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Heavy-Flavor Production at Accelerators

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Abstract

I discuss heavy flavor production at hadronic facilities. I present total cross sections and differential distributions for top quark, bottom quark, and charm quark production at the Tevatron and LHC colliders, and at fixed-target experiments such as HERA-B. The calculations include complete next-to-leading order corrections as well as higher-order soft-gluon corrections which are important near kinematical threshold.

Key words: top quark, bottom quark, charm quark, soft gluons
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1. Introduction

QCD corrections are typically large for heavy quark production. The current state-of-the-art theoretical calculations of cross sections include higher-order corrections beyond next-to-leading order (NLO). Soft-gluon corrections of the form $[\ln^k(s_4/m^2)/s_4]_+$, with s_4 the kinematical distance from threshold, are dominant near threshold and can be resummed. At next-to-leading-logarithm (NLL) accuracy this requires one-loop calculations in the eikonal approximation; at next-to-next-to-leading-logarithm (NNLL) it requires two-loop calculations. Approximate next-to-next-to-leading order (NNLO) cross sections can be derived from the expansion of the resummed cross section.

In the next section I present some recent calculations for top quark pair production at the Tevatron and the LHC. This is followed by a section on single top quark production, and a section on bottom and charm quark production at fixed-target facilities, including HERA-B. In the last section I discuss recent work on two-loop calculations in the eikonal

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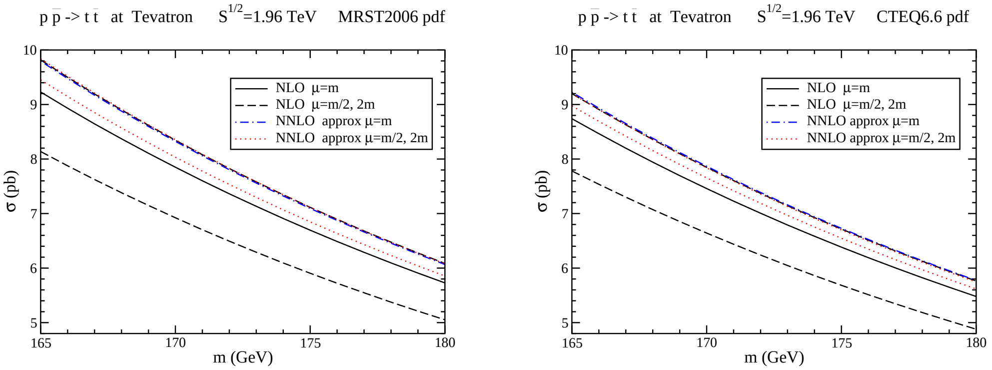

Fig. 1. The NLO and approximate NNLO $t\bar{t}$ cross sections in $p\bar{p}$ collisions at the Tevatron using the MRST 2006 NNLO (left) and CTEQ6.6M (right) pdf.

approximation that are relevant for increasing the accuracy of resummation for heavy quark production.

2. Top quark pair production

The dominant process for top quark production in hadron colliders is pair production via the processes, at leading order, $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$. There is very good agreement of theory, including soft-gluon corrections [1], with Tevatron data [2,3]. The same is expected to hold with future LHC data.

Figure 1 shows the cross section from an approximate NNLO calculation [1] for Tevatron energy, using two different parton distribution function (pdf) sets, MRST 2006 NNLO [4] and CTEQ6.6M [5].

