CERN LIBRARIES, GENEVA

CM-P00063988

DRELL-YAN VERSUS EXPERIMENT

F. Vannucci*)

Lab. de Physique des Particules (LAPP), Annecy, France

Contribution to the
Karlsruhe Summer Institute,
Karlsruhe, Germany,
September 1978

Geneva - 13 December 1978

*) Visitor at CERN, Geneva, Switzerland.

DRELL-YAN VERSUS EXPERIMENT

F. Vannucci

Lab. de Physique des Particules (LAPP), Annecy, France

Since the experiment which first measured dimuon production in hadron collisions¹, several similar searches were started, and some of them proved amazingly successful^{2,3}. The finding of new particles in the reaction

$$pN \rightarrow \ell^+ \ell^- + X$$

explains the flourishing of this kind of study, but the understanding of the continuum (the "background" under the J/ψ or the T) now proves to be of primary interest by itself, and this presentation will be restricted to this aspect of dilepton production. As we will see, lepton pair measurements provide a way of testing various ideas about the distribution of quarks inside the hadrons, and new results from the CERN Intersecting Storage Rings (ISR) will be used to test, in particular, the prediction of scaling and the connection with lepton deep inelastic scattering.

The presentation will be as follows:

- description of an experimental set-up,
- the Drell-Yan model and its predictions,
- first symptoms of $q\bar{q}$ annihilation,
- test of scaling,
- extraction of quark distributions,
- problems of the basic model.

1. DESCRIPTION OF AN EXPERIMENT

Dilepton searches have been favoured by the relative ease of experimental detection. For instance, $\Gamma(J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0)/\Gamma(J/\psi \rightarrow e^+e^-) = 0.5$, but in hadron collisions the J was found in the e^+e^- mode, and our only information about ψ decays comes from e^+e^- physics. This is explained by the fact that both electrons and muons have properties that are characteristic enough to allow extraction from an overwhelming hadronic background.

As an example, and because original data from this experiment will be presented in the following, I will describe a set-up now in use at the CERN ISR whose aim is the measurement of dimuon production⁴.

Muons do not undergo strong interactions and can traverse many collision lengths of matter without being absorbed, and it is this property that allows them to be filtered out by absorbing the hadrons. In order to measure the momentum, a magnetic field is needed, and these two functions of hadron absorber and magnetic field carrier are merged by using a set of magnetized iron toroids. The apparatus is shown in Fig. 1. There are two main sources of background in muon detection:

- hadron punch-through: in this experiment the filter represents a minimum of 15 collision lengths on the path of a particle.
- π or K decays giving a μ : the absorber starts 50 cm from the interaction point, thus drastically decreasing the probability of a decay.

Magnetized iron, run at saturation, is the cheapest way of filling a large volume with a high magnetic field (1.8 T), and the whole detector gives a minimum $B \cdot dl$ of 2.7 Tm over a solid angle of 8 sr. In polar angle the coverage is from 15° up to 110° . The drawback of this technique comes from multiple scattering, and the resolution in mass is about 10%.

The tracks are detected in large drift chambers giving a spatial resolution of 0.7 mm over an area of 800 m². Time-of-flight techniques allow the rejection of cosmic rays and also of stray particles accompanying the incoming beams.

The inner hole of the first yoke surrounding the interaction point is filled with drift wire and delay line chambers, which help reconstruct the vertex and give information on the hadrons produced together with the muon pair.

The shielding proves effective: about 10^7 charged particles are produced each second but the trigger rate is only 0.5 per second. The events which pass the analysis stream are very clean. This is shown

in Fig. 2, where one sees a dimuon event with only two tracks beyond the first iron yoke, while the inner detector registers many hadron tracks.

The resulting plot of the $\mu^+\mu^-$ mass is seen in Fig. 3. This plot is based on an integrated luminosity of $2.6 \times 10^{37} \text{ cm}^{-2} \text{ s}^{-1}$ and represents a total of about 600 events above $4 \text{ GeV}/c^2$. The background level is checked by the amount of like-sign pairs; it is negligible above a mass of $6 \text{ GeV}/c^2$.

