Production of new heavy particles in e^+e^- annihilation into hadrons

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It is shown that the observed structures in the main characteristics of the reaction $e^+e^- \to$ hadrons point to the production of pairs of new heavy particles.

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1. The experimental data on $e^+e^- \to$ hadrons at energies $\sqrt{s} = 2.4$ to 7.8 GeV (outside the ψ resonances) reduce in the main to the following:

a. Three regimes are observed in the behavior of $R = (\sigma_{e^+e^- \to \text{hadr}})/(\sigma_{e^+e^- \to \mu^+\mu^-})$: $R \approx R_1 \approx 2.5$ at $\sqrt{s} = 2.5$ to 3.5 GeV (region I), at $3.5 \leq \sqrt{s} \leq 5$ GeV (region II) R_{II} increases and reveals structures at $\sqrt{s} = 4.1$ and 4.4 GeV, and $R \approx R_{III} \approx 5$ at $\sqrt{s} = 5$ to 7.8 GeV (region III).

b. The inclusive spectra of the charged hadrons $h^{\pm}$ are approximately gauge-invariant at $x \gtrsim 0.45$ $(x = 2E^h/\sqrt{s})$; at $x < 0.45$, $f_e(x) = Rf(x) = (1/\sigma_{e^+e^- \to \mu^+\mu^-})\,(d\sigma_{h^{\pm}}/dx)$ increases rapidly with energy in region II, but the growth slows down in region III.

c. The average multiplicity $\langle n_{ch} \rangle$ and the average energy $\langle E_h \rangle$ increase with $\sqrt{s}$ in regions I and III, while structures seem to appear in region II.

d. Accurate to a number of ambiguities,[1,3] $\epsilon = E_{ch}/\sqrt{s} < 2/3$ and decreases with increasing s (predominantly in region II) from $\epsilon \sim 0.6$ to $\epsilon^{III} \sim 0.5$.

e. In region III there is observed a tendency for the hadrons to be grouped

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into two jets. $\langle p_\perp \rangle \sim 0.31$ GeV relative to the axis of the jet. No resonances were observed in the jet.

f. The relative yields of $\pi|K|p$ (at $p_h \lesssim 0.7$ GeV) change little with s.

g. The yields of $4\pi^\pm$ and $6\pi^\pm$ and the inclusive yields of the electrons do not increase in region II, nor are new resonances (with masses ~ 2 GeV) obtained in systems of two and three K_S^0, $K^\pm$, and $\pi^\pm$ mesons.

h. Starting with region II, a threshold behavior of $\sigma_{e\mu}/\sigma_{\mu\mu}$ is observed for the production of anomalous $\mu^\pm e^\mp$ pairs.

The purpose of the article is to show that the existence of new charged particles can be reconciled with the experimental data on the reaction $e^+e^- \to$ hadrons and to indicate methods of analyzing the data.

2. It is assumed that in region I the hadron production is mainly in accord with the standard quark parton picture from ordinary q quarks (parton (q) component). Favoring this hypothesis are: a) the proximity of $R_I \equiv R_q$ to the value $R = 2$ expected in the model of colored q quarks; b) the agreement of the logarithmic derivative $(\partial/\partial \ln s)\langle n_{ch}\rangle_q$ and of the value of $\langle n_{ch}\rangle_{\mathrm{I}}$ with the corresponding values for the hadronic, ep, and νp interactions. In the q component, R_q and $(f_e(x))$ do not depend on $\sqrt{s}$, and $\langle n_{ch}\rangle_q$ increases because of the increase in the region of small values of $x (x^q_{\min} \sim 2\langle p_\perp\rangle/\sqrt{s})$

$$\langle n_{ch}\rangle_q = \langle n_{ch}\rangle_{\sqrt{s}\,=\,3\,\mathrm{GeV}} + 2C \ln \frac{\sqrt{s\ \mathrm{GeV}^2}}{3\mathrm{GeV}}. \tag{1}$$

($C \approx 1.5$ was obtained from the spectrum of $h^\pm$ at $\sqrt{s} = 3.0$ GeV and $0.2 < x < 0.4$). The properties 1a—1e and 1h can be understood by assuming that a pair of heavy particles M (with masses 1.7—2.3 GeV) are produced in region II in addition to the q component and lead to almost constant $\langle n_{ch}\rangle = \langle n_{ch}\rangle_M$, (the M component). The M component can itself be multicomponent and even consist of particles of different types. For examples it can be made up of heavy leptons L and (or) a pair of V mesons of the type $q\bar{Q}_i$ or $\bar{q}Q_i$, where Q_i are new heavy quarks ($m_Q \approx 1.6$ GeV). The form factors of the U mesons are apparently not small in a wide energy interval beyond the threshold of their production,[4] and furthermore an appreciable number of different U particles is expected. It appears that the hypothesis that M constitutes only charmed mesons (D,F) is difficult to reconcile with 1a and 1f—1h.

The behavior 1b of $f_e(x)$ can be easily understood if the energy distribution in the rest system of the M particles is narrow enough $E_h^* \sim \langle E_h^*\rangle$. Then the increase of R_{II} and of $f_e(x)$ occurs mainly at $x < x_{\max} = (E_h^*/\bar{m})(1 + \beta_h V_{\bar{m}})$ ($\bar{m} \geq 1.7$ GeV and $V_{\bar{m}}$ are the mass and the velocity of the lightest of the M particles) and $\langle E_h\rangle_M \approx \langle E_h^*\rangle\sqrt{s}/2m_M$. To estimate $\langle E_h^*\rangle$ we assume that the production of M particles predominates in the jets (see 1e) at small x. We then obtain (assuming isotropy of the decays of M) $\langle p_h^*\rangle \approx \sqrt{3/2}\ \langle p_\perp\rangle$ and $\langle E_\pi^*\rangle \gtrsim 0.4$ GeV, $x^\pi_{\max} \sim 0.4$.

