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Theory overview of recent progress on single-top production predictions and tools

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In this writeup recent theory developments in differential predictions for single top production at hadron-hadron colliders are summarized. Particular emphasis is placed on the NNLO predictions for the t-channel process in the stable-top case, and on predictions that include full offshell and nonresonant effects, both at NLO and at NLO+PS accuracy.

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1. Introduction

Single top quark production is not only interesting and important to study as yet another cross check of the Standard Model, but additionally, due to its electroweak nature may actually be sensitive to effects of new physics that are not present in the $t\bar{t}$-production process. Single top quark production has historically been split up into three distinct production channels, the s- and t-channels and the Wt-associated production channel. Although this split is formally not theoretically well-defined at all orders in perturbation theory, it is possible to make sensible predictions for stable-top production in the s- and t-channel processes up to NLO without running into problems. Experimental sensitivity to these two channels can be also be enhanced via suitable selection cuts. On the contrary, there are well-known serious problems in the theoretical definition itself of the Wt-channel (in particular when including higher-order corrections). These are are best avoided by treating the Wt-channel as a single-resonant contribution to the $W^+W^-b\bar{b}$ process (in the 4-flavour scheme), which is known at NLO accuracy [1, 2].

Here the focus will be on recent progress in the predictions for the differential cross section of the s- and t-channel processes in the Standard Model.

2. The t-channel single top process at NNLO

An important milestone in the theoretical description of the t-channel process, for stable top-quarks, was achieved with the calculation of the fully-differential cross section at NNLO in QCD [3].[1] Whilst the technical details of the calculation can be found in the above paper (and references therein), it is apt to point out here the impact this calculation has on phenomenology.

Since the NLO corrections to the t-channel cross section, both inclusively and differentially, are typically very small, it is natural to query the reason for such a technically involved calculation in the first place. It was shown in Ref. [3] that the small NLO corrections come about via a large cancellation between the NLO corrections to the Born-level process and the new channel contributing at NLO. This very large cancellation between different NLO contributions makes it unwise to blindly trust the central value of the NLO prediction. The availability of NNLO predictions, for the first time allows *realistic* control of the perturbative uncertainties at the percent level. These improvements mean that alternative sources of error in the theoretical predictions, such as PDF uncertainties and uncertainties in the values of the top-quark mass and α_s, are now of equal importance as the intrinsic perturbative uncertainties. Current experimental measurements of the t-channel cross section show good agreement (within errors) with the NNLO predictions.

A further interesting outcome of this impressive calculation is the assessment of the perturbative stability of the ratio of the single-top to single-anti-top cross section. The outcome is that this ratio is remarkably stable with respect to higher-order corrections. It therefore presents an excellent opportunity to discriminate between and improve PDF sets once the errors in the experimental data are reduced.

In the near future, detailed NNLO predictions will be made available for LHC runII by the authors of Ref. [3]. A comparison of the fixed-order $p_T(t)$ distribution with data would be partic-

[1] Note: interferences between the s- and t-channels have been consistently dropped in this calculation. The effects of these are expected to be smaller than the residual perturbative uncertainty.

ularly intriguing, especially in light of the improvement seen at NNLO in the description of this distribution in the top-quark pair-production process [4]. Furthermore, in order to make predictions in fiducial regions (as well as to better describe the t-channel physical final state) the NNLO differential top-quark decay [5, 6] can also be included in the calculation of Ref. [3].

3. Top-quark decay and offshellness at fixed order

As mentioned above, going beyond the stable top-quark approximation becomes vital when predictions in fiducial detector regions are required and when one wishes to study observables sensitive to the decay products of top quarks. At fixed order, including the decay (with NLO effects in the decay) has been achieved via a series of more realistic (but more complicated) approximations.

Firstly, in the narrow-width approximation (NWA) the top quark is produced and decayed whilst its virtuality is fixed at $p_t^2 = m_t^2$. This constraint factorises the production subprocess from that of the decay, meaning that NLO corrections to both of these can be considered separately. Predictions at NLO in the NWA for the single top s- and t-channel processes can be found in Refs. [8, 9, 10, 11] and are also publicly available through the MCFM code [11]. As an improvement to the NWA, it is possible to relax the onshell top-quark assumption and consider the case where the reconstructed top quarks are resonant, namely, $p_t^2 \sim m_t^2$. This has been done at the fully-differential level via a systematic effective-theory-like (ET) expansion of the amplitudes for the W^+bj process (i.e. single top where the top is decayed) about the complex pole of the top-quark propagator [12, 13, 14]. Detailed studies of offshell effects for the s- and t-channel processes were performed in Refs. [12, 13]. Finally, one can consider the full amplitudes for the decayed final state, which include all resonant and non-resonant diagrams. In this case the virtuality of intermediate top quarks can in principle be arbitrary and the complex-mass scheme [15, 16] is normally employed to ensure that the top-quark width is introduced consistently at the level of the Lagrangian. In Ref. [7] the automated tool MADGRAPH5_AMC@NLO [17] was exploited to compute predictions at NLO for the t-channel process. The latter work additionally made a thorough comparison between the different available approximations and the main conclusions are captured by the features of Fig. 1. In particular, these are (a) that in phase space regions that