These data were taken at a c.m. energy $\sqrt{s} = 62 \text{ GeV}$. The mass plot can be compared to two previous results obtained at very different energies. Together with these data, Fig. 3 displays the BNL data¹ taken at $\sqrt{s} \approx 7 \text{ GeV}$ and those of the Columbia-FNAL-Stony Brook (CFS) Group³ obtained at $\sqrt{s} = 27.4 \text{ GeV}$; it will be the task of the scaling stratagem to relate quantitatively these very different cross-sections.

When compared to a stationary target experiment, the ISR experiment loses a large factor in luminosity, but the ISR still remains by far the highest energy machine, and this is important for testing scaling. Furthermore, as will be seen, the ISR measures the continuum in a region where the FNAL or the CERN Super Proton Synchrotron (SPS) experiments are blind because of resonance production. Finally, the low luminosity ceases to be a handicap for the study of associated hadrons, about which virtually no information is yet available.

For a discussion of the experimental problems of dilepton searches, one can refer to Ref. 5.

2. THE CLASSICAL DRELL-YAN MODEL⁶

According to this model the massive lepton pair production

$$A + B \rightarrow \ell^+ + \ell^- + X$$

takes place via the annihilation into a time-like photon of a quark of one incoming hadron with an antiquark of the other hadron. This is schematically shown in Fig. 4, where the kinematical variables are explained. It is essentially the inverse diagram of $e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}$.

The cross-section can be written as the sum of elementary processes weighted by the probability of finding quarks and antiquarks which are allowed to annihilate with each other:

$$\begin{aligned} \sigma(A + B \rightarrow \ell^+\ell^- + X) = & \iiint dx_i d\bar{x}_i \sum_i f_i^A(x_i) \bar{f}_i^B(\bar{x}_i) \times \\ & \times \sigma(q_i + \bar{q}_i \rightarrow \ell^+\ell^-) \delta[Q^2 - (k_i + \bar{k}_i)^2] dQ^2. \end{aligned}$$

The sum is over all types i of quarks and antiquarks present in the initial hadrons with probabilities $f_i^A(x_i)$, $\bar{f}_i^B(\bar{x}_i)$. The variables x_i , $\bar{x}_i$ are the fraction of initial momentum carried by the constituents:

$$k_i = x_i P_A, \quad \bar{k}_i = \bar{x}_i P_B.$$

The invariant mass squared of the photon, and thus of the dilepton, is

$$\begin{aligned} m^2 = Q^2 &= (k_i + \bar{k}_i)^2 \\ &= (x_i P_A + \bar{x}_i P_B)^2 \\ &\approx s x_i \bar{x}_i \end{aligned}$$

in the limit of large s , where s is the total c.m. energy squared:

$$s = (P_A + P_B)^2.$$

The model neglects any transverse momentum of the constituents. With this restriction the Feynman variable X for the lepton pair is simply

$$X = \frac{2P_L}{\sqrt{s}} = x_i - \bar{x}_i.$$

The model assumes a point-like coupling $\gamma q_i \bar{q}_i$; the elementary cross-section then reads:

$$\sigma(q_i + \bar{q}_i \rightarrow \ell^+ \ell^-) = \frac{4\pi\alpha^2}{3Q^2} e_i^2,$$

e_i being the charge of the quark of type i . The total cross-section now takes the form

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3Q^4} F(\tau)$$

$$\text{with } F(\tau) = \sum_i e_i^2 \frac{\tau}{N_c} \int_0^1 dx_i \int_0^1 d\bar{x}_i \delta(x_i \bar{x}_i - \tau) f_i^A(x_i) \bar{f}_i^B(\bar{x}_i),$$

where N_c is the number of colour and τ is a new variable representing the "scaled" mass squared of the dilepton system:

$$\tau = \frac{m^2}{s} = x_i \bar{x}_i, \quad 0 \leq \tau \leq 1.$$

It is also useful to write down the double differential cross-section:

