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DYNAMICAL CONCEPTS ON SCALING VIOLATION AND THE NEW RESONANCES IN e^+e^- ANNIHILATION

by

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ABSTRACT

We present the essential experimental results on the total and the single-particle inclusive cross sections in e^+e^- annihilation. They show scaling violation and extremely narrow resonances in the energy range beyond 3 Gev. The theoretical ideas about these phenomena are sketched and their characteristics and implications explained. New models are proposed.

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C O N T E N T S

1. INTRODUCTION

The recent discoveries of totally unexpected features in e^+e^- - physics have caused a large amount of theoretical speculations, estimations and predictions on the behaviour of electromagnetic interactions at extremely short distances. In this paper(*) we present the essential experimental discoveries - the non-scaling behaviour of $e^+e^- \to$ hadrons(1) and the narrow resonances(2) - and give an introduction to the theoretical explanations of these phenomena.

With the construction of high energy electron accelerators, deep-inelastic electron-proton scattering processes became experimentally possible which give us information how the off-shell photon (exchanged between electron and proton) interacts with the proton. Such experiments permit simultaneous variation of the photon mass $\sqrt{q^2}$ as well as the photon-proton CM-energy $(E_{CM})^2 = W^2$. In particular, in the energy region where $(-q^2, W^2)$ becomes very large, one expects the differential cross section to be only dependent on the dimensionless ratio of these two variables. The experiments in the region $(-q^2, W^2) \lesssim 40$ Gev^2 have sofar confirmed this scaling property(3).

The construction of e^+e^- intersecting storage rings made similar experiments possible however in the time-like region of q^2 . One expected that scaling would also hold in $e^+e^- \to \gamma \to$ hadrons; however, this was not the case. The scaling hypothesis predicts the energy dependence of the total hadronic cross section as : $\sigma(e^+e^- \to h) \propto 1/q^2$, whereas the early experimental results indicated $\sigma(e^+e^- \to h) \cong$ constant beyond 3 Gev. This scaling violation lead to a large amount of theoretical activity which we would like to sketch here[(4)].

A new aspect of this problem recently became apparent when extremely narrow resonances were found at 3.1 Gev and 3.7 Gev. A refined analysis of the experiment then showed more structure around 4.1 Gev and a cross section behaviour between 2.0 $\text{Gev}^2 \leq q^2 \leq 9.0\ \text{Gev}^2$ which is roughly in agreement with scaling[(5)]. It is possible that these two features (scaling violation and narrow resonances) are connected, however, a convincing dynamical mechanism is still lacking.

At the present time, it is difficult to present a conclusive analysis of the theoretical and experimental situation. We therefore sketch the theoretical schemes which suggest violation of scaling or non-asymptotic deviations, as well as the proposed models for the narrow resonances, intentionally not excluding models which, on the basis of the experimental information, seem to be in difficulties or which are based on unusual theoretical assumptions. Our intention is to present some of the proposed explanations, discussing their pros and cons and to maintain interest in ideas outside the main streams.

This paper is divided in three parts. In the first one we present the essential experimental results in e^+e^- annihilation before the discovery of the narrow resonances and subsequently discuss the new experimental data of the narrow resonances. The attempts to understand a possible scaling violation in the present energy range are sketched in the second part. In the third part we discuss the proposed explanations for the newly discovered narrow resonances and wide enhancement.

2. THE EXPERIMENTAL RESULTS

In this section we will present the experimental results of[1, 5, 6]

(1) $e^+e^- \to$ hadrons : $\sigma_h(q^2)$

(2) $e^+e^- \to h^\pm + X$: $E\,\frac{d^3\sigma}{dp3}$

(3) $e^+e^- \to \mu^+ + \mu^-$: $\sigma_\mu(q^2)$

Concerning the first reaction we are interested in the hadronic total cross section. The single-particle inclusive cross section of the second reaction gives us information on the photonic hadron production mechanism. The measurement results of μ-pair production are in agreement with QED calculations apart from the narrow resonances which appear in this channel too[7].

