Hadron multiplicities in $e^+e^-$
annihilation with heavy primary
quarks

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Abstract

The multiple hadron production in the events induced by the heavy
primary quarks in $e^+e^-$ annihilation is reconsidered with account of
corrected experimental data. New value for the multiplicity in $b\bar{b}$
events is presented on the basis of pQCD estimates.

1 Introduction

The so-called “naïve model” \cite{1,2} was the first attempt to give a framework
for calculating the multiplicity of hadrons produced in addition to decay
products of the heavy quark-antiquark pair in $e^+e^-$ annihilation. Later on,
it was argued \cite{3} that the difference between multiplicities in heavy and light
quark events ($l = u, d, s$),

$$\delta_{Ql} = N_{Q\bar{Q}}(W) - N_{ll}(W),$$

(1)
tends to a constant value at high collision energy:

$$\delta_{Ql} \rightarrow \delta_{Ql}^{MLLA} = 2n_Q - N_{ll}(m_Q^2 e).$$

(2)
Here and in what follows, $N_{QQ}$ and $N_{l\bar{l}}$ are mean multiplicities of charged hadrons in heavy and light quark events, respectively.

The comparison with the data has shown that the “naïve model” describes the data on $\delta_{bl}$ up to $W = 58$ GeV [1, 4, 5, 6], but underestimates the LEP and SLAC data [7, 8, 9]. As for the so-called MLLA formula (2), it significantly overestimates both low and high-energy data on $\delta_{bl}$.

The detailed QCD calculations of the difference between associated multiplicities of charged hadron in $e^+e^-$ annihilation were made in [10]. The QCD expressions for $\delta_{Ql}$ from Ref. [10] appeared to be in a good agreement with experimental measurements of associated hadron multiplicities in $e^+e^-$ annihilation (see, for instance, [11, 12]). Note that up to now, our formula provided the best description of all the available data on $\delta_{bl}$, see Fig. 1

Moreover, we made a prediction for $\delta_{cl}$ [10]. It is also in a very good agreement with all the data on $\delta_{cl}$ [1, 5, 8]. Let us stress that the very value of $\delta_{cl}$ was derived in [10] before the precise measurements of $\delta_{cl}$ were made [8], that allows to test QCD calculations.

As we will see below, it is the hadron multiplicity in the light quark events that enables one to calculate the multiplicity differences $\delta_{Ql}$. The mean charged multiplicities in $l\bar{l}$ events at different energies corrected for detector effects as well as for initial state radiation were recently cited in [13]. The corrected multiplicity differences averaged over all presently published results were also presented [13]:

$$\delta_{bl}^{exp} = 3.12 \pm 0.14 ,$$

$$\delta_{cl}^{exp} = 1.0 \pm 0.4 .$$

The first goal of this paper is to re-estimate our QCD predictions for the quantity $\delta_{bl}$, taking into account the corrected experimental data on $N_{l\bar{l}}(W)$ from [13]. The second goal is to argue that the MLLA formula (2) is nothing but some part of our QCD expression (see Section 2), and, as the comparison to the data shows, it should be regarded as a rather rough approximation of the QCD result.

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1Everywhere below, it is assumed that we deal with mean multiplicities of charged hadrons.

2In the low energy measurements [1, 5], the total error of $\delta_{cl}$ was about $\pm 1.5$.

3The shortcomings of the MLLA formula were already briefly discussed in Ref. [10].
Figure 1: QCD prediction [10] and MLLA result [3] vs. experimental data on the multiplicity difference $\delta_{bl}$. The data are not corrected as in Ref. [13]. The prediction of the "naïve model" is also shown.

