Strange–Beauty Meson Production by Fragmentation in Proton–Antiproton Collisions

Robert J. Oakes
Department of Physics and Astronomy, Northwestern University
Evanston, IL 60208, U.S.A.
e-mail: oakes@fnalv.fnal.gov

ABSTRACT

The cross sections for the production of $B_s$ and $B_s^*$ mesons through the fragmentation process in $\bar{p}p$ collisions were calculated. The input parameters were determined from the measured $B_s$ and $B_s^*$ production rates in $e^+e^-$ annihilation. The transverse momentum distributions $d\sigma/dp_T$ are given for $\sqrt{s} = 1.8$ TeV, the Fermilab Tevatron energy.

At LEP the DELPHI Collaboration has measured the probability for a $\bar{b}$ antiquark to hadronize into a weakly decaying strange B meson. Assuming the hadronization is dominated by the fragmentation of the heavy $\bar{b}$ antiquark, we determined the fragmentation functions $D_{\bar{b}\to B_s}(z, \mu)$ and $D_{\bar{b}\to B_s^*}(z, \mu)$ from the measured total probability for a $\bar{b}$ antiquark to hadronize into the lowest strange-beauty states $B_s(^1S_0)$ and $B_s^*(^3S_1)$. Here $z$ is the fraction of the $\bar{b}$ antiquark momentum carried by the $B_s$ or $B_s^*$ at the scale $\mu$. The momentum distributions of the $B_s$ and $B_s^*$ mesons produced in $e^+e^-$ annihilation at the energy of the $Z$ mass were then predicted.

We then extended our calculations to the production of the $B_s$ and $B_s^*$ states in $p\bar{p}$ annihilation at the Tevatron using the fragmentation functions previously determined.

In the parton model the cross section for the production by fragmentation of strange B mesons in proton-antiproton annihilation involves three main factors: the structure functions of the initial partons in the proton and antiproton, the subprocess in which the initial partons produce a particular parton in the final state, and the fragmentation of this final parton into the strange B meson. The transverse momentum distribution of the $B_s$ meson is then of the form

$$\frac{d\sigma}{dp_T} = \sum_{i,j,k} \int dx_i dx_j dz f_{i/p}(x_i)f_{j/\bar{p}}(x_j)\frac{d\hat{\sigma}}{d\hat{p_T}} \left(i(x_i)j(x_j) \to k\left(\frac{p_T}{z}\right)X, \mu\right) D_{k\to B_s}(z; \mu).$$

(1)

*Talk presented at the International Conference on Frontiers of Physics: Looking to the 21st Century, Shantou, P.R. China, 5-9 August 1995.
Here $f_{i/p}(x_i)$ and $f_{j/ar{p}}(x_j)$ are the structure functions of the initial partons $i$ and $j$ carrying fractions of the total momenta $x_i$ and $x_j$ in the proton and antiproton, respectively. The production of parton $k$ with momentum $p_T/z$ is described by the hard subprocess cross section $\hat{\sigma}$ at the scale $\mu$. And $D_{k\to B_s}(z;\mu)$ is the fragmentation function for the parton $k$ to yield the meson $B_s$ with momentum fraction $z$ at the scale $\mu$. The factorization scale $\mu$ is of the order of the transverse momentum of the fragmenting parton. The soft physics is contained in the structure functions, while the parton subprocess is a hard process and can be reliably calculated in perturbation theory. We have also treated the fragmentation of $\bar{b}$ into $B_s$ as if it was also a hard process and perturbation theory was applicable even though the $s$ quark is not very heavy. The main dependence on the $s$ quark mass is in the normalization of the fragmentation functions, which was empirically determined.

Clearly, there is a formula very similar to Eq. (1) for the production of the $B_s^*$, which we do not write explicitly. Because the radiative decay $B_s^* \to B_s + \gamma$ is so fast and the $B_s^*/B_s$ mass difference is so small, the transverse momentum of $B_s^*$ is hardly affected in the decay $B_s^* \to B_s + \gamma$, and thus contributes to the inclusive production of the $B_s$. We will, therefore, present each individually in the figures showing $d\sigma/dp_T$ and $\sigma(p_T > p_T^{\text{min}})$ and also include their sum in a table, for convenience.

In the fragmentation process $k \to B_s$ we have included gluons as well as $\bar{b}$ antiquarks. Although the direct $g \to B_s$ fragmentation process does not occur until order $\alpha_s^3$ there is a significant contribution coming from the evolution of the $\bar{b}$ antiquark fragmentation functions from the heavy quark mass to the collider energy scale $Q$, which is of order $\alpha_s^3 \log(Q/m_b)$ due to the splitting $g \to \bar{b}$. This has been shown to be significant for the production of $B_c$ mesons and it was also included.