2.1. The total cross section

In the following we will use the notation introduced in Fig. 1. The only invariant variable of this process is the CM-energy square $(E_{CM})^2 = q^2 = (p_+ + p_-)^2$. What is the asymptotic dependence of $\sigma_h(q^2)$ on q^2 ? For a long time it was a common belief that this quantity would decrease like $1/q^2$.

It was based on the scaling hypothesis which assumes that there is no fundamental scale length in electromagnetic and weak interactions; dimensionality considerations then predict such a characteristic. Early theoretical investigations such as field theory-, dual resonance-, parton- and light-cone-models and a number of other approaches predicted similar decrease. The measurements, extended to $q^2 \lesssim 25$ Gev^2 , indicated first an approximately constant behaviour (Fig. 2). Lateron a pronounced resonance structure became apparent (Fig. 3). It is one of the most eagerly awaited answers whether such behaviour will persist. Preliminary results indicate that it falls again for $q^2 > 25$ Gev^2 (13).

These results are often presented as the ratio of the total hadronic to total $\mu^+\mu^-$ -production cross sections

$$R(q^2) = \frac{\sigma(e^+e^- \to h)}{\sigma(e^+e^- \to \mu^+\mu^-)} \tag{2.4}$$

where the latter is supposed to follow the single-photon exchange approximation with electron and μ-meson point coupling :

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi}{3} \cdot \frac{\alpha^2}{q^2} \tag{2.5}$$

$R(q^2)$ is represented in Fig. 4 . Instead of a constant behaviour (scaling) the hadron to μ-pair ratio gradually rises beyond $q^2 = 9$ Gev^2 . More refined analysis showed some pronounced resonance structure around $\sqrt{q^2} = 4.1$ Gev followed by a dip around 4.6 Gev and again a rise. The early experimental results had large error bars and globally indicated a rise but gave little indication on the resonance-like structure which now becomes more and more apparent (Fig. 5).

2.2. The inclusive cross section

In a one-particle inclusive measurement the momentum of a chosen type of particle is measured. Such a particle can come from any scattering process : elastic, quasi-elastic, inelastic or deep-inelastic. Its origin is not distinguished.

In the measurements on $e^+e^- \to h + X$ there was no specific elementary particle chosen, but all charged hadrons instead. Therefore, $h \equiv \{\pi^\pm, K^\pm, p, \bar{p} \ldots\}$. The measured quantity is the sum of the individual cross sections for charged inclusive hadron production. Taking into account the ratio of the average number of produced particles from another measurement $\langle n_{\pi^\pm} \rangle : \langle n_{K^\pm} \rangle : \langle n_p \rangle = 100 : 10 : 1$ one concludes

$$\left(E \cdot \frac{d^3\sigma}{d^3p} \right)_{exp.} = \sum_{i \varepsilon h} E \cdot \frac{d^3\sigma^i}{d^3p} \approx E \cdot \frac{d^3\sigma^{\pi^+}}{d^3p} + E \cdot \frac{d^3\sigma^{\pi^-}}{d^3p} \qquad (2.6)$$

and expects deviations of the order of 10%. Note that the relative inclusive rates are momentum dependent - falling for $\pi^-/h^{(-)}$ and rising for $K^-/h^{(-)}$ respectively $\bar{p}/h^{(-)}$ (Fig. 6).

The most important experimental characteristics are :

i) From simple dimensionality arguments (scaling, section 3.1.) one expects $q^2 \frac{d\sigma}{dx} = f(x,q^2)$, plotted versus $x \equiv 2E/\sqrt{q^2}$, to show no variation with changing q^2 at asymptotic energies ($E \equiv$ energy of inclusive particle). The experiment, however, exhibits a clear q^2-dependence for $x < \frac{1}{2}$ (Fig. 7, 8).

ii) $\frac{1}{\sigma_h} \cdot \frac{d\sigma}{dx}$ is also dependent on x and q^2 (Fig. 9)

iii) The distribution $E \cdot \frac{d^3\sigma}{dp^3}$ versus p is independent of the initial CM-energy q^2 and decreases exponentially with growing momentum, like $\exp(-5 \cdot p)$ (Fig. 10, 11). A similar characteristic was found in hadronic reactions where $E \cdot \frac{d^3\sigma}{dp^3} = (X_\parallel, p)$ depends on E_{CM} only through the scaling variable $x_\parallel \equiv p_\parallel / p_{max}$, $p_{max} = \frac{1}{2} E_{CM}$.

