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Higher-order Threshold Corrections for Single Top Quark Production

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Abstract

I discuss single top quark production at the Tevatron and the LHC. The cross section, including soft-gluon threshold corrections through NNNLO, is presented for each partonic channel. The higher-order corrections provide significant contributions to the single top cross sections at both colliders.

1 Introduction

Single top quark production at hadron colliders can proceed through three distinct partonic processes: the t channel ($qb \rightarrow q't$ and $\bar{q}b \rightarrow \bar{q}'t$) which involves the exchange of a spacelike W boson, the s channel ($q\bar{q}' \rightarrow \bar{b}t$) which proceeds via a timelike W boson, and associated tW production ($bg \rightarrow tW^-$) [1]. The t channel processes are numerically the largest at both the Tevatron and the LHC. At the Tevatron the s channel is second in magnitude and tW production has the smallest cross section. At the LHC, tW production has a much bigger cross section than the s channel.

The cross sections for all these processes receive contributions from soft-gluon emission which can be dominant near threshold [2, 3]. Threshold resummation organizes these contributions and can be used to compute higher-order corrections for many processes [4, 5, 6]. For the partonic process with momenta $p_1 + p_2 \rightarrow p_3 + p_4$ we define $s = (p_1 + p_2)^2$, $t = (p_1 - p_3)^2$, $u = (p_2 - p_3)^2$ and $s_4 = s + t + u - m_3^2 - m_4^2$. Near threshold, s_4 approaches zero and the soft-gluon corrections take the form $[\ln^l(s_4/m_t^2)/s_4]_+$, where m_t is the top quark mass and $l \leq 2n - 1$ for the n -th order corrections. We calculate these corrections through next-to-next-to-next-to-leading order (NNNLO) in the strong coupling α_s at next-to-leading logarithmic (NLL) accuracy at the Tevatron [2]

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and the LHC [3]. This requires one-loop calculations in the eikonal approximation.

The NLO soft-gluon corrections can be written in the form

$$\frac{d^2\hat{\sigma}^{(1)}}{dt du} = F^B \frac{\alpha_s(\mu_R^2)}{\pi} \left\{ c_3 \left[\frac{\ln(s_4/m_t^2)}{s_4} \right]_+ + c_2 \left[\frac{1}{s_4} \right]_+ + c_1^\mu \delta(s_4) \right\}$$

where F^B is the Born term for each channel and μ_R is the renormalization scale. For the t and s channels the leading logarithm coefficient is $c_3^{t,s} = 3C_F$ while for the tW channel it is $c_3^{tW} = 2(C_F + C_A)$, where $C_F = (N_c^2 - 1)/(2N_c)$ and $C_A = N_c$ with $N_c = 3$ the number of colors. The NLL coefficient is $c_2^s = -\frac{7}{4}C_F + 2C_F \ln\left(\frac{s(s-m_t^2)}{(t-m_t^2)(u-m_t^2)}\right) - 2C_F \ln\left(\frac{\mu_F^2}{m_t^2}\right)$ for the s channel, where μ_F is the factorization scale, and similar expressions can be given for the other channels. The complete virtual corrections ($\delta(s_4)$ terms) cannot be derived from threshold resummation but one can derive the factorization and renormalization scale terms denoted by c_1^μ in the above equation [2].

The NNLO soft-gluon corrections for the t and s channels are

$$\begin{aligned} \frac{d^2\hat{\sigma}_{t,s}^{(2)}}{dt du} = & F^B \frac{\alpha_s^2(\mu_R^2)}{\pi^2} \left\{ \frac{1}{2} c_3^2 \left[\frac{\ln^3(s_4/m_t^2)}{s_4} \right]_+ \right. \\ & \left. + \left[\frac{3}{2} c_3 c_2 - \frac{\beta_0}{4} c_3 + C_F \frac{\beta_0}{8} \right] \left[\frac{\ln^2(s_4/m_t^2)}{s_4} \right]_+ \right\} \end{aligned}$$

plus subleading terms [2], where the appropriate expression for F_B and c_3 , c_2 for each channel must be used, and where $\beta_0 = (11C_A - 2n_f)/3$ is the lowest-order β function, with n_f the number of light quark flavors. A similar expression holds for the tW channel (by deleting $C_F\beta_0/8$ above). Since this is a NLL calculation, only the leading and NLL terms shown above are complete. However we can also calculate exactly terms involving μ_F and μ_R as well as terms with ζ constants in the subleading logarithms. Complete expressions and further details are provided in Ref. [2].

