PERTURBATIVE QCD FRAGMENTATION FUNCTIONS AS A PHENOMENOLOGICAL MODEL FOR CHARM/BOTTOM FRAGMENTATION

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ABSTRACT

The perturbative QCD fragmentation functions can be applied phenomenologically as a model for charm and bottom quark fragmentation into heavy-light mesons. The predictions by this model on the observables $P_V$ and $\langle z \rangle$ for $D - D^*$ and $B - B^*$ systems are compared with experimental data.

The dominant production mechanism for mesons and baryons that contain a single heavy quark is the fragmentation of the heavy quark, in which light quark-antiquark pairs are created out of the vacuum by the color force of the heavy quark and then the heavy quark captures the light quarks to form mesons or baryons. However, in this process, the creation of light quark-antiquark pairs tells us that the nonperturbative effects are important and so the fragmentation function, which describes the process, cannot be calculated from the first principle or from perturbative QCD.

Recently, there are new developments in the fragmentation of heavy quarks into heavy-heavy-quark bound states. The fragmentation process involves the creation of heavy quark-antiquark pair, which implies that the natural scale of the process should be of order of the mass of the heavy quark created, and so the process should be calculable by perturbative QCD (PQCD). Fragmentation functions for $c \to (c\bar{c}), \ b \to (bb),$ and $\bar{b} \to (\bar{b}c)$ in different spin-orbital states have been calculated to leading order in $\alpha_s$ using PQCD. In addition to the application that these PQCD fragmentation functions can predict the production rates of heavy-heavy-quark bound states without model dependence, they can also be applied as a phenomenological model to describe the charm and bottom quark fragmentation into heavy-light mesons.

Here we quote the results:

$$D_{b \to B_c}(z; \mu_0) = N \frac{rz(1-z)^2}{(1-(1-r)z)^6} \left[6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2ight. $$
$$-2(1-r)(6 + 19r + 18r^2)z^3 + 3(1-r)^2(1-2r+2r^2)z^4\left.\right] \quad (1)$$

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for the $^{1}S_{0}$ state and
\[ D_{b \rightarrow B^{*}_{c}}(z, \mu_{0}) = 3N \frac{r z (1 - z)^2}{(1 - (1 - r) z)^6} \left[ 2 - 2(3 - 2r)z + 3(3 - 2r + 4r^2)z^2 
- 2(1 - r)(4 - r + 2r^2)z^3 + (1 - r)^2(3 - 2r + 2r^2)z^4 \right] \]

for the $^{3}S_{1}$ state, where $N = 2\alpha_s(2m_c)^2|R(0)|^2/(81\pi m_c^3)$ and $r = m_c/(m_b + m_c)$.

The fragmentation functions in Eqs. (1) and (2) can also be regarded as two-parameter functions with $N$ and $r$ as free parameters. $N$ governs the overall normalization and $r = m_{\text{light}}/m_{\text{meson}}$ is the mass ratio. We vary the parameter $r$ to study the behavior of these fragmentation functions in the limit $r = m_{\text{light}}/m_{\text{meson}} \rightarrow 0$. We expect that in this limit these fragmentation functions can describe, to certain extent, the fragmentation of the heavy quark into heavy-light mesons, e.g., $c \rightarrow D, D^*$ and $\bar{b} \rightarrow B, B^*$. Although in the fragmentation $c \rightarrow D, D^*$ and $\bar{b} \rightarrow B, B^*$ there are probably large nonperturbative and relativistic effects that we have not taken into account, the PQCD fragmentation functions with the free parameters $N$ and $r$ can at least provide some insights to these systems while precise nonperturbative fragmentation functions for charm and bottom are not available yet.

