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# Higher-order corrections to top-antitop pair and single top quark production

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I present the latest results on the theoretical cross section for top-antitop pair production as well as for single top production at the Tevatron and the LHC. The calculations include higher-order soft-gluon corrections which are dominant near threshold. The top quark transverse momentum distribution is also presented.

## 1. Introduction

The top quark plays an important role in the Standard Model of particle physics as the most massive elementary particle, relevant to electroweak physics. The top was discovered via pair production [1, 2] and has also been more recently produced via single top [3, 4] channels at the Tevatron.

On the theoretical side, QCD corrections are significant for top quark production and even higher-order corrections are not negligible. An important class of corrections are contributions from soft-gluon emission, of the form  $\ln^k(s_4/m^2)/s_4$ , with  $s_4$  a variable that measures distance from threshold. Soft-gluon corrections are dominant near threshold and can be resummed. Resummation at NLL (NNLL) accuracy requires one-loop (two-loop [5]) calculations in the eikonal approximation. Approximate higher-order (NNLO or NNNLO) cross sections can be derived from the expansion of the resummed cross section [6, 7, 8, 9, 10].

We perform the resummation and higher-order expansions at the differential level. In contrast to simple resummation calculations that apply only to the total cross section and which involve additional approximations for the kinematics, our fully differential calculations have sensitivity to the exact kinematics and allow not only total cross section calculations but also differential  $p_T$  and other distributions.

## 2. Top pair production

For top quark hadroproduction the dominant process is pair production. At lowest order the partonic processes are  $q\bar{q} \rightarrow t\bar{t}$  and  $g\bar{g} \rightarrow t\bar{t}$ . The cross section has been measured at the Tevatron with increasing precision [11, 12]. There is very good agreement of theory including soft-gluon corrections [10] with Tevatron data.

We match at the differential level to the exact NLO [13] result and add NNLO soft-gluon corrections to obtain approximate NNLO cross sections [6, 10]. In Fig. 1 we plot the NLO and approximate NNLO cross sections for top pair production at the Tevatron using the MRST 2006 NNLO pdf [14]. Figs. 2 and 3 show

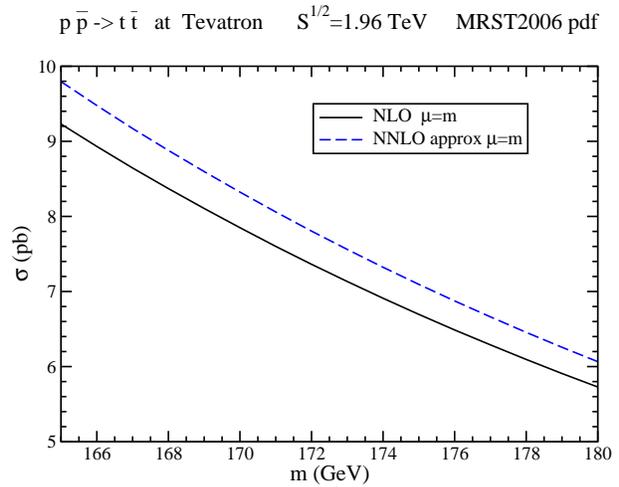


Figure 1: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $p\bar{p}$  collisions at the Tevatron using the MRST 2006 NNLO pdf.

the corresponding results using the CTEQ6.6M [15] and MSTW 2008 NNLO pdf [16], respectively. The NNLO threshold corrections provide an important enhancement as well as a very significant reduction in scale dependence. Below we give explicit results for top masses of 172 and 173 GeV for all three pdf sets. For a top quark of 172 GeV the cross sections together with the total uncertainty, calculated from the combination of kinematics, scale, and pdf uncertainties, are:

$$\begin{aligned} \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MRST}) &= 7.80_{-0.45}^{+0.39} \text{ pb}, \\ \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{CTEQ}) &= 7.39_{-0.52}^{+0.57} \text{ pb}, \\ \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MSTW}) &= 7.24_{-0.34}^{+0.30} \text{ pb}. \end{aligned}$$

