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A.V. Kisselev, V.A. Petrov

**Charged Hadron Multiplicity in e^+e^-
from Massive Quarks**

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Abstract

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The difference in the energy dependence of hadron multiplicities in e^+e^- events induced by heavy and light quarks in the framework of two approaches (the Naïve Model and the QCD-based Model) is discussed. Results of both approaches for the case of b -quarks are compared with data from LEP and SLC. Predictions are presented for e^+e^- – events induced by charm quarks.

Аннотация

Киселев А.В., Петров В.А. Множественность заряженных адронов из массивных кварков в e^+e^- : Препринт ИФВЭ 94-83. – Протвино, 1994. – 7 с., 4 рис., библиогр.: 9.

Обсуждается разность в энергетической зависимости множественности адронов в e^+e^- -событиях, индуцированных тяжелыми и легкими кварками, в рамках двух подходов (наивная модель и модель, основанная на КХД). Результаты обоих подходов для случая b -кварка сравниваются с данными LEP и SLC. Сделаны предсказания для e^+e^- -событий, порожденных c -кварками.

Introduction

Inclusive spectra of hadrons produced in e^+e^- annihilation and containing primary heavy quarks have a characteristic, strongly peaked at high momenta shape. For instance, hadrons stemming from the b -quark carry away nearly 70 per cent of the total energy. It would be natural to expect that the multiplicity of hadrons accompanying the decay products of heavy (b, c) quarks is significantly lower than that related to light (u, d, s) quarks. The matter is to estimate this effect quantitatively.

1. The Naïve Model (NM)

The NM is based on the assumption that the multiplicity of hadrons in e^+e^- induced by the quark q , N_q , is of the form

$$N_q(W) = 2n_q + \int dx dy \frac{1}{\sigma_q} \frac{d\sigma_q}{dx dy} n_0(M),$$

where n_q is the multiplicity of decay products of the primary quark, $\frac{1}{\sigma_q} \frac{d\sigma_q}{dx dy}$ is the inclusive joint density of primary hadrons with energies $xW/2$ and $yW/2$ and normalized to 1. The function $n_0(M)$ describes the multiplicity of hadrons associated with primary hadrons, which depends on the invariant mass $M = W\sqrt{(1-x)(1-y)}$ and is assumed to be a flavour independent universal function.

This is a mathematical statement that there exists at least one number $\bar{x}_q \in [0, 1]$ such that (assuming primary hadrons to be weakly correlated)

$$N_q(W) = 2n_q + n_0(W(1 - \bar{x}_q)).$$

The main assumption of the NM is the identification of this number (having no direct physical meaning) with the energy fraction carried away by the primary hadron

$$\bar{x}_q = \langle x_q \rangle,$$

whereof one has [1], [2]

$$N_q(W) = 2n_q + n_0(W(1 - \langle x_q \rangle)). \quad (1)$$

Making use of the universality of n_0 one can obtain the following relation between multiplicities induced by quarks Q and q [3]

$$N_Q(W) = 2(n_Q - n_q) + N_q \left(W \frac{1 - \langle x_Q \rangle}{1 - \langle x_q \rangle} \right).$$

So, if one knows experimental values for $\langle x_Q \rangle$, $\langle x_q \rangle$ and N_q , it is possible to predict $N_Q(W)$. Note that this does not demand knowledge of the functional form of n_0 . For $Q = b$, $q = u, d, s$ we are able to compare prediction for the difference $\delta_{bq} = N_b - N_q$ with experimental data [4], [5] (Fig.1). The agreement is quite good, except LEP/SLC energy.

Fig. 1. Modified NM in comparison with the data on δ_{bq} .

2. QCD

At present perturbative QCD fails to give predictions for hadron multiplicities as this is related to still unsolved confinement problem. Nonetheless, some

predictions are possible with the help of additional hypotheses ("preconfinement" [6]). The multiplicity is obtained from the BS equation for inclusive spectrum of hadrons displayed in Fig.2, where rectangular boxes represent two-gluon irreducible parts. Integration in hadron momenta gives the following equation for the hadron multiplicity

$$N_q(W) = 2n_q + C_F \int \frac{dk^2}{k^2} \frac{\alpha_s(k^2)}{\pi} n_q(k^2) E_q(W^2, k^2), \quad (2)$$

where $n_g(k^2)$ is the hadron multiplicity in a gluon jet with invariant masses up to k , while $E_q(W^2, k^2)$ represents the lower box in Fig.2.

Fig. 2. BS equation for the inclusive spectrum of hadrons.

It was argued in [7], that in the framework of the so called MLLA LPHD approximation to QCD the following asymptotic behaviour holds

$$\delta_{Qq}(W) = N_Q(W) - N_q(W) \rightarrow 2n_Q - N_q(\sqrt{em}), \quad W \rightarrow \infty, \quad (3)$$

where $\ln e = 1$, m is the mass of the quark Q , while quark q is assumed to be massless.

