Dominant QCD Backgrounds in Higgs Boson Analyses at the LHC: A Study of $pp \to t\bar{t} + 2$ Jets at Next-to-Leading Order

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(Received 11 March 2010; published 22 April 2010)

We report the results of a next-to-leading order simulation of top quark pair production in association with two jets. With our inclusive cuts, we show that the corrections with respect to leading order are negative and small, reaching 11%. The error obtained by scale variation is of the same order. Additionally, we reproduce the result of a previous study of top quark pair production in association with a single jet.

DOI: 10.1103/PhysRevLett.104.162002 PACS numbers: 12.38.Bx, 14.65.Ha, 14.80.Bn

Exploiting the relatively clean experimental signal and excellent theoretical understanding of the W^+W^- Higgs boson decay channel, the Tevatron collaborations continue excluding Higgs boson masses, M_H, in the vicinity of twice the W boson mass with ever growing confidence levels [1]. As a consequence, studies assuming a lighter Higgs boson are more timely than ever. Clearly, it is necessary to devise suitable scenarios that would allow for discovery and measurement of the basic properties of the scalar at the Large Hadron Collider (LHC). Among the many available scenarios, one is especially disputed. It has been argued that if $M_H < 135$ GeV, the production and decay chain $pp \to t\bar{t}H^* \to t\bar{t}b\bar{b}$ should provide an excellent opportunity owing to the large top and bottom quark Yukawa couplings. The question of discrimination between the large backgrounds and signal was expected to be solved by the sharp Breit-Wigner peak of the Higgs boson in the invariant mass distribution of the b quark jets. Unfortunately, application of realistic selection cuts and acceptances demonstrated a smearing of the resonance far beyond what would be expected from initial state radiation [2,3]. At this point it seems, therefore, that a very precise knowledge of the backgrounds is necessary, if the channel is to be of any usefulness [4].

A close scrutiny of the backgrounds shows [2,3] that the most relevant are the direct production of the final state $t\bar{t}b\bar{b}$ (irreducible background) and the production of a top quark pair in association with two jets, $t\bar{t}jj$ (reducible background). The latter needs to be taken into account due to the finite efficiency in identifying b quarks in jets (b tagging). We depict example diagrams contributing to the signal and the two backgrounds in Fig. 1. It is crucial that although $t\bar{t}jj$ has a cross section, which is larger than that of $t\bar{t}b\bar{b}$ by about 2 orders of magnitude, in the actual setup of [3], both backgrounds turn out to give very similar contributions. Recent studies [6–8] have demonstrated that the next-to-leading order QCD corrections to $t\bar{t}b\bar{b}$ are very large, undermining even further the feasibility of actual analyses in the channel at hand. A proposed solution [8] involves the use of a dynamical renormalization or factorization scale in simulations and, more importantly, the imposition of a jet veto on the third jet (upper bound on the allowed transverse momentum, p_T). The purpose of this Letter is to determine whether large corrections affect the $t\bar{t}jj$ channel.

In principle, the concept of a cross section of a process involving massless partons at leading order (LO), as is the case of $t\bar{t}jj$, is undefined due to potential soft and collinear divergences and requires the specification of separation cuts. This complicates somewhat our problem, since any conclusions we will draw will pertain to the particular setup we will have used. Therefore, in order to retain some level of generality, we will not attempt to reproduce the exact conditions of the Higgs boson analysis of [3]. On the contrary, we will mimic some of the general assumptions, but impose more inclusive cuts.

To be specific we consider proton-proton collisions at the LHC with a center of mass energy of $\sqrt{s} = 14$ TeV. We set the mass of the top quark to be $m_t = 172.6$ GeV and leave it on shell with unrestricted kinematics. The jets are defined by at most two partons using the k_T algorithm of [9,10] with a separation $\Delta R = 0.8$, where $\Delta R = \sqrt{(y_1 - y_2)^2 + (\phi_1 - \phi_2)^2}$, $y_i = 1/2 \ln(E_i - p_{i,z})/(E_i + p_{i,z})$ being the rapidity and ϕ_i the azimuthal angle of parton i. Moreover, the recombination is only performed

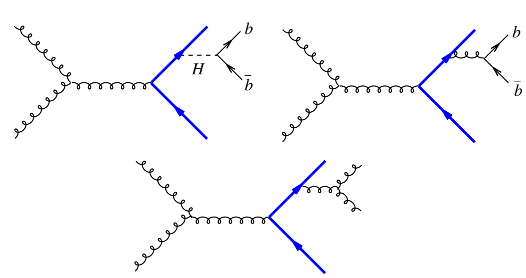

FIG. 1 (color online). Example diagrams contributing to the signal $t\bar{t}H^* \to t\bar{t}b\bar{b}$, and the irreducible background with the same final state, as well as the reducible background with two jets. Thick blue lines correspond to top quarks, the wiggly to gluons as usual.

