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AVERAGE CHARGED MULTIPLICITIES IN $Q\bar{Q}$ EVENTS ($Q=c,b,t$) AT LEP ENERGIES

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A B S T R A C T

Charged particle multiplicities in e^+e^- annihilation into hadronic states have been studied. Events with light and heavy initial quarks are treated separately. Particular attention is paid to multiple production in $t\bar{t}$ events at LEP energies.

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1. The e^+e^- annihilation process is one of the so-called hard processes. As is known, the multiple character of a hard process is mostly defined by small distances, at which quarks and gluons can be treated perturbatively.

That is why we expect to observe effects, predicted by perturbative QCD, at new e^+e^- colliders. Among them are rapid growths of charged hadron multiplicities, "pump-baked" spectrum, non-trivial topology of multijet events, etc. Due to an absence of initial-state hadrons, e^+e^- annihilation enables one to study the QCD-based mechanism of particle production in its cleanest form.

The multiple production of hadrons in e^+e^- annihilation has already been studied by using Monte Carlo models [1]. Notice that some particularities of parton shower evolution, previously obtained in perturbative QCD, are implemented in Monte Carlo models. For instance, taking account of coherence effects in soft gluon emission leads to the best overall description of the data [1].

Recently, some interesting data on charged multiplicities in hadronic $c\bar{c}$ and $b\bar{b}$ events at $W = 29$ GeV appeared [2]. In particular, it was shown in Refs. [2a] that hadronization of the non-leading part ("sea hadrons") does not depend on the flavour of initial quarks.

The aim of the present paper is to study multiple particle production in $c\bar{c}$, $b\bar{b}$ and, especially, $t\bar{t}$ events at the higher energies of the SLAC linear collider (SLC) and CERN colliders (LEP I and LEP II). In this we will concentrate mainly on two possible values of top quark mass $m_t = 45$ and 50 GeV.

Notice that particle production in events with light quarks $q = u, d, s$ is also of great interest. As has been shown in Ref. [3], there is a transparent relation between average multiplicity in deep inelastic scattering and n_{qq}^- , given at some effective energy.

2. The universal character of non-leading hadron production observed in Refs. [2a] can be explained within the framework of perturbative QCD. At high energy, multiple particle production is connected with gluon jet fragmentation. The rôle of the initial quark (antiquark) is to "trigger" massive gluon jets. The parton shower develops mainly via gluons. It is cut when gluon virtualities become equal to some fixed value Q_0^2 (of the order of one GeV).

The number of gluons with mass Q_0 in e^+e^- annihilation is given by the number of gluons in the gluon jet n_g^p :

$$n_{q\bar{q}}^P(W, Q_0) = 2 + n_{sea}^P(W, Q_0), \quad (1)$$

where

$$n_{sea}^P(W, Q_0) = \frac{2C_F}{C_A} \left[1 - \sqrt{\frac{\alpha_s C_A}{2\pi}} \left(\frac{1}{3} + \frac{n_f}{3C_A} - \frac{2n_f C_F}{3C_A^2} \right) \right]^{-1} \left[n_g^P((W-Q_0), Q_0) - 1 \right], \quad (2)$$

$C_F = (N^2 - 1)/2N$, $C_A = N$, N is the number of colours and n_f is the number of flavours. In deriving (1) we used the particle multiplicity ratio in gluon and quark jets calculated in the modified leading logarithmic approximation (MLLA) in Ref. [4]. The quantity $n_{q\bar{q}}^P$ satisfies $n_{q\bar{q}}^P|_{W=2Q_0} = 2$ (only quark and antiquark with masses Q_0 can be produced at $W = 2Q_0$).

