor products using Eq. (7) and momentum conservation. For example $\langle 1^- | p_A | 3^- \rangle = \ldots$
Permutations of \( m(1^+, 2^+, 3^+, 4^+) \) are obtained by permuting the momenta in the right side of Eq. (14). Permutations of \( m(1^-, 2^+, 3^+, 4^+) \) are obtained by permuting \( p_2, p_3 \) and \( p_4 \) in the right side of Eq. (15) then using the cyclic and reversal properties of the sub-amplitudes. Permutations of \( m(1^-, 2^-, 3^+, 4^+) \) are obtained by permuting the momenta in the denominators of the right side of Eq. (16) only. The amplitudes for the other helicity combinations can be obtained (modulo phases) by parity transformations.

Comparing these results to the scalar case \([6, 7]\), we see a remarkable similarity. The results for the helicity combinations in which helicity is not conserved, \(++++\) and \(−+++\), are identical to those for the scalar case and the result for the helicity-conserving \(−−++\) combination differs only in the relative sign between the two terms. All three sub-amplitudes vanish in the limit that the momentum of the pseudoscalar goes to zero. The behavior of the \(−+++\) amplitude in this limit is complicated by the fact that all the \(S_{ijk}\)'s vanish as well. However, momentum conservation implies that, for example, \(S_{123} = (p_4 + p_\Lambda)^2 \to 2p_4 \cdot p_\Lambda\) when \(p_\Lambda \to 0\). limit. Thus, the \(−+++\) amplitude is proportional to one power of \(p_\Lambda\). The \(−−++\) amplitude vanishes because the two terms in Eq. (16) cancel in the limit \(p_\Lambda \to 0\). [4].

5 The \(Aq\bar{q}gg\) Amplitude

The \(Aq\bar{q}gg\) amplitude can be obtained from the Feynman diagrams of Fig. 2. As was the case for the \(Agggg\) amplitude, the calculation can be simplified by judicious choice of color decomposition \([10, 9]\). The amplitude for a Higgs pseudoscalar, a quark–anti-quark pair with color indices \(i, j\), and \(n\) gluons with color indices \(a_1, ..., a_n\) can be written:

\[
\mathcal{M} = -ig^n g_\Lambda \sum_{\text{perms}} (T^{a_1} T^{a_2} ... T^{a_n})_{ij} m(p_1, \epsilon_1; ...; p_n, \epsilon_n),
\]

where the sum runs over all \(n!\) permutations of the gluons and the sub-amplitudes \(m(p_1, \epsilon_1; ...; p_n, \epsilon_n)\) have an implicit dependence on the momenta and helicities of the quark and anti-quark. For the case we are interested in there are only two subamplitudes which we will label as \(m(3, 4)\) and \(m(4, 3)\) since the gluon momenta are \(p_3\) and \(p_4\). Like the subamplitudes for the pure gluon case these subamplitudes are separately gauge independent and factorize in the soft gluon and collinear particle limits.
Since they are on the same fermion line, the quark and anti-quark must have opposite helicities. Labeling the helicity amplitudes by the helicity of the quark, anti-quark and the two gluons (in that order) we find

\[ m^{++-}(3,4) = \frac{(2-|p_A|^2)}{S_{124}} \left( \frac{1}{S_{12}} + \frac{1}{S_{14}} \right) - \frac{(2-|p_A|^2)}{S_{123}S_{12}} \left( \frac{1}{2} \right) \]

To get the subamplitude with the other ordering, \( m^{++-}(4,3) \), exchange \( p_3 \leftrightarrow p_4 \) in this expression. The other independent subamplitudes are

\[ m^{++-}(3,4) = \frac{\langle 24 \rangle^3}{\langle 12 \rangle\langle 23 \rangle\langle 34 \rangle} + \frac{[13]^3}{[12][14][34]} \]

\[ m^{++-}(4,3) = -\frac{[13]^2}{[12][24][34]} - \frac{\langle 14 \rangle^2}{\langle 12 \rangle\langle 13 \rangle\langle 34 \rangle} \]

The other helicity amplitudes (up to phases) can be obtained by parity, Bose symmetry, and charge conjugation [7].

Comparing to the results for the Higgs scalar we find the same pattern as in the four-gluon case. The helicity-violating case, \( +--- \), has the same subamplitudes as the scalar case, whereas the helicity conserving case, \( +--- \), differs only by a relative sign between the terms. Once again the subamplitudes vanish in the limit \( p_\alpha \to 0 \).

