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HADRON INDUCED LEPTON PRODUCTION

C.W. Fabjan

CERN, Geneva, Switzerland

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1. INTRODUCTION

In recent years the study of hadronic production of leptons has occupied a prominent place in high-energy physics, with a number of very important results to its credit. These are widely reviewed in the literature¹⁻⁶⁾ and discussed again here. Relatively more emphasis is, however, given to some very recent results, which have emerged from work carried out at the CERN Intersecting Storage Rings (ISR), where a broad programme of lepton studies was initiated a few years ago.

The original experiment was carried out some 14 years ago by a Columbia-BNL group, headed by L. Lederman. Although its goal -- the discovery of the weak intermediate boson through its decay $W^\pm \rightarrow \mu^\pm \nu$ -- remains elusive, these studies have proved so fruitful as we have learnt to interpret many diverse results in the language of the quark-parton model (Fig. 1). As one of the major contributions, these experiments have produced evidence for the existence of two new quark flavours in addition to the three originally invoked. Furthermore, the study of the dilepton continuum (Fig. 1a) has progressed to become a sensitive tool for probing the nucleon structure and parton dynamics, complementary to the deep inelastic lepton-nucleon scattering experiments (Fig. 1b). Another testing ground of parton dynamics is the production of particles with large transverse momentum (Fig. 1c), a process orders of magnitude stronger than Fig. 1a and originally discovered as a "background" in searches for leptons. Very recent results confirm the notion of an intimate connection between lepton pair production (Fig. 1a) and high- p_T phenomena (Fig. 1c): both processes point towards unexpectedly large transverse momentum distributions of the partons, thought to be at the origin of the reactions.

The experimenter has the option to detect muons or electrons. The choice is conditioned by many parameters, such as primary interaction rate, experimental sensitivity, detection of other particles in the final state, but most importantly perhaps by the strategy of eliminating the devastating background of the trivial sources of leptons: weak decay of π 's and K's in muon searches; Dalitz decay of π^0 and η , and external photon conversion for electron experiments. At the fixed

target accelerators the detection of muons is generally favoured for the following reasons: instantaneous interaction rates reach $\sim 10^{12}$ events/sec or more with a corresponding sensitivity to cross-sections at the level of $\lesssim 10^{-38}$ cm². These high rates impose the shielding of the detectors from all but the very rare secondary particles, a requirement easier satisfied in μ -experiments. Furthermore, the secondaries are Lorentz-boosted and the background from π and K decay is correspondingly reduced. As an example, the experimental layout of the Columbia-Fermilab-Stony Brook (CFS) Collaboration²⁾ is shown in Fig. 2. It is a classic double-arm spectrometer which in the course of several experimental phases has been carefully optimized for the conflicting requirements of experimental sensitivity and mass resolution.

Different arguments apply for experimentation at the CERN ISR: interaction rates are at the level of 10^6 sec⁻¹ and make it possible to look at the complete event; the absence of the Lorentz-boost for π 's and K's results in a more serious μ background. Electron detection is usually preferred. As an example for a large solid-angle electron experiment⁵⁾, the apparatus of the Brookhaven-CERN-Syracuse-Yale (BCSY) Collaboration is shown in Fig. 3. In this experiment the electrons are identified in two different types of detectors: firstly, for the identification of electrons with $p > 1$ GeV/c, transition radiation detectors⁷⁾ produce a signature of $E_{tr} \approx 30$ keV, which provides roughly a factor of 100 discrimination against π 's. The spatial characteristics of the electromagnetic shower induced by the electrons in large liquid-argon sampling calorimeters⁸⁾ provide a further signature with again about a factor of 100 in pion rejection.

The scope of the discussion is as follows: we first review the experimental results on lepton pair production with invariant mass above 2 GeV, a study which has proved enormously fruitful. Next, the experimentally, perhaps more difficult and less explored mass region below 2 GeV, is discussed. We finish with a discussion on the status of experiments where mostly one single lepton is detected.

2. THE MASSIVE DILEPTON SPECTRUM ($M_{\ell\bar{\ell}} \gtrsim 2$ GeV)

The study of the dilepton spectrum with invariant mass $M \gtrsim 2$ GeV has provided some most remarkable advances: it has led to the discovery of new quark

flavours, and inspired a generation of experiments which are optimized to explore the mass region up to and (perhaps) beyond 15 GeV. The measurements of the dilepton mass continuum are developing into a rather sensitive tool for probing the structure of the nucleon and the dynamics of its constituents. These results are also considered to provide a basis for extrapolation into a new energy domain, where new phenomena, such as the production of massive intermediate bosons, will be searched for.

We discuss first some recent results on "quarkonium" production, which were obtained at the fixed target accelerators (FNAL and the CERN SPS) and at the ISR, to be followed by a survey of the dilepton continuum measurements and their interpretation.

2.1 Charmonium family

The level scheme of the charmonium, shown in Fig. 4, emerged from studies which were carried out principally at the electron machines DORIS and SPEAR^{9,10}. The spectroscopy of these states is described in terms of confined, spin $\frac{1}{2}$ quarks, with quantum chromodynamics (QCD) providing the theoretical framework. In the static limit, the potential is assumed to be of the form

$$V(r) = - \frac{4\alpha_s}{3} \frac{1}{r} + \beta r , \quad (1)$$

with the first part representing the one-gluon exchange potential and with the linear part expressing the quark confinement. Corrections due to spin-dependent forces, much in analogy with atomic physics, should be applied to the short-range one-gluon exchange potential and are assumed to be responsible for the observed fine and hyperfine structure.

In Fig. 5 we show the excitation cross-section for J/ψ and ψ' . After the initial fast rise from $\sqrt{s} \approx 10$ GeV to $\sqrt{s} \approx 30$ GeV (BNL-FNAL/SPS energy range) the cross-section for J/ψ production continues to rise by a factor of five over the ISR energy range^{5,11}). The same results are displayed in Fig. 5b as a function of the scaling variable $M/\sqrt{s}$. The signal for ψ' production in the dilepton channel is at the level of one percent compared to the dilepton signature from J/ψ decay.