For reference, below is the cross section for a top mass of 172 GeV,

$$\sigma^{p\bar{p}\to t\bar{t}}(1.96\,\mathrm{TeV}, m_t = 172\,\mathrm{GeV}, \mathrm{MRST}) = 7.80 \pm 0.31^{+0.03+0.23}_{-0.27-0.19}\ \mathrm{pb} = 7.80^{+0.39}_{-0.45}\ \mathrm{pb}\,,$$

$$\sigma^{p\bar{p}\to t\bar{t}}(1.96\,\mathrm{TeV}, m_t = 172\,\mathrm{GeV}, \mathrm{CTEQ}) = 7.39 \pm 0.30^{-0.03+0.48}_{-0.20-0.37}\ \mathrm{pb} = 7.39^{+0.57}_{-0.52}\ \mathrm{pb}\,.$$

The first uncertainty indicated is a kinematics uncertainty arising from the choice of using single-particle-inclusive (1PI) or pair-invariant mass (PIM) kinematics; the second uncertainty is from scale variation over a range $m/2 \leq \mu \leq 2m$, and the third uncertainty is from the pdf and varies quite a bit between the MRST and CTEQ sets used. The total uncertainty indicated comes from the addition in quadrature of the three individual uncertainties. It is interesting to note that at present the experimental and theoretical uncertainties are of similar size. It is also clear from Figure 1 that the scale dependence is greatly decreased at NNLO.

Figure 2 shows the corresponding results [1] for LHC energy. The cross sections and uncertainties for $m_t = 172$ GeV are

$$\sigma^{pp\to t\bar{t}}(14\,\mathrm{TeV}, m_t = 172\,\mathrm{GeV}, \mathrm{MRST}) = 968 \pm 4^{+79+12}_{-50-13}\ \mathrm{pb} = 968^{+80}_{-52}\ \mathrm{pb}\,,$$

$$\sigma^{pp\to t\bar{t}}(14\,\mathrm{TeV}, m_t = 172\,\mathrm{GeV}, \mathrm{CTEQ}) = 919 \pm 4^{+70+29}_{-45-31}\ \mathrm{pb} = 919^{+76}_{-55}\ \mathrm{pb}\,.$$

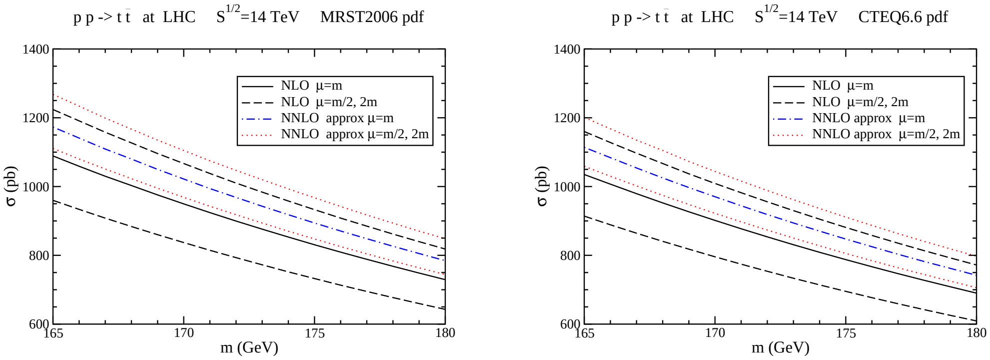

Fig. 2. The NLO and approximate NNLO $t\bar{t}$ cross sections in pp collisions at the LHC using the MRST 2006 NNLO (left) and the CTEQ6.6M (right) pdf.

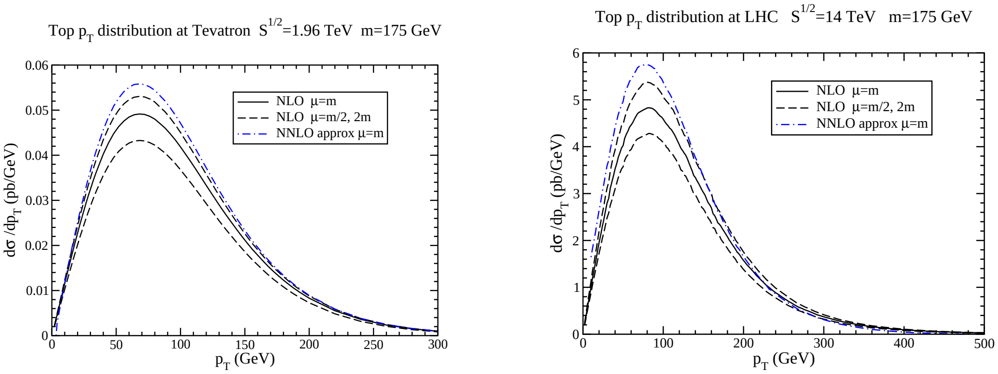

Fig. 3. The NLO and approximate NNLO top quark p_T distributions at the Tevatron (left) and the LHC (right).

