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Heavy Quark Weak Decays and Multiparticle Production in $e^+ e^-$ Annihilations

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Abstract:

The role of heavy quark weak decays in e^+e^- annihilations multiparticle production is discussed. The spectator diagram mechanism is used to estimate the excess multiplicity in heavy quark induced production processes: $\nu_b \lesssim 4$, $\nu_c \lesssim 2$.

Recent multiparticle production data in processes initiated by heavy quarks ($Q = c, b$), have shown that, in comparison with light quark processes ($q = u, d, s$), very clear differences exist. The study of the reactions $e^+e^- \to \gamma^*$ (or Z°) $\Rightarrow (q\bar{q})$ or $(Q\bar{Q})$ has lead to the following conclusions [1-4]:

i) The average charge multiplicity is higher in heavy quark induced processes,

$$\bar{n}_{Q\bar{Q}} = \bar{n}_{q\bar{q}} + \nu_Q \ ; \tag{1}$$

ii) The charged particle multiplicity distribution is similar but displaced in the multiplicity n,

$$P_{Q\bar{Q}}(n) = P_{q\bar{q}}(n - \nu_Q) \ , \tag{2}$$

with, in (1) and (2),

$$\nu_Q \simeq const > 0 \ , \tag{3}$$

being independent of energy. Of course, ii) implies i).

As most of the particles are produced strongly and the theory, QCD, is in colour space, a natural explanation for the observed differences is in terms of flavour kinematics, due to the fact that the masses of the quarks are different: $m_Q \gg m_q$. If one excludes weak decays of heavy mesons, independentely of the degree of sophistication of the theoretical treatment [5,6], one expects

$$\bar{n}_{Q\bar{Q}} < \bar{n}_{q\bar{q}} \qquad , \qquad \bar{n}_{Q\bar{Q}} - \bar{n}_{q\bar{q}} \simeq const. \ . \tag{4}$$

Even at high energies, $\sqrt{s} = m_{Z^\circ} \simeq 90$ GeV, the production of particles from weak decays of heavy quarks is about 50% of the total charged multiplicity [3]. It is then not at all clear, starting from inequality (4), how one recovers the simple laws (1) and (2) with (3), i.e., $\bar{n}_{Q\bar{Q}} > \bar{n}_{q\bar{q}}$. We would like to point out that with pure QCD like arguments one cannot go beyond (4), i.e., $\bar{n}_{Q\bar{Q}} < \bar{n}_{q\bar{q}}$.

It is our purpose here to justify (1) and (2) with (3), and to estimate the values of ν_Q by adding to the QCD hadronic cascade the effects resulting from the weak decays of heavy quarks.

The dominant diagram in the weak decay of heavy quark mesons is the one corresponding to the so scalled *spectator mechanism* [7,8,9] (see Fig.1 for the decay of B meson). The heavy quark decays as a free particle into lighter quarks and leptons by emitting a virtual charged vector boson (W^-). The Z° emission, corresponding to a flavour changing neutral current, is supressed. The decay may be semi-leptonic, with some probability α, or non leptonic, with probability $1 - \alpha$.

The kinematics for the reactions

$$b \to c(d\bar{u}) \quad \text{or} \quad b \to c(\ell^-\bar{\nu}) \ ,$$

assuming the masses of light quarks and leptons to be zero, is such that the c quark tends to take an energy close to the maximum possible energy, $x = E/E_M \simeq 1$, $E_M \simeq \left(m_b^2 + m_c^2\right) / \left(2m_b\right)$, with the $(d\bar{u})$ or $(\ell^-\bar{\nu})$ pair recoiling with a small effective mass $\left[\left(m_b^2 + m_c^2\right)(1-x)\right]^{1/2}$. The fast quark c will interact strongly with the light antiquark $\bar{q}$ producing particles. The pair $(d\bar{u})$ will also interact strongly, but as the effective mass of the pair is close to zero it will produce essentially one charged particle (π^-), the probability of emitting three or more charged particles being smaller. In the semi-leptonic case, one charged lepton (ℓ^-) is always produced.

If the $(b\bar{q})$ initial state is not a low lying B meson but a highly excited state, this state will degrade its mass with particle production by QCD radiation until the B meson formation and subsequent decay, the c quark continuing the radiation cascade (see Fig.2).

