Fragmentation production of heavy quark states

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Abstract

It has recently been noticed that heavy quark (Q) and gluon (g) fragmentation to heavy quarkonium states (QQ) can be calculated in perturbative QCD. This technique allows for the inclusion of a subset of higher order corrections to quarkonium production which dominates at large transverse momentum. A comparison will be presented between the new calculation of quarkonium production to the existing data from the Tevatron. In addition some new results on predictions for double heavy quark baryons at various colliders will be presented.

Our understanding of the production and decays of quarkonium states is not perfect. It was supposed that J/ψ production would be dominated by two sources, the charmonium production model (CPM)[1] and B meson decay (BPM)[2]. The CDF collaboration measured the J/ψ production cross section using their 1988-89 data[3], and found rather poor agreement with the sum of the two dominant production mechanisms. They were able to fit the data to a sum of these two mechanisms if the normalizations were allowed to float. This allowed an extraction of the fraction of J/ψ mesons from B meson decay, and that, in turn, allowed for the inclusion of inclusive J/ψ in the measurement of the b-quark p_T distribution. The J/ψ data points were significantly higher than the theoretical predictions[4], though the UA1 collaboration found good agreement between theory and experiment, using similar techniques[5]. This lead to many investigations of the gluon distribution in the proton and the of b-quark production[6].

The questions about the source of the disagreement between theory and experiment were settled when the CDF detector was upgraded to include a silicon vertex detector (SVX). With the SVX, it was possible to separate the prompt J/ψ mesons (i.e., those originating at the production vertex) from those produced in B meson decay (i.e., those with a displaced vertex). Using their 1992-93 data, the CDF collaboration was able to state that there were far too many prompt J/ψ’s, and the number produced in B meson decay was in good agreement with theoretical predictions[7]. Thus the problem shifted from our understanding of the gluon distribution and b-quark production to that of J/ψ production.

Due to the relatively large mass of the c-quark, α_s is small and heavy quarkonium production and decays can be calculated using perturbative QCD (pQCD), and these calculations were, of course, performed. S-wave state production and decay (J/ψ, η_c, ...) are well behaved. However, a long-standing problem in quarkonium physics that of the hadronic decay (and similarly in the hadronic production) of P-wave states. It was noticed that the matrix element of P-wave quarkonium states to 3 gluons has a soft singularity (again, even though the S-wave production and 3 gluon decays are well behaved)[8]. Reasonable results are obtained if one uses the binding energy, confinement radius or the radius of the bound state to cut-off the divergences, but these are completely unjustified and non-rigorous procedures.
The latter problem was addressed in Ref. [9] (which was later expanded into a rigorous theory called Non-Relativistic QCD, or NRQCD[10]). A physical hadronic state is made up of a superposition of an infinite number of Fock states:

$$| M \rangle = \psi_{QQ} | Q\bar{Q} \rangle + \psi_{QQg} | Q\bar{Q}g \rangle + \cdots$$  \hspace{1cm} (1)

Generally, the states with one or more gluons don’t contribute significantly, as the radiation of gluons by heavy quarks $Q$ is suppressed by order $v^2$. However, in the case of $P$-wave decays, the angular momentum barrier suppresses the $P$-wave annihilation by order $v^2$, relative to the $S$-wave annihilation. As the $Q\bar{Q}$ in the $| Q\bar{Q}g \rangle$ state can be in the $S$-wave, both the $P$-wave color singlet annihilation and the $S$-wave color octet annihilation are the same order in NRQCD. Thus the decay of the $P$-wave physical states is given by:

$$\Gamma(n[^3P_J] \rightarrow \text{hadrons}) = H_1(n)\hat{\Gamma}_1(Q\bar{Q}[^3P_J] \rightarrow \text{partons}) + H_8(n)\hat{\Gamma}_8(Q\bar{Q}[^3S_1] \rightarrow \text{partons})$$  \hspace{1cm} (2)

where the subscripts 1 and 8 refer to the color singlet and octet, respectively. The $H_1$ and $H_8$ are non-perturbative parameters. The soft divergence found in earlier works was due to the missing $H_8$ parameter.

**Fig. 1.** Contributions of the various mechanisms to prompt $J/\psi$ production at the Tevatron. The $\chi_J$ contributions include the branching ratio for radiative decay to $J/\psi$.

**Fig. 2.** The total prompt $J/\psi$ production rate at the Tevatron. The direct (dotted), fragmentation (dashed) and total (solid) contributions are shown separately; also shown are the CDF preliminary data points.

