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

(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

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

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

$$< p_{\pm} > \quad = \quad 0.4 \rightarrow 0.5 \quad \text{Gev}/_c \tag{2.7}$$

$$< n_{\pm} > \quad = \quad 3 \rightarrow 4 \rightarrow \ldots \tag{2.8}$$

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 $|\cos\theta| \lesssim 0.6$ 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)].

Gaussian shape distribution function for the energy resolution folded with a Breit-Wigner resonance permits much more precise determination of the actual widths. They were found to be in the range 50 - 100 kev corresponding to a life time of $\tau \sim 10^{-20}$ sec. The cross sections at the top of the resonance $\psi(3095)$ are :

$$\begin{aligned} &\sigma_\psi(e^+e^-\to h) \simeq 3000 \text{ nb} \qquad &\Gamma_{tot} = 69 \pm 15 \text{ kev} \\ &\sigma_\psi(e^+e^-\to\mu^+\mu^-, e^+e^-) \simeq 100 \text{ nb} \qquad &\Gamma_e = 4.8 \pm 0.6 \text{ kev} \end{aligned} \tag{2.13}$$

At the resonance $\psi'(3684)$ they are smaller

$$\begin{aligned} &\sigma_{\psi'}(e^+e^-\to h) \simeq 1000 \text{ nb} \qquad &\Gamma_{tot} = 225 \pm 56 \text{ kev}^{(13)} \\ &\sigma_{\psi'}(e^+e^-\to e^+e^-, \mu^+\mu^-) \simeq \ ? \qquad &\Gamma_e = 2.2 \pm 0.5 \text{ kev} \end{aligned} \tag{2.14}$$

Consequently, the ratio $R \equiv {}^{\sigma_h}/\sigma_\mu$ jumps from about 3 off the resonance to $R \gtrsim 30$ at the peak of ψ . The shape of ψ is drawn in Fig. 15 and in more details in Figs. 16, 17; similar curves exist for ψ' (Fig. 18). SPEAR has systematically searched for further narrow resonances in the energy range 3.2 - 5.9 Gev by scanning in ~ 2 Mev steps and by imposing $\int \sigma_h(E)\, dE \lesssim 10^3 \text{nb} \cdot \text{Mev}$. No further such objects were found[10d]. The search has been carried out at higher energies and no further narrow resonances were found.[13]

Measurements in the range 2.4 - 5.0 Gev showed a broad enhancement ψ'' with peak at 4.1 Gev (Fig. 3). In the vicinity of this region the cross section varies between 32 nb and 17 nb[10e]. Taking it as a resonance it would have a total width of $\Gamma_{\psi''} \sim 300$ Mev. Table I gives the essential characteristics of the important resonances in e^+e^- channels. The spin-parity of ψ (3.1) was determined by the angular distributions of $e^+e^- \rightarrow \mu^+\mu^-$, e^+e^- which are consistent with $J^P = 1^-$. One further knows that the transition : $\psi' \rightarrow \psi + \pi^+\pi^-$ exists (Fig. 19). The angular distribution of the $(\psi - 2\pi)$ system is in agreement with the spin-parity assignement $J^P = 1^-$ for ψ'(10f,10h). ψ' and ψ thus seem to carry the same quantum numbers as the photon and might well be directly coupled ' à la vector meson dominance'. Nothing is known sofar about the 4.1 enhancement ($J^P = 1^-$?) which could also be due to a threshold.

2.3.2. The Decay Modes

Some of the essential decay modes of ψ and ψ' and their (preliminary) branching ratios are represented in tables II and III. We mention : a relatively important decay is $2\pi^+ 2\pi^-$+missing mass (π^0?); the $2\pi^+ 2\pi^-$decay is substantially smaller. Off resonance the $2\pi^+ 2\pi^-$fraction is $\sim$ 1/20 of all hadronic decays. On resonance it is estimated by taking $\frac{1}{20}$ Γ ($\psi \rightarrow \gamma \rightarrow$ hadrons) $\sim$ 0.65 kev and is not very far from the experimental value 0.35 kev. Rough estimates predict 1/3 of all decays via single photon exchange. The 5 pion decay mode seems to be directly coupled. If it occurs via strong interactions, G-parity must be G = -1 and isospin I = 0 or 2 for ψ (3.1), an assignment which is consistent with other observed modes like $\pi^+\pi^-$ $p\bar{p}$, $p\bar{p}$, $\pi^+\pi^-$ K^+K^- and $\Lambda\bar{\Lambda}$. The cross section for an odd number of pions is substantially bigger than that for an even number of pions [5,10g,10i].