Fig.3 presents this limiting value (for $Q = b$) as compared with the experiment (with account of indeterminacies of N_q which are omitted in Fig.1). It is hardly possible to insist on a good agreement with the data. Reasons for disagreement may be various. For instance, one could check the accuracy of eq.(3) containing quite suspect effective energy $\sqrt{em}$.

Fig. 3. "MLLA LPHD" prediction for δ_{bq} versus the data.

3. Why $e^{1/2}$?

It is instructive to clarify the appearance of this mysterious factor $\sqrt{e}$. In the lowest order in $\alpha_s(k^2)$ (see more detailed discussion in [3]) one gets

$$\delta_{Qq} = 2n_Q - 2n_q - \int_{-\infty}^{Y_m} dy \nu(Y_m - y) \Delta E(y), \quad (4)$$

where $\nu \equiv C_F(\alpha_s/\pi)n_y$, $\Delta E = E_Q - E_q$, $Y_m = \ln(m^2/Q_0^2)$, $y = \ln(m^2/k^2)$. Integral converges at the lower limit because

$$\Delta E \approx \frac{11}{3} \exp(-|y|), \quad |y| \rightarrow \infty.$$

The expression for the "light" multiplicity can be cast into the similar form

$$N_q(W) = 2n_q + \int_0^Y dy \nu(Y - y) E(y),$$

$Y = \ln(W^2/Q_0^2)$, $y = \ln(k^2/Q_0^2)$. In the leading logarithm approximation one gets

$$\Delta E(y) \approx y - 1/2, \quad E(y) \approx y - 3/2$$

or $\Delta E^{as}(y) = E^{as}(y + 1)$. From this one can get (when neglecting the contribution from $y < -1$ in eq.(4)) eq.(3).

However, eq.(3) does not hold in general. Instead one could use the following inequality

$$\Delta E(y) > E(y + \Delta y), \quad (5)$$

where Δy is the solution of the equation

$$\Delta E(\ln(m^2/Q_0^2)) = E(\ln(m^2/Q_0^2) + \Delta y).$$

From eq.(5) the upper bound follows

$$\delta_{Qq}(\infty) < 2n_Q - N_q(m \exp(0.5\Delta y)).$$

For the case $Q = b$ and $Q_0 \approx 1 \text{ GeV}$ $\Delta y \simeq 1.6$. This gives

$$\delta_{bq}(\infty) < 3.7 \div 4.1 \quad (6)$$

for $m_b = 5.3 \div 4.7 \text{ GeV}$, respectively. For comparison, $\delta_{bq}^{MLLA-LPHD}(\infty) \simeq 5.5$ for $m_b = 4.8 \text{ GeV}$. So, inequality (6) shows that the account of the nonleading terms significantly lowers the "QCD" result for δ_{bq} .

For the c -quark the corresponding upper bound reads

$$\delta_{cq}(\infty) < 1.3 \div 1.7$$

for $m_c = 1.7 \div 1.3 \text{ GeV}$. The NM gives

$$\delta_{cq}(29 \text{ GeV}) = 1.2, \quad \delta_{cq}(35 \text{ GeV}) = 1.1, \quad \delta_{cq}(91 \text{ GeV}) = -0.5.$$

More definite results for δ_{cq} can be obtained with the use of functional form of $n_g(k^2)$. We choose the following "QCD inspired" parametrization

$$n_g(k^2) = 1.01 \left(1 + \ln(k^2/k_0^2)\right)^{-1.95} \exp\left(1.64\sqrt{\ln(k^2/k_0^2)}\right).$$

$k_0 = 0.80 \text{ GeV}$, which reproduces quite accurately (when inserted into eq.(2)) experimental values of hadron multiplicity from light quarks [8]. With this input we get, in particular,

$$\delta_{bq}(91 \text{ GeV}) = 3.68$$

for $m_b = 4.8$. This value is in reasonable agreement with the average value from SLD, OPAL and DELPHI [4]

$$\delta_{bq}(91 \text{ GeV}) = 3.16 \pm 0.47.$$

Fig.4 demonstrates both the upper bound and "exact" theoretical values of δ_{bq} versus experimental data.

For $Q = c$ we predict the following values

W. GeV	29	35	91	170	∞
δ_{cq}	1.02	1.02	1.01	0.99	0.81

Unfortunately, experimental data [1], [9] are very scarce and rough.

Fig. 4. "QCD" expectations for $\delta_{Qq}(W)$ and $\delta_{Qq}(\infty)$. Upper (lower) lines in both cases correspond to $m_b = 4.7(5.3)$ GeV.

Conclusions

The NM, when compared to the whole set of experimental data on δ_{bq} , can not (at worst) be ruled out. Its apparent deviation from the measured value of δ_{bq} at 91 GeV can be interpreted as an evidence that the spectrum of the primary hadron (containing b-quark) becomes not only softer but also gets broader at higher energies.

The "QCD-based" model does well for δ_{bq} (especially at higher energies).

Experimental data for δ_{cq} are needed because the NM and "QCD-based" model give different predictions, especially at SLC/LEP energy where they have opposite signs.

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А.В.Киселев, В.А. Петров.

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