Eur. Phys. J. C 13, 647–650 (2000)
Digital Object Identifier (DOI) 10.1007/s100520000267

THE EUROPEAN
PHYSICAL JOURNAL C

Asymmetries in heavy meson production from light quark fragmentation

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Received: 5 August 1999 / Published online: 17 March 2000 – © Springer-Verlag 2000

Abstract. We discuss the possibility of the asymmetry in D^-/D^+ production from π^- beams, being a direct consequence of the properties of the light quark fragmentation function into heavy mesons. The main features of the asymmetry, as a function of x_F, are easily described. An integrated sum rule for the D^-, D^+ multiplicity difference is presented. Predictions for the asymmetry in B meson production are given.

In the framework of perturbative QCD it is not easy to explain the observed asymmetry in the production of leading and non-leading charmed mesons in fixed target experiments with π^- beams [1]. In fact, in the $x_\mathrm{F} \geq 0$ region, an excess of $D^-(d\bar{c})$ over $D^+(\bar{d}c)$ is observed; the asymmetry, defined as

$$A(x_\mathrm{F}) \equiv \frac{N^-(x_\mathrm{F}) - N^+(x_\mathrm{F})}{N^-(x_\mathrm{F}) + N^+(x_\mathrm{F})}, \tag{1}$$

is increasing with x_F. This effect does not show an appreciable dependence on p_T.

In QCD, charmed quarks are generated by parton antiparton fusion and in this process the c quarks are produced with relatively small rapidities so that their fragmentation or coalescence probability is not likely to reproduce the observed asymmetry [2]. Some models, containing a recombination mechanism [3–6], fast c quark strings [7] and intrinsic charm [8,9] can be adjusted to reproduce the data.

In the present paper we argue that the asymmetry may be essentially due to the so far neglected $d \to D^-(d\bar{c})$ fragmentation which, for large x_F, gives the required D^- dominance.

Experimentally, not much is known about the production of D (or B) mesons from light quarks. In e^+e^- annihilation, most of the heavy mesons come from heavy quarks. Detection of a heavy meson in one hemisphere, with the **absence** of a heavy meson in the opposite hemisphere, would be an indication of fragmentation from the light quark. Note that, from a perturbative QCD point of view, this production can be seen as gluon splitting [10].

Theoretically, and taking as an example D^- meson production, if one looks at e^+e^- at the $Q = 2m_D$ threshold there are two possibilities: production from a d quark and production from a $\bar{c}$ antiquark (Fig. 1). At the m_D threshold the two fragmentation functions,

$$D_{D^-/d}(z, m_D) \quad \text{and} \quad D_{D^-/\bar{c}}(z, m_D), \tag{2}$$

are of the form [11,12]

$$D_{D^-/d}(z, m_D) \sim \delta(1-z), \tag{3}$$
$$D_{D^-/\bar{c}}(z, m_D) \sim \delta(1-z), \tag{4}$$

with $z = 2P \cdot Q/Q^2$, P and Q being the four-momenta of the D meson and the virtual photon, respectively. The normalizations in (3) and (4) are naturally different; a larger factor is expected in the $\bar{c}$ antiquark fragmentation. But in both cases the D^- meson takes all the energy available: $z = 1$. At the same threshold energy m_D the unfavored fragmentation functions $D_{D^-/c}(z, m_D)$ and $D_{D^-/\bar{d}}(z, m_D)$ are, for $z > 0$, identically zero. In our approach, it is this difference in the favored and unfavored fragmentation functions that is in the origin of the asymmetry.

