Recent Progress in the Theory of Heavy Quark and Quarkonium Production in Hadronic Collisions

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Abstract

We review heavy quark and quarkonium production in high energy hadronic collisions. We discuss the status of the theoretical calculations and their uncertainties. We then compare the current theoretical results with the most recent measurements from the Tevatron Collider experiments.

Heavy quark production in high energy hadronic collisions constitutes a benchmark process for the study of perturbative QCD. The comparison of experimental data with the predictions of QCD provides a necessary check that the ingredients entering the evaluation of hadronic processes (partonic distribution functions and higher order corrections) are under control and can be used to evaluate the rates for more exotic phenomena or to extrapolate the calculations to even higher energies. Likewise, production of quarkonium states, in addition to provide another interesting framework for the study of the boundary between perturbative and non-perturbative QCD, is important in view of the possible use of exclusive charmonium decays of $b$ hadrons for the detection of CP violation phenomena.

In this presentation we review the current status of theoretical calculations, and discuss the implications of the most recent experimental measurements of $b$ quarks and charmonium states performed at the Tevatron $p\bar{p}$ Collider. For more complete reviews, including a discussion of heavy quark production at fixed target energies, see Refs. [1, 2].

1. Open Flavour Production: Theory Overview

To start with, we briefly report on the current status of the theoretical calculations. One has to distinguish between calculations performed at a complete but fixed order in perturbation theory (PT), and those performed resumming classes of potentially large logarithmic contributions which arise at any order in PT. The exact matrix elements squared for heavy quark production in hadronic collisions are fully known up to the $\mathcal{O}(\alpha_s^3)$, both for real and virtual processes. These matrix elements have been used to evaluate at NLO the total production cross section [3], single particle inclusive distributions [4] and two particle inclusive distributions (a.k.a. correlations) [5].

Three classes of large logarithms can appear in the perturbative expansion for heavy quark production:

1. $[\alpha_s \log(S/m_Q^2)]^n \sim [\alpha_s \log(1/x_B)]^n$ terms, where $S$ is the hadronic CM energy squared. These small $x$ effects are possibly relevant for the production of charm or bottom quarks at the current energies, while should have no effect on the determination of the top cross section, given the large $t$ mass. Several theoretical studies have been performed [6, 7], and the indications are that $b$ production cross...
sections should not increase by more than 30-50% at Tevatron energies due to these effects.

2. \[ \alpha_s \log(m_Q/p_{TQQ}) \] terms, where \( p_{TQQ} \) is the transverse momentum of the heavy quark pair. These contributions come from the multiple emission of initial state soft gluons, similarly to standard Drell Yan corrections. These corrections have been studied in detail in the case of top production, where the effect is potentially large due to the heavy top mass \( \tilde{m} \). They are not relevant for the redefinition of the total cross section of \( b \) quarks, but affect the kinematical distributions of pairs produced just above threshold \( \Delta \phi = \pi \), or in regions at the edge of phase space, such as \( \Delta \phi \).

3. \[ \alpha_s \log(p_T/m_Q) \] terms, where \( p_T \) is the transverse momentum of the heavy quark. These terms arise from multiple collinear gluons emitted by a heavy quark produced at large transverse momentum, or from almost collinear branching of gluons into heavy quark pairs. Again these corrections are not expected to affect the total production rates, but will contribute to the large \( p_T \) distributions of \( c \) and \( b \) quarks. No effect is expected for the top at current energies. These logarithms can be resummed using a fragmentation function formalism. A first step in this direction was taken by Cacciari and Greco \[ 4 \], who convoluted the NLO fragmentation functions for heavy quarks \[ 11 \] with the NLO parton level cross section for production of massless partons \[ 11 \]. A significant improvement in the stability w.r.t. scale changes has been observed for \( p_T > 50 \) GeV.

2. Single Inclusive Bottom Production

The status of \( b \) production at hadron colliders has been quite puzzling for some time. Data collected by UA1 \[ 12 \] at the CERN Collider (\( \sqrt{\mathcal{S}} = 630 \) GeV) were in good agreement with theoretical expectations based on the NLO QCD calculations \[ 1 \]. On the contrary, the first measurements performed at \( 1.8 \) TeV by the CDF \[ 13 \] experiment at the Fermilab Collider showed a significant discrepancy with the same calculation.

