Single top quark $tW+X$ production at the CERN LHC: A closer look

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(Received 24 March 2000; published 10 January 2001)

We reexamine the $tW+X$ single top-quark production process, which is important at the CERN LHC, unlike what happens at the Fermilab Tevatron. Special attention is paid to the treatment of the $2 \rightarrow 2[Wt]$ process and part of its next-to-leading correction, the $2 \rightarrow 3[Wtb]$ process. We show that the $2 \rightarrow 3[Wtb]$ process has to be correctly taken into account with a proper subtraction of the top-pair contribution, and that it has qualitatively different kinematical distributions from the $2 \rightarrow 2[Wt]$ process. We present the total cross section of the $tW+X$ production as being about 62 pb, and at the proper QCD scale equal to the top quark mass, suggest a method of combining the Wt and Wtb processes with gauge-invariant subtraction of the $t\bar{t}$ part, which allows us to reproduce the kinematical properties correctly and perform a proper event simulation of the $tW+X$ process in the whole kinematical region.

DOI: 10.1103/PhysRevD.63.034012

PACS number(s): 14.65.Ha, 13.85.-t

I. INTRODUCTION

The study of electroweak single top-quark physics is a very important part of research programs at future TeV energy colliders. Such a study allows us to investigate, with a high enough accuracy, the properties of the top quark and to measure a Wtb coupling structure. It may shed light on the underlying theory which probably stands beyond the standard model [1–4]. In addition, single top-quark production at the CERN Large Hadron Collider (LHC) has a large rate of the order of 300 pb, and therefore it gives an important part of the background to various new physics processes.

In this paper, we concentrate on the $pp \rightarrow tW+X$ production process at the CERN LHC. This process was the subject of previous studies [5–7]. In Ref. [6] we reported on the calculations of it, as well as the other important processes at the Fermilab Tevatron and CERN LHC colliders. In order to separate the tWb process of the single top-quark production from the $t\bar{t}$ pair production we have introduced a cut on the invariant Wb mass window (approach I). In Ref. [7] the cross section of the tW process was calculated in a different approach, where the $t\bar{t}$ contribution was subtracted from the tWb process in the narrow width approximation (approach II). However, both approaches have different drawbacks, and some of their aspects have not been treated quite correctly. Therefore it deserves a closer look.

In approach I the results are formally $|m_{WB} - m_{top}|$ cut dependent. In Ref. [6] the chosen cut was too modest from the experimental point of view ($|m_{WB} - m_{top}| < 3\Gamma_t$), since the real experimental mass window for the top-quark is of the order of 20 GeV ≈ 10 –15 Γ_t . This was pointed out in Ref. [7]. However, in the present study we give the pure theoretical arguments on how the cut should be chosen and

explain why it has to be significantly larger than the top width. This cut should be of the order of 20 GeV, even in the case of an ideal detector. It is now clear that a formal cut dependence is significantly reduced. In particular, it should be stressed that approach I reproduces kinematical distributions correctly, which is the crucial point for a phenomenological analysis.

Approach II in turn is cut-independent but it does not contain any recipe to simulate Wtb events at all. In Ref. [7] the only $2 \rightarrow 2[Wt]$ process ($bg \rightarrow Wt$) has been used for an event simulation. However, in this case an important part of the Wtb events are absent and such an implementation of approach II leads to the wrong kinematical distributions for the $tW+X$ process. For the numerical values of the cross section the QCD scale $\hat{s}$ has been used. But one should point out that such a scale is too large and leads to a significantly lower rate, even for top quark-pair production as we know from next-leading order (NLO) calculations [8]. For the single top Wt process NLO results have not been obtained yet; however, one would expect a lower characteristic scale with respect to top-quark pair production.

In this paper we have developed approach I. We apply the reasonable $|m_{WB} - m_{top}|$ cut consistent with theoretical arguments and an experimental mass resolution for top-quarks. We have also calculated the cross sections, using approach II for the cross check.

For both methods, a subtraction procedure must be applied to avoid double counting. We have suggested the new procedure of combining the two different processes. This method implies the correct subtraction procedure, reproduces correct kinematical properties in the whole phase-space region, and gives stable results.

Our paper is organized as follows. In Sec. II we compare two different approaches of a subtraction of $t\bar{t}$ pair production from the process with the tWb final state. In Sec. III we develop the new approach for a treatment of double counting and combining two signal processes together. In Sec. IV we present the final results and draw the conclusions.

