

NLO QCD corrections to $W^+W^-b\bar{b}$ production and top quark observables

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We present the NLO QCD corrections to the production of a W^+W^- pair and two b -jets, including the leptonic decays of the W bosons. Contributions from singly resonant and non-resonant top quarks are fully taken into account. We also discuss observables relevant for top quark mass measurements and $t\bar{t}$ asymmetries.

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1. Introduction

Precision measurements of observables related to top quarks are of primary importance at the LHC and future colliders, to obtain more information on the Higgs sector as well as indirect hints of physics beyond the Standard Model. However, quantities like the top quark mass or the forward–backward asymmetry are unphysical observables, in the sense that they have to be reconstructed from the top quark decay products. It therefore is a non-trivial task to match the theory predictions with the quantities reconstructed from the experimental measurements. To have a precise description from the theory side, the predictions need to go beyond the simple approximation of factorising top quark production and decay. For example, finite width effects and non-factorising contributions to observables based on W boson decay products and b -jets can have a non-negligible impact on mass measurements.

The next-to-leading order QCD corrections to top quark pair production [1–5] recently have been enhanced by the NNLO corrections to the total cross section [6]. The NLO electroweak corrections are also known [7]. These calculations treat the top quarks as stable on-shell particles. If included, their decays have been computed in the narrow width approximation (NWA), where production and decay decouple. NLO calculations in the NWA were further improved in [8–10], where spin correlations between top quark production and decay have been taken into account.

The full process $pp(p\bar{p}) \rightarrow W^+W^-b\bar{b}$ was recently calculated at NLO QCD in [11–13]. It represents a $2 \rightarrow 4$ process which is of much higher complexity than the factorised process discussed above. In this talk we present the NLO QCD corrections to $pp(p\bar{p}) \rightarrow W^+W^-b\bar{b} \rightarrow (e^+ \nu_e)(\mu^- \bar{\nu}_\mu)b\bar{b}$ including singly-resonant and non-resonant contributions, corresponding to Feynman diagrams containing only one or no top quark propagator that can go on-shell. The impact of non-resonant W boson contributions has been studied in [12] and was found to be small. Therefore, non-resonant contributions from W bosons are neglected in our calculation. On the other hand, in contrast to the calculations in [11–13], contributions from massless b quarks in the initial state are included in our calculation.

2. Calculational Setup

The virtual corrections were calculated by the automated one-loop generator GOSAM [14].¹ The program combines cut-based integrand reduction techniques [15–18] with improved tensor reduction methods [19–21]. The basis integrals are taken from GOLEM95C [21] or ONELOOP [22].

For the real radiation and the NLO infrared subtraction terms as well as for the Monte Carlo integration, the event generator SHERPA [23, 24] has been used, interfaced to GOSAM via the Binot–Les–Houches accord (BLHA) [25, 26]. For more applications of GOSAM, we refer to the contributions [27, 28].

As mentioned in the introduction, our calculation includes singly-resonant and non-resonant contributions. To take the top quark decay width into account in a gauge invariant way, the complex mass scheme [29] is used. In our case, this amounts to replacing the top quark mass everywhere by a complex parameter μ_t according to $\mu_t^2 = m_t^2 - im_t\Gamma_t$.

¹GOSAM is publicly available at <http://gosam.hepforge.org/>.

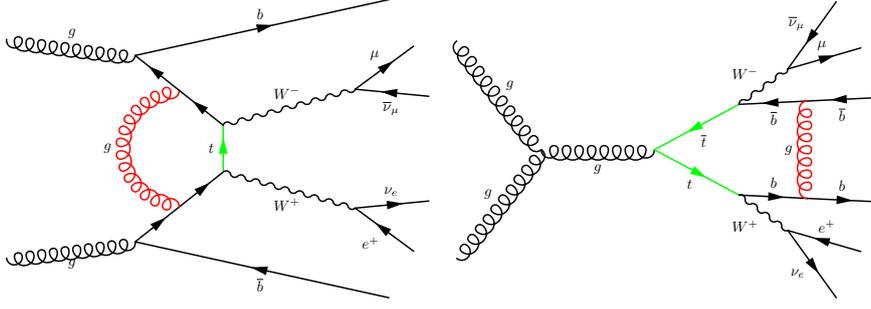


Figure 1: Example of a non-resonant diagram and a non-factorizable virtual contribution.