For a top mass of 173 GeV the corresponding results are shown below:

$$\begin{aligned} \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MRST}) &= 7.56_{-0.44}^{+0.37} \text{ pb}, \\ \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{CTEQ}) &= 7.16_{-0.50}^{+0.54} \text{ pb}, \\ \sigma_{p\bar{p} \rightarrow t\bar{t}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MSTW}) &= 7.01_{-0.33}^{+0.29} \text{ pb}. \end{aligned}$$

We note that current experimental and theoretical un-

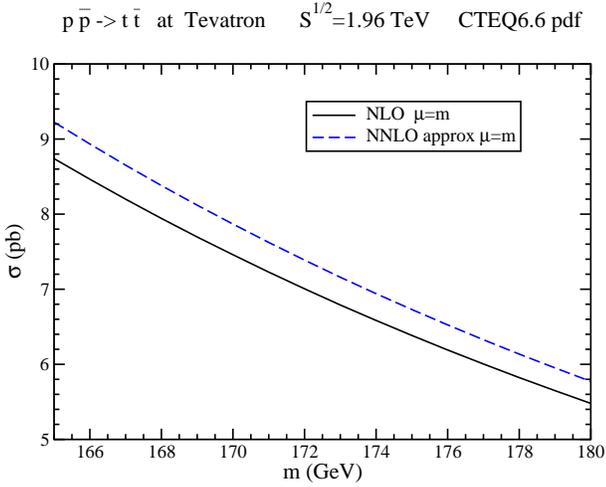


Figure 2: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $p\bar{p}$  collisions at the Tevatron using the CTEQ6.6M pdf.

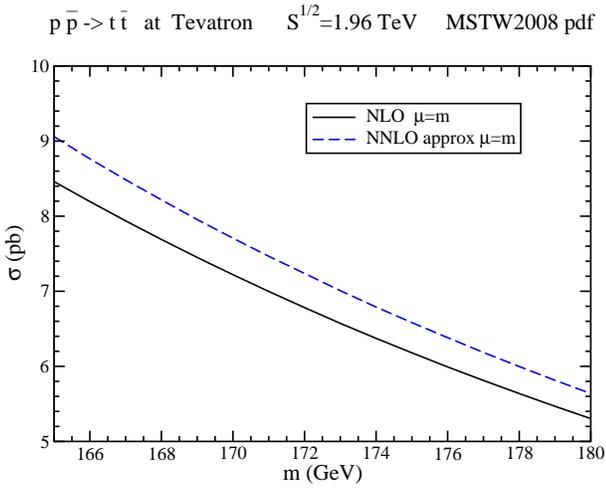


Figure 3: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $p\bar{p}$  collisions at the Tevatron using the MSTW 2008 NNLO pdf.

certainties are of similar size. Sometimes top masses of 170 and 175 GeV are used in top quark analyses. For  $m = 170$  GeV the result using MSTW pdf is 7.71 pb while for  $m = 175$  GeV it is 6.58 pb.

In Fig. 4 we plot the top quark transverse momentum distribution at the Tevatron. The exact NLO and approximate NNLO results are shown for a top mass of 175 GeV and, for comparison, also shown is the approximate NNLO result for a mass of 170 GeV. We notice an enhancement at NNLO relative to NLO, but similar shape [6, 17].

