Single top production in the Wt mode with MC@NLO

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Abstract

We consider whether it is possible to isolate single top production in the Wt mode as a process at the LHC. A precise definition of this mode becomes problematic beyond leading order due to interference with $t\bar{t}$ production. We give two definitions of the Wt mode whose difference mainly measures this interference, and implement both in the MC@NLO program. Comparison of the results allows us to conclude that is indeed feasible to try to separate the $t\bar{t}$ and Wt processes, subject to adequate cuts.

1 Introduction

Single top physics is of great interest at the Tevatron and LHC both within and beyond the Standard Model. Firstly, it allows detailed scrutiny of the electroweak interactions of the top quark e.g. a direct measurement of V_{tb}. Secondly, the fact the mass of the top quark lies around the electroweak scale means that the top sector could be a sensitive probe of new physics. In the Standard Model, there are three ways to produce a single top quark. The least well understood of these is the Wt mode, in which the final state top quark is accompanied by a W boson. Although rather too small to be observed at the Tevatron, the cross-section is significant at the LHC (i.e. about 20% of the total single top cross-section).

At LO, the Wt mode has a well-defined cross-section, which is much smaller than that of $t\bar{t}$ production. At NLO, however, a problem arises due to the real emission contributions shown in Fig. 1. These essentially consist of $t\bar{t}$ production at LO, followed by the decay of the antitop, and result in a very large correction to the LO Wt cross-section. This large NLO contribution results from regions of the phase space where the invariant mass m_{bW} of the $W\bar{b}$ pair becomes equal to the top mass i.e. when the antitop propagator becomes resonant. The question then arises as to whether it is still possible to define the Wt mode in such a way that it can be measured independently of top pair production at the LHC. This issue can only be fully addressed in the MC@NLO framework, in which a NLO matrix element is matched with a parton shower, due

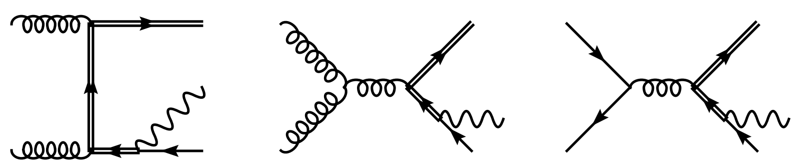

Fig. 1: Doubly resonant contributions to the Wt mode.

to the fact that the interference problem manifests itself at NLO and beyond. Furthermore, it is only in the presence of initial and final state showers that one has sufficiently realistic final states, which one may be reasonably confident of having an experimental applicable definition.

It could be argued that instead of isolating the Wt mode by itself, one should consider sums of processes with a given final state (in this case $W^+W^-b(\bar{b})$), as was done in the present context in [1]. However, such approaches are problematic given that NLO QCD corrections cannot be included. One knows, for example, that NLO corrections to $t\bar{t}$ production are large. This casts doubt on the accuracy of more inclusive approaches. Furthermore, it is unduly pessimistic to assume that interference with $t\bar{t}$ prevents the practical definition of the Wt mode. It is phenomenologically desirable to isolate this process, and if it can be done then this should be investigated fully. Furthermore, a suitable definition allows full NLO QCD corrections to be implemented, thus leads to the most accurate description.

The problem of isolating Wt production has been considered before in the literature, as it is necessary in any calculation beyond LO. Previous ideas for solving the interference problem include restricting m_{bW} directly so as to lie away from the top mass [2], or implementing a global subtraction term to remove the resonant $t\bar{t}$ contribution [3]. These methods were defined at the total cross-section level. A fully differential NLO definition was given in [4]. There, a transverse momentum veto was implemented on the b quark which did not originate from the top, if such a b was present. Harder b quarks tend to have originated from a $\bar{t}$ decay, thus such a veto can be used to filter out the $t\bar{t}$ contribution. Also in [4], some matrix elements with problematic initial states were removed ($\bar{q}q$ in all cases, and gg if the factorisation scale was equal to the transverse momentum veto).

