Single Top Quark Production and Decay at Next-to-Next-to-Leading Order

Hua Xing Zhu[1,2]
[1] *Department of Physics, Zhejiang University, Hangzhou, 310027, China*
[2] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

We present a phenomenological study of the Next-to-Next-to-Leading Order (NNLO) QCD correctoins on t-channel single top (anti-)quark production including subsequent semi-leptonic decay at the LHC. We find that while the NNLO corrections are generally small for inclusive quantities, they can be larger for differential distributions.

Single top-quark production provides a great opportunity for probing directly the electroweak Wtb vertex at hadron collider. At the LHC, t-channel single top production has the largest cross section, about 200 pb at 13 TeV. The large cross section allows precision measurement of top-quark properties through this channel, and therefore poses high demand for better theoretical accuracy of SM prediction.

There have been Significant efforts in improving the theoretical description. The next-to-leading order (NLO) QCD corrections were calculated in Refs. [1,2,3,4,5,6,7,8]. Full NLO corrections with top-quark leptonic decay were calculated in the on-shell top-quark approximation [9,10,7] and the complex mass scheme. Fast numerical evaluation code at NLO has been provided in Ref. [11]. Soft gluon resummation has been studied in Refs. [12,13,14,15]. Matching NLO calculations to parton showers was done in the framework of POWHEG and MC@NLO Refs. [16,17,18,19]. For experimental analyses at the LHC, predictions from POWHEG or MC@NLO are always used for modeling of the signal process in unfolding to parton level cross sections. The cross sections from measurement or prediction can have a theoretical uncertainty of about 10% [20]. Thus exclusive predictions incorporating further higher-order corrections are desirable for precision measurements.

Previously, NNLO QCD corrections to the production of t-channel single top has been computed in Ref. [21], under the approximation that the color cross-talk between light-quark line and heavy-quark line is ignored, namely the structure function approximation. Recently, the calculation has been extended to include also the leptonic decay of top quark at NNLO [22], using the on-shell top-quark approximation [23]. Under these approximation, the NNLO QCD corrections factorized into three simpler parts: the light-quark line, the heavy-quark line, and the decay part. A schematic diagram illustrating these approximation is depicted in Fig. 1. In this talk we present some further results based on Ref. [24].

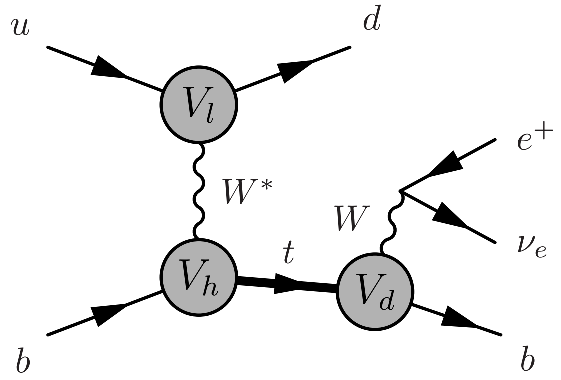

Figure 1 – Schematic diagram for t-channel single top-quark production at hadron colliders in the on-shell top quark approximation and structure-function approximation. The full QCD corrections factorized into three different parts in these approximations.

Care has to be taken when combining QCD corrections for production and decay to avoid double counting. Throughout to NNLO, we use the formula in Eq. (1) in our calculation,

$$
\begin{aligned}
\sigma^{\mathrm{LO}} &= \frac{1}{\Gamma_t^{(0)}} \mathrm{d}\sigma^{(0)} \otimes \mathrm{d}\Gamma_t^{(0)} \\
\delta\sigma^{\mathrm{NLO}} &= \frac{1}{\Gamma_t^{(0)}} \left[\mathrm{d}\sigma^{(1)} \otimes \mathrm{d}\Gamma_t^{(0)} + \mathrm{d}\sigma^{(0)} \otimes \left(\mathrm{d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \mathrm{d}\Gamma_t^{(0)} \right) \right] \\
\delta\sigma^{\mathrm{NNLO}} &= \frac{1}{\Gamma_t^{(0)}} \left[\mathrm{d}\sigma^{(2)} \otimes \mathrm{d}\Gamma_t^{(0)} + \mathrm{d}\sigma^{(1)} \otimes \left(\mathrm{d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \mathrm{d}\Gamma_t^{(0)} \right) \right. \\
&\quad \left. + \mathrm{d}\sigma^{(0)} \otimes \left(\mathrm{d}\Gamma_t^{(2)} - \frac{\Gamma_t^{(2)}}{\Gamma_t^{(0)}} \mathrm{d}\Gamma_t^{(0)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \left(\mathrm{d}\Gamma_t^{(1)} - \frac{\Gamma_t^{(1)}}{\Gamma_t^{(0)}} \mathrm{d}\Gamma_t^{(0)} \right) \right) \right], \qquad (1)
\end{aligned}
$$

where $\Gamma_t^{(0),(1),(2)}$ and $\sigma^{(0),(1),(2)}$ denote the Born, $\mathcal{O}(\alpha_S)$, and $\mathcal{O}(\alpha_S^2)$ top-decay width and production cross section, respectively. In Eq. (1) we have expanded the QCD corrections to both production and decay to the same order consistently. Eq. (1) can be applied to fully differential calculation. Integrating over the phase space gives the inclusive production cross section at given order. In order to have a correct treatment of spin correlation, the production cross section $\mathrm{d}\sigma$ and decay width $\mathrm{d}\Gamma_t$ must be calculated for a on-shell polarized top quark. We use the symbol $\otimes$ to denote the appropriate summation over polarization.