Next, we discuss the top quark pair cross section at the LHC. In Fig. 5 we plot the NLO and approximate NNLO cross sections for top pair production at

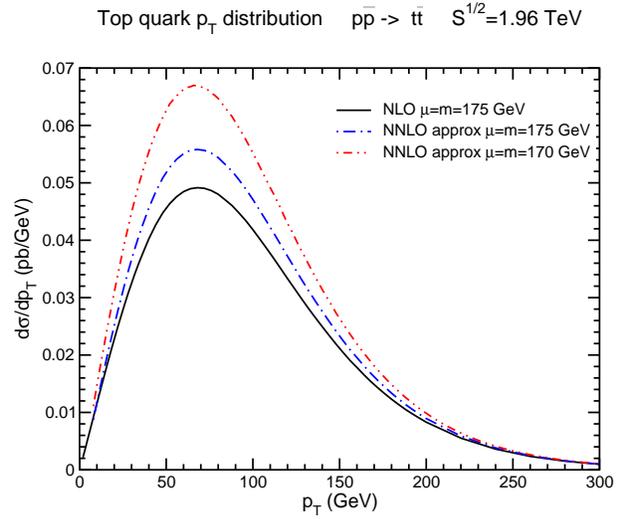


Figure 4: The NLO and approximate NNLO top quark transverse momentum distributions in  $p\bar{p}$  collisions at the Tevatron.

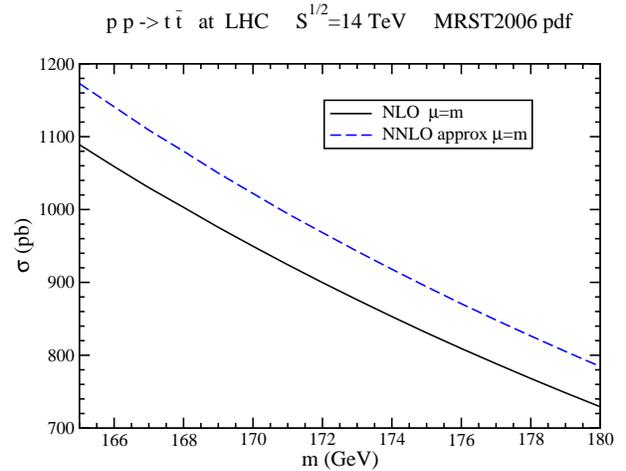


Figure 5: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $pp$  collisions at the LHC at 14 TeV using the MRST 2006 NNLO pdf.

the LHC at 14 TeV using the MRST 2006 NNLO pdf. Figs. 6 and 7 show, respectively, the results using the CTEQ6.6M and MSTW 2008 NNLO pdf. Again, the NNLO threshold corrections provide an overall enhancement and reduction in scale dependence. For a top quark of 172 GeV the cross sections together with the total uncertainty are

$$\begin{aligned}\sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MRST}) &= 968^{+80}_{-52} \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{CTEQ}) &= 919^{+76}_{-55} \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MSTW}) &= 943^{+66}_{-42} \text{ pb}.\end{aligned}$$

For a top mass of 173 GeV the corresponding results

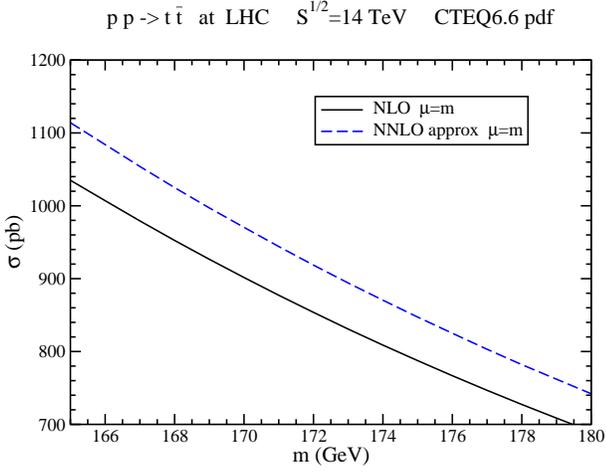


Figure 6: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $pp$  collisions at the LHC at 14 TeV using the CTEQ6.6M pdf.