For the parton distribution functions we used the most recent CTEQ version 3 in which we chose the leading-order fit, since our calculation is also a leading-order one. For the subprocesses we used the tree-level cross sections, to be consistent, since the parton fragmentation functions were calculated only to leading order. For the production of $\bar{b}$ antiquarks we included the processes $gg \to \bar{b}b$, $g\bar{b} \to gb$, and $qq \to \bar{b}b$, while for the production of gluons $g$ we included the processes $gg \to gg$, $gg(q) \to gg(q)$, and $gq \to gg$, where $q$ denotes any of the quarks, $u, d, s, c, b$.

For the running strong coupling constant $\alpha_s$ we used the simple one-loop result evolved from its value at $\mu = m_Z$:

$$\alpha_s(\mu) = \frac{\alpha_s(m_Z)}{1 + \frac{33-2n_f}{6\pi} \alpha_s(m_Z) \log \left( \frac{\mu}{m_Z} \right)} \quad (2)$$

Here $n_f$ is the number of active flavors at the scale $\mu$ and we chose $\alpha_s(m_Z) = 0.117$.

The scale $\mu$ superficially appears to have been invented only to separate the production of $B_s$ mesons into structure functions, subprocess cross sections, and fragmentation functions. In principle, this is so and the production is independent of the choice of $\mu$. But in practice, the results do depend on $\mu$, since only if all the factors are calculated to all orders in $\alpha_s$ will the dependence on $\mu$ cancel. However, for example, the fragmentation functions were calculated only to leading order and, consequently, the results will depend on $\mu$. We investigated the sensitivity of the results to the choice
of $\mu$ by varying $\mu$ from $\mu_R/2$ to $2\mu_R$, where $\mu_R = \sqrt{p_T^2(\text{parton}) + m_b^2}$ is our central choice of the scale $\mu$.

To obtain the fragmentation functions at the scale $\mu$ we numerically integrated the Altarelli-Parisi evolution equations, from the scale $\mu_0$, which is of the order of the $b$-quark mass. As boundary conditions in these calculations we used the fragmentation functions $D_{b \to B_s}(z, \mu_0)$ and $D_{b \to B_s^*}(z, \mu_0)$ at the scale $\mu_0$ calculated using perturbative QCD. The induced gluon fragmentation functions $D_{g \to B_s, B_s^*}(z, \mu)$ are of order $\alpha_s^3 \log(\mu/m_b)$ and become important at large values of the scale $\mu$ relative to the $\bar{b}$ antiquark fragmentation functions $D_{\bar{b} \to B_s, B_s^*}(z, \mu)$, which are of order $\alpha_s^2(\mu)$. The boundary conditions for the gluon fragmentation functions are $D_{g \to B_s}(z, \mu) = D_{g \to B_s^*}(z, \mu) = 0$ for $\mu \leq 2(m_b + m_s)$, the threshold for producing $B_s$ or $B_s^*$ mesons from a gluon.

We chose the $b$ quark mass to be $m_b = 5$ GeV and the strange-quark mass parameter $m_s$ was determined using the same initial fragmentation functions from the experimental value of the probability $f_s^w$ for a $\bar{b}$ antiquark to fragment into weakly decaying strange-beauty mesons:

$$f_s^w = \int_0^1 dz \left[ D_{\bar{b} \to B_s}(z, \mu_0) + D_{\bar{b} \to B_s^*}(z, \mu_0) \right].$$  \hspace{1cm} (3)

Since the total probability for the $\bar{b}$ antiquark to fragment into a $B$ meson is independent of scale, the initial scale $\mu_0$ in Eq. (3), which is of the order of the $b$-quark mass, was chosen to be $\mu_0 = m_b + 2m_s$. Then using the measured value $f_s^w = 0.19 \pm 0.06 \pm 0.08$ and $\alpha_s(m_Z) = 0.11$, we then obtain $m_s = 298 + 47 - 23$ MeV.

The evolution equations were numerically integrated and the fragmentation functions at the scale $\mu_R = \sqrt{p_T^2(\text{parton}) + m_b^2}$ were combined with the structure functions and parton cross sections for the subprocesses to obtain the cross section, Eq. (4). In Fig. 1 we show the cross section $d\sigma/dp_T$ for both $B_s$ and $B_s^*$ mesons produced in $p\bar{p}$ collisions at the Tevatron energy $\sqrt{s} = 1.8$ TeV. We assumed a cut-off on the transverse momentum of $p_T > 5$ GeV/c and considered only the rapidity range $|y| < 1$. To investigate the sensitivity of these results to the scale $\mu$ we have also included the results for $\mu = 2\mu_R$ and $\mu = \mu_R/2$. When the scale $\mu$ is less than $\mu_0 = m_b + 2m_s$, which only happens for the case of $\mu = \mu_R/2$, we chose the larger of ($\mu, \mu_0$). From Fig. 1 it is clear that the choice of scale $\mu$ is not critical for the transverse momentum distribution; in fact, the variation over the range $\mu_R/2 < \mu < 2\mu_R$ is comparable to the current discrepancies between the measured and calculated $b$ production cross sections. As one might expect, the $(3S_1)$ $B_s^*$ cross section is larger than the $(1S_0)$ $B_s$ cross section at all $p_T$, however, their ratio is not precisely the naive prediction 3 : 1, but is about 20% smaller.