Figure 3 shows the top quark transverse momentum, p_T, distribution at the Tevatron and the LHC for a top quark mass of 175 GeV [6].

3. Single top quark production

There is now evidence for single top production at the Tevatron [7] with a cross section consistent with theory [8]. The partonic processes at leading order are the t channel, $qb \to q't$ and $\bar{q}b \to \bar{q}'t$; the s channel: $q\bar{q}' \to \bar{b}t$; and associated tW production, $bg \to tW^-$. In the results below we include soft-gluon corrections at NNLO and NNNLO [8,9,10] and use the MRST 2004 NNLO pdf [11].

We begin with results for the Tevatron [8,10]. For the t channel we find

$$\sigma_{\rm top}^{t-{\rm channel}}(1.96\,{\rm TeV}, m_t = 172\,{\rm GeV}) = 1.14^{+0.02}_{-0.01} \pm 0.06 \text{ pb} = 1.14 \pm 0.06 \text{ pb}\,,$$

where the first uncertainty is from scale variation over $m/2 \le \mu \le 2m$ and the second is from the pdf, and we add the two in quadrature for the total uncertainty. The cross section for single antitop production is identical.

For the s channel we find

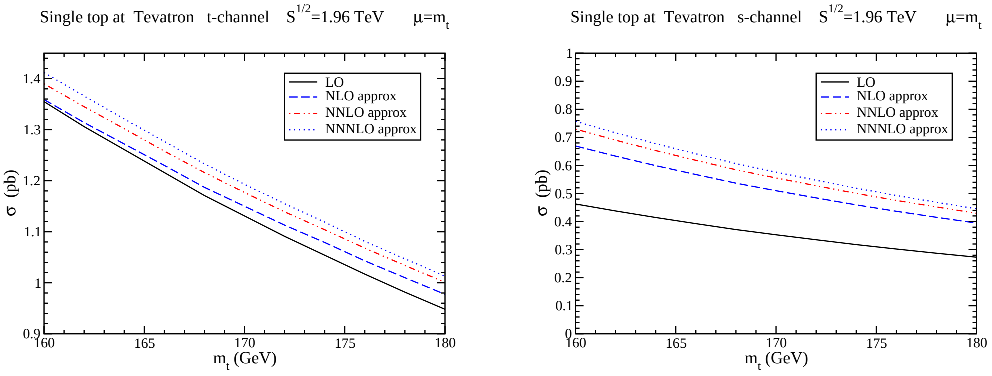

Fig. 4. The single top quark cross sections at the Tevatron in the t channel (left) and s channel (right).