Our main hypothesis here is that the QCD cascade, at a given energy, is the same independentely of the starting quark-antiquark pair. The difference in the charged particle multiplicity distribution arises exclusively at the $W\ell\nu$ or $Wq\bar{q}$ vertex: always one extra charged particle is produced.

For the e^+e^- situation, where the cascades start with a $q\bar{q}$ or a $Q\bar{Q}$ pair, we have for the n charged particle distribution the relations

$$P_{b\bar{b}}(n) = P_{c\bar{c}}(n-2) \ , \tag{5}$$

$$P_{c\bar{c}}(n) = P_{s\bar{s}}(n-2) \equiv P_{q\bar{q}}(n-2) \ , \tag{6}$$

and

$$P_{b\bar{b}}(n) = P_{q\bar{q}}(n-4) \ . \tag{7}$$

We then obtain,

$$\bar{n}_{b\bar{b}} = \bar{n}_{q\bar{q}} + 4 \quad \text{and} \quad \bar{n}_{c\bar{c}} = \bar{n}_{q\bar{q}} + 2 \ . \tag{8}$$

It is clear that we have arrived at (1) and (2) with

$$\nu_b = 4 \quad \text{and} \quad \nu_c = 2 \tag{9}$$

Note that our ν_Q are the δ_{Qq} parameters of [3]. Experimentally, the averaged values of ν_b and ν_c, in the $\sqrt{s} = 29 - 90$ GeV region [3], are

$$\nu_b = 4.3 \pm 0.9 \quad \text{and} \quad \nu_c = 2.3 \pm 1.0 \ , \tag{10}$$

respectively, to be compared with (9). Very recently, the Delphi collaboration at LEP [2] has obtained $\nu_b = 3.12 \pm 0.09 \pm 0.6$ and $\nu_c = 1.64 \pm .32 \pm \sigma_{syst.}$.

Within the same approximation, if we want to study the production of charged hadrons we have, for the average multiplicity,

$$\bar{n}^h_{b\bar{b}} = \alpha_b \; \bar{n}^h_{c\bar{c}} + (1-\alpha_b) \; (\bar{n}^h_{c\bar{c}} + 2) \tag{11}$$

and

$$\bar{n}^h_{c\bar{c}} = \alpha_c \; \bar{n}^h_{q\bar{q}} + (1-\alpha_c) \; (\bar{n}^h_{q\bar{q}} + 2) \tag{12}$$

where $\alpha_b(\alpha_c)$ is the fraction of semileptonic decays.

Specifying now the produced hadrons, we obtain the relations:

$$\bar{n}^K_{b\bar{b}} \simeq \bar{n}^K_{c\bar{c}} \; , \tag{13}$$

$$\bar{n}^\pi_{b\bar{b}} \simeq \bar{n}^\pi_{c\bar{c}} + 2 \; (1-\alpha_b) \; , \tag{14}$$

and

$$\bar{n}^\pi_{c\bar{c}} \simeq \bar{n}^\pi_{q\bar{q}} + 2 \; (1-\alpha_c) \; , \tag{15}$$

Experimentally [1],

$$\bar{n}^K_{b\bar{b}} = 1.7 \pm 0.6 \; , \; \bar{n}^K_{c\bar{c}} = 2.0 \pm 0.5 \; , \tag{16}$$

$$\bar{n}^\pi_{b\bar{b}} = 13.8 \pm 1.0 \; , \; \bar{n}^\pi_{c\bar{c}} = 10.8 \pm 0.9 \; , \; \bar{n}^\pi_{q\bar{q}} = 10.1 \pm 0.9 \; . \tag{17}$$

Eqs. (16) are consistent with (13). With $\alpha_b \simeq \alpha_c \simeq 0.25$, as observed in B and D decays [8,9], Eqs. (17) are consistent with (14) and (15).