As for n_g^P it has been recently calculated in MLLA and has the form [5a]

$$n_g^P(W, Q_0) = z(z/z_0)^{-B} \left[I_{B+1}(z) K_B(z_0) + K_{B+1}(z) I_B(z_0) \right], \quad (3)$$

where $z = \sqrt{4C_A/\pi b} \ln W/\Lambda$, $z_0 = \sqrt{4C_A/\pi b} \ln Q_0/\Lambda$; I_B , K_B are modified Bessel functions, $B = (11N + 2n_f/N^2)/b$, $12\pi b = 11N - 2n_f$.

The details of both parton decolorization and parton transition into hadrons depend on the chosen model of factorization [1]. However, according to local parton-hadron duality (LPHD) the averaged hadron multiplicity and the parton (gluon) multiplicity differ by an energy independent factor K [5a]

$$n_{q\bar{q}}^h = K n_{q\bar{q}}^P = 2K + K n_{sea}^P. \quad (4)$$

The conclusion about the validity of LPHD has been made in Ref. [5a] after comparing charged hadron spectra and multiplicities with perturbative QCD calculation in MLLA^{*})

Parton spectra and multiplicities become infra-red stable in MLLA (the limit $Q_0/\Lambda \rightarrow 1$ exists). In Ref. [5a] the conclusion was made that confinement does not disturb the perturbation theory picture of particle generation (provided one does not imagine an unnatural non-local scheme of hadronization). K is nothing but an

^{*}) It has been recently confirmed by explicit calculation of the processes $e^+e^- \rightarrow q\bar{q}g$ and $e^+e^- \rightarrow q\bar{q}g + q\bar{q}q\bar{q}$ that the distribution of hadrons follows that of the QCD partons rather closely [5b].

average number of hadrons per gluon with virtuality Q_0^2 . It depends on cut-off Q_0^2 and is of the order of unity.

Everything mentioned above concerns events with light initial quarks. Events with heavy initial quarks $Q = c, b, t$ have a specific character. The gluon emission off heavy quarks is suppressed as compared with that of light quarks. After joining a sea antiquark, a Q quark forms a $Q\bar{q}$ meson, which carries away the greatest fraction of quark momentum. That is why the effective energy W_{eff} , available for "sea particle" production, is much less than the collision energy W . This circumstance reduces the average number of hadrons produced in the central rapidity region. But, on the other hand, there is a rather large contribution to hadron multiplicity from the hadronic weak decay of corresponding heavy mesons $2n_Q^h$. As a result, the average charged hadron multiplicities in $Q\bar{Q}$ events are comparable with that in $q\bar{q}$ events.

In $Q\bar{Q}$ events, one has to apply LPHD for the non-leading part. It results in

$$n_{Q\bar{Q}}^h = 2n_Q^h + K n_{\text{sea}}^p(W_{\text{eff}}, Q_0). \quad (5)$$

W_{eff} can be estimated as follows

$$W_{\text{eff}} = W(1 - \bar{x}_Q), \quad (6)$$

where $\bar{x}_Q$ means the average fraction of initial quark energy, which is carried away by the corresponding heavy meson. For $\bar{x}_Q$ we use the expression obtained previously in Ref. [6], which we improve to take into account the condition $W_{\text{eff}}|_{W=2m_Q} = 0$

$$\bar{x}_Q = [\alpha_s(m_Q^2) / \alpha_s((W - m_Q)^2)]^{-a}, \quad (7)$$

where $a = 8C_F/12\pi b$. Notice that expression (7) becomes more reliable with the increase of m_Q [6].

The boundary between low and high energies [where formulae (4) and (5) can be applied] should be defined. If one looks at experimental data on average charged multiplicity in e^+e^- annihilation, it is clear that $n_{e^+e^-}$ exercises a change of growth, starting from $W = 7\div 10$ GeV [7a]. The data can be reasonably described by QCD-based formulae [7a, 7b], especially above the threshold of $b\bar{b}$ production (i.e., at $W \gtrsim 10$ GeV) [7c]. Moreover, the QCD-based fit describes combined data on $n_{e^+e^-}$ and forward multiplicity in deep inelastic μ^+p scattering [7d]. Thus, one comes to the conclusion that with the increase of the invariant mass of hadronic states, the mechanism of perturbative QCD starts to work.

