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Soft gluon resummation for the associated production of a top quark pair with a W boson at the LHC

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We present our results on soft gluon resummation in the invariant mass threshold applied to the associated production of a top quark pair with a W boson at the LHC in the Mellin space formalism.

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1. Introduction

The measurements of associated production of a vector boson with a top-antitop quark pair provide an important test for the Standard Model at the LHC [1, 2]. In particular these are the key processes to measure the top quark couplings to W/Z bosons. Furthermore they are relevant in searches for new physics due to both being directly sensitive to it and providing an important background. They also play an important role as a background for the associated Higgs boson production process $pp \to t\bar{t}H$. It is therefore necessary to know the theoretical predictions for $pp \to t\bar{t}W/Z$ with high accuracy. Fixed order cross sections up to next-to-leading order in α_S are already known for some time [3, 4]. They were recalculated and matched to parton showers in [5, 6, 7, 8, 9]. Furthermore QCD-EW NLO corrections have been obtained [10]. While NNLO calculations for this particular type of 2 to 3 processes are currently out of reach, a class of corrections beyond NLO from the emission of soft and/or collinear gluons can be taken into account with the help of resummation methods. This was done in the framework of the soft-collinear effective theory (SCET) for $pp \to t\bar{t}W$ [11] and with SCET-formulas expressed in Mellin-space for $pp \to t\bar{t}W/Z$ [12, 13].

In the following we present results for threshold-resummed cross sections in the invariant mass kinematics, obtained using the Mellin-space approach at NLL accuracy. The calculations are then improved beyond NLL by including non-logarithmic hard contributions of the order $\mathscr{O}(\alpha_S)$.

2. Resummation at invariant mass threshold

Here we treat the soft gluon corrections in the invariant mass kinematics, i.e we consider the limit $\hat{\rho} = \frac{Q^2}{\hat{s}} \to 1$ with $Q^2 = (p_t + p_{\bar{t}} + p_{W/Z})^2$. The logarithms resummed in the invariant mass threshold limit have the form

$$\alpha_S^m \left(\frac{\log^n (1-\hat{\rho})}{1-\hat{\rho}} \right)_+ \qquad m \leq 2n-1 \tag{2.1}$$

with the plus distribution $\int_0^1 \mathrm{d}x (f(x))_+ = \int_0^1 \mathrm{d}x (f(x) - f(x_0))$. The Mellin moments of the differential cross section $\frac{\mathrm{d}\sigma_{ij\to t\bar{t}W/Z}}{\mathrm{d}Q^2}$ are taken with respect to the variable $\rho = \frac{Q^2}{S}$. At the partonic level this leads to

$$\frac{\mathrm{d}\tilde{\hat{\sigma}}_{ij\to t\bar{t}W/Z}}{\mathrm{d}Q^2}(N, Q^2, m_t, m_{W/Z}, \mu_R^2, \mu_F^2) = \int_0^1 \mathrm{d}\hat{\rho}\,\hat{\rho}^{N-1} \frac{\mathrm{d}\hat{\sigma}_{ij\to t\bar{t}W/Z}}{\mathrm{d}Q^2}(\hat{\rho}, Q^2, m_t, m_{W/Z}, \mu_R^2, \mu_F^2) \tag{2.2}$$

for the Mellin moments for the process $ij \to t\bar{t}W/Z$ with i,j denoting two massless colored partons. In Mellin space the threshold limit $\hat{\rho} \to 1$ corresponds to the limit $N \to \infty$. Since the process involves more than 3 colored partons, the resummed cross section involves color matrices. In Mellin space the resummed partonic cross section has the form [14, 15]

$$\frac{\mathrm{d}\tilde{\hat{\sigma}}_{ij\to t\bar{t}W/Z}}{\mathrm{d}Q^2} = \mathrm{Tr}[\mathbf{H}_{ij\to t\bar{t}W/Z}\mathbf{S}_{ij\to t\bar{t}W/Z}]\Delta_i\Delta_j, \tag{2.3}$$

where $\mathbf{H}_{ij\to t\bar{t}W/Z}$ and $\mathbf{S}_{ij\to t\bar{t}W/Z}$ are color matrices and the trace is taken in color space. We describe the evolution of color in the s-channel color basis, for which the basis vectors are

$$c_{\mathbf{1}} = \delta_{a_i,a_j}\delta_{a_k,a_l} \qquad c_{\mathbf{8}} = T^c_{a_i,a_j}T^c_{a_k,a_l} \tag{2.4}$$