Whilst these solutions work well at the purely NLO level, they are not immediately applicable beyond this e.g. in a real experiment it is not possible to ascertain which decay products originated from a given particle in the hard matrix element. The removal of particular initial states is also theoretically problematic. Firstly, it violates renormalisation group invariance - thus invalidating one of the main motivations for going to NLO (i.e. reduced scale dependence). Secondly, removal of particular initial states is not meaningful in the presence of initial state showers, which mix different partonic subchannels. Nevertheless, we will see that some of the preceding ideas can be generalised in order to suitably define the Wt mode at the MC@NLO level.

2 Two definitions of the Wt mode

We have given two independent definitions of the Wt mode, both of which are applicable locally in phase space and to all orders in the perturbation expansion. By comparing results from the two definitions, we can be confident that theoretical ambiguities in each definition are under control. Our two definitions are named as follows:

1. DIAGRAM REMOVAL (DR). Here one simply removes double resonant diagrams from the Wt amplitude.
2. DIAGRAM SUBTRACTION (DS). Here one modifies the naïve Wt cross-section with a subtraction term, which removes the $t\bar{t}$ resonant contribution locally in phase space.

The difference between the definitions arises from the fact that the subtraction is carried out at the amplitude and cross-section levels respectively. Thus, the difference between DR and DS mainly measures the interference term between the Wt and $t\bar{t}$ production modes.

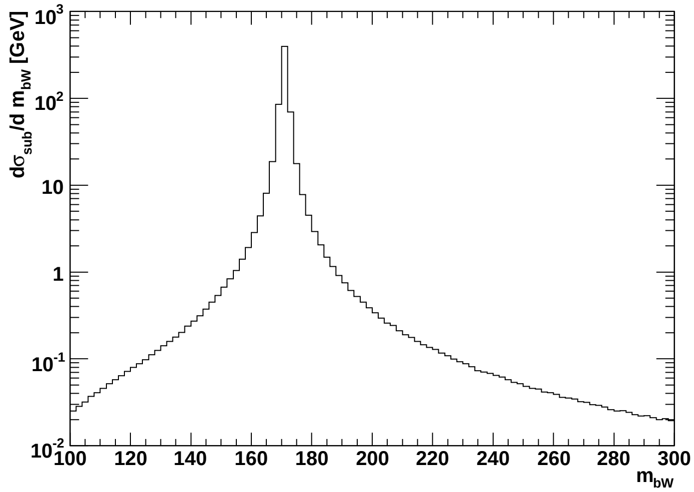

Fig. 2: The subtraction term used to form the DS cross-section, as a function of the invariant mass m_{bW} of the $W\bar{b}$ pair.

Each of the approaches has some theoretical difficulty. DR, for example, violates QCD gauge invariance. We performed detailed checks in a number of gauges to establish that this is not a problem in practice. In DS, there are some ambiguities in how one forms the subtraction term. All one ultimately requires is that it be strongly peaked when $m_{bW} \simeq m_t$, and that it falls away quickly as m_{bW} moves away from the top mass. We thus use a local subtraction term:

$$d\sigma_{sub} = |\tilde{A}(tW\bar{b})_{t\bar{t}}|^2 \times \frac{f_{BW}(m_{bW})}{f_{BW}(m_t)}. \qquad (1)$$