The correctness of our virtual amplitude has been checked by comparing it with the results of [12]. The real radiation part was checked by calculating the cross section for different values of the dipole α -parameter [30], i.e. for $\alpha_{\text{dip}} = \{0.1, 0.05, 0.01\}$, and the results were found to be in agreement within the statistical uncertainty.

At NLO, the NWA neglects non-resonant diagrams and radiative corrections that connect production and decay or both decays. Two example Feynman diagrams contributing to the virtual corrections, which are not present in the NWA, are given in Figure 1. One expects that the contributions neglected in the NWA are suppressed by powers of $\Gamma_t/m_t \lesssim 1\%$. While this is true for sufficiently inclusive observables, the corrections can be much larger for observables such as the invariant mass of the charged lepton plus b -jet, m_{lb} [31].

3. Phenomenological Results

3.1 General input parameters and LHC cross sections

For the (N)LO calculations, the MSTW2008(N)LO parton distributions [32] were used, taking the strong coupling constant α_s and its running as provided by these PDFs. For the electroweak parameters, we employ $G_\mu = 1.16637 \cdot 10^{-5} \text{ GeV}^{-2}$, $M_W = 80.399 \text{ GeV}$, $\Gamma_W = 2.0997 \text{ GeV}$, $M_Z = 91.1876 \text{ GeV}$, $\Gamma_Z = 2.5097 \text{ GeV}$. Diagrams involving a Higgs boson propagator are neglected in the entire calculation owing to their small contribution. All quarks other than the top quark are taken to be massless. For the top quark mass and widths at leading and next-to-leading order, we use $m_t = 172.0 \text{ GeV}$, $\Gamma_t^{\text{LO}} = 1.4426 \text{ GeV}$ and $\Gamma_t^{\text{NLO}} = 1.3167 \text{ GeV}$, respectively.

Results are presented for the LHC at 7 TeV centre-of-mass energy. All final state partons are clustered into jets with a geometric separation $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} > 0.5$ using the anti- k_T jet algorithm [33, 34] implemented in FASTJET [35]. Each event must contain at least two b -jets obeying the conditions $p_{T,b} > 30 \text{ GeV}$ and $|\eta_b| < 2.5$. The kinematic requirements on the charged leptons and the missing energy are: $p_{T,l} > 20 \text{ GeV}$, $|\eta_l| < 2.5$ and $\cancel{p}_T > 20 \text{ GeV}$.² The renormalisation and the factorisation scales are set to $\hat{H}_T/2$. The variable \hat{H}_T is defined as $\hat{H}_T = \sum_j p_{T,j}$, where the sum goes over *all* final-state partons, including leptons. The particular choice of $\hat{H}_T/2$ for the central scale is made because of the observation that the difference between the LO and NLO cross sections as well as the uncertainty introduced by the scale variation remain relatively small.

²Here, we determine the missing energy from the transverse vector sum of the neutrinos.