Besides the production ratio of ψ' to J/ψ , important information exists on J/ψ production with different incident particles¹²⁻¹⁴). As an example, we give results of a study carried out at the CERN SPS on the ratios of J/ψ production by $\pi^\pm$, $K^\pm$, and $p^\pm$ beams at $\sqrt{s} = 8.6$ GeV:

$$\sigma(\pi^+)/\sigma(\pi^-) = 0.87 \pm 0.14 \quad (2a)$$

$$\sigma(K^+)/\sigma(K^-) = 0.85 \pm 0.5 \quad (2b)$$

$$\sigma(p)/\sigma(\bar{p}) = 0.15 \pm 0.08 \quad (2c)$$

In addition to measurements on the vector states, information exists on the production of χ states, which can be excited directly in hadronic collisions, in contrast to e^+e^- annihilation. The BCSY group has recently reported¹⁵) on results of a measurement at the ISR, where the J/ψ was observed in coincidence with photons which were attributed to the cascade decay $\chi \rightarrow J/\psi + \gamma$:

$$\left. \frac{B(\chi \rightarrow J/\psi, \gamma) \, d\sigma_{\chi}/dy}{d\sigma_{J/\psi}/dy} \right|_{y=0} = 0.43 \pm 0.21 \quad .$$

Although the errors are large, the result could imply that a significant fraction of the J/ψ 's are produced via such cascade decays. When combined with results of ψ' production, one can estimate the production rates of the vector states relative to the χ states.

The total cross-section $\sum J/\psi$ for J/ψ production is related to the direct production cross-sections (σ) of the individual channels in the form

$$\sum J/\psi = \sigma_J + \sigma_{\psi'} [B(\psi' \rightarrow J) + B(\psi' \rightarrow P_c) B(P_c \rightarrow J)] + \sigma_{P_c} [B(P_c \rightarrow J)] \quad (3)$$

and implies

$$\begin{aligned} \sigma_{\psi'} &= (0.38 \pm 0.2) \sigma_J \\ \sigma(\chi_{3508}) + \sigma(\chi_{3552}) &= (3.5 \pm 1.7) \sigma_J \quad . \end{aligned} \quad (4)$$

To complete the discussion on the excitation of charmonium levels in hadron collisions, we mention the recent observation¹⁶) of a meson X of mass 2.85 GeV in the reaction $\pi^- p \rightarrow (X \rightarrow \gamma\gamma)n$ at $\sqrt{s} = 8.7$ GeV. The mass and the level of production ($\sigma \cdot B = 2 \times 10^{-34} \text{ cm}^2$) suggest identification with the lowest pseudoscalar state, η_c , of the charmonium family.

The information on $\sqrt{s}$ -dependence, the level of χ production, and the excitation by particles with different quark content provide some stringent tests on production models. We sketch here the principal assumptions and predictions of three of the most popular ones, which were specifically applied to the hadronic production of the charmonium states (Fig. 6).

The idea of the fusion of a c -quark with a $\bar{c}$ -quark from the sea distributions¹⁷⁾ of the colliding hadrons is pictured in Fig. 6a. A reasonable fit to the $\sqrt{s}$ - and x -dependence for J/ψ production is obtained, however, with a sea distribution $\sim (1-x)^N$, where $N = 5$; we shall see later that data on the lepton continuum favour a value of $N = 9$ or 10 . Intuitively one would expect to find in this model [although counter arguments have been given¹⁷⁾] the J/ψ 's frequently accompanied by $D\bar{D}$ pairs; this has not been observed experimentally: $\sigma(J/\psi + D\bar{D} + x)/\sigma(J/\psi + x) \lesssim 0.03$. Perhaps the most stringent test is implied by the result (2c), as this model would naively predict this ratio to be one. [See, however, A. Donnachie et al.¹⁷⁾ for more refined arguments.]

The two-gluon fusion mechanism has been proposed¹⁸⁾ as a possible explanation for the observed ratio of $\sigma(\psi)/\sigma(\psi')$ (Fig. 6b). In this process the χ states (together with S_0 states) are directly formed, and J/ψ production proceeds mostly through the cascade decays $\chi \rightarrow J/\psi + \gamma$. Again, J/ψ production by $\bar{p}$'s is not favoured over p -induced production.

The third model pre-supposes the fusion of ordinary quarks and antiquarks (Fig. 6c) to produce new quark flavours via massive virtual gluons¹⁹⁾. In this approach a large ratio of $(\bar{p} \rightarrow J/\psi)/(p \rightarrow J/\psi)$ at all values of $\sqrt{s}$ is one of the principal predictions. While we wait for more definitive tests, arguments are being advanced^{20, 21)} that an $\sqrt{s}$ -dependent mixture of various processes, in particular (6b) and (6c), is operative, with the contribution of gluon amalgamation (6b) increasing with $\sqrt{s}$ and dominating already at ISR energies.

2.2 The T family

The observation of narrow resonances in the 9-10 GeV mass region has been reported by the CFS Collaboration²²⁾ last year. Indication for this resonance was shortly afterwards also obtained in pp collisions at the CERN ISR²³⁾.

