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**S. Dawson**

Physics Department, Brookhaven National Laboratory, Upton, NY 11973

and

**R. Kauffman**

Physics Department, Franklin and Marshall College, Lancaster, PA 17604

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# QCD CORRECTIONS TO HIGGS BOSON PRODUCTION: AN UPDATE

S. Dawson* and R. Kauffman†

* Physics Department, Brookhaven National Laboratory, Upton, N.Y. 11793
†Physics Department, Franklin and Marshall College, Lancaster, PA.

**Abstract**

We compute analytic results for the QCD corrections to Higgs boson production in hadronic collisions in the limit in which the top quark is much heavier than the Higgs boson. The first non-leading corrections of $\mathcal{O}(\alpha_s^3 M_H^2/m_t^2)$ are given and numerical results presented for the LHC.

## 1. INTRODUCTION

One of the prime motivations for the construction of high energy hadron colliders is to unravel the mechanism of electroweak symmetry breaking. In the standard model of electroweak interactions there exists a physical scalar boson, called the Higgs boson, whose interactions generate the non-zero masses of the $W$ and $Z$ gauge bosons. The couplings of the Higgs boson are completely specified in the standard model; the only unknown parameter is the mass. For a given mass, therefore, it is possible to predict the properties and production mechanisms of the standard model Higgs boson unambiguously. In this note, we discuss the two-loop QCD radiative corrections of $\mathcal{O}(\alpha_s^3)$ to the production of the Higgs boson in hadronic interactions.

A particularly interesting mass region in which to search for the Higgs boson is the intermediate mass region, $80 < M_H < 150$ GeV. The dominant decay mode for the intermediate mass Higgs boson is $H \rightarrow b\bar{b}$. However, the formidable QCD background to this decay will probably necessitate using rare decay modes such as $H \rightarrow \gamma\gamma$ to search for the intermediate mass Higgs boson. Since the number of events remaining after cuts to remove backgrounds is small, it is vital to understand the effects of radiative corrections in this region in order to determine the viability of the signal.

In the intermediate mass region, the primary production mechanism is gluon fusion through a top quark loop. For a heavy top quark, $m_t > 150$ GeV, it makes sense to expand the results in powers of $r \equiv M_H^2/m_t^2$. In such a limit, the computation of the two loop QCD radiative corrections becomes greatly simplified and it is possible to obtain analytic results. The leading corrections for $m_t \rightarrow \infty$ have been computed previously and found to significantly increase the cross section.[1, 2]

Here we present analytic results for the first non-leading corrections of $\mathcal{O}(\alpha_s^3 r)$ to Higgs boson production in hadronic collisions and confirm the numerical results of Ref.[2], valid for arbitrary $M_H/m_t$.

## 2. PREVIOUS RESULTS

The lowest order amplitude for the gluon fusion of a Higgs boson is sensitive to all of the quarks which can couple to the gluon and to the Higgs boson, but has the property that it primarily depends on the heaviest quark mass (in practice, on the top quark mass). The contribution to the amplitude from a single heavy quark with mass $m_t$ has the form,

## 3. CALCULATIONAL TECHNIQUES

The evaluation of the two-loop diagrams arising in the virtual corrections to $gg \rightarrow H$ is an extension of the techniques used in the case of $\gamma\gamma \to H$.[3] The basic strategy is to expand the loop integrals in powers of the external momenta over $m_t$ at every stage. This technique has been successfully used to compute the 2–loop contribution to the $\rho$ parameter from a heavy top quark.[4] Each two loop graph gives a result of the form

$$\mathcal{A}_i^{\mu\nu} = -\delta_{AB}\frac{\alpha_s^2}{2\pi^2 v}\left(a_i g^{\mu\nu} k_1\cdot k_2 + b_i k_1^\nu k_2^\mu + c_i k_1^\mu k_2^\nu\right) \quad , \tag{2}$$

where the incoming gluons have momenta $k_1$ and $k_2$, polarization indices $\mu$ and $\nu$, and colors $A$ and $B$. Gauge invariance requires that

$$\sum_i a_i = -\sum_i b_i, \tag{3}$$

where the sum runs over all the diagrams (the $c_i$ terms do not contribute for on-shell gluons). In order to reduce the number of tensor structures and deal with scalar quantities only, we compute three contractions of each diagram : $\mathcal{A}_i^{\mu\nu} g_{\mu\nu}$, $\mathcal{A}_i^{\mu\nu} k_{1\mu} k_{2\nu}$ and $\mathcal{A}_i^{\mu\nu} k_{1\nu} k_{2\mu}$. From the contracted amplitudes the values of $a_i$ and $b_i$ can easily be found.