The ratio $P_{V}$ for the $D$ and $D^*$ system is defined as $P_{V} = \frac{P_{V}}{D + D^*}$, which is a measure of the relative population of $D^*$ in the production of $D$ and $D^*$ mesons. Since fragmentation is the dominant production mechanism, the production rates of $D$ and
$D^*$ can be replaced by the corresponding fragmentation probabilities as

$$P_V = \frac{P_{c \rightarrow D^*}}{P_{c \rightarrow D} + P_{c \rightarrow D^*}},$$

which is a function of $r$ only. The probabilities $P_{c \rightarrow D}$ and $P_{c \rightarrow D^*}$ are obtained by integrating $D_{c \rightarrow D}(z)$ and $D_{c \rightarrow D^*}(z)$ over $z$. The prediction by our fragmentation model is shown in Fig. 1(a). At $r = 0$, which is the heavy quark mass limit, the ratio $P_V = 0.75$ is exactly the value given by heavy quark spin symmetry. The average experimental value $P_V = 0.646 \pm 0.049$. For the charm system we choose $m_c = 1.5$ GeV and the light constituent quark mass $m_{u,d}$ inside the $D$ and $D^*$ mesons to be 0.3 GeV, therefore $r = 0.167$. The experimental data point ($r = 0.167, P_V = 0.646 \pm 0.049$) is plotted in Fig. 1(a). We found good agreement between the prediction of our fragmentation model and the data. Physically, $P_V < 0.75$ means that the production rate of $D^*$ is less than it should be as given by heavy quark spin symmetry. For the $B - B^*$ system, with the same value for $m_{u,d}$ and $m_b = 4.9$ GeV, we have $r = 0.058$. The value of $P_V$ at $r = 0.058$ is about 0.68, which is closer to the heavy-quark-symmetry prediction of 0.75 than the $D - D^*$ system.

The $\langle z \rangle$ is the average longitudinal momentum fraction that is transferred from the heavy quark to the meson. In terms of fragmentation functions, $\langle z \rangle^\mu$ at a scale $\mu$ for $c \rightarrow D^*$ fragmentation is given by

$$\langle z \rangle^\mu_{c \rightarrow D^*} = \frac{\int dz D_{c \rightarrow D^*}(z, \mu)}{\int dz D_{c \rightarrow D^*}(z, \mu)}. \quad (4)$$

The scaling behavior of $\langle z \rangle$ is given by $\langle z \rangle^\mu = \langle z \rangle^{\mu_0} [\alpha_s(\mu)/\alpha_s(\mu_0)]^{-2\gamma/b}$, where $\gamma = -4C_F/3, C_F = 4/3, b = (11N_c - 2n_f)/3, N_c = 3, n_f$ is the number of active flavors at the scale $\mu$, and $\langle z \rangle^{\mu_0}$ is the value determined at the initial scale $\mu_0$. Taking the inputs: $m_c = 1.5$ GeV, $m_{u,d} = 0.3$ GeV, and $\mu_0 = m_c + 2m_{u,d} = 2.1$ GeV, we have $r = 0.167, \langle z \rangle^{\mu_0}_{c \rightarrow D^*} = 0.77$, and $\langle z \rangle^{\mu=m/2}_{c \rightarrow D^*} = 0.50$. For $\bar{b} \rightarrow B^*$ fragmentation, we choose $m_b = 4.9$ GeV, $m_{u,d} = 0.3$ GeV, and $\mu_0 = m_b + 2m_{u,d} = 5.5$ GeV, we have $r = 0.058, \langle z \rangle^{\mu_0}_{\bar{b} \rightarrow B^*} = 0.87$, and $\langle z \rangle^{\mu=m/2}_{\bar{b} \rightarrow B^*} = 0.696$. The curves for $\langle z \rangle^\mu_{c \rightarrow D^*}$ and $\langle z \rangle^\mu_{\bar{b} \rightarrow B^*}$ versus $\mu$ are shown in Fig. 1(b).

Experimental data on $\langle z \rangle$ are available from the LEP detectors and from CLEO and ARGUS detectors. The LEP average $\langle x_E \rangle_{c \rightarrow D^*} = 0.504 \pm 0.0133$. For the bottom quark, only the inclusive hadron production has been measured and $\langle x_E \rangle_{\bar{b} \rightarrow H_b} = 0.694 \pm 0.0166$. The combined CLEO and ARGUS data is $\langle x_E \rangle_{c \rightarrow D^*} = 0.648 \pm 0.043$. The scale of the measurements is taken to be one half of the center-of-mass energy of the machines. These data are shown in Fig. 1(b). Excellent agreement is demonstrated.

Here, we have demonstrated the applications of the perturbative QCD fragmentation functions as a phenomenological model to describe the fragmentation of heavy quarks into heavy-light mesons and the agreement between the predictions by this model and the experimental data.

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