Published data from the CFS group are given in Table 1 and indicate that there are most likely three resonances with a width consistent with the experimental mass resolution. In the meantime the CFS group has obtained about five times more data, and their preliminary analysis now indicates a cross-section

$$B_{T \rightarrow \mu\mu} \left. \frac{d\sigma}{dy} \right|_{y=0} = 0.28 \pm 0.013 \times 10^{-36} \text{ cm}^2 \quad \text{at} \quad \sqrt{s} = 27.4 \text{ GeV}$$

and about a 3 st. dev. statistical significance of the third (T'') resonance²⁴). The $\sqrt{s}$ -dependence of the excitation cross-section is given in Fig. 5b, again as a function of the scaling variable $M/\sqrt{s}$. The solid line follows the scaling prediction of Halzen and Matsuda²⁵) where the production of a gluon of mass M is CVC-related to the measured cross-section of virtual photons. This model relates the production cross-section σ_V of vector mesons with mass M_V to the measured cross-section J/ψ in the form

$$\sigma_V(\sqrt{s}) = \frac{\Gamma_V}{\Gamma_{J/\psi}} \left(\frac{M_{J/\psi}}{M_V} \right) \sigma_{J/\psi} \left(\frac{M_{J/\psi}}{M_V} \sqrt{s} \right), \quad (5)$$

where Γ is the hadronic decay width of the state in question. With the plausible assumptions^{26,27}) of $\Gamma_T = 10 \text{ MeV}$ and $B(T \rightarrow \ell\ell) = 0.05$, one estimates with Eq. (5):

$$B_{T \rightarrow \ell\ell} \left. \frac{d\sigma}{dy} \right|_{y=0} = 0.36 \times 10^{-36} \text{ cm}^2 \quad \text{for} \quad \sqrt{s} = 28,$$

and a rise in the production cross-section of ~ 100 , in very good agreement with the observed cross-section²³) [we use $B(d\sigma/dy)_{T, T', T''} = 0.41 \pm 0.24 \times 10^{-34} \text{ cm}^2$ and the same relative intensities for T, T', T'' as in Ref. 24]:

$$B_T \left. \frac{d\sigma}{dy} \right|_{y=0} = 0.29 \pm 0.17 \times 10^{-34} \text{ cm}^2 \quad (\sqrt{s} = 63 \text{ GeV}).$$

Present theoretical prejudices favour an interpretation of the T family as the bound state of a new quark-antiquark flavour, with calculations on the level scheme faithfully modelled after the $c\bar{c}$ success story. This interpretation is particularly attractive, as it would associate with a new heavy lepton τ -- which is very probably seen in e^+e^- collisions²⁸) -- its new quark doublet

$$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \Rightarrow \begin{pmatrix} t \\ b \end{pmatrix}$$

extending the underlying hadron symmetry to $SU(6)[\text{flavour}] \times SU(3)[\text{colour}]$.

Although most people tend to agree on the principles, a literal translation of the charmonium ideas has not been an unqualified success: we are not yet sure whether we see the b^- or the t -quarks, or both, or a superposition; the same form of the potential, used to explain the charmonium level scheme, predicts three bound states for $M_q = 5$ GeV, but with some disagreement on the spacing, and perhaps worse discrepancy on the level intensities. However, this may just be a reflection of our growing pains, as QCD promises cures for all such diseases: it was recently shown²⁹⁾ that a logarithmic potential reproduces the measured level spacing correctly, and that in the QCD framework such a potential is "naturally" explained. It will be the role of the new intermediate energy e^+e^- machines (CESR at Cornell and the upgraded DORIS at DESY) to disentangle the complex spectroscopy very probably associated with the new quarks.

2.3 Dilepton mass continuum

The study of the dilepton continuum is of course experimentally intimately connected with the resonance physics discussed in the previous section: "it is the stage on which resonances perform"*). In the wake of the original BNL-Columbia experiment³⁰⁾, which observed a dimuon continuum for the first time, a number of theoretical interpretations were advanced, one of which seems to have survived as the fittest: Drell and Yan³¹⁾ developed the idea of regarding the lepton pair as the decay of a massive, virtual photon produced in the annihilation of partons with antipartons. The original agreement between the model and the data was poor^{31,32)}, mainly because

- most of the mass range was contaminated by the broad J/ψ peak;
- parton distributions (in particular the sea distribution) were poorly known;
- the experiment was carried out using uranium as the target, which requires a very good knowledge of the A -dependence of the cross-section.

*) *Sic dixit* Lederman in Ref. 2.

However, the recent high statistics data from Fermilab data³³⁾, experiments using different incident beams both at FNAL³⁴⁾ and at CERN³⁵⁾, and new data from the ISR²³⁾ -- with soon to be improved statistical significance -- are building up to an incisive confrontation with the model. Within the framework of the Drell-Yan (DY) concept these measurements provide:

- another test of our present constituent model ideas, as the DY production cross-section is evaluated with the structure functions, measured in deep inelastic lepton-nucleon scattering;
- a sensitive test of the colour degree of freedom;
- an indication of the parton transverse momentum through the measurement of the angular and p_T distribution of the pairs;
- based on the scaling prediction, an extrapolation into new energy domains and estimates on the production of new phenomena, such as Z^0 , or $W^\pm$.

We will first sketch the DY formalism, discuss some experimental evidence in support of the parton-antiparton annihilation idea, and then comment on the above four points³⁶⁾.

We consider colliding hadrons with four-momenta P_λ , P'_λ , which contain partons carrying fractional momenta $p_\lambda = x_1 P_\lambda$ and $p'_\lambda = x_2 P'_\lambda$. In the collision of these partons a system with invariant mass M is produced:

$$(p_\lambda + p'_\lambda)^2 = M^2 = (x_1 P_\lambda + x_2 P'_\lambda)^2 = x_1 x_2 s ,$$

$$0 < x_1 x_2 = \frac{M^2}{s} = \tau < 1 .$$

The cross-section, which is given in the form

$$\frac{d\sigma}{dM^2} = \frac{4\pi\alpha^2}{3M^4} F(\tau) , \quad (6)$$

depends, through $F(\tau)$, on the distribution of partons and antipartons in the colliding hadrons, with $F(\tau)$ given as

$$F(\tau) = \frac{1}{N_c} \frac{x_1 x_2}{\sqrt{x^2 + 4\tau}} \sum_{\substack{i \\ \text{all} \\ \text{flavours}}} e_i^2 [q_{1i}(x_1) \bar{q}_{2i}(x_2) + \bar{q}_{1i}(x_1) q_{2i}(x_2)] , \quad (7)$$

where

$$x = x_1 - x_2,$$

$$x_{1,2} = \frac{1}{2} (\sqrt{x^2 + 4\tau} \pm x),$$

N_c is the number of colours.