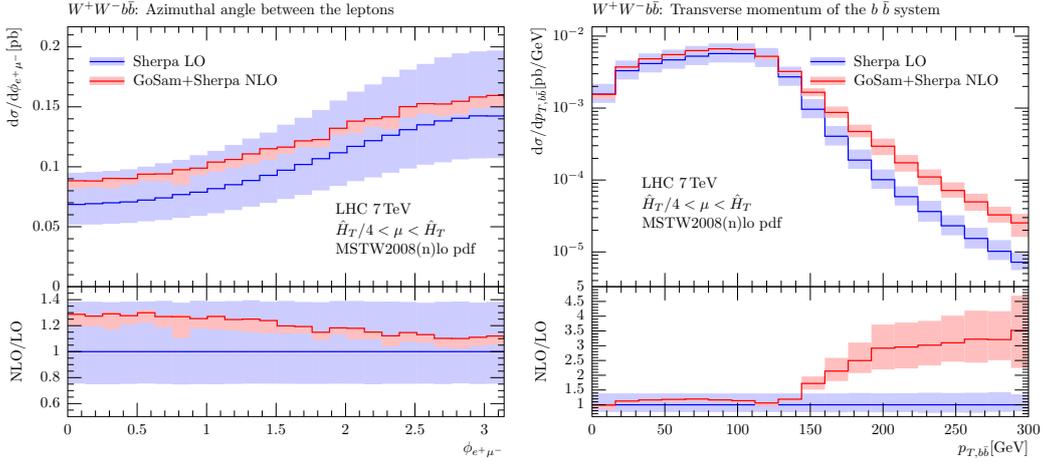


Figure 2: The azimuthal angle distributions of the two charged leptons (left) and the transverse momentum distributions of the $b\bar{b}$ system (right). The bands around the distributions are obtained by varying $\mu_{R,F}$ simultaneously by a factor of two around the central scale $\hat{H}_T/2$.

The cross sections obtained with the parameters given above are

$$\begin{aligned} \sigma_{\text{LO}} [\text{fb}] &= 638.4^{+38.5\%}_{-24.8\%} (\text{scale}) \pm 0.03\% (\text{stat}) \\ \sigma_{\text{NLO}} [\text{fb}] &= 758.5^{+2.5\%}_{-5.3\%} (\text{scale}) \pm 0.2\% (\text{stat}) . \end{aligned} \tag{3.1}$$

Figure 2, to the left, shows the distribution of the azimuthal angle between the two charged leptons, $\phi_{e^+\mu^-}$, stemming from the W boson decays. This angle plays an important role for the measurement of spin correlations. We observe a substantial reduction of the scale uncertainty at NLO. The $\phi_{e^+\mu^-}$ distribution receives large NLO corrections in regions where the separation between the two leptons is small, with a variation of the K -factor of $\sim 20\%$. Figure 2, to the right, shows the transverse momentum of the vector sum of the two b -jet momenta. While for low p_T , one again finds K -factors of $\mathcal{O}(1.2)$, this observable receives large NLO corrections above $p_T \simeq 150 \text{ GeV}$. The reason for this K -factor increase up to 3 in the tail of $p_{T,b\bar{b}}$ lies in the generation of real radiation at NLO. At LO, the $t\bar{t}$ pair has zero transverse momentum, which leads to a suppression of $b\bar{b}$ pairs with high transverse momentum. At NLO, it however can obtain transverse momentum by recoiling against the real radiation.

3.2 Reconstruction of the top quark mass

The mass m_t of the top quarks can be reconstructed by measuring kinematical distributions of their decay products. As m_t is not a physical observable, it is scheme dependent. The most commonly used mass definitions are the pole mass and the $\overline{\text{MS}}$ mass. The different masses are related by a perturbative series, see e.g. [36, 37]. There are several issues, which render a precise top quark mass determination at hadron colliders difficult, such as the dependence on the definition of the top quark mass, b -mass and non-perturbative effects in the Monte Carlo modeling, finite width effects and bound state effects. For a recent review, we refer to [38, 39].

Here we focus on the reconstruction of the top quark mass from the distribution of the invariant mass of a charged lepton and a b -jet, $m_{lb} = (p_l + p_b)^2$, shown in Figure 3. Top quark mass