$$\frac{d^2\sigma}{dQ^2 dX} = \frac{4\pi\alpha^2}{3N_c Q^4} \frac{\tau}{\sqrt{X^2 + 4\tau}} \sum_i e_i^2 f_i^A(x_i) f_i^B(\bar{x}_i)$$

$$x_{i,\bar{i}} = \frac{\sqrt{X^2 + 4\tau} \pm X}{2}.$$

By writing down the different flavours of quarks which can be excited in a given energy domain, one obtains

$$m^3 \frac{d\sigma}{dm dx} = \frac{8\pi\alpha^2}{3N_c} \frac{\tau}{\sqrt{X^2 + 4\tau}} \left\{ \frac{4}{9} (u \bar{u}^{A-B} + \bar{u}^A u^B) + \frac{1}{9} (d \bar{d}^{A-B} + \bar{d}^A d^B) + \right. \\ \left. + \frac{1}{9} (s \bar{s}^{A-B} + \bar{s}^A s^B) + \frac{4}{9} (c \bar{c}^{A-B} + \bar{c}^A c^B) \right\}.$$

This model gives straightforward predictions which can be tested experimentally⁷:

- the cross-section should follow the scaling law $m^3(d\sigma/dm) = F(\tau)$ or, if X is measured, $m^3(d^2\sigma/dm dx) = G(\tau, X)$, F and G being universal functions of the dimensionless variable τ , independent of energy;
- if quarks have colour the probability of pairing a quark i with its antiquark of the same colour is reduced; then the cross-section can be expected to be inversely proportional to N_c ;
- the quarks having spin $\frac{1}{2}$ and point-like coupling to the photon, the angular distribution of one lepton in the dilepton c.m. system is $1 + \cos^2 \theta$;
- the shape of the cross-section is determined by the quark distributions which are, in principle, measured in deep inelastic lepton scattering;
- the quarks having no transverse momenta, the intermediate photon is longitudinal to the beam, and the transverse momentum of the dilepton is expected to be small;
- finally the annihilation model predicts only two jets accompanying the lepton pair, in the direction of the initial hadrons.

3. FIRST SYMPTOMS OF $q\bar{q}$ ANNIHILATION

3.1 Target dependence

Because of shadowing effect, hadronic processes vary as $A^{2/3}$, where A is the atomic number of the target: the projectile sees the surface of the nucleus, and nucleons inside the nucleus act coherently.

The Drell-Yan process postulates an incoherent action of the different scatterers inside the nucleon. It can be expected that quarks inside different nucleons will also act incoherently, and the total cross-section, being the sum of incoherent elementary processes, will have a variation proportional to A .

Figure 5 shows the A dependence measured at Fermilab⁸⁻¹⁰⁾ with beryllium, carbon, copper, and tungsten targets. There is a clear transition from an $A^{2/3}$ dependence below a mass of 4-5 GeV/c to an A dependence above, indicative of a change of regime.

3.2 Beam dependence

The annihilation occurs between the quark of one hadron and the antiquark of the second hadron. The target consists of protons and neutrons for which antiquarks exist only in the sea; the projectile quark distribution offers more choice, and one expects the following relations, as a consequence of the valence-sea character of the quarks and of their charges¹¹:

$$\sigma(p\bar{p}) > \sigma(\bar{n}p) > \sigma(pp) > \sigma(np)$$

$$\sigma(\pi^-p) = \sigma(K^-p) > \sigma(\pi^+p) = \sigma(\bar{K}^0p) > \sigma(K^+p) = \sigma(K^0p) .$$

This last line holds if antiquarks in π and K have similar distributions. The ratio $\sigma(K^-N)/\sigma(\pi^-N)$ is found to be close to 1¹², while $\sigma(\pi^+N)/\sigma(\pi^-N)$ is shown in Fig. 6^{10,13}. The π^+ has a $\bar{d}$ of charge $1/3$, while π^- has a $\bar{u}$ of charge $-2/3$; then, on an isoscalar target and if the reaction takes place via $q\bar{q}$ annihilation, one expects

$$\frac{\sigma(\pi^+N)}{\sigma(\pi^-N)} = \frac{d(x)\bar{d}(x)}{u(x)\bar{u}(x)} = \frac{1}{4} .$$

