NLO QCD corrections to $WbW\bar{b}$ production at hadron colliders: new developments and new issues

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Abstract. This short summary reviews the recent progress in the computation of higher-order corrections to $W^+bW^-\bar{b}$ production. In addition, new phenomenological studies reveal potential problems that may affect precision measurements at the LHC.

1. Introduction
After the first round of LHC running at proton–proton collision energies of 7 and 8 TeV, the interest in, and demand for high precision calculations has increased substantially. The top quark sector has been in the focus with a large number of publications. In particular the flagship process, top quark pair production, attracted a lot of attention. However in the experiments, top quarks can only be traced via their decay products, which means that for any experimental selection, the more realistic, and more physical, final state description will be achieved by computing $W^+bW^-\bar{b}$ production directly, cf. [1, 2]. This way one includes effects that are beyond the ($t\bar{t}$-like) approximation of considering only double-resonant top quark propagators. The contributions from single-resonant ($Wt$-like) and non-resonant ($VV$-like) diagrams are also taken into account together with all related quantum interferences resulting from combining the various contributions. In addition, offshell effects will be well captured by this approach.

The first higher-order QCD calculations to the hadro-production of $W^+bW^-\bar{b}$ were provided by two different groups [3, 4, 5] and relied on the massless $b$ quark approximation, i.e. the five-flavour (5F) scheme was adopted to accomplish these computations. Furthermore, finite top quark and $W$ width effects were incorporated in a consistent manner by utilizing the complex mass scheme. Any preceding work was based on treating the top quarks in the narrow width approximation (NWA) [6, 7]. In this $\Gamma_t \rightarrow 0$ limit, only double-resonant contributions survive, and the pair production of onshell top quarks factorizes from their decays. The neglected contributions can be estimated to be suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$. For sufficiently inclusive observables and/or kinematical requirements projecting out the onshell $t\bar{t}$ contributions, small corrections were indeed seen in a number of comparisons between the predictions of the full and factorized approach [8, 5]. In [8], no more than 1% deviations were found for inclusive cross sections including experimental cuts. However, finite width effects can grow (significantly) larger in differential distributions such as the transverse momentum of the $b\bar{b}$ pair.

The renewed interest in $WbW\bar{b}$ calculations is twofold and firmly backed up by the rapid progress in QCD NLO automation. From a computational point of view, it is challenging to consistently incorporate the $b$ quark mass effects. From a phenomenological point of view, one needs to scrutinize whether the NWA can also be applied to more exclusive phase space regions.
Figure 1. Transverse mass distribution of the Higgs boson at NLO/LO (blue/black curve) for the \( pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} \) process calculated in the 4F scheme. Measurement cuts similar to the one-jet bin selection employed by ATLAS have been applied, and supplemented by the “Higgs signal” topology cuts, \( m_{ll} < 50 \text{ GeV} \) and \(|\Delta\phi_{ll}| < 1.8\). For the 4F NLO result, the envelope of a set of scale factor variations concerning \((\mu_R, \mu_F)\) is indicated by the dashed blue lines. The deviations between the full 4F calculations turn out to be larger than those occurring between the full 4F prediction at LO and the incoherent sum (dashed red line) of NWA predictions at LO for \( t\bar{t}, Wt \) and \( b \) quark associated \( ll\nu\nu \) production.

In addition, one starts worrying that at the current experimental precision this whole class of subleading corrections from offshell effects, non-factorizing contributions, the \( b \) quark mass dependence etc. has to be included one way or another. Certainly, over the course of the last year, new developments in both directions have occurred, and will be briefly discussed below.

2. Recent four-flavour scheme calculations and phenomenological applications

The end of last year has seen two new publications by two independent groups [9, 10] where the finite mass of \( b \) quarks has been taken into account in the NLO calculation of \( W^+bW^−\bar{b} \) final states leaving purely leptonic signatures. Thereby it is important to stress that these predictions have been obtained for the more complex \( pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} \) scatterings. The inclusion of finite \( m_b \) is a significant step in gaining better theoretical control of phase space regions with unresolved \( b \) quarks where offshell and single-top contributions are expected to play a more prominent role.

