Differential top pair cross section and top anti-top plus jets Physics  

Malgorzata Worek  
Theoretische Physik, Fachbereich C, Bergische Universität Wuppertal, D-42097 Wuppertal, Germany  
Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen University, D-52056 Aachen, Germany  
E-mail: worek@physik.rwth-aachen.de  

Abstract. A brief summary of the current status of the next-to-leading order QCD corrections to top quark pair production and the associated production of $t\bar{t}$ with jet(s) in different configurations, i.e. with one jet, two jets and another $t\bar{t}$ pair, is presented.

1. Introduction  
By the end of 2012 a successful run of the Large Hadron Collider (LHC) with proton-proton collisions at 8 TeV delivered 23.3 fb$^{-1}$ of collected data. This large available statistics has opened a window on entirely new measurements of more complex final states. Reducing theoretical uncertainties for correct interpretation of these data is among the highest priorities of the theoretical high energy community. A theoretical accuracy at least at next-to-leading order (NLO) level is desirable and for most analyses even demanded.

The major purpose of the LHC is a deeper understanding of the interactions among fundamental constituents of matter. To this end, the top quark plays a special role. At the LHC it is copiously produced via strong interactions in top anti-top pairs, so its production cross section, decays and properties are studied with high precision. Apart from being studied as a signal process, the top quark constitutes the main background in analyzes of the recently discovered Standard Model (SM) like Higgs boson. Distinguished by its large mass, the top quark is also potentially sensitive to physics beyond the SM (BSM), which concerns among others searches for non-SM Higgs bosons and supersymmetric particles. In order to understand and control top quark background processes to the SM and the BSM physics, precise predictions for these reactions at the differential level are indispensable.

In this contribution, a brief report on the recent activities in the calculations of the NLO QCD corrections to the differential top pair cross section and the associated production of $t\bar{t}$ with jet(s) in different configurations, i.e. with one jet, two jets and a $t\bar{t}$ pair, is given.

2. Top Anti-Top  
The NLO QCD corrections to the production of the top anti-top pairs followed by top decays in the so called narrow-width approximation (NWA) have already been available for some
time. In this approach the full amplitude is factorized into production of the unstable particles and their subsequent decays neglecting non-resonant and non-factorizable contributions to the amplitude. The NWA significantly simplifies calculations of higher order corrections on the one hand at the same time preserving gauge invariance. First calculations of the NLO QCD corrections to the differential cross section of top quark pair production in hadronic collisions taking only double resonance contributions into account and top and anti-top spin degrees of freedom in the production and decay have been presented in \[1,2\]. Mixed QCD and electroweak NLO corrections have been also calculated see e.g. \[3\] and references therein. In addition, several charge asymmetries have been computed for the $t \bar{t}$ production at the LHC and at the Tevatron \[4\]. Recently independent implementations of the NLO QCD corrections to top quark production and decay at fully differential level with all spin correlations appeared \[5,6\].

Moreover, NLO QCD corrections matched to parton shower for heavy flavor hadroproduction are obtainable via publicly available numerical programs like e.g. \textsc{MC@NLO} \[7\] and \textsc{Powheg} \[8\], however these programs do not fully include spin correlations through NLO QCD.

If resonant top production dominates, the NWA approach is very well motivated. Nevertheless the accuracy of the NWA needs to be tested, which requires a full NLO QCD calculation of off-shell effects, i.e. double-, single- and non-resonant top quark contributions of the order $O(\alpha_s^2\alpha^4)$ need to be taken into account. This has been done by two independent groups that have calculated NLO QCD corrections to the production of top anti-top pairs including interferences, off-shell effects, non-resonant contributions and spin correlations \[9–11\]. This required the introduction of a complex-mass scheme for unstable top quarks. Moreover, the intermediate W bosons were treated off-shell. These NLO calculations provide the most complete description of top anti-top pair production with leptonic decays of both $W^\pm$ gauge bosons. For the inclusive cut selection finite-width effects on $\sigma_{t \bar{t}}$ have been found to be around 1% both at the Tevatron and the LHC. In addition, the asymmetries for the top quark and the charged lepton in top anti-top production at the Tevatron and the LHC have been studied \[10,11\].

### 3. Top Anti-Top Plus Jet

For the $p\bar{p}$ and $pp$ collisions at the TeVatron and the LHC a substantial number of events in the inclusive top anti-top sample is accompanied by an additional jet. Since top quarks are produced with large energies and at high $p_T$, the probability for a top quark to radiate gluons considerably increases. Depending on the $p_T$ of the additional jet the fraction of events with an additional jet can easily be of the order of 30% or more \[12\]. Sample values for two different $p_T(j)$ cuts are given in Table 1, both for the TeVatron and the LHC, where results for $\sigma_{t \bar{t}j}^{NLO}$ have been taken from \[12\], while $\sigma_{t \bar{t}}^{NLO}$ have been calculated with the help of \textsc{Top++} \[13\].