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for the $q\bar{q}$ initial state and

$$c_{\mathbf{1}} = \delta_{a_i,a_j}\delta_{a_k,a_l} \quad c_{\mathbf{8S}} = d^{c,a_i,a_j}T^c_{a_k,a_l} \quad c_{\mathbf{8A}} = f^{c,a_i,a_j}T^c_{a_k,a_l} \tag{2.5}$$

for the gg initial state. This choice of color basis leads to a diagonal soft anomalous dimension matrix in the absolute threshold limit $\frac{(2m_t+m_{W/Z})^2}{\hat{s}} \to 1$, which is a special case of the invariant mass threshold limit. $\mathbf{H}_{ij\to t\bar{t}W/Z}$ describes the hard scattering contributions projected on the color basis, while $\mathbf{S}_{ij\to t\bar{t}W/Z}$ represents the soft wide angle emission. The (soft-)collinear logarithmic contributions form the initial state partons are taken into account by the functions Δ_i and Δ_j.

At NLL accuracy the evolution of the soft matrix $\mathbf{S}_{ij\to t\bar{t}W/Z}$ is given by the one-loop anomalous dimension matrix, see e.g. [18]. Since the soft anomalous dimension matrix is not diagonal in the invariant mass threshold, we use the method proposed in [15] to diagonalize the soft anomalous dimension matrix in a basis R. Then $\mathbf{S}_{ij\to t,\bar{t}W/Z}$ is given by [15]:

$$\mathbf{S}_{ij\to t\bar{t}W/Z,R} = \mathbf{S}^{(0)}_{ij\to t\bar{t}W/Z,R}\exp\left[\int_{\mu}^{Q/N}\frac{\mathrm{d}q}{q}(\lambda^*_{R,I}+\lambda_{R,J})\right] \tag{2.6}$$

where $\lambda_i, \lambda_j, \ldots$ are the eigenvalues of the soft anomalous dimension matrix and $\mathbf{S}^{(0)}_{ij\to t\bar{t}W/Z,R}$ is

$$\left(\mathbf{S}^{(0)}_{ij\to t\bar{t}W/Z}\right)_{IJ} = \mathrm{Tr}\left[c_I^\dagger c_J\right] \tag{2.7}$$

transformed into the R basis. $\mathbf{H}_{ij\to t\bar{t}W/Z}$ can be calculated perturbatively

$$\mathbf{H}_{ij\to t\bar{t}W/Z} = \mathbf{H}^{(0)}_{i,j\to t,\bar{t},W/Z} + \frac{\alpha_S}{\pi}\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z} + \ldots. \tag{2.8}$$

For NLL accuracy it is sufficient to include $\mathbf{H}^{(0)}_{i,j\to t,\bar{t},W/Z}$, which is given by the leading order cross section. To improve the predictions beyond NLL we can also include $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$. This factor collects non-logarithmic contributions of $\mathcal{O}(\alpha_S)$ in the large N limit [19, 20]. In particular it includes the virtual loop corrections, which are numerically extracted from the PowHel implementation [8, 9]. The initial state jet functions Δ_i and Δ_j have been known for a long time [16, 17] and depend only on the emitting parton.

3. Numerical results

The numerical results were obtained using $m_t = 173\,\mathrm{GeV}$, $m_W = 80.385\,\mathrm{GeV}$ and MMHT14 PDF sets [21] and for the center of mass energy $\sqrt{S} = 13\,\mathrm{TeV}$. The one-loop hard contributions to $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ and the NLO cross sections were calculated with the PowHel implementation [8, 9]. We use $\mu = \frac{M}{2} = m_t + \frac{m_W}{2}$ and $\mu = Q$ for the scales $\mu = \mu_R = \mu_F$. Total cross section results were obtained by integrating the resummed differential cross section $\frac{\mathrm{d}\tilde{\sigma}}{\mathrm{d}Q^2}$. These resummed results are then matched to fixed order NLO predictions [22].

