HEAVY QUARK HADROPRODUCTION: RESUMMING LARGE LOGARITHMS VIA HEAVY QUARK PDF'S

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Present NLO heavy quark hadroproduction calculations have large renormalization-scale dependence and lie well below experimentally measured values. We resum large initial and final state logarithms (via heavy quark parton distribution and decay functions) to extend and improve present NLO calculations. Implications for Tevatron experiments are presented.

1 Introduction

Present Next-to-Leading-Order (NLO) calculations of charm and bottom hadroproduction cross sections display two serious problems: *i)* the theoretical cross-sections fall well short of the measured values, and *ii)* they display a strong dependence on the unphysical renormalization scale[1] μ, (*cf.*, Fig. 1). Both these difficulties indicate that the existing NLO theory is missing important physics and is not adequate as it stands. A natural way to understand these deficiencies is that one expects sizable corrections to the traditional NLO calculations due to large logarithms associated with the new quark mass scale, such as $ln(s/m_Q^2)$ and $ln(p_T^2/m_Q^2)$. Pushing the calculation to one more order, formidable as it is, would not improve the situation since these large logarithms persist to every order of perturbation theory.

It is well-known from conventional parton theory that one class of large logarithms involving $ln(m_Q)$ (the so-called collinear singularity) can be resummed to all orders of perturbation theory in the form of parton distribution (PDF) and fragmentation functions. The same idea and technique can be applied to charm and bottom production,[2] thereby generalizing the conventional QCD parton theory to incorporate "heavy quarks." We will show that including these effects (which are neglected in the existing calculations) has a significant effect on the production cross section. The artificial dependence on the factorization scale μ is greatly reduced, and the theoretical cross-section is increased compared to the conventional NLO calculation. Both of these effects are needed to bring theory in agreement with experiment.

2 Flavor Excitation and Fragmentation Processes

The principle result of this paper is to include the leading-order flavor-excitation (LO-FE) graph (Fig. 2a) and the leading-order flavor-fragmentation (LO-FF) graph (Fig. 3a) in the traditional heavy quark calculation.

We begin with the production process of Fig. 2. The LO-FE contribution of Fig. 2a can not simply be added to the $\mathcal{O}(\alpha_s^3)$ calculation[1] as we would then be double counting. Specifically, LO-FE picks up the region of phase space where the initial heavy quark is parton-like (*i.e.*, collinear and on-shell), whereas the NLO-FE process (Fig. 2c) dominates for a virtual parton with high p_T. Therefore, we must subtract the region of phase space where these two contributions overlap; this is done with the subtraction, Fig. 2b.

Just above threshold, $\mu \gtrsim m_Q$, the heavy quark PDF turns on quickly due to the abundance of gluons. This unphysical increase is neatly compensated by the subtraction term which closely matches the LO-FE term for $\mu \gtrsim m_Q$. It is the difference between these curves that yields the physical contribution to the NLO-FC process that is not included in the traditional calculations.[1]

We now extract two important observations. *i)* The fact that the LO-FE and SUB-FE differ for relatively low values of μ/m_Q indicates that the heavy quark PDF contributions yield significant new information at relatively low scales. *ii)* This new contribution yields a result that *increases* with increasing μ scale; consequently, this will improve the μ-dependence of the full calculation, thus improving the predictive power of the theory. Note that this was not *a priori* guaranteed by the theory, but it is an important consequence.

For the final-state processes depicted in Fig. 3, the basic physics arguments are analogous to the production process (Fig. 2), however certain elements may be less familiar. Specifically, it is important to include the contribution arising from the fragmentation of a gluon (or other light partons) into a heavy quark,[3] *cf.*, Fig. 3a. Again, we need a subtraction term to eliminate the overlap with the NLO-FC diagram of Fig. 3c, and these contributions as a function of μ are shown in Fig. 3d. As in the production case, we find that the fragmentation term (with the overlap subtracted by Fig. 3b) yields a large physical contribution for relatively low μ scales, and the result increases with increasing μ scale leading to improved scale dependence.