Owing to recent progress, the situation has considerably clarified. The latest results from the Fermilab 1.8 TeV \( pp \) Collider have been presented at this Conference by CDF \[ 14 \] and by the new experiment, D0 \[ 15 \]. The current situation is summarized in Figs. ?? and ??, showing a comparison of the theoretical expectations with the results from CDF and D0 for integrated \( p_T \) distributions of \( b \) quarks.

The theoretical curves require some explanation. First of all, they do not differ much from the original prediction \[ 4 \] using the DFLM structure functions. New structure function fits, including the first results from HERA, have recently become available. We use in our prediction one of these sets, namely MRSA \[ 16 \]. Since the values of \( x \) probed by \( b \) production at the Tevatron in the currently measured \( p_T \) range only cover the region \( x > 5 \times 10^{-3} \), we observe no significant change relative to the results obtained using older fits.

The second important point is the choice of a range for \( \Lambda_5 \). Deep inelastic scattering results tend to favor small values of \( \Lambda \). For example, the set MRSA uses \( \Lambda_5 = 151 \) MeV. On the other hand, LEP data favor a higher value: the central value of \( \Lambda_5 \) at LEP is around 300 MeV. This value is also supported by other lower-energy results, such as the \( \tau \) hadronic width (for a review of \( \Lambda_5 \) determinations, see the work by Catani \[ 17 \]). It is therefore sensible to use the range from 151 to 300 MeV for \( \Lambda_5 \).

The upper curves in Fig.?? and Fig.?? correspond to the PDF set MRSA \[ 16 \], \( \Lambda_5 = 300 \) MeV, \( m_b = 4.5 \) GeV and \( \mu_R = \mu_F = \sqrt{p_T^2 + m_b^2}/2 \). The lower curves correspond to \( \Lambda_5 = 151 \) MeV, \( m_b = 5 \) GeV and \( \mu_R = \mu_F = 2\sqrt{p_T^2 + m_b^2} \). In the absence of fits with \( \Lambda_5 \) frozen to the desired values we chose to simply change the value of \( \Lambda_5 \) in the partonic cross section. A discussion of this choice can be found in \[ 4 \].

Studies shown in Ref. ?? also indicate that pre-HERA and post-HERA PDF sets predict \( b \) cross sections which do not differ by more than 5% within a large range of \( p_T \). While such a stability is partly artificial, being related to the large overlap of correlated measurements entering the determination of the parton distribution fits, it however suggests that by now the uncertainty in the structure functions does not leave much room by itself for significant changes in the expected \( b \) cross section at Tevatron energies.

Coming back to the comparison of theory and data, from Fig.?? we see that the CDF data points are now consistent with the fixed-order theoretical prediction, although on the high side. The D0 points, instead, comfortably sit within the theoretical range.

In order to better compare data among themselves and with theory, we plot the ratio between data points and the upper theoretical prediction on a linear scale (Fig.??). From this figure we see that the UA1 and D0 data are well consistent with the upper theoretical curve, while CDF points are slightly above. Until the apparent difference between D0 and CDF will be understood, it is therefore appropriate to conclude that at present no significant discrepancy between theory and data or between data at different energies is being observed. Once the experimental statistics and systematics will be further reduced, it will be reasonable to assume that residual discrepancies of the same order as those currently observed may be explained in terms of small-\( x \) effects. Additional theoretical studies of these effects, such as a better understanding of the matching with the
fixed-order next-to-leading-order calculations, should therefore be pursued.

3. Charmonium Production

The \( J/\psi \) and \( \psi' \) states are of particular interest since they are produced in abundance and are relatively easy to detect at a collider such as the Tevatron. In earlier calculations of direct charmonium production at large transverse momentum (\( p_T \)) in \( pp \) collisions \[18\], it was assumed that the leading-order diagrams give the dominant contributions to the cross section. These calculations did not reproduce all aspects of the available data \[15\], suggesting that there are other important production mechanisms. It was pointed out by Braaten and Yuan \[20\] in 1993 that fragmentation processes, while formally of higher order in the strong coupling constant \( \alpha_s \), will dominate at sufficiently large \( p_T \). The relevant fragmentation functions for the production of the S-wave and P-wave states have all been calculated to leading order in \( \alpha_s \) \[20\]-\[26\]. Explicit calculations of the contribution to \( \psi \) production at the Tevatron from the fragmentation of gluons and charm quarks have recently been completed by several groups \[3, 27, 28\].