if both partons satisfy $|y_i| < 5$ (approximate detector bounds). We note that the k_T algorithm specifies not only which partons are combined into jets, but also the momentum of the resulting jets. In our simulation, we assume that the four-momenta of the partons are added. We will comment on the importance of this point when we compare with the $t\bar{t}j$ calculation of [11,12]. We further assume that the jets are separated by $\Delta R = 1$ and have $|y_{\rm jet}| < 4.5$. Their transverse momentum is required to be larger than 50 GeV. It is mostly in ΔR and $p_{T,\rm min}$ that the present setup is different from that used in the case of $t\bar{t}b\bar{b}$ [6,7]. Here, we use a higher p_T cut similar to the $t\bar{t}j$ case of [12]. The additional separation in ΔR is only used to demonstrate the flexibility of our tools, but is believed to bear no impact on the final conclusions. Notice that our jets are allowed to contain b quarks, and therefore also the final state $t\bar{t}b\bar{b}$. This is irrelevant, since we know that this contribution is tiny and can be simply subtracted from our results (the summation is incoherent). Finally, we note that the third jet, which stems from real radiation, is not restricted. Nevertheless, we will also study the impact of a jet veto with $p_T = 50$ GeV.

The production of jets in hadronic collisions can be decomposed into many processes at the parton level. In Table I, we summarize the LO contributions of different subclasses. These were obtained with the kinematics specified above using the CTEQ6L1 LO parton distribution functions [13,14] and the LO running of the strong coupling constant up to the scale (common for renormalization and factorization) $\mu_0 = m_t$. There are two interesting conclusions to be drawn here. First, it comes as a surprise that the mixed channel qg is more important than gg. The proportions between the two depend, however, on the p_T cut. If $p_{T,\rm min} = 20$ GeV, the situation is reversed. The reason is that the lower the cut, the larger the soft gluon enhancement. If there are more gluons in the final state the enhancement will be higher, and therefore at some point $gg \to t\bar{t}gg$ must be larger than $qg \to t\bar{t}qg$. The second, more important, point is that the channels related to the $t\bar{t}b\bar{b}$ final states, in particular $gg \to t\bar{t}q\bar{q}$, are almost negligible compared to the two dominant (we referred to this before). This implies that whatever the result on the size of the corrections in the $t\bar{t}b\bar{b}$ case, $t\bar{t}jj$ requires a separate study.

TABLE I. The LO cross section for $pp \to t\bar{t}jj$ production at the LHC. The individual contributions of the various partonic channels are also presented separately. Both q and q' span all quarks and antiquarks.

Process	$\sigma^{\rm LO}$ [pb]	Contribution
$pp \to t\bar{t}jj$	120.17(8)	100%
$qg \to t\bar{t}qg$	56.59(5)	47.1%
$gg \to t\bar{t}gg$	52.70(6)	43.8%
$qq' \to t\bar{t}qq'$, $q\bar{q} \to t\bar{t}q'\bar{q}'$	7.475(8)	6.2%
$gg \to t\bar{t}q\bar{q}$	1.981(3)	1.6%
$q\bar{q} \to t\bar{t}gg$	1.429(1)	1.2%

Before we give our results for the next-to-leading order (NLO) corrections, we are compelled to present the computational framework used for the simulations. Similarly to our previous publication [7], we have used the HELAC-PHEGAS framework [15–17] and in particular HELAC-1L [18] for the evaluation of the virtual corrections. This tool uses the Ossola-Papadopoulos-Pittau (OPP) method [19] and CUTTOOLS [20–22] for the reduction of tensor integrals, as well as ONELOOP for numerical values of scalar integrals. The practical techniques involve reweighting of events and sampling over polarization and color (for details see [7]). The real radiation corrections were evaluated with HELAC-DIPOLES [23], which is an implementation of the Catani-Seymour subtraction formalism [24,25]. In order to check our results, we have explored the independence of the results on the unphysical cutoff in the dipole subtraction phase space (see [23] and references therein for details). We have also verified the cancellation of divergences between the real and virtual corrections. Finally, the numerical precision of the latter was assured by using gauge invariance tests and use of quadruple precision. We note that the only new virtual amplitudes are those involving a top quark pair and four gluons. These were presented for the first time in [18] and, due to their notorious complexity, still await an independent check by other groups.

For the evaluation of the NLO corrections, we have used the CTEQ6M parton distribution functions with NLO running of the strong coupling constant. At the central scale $\mu_0 = m_t$, we obtain

$$\sigma^{\rm NLO}_{pp\to t\bar{t}jj+X} = (106.94 \pm 0.17)\ \text{pb},$$

where the error comes from Monte Carlo integration. Compared to the LO result from Table I, this represents a negative shift of 11%, and allows us to conclude that the corrections to this process are small.