6 The \( Aq\bar{q}q\bar{q} \) Amplitude

The remaining processes producing a Higgs pseudoscalar plus two jets are those involving a combination of four quarks and anti-quarks. In the case where the two pairs are of different flavors the amplitude can be obtained from the Feynman diagram in Fig. 3. In the case when the two pairs are identical there is an additional diagram which can be obtained by switching the 2 \( \leftrightarrow \) 4 in the diagram of Fig. 3. We present the amplitude for the case of two different quark pairs, since the identical case can be obtained from it. The sole independent helicity amplitude can be labeled in terms of the helicities of the 1st quark, the 1st antiquark, the 2nd quark and the 2nd
antiquark (in that order):

\[\mathcal{M}^{+-+-} = ig_A g^2 T^a_{ij} T^a_{kl} \left( \frac{\langle 24 \rangle^2}{\langle 12 \rangle \langle 34 \rangle} - \frac{[13]^2}{[12][34]} \right). \tag{21}\]

Note that this result is identical to that for the scalar case except for the relative sign between the two terms. This sign difference causes the amplitude to vanish in the limit that the momentum of the pseudoscalar vanishes. The other helicity amplitudes can be obtained by parity and charge conjugation transformations.

7 Numerical Results and Conclusions

We will present numerical results for the CERN Large Hadron Collider (LHC) at a center-of-mass energy of \(\sqrt{S} = 14\) TeV. Since all the parton level cross sections are singular in the small \(p_T\) limit of one of the jets we will place a \(p_T\) cut on the outgoing jets. Since there are also collinear singularities we will require that the outgoing jets be separated by \(\Delta R \equiv \sqrt{\Delta \phi^2 + \Delta \eta^2} \geq 0.7\). We will also require the outgoing jets have rapidity \(|y| < 2.5\). Since there are no singularities depending on the momentum of the Higgs pseudoscalar we will allow it to be unconstrained, except for a \(p_T\) cut.

The total cross section for production of a Higgs pseudoscalar plus two jets is presented in Fig. 4. The dominant processes, which contribute roughly equally, are \(gg \rightarrow ggA\) and \(q(\bar{q})g \rightarrow q(\bar{q})g\). The cross section for each process can be obtained approximately by rescaling the scalar result: \(\sigma_A \simeq (A/g_A)^2 \sigma_H = (9/64) \sigma_H = (1/7.1) \sigma_H\), where \(A\) is the effective scalar coupling \(A = \alpha_s/8\pi v\) from Ref. [7]. The deviations from this approximate result range from a few per cent to 10\% for almost all the processes and for the total. The sole exception is the process involving four quarks/antiquarks which deviates from the rescaling by 10\%-20\% but contributes negligibly to the total. The largest deviations occur at the largest values of the \(p_T\) cutoff, as expected since the rescaling is exact in the small-\(p_T\) limit.

In summary, we have calculated the amplitudes for the production of a Higgs pseudoscalar accompanied by two jets. The calculation was performed in the heavy-top-quark limit using an effective Lagrangian. The amplitudes for the helicity-violating processes are identical in form to those for a scalar boson, differing only by an overall factor. In addition to the overall factor,
the helicity-conserving amplitudes have sign differences between terms which cause them to vanish in the limit $p_A \to 0$. We find that the cross section is around a few tenths of a picobarn at the LHC. Our results provide the four-dimensional part of the “real” corrections to Higgs pseudoscalar production at non-zero transverse momentum. They can be combined with the virtual corrections to complete the next-to-leading order calculation.

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Appendix. Squaring the Amplitudes

Since the pseudoscalar amplitudes are nearly identical in form to their scalar counterparts, the results for the squares of the scalar amplitudes can be easily modified to apply to the pseudoscalar case. Here we will only discuss the differences between the scalar and pseudoscalar cases and refer the reader to Ref. [7] for the scalar results.