The solution to the $J/\psi$ production at CDF problem is due to the existence of previously uncalculated fragmentation contributions. These contributions are higher order in $\alpha_s$, and so were thought to be negligible compared to the direct production mechanisms included in Ref. [1]. However, the direct production mechanisms required one to calculate $Q\bar{Q}$ production where the quark-anti-quark pair have both small relative momentum and the correct quantum numbers to form the relevant bound states. These restrictions modify the $p_T$ distributions of the produced states. For example, $g + g \rightarrow g + g$ falls off as $1/p_T^4$, while $g + g \rightarrow J/\psi + g$ falls off as $1/p_T^8$, at large $p_T$. The fragmentation of a gluon into a quarkonium state will not modify the $p_T$ distribution significantly. Including the proper factors of $\alpha_s$, the large $p_T$ limit of the fragmentation production of $J/\psi$ is of order $\alpha_s^5/p_T^4$, while direct production goes as $\alpha_s^3/p_T^8$; similarly, the large $p_T$ limit of $\chi_J$ (the $P$-wave, spin
1 states) production via fragmentation is of order \(\alpha_s^4/p_T^4\) while the direct production goes as \(\alpha_s^3/p_T^6\). At large enough \(p_T\), the slower fall-off with \(p_T\) of the fragmentation contributions can make up for the extra powers of \(\alpha_s\). The correct calculation of the fragmentation production of \(P\)-wave states requires the use of NRQCD, and the color octet contribution is important. Many fragmentation functions have involving heavy quark states have been calculated, and those used in for the following analyses are: gluon fragmentation to quarkonium states [11]; heavy quark fragmentation to quarkonium states [12]; photon fragmentation to \(J/\psi\) [13]; and heavy quark fragmentation to heavy quark-heavy quark diquarks [14].

Now the problem of \(J/\psi\) production at the Tevatron may be fully addressed. Three groups presented compatible results at very nearly the same time [15, 16, 17]. Results from Ref. [15] will be presented below. All 2 \(\rightarrow\) 2 subprocesses were included; MRSD0 [18] parton distribution functions were used, and \(\mu = p_T\) (of the fragmenting parton) for the fragmentation contributions and \(\mu = M_T\) (of the \(J/\psi\)) for the direct contributions unless otherwise noted (here \(\mu\) is the fragmentation, factorization and renormalization scale, all chosen to
be equal); $|\eta| < 0.6$ was used to simulate the detector acceptance. In Fig. 1, the various contributions to prompt $J/\psi$ production are shown. In Fig. 2, the total prompt $J/\psi$ production rate is shown; the scale $\mu$ is varied to show the theoretical uncertainties due to the scale choice. The direct contribution is taken from Ref. [19]. The theoretical results are compared to the CDF data [7]. In Fig. 3, the total $J/\psi$ rate is shown, including both prompt (direct and fragmentation) and $B$ decay mechanisms; theoretical results are compared to the CDF [7] and D0 [20] data. In Fig. 4, the results of $\psi'$ are shown, compared to the CDF [7] data. The total estimated theoretical error (including scale dependence, QCD and relativistic corrections) is of order a factor of 2. The $J/\psi$ production rate is now in good agreement with data; the $\psi'$ discrepancy will be discussed later.

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Fig. 7. $p_T$ distributions (at small rapidity) for the various contributions to double heavy quark baryon production at the Tevatron.

Fig. 8. $p_T$ distributions (at small rapidity) for the various contributions to double heavy quark baryon production at the LHC.