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FIG. 1. Diagrams for leading order $2 \rightarrow 2$ tW production (A) and the $\mathcal{O}(1/\log[m_t^2/m_b^2])$ $2 \rightarrow 3$ process (B),(C).

II. LEADING ORDER $2 \rightarrow 2$ AND $\mathcal{O}(1/\log[M_T^2/M_B^2])$ $2 \rightarrow 3$ PROCESSES: SUBTRACTION OF $t\bar{t}$ PAIR PRODUCTION

In Fig. 1 we present the complete gauge-invariant set of leading-order and $\mathcal{O}(1/\log[m_t^2/m_b^2])$ diagrams contributing to the $tW+X$ final state.

There are two problems one should avoid in order to correctly combine different contributions to the tW single top-quark production: one should remove the contribution from $t\bar{t}$ production, giving the same tWb final state, and take care of the double counting that takes place when one simply adds a contribution from two $2 \rightarrow 2$ and $2 \rightarrow 3$ processes.

This happens because the $2 \rightarrow 3$ process is singular in the region of collinear b -quarks coming from gluon splitting. The same singularity has been resolved for the $2 \rightarrow 2$ process when the b -quark parton distribution function (PDF) was defined and the collinear contributions of b quark were resummed. The contribution from the collinear region should be taken only once, and therefore one should apply a subtraction procedure. It should be noticed that $2 \rightarrow 2$ and $2 \rightarrow 3$ processes overlap only in the leading log gluon splitting term.

In this section we would like to compare two different

approaches of solving the first problem—subtracting the contribution from the top-quark pair production. As for double counting, we use the conventional solution in this section [6,7], namely, the subtraction of the gluon splitting term

$$\sigma(gb + gg \rightarrow tW + X)_{real} = \sigma(gb \rightarrow tW) + \sigma(gg \rightarrow tW\bar{b}) - \sigma(g \rightarrow b\bar{b} \otimes gb \rightarrow tW). \quad (1)$$

As was mentioned in the Introduction, there are two basic approaches to remove the contribution from top-quark pair production in a gauge invariant-way. The first (approach I) is the application of the cut on the invariant mass of the Wb pair in order to remove the resonant $t\bar{t}$ contribution. This procedure is cut-dependent, but it is a straightforward recipe on how to simulate single top-quark production events with the proper kinematics. It should be noted, however, that the cut dependence is not arbitrary since the cut should be applied according to well known mass resolution [9], which is typically 10–15 GeV. In terms of the top-quark width the window cut that should be applied to remove the $t\bar{t}$ contribution would be of the order of $\approx \pm 20$ GeV $\approx 10\text{--}15\Gamma_{top}$.

TABLE I. Cross section for the $gg \rightarrow tW\bar{b}$ process for two different approaches.

PROCESS	CS(pb), CTEQ4L			
	$\mu = m_W$	$\mu = m_{top}$	$\mu = m_{top} + m_W$	$\mu = \hat{s}$
$gg \rightarrow tW\bar{b}$ ($\pm 10\Gamma_{top} W^- b$ mass cut) _I	42.7	30.9	27.0	20.8
$gg \rightarrow tW\bar{b}$ ($\pm 15\Gamma_{top} W^- b$ mass cut) _I	33.3	24.3	21.2	16.5
$gg \rightarrow tW\bar{b}$ (no cuts)	737	536	469	368
$gg \rightarrow t\bar{t} \otimes BR$	717	523	457	358
inter[$t\bar{t} \otimes tWb$]	−14.6	−10.7	−9.19	−7.14
$gg \rightarrow tW\bar{b}_{II}$	34.6	23.7	21.2	17.1

TABLE II. Cross section for the $q\bar{q} \rightarrow tW^- \bar{b}$ process.