By making use of threshold energy fragmentation functions and applying QCD non-singlet evolution and (possible) spin and resonance effects [12], one arrives, at $Q > 2m_D$, at the fragmentation functions

$$D_{D^-/d}(z, Q) - D_{D^-/\bar{d}}(z, Q) \tag{5}$$

and

$$D_{D^-/\bar{c}}(z, Q) - D_{D^-/c}(z, Q). \tag{6}$$

The key idea is that these two non-singlet fragmentation functions, as QCD is flavor independent, remain similar in shape. The functions (5) and (6) are peaked at an intermediate value of z [12], and can be represented, for instance, by Peterson's parameterization [13]. The main result is that the $d \to D^-$ fragmentation will produce,

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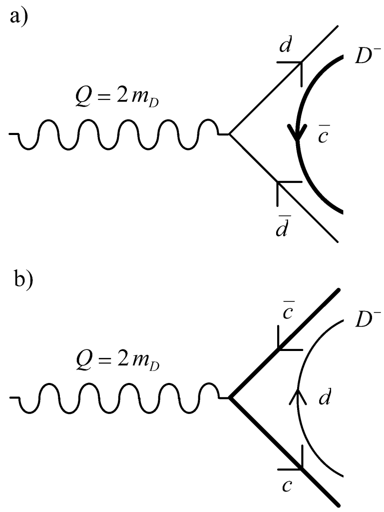

Fig. 1a,b. The fragmentation functions, **a** $d \to D^-$ and, **b** $\bar{c} \to D^-$ at the $Q = m_D$ threshold. The two functions have the same shape in z, even after a QCD evolution

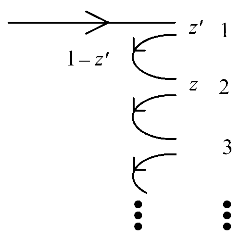

Fig. 2. Model to generate fragmentation functions with ordered mesons, rank 1, 2, 3, etc. See (8) and (9)

like $\bar{c} \to D^-$ fragmentation, fast mesons. Note that a similar behavior is also observed in $u \to K^+$ and $\bar{s} \to K^+$ fragmentation functions [14]. Very recently, these effects were observed in high energy e^+e^- processes [15].

One should notice that in (5), because of charge conjugation, we have the difference between leading and non-leading D mesons, with π^- beams, as it appears in the numerator of the asymmetry (1):

$$D_{D^-/d}(z, Q) - D_{D^+/d}(z, Q). \quad (7)$$

At large x_{F} the D mesons must come from a fast quark and $x_{\mathrm{F}} \simeq z$. This means that, at least for large x_{F}, (7) must behave similarly to the Peterson's formula. Within large errors, this is consistent with the data, as we shall see later.

In order to construct the full fragmentation functions, as the perturbative QCD is not simple and is too ambiguous, concerning final states, we shall make use of an old non-perturbative model of Krzywicki and Peterson [16], further developed in [17]. The mesons in the quark fragmentation are generated via an integral equation and are produced ordered in rapidity (see Fig. 2), such that meson 1 is, on the average, faster than meson 2, etc. If $D_1(z)$ is the fragmentation function for the first rank meson, $D_2(z)$ the fragmentation function for the second rank meson, etc., we have [16]

$$D_2(z) = \int_0^{1-z} D_1(z') D_1\left(\frac{z}{1-z'}\right) \frac{\mathrm{d}z'}{1-z'}, \quad (8)$$

and, in general,

$$D_k(z) = \int_0^{1-z} D_1(z') D_{k-1}\left(\frac{z}{1-z'}\right) \frac{\mathrm{d}z'}{1-z'}. \quad (9)$$

The functions $D_k(z)$ are normalized to 1. The full fragmentation function is

$$D(z) = \sum_k D_k(z). \quad (10)$$

As only the leading meson can be of rank 1, the function $D_1(z)$ is nothing but the difference between the leading and non-leading fragmentation functions (see (7)).

Note that it is implicit in (8) and (9) that the mechanism of producing rank 1, rank 2, etc., mesons is always the same. In terms of perturbative QCD such a mechanism could perhaps be identified with $c\bar{c}$ production by gluon splitting.