The various two-loop diagrams have either one, two or three gluon propagators. Diagrams with one gluon propagator can be written such that the gluon propagator contains no external momenta. For those diagrams with more than one gluon propagator we employ Feynman parametrization to combine the massless gluon propagators (top quark propagators are left alone); the loop momenta are then shifted to move the external momenta into the top-quark propagators.

The denominators arising from the heavy-quark propagators can be expanded in powers of the external momentum, e.g.,

$$\frac{1}{(q-k_1)^2 - m_t^2} = \frac{1}{q-m_t^2}\left(1 + \frac{2q\cdot k_1}{q-m_t^2} + \ldots\right) \quad . \tag{4}$$

To obtain the terms of $\mathcal{O}(M_H^2/m_t^2)$ each denominator must be expanded up to terms containing two powers of $k_1$ and two powers of $k_2$. The Feynman integrals are easily performed after the momentum integrations.

After contracting the two-loop amplitudes as in Eq. (5) and expanding the denominators all the contributions have the form

$$\int \frac{d^n p}{(2\pi)^n}\int\frac{d^n q}{(2\pi)^n}\frac{(p\cdot k_i)^\alpha (q\cdot k_i)^\beta (p^2)^\gamma (q^2)^\delta (p\cdot q)^\tau}{(q^2-m_t^2)^k (p^2-m_t^2)^l [(p-q)^2 - m^2]^j} \tag{5}$$

where $m^2$ can be zero or a product of Feynman paramaters times $M_H^2$. Using the symmetries of the numerators the powers of $p\cdot k_i$ and $q\cdot k_i$ can be written in terms of powers $p^2$, $q^2$, and $p\cdot q$ times powers of $k_1\cdot k_2 = M_H^2/2$. The integrals can then be reduced to the symmetric form

$$\int \frac{d^n p}{(2\pi)^n}\int\frac{d^n q}{(2\pi)^n}\frac{1}{[(p-q)^2-m^2]^j (p^2-m_t^2)^k (q^2-m_t^2)^l}. \tag{6}$$

These integrals are well known in the literature.

## 4. RESULTS

To compute the radiative corrections for the inclusive production of the Higgs boson from gluon fusion, we need both the real contribution from $gg \to gH$ and the virtual corrections from $gg \to H$.

The final result for $gg \to gH$ can be written in the compact form:[2,5]

$$\begin{aligned}\sigma_{TOT}(gg\to HX) = \sigma_0\Big\{\delta(1-z) + \frac{\alpha_s(\mu)}{\pi}\Big[h(z) &+ \bar{h}(z)\log\left(\frac{M_H^2}{\mu^2}\right) + \frac{34r}{135}\delta(1-z) \\ &- \frac{3r}{20}z(1-z)\Big]\Big\} + \mathcal{O}(r^2)\end{aligned} \tag{7}$$

where $\sigma_0$ (with $\alpha_s$ evaluated at $\mu$) is given in Eq. (1) and the functions $h(z)$ and $\bar{h}(z)$ are the same as those of Ref. [5] :

$$\begin{aligned} h(z) &= \delta(1-z)\left(\pi^2 + \frac{11}{2}\right) - \frac{11}{2}(1-z)^3 \\ &\quad + C_A z\bar{P}_{gg}(z)\log\left(\frac{(1-z)^2}{z}\right) \\ \bar{h}(z) &= C_A z \bar{P}_{gg}(z) \\ \bar{P}_{gg}(z) &= 2\left\{\left(\frac{z}{1-z}\right)_+ + \frac{1-z}{z} + z(1-z)\right\}. \end{aligned} \tag{8}$$

The form of Eq. (7) makes it clear that the dominant contributions to the result are just a rescaling of the $r=0$ result by the ubiquitous factor $1+7r/60$. Note the cancellation of the $\log(m_t/M_H)$ terms. There are also no terms proportional to $s/m_t^2$ which would invalidate the expansion.

The results for $q\bar{q}\to gH$ and $qg \to qH$ are given in Refs. [2,5]. At LHC energies, these subprocesses give a negligible contribution to the final result.