PROCESS	CS(pb), CTEQ4L			
	$\mu = m_W$	$\mu = m_{top}$	$\mu = m_{top} + m_W$	$\mu = \hat{s}$
$q\bar{q} \rightarrow tW^- \bar{b}$ ($\pm 10\Gamma_{top} W^- b$ mass cut)	2.9	2.3	2.1	1.7
$q\bar{q} \rightarrow tW^- \bar{b}$ ($\pm 15\Gamma_{top} W^- b$ mass cut)	1.9	1.5	1.3	1.1

The second (approach II) way of subtracting the $t\bar{t}$ contribution is the narrow width limit approach [7],

$$\sigma(gg \rightarrow tWb)_{single\,top} = \sigma(gg \rightarrow tWb)_{total} - \sigma(gg \rightarrow t\bar{t}) * Br(t \rightarrow Wb) - \text{inter}[t\bar{t} \otimes tWb], \quad (2)$$

where $\text{inter}[t\bar{t} \otimes tWb]$ means the interference of the $t\bar{t}$ diagrams with the nonresonant ones. This procedure should formally reproduce the correct production rate for the single top-quark. But from the practical point of view, it does not give any recipe on how to simulate the event of single top-quark production, which is crucial for further kinematical studies. Table I shows the results for two methods of subtraction of the $t\bar{t}$ contribution for the $gg \rightarrow tW^- \bar{b}$ process.

The contribution from the $q\bar{q} \rightarrow tWb$ process has also been taken into account in our study. The contribution from this process is not negligible, as we can see from the Table II: it is of the order of 7% for the tWb final state after removing the $t\bar{t}$ contribution. All the numerical results have been obtained by means of the CompHEP program [10].

In order to give an idea of how strong the dependence on the Wb invariant mass cut is, we present numbers for two window cuts, 10 and $15\Gamma_{top}$, which correspond to ± 16 and 24 GeV mass windows, respectively. For the further study of the result on the Wb invariant mass cut we have analyzed the the Wb invariant mass distribution at the parton level presented in Fig. 2.

FIG. 2. Parton Wb invariant mass distribution for $gg \rightarrow tW^- \bar{b}$ processes.

From this figure one can clearly see that the ≈ 25 GeV Wb mass window completely removes the $t\bar{t}$ contribution with its interference to the $gg \rightarrow tW^- \bar{b}$ processes. We have performed the fitting procedure, which quantitatively confirms the size of this window and gives those values as 25 GeV. This procedure significantly reduces the ambiguity in the choice of this window cut. Besides the parton-level fit described above one should also notice that experimental mass resolution also requires the same order size of the window cut. This means that subtraction of the $t\bar{t}$ contribution can be done both theoretically and experimentally.

In Fig. 3 we illustrate the $|m_{top} - m_{Wb}|$ cut dependence for the $gg \rightarrow W^- t\bar{b}$ process, the $q\bar{q} \rightarrow W^- t\bar{b}$ process, and their sum. One can notice that in the region of $|m_{top} - m_{Wb}| > 20$ GeV, the process became much less $|m_{top} - m_{Wb}|$ -cut dependent once the resonant $t\bar{t}$ region was removed.

The results in Tables I and II are shown for several characteristic QCD factorization/normalization scales: $Q = m_W$, m_{top} , and $m_{top} + m_W$, which gives a natural scale interval for the process under study. In the last column, we also show the results at $Q^2 = \hat{s}$ for a comparison with previous [7] calculations. Figure 4 illustrates dependence of the $gg \rightarrow W^- t + X$ cross section on the QCD scale for two methods.

Table I and Fig. 4 both clearly show that approach II, with subtraction of the $t\bar{t}$ contribution, gives a cross section for the $gg \rightarrow W^- t + X$ process consistent with approach I for $\pm 15\Gamma_{top} W^- b$ mass window cuts at various QCD scales. For example, the results are 24.3 and 23.7 pb, respectively,

FIG. 3. $|m_{top} - m_{Wb}|$ -cut dependence of the $gg \rightarrow W^- t\bar{b}$ process, the $q\bar{q} \rightarrow W^- t\bar{b}$ process, and their sum.

FIG. 4. Cross section of the $gg \rightarrow W^- t + X$ process versus the QCD scale for two methods of subtraction of the $t\bar{t}$ contribution.

for these two methods at $\mu = m_{top}$. On the other hand, approach I for the $\pm 10\Gamma_{top}$ W^-b mass window cut gives a 5–7 pb higher cross section. Since approach I is more physical in the sense that it allows the reproduction of the correct kinematical distribution, we use it with the $\pm 15\Gamma_{top}$ W^-b mass window cut for the final results.