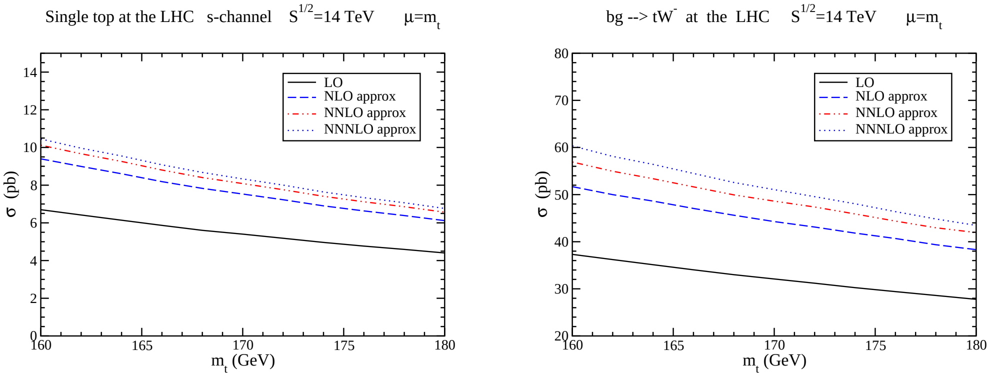

Fig. 5. The single top quark cross sections at the LHC in the s channel (left) and tW channel (right).

$$\sigma_{\rm top}^{s-{\rm channel}}(1.96\,{\rm TeV}, m_t=172\,{\rm GeV}) = 0.53 \pm 0.02 \pm 0.01 \text{ pb} = 0.53 \pm 0.02 \text{ pb}\,.$$

Again, the cross section for single antitop production is identical.

In Figure 4 we plot the cross sections for the t and s channels at various orders versus the top quark mass, with the scale set at $\mu = m_t$.

The cross section for single top production at the Tevatron via the tW channel is smaller: $\sigma^{tW}(1.96\,{\rm TeV}, m_t = 172\,{\rm GeV}) = 0.14 \pm 0.02 \pm 0.02$ pb $= 0.14 \pm 0.03$ pb, with an identical result for $\bar{t}W$ production.

We continue with single top production at the LHC [9,10]. We note that here in the t and s channels the results are different for the single top and single antitop cross sections.

In the t channel the threshold approximation is not good at the LHC energy, and thus we do not include soft-gluon corrections. The exact NLO cross section for single top is $\sigma_{\rm top}^{t-{\rm channel}}(14\,{\rm TeV}, m_t = 172\,{\rm GeV}) = 149 \pm 5 \pm 3$ pb $= 149 \pm 6$ pb, while for single antitop it is $\sigma_{\rm antitop}^{t-{\rm channel}}(14\,{\rm TeV}, m_t = 172\,{\rm GeV}) = 91 \pm 3 \pm 2$ pb $= 91 \pm 4$ pb.

In the s channel the cross section, including soft-gluon corrections through NNNLO, for single top production is

$$\sigma_{\rm top}^{s-{\rm channel}}(14\,{\rm TeV}, m_t = 172\,{\rm GeV}) = 7.7^{+0.6}_{-0.5} \pm 0.1 \text{ pb} = 7.7^{+0.6}_{-0.5} \text{ pb}\,,$$

