Heavy-quark recombination in $Z^0$ decay

Yu Jia

Department of Physics and Astronomy, Michigan State University
East Lansing, MI 48824

Abstract. We briefly review the recent advances of heavy-quark recombination mechanism. This mechanism predicts a class of power-suppressed 3-jet events in $Z^0$ decay, such as $b\bar{b}q$ and $b\bar{b}q$. Furthermore, heavy quark fragmentation function also receives a contribution from this mechanism. Some light can be shed on the scaling of the maximum of the fragmentation function for S-wave heavy hadrons. We finally comment on a new variant of this mechanism which has important impact on the precision electroweak physics.

Heavy flavor production serves as an excellent testing ground for perturbative QCD [1]. So far, the heavy quark cross sections in all different processes have been computed to at least the next-to-leading order. However, in order to compare with experimental data, a sound understanding of how a heavy quark turns into a heavy hadron is crucial. The standard strategy is to implement the heavy quark fragmentation as the sole hadronization mechanism.

Inspired by the Non-relativistic QCD factorization for the formation of heavy quarkonium [2], a new hadronization mechanism, dubbed heavy-quark recombination (HQR) was recently developed [3]. It was initially motivated as a “higher twist” mechanism, to supplement the usual fragmentation. The central picture of this mechanism is quite simple: after a hard scattering, a heavy quark may capture a nearby light parton which emerges from the hard scattering and happens to carry soft momentum in the heavy quark rest frame. Subsequently they can materialize into a heavy hadron, plus additional soft hadrons. A typical HQR process in hadron collision at $Q(\alpha_s^2)$ is $\bar{q}g \rightarrow B + \bar{b} + X$, where $\bar{B}$ is produced from the $b\bar{q}$ recombination. Similarly, $c\bar{q}$ recombination has later been introduced to account for $\Lambda_c$ production [4].

HQR is drastically distinct from the other “higher-twist” mechanisms – conventional recombination model [5], intrinsic charm model [6], and so on. In all these cases, the beam remnants participate in the dynamics of forming a heavy hadron. In contrast, the beam remnants play no role in HQR processes, which leads to great simplifications. In fact, HQR respects a simple factorization formula. Namely, inclusive production of heavy hadron in HQR can be expressed as a product of hard-scattering parton cross section, which is calculable in perturbative QCD, and a nonperturbative parameter (recombination factor), which characterizes the probability for the heavy quark and the light parton to evolve into a state containing the heavy hadron [3].

One important achievement of HQR is that it can explain the charm meson and baryon production asymmetries observed in a number of fixed-target experiments, in a simpler, more coherent and controlled fashion than those aforementioned models [7, 4]. The charm asymmetry is simply attributed to the asymmetry between the densities of light
Although this success constitutes a strong evidence for HQR, the complicated hadronic environment in fixed-target experiments prevents us from excluding other hadronization models. Most probably, the asymmetries arise from the interplay of several different mechanisms, one of which is HQR. A curious question thereby is, is there a cleaner playground where HQR can be unambiguously singled out?

The answer is yes, because the physical idea of HQR is quite general, so its applications are not only confined in the hadroproduction of heavy hadron. In fact, heavy flavor production in $e^+e^-$ annihilation is an ideal place to test HQR [8, 9]. In particular, we will be interested in $B$ production on the $Z^0$-pole, thanks to the huge statistics of $Z^0$ samples. Clearly, those “higher-twist” mechanisms which rely on the beam remnants in hadron collision, are simply absent here.

Let us consider $B$ production at $O(\alpha_s^2)$ through $Z^0 \rightarrow b\bar{b}q\bar{q}$. If each quark independently fragments, then it represents a regular 4-jet event. Nonetheless, in a small corner of phase space where $q$ is soft in the $b$ rest frame, they can form a composite $bq$ state with definite color and angular momentum. Subsequently this state hadronizes into a $B$ meson plus soft hadrons. We thereby end up with a jet containing $\bar{B}$ from the recombination, the recoiling $b$ jet and a light quark jet [8]. The corresponding Feynman diagrams are shown in Fig. 1. The inclusive $\bar{B}$ production rate from HQR can be written

$$\frac{d\Gamma[\bar{B}]}{dt} = \sum_n d\Gamma[Z^0 \rightarrow b\bar{q}(n) + \bar{b} + q] \rho[b\bar{q}(n) \rightarrow \bar{B}]$$

where $d\Gamma_n$ are the perturbatively calculable parton cross sections, and $\rho_n$ are the recombination factors, and $n$ denotes the color and angular momentum quantum numbers of $b\bar{q}$. These $\rho_n$ parameters have recently been defined in terms of nonperturbative QCD matrix elements [10]. An important property of these parameters is that they scale as $\Lambda_{QCD}/m_b$. While $\bar{B}$ can be produced in four different recombination channels, the color-singlet, spin-matching channel is expected to dominate. Adopting the fitted value of $\rho_1^b$ from Ref. [7, 4], and using its scaling property, we can obtain $\rho_1^b = 0.1$.