For the sake of clarity the contribution from the $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ process to the single top $tW + X$ final state is presented separately in Table III. In this table we show the value of the cross section of the $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ process together with the subtraction term $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ for the various QCD scales. From Table III one can see that the subtraction term $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ is of the order of 80% of the $(gb + bg) \rightarrow W^- t$ cross section.

Finally, Table IV presents the combined cross section for $W^- t + X$ signature.

One should notice that cross sections are quite scale-dependent. For three QCD scales, $Q = m_W$, m_{top} , and $m_{top} + m_W$, the uncertainty due to the choice of different scales is of the order of 25–30%. The choice of the scale $Q = \sqrt{\hat{s}}$ gives significantly lower results. But we should stress that the high QCD scale $Q = \sqrt{\hat{s}}$ seems to be the unphysical one since the cross section it gives is lower by a factor of almost two for t -channel W -gluon fusion single top production [11] and even for $t\bar{t}$ -pair production [8], at tree level, then the next-to-leading order (NLO) result is. For $Q = m_{top} = 175$ GeV, the tree-level result is much closer to the NLO one. Therefore it is quite reasonable to use the $Q = m_{top}$

$= 175$ GeV choice for the processes involving tW single top-quark production.

We have estimated uncertainties due to a choice of the QCD scale within the range $m_W < \mu < M_{top} + m_W$, taking the central value as $\mu = m_{top}$. For the event simulation we use this central value of the QCD scale and present the respective total cross section in Table IV.

III. MONTE CARLO SIMULATION AND COMBINING OF THE Wt AND tWb PROCESSES

Results from Table IV have been obtained using the conventional subtraction procedure. However, one needs to study how the $2 \rightarrow 2$ and $2 \rightarrow 3$ processes should be combined in order to reproduce not only the total cross section but also the correct event kinematics for the proper Monte Carlo (MC) simulation.

The point is that we know the value of double counting but it is not known *a priori* which part of this value should be subtracted from the tW process and the tWb process. In this section we study this question in detail. In principle, one could straightforwardly generate the $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ subtraction process with negative weight and use it in the further analysis. But the procedure of using events with negative weights is not well defined and could even be dangerous if one deals with the small statistics. One could try to redefine the gluon structure function and subtract the $g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$ double counting part only from the tW process. But this would also be not quite correct since some part of the double counting should be subtracted from the tWb process.

Therefore we have proposed a method of combining the two contributions which allows us to generate events without negative weights using the standard set of PDF. The method results in smooth distribution and takes into account explicit matrix element calculations for the Wtb process in the hard kinematical region ($P_T^b > P_T^{cut}$) and the resummed contribution from the Wt process in the soft region ($P_T^b < P_T^{cut}$). In the latter case an additional b quark appears as a b quark (mainly collinear) coming from the gluon splitting provides distribution of another b quark in the proton. From this moment we call this signature the $tW^- + b_{split}$ in order to separate it from the tWb signature of real $gg \rightarrow tW^- b$ processes.

We have used the following procedure to work out the recipe for this: We have compared various kinematical distributions of the $pp(bg) \rightarrow tW^- + b_{split}$, the $2 \rightarrow 2$ process with an additional b quark from the gluon splitting (using the PYTHIA5.7 [12] generator), and the complete $2 \rightarrow 3$, $pp(gg + q\bar{q}) \rightarrow tW^- \bar{b}$, process. We have found a proper matching

TABLE III. Cross section for the tW process and subtraction term.

PROCESS	CS(pb), CTEQ4L			
	$\mu = m_W$	$\mu = m_{top}$	$\mu = m_{top} + m_W$	$\mu = \hat{s}$
$(gb + bg) \rightarrow W^- t$	29.4	29.1	28.6	27.8
$g \rightarrow b\bar{b} \otimes (gb + bg) \rightarrow tW^-$	25.3	23.9	22.9	21.8

TABLE IV. Combined section for the processes contributing to $pp(q\bar{q}+gg+gb)\rightarrow tW^-+X$ production.