The scale dependence of the corrections is illustrated in Fig. 2. At first, we observe a dramatic reduction of the scale uncertainty while going from LO to NLO. Varying the scale up and down by a factor 2 changes the cross section by +72% and −39% in the LO case, while in the NLO case we have obtained a variation of −13% and −12%. Second, the central scale that we have chosen is very close to the point of minimal corrections and slightly above the point of maximum of the NLO cross section. Indeed, both $\mu = 1/2\mu_0$ and $\mu = 2\mu_0$ give smaller values.

Taking into account the above dependence on the scale choice, it is to be expected that adding a jet veto will only worsen the result. In order to make this more transparent, it is best to consider the difference between the cross section without and with the jet veto. This difference is given by a LO calculation, since it requires the existence of three separated jets with a lower cut on their respective trans-

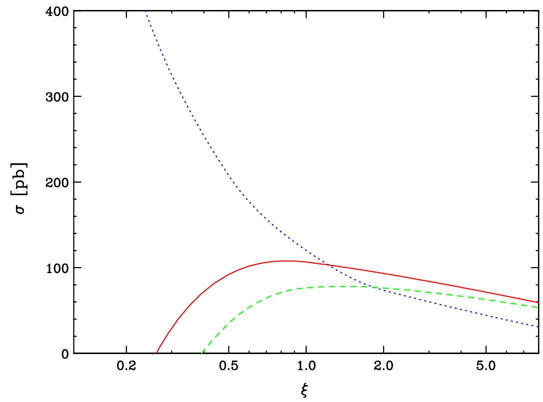

FIG. 2 (color online). Scale dependence of the total cross section for $pp \to t\bar{t}jj + X$ at the LHC with $\mu_R = \mu_F = \xi\mu_0$ where $\mu_0 = m_t$. The blue dotted curve corresponds to the LO, the red solid to the NLO result, whereas the green dashed to the NLO result with a jet veto of 50 GeV.

verse momenta. Clearly, not only will it be negative, but it will also have to grow more negative with diminishing scale (since this is almost entirely governed by the behavior of the strong coupling constant alone). At this point it is difficult to decide whether a jet veto will or will not be necessary for the complete Higgs boson analysis. What we can give is the lower bound on the corrections, assuming that a jet veto of less than $p_T = 50$ GeV is likely to endanger the stability of the perturbative expansion. The total cross section with a jet veto of 50 GeV is

$$\sigma^{\mathrm{NLO}}_{pp\to t\bar{t}jj+X}(p_{T,X} < 50\ \mathrm{GeV}) = (76.58 \pm 0.17)\ \mathrm{pb},$$

with a scale variation of -54% and -0.3% (see Fig. 2). The plots show that choosing a higher scale in the case of the jet veto would lead to a result with virtually no scale dependence. This should be considered as severely underestimating the error.

While the size of the corrections to the total cross section is certainly interesting, it is crucial to study the corrections to the distributions. The most important for us is the invariant mass of the two tagging (highest p_T) jets, since this is the observable entering Higgs boson studies. We plot the LO and NLO results in Fig. 3. While we notice a long tail, we keep the dependence only in a modest range up to 400 GeV due to our phenomenological motivation. The distribution starts above about 45 GeV due to the ΔR and p_T cuts, and shows tiny corrections up to at least 200 GeV, which means that the size of the corrections to the cross section is transmitted to the most relevant distribution.

Of course, there are observables showing much larger effects. The classic example is the transverse jet momentum distribution at high p_T. We illustrate the phenomenon in Figs. 4 and 5, which demonstrate the strongly altered shapes in the cases of the hardest and second hardest jets. It is well known that this kind of correction can only be correctly described by higher order calculations. On the

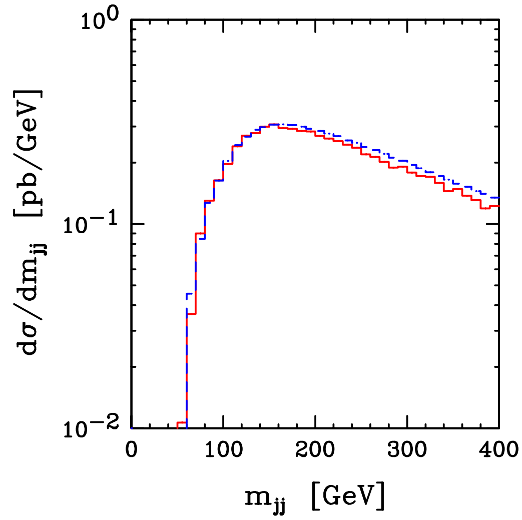

FIG. 3 (color online). Distribution of the invariant mass m_{jj} of the first and the second hardest jet for $pp \to t\bar{t}jj + X$ at the LHC. The red solid line refers to the NLO result, while the blue dotted line to the LO one.

other hand, the behavior at low p_T is certainly further altered by soft-collinear emissions, which are best simulated by parton showers. With our lower cut of $p_{T,\min} = 50$ GeV, we expect to be mostly in the safe range, where fixed order perturbation theory does not break down.