In the $Agggg$ process the only subamplitudes which differ from the scalar case are those with gluon helicities $-\pm\pm$. The two independent subamplitudes squared are:

\[
|m(1^-, 2^-, 3^+, 4^+)|^2 = \frac{S_{12}^3}{S_{14}S_{23}S_{34}} + \frac{S_{34}^3}{S_{12}S_{14}S_{23}} - \frac{(1234)^2 - 2S_{12}S_{23}S_{34}S_{41}}{S_{14}S_{23}^2}
\]

\[
|m(1^-, 3^+, 2^-, 4^+)|^2 = \frac{S_{12}^4 + S_{34}^4}{S_{13}S_{14}S_{23}S_{34}}
\]

\[
- \left[ (\{1234\}^2 - 2S_{12}S_{23}S_{34}S_{41})(\{1243\}^2 - 2S_{12}S_{24}S_{43}S_{31})
\right.
\]

\[
+ \{1234\}\{1243\}(\{1234\}\{1243\} + 2S_{12}S_{34}\{1324\})
\]

\[
/ [2(S_{13}S_{14}S_{23}S_{34})^2].
\]

(Compare to Eq. (A12) from Ref. [7].)
In the $Aq\bar{q}gg$ process the amplitude squared for helicities $++--$ is given by Eqs. (A13)-(A16) of Ref. [7] with the parameter $A$ replaced by $g_A$. The other independent helicity amplitude squared is given by Eq. (A17) of Ref. [7] with the parameter $A$ replaced by $g_A$ and with

$$|m^{++-}(3, 4)|^2 = \frac{S^2_{13}}{S_{12}S_{14}S_{34}} + \frac{S^2_{24}}{S_{12}S_{23}S_{34}} - \frac{1}{S_{14}S_{23}S^2_{12}S^2_{34}} \times \left[ - \{1243\}^2\{1324\} - S_{13}S_{24}\{1234\}\{1243\} + S_{12}S_{13}S_{24}S_{34}\{1324\} \right],$$

$$|m^{+-++}(4, 3)|^2 = \frac{S^2_{13}S_{23}}{S_{12}S_{24}S_{34}} + \frac{S^2_{14}S^2_{24}}{S_{12}S_{13}S_{34}} - \{1243\}\{1234\} + S_{12}S_{34}\{1324\},$$

$$2\text{Re}[m^{++-}(3, 4)m^{+-++}(4, 3)^*] = -\{1324\} \left( \frac{S^2_{13}}{S_{14}S_{24}} + \frac{S^2_{24}}{S_{13}S_{34}} \right) - \frac{2}{S_{12}S_{23}S_{34}} \{1243\}^2 - 2S_{12}S_{13}S_{24}S_{34}. \quad (23)$$

(When comparing to Eq. (A18) of Ref. [7], note that the third equation is incorrect; it should contain a term opposite in sign to the second line of the third equation in Eq. (23) above.)

For the $Aq\bar{q}q'q'$ process, the square of Eq. (24) gives

$$|\mathcal{M}^{++-}|^2 = \frac{g^2g^4(N^2-1)}{4S_{12}S_{34}} \left[ (S_{13} + S_{24})^2 - \frac{\{1243\}^2}{S_{12}S_{34}} \right]. \quad (24)$$

In the case of identical quark pairs, there is a second diagram whose square can be obtained by switching $1 \leftrightarrow 3$ in Eq. (24). The interference term which arises is

$$-2\text{Re}[\mathcal{M}\mathcal{M}^* (1\leftrightarrow 3)] = \frac{-A^2g^4(N^2-1)}{4N} \left[ (S_{13} + S_{24})^2\{1234\} + 2\{1324\}\{1243\}\{1234\} \right]. \quad (25)$$

(Compare with Eqs. (A19) and (A20) from Ref. [7].)

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**Figure Captions**

**Fig. 1.** The Feynman diagrams for the $gggA$ amplitude. Curly lines represent gluons and the dashed lines represent the pseudoscalar. There are 12 diagrams of type a), 3 of type b), 4 of type c), and 6 of type d).

**Fig. 2.** The Feynman diagrams for the $qar{q}ggA$ amplitude. There is one diagram of type a), two of type b), 4 of type c) and one of type d).

**Fig. 3.** The Feynman diagram for the $qar{q}q'q'A$ amplitude. In the case when the quark pairs are identical there is a second diagram with the quark lines switched.

**Fig. 4.** The cross section for production of a Higgs boson plus two jets at the LHC for three values of the $p_T$ cut.
Figure 1
Figure 2
Figure 3
Figure 4

- $p_T > 25$ GeV
- $p_T > 50$ GeV
- $p_T > 100$ GeV