while for single antitop production it is

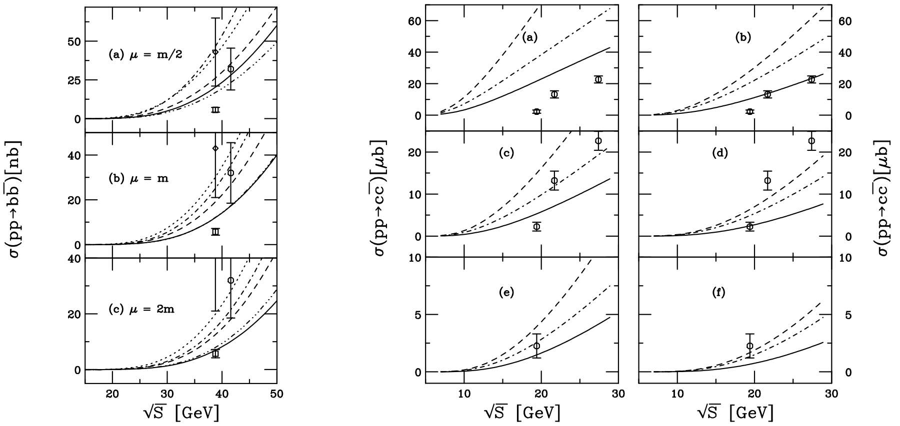

Fig. 6. (Left) The $b\bar{b}$ cross section in pp collisions. Shown are NLO (solid) and NNLO-NNLL (dot-dashed) results for $m_b = 4.75$ GeV, and NNLO-NNNLL+ζ results for $m_b = 4.5, 4.75, 5$ GeV (other curves) with $\mu = m_b/2$ (a), $\mu = m_b$ (b) and $\mu = 2m_b$ (c). (Right) The $c\bar{c}$ cross section in pp collisions. Shown are NLO (solid), NNLO-NNLL (dashed) and NNLO-NNNLL+ζ (dot-dashed) results for $m_c = 1.2$ GeV (a,b), 1.5 GeV (c,d) and 1.8 GeV (e,f), with $\mu = m_c$ (a,c,e) and $\mu = 2m_c$ (b,d,f).

$$\sigma^{s-\text{channel}}_{\text{antitop}}(14\,\text{TeV}, m_t = 172\,\text{GeV}) = 4.3 \pm 0.1 \pm 0.1 \text{ pb} = 4.3 \pm 0.2 \text{ pb}\,.$$

In the tW channel the cross section, including soft corrections through NNNLO, is

$$\sigma^{tW}(14\,\text{TeV}, m_t = 172\,\text{GeV}) = 43 \pm 5 \pm 1 \text{ pb} = 43 \pm 5 \text{ pb}\,,$$

with an identical result for $\bar{t}W$ production.

In Figure 5 we plot results for the s channel and tW production at the LHC.

4. Bottom and charm quark pair production

We now turn to bottom pair and charm pair production at fixed-target facilities. In Figure 6 we show results for the theoretical cross section [12] in pp collisions versus $\sqrt{S}$ using the MRST 2002 NNLO pdf [13], and compare with some experimental data. For both $b\bar{b}$ and $c\bar{c}$ production there are large theoretical and experimental uncertainties.

For the HERA-B experiment the theoretical cross section is [12]

$$\sigma^{pp\to b\bar{b}}(41.6\,\text{GeV}, m_b = 4.75\,\text{GeV}) = 28 \pm 9^{+15}_{-10} \text{ nb}\,,$$

where the first uncertainty is due to scale variation and the second is due to uncertainty in the bottom quark mass, $4.5 \le m_b \le 5$ GeV. This is in agreement with HERA-B data [14].

5. Two-loop soft-gluon resummation for heavy quarks

Further progress in the soft-gluon resummation program at NNLL requires two-loop calculations in the eikonal approximation. Resummation is controlled by a soft anomalous dimension matrix, Γ_S [15], which can be calculated by the evaluation of dimensionally regularized graphs with Wilson lines.

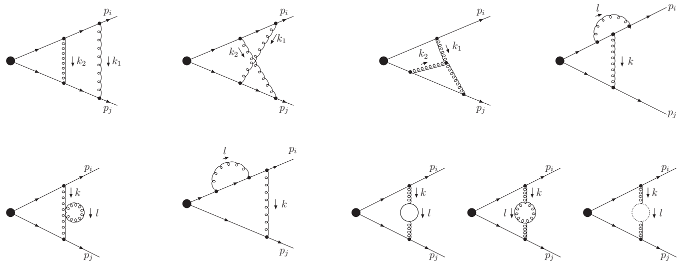

Fig. 7. Two-loop diagrams with heavy-quark eikonal lines.

Figure 7 shows some typical two-loop diagrams with heavy-quark lines; there are additional graphs not shown here including heavy-quark self-energies and one-loop counterterms. For massless quarks Γ_S was calculated at two loops in Ref. [16] and shown to be proportional to the one-loop result. The mass makes the corresponding calculation for heavy quarks more difficult but several results for the required integrals have appeared in Refs. [17,18] and work is ongoing. It is clear that the two-loop $C_F n_f$ terms in the massive case obey the same relation with respect to the one-loop result as in the massless case, but the $C_F C_A$ terms are more challenging.

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