Physically, non-motivated fits (see, for example Table 4 in Ref. [7b]) on being extrapolated to higher energies, gives values which contradict Monte Carlo model calculations [1,8] (logarithmic fits are slow, while power-type fit is too fast).

Taking into account everything said above, the range $W > 10$ GeV ($W < 10$ GeV) is everywhere below called the high (low) energy range.

At low energies, the mechanism of multiple particle production has a mainly non-perturbative character. Resting upon the results of Ref. [2a], we propose the following formula

$$n_{q\bar{q}}^h(q\bar{q}) = 2n_{Q(q)}^h + n_{sea}^h(W_{eff}), \quad (8)$$

where the phenomenological function n_{sea}^h is the same for any initial flavour and it satisfies $n_{sea}^h|_{W_{eff}=0} = 0$. One must put $W_{eff} = W$ for $q\bar{q}$ events. We choose the function

$$n_{sea}^h(W) = A \ln(1+W) + C' \ln^2(1+W). \quad (9)$$

In what follows we use $\Lambda = 0.3$ GeV, charm quark mass $m_c = 1.5$ GeV, bottom quark mass $m_b = 5.0$ GeV. Then Eq. (7) gives $\bar{x}_c = 0.62$, $\bar{x}_b = 0.81$ for $W = 29$ GeV in agreement with data [9].

Average charged multiplicities in weak decays of heavy mesons have been obtained in Ref. [10]

$$n_c^h = 2.5 \pm 0.1, \quad n_b^h = 6.0 \pm 0.3, \quad n_b^{av} = 5.5 \pm 0.3. \quad (10)$$

3. After determining the quantities $n_{q\bar{q}}^h$, $n_{Q\bar{Q}}^h$, we are able to introduce the average charged hadron multiplicity in e^+e^- annihilation

$$\begin{aligned} & \left[\sum_{\bar{q}} P_{q\bar{q}} + \sum_Q P_{Q\bar{Q}} \theta(W-2m_Q) Br^2(Q \rightarrow X) \right] n_{e^+e^-}^h(W) = \\ & = \sum_{\bar{q}} P_{q\bar{q}} n_{q\bar{q}}^h(W) + \sum_Q P_{Q\bar{Q}} \theta(W-2m_Q) Br^2(Q \rightarrow X) n_{Q\bar{Q}}^h(W_{eff}) \end{aligned} \quad (11)$$

where $P_{f\bar{f}}$ denotes the weight of the $f\bar{f}$ event

$$P_{ff} = \beta_f (3 - \beta_f^2)/2 \left[4\pi/W^2 \alpha^2 e_f^2 - 4/\sqrt{2} G_F \times \right. \\ \times (1 - W^2/m_Z^2) D^{-1} v_e e_f v_f + 1/2\pi G_F^2 W^2 D^{-1} \times \\ \left. \times (v_e^2 + a_e^2) v_f^2 \right] + \beta_f^3 1/2\pi G_F^2 W^2 D^{-1} (v_e^2 + a_e^2) a_f^2. \quad (12)$$

In this $D = (1 - W^2/m_Z^2)^2 + (\Gamma_Z^h/m_Z)^2$, $\beta_f = \sqrt{1 - 4m_f^2/W^2}$. Quantities a_f , v_f are expressed in terms of the third component of the weak isospin T_{3f} , the weak mixing angle θ_W and charge values e_f : $a_f = T_{3f}$, $v_f = T_{3f} - 2e_f \sin^2 \theta_W$.

The hadronic width Γ_Z^h weakly depends on the top quark mass m_t , at least in the range $40 < m_t < 50$ GeV [11]. According to Ref. [11] it equals for instance 2.25 GeV for $m_t = 44$ GeV.