This is true in the limit of no sea-quark contamination. As seen in Fig. 6 the experimental result indicates a transition from a ratio of 1 expected for hadronic production to a ratio of 0.25 for an 8 GeV/c² dimuon consistent with a $q\bar{q}$ annihilation process. The result for $\sigma(\pi^-N)/\sigma(pN)$ ¹³ is even more remarkable, as shown in Fig. 7. The ratio becomes much bigger than 1 (270 at a mass of 10 GeV/c²), consistent with the existence of valence antiquarks in the π^- , while p has only sea antiquarks. This also corroborates the idea of distributions $f(x)$ dying off much more rapidly for sea than for valence constituents.

There are other sum rules coming from simple charge counting:

$$\begin{aligned}\sigma(\pi^-p) - \sigma(K^+p) &= 4[\sigma(\pi^+n) - \sigma(K^+n)] \\ \sigma(\pi^-n) - \sigma(K^+n) &= 4[\sigma(\pi^+p) - \sigma(K^+p)] .\end{aligned}$$

No data are as yet able to test those predictions.

3.3 Angular distribution

In the dimuon frame, the angular distribution of a final lepton is predicted to have the form

$$\frac{d\sigma}{d\Omega} = A(1 + \alpha \cos^2 \theta) .$$

If the quarks have no transverse momentum, the longitudinal direction is the direction of the initial hadrons.

New results from the CP II experiment at Fermilab¹³ are shown in Fig. 8. While the distribution is flat for the J/ψ region, it is consistent with a form $1 + \alpha \cos^2 \theta$ with $\alpha = 1$ above the J/ψ . It has also the same shape below the J/ψ , although this region should not be dominated by the annihilation diagram!

These various observations all indicate very remarkably that lepton pairs at sufficiently high mass are not produced by normal hadronic interactions, and the annihilation mechanism seems to set in above a dilepton mass of $\sim 5 \text{ GeV}/c^2$ at Fermilab energies, corresponding to $\tau \sim 0.04$. If the transition occurred at a given τ , it should develop beyond a mass of $10 \text{ GeV}/c^2$ at the ISR. There are good reasons to believe that dimuon production is already accounted for by the Drell-Yan mechanism at lower masses. The transition then really seems related to a threshold mass or a threshold Q^2 below which a mechanism different from annihilation takes place independently of quark distributions unless we imagine some kind of coherent effect among quarks. This also indicates that to probe the very small τ region (the deeper sea?) one has to go to higher energies, and not to smaller mass.

4. TESTS OF SCALING

The scaling law $m^3(d\sigma/dm) = F(\tau)$ is a basic prediction of the Drell-Yan model. However, it is more simply a consequence of dimensional analysis, a cross-section having dimension m^{-2} (in the system $\hbar = c = 1$). Scaling implies that the quark distributions are only

functions of the dimensionless variable x , and are in particular independent of q^2 . Scaling violations, on the other hand, could be generated by some quark form factors dependent on q^2 .

Two experimental studies^{9,14)} of the scaling law have compared dimuon production for incident proton energies of 200, 300, and 400 GeV; $\sqrt{s}$ then varies from 20 GeV to 27.4 GeV. Figure 9a shows the mass spectra obtained for those three energies as a function of m , while Fig. 9b shows the same data plotted in a different way: the quantity $s \frac{d^2\sigma}{d\sqrt{\tau} dy}$ versus $\sqrt{\tau}$. The contrast between these two plots is a good illustration of the significance of the scaling test. Here, y is the rapidity variable,

$$y = \frac{1}{2} \log \frac{E + P_L}{E - P_L}.$$

Actually, if the experimental cross-section often measured is $d^2\sigma/dm dy$, the quantities which should rigorously scale are $m^3(d\sigma/dm)$ and $m^3(d\sigma/dm dx)$. To compare results from different experiments, we need a conversion formula between these different expressions. First we can write

$$\left. \frac{d^2\sigma}{dm dx} \right|_{x=0} = \frac{\sqrt{s}}{2m} \left. \frac{d^2\sigma}{dm dy} \right|_{y=0}.$$