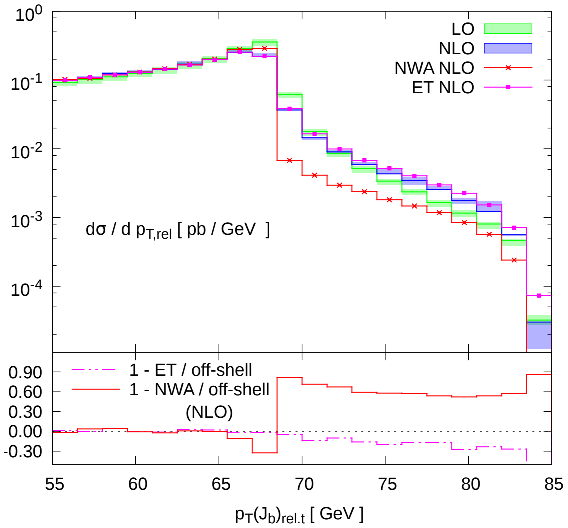

Figure 1: Plot of the transverse momentum of b-jet in reconstructed top-quark rest frame, relative to flight of reconstructed top, $p_T(J_b)_{\text{rel.t}}$. The upper panel shows the LO and NLO complex-mass scheme results (green and blue bands), the NWA NLO result (solid red) and the ET result (solid magenta). The lower panel indicates the difference between the NLO results of the NWA (red) and ET (magenta) results with the fully offshell result at NLO. The figure is taken from Ref. [7].

are inclusive in the invariant mass of the reconstructed top (the region of $p_T(J_b)_{\text{rel.t}}$ below the peak in Fig.1), the three approaches are equally valid, indicating that the onshell approach of the NWA provides a good description here, whilst (b) offshell and nonresonant effects grow in size as one moves into more exclusive regions of phase space (around the sharp edge and tail of $p_T(J_b)_{\text{rel.t}}$). It is clear from the figure that in these phase space regions, including offshell effects is vital for the good description of the shapes of distributions such as $p_T(J_b)_{\text{rel.t}}$ (or $M(J_b, l^+)$).

4. The t-channel single-top process at NLO+PS accuracy, with NLO decay and offshell effects

Closest contact is made with observables measured by the experiments when theory predictions are available at the hadron-level. The latter requires the matching of fixed-order calculations to parton showers (PSs). For stable single top production this has been done for all channels at NLO+PS accuracy in Refs. [18, 19, 20, 21, 22] in the MC@NLO [23] and POWHEG [24, 25] approaches. The decays of the top quarks can either be performed by the PSs themselves, or via a reweighting technique that includes the full spin-correlated decays at LO [26]. However, in order to properly validate stable top-quark approaches it is necessary to study hadron-level differential cross sections in which the hard subprocess contains full NLO decay as well as offshell and nonresonant effects. A systematic method for overcoming the issues of matching a fixed order calculation which contains intermediate coloured resonances to PSs in the POWHEG framework has been presented in [27, 28] (see also the discussion in Ref. [29]). Here we briefly focus on ongoing work in the MC@NLO framework (within MADGRAPH5_AMC@NLO) where there are also a couple of problems that must be overcome [30].

In order that a PS conserves the invariant mass of the W^+b-system, and thus that the zero-width limit is is also satisfied, it is necessary that LesHouches events contain information on intermediate top quarks, at least for invariant masses near the top-quark pole mass. In practice, a prescription must be chosen for writing intermediate top quarks into the LesHouches event files, which at present is done using the general approach present in MADGRAPH5_AMC@NLO. This is based on writing (or not) a top quark in the event according to the distance of the invariant mass of the W^+b system from the top quark pole mass. When intermediate coloured resonances are present in event files, then generically PSs proceed in a factorised fashion, first showering off the top-quark production system (including off the top quark) and then showering off the decay products. Given that Monte Carlo counterterms for non-divergent real emissions (which are present in the real corrections to the fully offshell process) are not (yet) available in the MC@NLO scheme, in order to prevent double-counting of emissions, it is necessary to veto PS emissions off intermediate top quarks.[2] To maintain formal NLO accuracy one must also ensure that the recoil strategy in the counterterms is the same as that of the first PS emission.

When comparing with simulations based on showering onshell single top hard events to simulations that include full offshell effects at NLO, significant differences in some distributions (similar to those observed between corresponding predictions at fixed-order) are observed. A discussion of the details of the matching as well as a full comparison of simulations based on different approximations and different PSs (HERWIG6 and PYTHIA8) will be presented in a forthcoming publication

[2] The effect of shower emissions off the top quark however, tends to be quite mild.

[30]. A direct comparison between the simulations with full offshell effects in the POWHEG and MC@NLO frameworks will also be of significant interest. Finally, the comparison of these new, theory-improved, state-of-the-art simulations to experimental observables sensitive to top-quark decay products is highly desirable and would provide useful input for future Monte Carlo improvements.

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