The momentum dependence of inclusive (π, K, p) - production is shown in Fig. 12.

iv) The mean momentum per charged particle (hadrons + leptons + ... !) and mean charged multiplicity rise slowly with increasing initial CM-energy : $3.0 \leq \sqrt{q^2} \leq 7.0$ Gev

$$< p_\pm > \quad = \quad 0.4 \rightarrow 0.5 \quad \text{Gev}/c \qquad (2.7)$$

$$< n_\pm > \quad = \quad 3 \rightarrow 4 \rightarrow \ldots \qquad (2.8)$$

Most recent results indicate $<n_\pm>$ to go beyond 4.5 at $\sqrt{q^2} \sim 7$ Gev (Fig. 13).

v) The inclusive angular distribution of the charged particles (expected to be like $(1 + \cos^2\theta)$ in the parton model) is consistent with isotropy for $|\cos\theta| \leq 0.6$ and $3.0 \leq \sqrt{q^2} \leq 5.0$ Gev (Fig. 14).

The hadronic total - and inclusive cross sections are connected by the energy momentum conservation sum rule

$$P_\mu \cdot \sigma_{tot} = \sum_{all} \int d^3p \cdot p_\mu \cdot \left(\frac{d^3\sigma}{d^3p}\right) \qquad (2.9)$$

from which we deduce the relation

$$E_{CM} = \{ \langle n_\pm \rangle \cdot \langle E_\pm \rangle + \langle n_o \rangle \cdot \langle E_o \rangle \} = (\sqrt{q^2}) \qquad (2.10)$$

$\langle E_{\pm,o} \rangle$ is the average energy going into one charged/neutral particle. Experimentally, the first term rises since $\langle E_\pm \rangle$ and $\langle n_\pm \rangle$ rise ; however, its relative contribution $\langle E_\pm \rangle \cdot \langle n_\pm \rangle / E_{CM}$ diminishes. Consequently, more energy goes into neutral particles with growing CM-energy.

(Note $$\langle n \rangle = \sum_h \int_{\frac{2m_\pi}{\sqrt{q^2}}}^{1} \frac{1}{\sigma_h} \cdot \left(\frac{d\sigma}{dx}\right) dx \qquad \left(x \equiv \frac{2E}{\sqrt{q^2}} \right) \qquad (2.11)$$

is the charged hadronic multiplicity).

In Fig. 4 we have drawn

$$R_{(\pm)} = \frac{\sigma(\pm)}{\sigma_\mu}, \quad \sigma(\pm) = \frac{\langle n_\pm \rangle \langle E_\pm \rangle}{E_{CM}} \sigma_h \qquad (2.12)$$

which indicates the percentage of energy going into charged particles and reflects the non-gegligible amount of energy going into uncharged particles like $\pi^o, K^o, \ldots$, photons, etc. This characteristic is known under the heading "energy crisis". Note that it can also be explained by the rough experimental data and might finally disappear[8].

2.3. The New Resonances

The experimental features just presented are explained by a variety of theoretical schemes which globally can (or cannot) describe the data; they will be presented later. The question of why scaling does not set in as early as in deep inelastic electron proton scattering however is still an unsolved problem. The discovery of extremely narrow resonances in the e^+e^- channel of the reaction $p + Be \rightarrow e^+e^- + X$ at Brookhaven[9] opened another aspect of e^+e^- physics which might be related to the unexpected general characteristics.

2.3.1. The Resonances ψ

Measurements at SLAC[10], ADONE[11] and DESY[12] show resonance spikes in the reactions $e^+e^- \rightarrow$ hadrons and $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu$ at 3095 Mev and 3684 Mev. They were given the names J (Brookhaven), ψ (SLAC) for the first one and ψ' (SLAC) for the second one. The experimental determination of their widths is limited by the beam resolution : $\Gamma_\psi \lesssim 1.9$ Mev[10].