It is easily seen that in the limit $z \to 1$ from (8) and (9) we obtain

$$D_2(z) \underset{z\to 1}{\sim} D_1(0) D_1(z)(1-z), \quad (11)$$

and

$$D_k(z) \underset{z\to 1}{\sim} D_1(0)^{k-1} D_1(z)(1-z)^{k-1}. \quad (12)$$

In this limit, keeping only the most important terms, D_1 and D_2, and identifying $z \simeq x_{\mathrm{F}}$ we obtain for the asymmetry (1)

$$\begin{aligned} A(x_{\mathrm{F}})_{x_{\mathrm{F}}\to 1} &= \frac{D_1(x_{\mathrm{F}}) + D_2(x_{\mathrm{F}}) - D_2(x_{\mathrm{F}})}{D_1(x_{\mathrm{F}}) + D_2(x_{\mathrm{F}}) + D_2(x_{\mathrm{F}})} \\ &\simeq 1 - 2D_1(0)(1 - x_{\mathrm{F}}). \end{aligned} \quad (13)$$

Two remarks can be made regarding (13). The first one is that the asymmetry increases and approaches 1 as $x_{\mathrm{F}} \to 1$. The second one is that the approach of the $x_{\mathrm{F}} \to 1$ limit is controlled by the behavior of $D_1(z)$ at $z \to 0$. In order to see the importance of this point let us assume that in the $z \simeq 0$ region the function D_1 behaves as

$$D_1(z) \underset{z\to 0}{\to} z^{\alpha}, \quad (14)$$

with $\alpha > -1$. The function $D_2(z)$, in the $z \to 1$ limit, will behave as

$$D_2(z) \underset{z\to 1}{\to} D_1(z)(1-z)^{\alpha+1}, \quad (15)$$

and the asymmetry

$$A(x_{\mathrm{F}}) \underset{x_{\mathrm{F}}\to 1}{\simeq} 1 - c(1 - x_{\mathrm{F}})^{\alpha+1}, \quad (16)$$

c being some normalization constant. By computing the second derivative $\mathrm{d}^2 A/\mathrm{d}x_{\mathrm{F}}^2$ one immediately sees that the $x_{\mathrm{F}} \to 1$ limit is approached with negative curvature if $\alpha > 0$, with positive curvature if $-1 < \alpha < 0$, and in a straight line manner if $\alpha = 0$. As we shall see later,

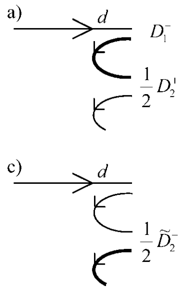

Fig. 3a–d. Fast, rank 1 and rank 2 contributions to the $D^{\mp}$ fragmentation functions. Only diagram **a** contributes to the asymmetry

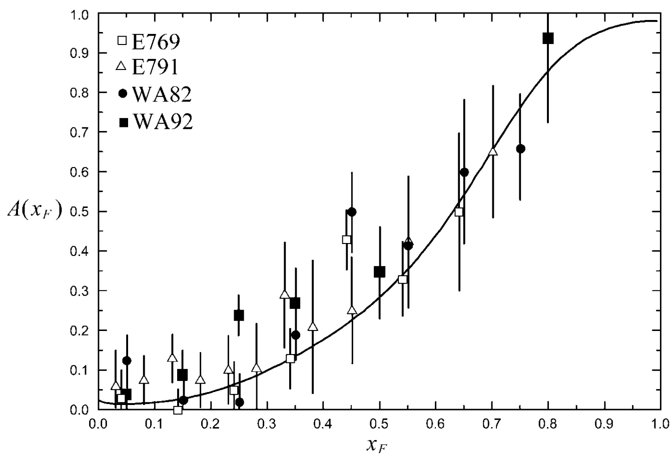

Fig. 4. Comparison of (20) for the asymmetry $A(x_{\mathrm{F}})$ with experimental data [17–21]

the data favor a behavior of $D_1(z)$ in the $z \to 0$ limit with $\alpha \gtrsim 0$, as expected from the QCD non-singlet evolution [12] and from Peterson's formula [13].