Here $\tilde{A}(tW\bar{b})_{t\bar{t}}$ is the amplitude for $tW\bar{b}$ production coming from $t\bar{t}$-like diagrams, where the kinematics are reshuffled to place the $\bar{t}$ on-shell. This is then damped by a ratio of Breit-Wigner functions f_{BW} when the invariant mass m_{bW} lies away from the top mass m_t. For more details see [5]. A plot of our subtraction term is shown as a function of m_{bW} in Fig. 2. One can see that is indeed strongly peaked when $m_{bW} \to m_t$, and falls off quickly for other values of m_{bW}. It cannot be zero for $m_{bW} \neq m_t$ without violating gauge invariance, as happens in the DR definition. Having given two definitions of the Wt mode which are directly applicable in an all orders calculation, we have implemented both of them in the MC@NLO package of [6]. This required the recalculation of the Wt cross-section in the subtraction formalism of [7], and now completes the description of single top production modes in MC@NLO, as the s and t-channel modes have already been included [8]. Spin correlations of decay products were implemented for the DR cross-section using the method of [9].

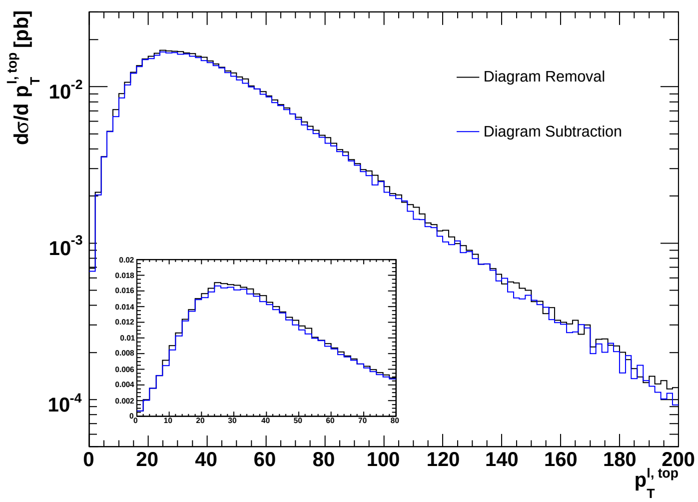

Fig. 3: Transverse momentum spectrum of the lepton from the top decay in both the DR and DS approaches, for $p_{t,veto} = 50$GeV.

3 Results

We considered example results in which all final state heavy particles decay leptonically. Furthermore, in order to address in more detail the issue of separation of the $t\bar{t}$ and Wt processes, we implemented a transverse momentum veto on the second hardest B hadron by analogy with [4]. That is, events are *not* accepted if they contain a second hardest B hadron whose pseudo-rapidity satisfies $|\eta| < 2.5$ and which has a transverse momentum $p_t^b < p_{t,veto}$. This then acts to reduce the interference term between Wt and $t\bar{t}$, due to the fact that harder b quarks tend to originate from a top decay.

We studied a number of observables, and compared the results from the DS and DR definitions of the Wt mode for various choices of $p_{t,veto}$. As a worst case scenario among the observables studied, we present results for the transverse momentum spectrum of the lepton from the top decay in Fig. 3. The results from the two definitions agree closely, except for at very high transverse momenta. However, the cross-section is small here. We also examined the effect of spin correlations, and of varying renormalisation and factorisation scales. These latter effects were larger than that arising from the difference between the DR and DS definitions in all cases.

4 Conclusion

QCD corrections threaten to undermine the definition of the Wt mode beyond LO due to interference with $t\bar{t}$ production. However, it is of clear phenomenological interest to be able to separate the former process in its own right. We have given two workable definitions of this process, implemented in the MC@NLO framework, such that the difference between the definitions mostly measures the interference between Wt and $t\bar{t}$ production.

Comparison of results obtained from the two definitions suggests that they agree closely subject to adequate cuts, and thus that it seems feasible to attempt to isolate Wt production at the LHC. Although further phenomenological analysis is needed to determine whether the $t\bar{t}$ background itself can be sufficiently reduced, the resulting MC@NLO codes nevertheless represent the state of the art description of the Wt mode.

Acknowledgements

This work was done in collaboration with S. Frixione, E. Laenen, P. Motylinski and B. Webber. CDW is supported by the Dutch National Foundation for Fundamental Physics Research (FOM).

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