Single-top t-channel production with off-shell and non-resonant effects

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Abstract

This letter details and discusses the next-to-leading order QCD corrections to t-channel electro-weak W^+bj production, where finite top-width effects are consistently taken into account. The computation is done within the aMC@NLO framework and includes both resonant and non-resonant contributions as well as interferences between the two. Results are presented for the LHC and compared to those of the narrow-width approximation and effective theory approaches.

Keywords: Top quark, finite width effects, LHC

1. Introduction

Since its observation at the Tevatron in 2009 [1, 2], single-top production has played an important role in top-quark phenomenology at hadron colliders despite having a smaller cross section than that of $t\bar{t}$. This channel is not only an important background to other processes, such as top-pair and Higgs production, but it is also interesting in its own right, for example for its potential to allow a direct determination of the CKM matrix element V_{tb} (see [3] for a recent discussion on this point), as well as being sensitive to new physics effects in many beyond-the-Standard Model scenarios. Single-top production is also a process through which the measurements of key top quark properties such as the mass, m_t, can be performed independently from those in $t\bar{t}$ production. This is particularly useful because the majority of the systematic uncertainties are expected to be fairly different in these two processes.

It is of no surprise therefore that over the last three decades much effort has been invested in providing accurate predictions for single-top cross sections. Stable single-top production was first discussed at the leading order (LO) in [4]. Next-to-leading order (NLO) QCD corrections in the five-flavour (5F) scheme were first computed in [5] and in the four-flavour (4F) scheme in [6, 7], whilst electroweak (EW) corrections were investigated in [8]. Furthermore, soft and collinear gluon resummation has been studied in [9, 10, 11, 12] and stable single-top at NLO matched to parton showers has been achieved in [13, 14, 15] for both the 5F and 4F schemes. Incorporating the decay of the top quark, $t \to W^+b$, as part of the hard process matrix elements was accomplished via the narrow-width approximation (NWA) in [16, 17, 18], in which NLO corrections to both production and decay were included. Going beyond the NWA, a study of off-shell and non-resonant effects at LO was performed in [19] and final-state non-factorizable corrections in the s-channel were examined in [20]. In [21, 22], effective theory (ET) techniques were employed to relax the assumption of an on-shell top quark in the amplitudes, allowing for a systematic study of finite top-width (Γ_t) effects in the resonant regions of phase space.

The full computation of α_s-corrections to EW W^+bj production (i.e. the process that includes single-top production) has so far been missing in the literature. Given the opportunity for precision top physics provided by the LHC, it is of phenomenological interest to understand the effects of off-shell top quarks versus top quarks in the NWA. In this letter we present such a computation for the t-channel process in the 5F scheme, and make a direct comparison to results in the NWA as well as to those obtained by using the ET method. The s-channel and Wt-production processes are not considered here.

The expectation is that for inclusive observables off-shell effects are small [23, 24, 25] (i.e., parametrically of $\mathcal{O}(\Gamma_t/m_t)$), whilst they should be noticeable in the case of less inclusive observables, such as the invariant or transverse masses of the reconstructed top. Indeed, differences between NWA and ET or off-shell calculations have already been highlighted for 5F scheme single-top [21, 22] and top-pair [26, 27, 28, 29] production. We shall confirm these findings here.

This paper is organized as follows. In Sect. 2 we briefly discuss the NWA, ET, and off-shell approaches in view of their application to single-top production; results for total rates and for a few selected distributions are presented in Sect. 3; we conclude in Sect. 4.

2. Unstable single-top production

In the NWA limit $\Gamma_t \to 0$ the following replacement is made in the squared amplitude,

$$\frac{1}{(p_t^2 - m_t^2)^2 + \Gamma_t^2\, m_t^2} \;\longrightarrow\; \frac{\pi}{m_t \Gamma_t} \delta(p_t^2 - m_t^2)\,. \tag{1}$$

The error introduced by making this approximation is expected to be of order Γ_t/m_t. The replacement above leads to an exact factorization of the matrix elements into terms describing the production and the decay of on-shell top quarks. This factorization can be combined with a strict expansion of Γ_t in α_s to yield results correct to $\mathcal{O}(\alpha_s)$ [30, 31].

Maintaining a finite width and subsequently relaxing the on-shell assumption in standard fixed-order perturbation theory entails the computation of much more than the resonant diagrams (i.e., those that feature an s-channel top-quark propagator) required in the NWA. Namely, at any given perturbative order one should include all the resonant *and* non-resonant diagrams (the latter feature a W-boson and a b quark, which are not connected to each other in a tWb vertex) in order not to break gauge invariance.

In the region where the invariant mass of the Wb pair is close, but not necessarily equal to m_t, the cross-section is dominated by resonant diagrams. It is possible to make use of this fact to construct an expansion of the matrix elements around the pole of the top-quark propagator [32, 33]. The pole expansion has been generalized through the use of ET techniques in [21, 22, 29], where applications to the processes of single-top and top-pair production were also made, thus capturing the dominant finite-width effects.

The disadvantage of both the NWA and ET approaches is that they are in principle only valid in regions of phase space where the top quarks are either on or near their mass-shell. A gauge-invariant way of introducing a finite-width whilst ensuring that the final result is valid over the full phase space is the complex-mass scheme (CMS) [34, 35], whereby the top-quark width is consistently included at the level of the Lagrangian via the procedure of renormalization. The CMS is a generalization of the on-shell renormalization scheme and has been recently employed by two groups to perform NLO calculations of unstable top-pair production [26, 27, 28]. For the case of unstable top quarks, it amounts to expressing the bare mass in terms of a complex renormalized mass and a complex counter-term,

$$m_{t,0} = \mu_t + \delta\mu_t, \tag{2}$$