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Top-pair and $tW$ production at approximate $N^3$LO

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1 Introduction

I present approximate $N^3$LO theoretical results for top-antitop pair production, and for single-top production in association with a $W$ boson. The higher-order corrections are from soft-gluon radiation, which is dominant near partonic threshold. I present results for total cross sections as well as transverse-momentum and rapidity distributions of the top quark, and compare with data at LHC energies.

2 Top-pair production

The top quark is the heaviest elementary particle to have been discovered to date. Because of its large mass, its near-threshold production at current colliders receives large radiative corrections from soft-gluon emission. These corrections have long been known to be significant for $t\bar{t}$ production, and they approximate exact results, when known, very accurately.

Resummation of the double-differential cross section at next-to-next-to-leading logarithm (NNLL) accuracy in moment space was derived in Ref. [1] using the two-loop soft anomalous dimension [1, 2]. Fixed-order expansions of the resummed cross section in momentum space bypass the problem of using a prescription for divergences, and they provide excellent and reliable predictions for the higher-order corrections. General expressions for the expansions have been derived and used for various processes at NNLO [3] and $N^3$LO [4]. Approximate $N^3$LO (aN$^3$LO) predictions for double-differential cross sections in $t\bar{t}$ production have appeared in Ref. [5]. These aN$^3$LO corrections are needed for precision physics as they considerably enhance the total cross section and differential distributions.

An interesting question in the study of $t\bar{t}$ production is the effect of scale choice on the top-quark $p_T$ distributions. Traditionally, two central choices have been made

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for the factorization and renormalization scales: $\mu = m$, the top quark mass; and $\mu = m_T = (p_T^2 + m_T^2)^{1/2}$, the transverse mass. The difference in the $p_T$ distributions using the two scales thus grows with $p_T$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Top quark aN$^3$LO normalized $p_T$ distributions compared with CMS dilepton data at (left) 7 TeV \cite{6} and (right) 13 TeV \cite{7} LHC energies.}
\end{figure}

In Fig. 1 we display the top quark normalized $p_T$ distributions at 7 TeV (left plot) and 13 TeV (right plot) LHC energies. We compare with data from CMS in the dilepton channel at 7 TeV \cite{6} and 13 TeV \cite{7}. We find excellent agreement in both cases, especially with the choice $\mu = m_T$, which better describes the data at high $p_T$. We have used MMHT2014 pdf \cite{8}; the results with CT14 pdf \cite{9} are similar.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2}
\caption{Top quark aN$^3$LO $p_T$ distributions compared with (left) ATLAS \cite{10} and (right) CMS \cite{11} lepton+jets data at 8 TeV LHC energy.}
\end{figure}
In Fig. 2 we display the boosted top quark $p_T$ distributions, with theoretical uncertainty, at 8 TeV LHC energy, and compare with lepton+jets data from ATLAS [10] (left plot) and CMS [11] (right plot). Again, the calculations with the choice $\mu = m_T$ better describe the data at high $p_T$.

3 $tW$ production

The associated production of a top quark and a $W$ boson, via the partonic process $bg \to tW^-$, was studied at NNLL accuracy in Ref. [12] using results for the two-loop soft anomalous dimension. Approximate NNLO (aNNLO) predictions for the total $tW^-$ production cross section were given in [12]. The cross section for $\bar{t}W^+$ production is the same.

Top-quark $p_T$ distributions at aNNLO for this process were given in Ref. [13]. More recently, aN$^3$LO results for the total cross section and the top $p_T$ and rapidity distributions in $tW$ production were presented in Ref. [14].

![Figure 3: Total aN$^3$LO cross section for $tW$ production at LHC energies compared with data [15, 16, 17, 18] from ATLAS and CMS.](image)

In Fig. 3 we show the total aN$^3$LO cross section, together with theoretical uncertainty, for $tW$ production and compare with LHC data. The theoretical predictions are in very good agreement with the data from ATLAS [15] and CMS [16] at 7 TeV, an ATLAS/CMS combination at 8 TeV [17], and ATLAS at 13 TeV [18].
The inset plot in Fig. 3 shows the aN³LO/aNNNLO ratio. It is clear that the third-order soft-gluon corrections are non-negligible.

Figure 4: Top quark aN³LO \( p_T \) and rapidity distributions in \( tW \) production.

In the left plot of Fig. 4 we display the aN³LO top quark \( p_T \) distributions in \( tW \) production at LHC energies. The inset plot shows the distribution at 13 TeV energy together with the theoretical uncertainty.

In the right plot of Fig. 4 we display the aN³LO top quark rapidity distributions in \( tW \) production at LHC energies. The inset plot shows the aN³LO/aNNLO ratio, with theoretical uncertainty, at 13 TeV. We observe that the soft-gluon corrections are substantial, particularly at large values of rapidity.

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