In order to be somewhat more precise we shall look more carefully to D^- and D^+ production from the π^- beam, keeping the relevant functions, in the $x_{\mathrm{F}} \to 1$ limit, D_1 and D_2. We have the contributions of Fig. 3. While contributions (a) and (b) involve the function D_1 with a charm quark, the contributions (c) and (d) involve the function $\tilde{D}_1$ without charm quark ($d \to d\bar{u}$ or $\bar{u} \to \bar{u}d$). The signals $-$ and $+$ indicate D^- and D^+ meson production, respectively, but $D_1^+ = D_1^-$, etc. The factors 1/2 account for isospin (strange quarks are neglected in comparison with the u and d quarks). The function $\tilde{D}_2$ is written (see Fig. 3)

$$\tilde{D}_2(z) = \int_0^{1-z} \tilde{D}_1(z') D_1\left(\frac{z}{1-z'}\right)\frac{\mathrm{d}z'}{1-z'}. \tag{17}$$

We can finally write the fragmentation functions $D^-(z)$ and $D^+(z)$, keeping only the D_1, D_2 and $\tilde{D}_2$ contributions, and identifying again $x_{\mathrm{F}} \simeq z$, as

$$D^-(x_{\mathrm{F}}) = D_1(x_{\mathrm{F}}) + \frac{1}{2}D_2(x_{\mathrm{F}}) + \frac{1}{2}\tilde{D}_2(x_{\mathrm{F}}) + \ldots \tag{18}$$

$$D^+(x_{\mathrm{F}}) = \frac{1}{2}D_2(x_{\mathrm{F}}) + \frac{1}{2}\tilde{D}_2(x_{\mathrm{F}}) + \ldots \tag{19}$$

and, for the asymmetry,

$$A(x_{\mathrm{F}}) \underset{x_{\mathrm{F}}\to 1}{\simeq} \frac{D_1(x_{\mathrm{F}})}{D_1(x_{\mathrm{F}}) + D_2(x_{\mathrm{F}} + \tilde{D}_2(x_{\mathrm{F}}) + \ldots} \tag{20}$$

In an attempt to compare (20) with experiment we have used for $D_1(z)$ and $\tilde{D}_1(z)$ Peterson's parameterization, with $\varepsilon = 0.06$ ($\langle z\rangle_{d\bar{c}} \simeq 0.8$) for D_1 and $\varepsilon \simeq 3.3$ ($\langle z\rangle_{\bar{u}d} \simeq 0.35$) for $\tilde{D}_1$, and (8) and (17) to compute D_2 and $\tilde{D}_2$. Note that the use of Peterson's formula is theoretically not justified for $d \to d\bar{u}$ or $\bar{u} \to \bar{u}d$ fragmentation; the reason why we used it is that it reasonably fits the data and the parameterizations of $\tilde{D}_1 \equiv 2(D_{\pi^+/u} - D_{\pi^-/u})$ [14, 12, 16].

In Fig. 4 we directly compare our formula (20) with the data on the $\pi^- \to D^{\pm}$ asymmetry. The agreement is reasonable, better than it should. The limit $A = 1$ is approached with negative curvature due to the fact that D_1 and $\tilde{D}_1$, experimentally and in agreement with Peterson's formula, smoothly vanish as $z \to 0$ (see (14)). Including higher rank D meson production, i.e., the $D_3, \tilde{D}_3, D_4, \tilde{D}_4$, etc., fragmentation functions, (20) goes to zero faster than in the figure, as x_{F} moves to zero.