The X variation of the cross-section has been measured in the range 3.5 to 4.5 GeV/c²; it is found to be

$$\left. \frac{d^2\sigma}{dm dx} \right|_{x=0} = \left. \frac{d^2\sigma}{dm dx} \right|_{x=0} (1 - X)^{2.8}.$$

Note that the scaling test depends very sensitively on the exponent of this expression. We can then write the final correspondence formula:

$$\frac{d\sigma}{dm} = \frac{\sqrt{s}}{3.8 m} \left. \frac{d^2\sigma}{dm dy} \right|_{y=0}.$$

With the help of this formula we can compare different experiments performed at energies over as wide a range as possible, and in particular we can try to relate the curves given in Fig. 4. Such an attempt has been made, comparing BNL data with Fermilab data¹⁵. The BNL data are essentially below a mass of 4 GeV/c², and the Drell-Yan regime is not expected to be dominant. In any case (precocious?) scaling is the conclusion of the study.

Here we will add a new energy region, namely $\sqrt{s} = 62$ GeV, into the test. For the following comparison I have converted the CFS data at 400 GeV in order to plot the quantity $m^3(d\sigma/dm) = F(\tau)$. The resulting curve is shown in Fig. 10 as a function of $\sqrt{\tau}$. It represents an experimental measurement of $F(\tau)$, and it is clear that, in the range where it is measured ($0.2 < \sqrt{\tau} < 0.5$), $F(\tau)$ follows an exponential fall-off very nicely. The region around $\sqrt{\tau} = 0.35$ corresponds to the T , and experimental points have been ignored. The line represents a straightforward fit:

$$F_1(\tau) = 13 \times 10^{-32} \exp(-18.6 \sqrt{\tau}) .$$

Now let us faithfully follow the rule, and scale this formula to the ISR energy. Figure 11 shows the result. It is rather remarkable that such a simple procedure works so well considering that the cross-sections measured at Fermilab and at the ISR differ by a factor of 10 at a mass 5 GeV/c² and a factor of 100 at a mass 12 GeV/c². It is even more remarkable because a very different fit will give the same agreement. One can try a formula¹⁶ diverging for $\tau = 0$:

$$F_2(\tau) = 5.23 \times 10^{-33} (1 - \sqrt{\tau})^{10} / \sqrt{\tau} ,$$

and the result is shown by the dashed line, in both Figs. 10 and 11.

The insensitivity of the test can be understood by plotting the ISR result in the same way as we plotted the CFS data: $m^3(d\sigma/dm)$ versus $\sqrt{\tau}$. The two experiments do not overlap in $\sqrt{\tau}$: the CFS data map the function $F(\tau)$ for $\sqrt{\tau} > 0.2$, while the ISR data add points in the region $0.05 < \sqrt{\tau} < 0.15$. This indicates two facts: a real test of scaling must be done for the same $\sqrt{\tau}$ values, and this could be obtained with ISR data taken at energies 15 GeV $\times$ 15 GeV. On the other hand, the present ISR result gives unique information impossible to obtain at Fermilab, and we need even higher energies to continue mapping $F(\tau)$ at very small $\sqrt{\tau}$.

The conclusion of this scaling test is that any "smooth" extrapolation of $F(\tau)$ in the ISR range of τ works well.