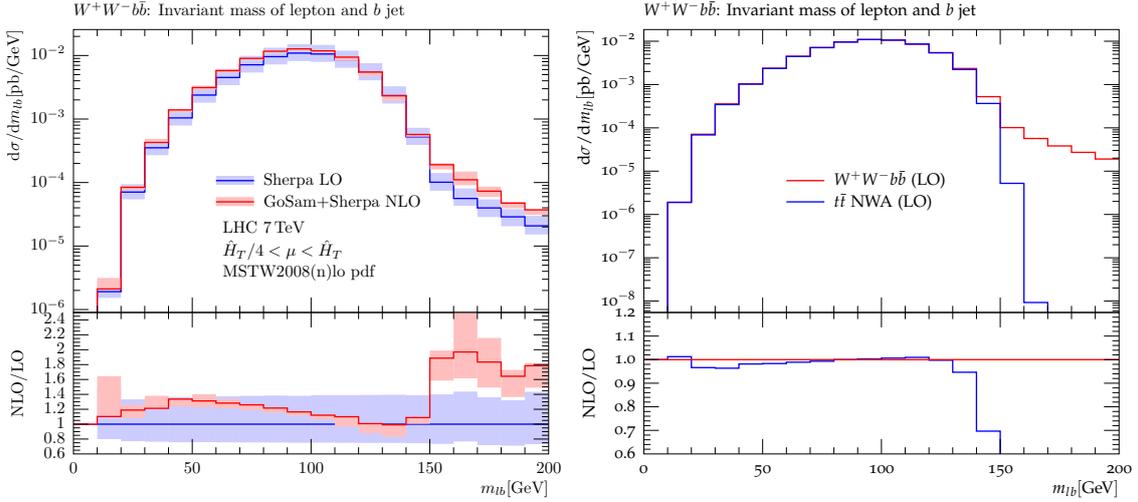


Figure 3: The invariant mass m_{lb} distribution at NLO and LO (left) and the comparison to the LO prediction in the NWA (right).

measurements based on this observable have been performed e.g. in [40–44]. For our calculation of the m_{lb} distribution, we use the ATLAS cuts of [41]. We require exactly two oppositely charged leptons (electrons with $p_{T,e} > 25$ GeV and muons with $p_{T,\mu} > 20$ GeV) with $|\eta_l| < 2.5$ and two b -jets with $p_{T,b} > 25$ GeV, $|\eta_b| < 2.5$ and $\Delta R > 0.4$. The leptons have to be isolated from the jets according to $\Delta R_{l,jet} > 0.4$. Furthermore, H_T defined as the sum over the transverse momenta of charged leptons and jets has to be larger than 130 GeV.

One complication arises from the fact that there are two top quarks and therefore two possible m_{lb} values in each event per charged lepton. Since the charge of the bottom quark initiating the jet has not been reconstructed experimentally, one needs a criterion to assign b -jets to the “correct” lepton. Different strategies for the assignment were tested based on Monte Carlo studies. It turned out that the requirement of minimising the sum of both m_{lb} led to the best criterion in identifying the optimal lb pairings, with a recombination efficiency of about 77 percent [41]. The histogram to the right in Figure 3 shows a LO comparison between the full $W^+W^-b\bar{b}$ calculation and the NWA. In the NWA, m_{lb} ideally has a sharp cut-off at $\sqrt{m_t^2 - m_W^2}$, which corresponds to the limit of vanishing neutrino momentum. The non-resonant contributions included in the full calculation lead to a tail in the distribution. This shows that, while the integrated cross section receives only small corrections, non-resonant contributions can become sizeable for some distributions.

3.3 Top quark asymmetries

At $p\bar{p}$ colliders, the top quark forward–backward asymmetry $A_{t\bar{t}}^{FB}$ is defined as

$$A_{t\bar{t}}^{FB} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)} \quad (3.2)$$

using the rapidity difference $\Delta y = y_t - y_{\bar{t}}$. For $t\bar{t}$ production calculated at LO in QCD, this asymmetry vanishes. The first non-zero contribution to $A_{t\bar{t}}^{FB}$ appears at NLO. Measurements of $A_{t\bar{t}}^{FB}$ at the Tevatron [45, 46] give a significantly larger value than the Standard Model prediction [47–49].