A striking signal of these novel 3-jets is that the third jet is initiated by a light quark, instead of by a gluon. However, distinguishing quark and gluon jets experimentally requires a large statistics. OPAL collaboration has selected 3,000 symmetric 3-jet events at the $Z$ resonance, in which the most energetic jet is tagged to contain $b$, and the angle between this $b$-jet and each of the two low energy jets is roughly 150° [11]. These samples were assumed to all be the $b\bar{b}g$ events. However now we know there must be a
small fraction of them are actually made of HQR 3-jets. Simple dimensional argument suggests these 3-jets are suppressed by a factor of $\alpha_s(M_Z)\Lambda_{QCD}^2 m_b/M_Z^2 \sim 10^{-5}$ relative to $b\bar{b}g$. However, a more quantitative study indicates that the ratio of the yield for HQR 3-jet events to that for the $bbg$ in such a topology is roughly 0.012. So there are about 36 new events out of 3,000 OPAL samples, seemingly not statistically important. We hope that prospective Giga-Z experiments with a much larger number of $Z^0$ samples will confirm the existences of these 3-jet events definitely. If true, it should be viewed as a decisive triumph of the HQR mechanism.

Though the HQR cross section is highly suppressed for 3-jet, its magnitude becomes much larger when $\bar{B}$ and $q$ lie in the fragmentation region, i.e., with a small invariant mass, because the virtuality of the internal gluon that splits into $q\bar{q}$ (see Fig. 1) becomes much smaller in this region. This motivates us to examine if this $b\bar{q}$ recombination process also contributes to the $b$ fragmentation function.

Fragmentation functions are nonperturbative objects and usually defy a tackle from perturbation theory. This is true for $q, g$ to fragment into $\pi, K$. However, the fact that $b$ is heavy ($m_b \gg \Lambda_{QCD}$) may allow us to proceed further. Armed with knowing how a heavy quark hadronizes in the recombination picture encoded in Eq. (1), we can readily derive the HQR contribution to $b$ fragmentation function by integrating the inclusive $\bar{B}$ differential cross sections over some appropriate kinematic variables. For example, the HQR contribution to $b$ fragmentation into $B^*$ turns out to be

$$D^{\text{HQR}}_{b \rightarrow B^*}(z) = \frac{32 \rho_b^b \alpha_s^2(m_b) z(2 - 2z + 3z^2)}{81 (1 - z)^2},$$

where $z$ is the energy fraction carried by $B^*$ relative to $b$. This HQR fragmentation function is not away from zero until $z$ becomes large, and finally diverges quadratically as $z \rightarrow 1$. This divergence is a symptom that perturbative calculation in the endpoint region becomes invalid. Yet, one can show that Eq. (2) is still valid as long as $1 - z \gg \Lambda_{QCD}$. The $z$ distribution in Eq. (2) is much harder than the widely-used Peterson fragmentation function [13]. This may suggest that $b$ hadronizing via picking up a $\bar{q}$ from vacuum is still non-negligible, even at relatively small $z$. However, some model-independent extraction of the nonperturbative part of $b$ fragmentation function shows also a harder spectrum than Peterson parameterization [12].

Insight may be gained if we assume that $z \sim 1 - \Lambda_{QCD}$ is where the peak of fragmentation function is located. While a perturbative QCD treatment from HQR is ceasing to work when close to the endpoint region, $D^{\text{HQR}}_{b \rightarrow B^*}(1 - \Lambda_{QCD}/m_b)$ may still betray the correct order of magnitude of the maximum of the “true” fragmentation function. If this is true, then the fragmentation function of $b$ to $B^{*-}$ is expected to peak around $z = 0.93$, with a height roughly $\frac{32}{27} \rho_b^b \alpha_s^2(m_b)(m_b/\Lambda_{QCD})^2 \approx 1.5$. If we approximate the “true” $B^{*-}$ fragmentation function by Peterson function $D(z; \varepsilon_b)$ with $\varepsilon_b = 0.006$, and take the fragmentation probability $f_{b \rightarrow B^{*-}} \approx 0.3$, the “true” peak is also around $z \approx 0.93$ with a height about 1.7, in good agreement with our naive estimate. Since $\rho_b^b \approx \Lambda_{QCD}/m_b$, we thereby propose the maxima of the fragmentation functions for S-wave heavy hadrons scale as $\alpha_s^2(m) m/\Lambda_{QCD}$. For charmed hadrons, this scaling law doesn’t hold so well, but still conveys the correct order of magnitude.
A comprehensive understanding of $Z^0$ decay to heavy flavor is important to precision electroweak physics [14]. If we were able to extract the finite power correction from the linearly divergent total HQR cross section, it would represent an $O(\alpha_s^2 \Lambda_{\overline{QCD}} m_b / M_Z^2) \sim 10^{-6}$ correction to the partial width of $Z^0$ to $b\bar{b}$. The $Z^0$ width has been measured to per mille accuracy, thus the contribution associated with Fig. 1 can be neglected.

However, there is a new HQR process, as depicted in Fig. 2, occurring at order $\alpha_s$ only, with a genuine “higher twist” contribution of order $\Lambda_{\overline{QCD}} / m_b$ [9]. To accomplish this, $bg$ recombination needs to be invoked. The net contribution of this new mechanism to the partial width of $Z^0$ to $b\bar{b}$ turns out to be $\Delta \Gamma[b\bar{b}] = 32 \pi \alpha_s (M_Z) \xi^b_3 / 9 \Gamma_0[b\bar{b}]$, where $\xi^b_3$ is an unknown color-triplet recombination factor. Both $\xi^b_3$ and $\xi^c_3$ may be fitted from the global electroweak analysis, and consequently the Standard Model predictions of various electroweak observables will be updated.

All the three HQR mechanisms, $b\bar{q}$, $bq$ and $bg$ recombination have now been fulfilled.

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