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Single-top production in the *s*-channel and the top-quark mass

Sergey Alekhin [ab], **Sven-Olaf Moch** [a], **and Stephan Thier**[∗a]
[a] *II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany*
[b] *Institute for High Energy Physics, 142281 Protvino, Moscow region, Russia*
E-mail: sergey.alekhin@desy.de, sven-olaf.moch@desy.de, stephan.christoph.thier@desy.de

We use a fixed-order expansion of resummed soft-gluon corrections to determine an approximate NNLO formula for the partonic cross section of single-top production in the *s*-channel. This formula is implemented in the program Hathor for the numerical evaluation of hadronic cross sections. With the resulting code, we perform a fit of the top-quark mass to Tevatron cross section data. Results for m_t are given in the pole-mass scheme and in the $\overline{\mathrm{MS}}$ scheme.

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∗Speaker.

1. Introduction

Single-top production proceeds via an electroweak interaction, which puts it into contrast to top-quark pair production where strong interactions generate the largest part of top-quarks that are produced in hadron collisions. Due to the different interactions, single-top production can be used as a complementary way to access top-quark parameters with minimal dependence on strong interactions. This complementary perspective can be enhanced by considering the *s*-channel of single-top production, which proceeds at leading order (LO) via quark–anti-quark annihilation to a W boson that subsequently decays into a top-quark and, in most cases, a bottom quark. There is no contribution of initial-state gluons to this process in contrast to their dominant contribution to top-quark pair production.

While fixed-order corrections for single-top production in the *s*-channel are known to next-to-leading order (NLO) in perturbative QCD [1], further soft-gluon corrections have been considered and were found to be sizeable [2, 3, 4]. The emission of soft gluons generates logarithmic terms which become large near the production threshold. After resummation of these logarithms, an expansion in powers of the strong coupling allows to extract important QCD corrections at fixed orders in perturbation theory beyond NLO.

In this paper, we calculate an approximate next-to-next-to-leading order (aNNLO) formula for the partonic cross section of single-top production in the *s*-channel based on the fixed-order expansion of soft-gluon corrections which was presented in [2]. Subsequently, we implement this formula in the program HATHOR [5, 6] to evaluate the hadronic cross section numerically. With this code, we perform fits to Tevatron cross-section data and determine the top-quark mass in both the pole-mass scheme and the $\overline{\mathrm{MS}}$ scheme.

2. Calculation

We consider the partonic cross section σ in perturbation theory as a power series in the strong coupling α_s,

$$\sigma = \sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}\,, \tag{2.1}$$

with the LO partonic cross section for the process $u\bar{d} \to t\bar{b}$ given by

$$\sigma^{(0)} = \frac{\pi\alpha^2 V_{tb}^2 V_{ud}^2 (m_t^2 - s)^2 (m_t^2 + 2s)}{24 s^2 \sin^4\theta_W (m_W^2 - s)^2}. \tag{2.2}$$

and the exact NLO result $\sigma^{(1)}$ computed in [1], while $\sigma^{(2)}$ in Eq. (2.1) is currently unknown. Here s is the partonic center-of-mass energy squared, m_t and m_W are the top-quark and W-boson masses respectively, and α, $\sin\theta_W$, V_{tb} and V_{ud} are the electro-weak and CKM parameters [6].

To validate our approach, we start with the approximate next-to-leading order (aNLO) double-differential cross section of Ref. [2] for single-top production in the *s*-channel and compare the results of our procedure to the complete NLO corrections that are implemented in HATHOR. First, we perform an analytic integration over the Mandelstam variables t and u to obtain the partonic cross section as a function of the top-quark velocity $\beta = (1 - m_t^2/s)^{1/2}$ only. In accordance with the soft-gluon approximation, that is valid near the production threshold, we keep only the lowest order in β during this integration. To avoid overestimating contributions at large β in this approach, we multiply the result by a kinematical suppression factor $1-\beta^2 = m_t^2/s$ and find $\sigma^{(1)} \simeq R_{\text{aNLO}}\sigma^{(0)}$ with

$$R_{\text{aNLO}} = \frac{\alpha_s C_F}{8\pi}\left(1-\beta^2\right)\left(112\log^2(\beta) - 148\log(\beta) + 63 - 4\log\left(\frac{\mu_F^2}{m_t^2}\right)(8\log(\beta)-3)\right) + \mathcal{O}(\beta)\,, \tag{2.3}$$

where the strong coupling $\alpha_s = \alpha_s(\mu_R)$ is taken at the renormalization scale μ_R, which is kept separate from the factorization scale μ_F.

For numerical evaluation of hadronic cross sections, we implement our result in the program HATHOR, that was developed for the evaluation of the inclusive cross section in both $t\bar{t}$ production [5] and single-top production [6]. To parametrize the partonic content of nucleons, the ABM12 parton distribution functions [7] are employed.