If we assume a model of a $SU(4) \times SU(3)$ colour gauge theory, we have $N_c = 3$ and altogether eight quark distributions $q_i(x)$ and $\bar{q}_i(x)$. The electron- and neutrino-nucleon scattering data provide six relations on the quark distributions, which can be supplemented by the assumption

$$s(x) = \bar{s}(x) \quad \text{and} \quad c(x) = \bar{c}(x)$$

on the sea quarks.

i) *Experimental indication for quark-antiquark annihilation:* suggestions for such an underlying mechanism are derived from experiments where the projectile, and hence its quark distributions, are systematically varied. One such prediction concerns the relative magnitude of DY production by π^+ and π^- on an isoscalar target, such as carbon. In the limit of neglecting sea-quark distributions, one expects

$$\left. \frac{\sigma(\pi^+C)}{\sigma(\pi^-C)} \right|_{\text{valence only}} = \frac{\bar{d}(x_1) \cdot d(x_2)}{\bar{u}(x_1) \cdot u(x_2)} = \frac{1}{4}.$$

Experimentally (Fig. 7), one finds³⁴⁾ a value around ~ 0.5 , which is not in disagreement with the simplified estimate accepting a reasonable level of antiquark contamination from the sea.

Similar support is given by the ratio $\sigma(\pi^+C)/\sigma(pC)$ which for masses $1 < M < 4$ GeV was measured³⁴⁾ to be ~ 2 : a hadronic production mechanism for the lepton pairs would be expected to follow the total hadronic cross-section, which is $\sigma_{\text{tot}}(\pi N) < \sigma_{\text{tot}}(pN)$. The above ratio of ~ 2 is considered an indication of the scarcity of antipartons in the proton.

The x-distribution of the inclusive cross-section can be fitted in a form $(1-x)^c$. Experimentally³⁴⁾, one observes

$$\sigma(pC)/\sigma(\pi C) \sim (1-x)^2$$

for $x \rightarrow 1$, i.e. $x_1 \rightarrow 1$, $x_2 \rightarrow 0$. The projectile provides the quark, whereas the antiquark comes from the target. The above x -dependence follows then from the quark counting rules for the proton and pion.

Finally, the ratio $\sigma(K^-)/\sigma(\pi^-)$ was found^{35,37)} to be ~ 1 . This is expected, as in both projectiles the antiquark is the $\bar{u}$.

ii) *Comparison of the data with the model:* the new high-statistics data³³⁾ impose tight constraints on the model. The largest uncertainty continues to be knowledge of the parton distributions. As an example, we give the distributions extracted from a recent analysis³⁸⁾:

$$u(x) = \frac{1.79}{\sqrt{x}} (1-x)^3 (1 + 2.3 x) + s(x) ,$$

$$d(x) = \frac{1.07}{\sqrt{x}} (1-x)^{3.1} + s(x) ,$$

and for the SU(3) symmetric assumed sea,

$$\bar{u}(x) = \bar{d}(x) = \bar{s}(x) = s(x) = \frac{0.15}{x} (1-x)^7 .$$

In Fig. 8 the FNAL results are shown together with the model prediction for different sea distributions. Applying faithfully the conventional DY formalism [Eqs. (6) and (7)], a sea distribution of the form $s(x) = (0.6/x)(1-x)^{10}$ is extracted to give the best agreement with the data. Further analysis by the same group²⁴⁾ indicates that the assumption of an SU(3) symmetric sea may be too simplistic and that the $\bar{u}(x)$ -distributions in the proton contribute less than the $\bar{d}(x)$ -distributions, a result anticipated by Field and Feynman in their study of high- p_T phenomena³⁹⁾.

iii) *Parton p_T -distribution and scale breaking:* recent data^{23,33)} on the mass dependence of the average $\langle p_T \rangle$ of the dilepton system is shown in Fig. 9. The data no longer support the earlier hint of low-statistic data of an unchecked rise in $\langle p_T \rangle$, but rather saturate at a value of $\langle p_T \rangle \approx 1.2$ GeV/c. These rather high-average p_T values, somewhat less dramatic in the new data, were once one of the more serious objections to the "naive" DY formalism which gave the typically hadronic values of $\langle p_T \rangle \sim 300$ -500 MeV/c. Today, we know that the original parton model is too simplistic in the following respects: it predicts exact scaling,

which is observed to be violated in deep inelastic scattering; furthermore, results on high- p_T production of single particles or jets also suggest, when interpreted in this parton language, that the constituents have a broader k_T -distribution than thought originally. Several theoretical proposals treat these questions, either in the conventional framework⁴⁰⁾, or in a reformulated parton model, which predicts scaling violations⁴¹⁾ or even suggests somewhat different mechanisms for the pair production⁴²⁾. Further, more quantitative, theoretical work is needed before one can apply the parton formalism to extract all information on the quark distribution contained in these high-accuracy measurements.

iv) *Scaling*: soon after the original Columbia-BNL dimuon experiment it was noted that on dimensional arguments

$$\frac{d\sigma}{dM} = A \frac{1}{M^3} F(M^2/s) , \quad (8)$$

a prediction clearly also contained in the DY formalism [Eq. (6)]. Data are summarized^{3,23)} in Fig. 10, with the straight line seemingly verifying the scaling assumption. For some time such scaling behaviour has been used to estimate production cross-sections σ_W for $W^\pm$'s and Z^0 . Based on the CVC theory, and Eq. (6), substituting $J_\mu^{\text{em}} \rightarrow J_\mu^W$, $\ell^+\ell^- \rightarrow W^\pm$, $M^2 \rightarrow M_W^2$, we arrive at a relationship of the form

$$\sigma_W \approx 0.1 \times M_W^3 \left. \frac{d\sigma}{dM_{\ell\ell}} \right|_{M=M_W} . \quad (9)$$

The expectations of one of the most recent evaluations³⁸⁾ are given in Fig. 11.