Now let us estimate hadronic branchings $Br(Q \rightarrow X)$, entering (11). Suppose that the charm quark turns into D^0 and D^+ with equal probabilities, then

$$Br(c \rightarrow X) = (\Gamma_h^0 + \Gamma_h^+)/(\Gamma_{tot}^0 + \Gamma_{tot}^+). \quad (13)$$

As for partial widths Γ , the following ratios are experimentally obtained [12]

$$\Gamma_{s,l}^0 \simeq \Gamma_{s,l}^+ = (1.19 \pm 0.13) 10^{-10} \text{ MeV}, \quad \Gamma_h^0/\Gamma_h^+ = 2.7 \pm 0.3. \quad (14)$$

One finds from (13) and (14)

$$Br(c \rightarrow X) = 89.3\%. \quad (15)$$

The transition $b \rightarrow c$ dominates the weak decay of the bottom quark, $Br(b \rightarrow u)/Br(b \rightarrow c) < 0.08$ [12]. Therefore,

$$Br(b \rightarrow X) = Br(b \rightarrow c X) Br(c \rightarrow X). \quad (16)$$

Taking into account that $Br(b \rightarrow X \bar{\nu}_\mu) \simeq (11.7 \pm 0.6)\%$ [12], we obtain

$$Br(b \rightarrow X) = 68.0\%. \quad (17)$$

Thus, we have described all the quantities, entering formula (11). We define the values of the phenomenological parameters introduced by comparing formula (11) with the e^+e^- annihilation multiplicity data in the range $3 < W < 41.5$ GeV. We require

n_{qq}^h and $\partial n_{qq}^h / \partial W$ to be continuous functions at $W = 2m_b$, because n_{qq}^h has to be insensitive to the $b\bar{b}$ threshold. The fit results in

$$A = 0, \quad C = 1.13, \quad n_q = 0.61, \quad Q = 0.60 \text{ GeV}, \quad K = 1.42. \quad (18)$$

By using (18), a number of charged multiplicities of $W = 29 \text{ GeV}$ have been calculated. They are listed in Table 1 in comparison with data.

4. As has been said above, the main purpose of this paper is to give predictions concerning charged hadron multiplicities in $t\bar{t}$ events at LEP energies. The predictions depend on the top quark mass m_t . The UA1 Collaboration has recently emphasized that m_t satisfies $m_t > 44 \text{ GeV}$ [13a]. By using UA1 data the lower limit $m_t > 41 \text{ GeV}$ has been found in Ref. [13b], which is much better justified. In what follows we study mostly two possible values $m_t = 45$ and 50 GeV . Some calculations are also done for other values of m_t in order to compare our results with those obtained by different methods.

Model-dependent estimates of top quark branching $\text{Br}(t \rightarrow bX)$ are collected in Table 2. Taking into account only the first three lines in Table 2, we chose the average value

$$\text{Br}(t \rightarrow bX) = 66.8\% . \quad (19)$$

Then one has

$$\text{Br}(t \rightarrow X) = \text{Br}(t \rightarrow bX) \text{Br}(b \rightarrow X) = 45.4\% , \quad (20)$$

because the transition $t \rightarrow b$ completely dominates top quark weak decay [11,14].

An important part of our consideration is an estimation of charged multiplicity in hadronic top decay n_t^h . Suppose that the leading contribution to n_t^h is given by the process

$$\begin{array}{c} t \rightarrow b \quad W^* \\ \quad \quad \quad \swarrow \quad \searrow \\ \quad \quad \quad f\bar{f} \rightarrow X_2 \\ \quad \quad \quad \downarrow \\ \quad \quad \quad X_1 \end{array} \quad (21)$$

where X_1, X_2 mean hadronic states. Let $M_{f\bar{f}} = \sqrt{(p_f + p_{\bar{f}})^2}$ be the invariant mass of the $f\bar{f}$ pair ($f = q$ or Q). In the approximation (21), the partial decay rate of the top quark in its rest frame is given by the following expression