In the earlier calculations [3, 4, 5] based on the 5F treatment, the requirement of two hard \( b \) jets was absolutely necessary to produce infrared finite results. In the four-flavour (4F) scheme however, this does not have to be the case. Here, a fully differential, NLO accurate description of both final state \( b \) jets is achieved, which permits the application of jet vetoes, and enables one to separate, in a gauge-invariant way, the narrow width top quark contributions from those of the finite width remainder. In other words, a unified description of \( t\bar{t} \) and \( Wt \) production is provided. Hence, the 4F scheme \( WbW\bar{b} \) computation can be used to obtain reliable estimates in many analyses where top quark pair, \( Wt \) and \( b \) quark associated \( WW \) contributions constitute an important background to BSM searches or SM measurements in the electroweak sector.

In the study by R. Frederix, see Ref. [9], the focus is on one example of particular importance to Higgs boson measurements at the 8 TeV LHC. Considering the \( WW^{(*)} \) channel with fully leptonic decays, the top quark induced background in the one-jet bin has been evaluated using the newly available 4F calculation of \( WbW\bar{b} \) production. The parton level computations were performed within the MADGRAPH5_AMC@NLO framework, and the events were required to pass a one-jet bin selection closely following the actual ATLAS strategy for this measurement. Figure 1 shows one example plot of the analysis carried out in [9], including the final step of imposing the “Higgs signal” topology cuts.

The work of F. Cascioli et al. provides a detailed discussion of the impact of NLO and finite (top quark and \( W \)) width corrections for many jet bin definitions of interest [10]. Particular attention has been paid to the effects of jet \( p_T \) vetoes of different strengths, \( n_{\text{jet}} \) and jet flavour requirements. The results have been obtained with an in-house NLO parton level generator using the capabilities of OPENLOOPS+COLLIER. As the ill-defined \( tt/Wt \) separation of the 5F scheme is avoided, they furthermore introduce a dynamical scale based on transverse energies.
$E_{T,i} = (m_i^2 + p_{T,i}^2)^{1/2}$, which interpolates between $\mu_{tt}^2 = E_{T,i} E_{T,l}$ and $\mu_{WW}^2 = E_{T,i} E_{T,b}$ for $tt$ and single-$t$ topologies, respectively. This better accounts for the multi-scale problem at hand. Figure 2 compares results based on this new scale choice, $\mu = \mu_{WWb\bar{b}}$, and the more commonly used scale choice $\mu = m_t$. The presentation is broken down into different $n_{jet}$ contributions that add up to the fully inclusive result. This makes it clear that the global $O(1)$ $K$-factor emerges mainly from the large inclusive two-jet bin corrections, which are slightly larger for the computation relying on the dynamical scale. One observes that the finite top quark width effects are strongly enhanced for the exclusive one-jet and zero-jet selections. They may grow as large as 30% if no jets are allowed. This is also nicely demonstrated in Figure 3 visualizing the differential distribution of the azimuthal angle separation between the two leptons in the event. This observable is key to precision measurements of spin correlations in $tt$ production [11], and clearly, a flattening of the $\phi_{+1-}$ shape as a result of the NLO treatment leads to effects in determining parameters such as $f_{SM}$, which quantifies how SM-like the spin correlations are [11].

The rather different impact of using a finite $\Gamma_t$ is also depicted in Figure 4. A numerical extrapolation to the NWA is applied to compare the relative cross section differences $\sigma_{tt-like}/\sigma_{WWb\bar{b}} - 1$ between a rather inclusive event selection and one requiring two hard $b$ jets.

Figure 2. 4F scheme $W^+W^-\bar{b}b$ cross sections, $K$-factors and finite $\Gamma_t$ contributions in the 0-jet, 1-jet and inclusive 2-jet bin, using two different scales.

Figure 3. 0-jet bin distribution of the transverse opening angle of the charged leptons. The red/blue bands indicate scale uncertainties at NLO/LO.