3. THE DILEPTON SPECTRUM BELOW THE J/ψ

The study of the lepton spectrum below the J/ψ provides information on the following points:

- measurement of the production cross-section of the "old" vector meson ρ , ω , and ϕ and their contribution to the direct lepton production;
- existence of any unknown resonances;
- investigation of the continuum spectrum: origin, systematics, and implications.

Experimentally, work in this mass region has proved to be more difficult than the measurement of the high-mass domain: varied and strong sources of background obscure the signal even more, and frequently the disposition of the experimental equipment limits the accessible kinematic region of lepton production. Some information on the production of the "old" vector mesons⁴³⁾ is summarized in Table 2.

Measurements of ρ production in the fragmentation region are consistent with a level of 10% of π production; at large p_T , however, several measurements carried out at the ISR show that the ratio ρ/π approaches one for $p_T > 1.5$ GeV/c.

Inclusive hadronic production of ω has not been measured at high energies; bubble chamber experiments at $\sqrt{s} = 5$ and 7 GeV indicate approximate equality between ρ and ω production. Inclusive ϕ production has been measured in a range of $\sqrt{s}$ from 5 to 63 GeV. At the highest $\sqrt{s}$ -values the BCSY group⁴⁴⁾ finds for $p_T > 2$ GeV, and assuming a p_T -dependence of particle production as $(m^2 + p_T^2)^{-4} = E_T^{-8}$, the ratio $\rho/\phi = 12.4 \pm 2.9$. In summary, the production of the old vector mesons is consistent with simple quark-model notions which imply $\rho = \omega = \pi$ and $\phi = 1/9 \pi$. Their contribution to the direct lepton spectrum has been very carefully evaluated⁴⁵⁾ and is summarized in Fig. 12; it is at the level of $\sim 10\%$.

The search for any new resonance structure in the 1-3 GeV mass region has so far not been conclusive. As yet, no evidence is claimed in hadron production, but studies at Frascati (ADONE) and Orsay (DCI) on e^+e^- annihilation point towards a rich and complicated structure⁴⁶⁾. Interpretation of these structures is difficult, as it requires a systematic study of the hadronic decay modes and branching ratios which has not been made yet.

Data on the continuum below the J/ψ are available from experiments at FNAL³⁴⁾, the SPS³⁵⁾, and the ISR⁴⁴⁾. Some results of one very systematic study³⁴⁾ are shown in Fig. 13, together with an estimate of the Drell-Yan continuum. Whereas the Drell-Yan limit seems to be well reached above $M > 4$ GeV, DY production is insufficient to explain completely the observed continuum below J/ψ . Theoretically, this is not too surprising as the limiting assumptions on the DY are not expected to be fully valid, and various explanations for enhanced dilepton

production have been advanced⁴⁷⁾. However, much difficult and detailed work will be necessary before the 1-3 GeV mass region will be finally understood.

Some experimental information is available on the dilepton continuum below the ρ mass, in several limited kinematical regions^{4,44)}. A summary is found in Table 3. A significant level of pair production is observed in the forward direction; its interpretation is not clear and awaits detailed confrontation with theoretical suggestions⁴⁸⁾. The large-angle, high- p_T data of the BCSY group, however, cover a kinematics region for which more definite theoretical predictions exist: here we discuss the implication of this data on the level of direct photon production in pp collisions (Fig. 14).

Copious production of prompt photons is one mechanism which was suggested to contribute substantially to the observed direct electron yield⁴⁹⁾. Subsequent work showed that direct photon production is a general feature of hadron constituent models in their description of large- p_T phenomena, and that the level of production offered a sensitive test for discriminating between the various models^{49,50)}. For a large class of models, photon production is estimated to be $\sim 0.1 \times \pi^0$ for $p_T \approx 1-2$ GeV, and predicted to be rising with p_T . Similar predictions were recently made, based on a calculation within the conventional QCD framework⁵¹⁾: a level of 10% is predicted at $p_T = 2-3$ GeV/c, rising to 100% at $p_T = 15$ GeV/c!

Several attempts⁵²⁻⁵⁴⁾ to detect directly produced photons are summarized in Fig. 15. The analysis of these experiments is exceedingly difficult, as the background, e.g. partially detected π^0 's, dominates the expected signal by an order of magnitude even in the most favourable experimental situations and requires delicate Monte Carlo subtractions. To avoid these experimental difficulties, the BCSY Collaboration^{44,55)} studied the production of virtual photons in the reaction

$$\begin{array}{l} pp \rightarrow \gamma \text{ virtual} + \text{anything} \\ \quad \quad \quad \downarrow \\ \quad \quad \quad e^+e^-, \end{array}$$

over a limited mass region ($200 < m_{ee} < 500$ MeV) and p_T domain ($2.0 < p_T < 3.0$ GeV).

The production of virtual photons with mass m and transverse momentum q_T is related to real photon production at the same transverse energy E_T by the photon propagator $1/m^2$. At large transverse momentum this relation is expressed as

$$q_0 \frac{d\sigma(\gamma \rightarrow ee)}{dm^2 d^3q} = \frac{1}{2\pi m^2} R_{E_T}\left(\frac{\gamma}{\pi^0}\right) \times E \frac{d\sigma}{d^3p} \bigg|_{\substack{p_L=q_L \\ p_T^2=q_T^2+m^2}} (\pi^0) .$$

$R_{E_T}(\gamma/\pi^0)$ is the ratio of the direct production of real photons to the production of π^0 at E_T , the factor $1/2\pi$ implying production of virtual photons with equal and incoherent transverse and longitudinal polarization. The ratio $R_{E_T}(\gamma/\pi^0)$ incorporates the model-dependent connection between real photons and π^0 production. It is a function of E_T and can be expressed as

$$R_{E_T}\left(\frac{\gamma}{\pi^0}\right) = r\left(\frac{\gamma}{\pi^0}\right) f(E_T) .$$