The NNNLO soft-gluon corrections for each channel can be written as

$$\begin{aligned} \frac{d^2\hat{\sigma}^{(3)}}{dt du} = & F^B \frac{\alpha_s^3(\mu_R^2)}{\pi^3} \left\{ \frac{1}{8} c_3^3 \left[\frac{\ln^5(s_4/m_t^2)}{s_4} \right]_+ \right. \\ & \left. + \left[\frac{5}{8} c_3^2 c_2 - \frac{5}{48} \beta_0 c_3 (2c_3 - C_F) \right] \left[\frac{\ln^4(s_4/m_t^2)}{s_4} \right]_+ \right\} \end{aligned}$$

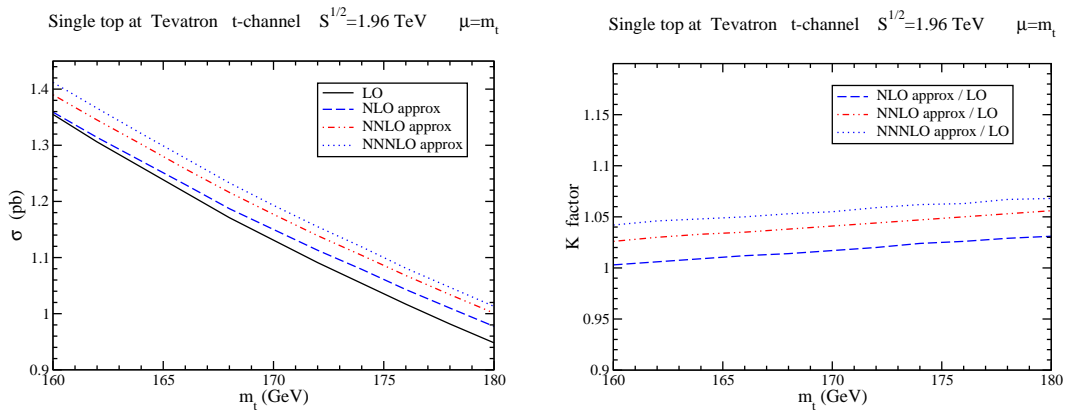


Figure 1: t -channel single top quark cross section at the Tevatron.

plus subleading terms [2], again with the appropriate expression for F_B and c_3 , c_2 .

2 Single top quark production at the Tevatron

We now calculate the contribution of these corrections to the single top cross section at the Fermilab Tevatron. The MRST 2004 NNLO parton densities [7] are used for the numerical results. We find that the threshold corrections are dominant in all partonic channels.

Figure 1 shows the results for the cross section in the t channel. In the left-hand plot we show the leading-order (LO) cross section as well as the cross sections with the NLO, NNLO, and NNNLO soft-gluon corrections included versus the top quark mass m_t , with the factorization and renormalization scales set equal to m_t . On the right-hand plot we show the K factors, which are the ratios of the higher-order cross sections to LO. We see that the corrections in this channel are relatively small. Our best estimate for the cross section is calculated after matching to the exact NLO cross section [8], i.e. by adding the soft-gluon corrections through NNNLO to the exact NLO cross section. Below we give results for two choices of the top quark mass, $m_t = 170$ GeV and $m_t = 175$ GeV. We find $\sigma^{t\text{-channel}}(m_t = 170 \text{ GeV}) = 1.17 \pm 0.06$ pb and $\sigma^{t\text{-channel}}(m_t = 175 \text{ GeV}) = 1.08 \pm 0.06$ pb. The uncertainty indicated includes the scale dependence and the pdf uncertainties.

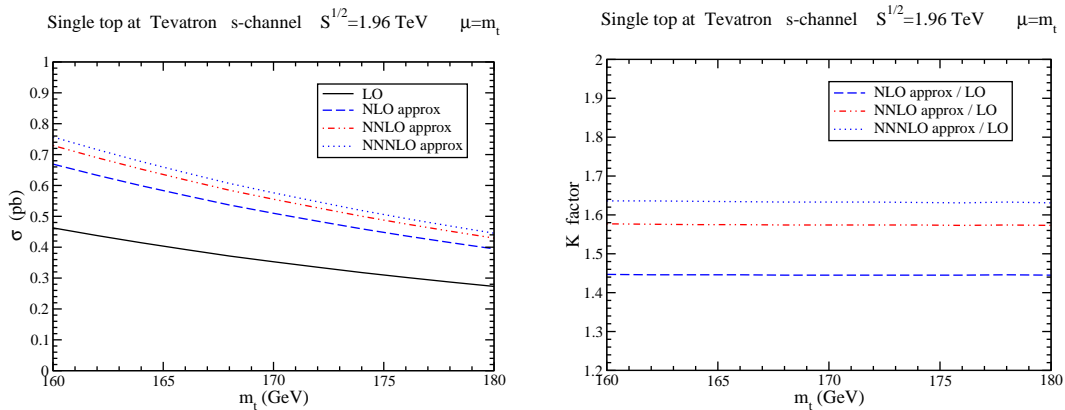


Figure 2: s -channel single top quark cross section at the Tevatron.

Figure 2 shows the results for the cross section and K factors in the s channel. In this channel the corrections are large, providing up to 65% enhancement of the leading-order cross section. After matching, we find $\sigma^{s\text{-channel}}(m_t = 170 \text{ GeV}) = 0.56 \pm 0.03 \text{ pb}$ and $\sigma^{s\text{-channel}}(m_t = 175 \text{ GeV}) = 0.49 \pm 0.02 \text{ pb}$.