While the above comments conclude our analysis of $t\bar{t}jj$, we would like to make a few statements about the process with only one jet, $t\bar{t}j$. While preparing our calculation, we have made a comparison with the results of [12]. Using exactly the same setup as that work, we were able to obtain the following value for the cross section,

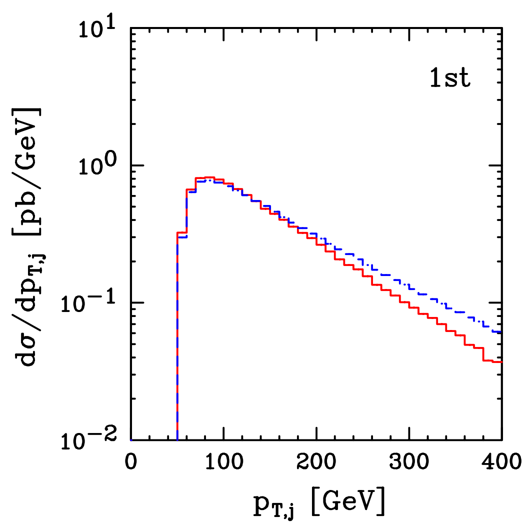

FIG. 4 (color online). Distribution in the transverse momentum p_{T_j} of the first hardest jet for $pp \to t\bar{t}jj + X$ at the LHC. The red solid line refers to the NLO result, while the blue dotted line to the LO one.

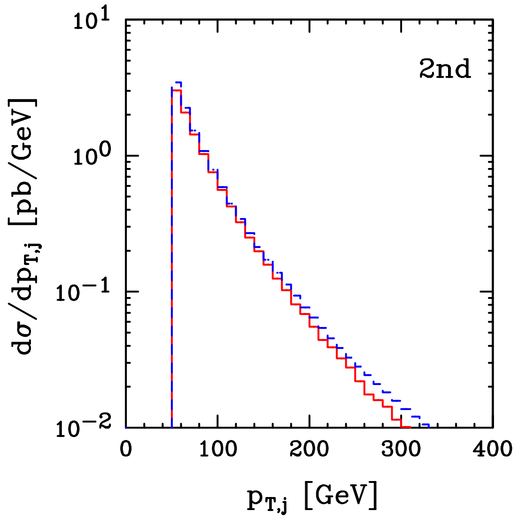

FIG. 5 (color online). Distribution in the transverse momentum p_{T_j} of the second hardest jet for $pp \to t\bar{t}jj + X$ at the LHC. The red solid line refers to the NLO result, while the blue dotted line to the LO one.

$$\sigma^{\rm NLO}_{pp\to t\bar{t}j+X} = (376.6 \pm 0.6)\ \text{pb},$$

demonstrating perfect agreement [[12] quotes (376.2 ± 0.6) pb]. We note that besides a different value of the top quark mass ($m_t = 174$ GeV) and $\Delta R = 1$ in the jet algorithm, the authors used a k_T algorithm, where the momenta of the partons being combined into a jet are not simply added. Instead, massless jets are constructed using transverse momenta (which are trivially added) and rapidities. The version that we use would lead to a lower value of the cross section, since the transverse momentum of the sum of momenta is never larger than the sum of the transverse momenta, and the only relevant cut is applied to the jet p_T. Our value would instead be (372.2 ± 0.6) pb. On the other hand, with all parameters and cuts as given in the introduction the final result is (376.1 ± 0.7) pb.

Let us conclude by pointing out that while we demonstrated that the corrections in $t\bar{t}jj$ are small for one setup, comparison to the behavior of the corrections for different setups in the $t\bar{t}j$ case [12] provides a viable argument that our conclusions will remain true for other input parameters. Nevertheless, we are planning to present a much wider study involving, in particular, a variation of the center of mass energy, cone size in the jet algorithm, transverse momentum cuts, and jet vetoes.

The simulations presented in this work have been performed at the DESY Zeuthen Grid Engine computer cluster. The work of M. C. was supported by the Heisenberg Programme of the Deutsche Forschungsgemeinschaft. The authors were funded in part by the RTN European Programme MRTN-CT-2006-035505 HEPTOOLS—Tools and Precision Calculations for Physics Discoveries at Colliders. M. W. was additionally supported by the Initiative and Networking Fund of the Helmholtz Association, Contract No. HA-101 (Physics at the Terascale).

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