The next set of results to be presented are preliminary, and based upon work in progress. Using the fragmentation functions calculated by Falk and collaborators [14], the production rate for double heavy quark diquarks can be calculated: $c \rightarrow (cc); b \rightarrow (bb); c, b \rightarrow cb;$ and $c, b \rightarrow cb^*$. The notation is that $(QQ)$ is the spin 1 diquark made up of the same flavor quarks, $QQ'$ is the spin 0 diquark made up of different flavor quarks and $QQ'^*$ is the spin 1 diquark made up of different flavor quarks. It is assumed that the diquark always hadronizes into a double heavy quark baryon. The fragmentation probabilities for $c \rightarrow \Sigma_{cc}, \Sigma_{cc}^*$; $b \rightarrow \Lambda_{bc};$ and $b \rightarrow \Sigma_{bc}, \Sigma_{bc}^*$ are all of order $10^{-5}$, while the remaining probabilities are strongly suppressed by a factor of $(m_c/m_b)^3$. The production rates at the NLC (assumed to be a $60 fb^{-1}/yr, 500 GeV e^+e^-$ collider) are small, of order 30 events/year. A similar event rate was obtained at HERA. Event rates are substantial at both the Tevatron (of order 20k events/year) and the LHC ($10^7$ events/year). In Fig. 5, the pseudorapidity $\eta$ distributions at the Tevatron are shown for the various contributions. In Fig. 6, the momentum fraction distributions at the Tevatron are shown, demonstrating the strong peaking at large $z$ ($z$ is defined to be the ratio of the momentum of the double heavy quark hadron to that of the fragmenting heavy quark). Similar results on the $\eta$ and $z$ distributions are obtained for the LHC, with the primary difference being a smaller relative contribution of the process $c \rightarrow (cc)$ at the LHC. In Figs. 7 and 8, $d\sigma/dp_T/d\eta$ at $\eta = 0$ is shown at the Tevatron and the LHC, respectively. Reconstruction of these states will pose a challenge to the experimentalists. Work on this project is continuing, and final results will soon be ready.
The authors of Ref. [23] calculated the production of $B_c$ mesons in photon-photon collisions, using the Feynman diagrams shown in Fig. 9 (the set (I) can be subdivided into $(I_b)$ and $(I_c)$ depending on which flavor quark is connected to the photons). They find that the recombination diagrams (set (II)) contribute strongly, and that in this case, the heavy quark state production cannot be well described by a fragmentation process. Fig. 10 shows a comparison of the cross section for the full calculation, and for sets $(I_b)$ and $(I_c)$ separately, as a function of center of mass energy. Furthermore, the authors of Ref. [23] compare the results of set (I) to the relevant heavy quark fragmentation result; the $c$ fragmentation contribution does not agree well with set $(I_c)$ while the $b$ fragmentation contribution is in relatively good agreement with set $(I_b)$. The inclusion of the additional diagrams for the gluon-gluon fusion into $B_c$, as well as the convolution of the parton level subprocess with parton distributions may change the conclusions at a hadron collider. It should be noted that the conclusions of Ref. [23] apply to heavy quark fragmentation contributions only, and so may affect the production rate of double heavy quark baryons; the results on $J/\psi$ production via fragmentation are dominated by gluon fragmentation, and the argument of Ref. [23] do not apply. After this presentation, another paper discussing the production of $B_c$ mesons in hadron colliders appeared [24]. The parton level cross sections $(g+g \to B_c+X)$ are still found to be significantly different, depending on whether the full calculation or just the fragmentation approximation is used. After convoluting the parton level cross sections with the gluon distributions in the proton, the fragmentation approximation is found to be in good agreement with the full calculation for $p_t > 10$ GeV. It is thus likely that the results presented here on double heavy quark baryon production at the Tevatron and at the LHC will be in quite good agreement with a full (though much more complicated) calculation.

There remains a large discrepancy between the theoretical predictions for $\psi'$ production and the CDF experimental data (see Fig. 4). As can be seen from Fig. 1, $J/\psi$ production

Fig. 9. Different topologies of the lowest-order Feynman diagrams contributing to $\gamma\gamma \to B_c\bar{b}c$.

Fig. 10. Integrated cross sections for $\gamma\gamma \to B_c\bar{b}c$ versus the c.m. energy. The different calculations are explained in the text. The production mechanisms are as classified in Fig. 9.
is dominated by $\chi_J$ production followed by the radiative decay $\chi_J \rightarrow J/\psi + \gamma$. The $\psi'$ is more massive than the $\chi_J$ family, and it is expected that the radial excitation $\chi'_J$ family will be above open charm threshold. However, the fall-off of the observed $p_T$ distribution of $\psi'$ appears to be consistent with a fragmentation type production and completely inconsistent with a conventional, hard (i.e., direct) production mechanism. Several authors suggest a metastable $\chi'_J$, produced dominantly via gluon fragmentation and decaying with large branching ratio to $\psi'$ as a plausible solution to this problem\cite{25, 26, 27}. A search strategy for these $\chi'_J$ in $B$ meson decays at the CLEO II detector has been proposed\cite{28}. Similarly, conventional $c\bar{c}$ states above open charm threshold, but with quantum numbers forbidding the decay into $D\bar{D}$ have been proposed as a possible solution\cite{26}, as have hybrid $c\bar{c}g$ states\cite{26}. These states would also be produced dominantly via gluon fragmentation, and decay with large branching ratio to $\psi'$. Finally, it has been suggested that color octet $c\bar{c}$ can be produced via fragmentation, and these $c\bar{c}$ can evolve nonperturbatively to a $\psi'$ plus hadrons\cite{29}.

After this presentation, Ref. \cite{30} appeared. It generalizes the fragmentation mechanism and includes additional terms from the NRQCD expansion. Their results are in excellent agreement with data for $J/\psi$, $\psi'$ and the lowest three $\Upsilon$ states.

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