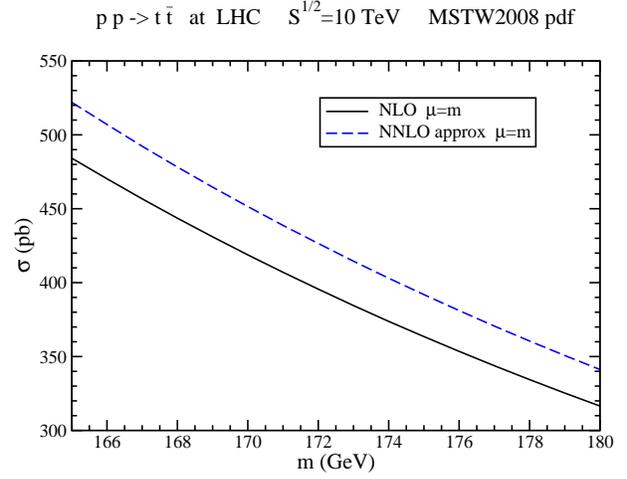


Figure 8: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $pp$  collisions at the LHC at 10 TeV using the MSTW 2008 NNLO pdf.

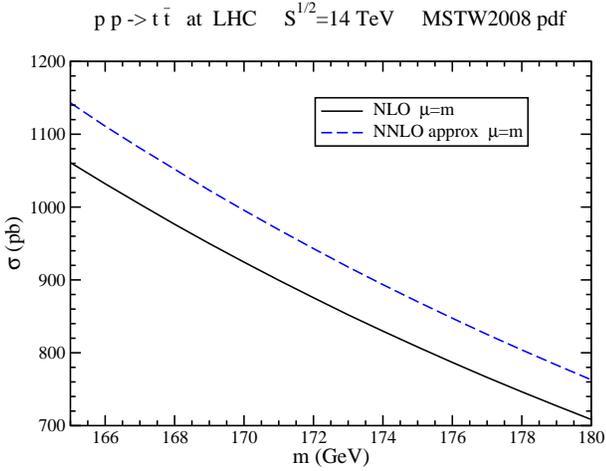


Figure 7: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $pp$  collisions at the LHC at 14 TeV using the MSTW 2008 NNLO pdf.

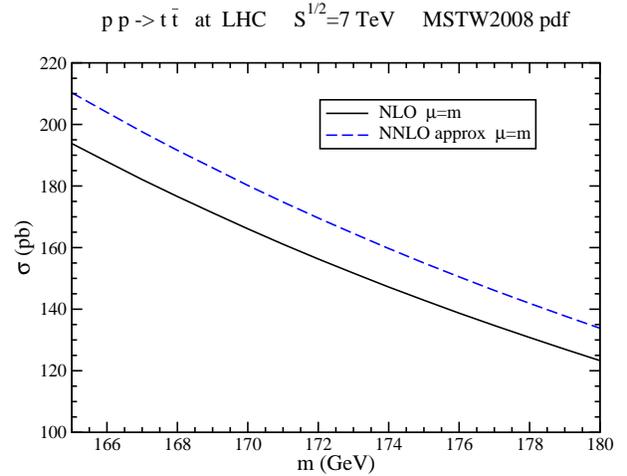


Figure 9: The NLO and approximate NNLO  $t\bar{t}$  cross sections in  $pp$  collisions at the LHC at 7 TeV using the MSTW 2008 NNLO pdf.

are

$$\begin{aligned}\sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MRST}) &= 943^{+78}_{-51} \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{CTEQ}) &= 894^{+74}_{-54} \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 14 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MSTW}) &= 918^{+64}_{-41} \text{ pb}.\end{aligned}$$

In Fig. 8 the top pair cross section is plotted for an LHC energy of 10 TeV. At 10 TeV, using the MSTW pdf, the cross section is

$$\begin{aligned}\sigma_{pp \rightarrow t\bar{t}, 10 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MSTW}) &= 427^{+32}_{-19} \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 10 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MSTW}) &= 415^{+31}_{-19} \text{ pb}.\end{aligned}$$

In Fig. 9 the  $t\bar{t}$  cross section is shown for the starting LHC energy of 7 TeV. At 7 TeV, using the MSTW

pdf, we find

$$\begin{aligned}\sigma_{pp \rightarrow t\bar{t}, 7 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{MSTW}) &= 170 \pm 10 \text{ pb}, \\ \sigma_{pp \rightarrow t\bar{t}, 7 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{MSTW}) &= 165 \pm 10 \text{ pb}.\end{aligned}$$

The top quark transverse momentum distribution at the LHC is enhanced at NNLO relative to NLO, but with little change in shape [6, 17].