Here $r(\gamma/\pi^0)$ is the measured ratio of photon to π^0 production at a given E_T , and $f(E_T)$ relates the E_T dependence of the photon spectrum to the E_T dependence of the π^0 spectrum. In most models the difference in E_T dependence is weak [$1 < f(E_T) < E_T^2$] and is inconsequential for the interpretation. Various errors in normalizing experimental cross-sections are conveniently avoided by measuring the virtual photon yield relative to $(\rho + \omega)$ production. One then measures the ratio

$$\frac{\gamma \rightarrow ee}{(\rho^0 + \omega^0) \rightarrow ee} = \frac{1}{2\pi} r\left(\frac{\gamma}{\pi^0}\right) \frac{\int dp_T \int \frac{dm^2}{m^2} Y_\gamma(p_T, m) f(E_T)}{\int dp_T [Y_\rho(p_T) B_{\rho \rightarrow ee} + Y_\omega(p_T) B_{\omega \rightarrow ee}]} \left[\frac{m_\rho^2 + p_T^2}{m_\pi^2 + E_T^2} \right]^4 .$$

The e-pair spectrum, measured relative to $(\rho^0 + \omega^0)$ production, corrected for η -Dalitz decays, is shown in Fig. 16 together with the expected e-pair spectrum, which would result from direct γ -production at the level of $\gamma/\pi^0 = 0.1$. One concludes: $r(\gamma/\pi^0) = 0.55 \pm 0.92\%$, $2.0 < p_T < 3.0$ GeV [$f(E_T) = 1$]. For $f(E_T) > 1$, as in deep production models, the ratio γ/π^0 would decrease. Thus the ratio γ/π^0 , as determined from virtual photon production, is of $O(\alpha)$ and is consistent with models based on scale-invariant fragmentation of scattered quarks.

This result is also consistent with predictions based on a generalized Drell-Yan model⁴⁷⁾ or on a generalized vector-dominance model⁴⁵⁾. As an example, we show in Fig. 17 the result of such a calculation and its sensitivity to various levels of direct γ -production. The measured γ -yield does not support the simplest predictions of "deep" production mechanisms in which scale invariance is imposed on the large p_T scattering of quarks.

4. SINGLE LEPTON PRODUCTION

The investigation of single direct lepton production continues to be of topical interest, as it is one of the striking signatures of weak decays of heavy hadrons (e.g. charmed hadrons).

The data for leptons with $p_T > 1$ GeV are -- within the limit of experimental uncertainties -- reasonably well understood and can be summarized as follows:

- i) The ratio lepton/pion $\approx 10^{-4}$ [Staudé⁵⁶⁾].
- ii) The observed single yield can be accounted for by the measured yield of lepton pairs. However, experimental errors are still quite large (no large acceptance experiments have been carried out that are sensitive to single leptons and lepton pairs simultaneously) and other sources contributing at the level of 10 to 20% cannot be convincingly excluded. The quality of the data and of our understanding in this p_T regime is shown in Figs. 12 and 18^{45,57)}.
The data show perhaps a slow increase of ℓ/π as a function of p_T .
- iii) Charge symmetry, again within considerable experimental errors, is valid, i.e. $\sigma(\ell^+) = \sigma(\ell^-)$ and the polarization of the direct μ 's is zero; both aspects are consistent with an electromagnetic origin of the leptons^{4,56)}.

The explanation for the lepton yield with $p_T < 1$ GeV is considerably less well understood. The main feature, a considerable increase in the ratio e/π for $p_T < 1$ GeV, has been consistently observed in different experiments, at vastly different values of $\sqrt{s}$ ⁵⁶⁾. Known sources of leptons, including various estimates for charm production, cannot fully explain the data. Possibly, the observed pair production in the forward direction, in excess of the standard DY yield and not included as a possible source in the comparison, is responsible for a fraction of the observed single yield⁴⁸⁾.

An illustration of this rise of ℓ/π for low p_T and the level of possible charm production is given in Fig. 18. A level of $D, \bar{D}$ production corresponding to $B_{D \rightarrow \ell \nu} \cdot \sigma = 3 \times 10^{-30}$ is seen to be consistent with measured lepton yields with $p_T > 1$ GeV. The results of a recent evaluation, which carefully considered the contribution of the low-mass vector mesons to the low- p_T lepton spectrum, is shown in Fig. 12. Although they strongly contribute to the yield at very low p_T , the level of this yield is insufficient to explain the observations.

The upper limit on charm production at the level of $B\sigma \approx 5 \times 10^{-30}$ implied by the observed lepton/pion ratio, is consistent with upper limits obtained in several charm searches, where limits at the level of 50-100 μb were obtained^{4,5}). A signal consistent with these values was observed in the recent CERN "beam dump" experiment⁵⁸). If the observed signal is interpreted as coming only from the decay of charmed hadrons h_c , one evaluates

$$(pN \rightarrow h_c + \text{anything}) \lesssim 2.8 \mu\text{b} \quad \text{for} \quad x > 0.2 ,$$

a result which translates into an inclusive cross-section [assuming a $(1-x)^3$ -dependence] of

$$\sigma_{\text{incl}}(pN \rightarrow h_c + \text{anything}) \approx 50 \mu\text{b} .$$

5. OUTLOOK

The investigation of lepton production continues with increasingly more powerful experimental armature⁵). Within the framework of today's "conventional" physics concepts, it might be expected that work at the fixed target accelerators will provide information on the dimuon continuum up to masses of $M_{\mu^+\mu^-} \sim 15 \text{ GeV}/c^2$. If new vector mesons exist below masses of $M_V \lesssim 17\text{-}18 \text{ GeV}$, they again will be found at these machines. At the CERN ISR, several large-acceptance experiments⁵) are committed to lepton studies (Table 4). Vector mesons in the mass range $M \approx 18$ to 20 GeV will be accessible when searched for in the dilepton channel; the sensitivity may extend to $M \lesssim 30 \text{ GeV}$, provided detection via hadronic decays is successful (Fig. 19). The accessible mass range for weakly produced objects, such as $W^\pm$'s or Z^0 's, extends even further up to $\gtrsim 40 \text{ GeV}$, again if the dijet

decays are measured (Fig. 19). For some time, therefore, the ISR will continue to have a perhaps very important advantage in the study of these phenomena.