PROCESS	CS(pb), CTEQ4L			
	$\mu=m_W$	$\mu=m_{top}$	$\mu=m_{top}+m_W$	$\mu=\hat{s}$
$W^-t+[W^-tb]_{I(\pm 10\Gamma)}-[g\rightarrow b\bar{b}\otimes(gb+bg)\rightarrow tW^-]$	49.7	38.4	34.8	28.5
$W^-t+[W^-tb]_{I(\pm 15\Gamma)}-[g\rightarrow b\bar{b}\otimes(gb+bg)\rightarrow tW^-]$	39.3	31.0	28.2	23.6

between the resummed contribution at the collinear region for the b quark and the complete tree-level contribution in the hard region. Figure 5 shows the transverse momenta and rapidity distributions for all three particles in the final state. As expected the difference is clear in the b -quark distributions. For the $pp(bg)\rightarrow tW^-+b_{split}$ process it is much softer and less central than that for the $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ process. At the same time one can see that W -boson and t -quark distributions are nearly the same.

FIG. 5. Transverse momenta and rapidity distributions for the final-state particles of the $pp(bg)\rightarrow tW^-+b_{split}$ process (dashed line), a $2\rightarrow 2$ process with an additional b quark from initial-state radiation, and the true $2\rightarrow 3$ $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ process (solid line).

Since we know the absolute value of the combined cross section, we propose the following method to match collinear and hard kinematical regions: One can use the kinematical p_T^b separation of the $pp(bg)\rightarrow tW^-+b_{split}$ and $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ processes in the regions $p_T^b < P_T^{cut}$ and $p_T^b > P_T^{cut}$, respectively.

Now move the p_T^b cut in order to satisfy two requirements; namely, (1) the common rate of $pp(bg)\rightarrow tW^-+b_{split}$ with $p_T^b < P_T^{cut}$, and $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ with $p_T^b > P_T^{cut}$, gives the combined total rate computed in the previous section; in other words, one can normalize a rate in a collinear region on the $\sigma_{total}-\sigma[pp(gg+q\bar{q})\rightarrow tW^-\bar{b}, p_T^b > P_T^{cut}]$; (2) the overall p_T^b distribution should be smooth. The result is illustrated in Fig. 6, where we show several variants of the combination of those two processes for various values of P_T^{cut} . We have found that the optimal P_T^{cut} providing a smooth sewing for these two processes at the CERN LHC is equal to about 20 GeV. This value gives physically reasonable answers to the main questions of this section: (a) in which kinematical regions the $pp(bg)\rightarrow tW^-+b_{split}$ and $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ processes should

FIG. 6. Transverse momenta distribution of the b quark sewed for various values of P_T^{cut} for the $pp(bg)\rightarrow tW^-+b_{split}$ and $pp(gg+q\bar{q})\rightarrow tW^-\bar{b}$ processes.

be considered and how one should properly simulate them, and (b) how the subtraction term is distributed between the $pp(bg) \rightarrow tW^- + b_{split}$ and $pp(gg + q\bar{q}) \rightarrow tW^- \bar{b}$ processes and what part of double counting should be subtracted from each subprocess.

We conclude that the method of combining the p_T^b distribution of Wtb_{split} gluon and the complete tree-level tWb process allows us to find the physically motivated p_T cut on the b quark which allows us to treat those processes together and simulate them in different kinematical regions of p_T^b . Namely, one should generate Wtb_{split} events using PYTHIA or any other analogous generator, and use them in the kinematical region $p_T^b < P_T^{cut}$ with the weight, corresponding to the $\sigma_{total} - \sigma[pp(gg + q\bar{q}) \rightarrow tW^- \bar{b}, p_T^b > P_T^{cut}]$ cross section; in the region $p_T^b > P_T^{cut}$, one should use Wtb events.

IV. FINAL RESULTS AND CONCLUSIONS

We have re-examined the $tW+X$ single top-quark production process, which is important at the CERN LHC. We have shown that the $2 \rightarrow 3[Wtb]$ process has to be correctly taken into account, with a proper subtraction of the top-quark pair contribution, and that its kinematical distributions are qualitatively different from those of the $2 \rightarrow 2[Wt]$ process.

We suggest a new method of kinematical sewing for the two different processes contributing to the $tW+X$ produc-

tion, using the transverse b -quark momenta distribution. This method allows an unambiguous simulation of the correct kinematical distribution of the total process of $tW+X$ production in the whole kinematical region and generates events without negative weights using the standard sets of PDF.