**Table 1.** Fraction of events in the inclusive top anti-top sample that is accompanied by an additional jet depending on the $p_T$ of the additional jet at the TeVatron and the LHC.

| $\sqrt{s}$ | $\sigma_{t \bar{t}j}^{NLO}/\sigma_{t \bar{t}}^{NLO}$ | $\sqrt{s}$ | $\sigma_{t \bar{t}j}^{NLO}/\sigma_{t \bar{t}}^{NLO}$ |
|------------|-------------------------------------------------|------------|-------------------------------------------------|
| $\sqrt{s} = 1.96$ TeV |  $p_T \geq 20$ GeV 30% | $\sqrt{s} = 14$ TeV |  $p_T \geq 50$ GeV 47% |
| $\sqrt{s} = 1.96$ TeV |  $p_T \geq 40$ GeV 11% | $\sqrt{s} = 14$ TeV |  $p_T \geq 100$ GeV 22% |

Production of a top anti-top pair together with an additional jet is therefore crucial for a more precise understanding of the topology of top anti-top events. The $t \bar{t}j$ production is, however, also a dominant background to various new physics searches. Among others, the analysis of the
SM Higgs boson in the vector boson fusion process is a prominent example. In this case, precise theoretical predictions are indispensable.

NLO QCD corrections to the on-shell production of $t\bar{t}j$ have been first calculated in [14] and subsequently confirmed in [16,32]. Furthermore in [16] top quark decays at leading order (LO) in the NWA were included. Quite recently NLO QCD corrections to the production and top quark decays in the NWA together with jet radiation in top quark decays have been presented in [17]. Moreover, spin correlations were preserved throughout the entire decay chain. This state-of-the-art calculation of the NLO QCD corrections to the $t\bar{t}j$ process has shown that NLO QCD corrections and jet radiation in decays can lead to significant changes in shapes of distributions. Therefore, they need to be included for a fully consistent description of top anti-top plus jet production.

First results for the top anti-top plus jet process at NLO combined with parton shower via Powheg method [18, 19] are also available [20, 21]. However, in both cases only NLO QCD corrections to the on-shell production are calculated and LO decays in NWA are included through the parton shower programs. Consequently full spin correlations at NLO are omitted.

4. Top Anti-Top Plus Two Jets

Even thought a fraction of events in the inclusive top anti-top sample that is accompanied by two additional jets is only at the few percent level [22], see Table 2, $t\bar{t}$ plus two jets is an important background for the SM Higgs boson studies at the LHC. Two noticeable examples include:

(i) $H \rightarrow WW^* \rightarrow \ell\ell\nu\bar{\nu}$ where the Higgs boson is produced via weak boson fusion [23, 24],
(ii) $H \rightarrow b\bar{b}$ where the Higgs boson is produced via associated production with a $t\bar{t}$ pair [25,26].

In both cases the invariant mass of the Higgs decay products cannot be directly reconstructed. Either because of the two missing neutrinos in the decay of the two $W$ gauge bosons or because the $b\bar{b}$ pair can be chosen incorrectly within the complex $W^+W^-b\bar{b}b\bar{b}$ final state. In the latter case also the b-tagging efficiency plays a crucial role since two b-jets can arise from mistagged light jets. Consequently, a very precise knowledge of QCD backgrounds, i.e. $t\bar{t}jj$ as well as $t\bar{t}bb$ is essential. Lately however, a new strategy for the $Ht\bar{t}$ channel, based on a boosted Higgs boson and a boosted top quark, has been explored that should help to reduce complicated QCD backgrounds and resolve a multi b-jet combinatorial problem [27]. Fortunately, the NLO QCD corrections have already been calculated for both $t\bar{t}bb$ [28–31] and $t\bar{t}jj$ [22,32] background processes at the TeVatron and the LHC. In the former case two independent calculations exist and the per-mille level agreement between them have been obtained. Nevertheless, due to complexity of the NLO calculations for the $2 \rightarrow 4$ processes only corrections to the on-shell top production have been evaluated in all cases. Furthermore, they have not yet been matched to the parton shower programs.