For the charged lepton (ℓ) production we obtain

$$\bar{n}^\ell_{b\bar{b}} = 2\,(\alpha_b + \alpha_c) \tag{18}$$

and

$$\bar{n}^\ell_{c\bar{c}} = 2\alpha_c \tag{19}$$

Experimentally [1],

$$\bar{n}^\ell_{b\bar{b}} = 0.8 \; , \; \bar{n}^\ell_{c\bar{c}} = 0.3 \; , \tag{20}$$

with large errors. Eqs. (20), with $\alpha_b \simeq \alpha_c \simeq 0.25$, are in rough agreement with (18) and (19).

Note that we can apply our relations (5-9) at the $B\bar{B}$ and $D\bar{D}$ thresholds in e^+e^- annihilations, to obtain

$$\bar{n}_{B\bar{B}} = 4 + \bar{n}_{q\bar{q}}(\sqrt{s} = 2m_B) \; , \tag{21}$$

$$\bar{n}_{D\bar{D}} = 2 + \bar{n}_{q\bar{q}}(\sqrt{s} = 2m_D) \; . \tag{22}$$

From experiment [1],

$$\bar{n}_{B\bar{B}} = 11.0 \pm 0.2 \ , \ \bar{n}_{D\bar{D}} = 5.2 \pm 0.3 \tag{23}$$

$$\bar{n}_{q\bar{q}}(2m_B) = 6 \pm 0.5 \ , \ \bar{n}_{q\bar{q}}(2m_D) = 3.5 \pm 0.5 \ . \tag{24}$$

With the values of (23) and (24), Eqs. (21) and (22) are roughly satisfied.

Note that in a simplified QCD calculation [3], there is a result, used to experimentally determine ν_c and ν_b, that is similar to (21) and (22) but with $\bar{n}_{q\bar{q}}$ computed at $\sqrt{e}\ m_D$ and $\sqrt{e}\ m_B$ instead of $2m_D$ and $2m_B$, respectively. Eqs. (21) and (22) seem to agree better with data.

We know that our model is oversimplified. For instance, the decay $b \to c(\bar{c}s)$, which has a theoretical branching ratio roughly 30% of the branching ratio of $b \to c(\bar{u}d)$, is also present and the kinematics is not the kinematics of $b \to c(\bar{u}d)$.

On the other hand, in the spectator model, not just the *external* diagrams of Fig.2 should be considered. The non leptonic decay *internal* diagrams of Fig.3 may also contribute. They are supressed by a colour factor of 1/3 but give a well known contribution in the case of $b \to c(\bar{c}s)$.

In a crude way, if β is the weight of the external spectator diagram – before we had assumed $\beta = 1$ –, neglect interference contributions and assume that the W participates like a gluon in the QCD cascade, we obtain for the charge particle distribution in *one hemisphere* of e^+e^- annihilation:

$$P_Q(n) = \alpha_Q P_q\ (n-1) + (1-\alpha_Q)\left[\beta_Q P_q(n-1) + (1-\beta_Q)P_q(n)\right] \tag{25}$$

Following, [4], we can, from (4) and (5), approximately write,

$$P_c(n) \simeq P_q(n - (\alpha_c + (1-\alpha_c)\beta_c)) \tag{26}$$

and

$$\begin{aligned} P_b(n) &\simeq P_c(n - (\alpha_b + (1-\alpha_b)\beta_b)) \\ &\simeq P_q(n - (\alpha_c + (1-\alpha_c)\beta_c) - (\alpha_b + (1-\alpha_b)\beta_b)) \end{aligned} \tag{27}$$

The expressions for ν_c and ν_b are:

$$\nu_c = 2(\alpha_c + (1-\alpha_c)\beta_c) \tag{28}$$

and

$$\nu_b = 2(\alpha_c + (1-\alpha_c)\beta_c) + 2(\alpha_b + (1-\alpha_b)\beta_b) \ . \tag{29}$$

In the limit of complete absence of the interior spectator diagrams, $\beta_c = \beta_b = 1, \nu_c = 2$ and $\nu_b = 4$, as seen before. Experimentally, the the contribution from spectator interior

diagrams is small but not negligeable, $\beta_c \lesssim 1$, $\beta_b \lesssim 1$, and its effect is to reduce ν_c and ν_b:

$$\nu_c \lesssim 2 \quad \text{and} \quad \nu_b \lesssim 4 \ , \tag{30}$$

in agreement with [2]. Taking $\alpha_b \simeq \alpha_c \simeq 0.25$ and $\beta_c \simeq \beta_b \simeq 0.95$ [8,9] we obtain, from (28) and (29):

$$\nu_c \simeq 1.9 \quad \text{and} \quad \nu_b \simeq 3.8 \tag{31}$$

The model presented here is naturally very crude, but it is not necessarly wrong. As far as we known it is the only model that goes beyond QCD calculations, gives estimates for the values of ν_Q (or δ_{Qq}) and is critically dependent on the structure of the heavy quark weak decay diagrams.