### 3. Single top quark production

The recent observation of single top production [3, 4] provides opportunities for the study of electroweak properties of the top, such as extracting the

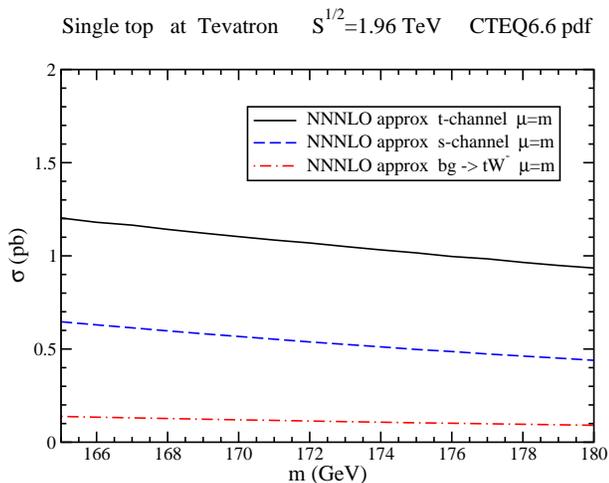


Figure 10: The approximate NNNLO single top cross sections in the  $t$ ,  $s$ , and  $bg \rightarrow tW^-$  channels at the Tevatron using the CTEQ6.6M pdf.

$V_{tb}$  CKM matrix element [18]. Single top production can proceed via three partonic channels: the  $t$ -channel,  $qb \rightarrow q't$  and  $\bar{q}b \rightarrow \bar{q}'t$ ; the  $s$ -channel,  $q\bar{q}' \rightarrow \bar{b}t$ ; and associated  $tW$  production,  $bg \rightarrow tW^-$ .

Figure 10 shows the approximate NNNLO cross sections for single top production at the Tevatron in all three channels using CTEQ6.6M pdf (note that the cross sections for anti-top production are the same). The  $t$ -channel has the largest cross section followed by the  $s$ -channel, while  $bg \rightarrow tW^-$  is relatively small. Below are listed the cross sections for  $m = 172$  GeV:

$$\sigma_{t\text{-chan}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{CTEQ}) = 1.07 \pm 0.11 \text{ pb},$$

$$\sigma_{s\text{-chan}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{CTEQ}) = 0.54 \pm 0.03 \text{ pb},$$

$$\sigma_{bg \rightarrow tW, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 172, \text{CTEQ}) = 0.11 \pm 0.04 \text{ pb},$$

and for  $m = 173$  GeV:

$$\sigma_{t\text{-chan}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{CTEQ}) = 1.05 \pm 0.11 \text{ pb},$$

$$\sigma_{s\text{-chan}, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{CTEQ}) = 0.52 \pm 0.03 \text{ pb},$$

$$\sigma_{bg \rightarrow tW, 1.96 \text{ TeV}}^{\text{NNLOapprox}}(m = 173, \text{CTEQ}) = 0.11 \pm 0.04 \text{ pb}.$$

Detailed results using MRST pdf are given in [8, 17, 19].

At the LHC the  $t$ -channel is numerically dominant and  $tW$  production is second in cross section. The  $s$ -channel, which is second largest at the Tevatron, is relatively small at the LHC.

At LHC energies the threshold approximation does not work well for the  $t$ -channel so only NLO results are known, but approximate NNNLO results for the  $s$ -channel and  $tW$  production are given in [9, 17, 19]. More work on NNLL soft-gluon corrections and on purely collinear corrections [20] may improve the approximation for LHC energies.

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