We have estimated the cross section of the single top-quark $tW+X$ production, taking into account uncertainties due to the choice of the QCD scale. The cross sections for single top- and single anti-top-quark production – $tW^- + X$ and $\bar{t}W^+ + X$ at the CERN LHC are equal to each other, contrary to other processes of single top-quark production. So, the combined $[tW^- + X + \bar{t}W^+ + X]$ cross section is $62.0^{+16.6}_{-3.6}$ pb.

ACKNOWLEDGMENTS

We thank C.-P. Yuan for useful remarks and discussions. E.B. is grateful to the Russian Ministry of Science and Technologies, the Russian Foundation for Basic Research (grant 99-02-04011), the INTAS-CERN Foundation (grant No. 377), and the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBF) (project No. HTE0499 Manakos) for partial financial support. E.B. would like to thank P. Manakos and Th. Ohl for their kind hospitality during a visit to the Darmstadt University of Technology, where the paper was completed.

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- [1] S. Willenbrock and D. Dicus, Phys. Rev. D **34**, 155 (1986); C.-P. Yuan, *ibid.* **41**, 42 (1990); G. V. Jikia and S. R. Slabospitsky, Phys. Lett. B **295**, 136 (1992); R. K. Ellis and S. Parke, Phys. Rev. D **46**, 3785 (1992); G. Bordes and B. van Eijk, Z. Phys. C **57**, 81 (1993); D. O. Carlson and C.-P. Yuan, Phys. Lett. B **306**, 386 (1993); G. Bordes and B. van Eijk, Nucl. Phys. B **435**, 23 (1995); S. Cortese and R. Petronzio, Phys. Lett. B **253**, 494 (1991); D. O. Carlson, E. Malkawi, and C.-P. Yuan, *ibid.* **337**, 145 (1994); T. Stelzer and S. Willenbrock, *ibid.* **357**, 125 (1995); R. Pittau, *ibid.* **386**, 397 (1996); M. Smith and S. Willenbrock, Phys. Rev. D **54**, 6696 (1996); D. Atwood, S. Bar-Shalom, G. Eilam, and A. Soni, *ibid.* **54**, 5412 (1996); C. S. Li, R. J. Oakes, and J. M. Yang, *ibid.* **55**, 1672 (1997); **55**, 5780 (1997); G. Mahlon and S. Parke, Phys. Rev. D **55**, 7249 (1997); A. P. Heinson, A. S. Belyaev, and E. E. Boos, *ibid.* **56**, 3114 (1997); T. Stelzer, Z. Sullivan, and S. Willenbrock, *ibid.* **56**, 5919 (1997); T. Tait and C.-P. Yuan, hep-ph/9710372; D. Atwood, S. Bar-Shalom, G. Eilam, and A. Soni, Phys. Rev. D **54**, 5412 (1998); T. Stelzer, Z. Sullivan, and S. Willenbrock, *ibid.* **58**, 094021 (1998).
 - [2] E. Boos, A. Pukhov, M. Sachwitz, and H. J. Schreiber, Z. Phys. C **75**, 237 (1997); Phys. Lett. B **404**, 119 (1997).
 - [3] J.-J. Cao, J.-X. Wang, J.-M. Yang, B.-L. Young, and X. Zhang, Phys. Rev. D **58**, 094004 (1998).
 - [4] E. Boos, L. Dudko, and T. Ohl, Eur. Phys. J. C **11**, 473 (1999).
 - [5] S. Moretti, Phys. Rev. D **56**, 7427 (1997).
 - [6] A. S. Belyaev, E. E. Boos, and L. V. Dudko, Phys. Rev. D **59**, 075001 (1999).
 - [7] T. M. Tait, Phys. Rev. D **61**, 034001 (2000).
 - [8] R. Bonciani, S. Catani, M. L. Mangano, and P. Nason, Nucl. Phys. B **529**, 424 (1998).
 - [9] ATLAS: Detector and Physics Performance, Technical Design Report, Volume 2, CERN-LHCC-99-15.
 - [10] E. E. Boos *et al.*, hep-ph/9503280; P. Baikov *et al.*, in Proceedings of the Xth International Workshop on High Energy Physics and Quantum Field Theory, QFTHEP-95, Moscow, 1995, edited by B. Levchenko and V. Savrin, p. 101; A. Pukhov *et al.*, hep-ph/9908288.
 - [11] T. Stelzer, Z. Sullivan, and S. Willenbrock, Phys. Rev. D **56**, 5919 (1997).
 - [12] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).