## 5. RESULTS

In this section we present numerical results for Higgs production in $pp$ collisions at $\sqrt{s} = 15$ TeV. For our non-leading order parton distribution functions, we use the S1 fit of Morfin and Tung[6] translated into the $\overline{MS}$ prescription. For our leading order parton distribution functions, we also use a set provided by Morfin and Tung which is suitable for using with lowest order

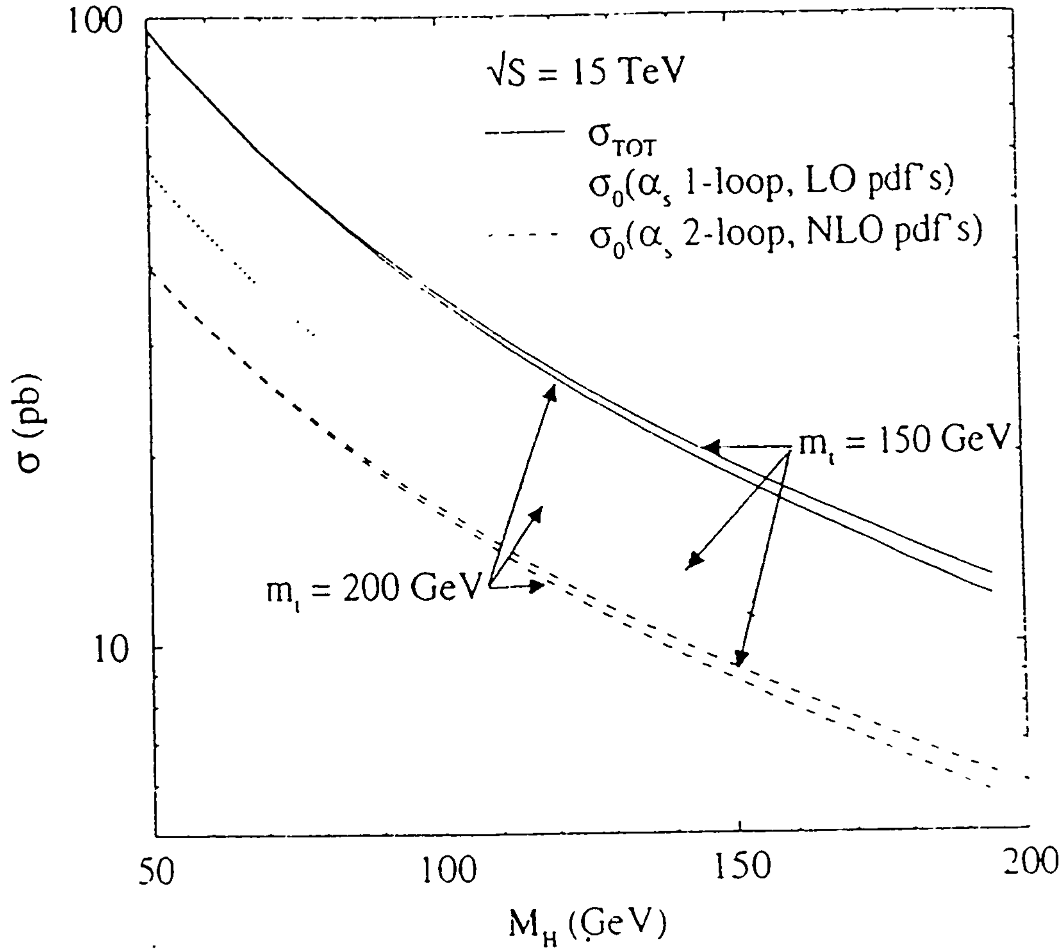


Figure 1. Lowest order (dotted and dashed) and radiatively corrected (solid) cross sections for $pp \to HX$ at the LHC, $\sqrt{s} = 15$ TeV. The curves labelled LO pdf and NLO pdf use the lowest order and next to leading order parton distribution functions of Morfin and Tung, respectively.

predictions for hard scattering processes. We take the renormalization scale $\mu = M_H$.

In Figure 1 we show the lowest order and the radiatively corrected cross sections for $m_t = 150$ GeV and $m_t = 200$ GeV at the LHC. In all cases, the radiative corrections increase the cross section by a factor between 1.5 and 2. In this figure we have shown the contribution of changes in the structure functions and $\alpha_s$ by defining the lowest order cross section in two ways. In the first definition, we use the 1-loop value for $\alpha_s$ and the lowest order parton distribution functions, while the second definition uses the 2-loop value for $\alpha_s$ and the non-leading order parton distribution functions. Both definitions of the lowest order cross section are completely consistent to $\mathcal{O}(\alpha_s^2)$, but we see a significant numerical difference between the two in Figures 1.

To emphasize this we have plotted the ratio of the radiatively corrected cross section for gluon fusion of Eq. (7) to the Born cross section of Eq. (1) in Fig. 2. This ratio is often called "the" $K$ factor. The results of Ref. [2] correspond to the dotted curves in Fig. 2 and our results agree completely with theirs. It should be stressed, again, that both definitions of a $K$ factor as shown in Fig. 2 are completely consistent to $\mathcal{O}(\alpha_s^3)$, but differ by 50% numerically. From this figure we see that many of the $\mathcal{O}(\alpha_s^3)$ corrections can be absorbed into a redefinition of the parton distribution functions and the running of $\alpha_s$.