Figure 4. Numerical extrapolation to the $\Gamma_t \to 0$ limit of the NLO (red lines) and LO (blue lines) cross sections for $W^+W^-\bar{b}b$ hadro-production. The results are presented in terms of relative differences that employ the respective 4F scheme cross sections obtained with the physical top quark width as their reference. The numerical NWA used here is expressed as $d\sigma_{tt} = \lim_{\Gamma_t \to 0} (\Gamma_t/T_{t}^{phys})^2 d\sigma_{WWb\bar{b}}(\Gamma_t)$, and shown for two jet phase space selections (including leptonic cuts): one that reflects the inclusive case (solid lines) and one where two $b$ jets have to be resolved (dotted lines). While the $tt$ signal-like selection shows little dependence on finite width corrections, it is crucial to take them into account for the inclusive phase space. The finite top quark width remainder turns out to be dominated by $Wt$ contributions.
LHC 7 TeV
\[ \mu_R = \mu_F = \hat{H}_T /2 \]
MSTW2008 (n)lo pdf
NLO, \( m_t = 172.5 \) GeV
NLO, \( m_t = 165.0 \) GeV
NLO, \( m_t = 180.0 \) GeV

\( \frac{1}{\sigma} \frac{d\sigma}{dm_{lb}} \) [1/GeV]
0 50 100 150 200
0.5
1
1.5
2
2.5
3

(1/\sigma) \frac{d\sigma}{dml_b} [1/GeV]
0 50 100 150 200
0.6
0.8
1
1.2
1.4

\( m_{lb} \) [GeV]
Ratio

\( m_t \) predictions at given \( m_{lb} \) distribution in dilepton events to determine the top quark mass as

\( m_t = \frac{m_t}{\hat{H}_T} \) ± 64 (stat) ± 50 (syst) [13]. The result of this one-dimensional template fit is based on data collected at the 7 TeV LHC with an integrated luminosity of 4.7 fb. While the systematic uncertainty is dominated by that of the jet energy scale, the ATLAS estimate for the theoretical uncertainty amounts to 0.8 GeV. The success of the \( m_{lb} \) approach therefore depends on a solid understanding of the theoretical uncertainties associated with the \( m_{lb} \) shape.

Using factor-two scale variations, one can test the robustness of the \( m_{lb} \) shape at the parton level in a straightforward way. In a factorized, spin correlation preserving approach where the core \( t\bar{t} \) production is described at NLO and supplemented with LO decays, one obtains very stable results as depicted in the right panel of Figure 5. This should serve as a fairly accurate model of the current parton level theory standard used in the experiments which is based on NLO+PS matching as provided for example by PowHEG or MC@NLO. If one instead uses a full NLO treatment of the \( W^+bW^-\bar{b} \) final state as done in Refs. [14, 15], very different, much more pronounced shape variations are found surprisingly. The results in the left panel of Figure 5 originate from a 5F GoSAM+Sherpa computation, and in comparison to the \( m_t \) sensitivity of the \( m_{lb} \) shape displayed in the middle panel, it is obvious that the scale factor variations of the full calculation mimic shape changes as induced by different \( m_t \) values. Against usual expectations, the more accurate theory approach will therefore produce larger theoretical uncertainties in the determination of the top quark mass.

This has been demonstrated in a parton level analysis in Ref. [14] where the \( m_{lb} \) template fitting procedure, cf. [13], has been applied to pseudo-data generated from NLO and LO predictions at given \( m_t^{\text{in}} \). This has been done separately for both the full and factorized approach.
as well as the default scale and scale varied choices. The different sets of pseudo-data are then
tested against the theory hypotheses defined by the NLO and LO templates one obtains from
the corresponding default scale choice predictions at different top quark masses. The templates
thus parametrize this $m_t$ dependence, and by varying the sets of pseudo-data and hypotheses
one can single out two effects, the one caused by the NLO corrections and the one stemming
from scale uncertainties. The outcome of these parton level template fits is summarized in
Figure 6 showing the $m^\text{out}_t - m^\text{in}_t$ differences for the full and factorized approach separately in
the left and right panel, respectively. The plots convey a clear message: the full calculation
gives rise to (significantly) larger mass shifts whether one compares NLO versus LO descriptions
(indicated by the separation of the red and blue horizontal lines) or scale variations by factors
of two (indicated by the red and blue bands).

Of course for the full approach, the fact of larger theory uncertainties needs to be verified in a
more realistic context. This however requires matching the new calculations to parton showers,
which has not been fully solved yet due to the issue of intermediate resonances. Nevertheless,
some first studies have recently been presented in the literature $[16, 17]$. 

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Figure 6. The $m_t$ offset predictions, for three $m_t$ input values, as estimated from various
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and their statistical uncertainty. The bands indicate how the offset varies owing to theoretical
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