No special features are known on the $\psi''(4.1)$-enhancement sofar. Decays like $\psi'' \to \psi' + \pi\pi$ or $\psi + \pi\pi$ have apparently not been detected. The leptonic decay width is a few kev.

2.3.3. Inclusive Distributions

A DASP group has measured the inclusive distribution at ψ (3.1) and preliminary results indicated that it also decreases exponentially, roughly [12e]. More recent data from SLAC, which compare the re-scaled inclusive ψ-distribution with the one outside the resonance exhibit deviations of a factor $\sim \frac{1}{2}$ at large x (Fig. 20) [10i]. Apart from the difference in the counting rates, all measured quantities such as $\langle p_{\pm} \rangle$, $\langle n_{\pm} \rangle$, etc. on and off the resonance seem to be the same. The ratios $\left(\frac{\pi^-}{h^{(-)}}, \frac{K^-}{h^{(-)}}, \frac{\bar{p}}{h^{(-)}}\right)$ indicate relatively small changes on and off the resonance ψ (3.1) (Fig. 21). However, more recent results on the K^--fraction (Fig. 22) reveal that K^--production is suppressed by $\sim$ 20% at ψ (3.1) . Note that most recent data on particle ratios, in comparison with earlier curves (Fig.21 vs Fig. 6) show a more pronounced decrease in $\pi^-/h^{(-)}$ and increase with $K^-/h^{(-)}$ with growing momentum p [13].

2.3.4. Hadronic Production

$\psi(3.1)$ has been found in the mass spectrum $M^2_{e^+e^-}$ of $p = Be \to e^+e^- + X$ [14a]. The initial energy was 28.5 Gev.

The cross section estimate is not without problems since the inclusive distribution in p_t and $p_{//}$ is unknown. The assumption of an exponential cut-off gives :

$$\sigma(p+Be \to \psi+X) \sim 0.1\ {}^{nb}/\text{nucleon} \Rightarrow \sigma(p+N \to \psi+X) \sim 1.5\ {}^{nb}/\text{nucleon}$$

Apparently, the ψ-enhancement disappears at 20 Gev initial energy[14b]. Search for $pp \to \psi' + X$ was negative; this is partially explained by the small branching ratio into $\ell^+\ell^-$ [14c]. The background contribution in the 28.5 Gev experiment is small. The resonance to background ratio for e^+e^- - and pp - initiated ψ-production is

$$R(e^+e^-) = 300 \text{ Mev} \; ; \; R(pp) = 1200 \text{ Mev}$$

where we have used the definition : $R(pp) \equiv \left(\frac{\text{Res. - events}}{\text{BG. - events/Mev}}\right)_{pp}$ The Brookhaven ratio is larger than the SPEAR ratio, but in the same order of magnitude[14d,e].
Results with initial neutron energies peaked at 250 Gev show[14f,g]

$$\sigma(n+Be \to \psi+X) \sim 3\ {}^{nb}/\text{nucleon} \Rightarrow \sigma(n+N \to \psi+N) \sim 45\ {}^{nb}/\text{nucleon.}$$

considerably larger values.

2.3.5. Photoproduction

Search for ψ's produced in photo-initiated reactions initially gave only upper limits of the cross section :

$$E\gamma = 11.1 \text{ Gev} \quad \sigma(\gamma N \to \psi N) \lesssim 1 \text{ nb}^{(15a)},\ 0.65 \text{ nb}^{(15b)}.$$

$$E\gamma = 18.2 \text{ Gev} \quad \sigma(\gamma N \to \psi N) \lesssim 29 \text{ nb}^{(15c)},\ 3.7^{+2.2}_{-1.5} \text{ nb}^{(15d)}.$$

Preliminary information from SLAC indicates

$$E\gamma \;=\; 17 \text{ Gev} \quad \frac{d\sigma}{dt}\,(\gamma p \to \psi + X) \propto \cdot\; e^{(2.6\,\pm\,0.9)\,\cdot\,t}$$

The integrated cross section $\sigma(\gamma p \to \psi X)$ rises by a factor of 2 in the range 15 Gev $\leq E\gamma \leq$ 18 Gev [15e]. Experiments at FNAL [15f] have discovered a ψ-enhancement and are able to determine the (expected) diffractive shape with an extimated slope around $b \sim 4$ Gev^{-2} . The cross section value is

$$E\gamma < 200 \text{ Gev} \quad \sigma(\gamma + Be \to \psi + X) = 16 \pm 5 \text{ nb/nucleon}$$

giving $\sigma_{tot}\,(\psi N) \cong 1$ nb . Table VI summarises the parameters of the diffractively produced vector mesons : ρ, ω, ϕ, ψ [15c].