We form the complete cross section in Fig. 3. For $\mu \leq m_Q$, the FE and FF contributions vanish, and the result reduces the traditional NLO calculation. As μ increases above m_Q, the extra contributions due to the FE and FF terms turn on, and this helps to compensate the decreasing μ-dependence of the FC terms, (driven primarily by $\alpha_S(\mu)$ and $g(x,\mu)$). Specifically, for $p_T = 20\,GeV$, including the FE and FF terms decreases the μ-variation by more than a

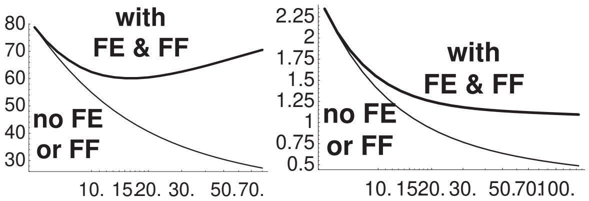

Figure 1: The differential cross section $d^2\sigma/dp_T^2/dy_1$ at $p_T = 20, 40\,GeV$ and $y_1 = 0$ in (pb/GeV^2) *vs.* μ. The lower curves (thin line) are the heavy quark production cross sections *ignoring* flavor-excitation (FE) and flavor-fragmentation (FF). The upper curves (thick line) are the heavy quark production cross sections *including* FE and FF. Clearly, FE and FF significantly increase the cross section and reduce the μ-scale dependence.

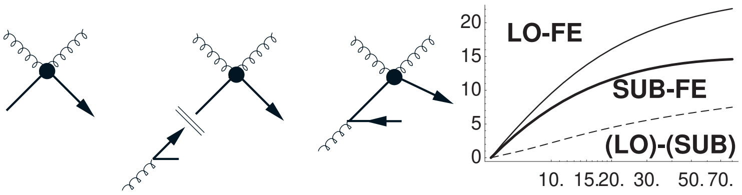

Figure 2: a) Generic leading-order diagram for flavor-excitation (LO-FE), $gQ \to gQ$. b) Subtraction diagram for flavor-excitation (SUB-FE), ${}^1f_{g\to Q} \otimes \sigma(gQ \to gQ)$. c) Next-to-leading-order diagram for flavor-creation (NLO-FC). [In general, we use the gluon lines to represent all light degrees of freedom (gluons and light quarks) where appropriate.] d) Contributions to the differential cross section $d^2\sigma/dp_T^2/dy_1$ (*cf.*, Fig. 1), for the LO-FE process, SUB-FE process, and the difference which is the physical contribution not previously included heavy quark calculations.

factor of 2 compared with the traditional calculation. Furthermore, if one were to make the common choice $\mu \sim p_T$, we see that the theoretical prediction is increased by more than 50%. This will improve agreement between the theoretical heavy quark predictions and the experimental values.

3 Conclusion

The traditional NLO calculations using only FC processes are deficient in three respects: *i)* they are not stable with respect to the unphysical scale μ; *ii)* they contain collinear divergences which should more properly be relegated to non-perturbative parton distribution functions and decay functions; *iii)* they lie well below the experimentally measured results.

All three problems can be resolved by resumming large logarithms via

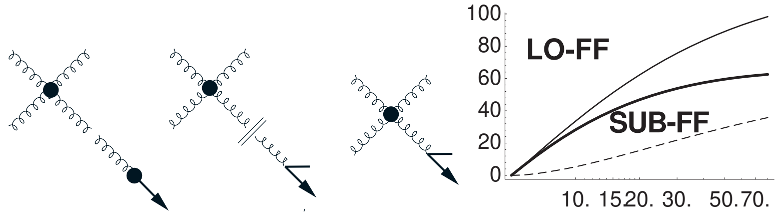

Figure 3: a) Generic leading-order diagram for flavor-fragmentation (LO-FF), $\sigma(gg \to gg) \otimes D_{g\to Q}$. b) Subtraction diagram for flavor-fragmentation (SUB-FF), $\sigma(gg \to gg) \otimes {}^1 d_{g\to Q}$. c) Next-to-leading-order diagram for flavor-creation (NLO-FC). d) Contributions to the differential cross section $d^2\sigma/dp_T^2/dy_1$ (*cf.*, Fig. 1), for the LO-FF process, SUB-FF process, and the difference which is the physical contribution not previously included heavy quark calculations.

the parton distribution and decay functions. The FE and FF contributions flatten the μ-scale dependence, eliminate the collinear divergences, and move the theoretical predictions toward the data. The final result includes all the features of the traditional NLO process (as it is reproduced in the limit $\mu \leq m_Q$), and extends region of validity for the heavy quark calculation. This is an essential step necessary to bring theory in agreement with experiment.[4]

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