2 QCD formula for multiplicity difference

The hadron multiplicity in a $q\bar{q}$ event, $N_{q\bar{q}}(W)$, looks like [10]

$$N_{q\bar{q}}(Y) = 2 n_q + \int_0^Y d\eta \hat{n}_g(Y - \eta) E_q(\eta),$$

where variables

$$\eta = \ln \frac{W^2}{k^2},$$

(6)
and

\[ Y = \ln \frac{W^2}{Q_0^2} \]  

(7)

are introduced. In what follows, the notation \( q = Q \) will mean charm or beauty quarks, while the notation \( q = l \) will correspond to a massless case (when a pair of \( u, d \) or \( s \)-quarks is produced, whose masses are assumed to be zero).

The first term in the r.h.s. of Eq. (5), \( 2n_q \), is the multiplicity of primary hadron decay products. It is extracted from the data (\( 2n_c = 5.2, 2n_b = 11.0 \) \[3\], and \( 2n_l = 2.4 \) \[11\]).

The term \( E_q(k^2/W^2) \) in (5) is the inclusive spectrum of a gluon jet with a virtuality up to \( k^2 \) emitted by primary quarks \[4\]. It is defined by the discontinuity of of the two-gluon irreducible \( \gamma^* g^* (Z^* g^*) \) amplitude normalized to the total \( e^+ e^- \) rate. The quantity \( \hat{n}_q(k^2) \) is related to \( n_g(k^2) \), the mean multiplicity of hadrons inside this jet:

\[ \hat{n}_q(k^2) = \frac{C_F}{\pi} \frac{\alpha_s(k^2)}{n_g(k^2)}. \]  

(8)

Here \( \alpha_s(k^2) \) is a strong coupling constant, and \( C_F = (N_c^2 - 1)/2N_c \), with \( N_c \) being the number of colors.

The physical meaning of the function

\[ N_q(Y) = \int_0^Y d\eta \hat{n}_q(Y - \eta) E_q(\eta) \]  

(9)

in Eq. (5) is the following. It describes the average number of hadrons produced in virtual gluon jets emitted by primary quark (antiquark) of the type \( q \). In other words, it is the multiplicity in \( q\bar{q} \) event except for the multiplicity of the decay products of these quarks at the final stage of hadronization (the first term in (5)).

For the massless case, the function \( E \equiv E_l \) was calculated in our paper \[10\]. In terms of a dimensionless variable

\[ \sigma = \exp(-\eta) \]  

(10)
it looks like

\[
E(\eta(\sigma)) = (1 + 2\sigma + 2\sigma^2) \ln \frac{1}{\sigma} - \frac{3 + 7\sigma}{2} (1 - \sigma) - \sigma(1 + \sigma) \left( \ln \frac{1}{\sigma} \right)^2
+ 4\sigma(1 + \sigma) I(\sigma),
\]

(11)

with

\[
I(\sigma) = \int_{\sigma}^{1} \frac{dx}{1 + x} \ln \frac{1}{x} \equiv \frac{\pi^2}{4} - \text{Li}_2(1 + \sigma),
\]

(12)

where \( \text{Li}_2(z) \) is the Euler dilogarithm. The function \( E(\eta) \) is presented in Fig. 2. It has the asymptotics \( E(\eta)|_{\eta \to \infty} = E^{(\text{asym})}(\eta) = \eta - 1/2. \)

![Figure 2: The function \( E(y \equiv \eta) \).](image)

The derivative of \( E(\eta) \) is positive, as one can see in the next Fig. 3 with \( \partial E(\eta)/\partial \eta = 0 \) at \( \eta = 0 \), and \( \partial E(\eta)/\partial \eta = 1 \) at \( \eta = \infty \). As a result, associative multiplicity \( N_q(W) \) \( \text{[10]} \) is a monotone increasing function of the energy \( W \) for any positive function \( n_g(k^2) \) \( \text{[10]} \).