The single top cross section at the Tevatron in the tW channel is rather small, even though the K factors are large (up to 85% enhancement). Our estimate for the cross section is $\sigma^{tW}(m_t = 170 \text{ GeV}) = 0.15 \pm 0.03 \text{ pb}$ and $\sigma^{tW}(m_t = 175 \text{ GeV}) = 0.13 \pm 0.03 \text{ pb}$.

For all three channels at the Tevatron the cross section for single anti-top production is identical to that shown above for single top production.

Finally, we note that there has been recent evidence for single top quark production at the Tevatron [9] with a cross section consistent with the above results.

3 Single top quark production at the LHC

Next we calculate the threshold corrections for the single top cross section at the CERN LHC. It turns out that in the t channel the threshold corrections are not a good approximation of full QCD corrections, hence we only update the exact NLO result [8], while in the s and tW channels the threshold approximation holds and we provide results including the NNNLO soft-gluon corrections. Also at the LHC the cross section for single top is different from

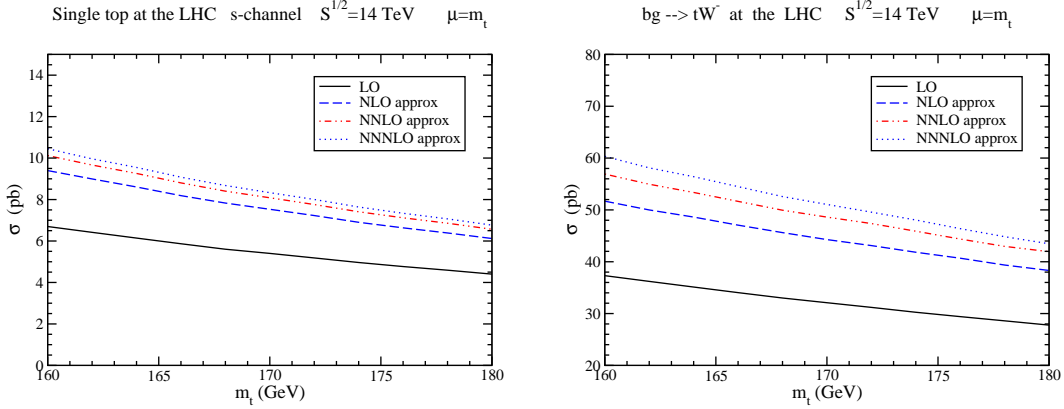


Figure 3: s -channel single top (left) and tW (right) cross sections at the LHC.

that for single antitop production in the t and s channels.

The exact NLO cross section for single top production in the t channel at the LHC is $\sigma_{\text{top}}^{t\text{-channel}}(m_t = 170 \text{ GeV}) = 152 \pm 6 \text{ pb}$ and $\sigma_{\text{top}}^{t\text{-channel}}(m_t = 175 \text{ GeV}) = 146 \pm 5 \text{ pb}$. For single antitop production in the t channel the exact NLO cross section is $\sigma_{\text{antitop}}^{t\text{-channel}}(m_t = 170 \text{ GeV}) = 93 \pm 4 \text{ pb}$ and $\sigma_{\text{antitop}}^{t\text{-channel}}(m_t = 175 \text{ GeV}) = 89 \pm 4 \text{ pb}$.

Figure 3 (left) shows results for single top production in the s channel at the LHC. The contribution from soft gluons is significant (up to 55% enhancement). After matching to the exact NLO cross section [8], we find $\sigma_{\text{top}}^{s\text{-channel}}(m_t = 170 \text{ GeV}) = 8.0^{+0.6}_{-0.5} \text{ pb}$ and $\sigma_{\text{top}}^{s\text{-channel}}(m_t = 175 \text{ GeV}) = 7.2^{+0.6}_{-0.5} \text{ pb}$.

The corresponding results for single antitop production at the LHC in the s channel are $\sigma_{\text{antitop}}^{s\text{-channel}}(m_t = 170 \text{ GeV}) = 4.5 \pm 0.2 \text{ pb}$ and $\sigma_{\text{antitop}}^{s\text{-channel}}(m_t = 175 \text{ GeV}) = 4.0 \pm 0.2 \text{ pb}$. Here the soft-gluon corrections are somewhat smaller (less than 20%).

Figure 3 (right) shows results for single top production at the LHC in the tW channel. This channel has a significant cross section at the LHC. Also the soft-gluon corrections are quite large, providing around 60% enhancement. After matching to the exact NLO cross section [10], we find $\sigma^{tW}(m_t = 170 \text{ GeV}) = 44 \pm 5 \text{ pb}$ and $\sigma^{tW}(m_t = 175 \text{ GeV}) = 41 \pm 4 \text{ pb}$. The cross section for associated antitop production is identical to that for a top quark.

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