Table 1: Fiducial cross sections for top (anti-)quark production with decay at 13 TeV at various orders in QCD with a central scale choice of m_t in both production and decay. The scale uncertainties correspond to a quadratic sum of variations from scales in production and decay, and are shown in percentages. Corrections from pure production and decay are also shown.

fiducial [pb]		LO	NLO	NNLO
t quark	total	$4.07^{+7.6\%}_{-9.8\%}$	$2.95^{+4.1\%}_{-2.2\%}$	$2.70^{+1.2\%}_{-0.7\%}$
	corr. in pro.		-0.79	-0.24
	corr. in dec.		-0.33	-0.13
$\bar{t}$ quark	total	$2.45^{+7.8\%}_{-10\%}$	$1.78^{+3.9\%}_{-2.0\%}$	$1.62^{+1.2\%}_{-0.8\%}$
	corr. in pro.		-0.46	-0.15
	corr. in dec.		-0.21	-0.08

We shows the predictions of the fiducial cross sections in Table 1, with scale variations shown in percentages. We also show the QCD corrections from production and decay separately as defined in Eq. (1). We use the anti-k_T jet algorithm [25] with a distance parameter $D = 0.5$. Jets are defined to have transverse momentum $p_T > 40$ GeV and pseudorapidity $|\eta| < 5$. We require exactly two jets in the final state, following the CMS and ATLAS analyses, meaning that events with additional jets are vetoed, and we require at least one of these to be a b-jet with $|\eta| < 2.4$ [26]. We demand the charged lepton to have a p_T greater than 30 GeV and rapidity $|\eta| < 2.4$. For the fiducial cross sections reported below we include top-quark decay to only one family of leptons.

We note that the full NNLO correction is substantial, about -6% of the fiducial cross section at LO. Furthermore, all three error bands from LO, NLO, and NNLO do not overlap with each other which suggests that scale variations may underestimate the remainning perturbative uncertainties in this case. It is therefore important to include the NNLO results into the analysis of precision measurements.

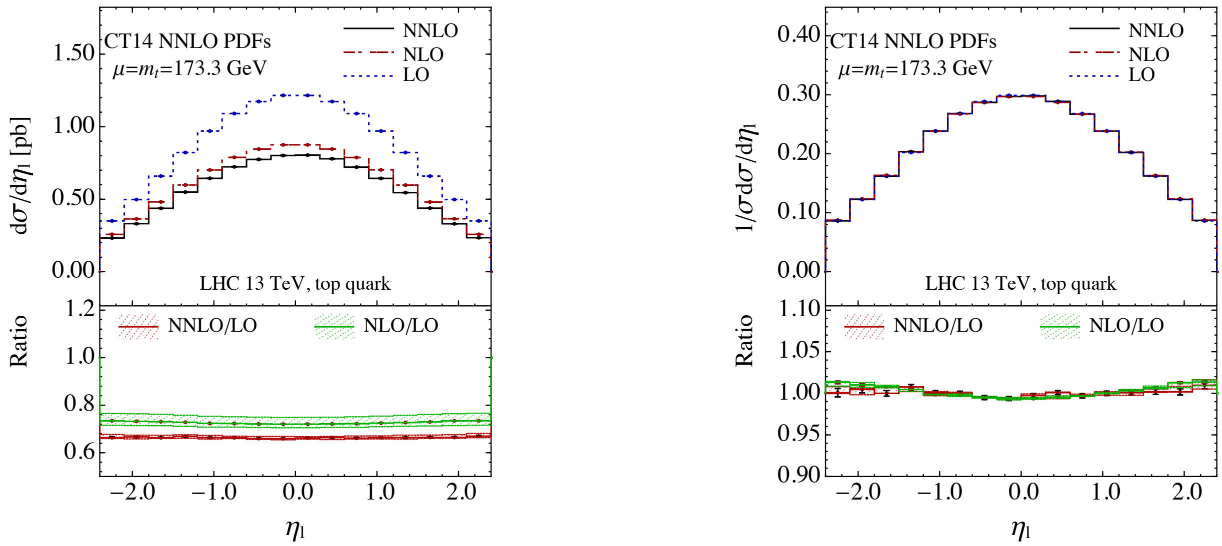

Figure 2 – Predicted pseudo-rapidity distribution of the charged lepton from t-channel single top-quark production at the LHC 13 TeV after applying fiducial cuts, including full corrections, with and without normalization respectively.

It is also useful to compare theoretical predictions diretly with the experemental measurements without relying on even more complicated unfolding procedures for distributions. In Fig. 2 we plot the pseudo-rapidity distribution of the charged lepton without and with normalization to the total rate for top quark production. For the absolute distribution, NNLO corrections are substantial. It is easy to see that simple scale variations by a factor of two might underestimate the missing contribution from higher order. For the normalized distributions the QCD corrections are small and within 1% in general.

In summary we have talked about the next-to-next-to-leading order QCD corrections on t-channel single top (anti-)quark production including subsequent semi-leptonic decay at the LHC. The NNLO corrections are in general substantial for rate or distributions in fiducial volume, and should be taken into account for precision measurements.

Acknowledgments

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