Now let us consider the difference between multiplicities in heavy and light quark events, \( \delta_{Ql} \), which is defined by Eq. (1). The following representation was found in Ref. \( \text{[10]} \):

\[
\delta_{Ql}^{QCD} = 2(n_Q - n_l) - \Delta N_Q(Y_m).
\]

(13)

\[ ^5 \text{[5] It results from the relation } \partial N_g(Y)/\partial Y = \int_0^Y d\eta \tilde{n}_g(\eta) \partial E(Y - \eta)/\partial Y. \]
Here new notation,
\[ \Delta N_Q(Y_m) = N_q - N_Q = \int_{-\infty}^{Y_m} dy \, \hat{\mathcal{N}}_g(Y_m - y) \Delta E_Q(y) , \]  
(14)
as well as variables
\[ y = \ln \frac{m_Q^2}{k^2} \]
(15)
and
\[ Y_m = \ln \frac{m_Q^2}{Q_0^2} \]
(16)
are introduced.

The non-trivial result which was obtained in Ref. [10] is that the function
\[ \Delta E_Q = E_l - E_Q \equiv E - E_Q \]
(17)
depends only on a variable
\[ \rho = \exp(-y) \]
(18)
but not on energy W. The explicit form of $\Delta E_Q$ is known to be
\[ \Delta E_Q(y(\rho)) = (1 - 3\rho + \frac{7}{2} \rho^2) \ln \frac{1}{\rho} + \rho(7\rho - 20) J(\rho) + \frac{20}{\rho - 4}[1 - J(\rho)] \]
\[ + \, 7\rho + \frac{9}{2} \, , \]
(19)
where

\[
J(\rho) = \begin{cases}
\sqrt{\frac{\rho}{\rho-4}} \ln \left( \frac{\sqrt{\rho} + \sqrt{\rho-4}}{2} \right), & \rho > 4 \\
1, & \rho = 4 \\
\sqrt{\frac{\rho}{4-\rho}} \arctan \left( \frac{\sqrt{4-\rho}}{\rho} \right), & \rho < 4.
\end{cases}
\] (20)

Since \( \Delta E_Q(y) \) has the asymptotics

\[
\Delta E_Q(y) \bigg|_{y \to -\infty} \simeq \frac{11}{3} \exp(-|y|),
\] (21)

the integral in Eq. (14) converges rapidly at \( y \to -\infty \). The function \( \Delta E_Q(y) \) is shown in Fig. 4. We find that \( \Delta E_Q(y) \big|_{y \to \infty} = \Delta E_Q^{(\text{asym})}(y) = y - 3/2 \).

Figure 4: The function \( \Delta E_Q(y) \).

One should mention the following important relation\(^6\)

\[
\Delta E_Q(y-1) - E(y) \bigg|_{y \to \infty} \simeq \frac{5}{2} \sqrt{\text{e}} \ln 2 \exp(-y/2).
\] (22)

In other words,

\[
\Delta E_Q(y) \simeq E(y + 1)
\] (23)

at large \( y \).

\(^6\)Here (and below) \( \text{e} \) means the base of the natural logarithm.
If one puts $\Delta E_Q(y) = E(y + 1)$, then (neglecting also the contribution from the region $y < -1$):

$$
\Delta N_Q = N_{l\bar{l}}(m_Q^2 e) - 2 n_l .
$$

(24)

Correspondingly, the approximate expression for $\delta_Q$ is then of the form:

$$
\delta_Q^{(appr)} = 2n_Q - N_{l\bar{l}}(m_Q^2 e) = \delta_{Ql}^{MLLA} ,
$$

(25)

where $\delta_{Ql}^{MLLA}$ is the MLLA prediction for the multiplicity difference from Ref [3]. Remember that the function $N_{l\bar{l}}(W)$ describes the hadron multiplicity in light quark event at colliding energy $W$.

However, Eq. (23) is very far from being satisfied at relevant $y < Y_m$ as it is clearly seen in Fig. 5. As a result, there could be a large difference between $\delta_Q^{(appr)}$ (25) and QCD expression $\delta_Q^{QCD}$ (13).

Figure 5: The difference $\Delta E_Q(y - 1) - E(y)$ as a function of the variable $y$.