In table 1 we show the total cross section for $t\bar{t}W^{+/-}$ production at the two different central scale choices and their scale uncertainty calculated with the seven point method. Figures 1, 2, 3 and 4 show the scale dependence of the $t\bar{t}W^{+/-}$ production cross section by varying simultaneously the renormalization and factorization scale $\mu = \mu_R = \mu_F$. In all figures the NLO results are compared

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process	μ_0	NLO	NLO + NLL	NLO+NLL w $\mathbf{H}^{(1)}$
$t\bar{t}W^+$	Q	$329.9^{+12.5\%}_{-11.1\%}$ fb	$332.1^{+12.5\%}_{-11.2\%}$ fb	$341.1^{+10.7\%}_{-8.6\%}$ fb
$t\bar{t}W^+$	$\frac{M}{2}$	$422.1^{+12.8\%}_{-11.5\%}$ fb	$423.5^{+13.2\%}_{-11.5\%}$ fb	$418.4^{+12.8\%}_{-10.0\%}$ fb
$t\bar{t}W^-$	Q	$168.5^{+12.7\%}_{-11.2\%}$ fb	$170.0^{+12.1\%}_{-10.7\%}$ fb	$175.3^{+9.9\%}_{-8.4\%}$ fb
$t\bar{t}W^-$	$\frac{M}{2}$	$215.6^{+13.4\%}_{-11.8\%}$ fb	$216.4^{+13.8\%}_{-11.6\%}$ fb	$214.4^{+13.4\%}_{-10.1\%}$ fb

Table 1: Total $t\bar{t}W^{+/-}$ cross sections for the two different central scale choices and their scale uncertainty, which was calculated with the seven point method

with the resummed NLO + NLL and NLO + NLL with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W}$ results for two different central scale choices $\mu = Q$ and $\mu = \frac{M}{2}$. The resummed NLL matched to NLO with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W}$ cross section is less sensitive to scale variation as compared to the NLO result. At large scales the inclusion of $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ has a bigger impact on the cross section than the logarithmic contributions. At central scale the cross section is increased by 3.4% ($t\bar{t}W^+$) and 4% ($t\bar{t}W^-$) for $\mu_0 = Q$ and decreased by 0.9% ($t\bar{t}W^+$) and 0.6% ($t\bar{t}W^-$) for $\mu_0 = m_t + \frac{m_W}{2}$. The resummation reduces the scale uncertainty and brings the predictions for the two different scale choices closer together.

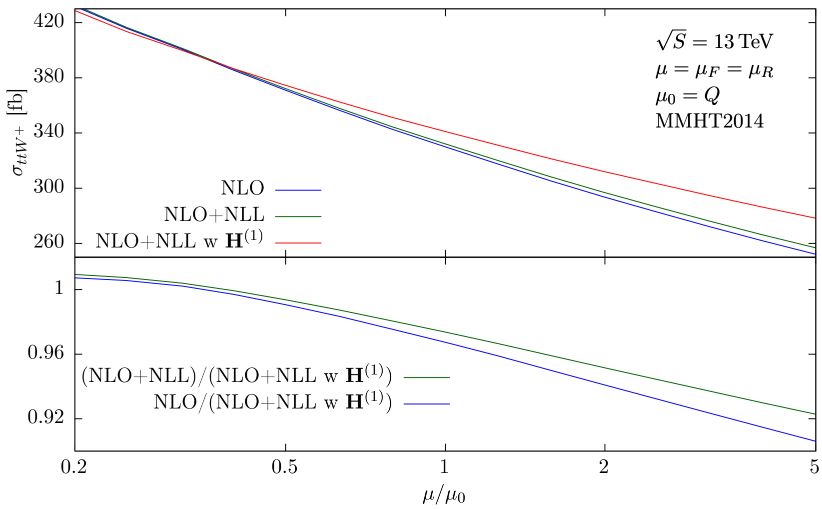

Figure 1: Scale dependence of the total $pp \to t\bar{t}W^+$ cross section at NLO, NLL matched to NLO and NLL matched to NLO improved with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ for the central scale $\mu_0 = Q$.