We assume that the deviation of ϵ_q from 2/3 is due to ambiguities in its determination (see[1,3]). Then the dependence of $\langle n_{ch}\rangle$ and of ϵ on $\sqrt{s}$ is given by

$$\langle n_{ch}\rangle = \langle n_{ch}\rangle_M + \frac{R_q}{R(s)}(\langle n_{ch}\rangle_q - \langle n_{ch}\rangle_M), \tag{2}$$

$$\epsilon = \epsilon_M + (\epsilon_q - \epsilon_M) R_q / R(s). \tag{3}$$

From (2), (3), and (1a) and (1d) it follows directly that $\partial n_{ch}/\partial \ln s$ in region III is smaller than unity by approximately a factor of 2, and that $\epsilon_M \sim 0.4$ and $\langle n_{ch}\rangle_M \approx 2\langle m_M\rangle \epsilon_M/\langle E_h^*\rangle \sim 3.5$ to $4 \leq \langle n_{ch}^{II}\rangle_q$. (Comparison of (1b) with the experimental data[1,2] leads to $\langle n_{ch}\rangle_M \approx 3.75$). It follows from (2) and (3) that a growth of R_{II} should correspond to a gently-sloping behavior of $\langle n_{ch}\rangle_{II}$ and the minima of R_{II} correspond to maxima in $\langle n_{ch}\rangle_{II}$ (see (1c)). The experimental data on $\langle n_{ch}\rangle_{II}$ exhibit the indicated tendencies, with a maximum occurring at $\sqrt{s} = 4.6$ GeV (corresponding exactly to a minimum of R[1,2]). For $\langle E_h\rangle_{II}$ we analogously expect a gently sloping behavior in accord with experiment.[1,2]

The considered scheme lends itself to experimental verification: events in which at least one $h^\pm$ has $x > 0.4$ should correspond to larger values of $\langle n_{ch}\rangle \approx \langle n_{ch}\rangle_q$ ($\langle n_{ch}\rangle_q \sim 6.5$ at $\sqrt{s} \sim 8$ GeV) and should have $\epsilon \approx \epsilon_q$ with $f_e(x)$ gauge-invariant. The properties of the M component should be investigated with the remaining events.

We note that there are indications[2] of structures in $\langle n_{ch}\rangle$, $\langle E_{ch}\rangle$, and $f_e(x)$ at $\sqrt{s} = 6$ to 7 GeV possibly corresponding to the opening of new thresholds. A certain increase of R should then be observed in the indicated region.

3. The assumption that the M component is due only to L pairs explains the properties 1a—1g and particularly 1h. Contradicting this hypothesis is the absence of coupling between L and the ψ mesons, although the scale of the phenomena in ψ production and in region II seems to be of the same nature. In addition, the function $f_e(x)$ averaged over the region $\sqrt{s} = 4.1$ to 4.4 GeV of the structures agrees fully with its value at $\sqrt{s} = 4.8$ GeV.[2]

On the other hand if M constitutes U mesons, then to avoid a discrepancy with the data 1d—1h it must be assumed that some of them have a spin $J > 0$. $[\Gamma_U \to e(\mu) + \nu + \text{hadr})]/\Gamma_U \sim 10$ to 25% and that in the nonleptonic mode, apparently, an important role is played by production of resonances of the type η, $X_0, \ldots$, and (or) transitions of the type $U' \to U + \gamma$ are important.[3,4] Simple estimates of weak decays of U in the quark model show that leptonic decays are small, and the nonleptonic ones are several times larger than the semileptonic decays. In the estimate of ϵ_U it must be borne in mind that the production of new particles is an additional source of radiative corrections.

It is difficult to exclude the possibility that L and U mesons are produced simultaneously and that there exists a symmetry connecting L and Q.

We note in conclusion that an alternative to the scheme discussed above might be the production of a large number of narrow resonances (of the type ψ) in the M component.

Observation of the production of pairs of hadrons of the type $U = p\bar{Q}$ in $e^+e^- \to$ hadrons would mean observation of a new scale in strong interaction. It is interesting that such a scale arises in natural fashion in the quark model, since by virtue of the Zweig rule the amplitude of the $Q\bar{Q} \to q\bar{q}$ transition is suppressed.[4] Let us list the main consequences of the hypothesis on the mass increase of the heavy quark:

1) The form factors of mesons of type U contain a contribution that varies slowly over scales on the order of $s \sim m_\psi^2$.

2) The radius of particles of the type $\psi = Q\bar{Q}$ is $r \sim 1/m_\psi$, and this helps explain the following: (a) the anomalously large value of $\Gamma[\psi(3.1) \to e^+e^-]/\Gamma[\psi(3.1) \to \gamma + \text{hadr}]$ as a result of the low probability that ordinary hadrons will emerge from a small volume; (b) the large multiplicity in the decay of new particles; (c) the suppression of radiative decays of the type $\psi(3.7) \to p_c + \gamma$ and $\gamma(3.1) \to \eta_c + \gamma$; etc.

3) In a wide range, the reaction $e^+e^- \to$ hadrons occurs in such a picture as production of heavy particles of the $q\bar{Q}$ type. The continuous spectrum becomes significant at $|p_Q|/m_Q \gg 1$.

4) In processes occurring over small distances, where the masses of the quarks are insignificant, the broken symmetries $SU(3)$, $SU(4)$, etc. should be restored.

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