To demonstrate this, it is convenient to represent expression for $\Delta N_Q$ (14)

\footnote{For the beauty case, one has $Y_m \lesssim 3.2$.}
in the form:

\[
\Delta N_Q(Y_m) = \int_0^{Y_m+1} dy \hat{n}_g(Y_m + 1 - y)E(y)
\]

\[
+ \int_{-\infty}^{Y_m} dy \hat{n}_g(Y_m - y) \Delta E_Q(y)
\]

\[
+ \int_0^{Y_m+1} dy \hat{n}_g(Y_m + 1 - y)[\Delta E_Q(y - 1) - E(y)]
\]

\[
\equiv [N_{hl}(m_Q^2e) - 2 n_l] + \delta N^{(1)}_Q(Y_m) + \delta N^{(2)}_Q(Y_m)
\] (26)

that results in the formula (see Eq. 13)

\[
\delta_{Ql}^{QCD} = 2 n_Q - N_{hl}(m_Q^2e) - \delta N^{(1)}_Q(Y_m) - \delta N^{(2)}_Q(Y_m)
\]

\[
= \delta^{(\text{appr})}_{Ql} - \delta N^{(1)}_Q(Y_m) - \delta N^{(2)}_Q(Y_m)
\] (27)

Here we have introduced the notations

\[
N^{(1)}_Q(Y_m) = \int_{-\infty}^{-1} dy \hat{n}_g(Y_m - y) \Delta E_Q(y)
\]

and

\[
N^{(2)}_Q(Y_m) = \int_0^{Y_m+1} dy \hat{n}_g(Y_m + 1 - y)[\Delta E_Q(y - 1) - E(y)]
\]

Note, both \(N^{(2)}_Q(Y_m)\) and \(N^{(2)}_Q(Y_m)\) are positive functions, since \(\Delta E_Q(y) > 0\) at all \(y\) and \(\Delta E_Q(y - 1) - E(y) > 0\) at \(y \geq 0\) (see Fig. 3 and Fig. 4).

In order to exploit the corrected data on \(N_{hl}(W)\) at \(W = 8\) GeV,

\[N_{hl}(8.0\ \text{GeV}) = 6.70 \pm 0.34\] (30)

we have chosen the mass of b-quark to be \(m_b = 4.85\) GeV, which corresponds to \(m_b\sqrt{e} = 8\) GeV.

The estimates show that the dominant correction to \(\delta_{Ql}^{QCD}\) is \(\delta N^{(2)}_Q\), not \(\delta N^{(1)}_Q\). To calculate a lower bound of \(\delta N^{(2)}_b\), let us use the following inequality:

\[
\Delta E_Q(y) = E(y + \Delta y_Q)
\] (31)
Note that $\Delta y_Q$ is a monotone non-increasing function of $y \geq 0$ and it tends to 1 at large $y$. It solves the equation:

$$\Delta E_Q(Y_m) \geq E(Y_m + \Delta y_Q),$$

(32)

where $Y_m$ is defined above (16). Then we get from Eqs. (29) and (31):

$$\delta N_{Q}^{(2)} \geq N_{\bar{l}l}(Y_m + \Delta y_Q) - N_{\bar{l}l}(Y_m + 1) - \int_{0}^{\Delta y_Q - 1} dy \hat{n}_g(Y_m + \Delta y_Q - y) E(y).$$

(33)

For our further estimates, we need to know the hadron multiplicity in light quark events in the energy interval $2.5 \text{ GeV} \leq W \leq 28 \text{ GeV}$. By fitting the data on hadron multiplicity in the light quark events at low $W$, we get the expression:

$$N_{\bar{l}l}(W) = 2.07 + 1.11 \ln W + 0.54 \ln^2 W.$$ 

(34)

Putting $Q_0 = 1 \text{ GeV}$, we find $\Delta y_b = 1.61$. Taking into account that the last term in Eq. (33) is negligible, we get from (33), (34):

$$\delta N_{b}^{(2)} \geq 1.07.$$ 

(35)