| TeVatron $\sqrt{s} = 1.96$ TeV | LHC $\sqrt{s} = 7$ TeV |
|-----------------------------|-----------------------------|
| $\sigma_{t\bar{t}jj}^{NLO}$ / $\sigma_{t\bar{t}}^{NLO}$ | $\sigma_{t\bar{t}jj}^{NLO}$ / $\sigma_{t\bar{t}}^{NLO}$ |
| $p_T \geq 20$ GeV | $p_T \geq 50$ GeV |
| 4% | 6% |
| $p_T \geq 40$ GeV | $p_T \geq 100$ GeV |
| 1% | 1% |
**Figure 1.** Differential cross section distributions as a function of the invariant mass of the $t\bar{t}t\bar{t}$ system (left panel) and the $t\bar{t}$ pair (right panel) for $pp \rightarrow t\bar{t}t\bar{t} + X$ production at the LHC with $\sqrt{s} = 14$ TeV. The dash-dotted (blue) curve corresponds to the LO, whereas the solid (red) one to the NLO result. The scale choice is $\mu_F = \mu_R = H_T/4$. The uncertainty bands depict scale variation. The lower panels display the differential $K$ factor.

5. Top Anti-Top Plus Top Anti-Top
At the LHC the energy is sufficient to produce a four top final state at a sensible rate, see Table 3, where results obtained with the HELAC-Dipoles Monte Carlo program [33], for four different center of mass energies are given. The four top final state is an interesting channel to probe several realizations of BSM Physics. The most noticeable models being [34]

(i) Higgs and top compositeness,
(ii) new resonances from the Randall-Sudrum warped extra dimensions,
(iii) effective four-top quark interactions.

In addition, $t\bar{t}t\bar{t}$ is a major background for many processes arising from supersymmetric extensions of the SM, among others, the production of a heavy Higgs boson or long cascade

| LHC $\sqrt{s}$ [TeV] | $\sigma_{t\bar{t}t\bar{t}}^{LO}$ [fb] | Number of Events |
|----------------------|------------------------|-----------------|
| $\sqrt{s} = 7$ TeV   | 0.624(1)               | 3               |
| $\sqrt{s} = 8$ TeV   | 1.173(3)               | 27              |
| $\sqrt{s} = 13$ TeV  | 9.08(3)                | 908             |
| $\sqrt{s} = 14$ TeV  | 12.07(4)               | 3621            |
decays of colored new particles like squarks or gluinos, see e.g. [34] and references therein. Therefore, a precise theoretical description of the four-top production rate in the SM might help to constrain new physics scenarios.

The NLO QCD corrections to the four top quark final state have been recently computed for on-shell tops [35]. Despite its relatively small cross section at NLO of the order of

\[ \sigma_{\text{NLO}}^{\text{t\bar{t}tt\bar{t}}}(\text{LHC } 14\text{ TeV}, m_t = 173.2 \text{ GeV}, \text{MSTW2008NLO}) = 17 \pm 4 \text{ [scales]} \pm 1 \text{ [PDF]} \text{ fb} \]  

(1)
a theoretical control over \( pp \rightarrow t\bar{t}t\bar{t} \) is relevant if we take into account that typical predictions of various new physics scenarios are set in the range of 1-100 fb for \( m_{\text{new}} = 1-3 \text{ TeV} \) [34], where \( m_{\text{new}} \) is a mass of the new heavy particle or in general the energy scale that is associated with new physics.

In addition, a judicious choice of a dynamical scale has been presented, that allowed to obtain nearly constant \( K \)-factors in most differential cross sections. Two examples, the invariant mass of the \( t\bar{t}t\bar{t} \) system and the averaged invariant mass of the \( tt \) pair are shown in Figure 1.

6. Summary

Driven by the LHC needs, a tremendous development in the NLO QCD calculations for top quark physics has recently been achieved. Currently, \( 2 \rightarrow 4 \) processes are scrutinized at NLO. In many cases dynamical scales that depend on the event structure have been applied that allow for a better understanding of the high \( p_T \) tails of distributions. For the top anti-top pair production with leptonic decays the situation is the most satisfying, since complete off-shell and finite width effects of top quark have been calculated at NLO. Studies to match these calculations to the parton shower programs via POWHEG method are currently ongoing [36]. For the semi-leptonic decay channel and more complex final states progress is still needed, an ultimate goal being a description of a fully realistic final state such as \( W^+W^-b\bar{b} + X \) with \( X = j, jj, H, Z, W^\pm, \gamma \) matched to parton shower with higher than LL accuracy.

Meanwhile a huge progress in attempts to calculate the \( t\bar{t} \) cross section beyond NLO has been attained. An outstanding example being a first genuine calculation of next-to-next-to-leading order QCD corrections to top anti-top pair [37–39].

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