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Table 1

Resonance fit to T structure (Ref. 22)

		Fit to	
		2 peaks	3 peaks
T	M	9.41 ± 0.013	9.40 ± 0.013 GeV
	$B_{\mu\mu} \frac{d\sigma}{dy} \Big _0$	0.18 ± 0.01	0.18 ± 0.01 pb
T'	M	10.06 ± 0.03	10.01 ± 0.04 GeV
	$B \frac{d\sigma}{dy} \Big _0$	0.069 ± 0.006	0.065 ± 0.007 pb
T''	M	-	10.40 ± 0.12 GeV
	$B \frac{d\sigma}{dy} \Big _0$	-	0.011 ± 0.007 pb
χ^2		19.3/18 DF	14.2/16 DF

Table 2

Production of "old" vector mesons

Particle	Reaction	Result	Ref.
ρ^0	$pp \rightarrow \rho^0 + \text{anything}$ (+ charged particles only) $\sqrt{s} = 5 \text{ GeV}$ $\sqrt{s} = 7 \text{ GeV}$	$1.8 \pm 0.25 \text{ (} 0.32 \pm 0.06 \text{) mb}$ $3.5 \pm 0.42 \text{ (} 0.30 \pm 0.05 \text{) mb}$	(a)
	$pp \rightarrow \rho^0 + \text{anything}$ $\sqrt{s} = 19.6 \text{ GeV}$	$\rho^0/\pi^- = 0.13 \pm 0.02$	(b)
	$pp \rightarrow \rho^0 + \text{anything}$ $\sqrt{s} = 53 \text{ GeV}$	$\rho^0/\pi^\pm = 1.1 \pm 0.1$ for $p_T > 1.4 \text{ GeV/c}$	(c)
	$pp \rightarrow \rho^0 + \text{anything}$ $\sqrt{s} = 53, 63 \text{ GeV}$	$\frac{d\sigma}{dy}\bigg _{y=0}^\rho = 0.12 \frac{d\sigma}{dy}\bigg _{y=0}^{(\pi^++\pi^-)/2}$ $p_T > 1 \text{ GeV}$	(d)
		$\frac{d\sigma}{dy}\bigg _{y=0}^\rho = 0.77 \frac{d\sigma}{dy}\bigg _{y=0}^{(\pi^++\pi^-)/2}$ $p_T > 3 \text{ GeV}$	
$\rho^\pm$	$pp \rightarrow \rho^\pm + \text{anything}$ $\sqrt{s} = 53$	$\frac{1}{2}(\rho^+ + \rho^-)/\pi^0 = 0.8 \pm 0.2$	(e)
ω	$pp \rightarrow \omega + \text{charged particles}$ $\sqrt{s} = 5 \text{ GeV}$ $\sqrt{s} = 7 \text{ GeV}$	$0.32 \pm 0.02 \text{ mb}$ $0.32 \pm 0.03 \text{ mb}$	(a)
	$pp \rightarrow \omega + \text{anything}$ $\sqrt{s} = 53 \text{ GeV}$	$\rho^0/\omega = \frac{1.19 \pm 0.25}{1.59 \pm 0.28}$	(f)
ϕ	$pp \rightarrow \phi + \text{anything}$ $\sqrt{s} = 7$	$0.16 \pm 0.04 \text{ mb}$	(g)
	$p\text{Be} \rightarrow \phi + \text{anything}$ $\sqrt{s} = 24$	$\phi/\pi \leq 0.055 \text{ (} p_T = 2.5 \text{ GeV)}$ $\leq 0.103 \text{ (} p_T = 3.3 \text{ GeV)}$	(h)
	$pp \rightarrow \phi + \text{anything}$ $\sqrt{s} = 53, 63$	$\phi/\pi \approx 0.15 \text{ (} p_T \gtrsim 3 \text{ GeV)}$	(d)

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Table 3

Some experiments on dileptons with $M_{\ell\ell} < M_\rho$

Reaction	Kinematics	Result	Ref.
$\pi p \rightarrow \mu^+\mu^- + \text{anything}$	$\sqrt{s} = 5.5 \text{ GeV}$, $X_F > 0.3$ $M_{\mu\mu} > 0.2 \text{ GeV}$ $\langle p_T \rangle = 0.43 \text{ GeV}/c$	$280 \pm 70 \text{ nb}$ $\frac{\mu^+\mu^-}{\pi^+\pi^-} = \frac{1}{3} 10^{-4}$	(a)
$\pi Be \rightarrow \mu^+\mu^- + \text{anything}$		Excess over Dalitz contribution $\int_{200}^{600} \frac{d\sigma}{dm} dm = 130 \text{ nb/nucleon}$	(b)
$p Be \rightarrow \mu^+\mu^- + \text{anything}$	$\sqrt{s} = 17 \text{ GeV}$, $X_F > 0.15$ $M > 0.2 \text{ GeV}$	Excess over Dalitz contribution $\int_{200}^{600} \frac{d\sigma}{dm} dm = 1.3 \text{ } \mu\text{b/Be nucleus}$	(c)
$pp \rightarrow e^+e^- + \text{anything}$	$\sqrt{s} = 52, 63 \text{ GeV}$ $\langle p_T \rangle = 2.3 \text{ GeV}$ $0.2 \text{ GeV} < M < 0.5 \text{ GeV}$	$\frac{e^+e^-}{(\rho + \omega)_{e^+e^-}} = 0.13 \pm 0.22$	(d)

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Table 4
Lepton studies at the CERN ISR (see also Ref. 5)