Correspondingly, our prediction accounting the revision of the data on the multiplicity in the light quark events,

$$\delta_{bl}^{QCD} \leq 2n_b - N_{\bar{l}l}(Y_m + \Delta y_b) = 3.33 \pm 0.38,$$

appears to be lower than our previous result $\delta_{bl} = 3.68$ [10]. We used the value

$$2n_b = 11.10 \pm 0.18.$$ 

(37)

The error of $N_{\bar{l}l}$ was taken to be $\pm 0.34$. Let us stress that our upper bound [60] is very close to the present experimental value of $\delta_{bl}^{exp}$ [3].

Now let us derive a lower bound on $\delta_{bl}^{QCD}$. To do this, let us start from Eq. (14). It is convenient to represent the integral in (14) as a sum of two terms:

$$\Delta N_b = \int_{-4}^{-1} dy \hat{n}_g(Y_b - y) \Delta E_b(y) + \int_{-4}^{Y_b} dy \hat{n}_g(Y_m - y) \Delta E_b(y)$$

$$= \Delta N_{b}^{(1)} + \Delta N_{b}^{(2)},$$

(38)

$^8$Since $E(y) < 0.02$ in the region $0 \leq y \leq \Delta y_b - 1 = 0.61$.

$^9$We took into account that the region $-\infty < y < -4$ gives a negligible contribution to $\Delta N_b$. 

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with \( Y_b = \ln\left(\frac{m_b^2}{Q_0^2}\right) \approx 3.16 \). Consider the first term in (38). One can check that

\[
\Delta E(y) < 0.18 \, E(y + 5.8)
\] (39)

in the region \(-4 < y < -1\), that leads to the inequality

\[
\Delta N_b^{(1)} < 0.18 \int_{1.8}^{4.8} dy \, \hat{n}_g(Y_b + 5.8 - y) \, \Delta E_b(y) \, .
\] (40)

The estimations show that \( \hat{n}_g(Y_b + 5.8 - y) < 2 \hat{n}_g(4.8 - y) \) when \( y \) varies from 1.8 to 4.8. Thus, we get:

\[
\Delta N_b^{(1)} < 0.36 \left[ N_{ll}(W = 11 \, \text{GeV}) - N_{ll}(W = 2.5 \, \text{GeV}) \right] = 1.54 \pm 0.17 \, .
\] (41)

The second term in (38) can be estimated by using the inequality

\[
\Delta E(y) < 0.62 \, E(y + 3.5)
\] (42)

which is valid in the region \(-1 < y < Y_b\). Then

\[
\Delta N_b^{(2)} < 0.62 \left[ N_{ll}(W = 28 \, \text{GeV}) - N_{ll}(W = 3.5 \, \text{GeV}) \right] = 4.61 \pm 0.30 \, .
\] (43)

As a result, we obtain from Eqs. (13), (14) and (41), (43) the lower bound on \( \delta_{QCD}^{\ell \ell} \):

\[
\delta_{QCD}^{\ell \ell} > 2.55 \pm 0.39 \, .
\] (44)

Fig. 6 demonstrates that our QCD predictions for \( \delta_{QCD}^{\ell \ell} \) are very close to the corrected experimental data.

Our results can be compared with the MLLA expectation reported recently in Ref. [13] :

\[
\delta_{\text{MLLA}}^{\ell \ell} = 4.4 \pm 0.4 \, .
\] (45)

Note that the scheme of Ref. [13] is not stable against next-to-MLLA corrections. According to Eq. A(30) from [13], the MLLA prediction (25) is modified as follows:

\[
\delta_{Ql}^{N\text{MLLA}} = 2n_Q - N_{ll}(m_Q^2) \left\{ 1 + \frac{3\alpha_s(m_Q)}{2\pi} \left[ \frac{\pi^2}{24} + \left( \frac{\pi^2}{3} - \frac{5}{4} \right) \right] \right\} \, .
\] (46)

The next-to-MLLA corrections in (46) change the result (45) to

\[
\delta_{\text{NMLLA}}^{\ell \ell} = 2.6 \pm 0.4 \, .
\] (47)
The situation is worse in the case of c-quark. The formula (46) results in a unsatisfactory low value
\[
\delta_{c}^{\text{NMLLA}} = -0.1 \pm 0.4 .
\] (48)

This demonstrates us once more that the lowest-order MLLA expression (2) is not correct.