The ratio of the cross section in our aNLO approximation to the complete NLO result for different hadronic center-of-mass energies is given in Fig. 1. All results presented here refer to $p\bar{p}$ collisions with a pole mass $m_{t,\text{pole}} = 172.5$ GeV. While the agreement of our approximation with the exact result is quite good over the considered energy range, it gets better at smaller energies as expected for the threshold approximation that forms the foundation of our calculation. This validation justifies application of the same procedure at NNLO to obtain an estimate for the corrections at the next order in perturbation theory.

To determine the partonic cross section at aNNLO, we follow the same steps that were described above at aNLO using the approximate NNLO double-differential partonic cross section of Ref. [2], which is accurate to the next-to-leading logarithm. In this way, we obtain exact expressions for the leading terms, $\log^4(\beta)$ and $\log^3(\beta)$, and terms proportional to $\log^2(\beta)$ except for the interference with the term $\sim \beta^0$ at NLO. We find $\sigma^{(2)} \simeq R_{\text{aNNLO}}\sigma^{(0)}$ with

$$\begin{aligned}
R_{\text{aNNLO}} = \frac{\alpha_s^2 C_F}{24\pi^2}\left(1-\beta^2\right)\Bigg(&1584C_F\log^4(\beta) - 8\log^3(\beta)(5\beta_0 + 549C_F) \\
&+ \log^2(\beta)\left(90\beta_0 + 42\left(153-4\pi^2\right)C_F\right) \\
&+ \log\left(\frac{\mu_F^2}{m_t^2}\right)\Bigg[-1344C_F\log^3(\beta) + \log^2(\beta)(36\beta_0 + 2568C_F) \\
&\qquad + \log(\beta)\left(4\left(20\pi^2-591\right)C_F - 54\beta_0\right) \\
&\qquad + (18\beta_0 - 24\beta_0\log(\beta))\log\left(\frac{\mu_R^2}{\mu_F^2}\right)\Bigg] \\
&+ \log^2\left(\frac{\mu_F^2}{m_t^2}\right)\left[192C_F\log^2(\beta) - 12\log(\beta)(\beta_0 + 12C_F) + 9\beta_0 + \left(60-8\pi^2\right)C_F\right] \\
&+ \log\left(\frac{\mu_R^2}{\mu_F^2}\right)\left(36\beta_0\log^2(\beta) - 54\beta_0\log(\beta)\right)\Bigg) + \mathcal{O}(\beta),
\end{aligned} \tag{2.4}$$

where $\beta_0 = (11C_A - 2n_f)/3$ and n_f is the number of quark flavours.

Hadronic cross sections at different energies from the implementation of our aNNLO result in HATHOR are given in Fig. 2 for the nominal scale choice $\mu_R = \mu_F = m_{t,\text{pole}}$ and compared to the exact NLO result. In contrast to the large NLO corrections, the approximate NNLO corrections are

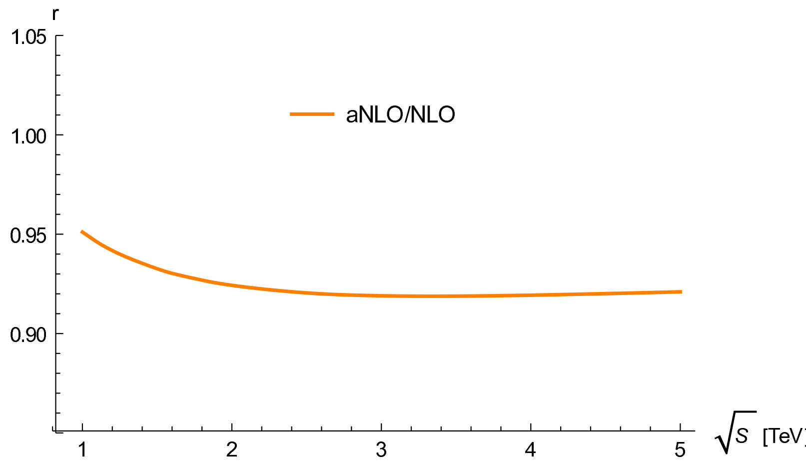

Figure 1: Ratio of the aNLO formula to the exact NLO result $r = (R_{\rm aNLO}\sigma^{(0)})/\sigma^{(1)}$ for the cross section of single-top production in the s-channel as function of the hadronic center-of-mass energy.

moderate thus demonstrating apparent convergence of the perturbative expansion. At the Tevatron center-of-mass energy $\sqrt{S} = 1.96$ TeV, the cross section is enhanced by $+39\%$ at NLO compared to LO. When our aNNLO corrections are included, this enhancement grows to $+47\%$ at the nominal scale.