Acknowledgement:

I would like to thank Luís Lavoura for discussions and advice on the kinematics of heavy quark weak decays.

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Figure Captions:

Fig.1 - Spectator Diagram in the semi-leptonic or non leptonic decay of heavy meson B.

Fig.2 - Cascading of excited $(b\bar{q})$ state with formation of B meson, followed by weak decay and radiation of excited $(c\bar{q})$ state with formation of D meson.

Fig.3 - Internal Spectator Diagram in non leptonic weak decay.

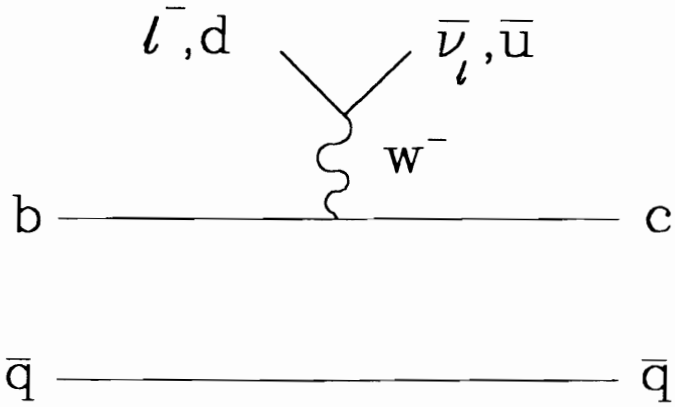

Fig. 1

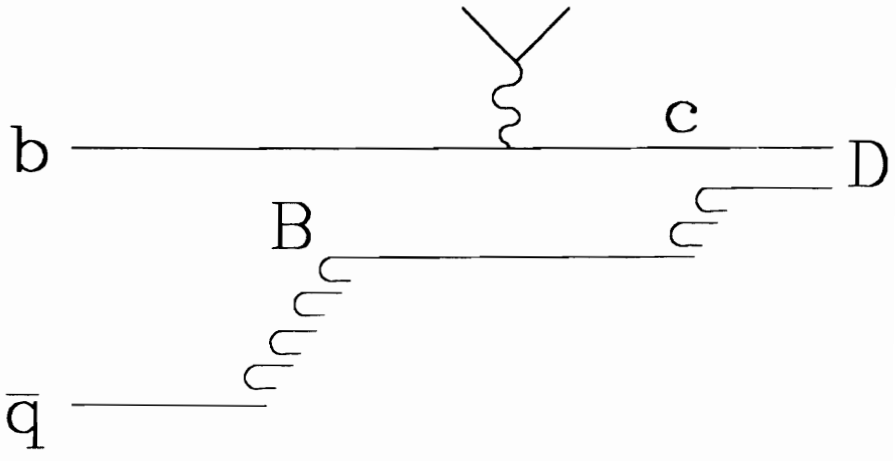

Fig. 2

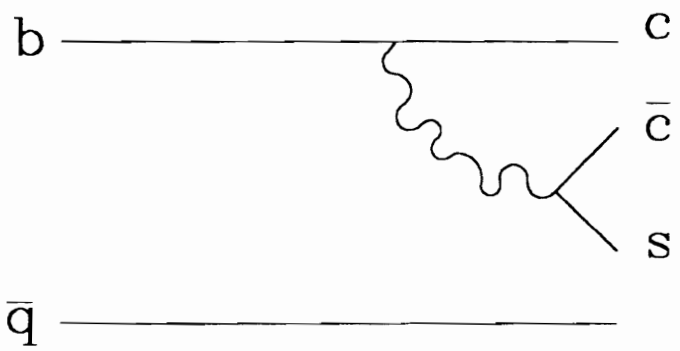

Fig. 3