In Fig. ??, the sum of the fragmentation and of the leading-order contributions are compared with preliminary CDF data for prompt \( \psi \) production \[24, 14\]. \( \psi \)'s from \( \chi \) production and decay are included, both in the theory curves and in the data. The contribution to \( \psi \) production from \( b \)-hadron decays has instead been removed from the data via detection of the secondary vertex from which the \( \psi \)'s originate \[24, 14\]. While the shapes of the leading-order curve and the fragmentation curve are both consistent with the data over the range of \( p_T \) that is available, the normalization of the leading-order contribution is too small by more than an order of magnitude. The fragmentation contribution has the correct normalization to within a factor of 2 or 3, which can be easily accounted for by the uncertainties of such a LO calculation (for a discussion of these uncertainties, see \[2\]). We conclude that the fragmentation calculation is not inconsistent with the CDF data on prompt \( \psi \) production. A similar conclusion can be reached \[2\], after inclusion of the \( b \to \psi \) contributions, from a comparison with the D0 data \[13\].

We next consider the production of \( \psi' \), which should not receive any contributions from known higher charmonium states. The \( \psi' \) fragmentation contribution can be obtained from the \( g \to \psi, c \to \psi \), and \( \gamma \to \psi \) fragmentation contribution simply by multiplying by the ratio of the electronic widths of the \( \psi' \) and \( \psi \). The results are shown in Fig. ??, along with the preliminary CDF data \[24\]. Again the contribution from \( b \)-hadron decays has been subtracted using the secondary vertex information. In striking contrast to the case of \( \psi \) production, the normalization of the fragmentation contribution to \( \psi' \) production is too small by more than an order of magnitude. That there is such a large discrepancy between theory and experiment in the case of \( \psi' \), but not for \( \psi \), is extremely interesting. It suggests that there are other important mechanisms for production of S-wave states at large \( p_T \) beyond those that have presently been calculated. While such processes would certainly affect \( \psi \) production as well, their effect may not be as dramatic because of the large contribution from \( \chi_c \)-production in the case of the \( \psi \).

One possible such mechanism is the process \( gg \to \psi gg \), with a gluon exchanged in the \( t \)-channel, which we expect to be at least as large as the direct and fragmentation processes calculated so far in the relevant region of \( p_T \). However, this would not be enough to explain the factor of 3 or so observed discrepancy. A more likely possibility is that as yet undetected higher charmonium states, with significant BR’s into \( \psi' \), can be produced with large rates in \( pp \) collisions. At this meeting, an interesting possibility was raised by F. Close \[30\]: possible hybrid charmonium states (\( c\bar{c}g \) hadrons) are expected to have masses around 4.2 GeV, below the threshold for their only open charm decay to \( DD^{**} \). If such states existed, they would have large BR’s into \( \psi' \gamma \) or \( \psi' \eta \). Other suggestions have also been made, including the possibility of \( 2\gamma \) (\( \chi \)-like) states \[31, 32\]. Since the production rate for these states would be very big, even relatively small BR’s could easily accomodate the current puzzling rate \[32\]. Searches for resonances in such channels are therefore encouraged.

4. Conclusions

Significant progress has taken place in this field over the past few years, both in theory and experiments. The latest measurements at 1.8 TeV indicate an acceptable agreement between the data and NLO QCD predictions for the \( b \) inclusive \( p_T \) spectrum, and the presence now of two experiments will hopefully reduce experimental uncertainties. Previously detected discrepancies, observed in the inclusive \( \psi \) final states, are now attributed to large sources of \( \psi \) direct production. New theoretical work has explained the abundance of \( 1^3S \) production (mostly understood as coming from gluon fragmentation into \( \chi \) states), but cannot as yet account for the observed \( 2^3S \) rate. The possibility that new and possibly exotic charmonium states are being produced and observed at the highest energies available today opens perhaps new interesting frontiers for the already rich field of hadronic collider physics.
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