In Fig. 2 we show the total cross section for the production of $B_s$ and $B_s^*$ mesons with transverse momentum above a minimum value $p_T^{\text{min}}$. As in Fig. 1 only the range $p_T > 5$ GeV and $|y| < 1$ was considered. The sensitivity to the scale $\mu$ was investigated, as before, by considering $\mu = \mu_R/2$ and $\mu = 2\mu_R$, and the choice of this scale is clearly not critical. Figure 2 provides useful estimates of the production rates of $B_s$ and $B_s^*$ mesons at the Tevatron due to the fragmentation process.
Fig. 1. The transverse momentum distributions of $B_s$ and $B_s^*$ mesons for $p_T > 5$ GeV, $|y| < 1$, and $\mu = \mu_R/2, \mu_R$, and $2\mu_R$ at $\sqrt{s} = 1.8$ TeV.

For convenience, we have also summarized these cross section estimates, including the sum $\sigma(B_s) + \sigma(B_s^*)$, in Table 1.

Table 1. Total $B_s$ and $B_s^*$ cross sections in nb versus $p_T^{\text{min}}$ for $p_T > 5$ GeV and $|y| < 1$ at $\sqrt{s} = 1.8$ TeV. Variation with the scale $\mu$ are shown.

| $p_T^{\text{min}}$ | $\sigma(B_s)$ | $\sigma(B_s^*)$ | $\sigma(B_s) + \sigma(B_s^*)$ |
|-------------------|----------------|----------------|----------------------------|
| $\mu_R/2$        | $\mu_R$        | $2\mu_R$      | $\mu_R$        | $2\mu_R$      | $\mu_R$        | $2\mu_R$      |
| 5                 | 300            | 470            | 650            | 700            | 1100           | 1500           |
| 10                | 45             | 62             | 65             | 110            | 145            | 150            |
| 15                | 14             | 16             | 14             | 32             | 37             | 33             |
| 20                | 5.2            | 5.1            | 4.4            | 12             | 12             | 10             |

The production rates and transverse momentum distributions for $B_s$ and $B_s^*$ meson production in $p\bar{p}$ collisions presented here assume that fragmentation is the dominant process and, therefore, are probably underestimates. At large enough transverse momentum the fragmentation process should dominate, as it falls off more slowly, even though it is only a part of the full order $\alpha_s^4$ contribution. A comparative study of the relative importance of the various contributions in the full order $\alpha_s^4$ calculation is now being carried out, which will clarify the range of validity of the fragmentation approximation. And the comparison with forthcoming data from the Fermilab Tevatron will be very instructive.
Fig. 2. The $B_s$ and $B_s^*$ total cross sections for $p_T > p_T^\text{min}$ with $p_T > 5 \text{ GeV}$, $|y| < 1$, and
$$\mu = \mu_R/2, \mu_R, \text{ and } 2\mu_R$$
at $\sqrt{s} = 1.8 \text{ TeV}$.

These calculations were carried out in collaboration with Kingman Cheung and are reported in greater
detailed in references [2] and [3]. This work was supported
by the U.S. Department of Energy, Division of High Energy Physics, under Grant
DE-FG02-91-ER40684 and DE-FG03-93ER40757.

References

1. P. Abrau et al. (DELPHI Collaboration), Z. Phys C61, 407 (1994).
2. K. Cheung and R.J. Oakes, Phys. Lett. B337, 181 (1994).
3. K. Cheung and R.J. Oakes, Phys. Rev. D, to appear.
4. K. Cheung, Phys. Rev. Lett. 71, 3413,(1993); K. Cheung and T.C. Yuan, Phys. Lett. B325, 481 (1994); K. Cheung and T.C. Yuan, preprint CPP-94-37 (Feb 1995),
hep-ph/9502250.
5. H.L. Lai et al. (CTEQ Collaboration), Phys. Rev. D51, 4763 (1995).
6. Particle Data Group, Phys. Rev. D45, 51 (1992).
7. G. Altarelli and G. Parisi, Nucl. Phys. B126, 298 (1977).
8. E. Braaten, K. Cheung, and T. C. Yuan, Phys. Rev. D48, R5049 (1993).
9. Y.-Q. Chen and R. J. Oakes, NUHEP-TH-95-15.