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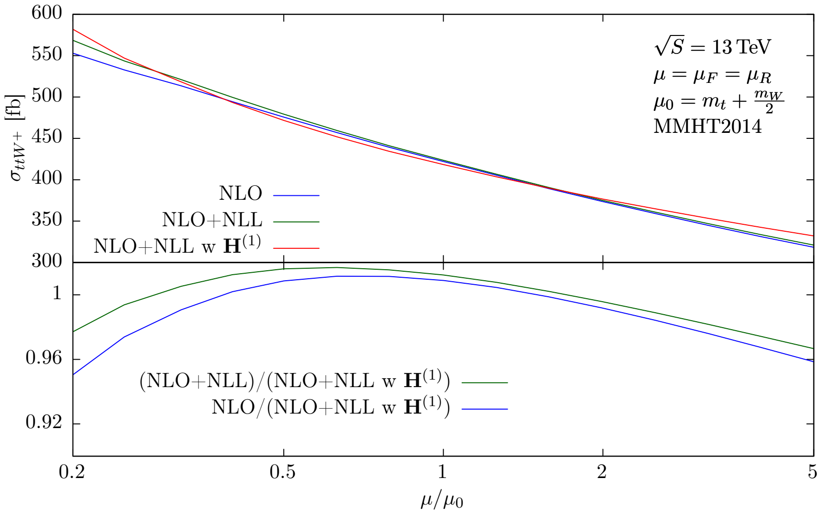

Figure 2: Scale dependence of the total $pp \to t\bar{t}W^+$ cross section at NLO, NLL matched to NLO and NLL matched to NLO improved with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ for the central scale $\mu_0 = \frac{M}{2}$.

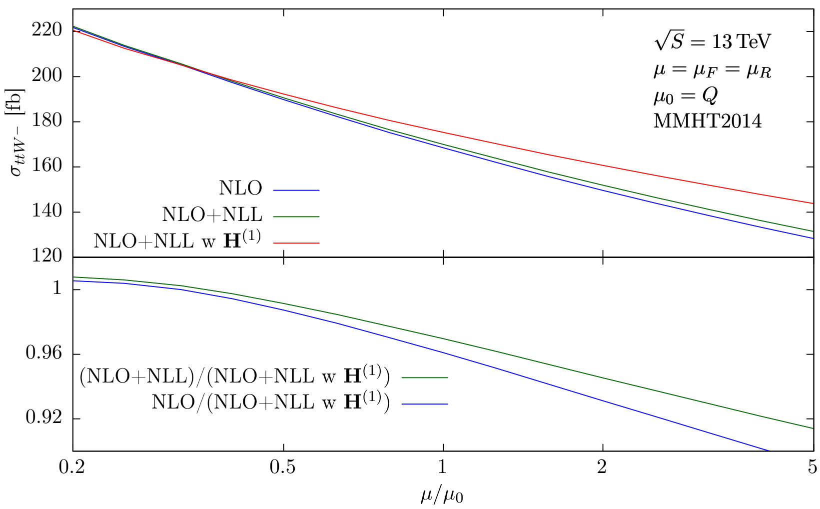

Figure 3: Scale dependence of the total $pp \to t\bar{t}W^-$ cross section at NLO, NLL matched to NLO and NLL matched to NLO improved with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ for the central scale $\mu_0 = Q$.

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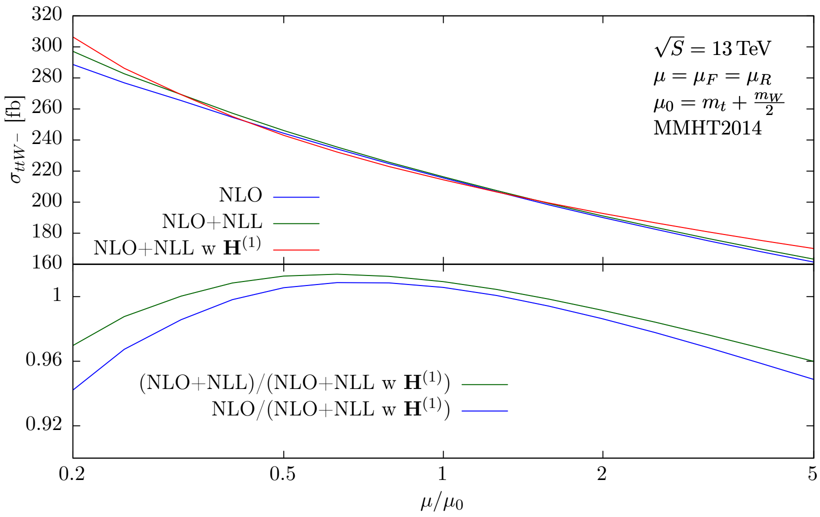

Figure 4: Scale dependence of the total $pp \to t\bar{t}W^-$ cross section at NLO, NLL matched to NLO and NLL matched to NLO improved with $\mathbf{H}^{(1)}_{ij\to t\bar{t}W/Z}$ for the central scale $\mu_0 = \frac{M}{2}$.

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