$$\frac{d\Gamma_{ff}}{dM_{ff}^2} \sim \frac{1}{m_t^3} \frac{1}{(m_t^2 - m_W^2)^2} \left[(m_t^2 - m_b^2)^2 - M_{ff}^4 \right] \times \\ \times \sqrt{[m_t^2 - (M_{ff} + m_b)^2][m_t^2 - (M_{ff} - m_b)^2]} \sqrt{1 - 4m_f^2/M_{ff}^2}, \quad (22)$$

where m_W is the W-boson mass.

It is natural to suppose that the hadronization of this quark-antiquark pair in top decay (21) and in e^+e^- annihilation are the same. Then one can write

$$n_t^h = \sum_f Br^2(f \rightarrow X) \int dM_{ff}^2 \frac{1}{\Gamma} \frac{d\Gamma_{ff}}{dM_{ff}^2} n_{ff}^h(M_{ff}^2) + n_b^h, \quad (23)$$

where

$$\Gamma = \sum_f Br^2(f \rightarrow X) \int dM_{ff}^2 \frac{d\Gamma_{ff}}{dM_{ff}^2} \quad (24)$$

and $Br(q \rightarrow X) = 1$ is assumed. The quantities n_{ff}^h ($f = q, Q$) have been studied above.

An analogous treatment works in the case of hadronic b decay. After changing $t \rightarrow b$, $b \rightarrow c$ in formulae (21) and (22), one obtains $n_b^h = 6.1$ in agreement with data [10].

In the same manner both the charged multiplicity in semi-leptonic top decay $n_t^{s.l.}$ and the averaged charged multiplicity n_t^{av} should be considered. The results of our calculations are listed in Table 3. Our prediction for $m_t = 45$ GeV can be compared with the result of Ref. [15]: $n_t^{s.l.} = 8.0$, $n_t^{av} = 14.8$. Using CALTECH-II branching $Br(t \rightarrow bX) = 74.8\%$ (see Table 2), we obtain $n_t^h = 17.1$.

It is worth estimating the average charged hadron multiplicity n_{tt}^h in the process $e^+e^- \rightarrow Z^0 \rightarrow t\bar{t}$. One expects the fragmentation function of the top quark to be peaked toward $\bar{x}_t = 1$. Calculations done by using (7) confirm that $\bar{x}_t$ is close to unity (see Table 4). The values obtained for n_{tt}^h can be compared with the results of different approaches (Table 1 in Ref. [16a]). We associated a binding energy 400 MeV with the formation of t-meson [16b].

Values, listed in Table 5, correspond to $m_t = 40$ GeV, $W = 93$ GeV. Our results are seen to agree with those obtained in Monte Carlo models.

A number of charged multiplicities in e^+e^- annihilation at LEP energy are presented in Table 6. In this the value of $n_{e^+e^-}^h$ corresponds to $m_t = 45$ GeV. Notice that it depends on m_t very weakly.

The final remark concerns $t\bar{t}$ production in events with light initial quarks. It can take place, for instance, at LEP II, provided $m_t = 45$ GeV. "Sea hadron" multiplicity in such events is estimated as follows

$$\begin{aligned} n_{sea}^h &= n_{q-jet}^h(W/2) + n_{\bar{q}-jet}^h(W/2 - 2m_t) = \\ &= \frac{1}{2} n_{q\bar{q}}^h(95 \text{ GeV}) + \frac{1}{2} n_{q\bar{q}}^h(5 \text{ GeV}) \approx 12.2. \end{aligned} \quad (25)$$

Then we find $n_{t\bar{t}}^h = 46.8$, $n_{t\bar{t}}^{av} = 38.4$. Notice that the $t\bar{t}$ production probability in $q\bar{q}$ events is rather small in comparison with that in $t\bar{t}$ events.