Detector	Solenoid	Muon detector	SPM	R806	AFS	R606/R607	Double arm spectrometer
Technique	Superconducting solenoid (~ 1.5 T), cylindrical drift chambers; lead glass	Iron toroid magnet; plane drift chambers; vertex detector	Dipole magnet; MWPC; lead-scintillator sandwich; Cerenkovs	Lead-liquid argon-calorimeter; transition radiation detectors;	Helmholtz-coil-magnet; high-density drift-chambers; uranium-scintillator hadron calorimeter	Air coil, toroidal magnet, Cerenkovs, iron-scintillator sandwich	Window frame magnets; drift chambers; lead glass
Solid angle (charged particles) (sr)	8	close to 4π	close to 4π	4	~ 10	~ 2	2×0.5
Lepton detection							
Solid angle (sr)	1.4π	8.4	0.5 sr	4	~ 9	1.4	2×0.5 (electrons) 0.4 for μ 's $\phi = \pm 15^\circ$
Azimuthal coverage	$\phi = \pm 45^\circ$ $180 \pm 45^\circ$	$\phi \sim 2\pi$		$\phi \approx \pi$	$\phi \sim 2\pi$	$15^\circ \leq \phi \leq 155^\circ$	
Polar coverage	$\theta = 90^\circ \pm 45^\circ$	$15^\circ < \theta < 110^\circ$		$45^\circ \leq \theta \leq 135^\circ$	$40^\circ \leq \theta \leq 140^\circ$	$20^\circ \leq \theta \leq 40^\circ$	$50^\circ < \theta < 130^\circ$
Lepton physics programme	Electron pairs, photons	μ pairs	Charmed particles	Lepton pairs, photons	Lepton pairs, $e\mu$, photons (neutrinos via missing energy?)	Charm search	Lepton pairs, charm search

Figure captions

- Fig. 1 : Diagrams for three processes related in the quark-parton picture:
- a) the annihilation of a quark with an antiquark producing a pair of leptons;
 - b) deep inelastic lepton-nucleon scattering;
 - c) deep inelastic parton-parton scattering and the production of particles with large transverse momentum.
- Fig. 2 : Schematic view of the double-arm spectrometer used by the Columbia-FNAL-Stony Brook Collaboration at FNAL to search for $\mu^+\mu^-$ pairs. Each spectrometer arm includes eleven PWCs P1-11, seven scintillation counter hodoscopes H1-7, a drift chamber D1, and a threshold Čerenkov counter Č.
- Fig. 3 : Cross-section through the apparatus used by the Brookhaven-CERN-Syracuse-Yale Collaboration used for the study of electron and photon production at the CERN ISR.
- Fig. 4 : The level diagram of charmonium with the main branching ratios (in percent) (Ref. 10).
- Fig. 5 : a) Some values of the excitation cross-section for J/ψ and ψ' as a function of $\sqrt{s}$;
b) Some values of the excitation cross-section for J/ψ and T as a function of $\tau = M/\sqrt{s}$.
- Fig. 6 : Diagrams for possible production mechanisms for J/ψ .
- a) $c\bar{c}$ fusion;
 - b) production of χ states via two-gluon amalgamation;
 - c) quark-antiquark fusion.
- Fig. 7 : The ratio of continuum pair production by 225 GeV/c π^+ and π^- on a carbon target (Ref. 34).
- Fig. 8 : Recent high statistics on muon pair production by the CFS group. The solid line represents the best fit to the continuum data and is obtained for a sea distribution of the form $s(x) = (0.6/x)(1-x)^{10}$; the dash-dotted curve is computed with $s(x) = (0.5/x)(1-x)^8$, whereas the dashed curve is based on the structure functions of Ref. 39 (from Ref. 33).
- Fig. 9 : The mass dependence of the average transverse momentum of the dilepton system (Refs. 23, 33, and 34).

- Fig. 10 : Scaling behaviour of the dilepton continuum. The data of the BCSY group are from Ref. 23, those of the CPI group from L. Klugberg et al., Phys. Rev. Letters 37, 1451 (1976); The CFS data are given by: S.W. Herb et al., Phys. Rev. Letters 39, 252 (1977).
- Fig. 11 : The predicted production cross-section for $W^\pm$ by protons and anti-protons as a function of s/m_W^2 (Ref. 38).
- Fig. 12 : The contribution of vector mesons to the observed electron/pion ratio (Ref. 45).
- Fig. 13 : Typical dilepton spectra covering the mass region up to the J/ψ (Ref. 34).
- Fig. 14 : High-transverse momentum electron pair spectra covering the mass region for $m = 0.2$ GeV up to the J/ψ . The data are not corrected for acceptance (Ref. 55).
- Fig. 15 : Summary of information on direct photon production. The value of the BCSY Collaboration represents the yield average over the momentum bin from 2-3 GeV (Refs. 52-54).
- Fig. 16 : Corrected $(\gamma \rightarrow \ell\ell)/(\rho^0 + \omega^0 \rightarrow \ell\ell)$ ratio as a function of the effective mass of the electron pair. Also shown is the expected signal for direct photon production at the level of 10% of π^0 production (Ref. 55).
- Fig. 17 : The mass distribution of electron pairs for large transverse momenta ($p_T > 1$ GeV). The mass distribution resulting from ρ^0 - ω dominance is compared with the e^+e^- spectrum for various assumed levels of direct photon production (Ref. 45).
- Fig. 18 : The measured lepton/pion ratio as a function of p_T . Together with the known sources for leptons, a contribution of $D, \bar{D}$ production at the level of $B\sigma = 3 \times 10^{-30}$ is seen to be consistent with the data (Ref. 57).
- Fig. 19 : Cross-section limits which can be obtained with large acceptance detectors at the ISR. The invariant mass of dijets is extrapolated from present data. Rates for "quarkonium" is computed with the scaling assumption, the measured cross-section for T , and assuming the detection of all hadronic decay channels. Rate estimates for $W^\pm$ are based on the measured dilepton continuum, assuming scaling and detection sensitivity to all hadronic decay channels.

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