It is clear that the comparison of (20) with the data in Fig. 4, except in the $x_{\mathrm{F}} \to 1$ region, is far from being justified. In general, one requires the convolution of parton structure functions $f(x)$ with the fragmentation functions $D(z)$, with $x_{\mathrm{F}} = zx$, at least for the valence $\bar{u}$ and d quarks. In doing so, one realizes that leading particles, D^-, can be produced even at small x_{F} (from small x quarks) and, in a pure fragmentation approach as considered here, the asymmetry is *not* expected to approach zero as $x_{\mathrm{F}} \to 0$.

We believe that in our comparison with the data in Fig. 4 we are making two, somehow compensating, mistakes. Inclusion of the $D_3, \tilde{D}_3, D_4, \tilde{D}_4$, etc. contributions would have decreased the asymmetry for small x_{F}. Inclusion of simultaneous fragmentation of $\bar{u}$ and d would have increased the asymmetry for small x_{F}. As we mentioned above our results are better than they should have been, but we think that we understand why that is so.

An essential point in our approach that can easily be tested, is that the difference $N^-(x_{\mathrm{F}}) - N^+(x_{\mathrm{F}})$, appropriately normalized should be similar to the Peterson's curve for c quark fragmentation function.

There is a general result, from our approach, which is independent of the convolution calculations involving structure functions. If one selects the sample of events where D^- and/or D^+ are produced, and does not consider the possibility of simultaneous $D^{\pm}$ production from the $\bar{u}$ and d quarks, then

$$\langle N^-\rangle - \langle N^+\rangle = 1/2, \tag{21}$$

where $\langle N^{\mp}\rangle$ is the $D^{\mp}$ average multiplicity, with $x_{\mathrm{F}} > 0$, in the D^-, D^+ sample. In principle, it is not difficult to test (21) experimentally. This equation can only be understood in a fragmentation model like ours, where the diagrams in Fig. 3, and higher rank ones, all have the same weight. Models that mix different $D^{\pm}$ production mechanisms cannot obtain (21).

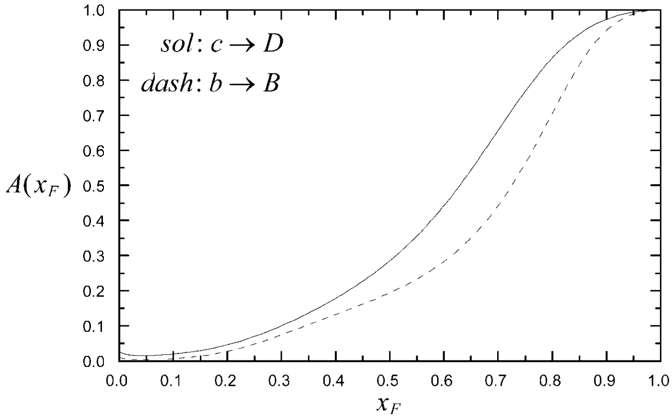

Fig. 5. $D^{\mp}$ and $B^{\mp}$ asymmetry as a function of x_{F}

In Fig. 5 we show our prediction for the B^-, B^+ asymmetry. As the b quark fragmentation D_1 is, in this case, closer to a δ function ($\varepsilon = 0.018, \langle z\rangle_{u\bar{b}} \simeq 0.87$, in Peterson's formula) the asymmetry becomes important closer to $x_{\mathrm{F}} \to 1$.

Concerning $D^0, \bar{D}^0$ production from π^- beams, an asymmetry essentially identical to the D^-, D^+ asymmetry is expected. In the case of D_s^-, D_s^+ production, naturally no asymmetry is expected [17].

Acknowledgements. J.D.D. thanks the hospitality at the Instituto de Física, Universidade de S. Paulo, and useful discussions with Fernando Navarra. F.D. thanks the hospitality at the Departamento de Física and CENTRA, Instituto Superior Técnico, where most of this work was done, and the help from everybody there. F.D. acknowledges grant from CAPES and FAPESP (98/2249-4 and 98/08768-6), Brasil. This work was supported by the contract PRAXIS/PCEX/P/FIS/124/96.

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