In Fig. 12 I have summarized our present knowledge of $F(\tau)$, adding together the different measurements obtained so far, including the early BNL data after subtraction of the J contribution and some early ISR results¹⁷. I have also plotted a few points corresponding to low-mass dimuons ($1.5 < m < 2.5$ GeV/c²) obtained with a 225 GeV proton beam¹⁰ and the recent Omega result¹² at 40 GeV beam energy. The low-mass results coming from Fermilab show that, for the same τ , $m^3(d\sigma/dm)$ is up to an order of magnitude above the scaling prediction. This again stresses the point that the Drell-Yan mechanism is not applicable at low masses. To dramatize this effect, I have plotted in Fig. 14 the ratio $R_{DY} = (d\sigma/dm)/DY$, where DY is taken equal to

$m^{-3}F(\tau)$. Above a mass of $4 \text{ GeV}/c^2$, by construction, R_{DY} is compatible with 1 for measurements ranging from $\sqrt{s} = 20 \text{ GeV}$ to $\sqrt{s} = 62 \text{ GeV}$, while below $3 \text{ GeV}/c^2$ the ratio R_{DY} , measured at three different energies, is consistently higher than 1. It is symptomatic that this change should occur for the same mass of the intermediate photon than is the case for the famous $R_{e^+e^-} = \sigma(e^+e^- \rightarrow \text{had.})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ also plotted in Fig. 13. The ratio R_{DY} decreases while $R_{e^+e^-}$ increases at this threshold. It is tempting to link both effects to the same cause. The ratio R_{DY} is inversely proportional to the number of colour N_c , while $R_{e^+e^-}$ is proportional to N_c , and a colour thaw would qualitatively point towards the right direction. But this idea is probably heretical, and if the jump in $R_{e^+e^-}$ is associated with the charm threshold, the fall in R_{DY} does not yet seem to be well understood, and more low-mass experimental results are needed to confirm the trend.

5. EXTRACTION OF QUARK DISTRIBUTION

The scaling law is a consequence of the Drell-Yan model, but a more stringent prediction is given by the meaning of $F(\tau)$:

$$F(\tau) \propto \tau \sum_i e_i^2 \int_0^1 dx_i \int_0^1 d\bar{x}_i f_i^A(x_i) \bar{f}_i^B(\bar{x}_i) \delta(x_i \bar{x}_i - \tau) ,$$

where $f(x)$ are the quark distributions measured in deep inelastic scattering experiments. If the idea of constituents is at all relevant, one expects the same distributions to be present in the hadron, irrespective of the probe used to measure them.

There is a total of eight distributions to be extracted: $u(x)$, $\bar{u}(x)$, $d(x)$, $\bar{d}(x)$, $s(x)$, $\bar{s}(x)$, $c(x)$, $\bar{c}(x)$.

The photon couples to all types of quarks, and deep inelastic electron or muon scattering gives the following relations on proton and neutron targets:

$$\begin{aligned} vW_2^{\text{ep}}(x) &= \frac{4}{9} x(u + \bar{u}) + \frac{1}{9} x(d + \bar{d}) + \frac{1}{9} x(s + \bar{s}) + \frac{4}{9} x(c + \bar{c}) \\ vW_2^{\text{en}}(x) &= \frac{1}{9} x(u + \bar{u}) + \frac{4}{9} x(d + \bar{d}) + \frac{1}{9} x(s + \bar{s}) + \frac{4}{9} x(c + \bar{c}) . \end{aligned}$$

On the other hand, $\nu(\bar{\nu})$ can only interact with d , $\bar{u}$, s , $\bar{c}$ ($\bar{d}$, u , $\bar{s}$, c) because of its left-handedness (right-handedness). This gives

$$\nu W_2^{\nu P}(x) = 2x(\bar{u} + d + s + \bar{c})$$

$$\nu W_2^{\bar{\nu} P}(x) = 2x(u + \bar{d} + \bar{s} + c)$$

$$\nu W_3^{\nu P}(x) = 2x(\bar{u} - d - s + \bar{c})$$

$$\nu W_3^{\bar{\nu} P}(x) = 2x(\bar{d} - u + c - \bar{s}) .$$

W_2 and W_3 are the usual structure functions measured in lepton scattering.