Moreover, as we have shown above, the deviation of the function \( \Delta E_{Q}(y) \) from \( \Delta E_{Q}^{\text{asym}}(y) = y - 3/2 \), as well as the deviation of \( E(y) \) from \( E^{\text{asym}}(y) = y - 1/2 \), cannot be neglected. In other words, the MLLA formula (25) is, in fact, not a full QCD result. It is nothing but a part of the correct QCD formulae (1), (14) in a very rough approximation \( E(y) = \Delta E_{Q}(y - 1) \). So it is senseless to try to “improve” it with next-to-MLLA calculations.

It explains why formula (45) overestimates the data by more than one unit.
3 Conclusions

We have derived the QCD formula for the difference between hadron multiplicities in heavy and light quark events in $e^+e^-$ annihilation (with $Q$ being a type of a heavy quark):

$$
\delta_{Ql}^{QCD} = 2n_Q - N_{ll}(m_Q^2 e) \\
- \int_{Q_0^2}^{m_Q^2 e} \frac{dk^2}{k^2} \hat{n}_g(k^2) \left[ \Delta E_Q \left( \frac{m_Q^2}{k^2} \right) - E \left( \frac{m_Q^2}{k^2} \right) \right] \\
- \int_{m_Q^2 e}^{\infty} \frac{dk^2}{k^2} \hat{n}_g(k^2) \Delta E_Q \left( \frac{m_Q^2}{k^2} \right) .
$$

Here $n_g(k^2)$ describes the mean number of charged hadrons in the gluon jet with the virtuality up to $k^2$, and $E$, $\Delta E_Q$ are known functions.

By using the data on the hadron multiplicity in light quark events $N_{ll}$, corrected for the detector effects and initial state radiation effects [13], we have obtained from (49) the bounds:

$$
2.2 < \delta_{bl}^{QCD} < 3.7 .
$$

Let us note that this estimate does not depend on a specific choice of the function $n_g(k^2)$, and it is in a good agreement with the average experimental value $\delta_{bl}^{exp} = 3.12 \pm 0.14$.

Two last terms in (49) are positive and numerically large\(^{11}\) As a result, a deviation of the MLLA prediction,

$$
\delta_{bl}^{MLLA} = 2n_b - N_{ll}(m_b^2 e) ,
$$

from the QCD expression\(^{12}\)

$$
\delta_{bl}^{QCD} = 2(n_b - n_t) - \int_{Q_0^2}^{m_b^2 e} \frac{dk^2}{k^2} \hat{n}_g(k^2) \Delta E_Q \left( \frac{m_b^2}{k^2} \right) ,
$$

\(^{11}\)In particular, the second term in (49) (dominating the third one) is equal to 1.1 for the case of the beauty pair production ($m_Q = m_b$, $n_Q = n_t$).

\(^{12}\)This formula is an equivalent compact form of Eq. (49) for $Q = b$.  

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appears to be significant.

As one can see, the MLLA formula is a too rough approximation of the QCD formula. The former results from the latter on the assumption that the quantities $E(y)$ and $\Delta E_Q(y)$ can be replaced by their asymptotics at $y \rightarrow \infty$. Since the relevant values of $y$ are far from being very large, this assumption is not correct, and it leads to a significant overestimation of $\delta_{bl}$. Thus, any attempt to use the MLLA expression (2) as a first-order approximation for higher-order calculations (as it is done in [13]) is poorly justified.

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