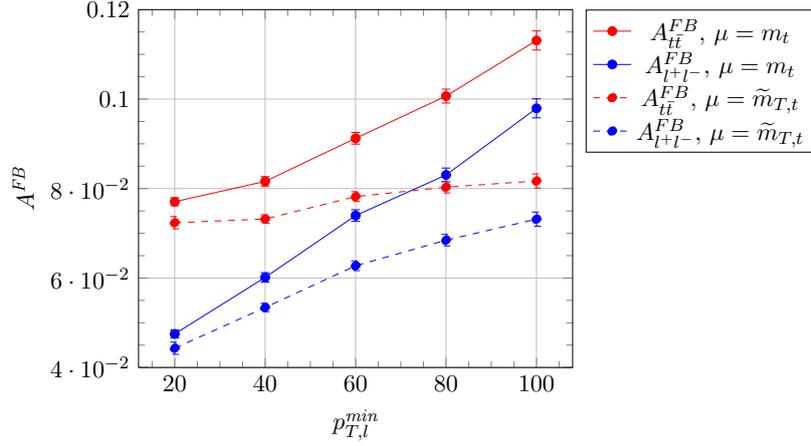


Figure 4: Dependence of the $t\bar{t}$ and leptonic asymmetries on the minimal charged-lepton transverse momentum $p_{T,l}^{\min}$. Note that the change of A^{FB} with $p_{T,l}^{\min}$ also depends on the scale choice.

As the top quarks have to be reconstructed from their decay products, the experimental results for $A_{t\bar{t}}^{FB}$ depend on the reconstruction method. To avoid a bias in this procedure, one can also define a leptonic asymmetry

$$A_{l^+l^-}^{FB} = \frac{\sigma(\Delta\eta > 0) - \sigma(\Delta\eta < 0)}{\sigma(\Delta\eta > 0) + \sigma(\Delta\eta < 0)} \quad (3.3)$$

based on the pseudo-rapidity difference $\Delta\eta = \eta_{l^+} - \eta_{l^-}$. The drawback of the leptonic asymmetry is that its value is much smaller than the one based on the top quarks themselves.

At the LHC these forward–backward asymmetries cannot be measured, because of the symmetric pp initial state. However, one can measure the charge asymmetry using $\Delta|y| = |y_l| - |y_{\bar{l}}|$:

$$A_{t\bar{t}}^C = \frac{\sigma(\Delta|y| > 0) - \sigma(\Delta|y| < 0)}{\sigma(\Delta|y| > 0) + \sigma(\Delta|y| < 0)}. \quad (3.4)$$

This asymmetry was measured by ATLAS [50] and CMS [51] and found to be in agreement with the Standard Model predictions. The leptonic charge asymmetry is defined analogously.

Here we focus on a study of the forward–backward asymmetries in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, where we apply the anti- k_T jet algorithm and the constraints $\Delta R > 0.4$, $p_{T,b} > 20$ GeV, $p_{T,l} > 20$ GeV, $|\eta_b| < 2.5$, $|\eta_l| < 2.5$, $\cancel{p}_T > 25$ GeV. As expected, we observe NLO corrections leading to a shift towards positive values in both the Δy and $\Delta\eta$ distributions. We also investigated the dependence of the asymmetry on the p_T requirement on the l^\pm transverse momentum, $p_{T,l}^{\min}$, and on the scale choice, where we compared the scales $\mu = \mu_R = \mu_F = \{m_t, \tilde{m}_{T,t}\}$ defining $\tilde{m}_{T,t} = \sqrt{m_t^2 + p_{T,\text{lead,jet}}^2}$. The results are shown in Figure 4. We observe that the correlation between $A_{t\bar{t}}^{FB}$ and $A_{l^+l^-}^{FB}$ becomes stronger as we increase $p_{T,l}^{\min}$, see also Ref. [52]. It also becomes clear that the change of $A_{t\bar{t}}^{FB}$ and $A_{l^+l^-}^{FB}$ with $p_{T,l}^{\min}$ depends rather strongly on the scale choice.

4. Conclusions

We have calculated the NLO QCD corrections to the production of a W^+W^- pair in association with two b -jets, including the leptonic decays of the W bosons, and full off-shell effects of the top

quarks. We use our results to study the observable m_{lb} , the invariant mass of a charged lepton and a b -jet, which is relevant for top quark mass measurements. We also studied the correlation between the $t\bar{t}$ and leptonic forward–backward asymmetries at the Tevatron, and their dependence on the minimum value required for the charged lepton transverse momentum, $p_{T,l}^{\min}$, and on the scale choice.

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