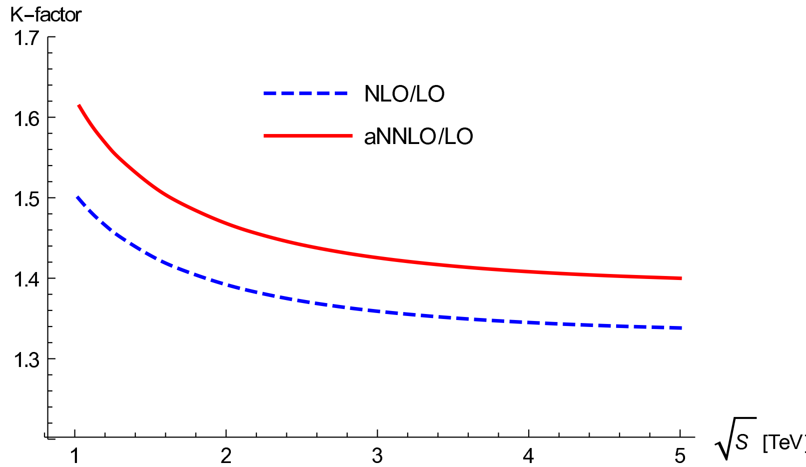

Figure 2: The K-factors of the cross section for single-top production in the s-channel relative to the cross section at LO as function of the hadronic center-of-mass energy at NLO $(\sigma^{(0)} + \sigma^{(1)})/\sigma^{(0)}$ (blue, dashed) and aNNLO $(\sigma^{(0)} + \sigma^{(1)} + R_{\rm aNNLO}\sigma^{(0)})/\sigma^{(0)}$ (red, solid).

As a cross-check of the perturbative stability of our aNNLO results, we also study their dependence on unphysical scales. In Fig. 3, we compare the scale dependence at NLO to the one at aNNLO based on Eq. (2.4) and to the exact NNLO scale dependence that is included in HATHOR. Both the renormalization scale μ_R and the factorization scale μ_F are varied simultaneously by a factor between $1/8$ and 8. When both scales are varied independently, it becomes apparent that our approximation does not include all scale-dependent terms. In this case, variations of uncancelled terms lead to a scale dependence which is similar in magnitude to the one at NLO.

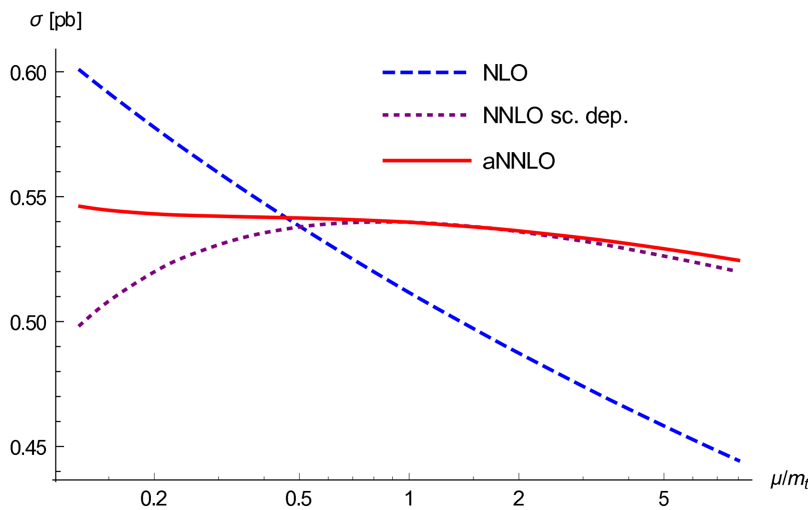

Figure 3: Cross section of single-top production in the s-channel at $\sqrt{S} = 1.96$ TeV as function of μ/m_t with $\mu = \mu_R = \mu_F$ at NLO (blue, dashed), aNNLO (red, solid), and aNNLO with scale dependence exact at NNLO (purple, dotted).

3. Mass Fit

We use the implementation of our aNNLO formula for s-channel single-top production in HATHOR to extract the top-quark mass from the total cross section which was measured at the Tevatron. Combined observations by CDF and D0 [8] allowed to determine $\sigma_s = 1.29^{+0.26}_{-0.24}$ pb with a statistical significance of 6.3 standard deviations.

Our result for the top-quark pole mass at aNNLO accuracy is $m_{t,\mathrm{pole}} = 165.7^{+7.9}_{-6.9}$ GeV. Since the top-quark is a colour-charged particle, strong dynamics limit the accuracy with which a pole mass can be defined. It is thus advantageous to consider other mass definitions which follow a theoretically well-defined prescription, e.g. the $\overline{\mathrm{MS}}$ mass. We implement in our code a translation from the pole mass to the $\overline{\mathrm{MS}}$ mass at NNLO accuracy [9] and perform a mass fit which leads to $m_{t,\overline{\mathrm{MS}}} = 157.9^{+7.5}_{-6.6}$ GeV at the scale $\mu_R = m_{t,\overline{\mathrm{MS}}}$.

4. Conclusions

We have used a fixed-order expansion of resummed soft-gluon corrections to s-channel single-top production in order to derive a compact analytic formula which approximates the partonic cross section at NNLO. Based on the implementation of these results in HATHOR, hadronic cross sections have been evaluated and the impact of the approximate NNLO corrections was found to be moderate. Fits of the top-quark mass in the pole-mass scheme and in the $\overline{\mathrm{MS}}$ scheme to the total cross section exhibit a tendency to smaller mass values compared to conventional methods for the extraction of m_t however the results are compatible within uncertainties.

Acknowledgments

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