It is also interesting to consider the $\mu$ dependence of our results. Contrary to naive expectations, the radiative corrections do not generally reduce the dependence of the cross section on $\mu$. Indeed for a light Higgs boson ($M_H/m_t <$) the dependence on $\mu$ of the NLO result is more severe than the leading order result.

## 6. CONCLUSIONS

We have computed the $\mathcal{O}(\alpha_s^3 \tau)$ contributions to $pp \to gH$. They are dominated by the gluon fusion contribution and typically increase the lowest order

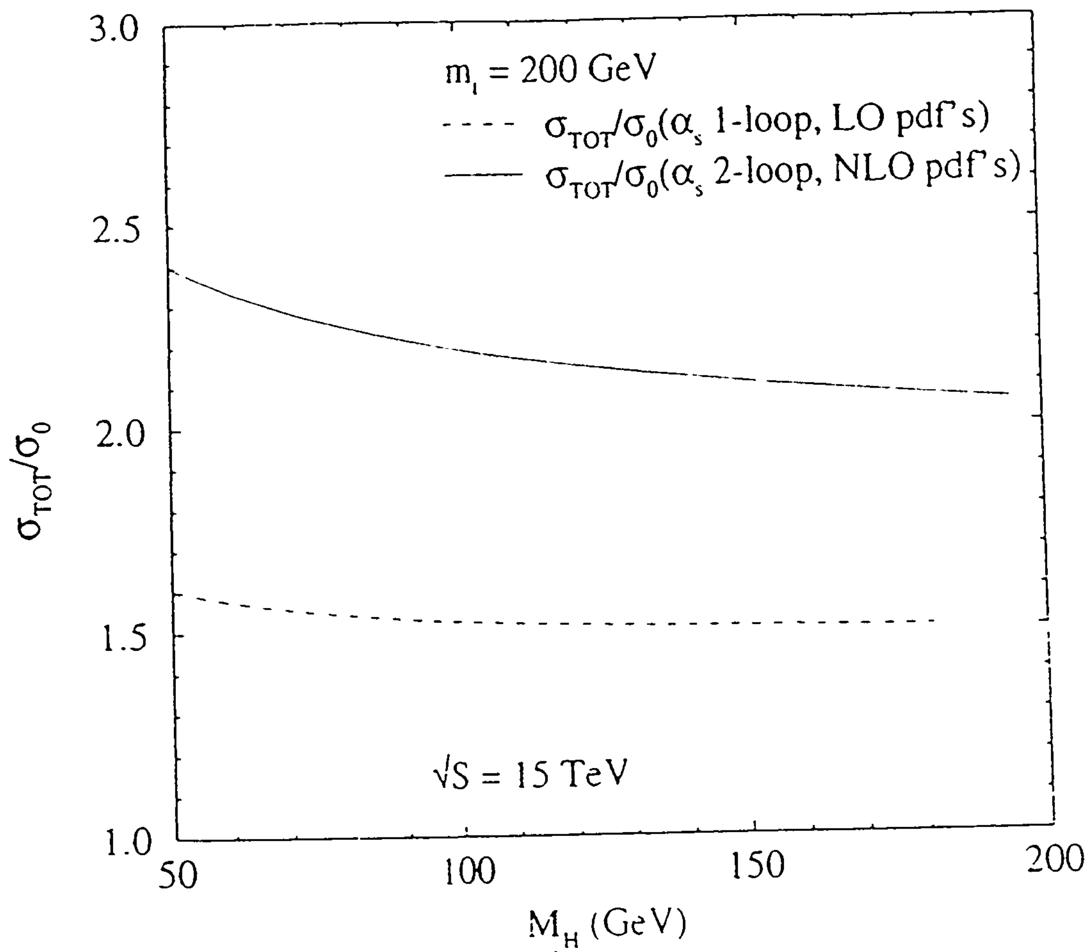


**Figure 2.** Ratio of the radiatively corrected cross section to the Born cross section at the LHC, $\sqrt{s} = 15$ $TeV$ with $m_t = 200$ $GeV$.

cross section by a factor of between 1.5 and 2. The lowest order cross section is sensitive to whether the 1-loop or 2-loop $\alpha_s$ is used and which distribution functions are used.

The dominant numerical corrections to the gluon fusion contribution can be found from the $m_t \to \infty$ $\mathcal{O}(\alpha_s^3)$ results of Refs. [1] and [2] by rescaling the cross section by the factor $(1 + 7r/60)$. The smallness of the $\mathcal{O}(\alpha_s^3 r)$ terms demonstrates the valididty of the $m_t \to \infty$ limit for the gluon fusion subprocess. Indeed, Ref. [2] found that the $m_t \to \infty$ results were good to within 15% even for $M_H > m_t$.

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