5. Charged particle multiplicities in e^+e^- annihilation have been studied in the present paper. We suggest a formula which includes both a low-energy part (corresponding to the non-perturbative mechanism of hadronization) and a high energy one (corresponding to QCD-based mechanism of multiple production). We treated separately events with light and heavy initial quarks. Main attention has been paid to $t\bar{t}$ events at LEP energies. In passing, we have calculated hadronic, semi-leptonic and averaged charged multiplicities in top weak decays. The comparison of some of our results with analogous ones of Monte Carlo models were presented.

In conclusion let us touch upon two points. First, formulae (2) and (3) have been derived in MLLA. Some facts indicate that analytical expressions, obtained within the framework of perturbative QCD in this approximation work at present energies. We recall, for example, the similarity of parton and hadron spectra at $W > 14$ GeV [5] and the reasonable description of hadronic energy flow in $q\bar{q}g$ and $q\bar{q}\gamma$ events at $W = 34$ GeV [18]. Nevertheless, the boundary between low and high energies cannot be exactly fixed for the time being.

Secondly, we ignored $q\bar{q}$ production in the parton shower, because it develops via gluons in MLLA. The account of $g \rightarrow q\bar{q}$ splittings in parton shower evolution may change the average number of partons and, as a by-product, the value of K . However, this circumstance would not significantly influence our estimates of $n_{t\bar{t}}^-$. So, W_{eff}

is less than 20 GeV in $t\bar{t}$ events at LEP II, while K is determined by fitting e^+e^- annihilation multiplicity data in the range $3 < W < 41.5$ GeV. As for "sea hadron" production in $t\bar{t}$ events at LEP I, it is of non-perturbative character and the corresponding multiplicity $n_{t\bar{t}}$ is insensitive to the value of K .

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	Our estimate	Experiment
$n_{q\bar{q}}^h$	12.2	$12.2 \pm 0.4 \pm 1.3$ [2a]
$n_{av,jet}^h$	6.30	6.16 ± 0.01 [2b]
$n_{b\bar{b}}^{av}$	15.0	$16.1 \pm 0.5 \pm 1.0$ [2a]
n_{b-jet}^{av}	7.48	7.61 ± 0.46 [2b]

TABLE 1

Br($t \rightarrow bX$), %	Model
67.7	Al1 [11]
66.0	LUND [14]
66.6	Webber [14]
74,8	Gottschalk [14]

TABLE 2

m_t GeV	40	45	50	60	70	80
n_t^h	16.6	17.3	17.9	19.1	20.4	21.8
$n_t^{s.l}$	9.0	9.3	9.5	10.0	10.5	11.0
n_t^{av}	12.5	13.1	13.4	14.3	15.1	16.1

TABLE 3

	$m_t = 40 \text{ GeV}$	$m_t = 45 \text{ GeV}$
$\bar{x}_t$	0.97	0.99
n_{tt}^{sea}	1.13	0
n_{tt}^h	34.3	34.6

TABLE 4

	Our estimate	Model
$n_{e^+e^-}^h$	20.2	18-23 LUND Shower LUND MA Webber [17] CALTECH-II
n_{qq}^h	19.5	18 LUND MA 20 Webber [14]
n_{tt}^{ay}	26.8	26 LUND MA 27 Webber [14]

TABLE 5

W, GeV	$n_{e^+e^-}^h$	n_{qq}^h	n_{cc}^h	n_{bb}^h	n_{tt}^h / n_{tt}^{ay}		
					$m_t = 45 \text{ GeV}$	$m_t = 50 \text{ GeV}$	$m_t = 80 \text{ GeV}$
110 (LEP I)	22.5	21.6	21.1	23.1	36.8/28.4	36.4/27.4	-
190 (LEP II)	27.9	27.0	26.5	27.0	43.4/35.0	44.0/35.0	47.1/35.7

TABLE 6

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