If we neglect the charm contribution, or if we assume the sea to be SU(3) symmetric, those six relations are, in principle, sufficient to obtain all quark distributions. Field and Feynman¹⁸ (FF) have extracted those distributions, and have found for the valence quarks:

$$xu(x) \sim (1-x)^3 \quad \text{and} \quad xd(x) \sim (1-x)^4$$

for large x , and for x near 0:

$$xu(x) \sim xd(x) \sim \sqrt{x}(1-x)^2 .$$

The experimental results used so far are linear in the quark distributions and will be insensitive to the sea-quark content which is expected to be small. The advantage of dimuon production is that it gives a quantity that is quadratic in the quark distributions and directly proportional to the sea-quark content. This is where dilepton results can bring new information, and may prove to be the only way of extracting sea-quark distributions at relatively large X .

Berger¹⁹ has fitted the CFS data with the FF distributions. As shown in Fig. 14, the FF prediction falls below the data by a factor of 3 for masses of ~ 5 GeV/c. Then Berger uses the experimental curve to extract the sea-quark content, while keeping the valence-quark distributions of FF. He finds, assuming all sea quarks to have the same distribution, $\bar{x}S(\bar{x}) = 0.42(1-\bar{x})^9$, and his fit reproduces the data very well, as is also shown in Fig. 15.

Another method has been used to extract the same information from the same data without the need of explicit valence-quark distributions. The idea is to feed the deep inelastic results directly into $(d^2\sigma/dm dy)_{y=0}$ ²⁰ ($y=0$ corresponds to $x_1 = \bar{x}_1 = x = \sqrt{\tau}$). Forgetting $c(x)$ and $\bar{c}(x)$ and assuming $\bar{u}(x) = \bar{d}(x) = s(x) = \bar{s}(x) \equiv S(x)$, we obtain the following relation:

$$\left. \frac{d^2\sigma}{dm dy} \right|_{y=0} = \frac{8\pi\alpha^2}{9m^3} \bar{x}S(\bar{x}) \left[\nu W_2^{\ell P}(x) + \nu W_2^{\ell n}(x) - \frac{4}{3} \bar{x}S(\bar{x}) \right]$$

The authors then find

$$\bar{x}S(\bar{x}) = 0.6(1 - x)^{10}, \quad 0.2 < x < 0.5 .$$

Much flatter distributions have been obtained in neutrino scattering, but at much smaller $q^2 \sim 20 \text{ GeV}^2$, and they are not in contradiction with the present results.

There is another kinematic region where further simplification occurs²¹. At small τ we have $x_i \approx X$, $\bar{x}_i \approx 0$; then:

$$\frac{d^2\sigma}{dm dX} = \frac{8\pi\alpha^2}{9m^3} \frac{1}{X} \bar{x}S(\bar{x}) 2vW_2^{ep}(X) .$$

The only dimuon data existing for such a comparison correspond to low masses¹⁰, and an over-all discrepancy of a factor of 3, already discussed, is apparent. Here the ISR result could shed some light, as it corresponds to small τ ; unfortunately, no x -dependence exists as yet from this experiment. Still, we can try the following consistency check:

The ratio of cross-sections for $\tau_1 = 0.0053$ and $\tau_2 = 0.0166$ is found to be 16:

$$\frac{d\sigma}{dm} = \frac{8\pi\alpha^2}{9m^3} \bar{x}S(\bar{x}) \int dX \frac{2vW_2^{ep}(X)}{X} .$$

Using the sea-quark distribution previously quoted, we arrive at

$$\frac{d\sigma/dm(\tau_1)}{d\sigma/dm(\tau_2)} = \left(\frac{m_2}{m_1}\right)^3 \left(\frac{1 - \bar{x}_1}{1 - \bar{x}_2}\right)^{10} = 16 .$$

Now it is interesting to notice that for small τ ,

$$\Delta\tau = x_i \Delta\bar{x}_i + \bar{x}_i \Delta x_i \approx x_i \Delta\bar{x}_i ,$$

the variation of τ mainly reflects the variation in sea-quark content. Let us then assume that X varies little in the range explored in τ :

$$\tau \approx \langle x_i \rangle \bar{x}_i .$$

Then the relation between cross-sections give an average x_i value for the valence quark,

$$\langle x_i \rangle \approx 0.12 .$$

This was just a small exercise, but it is interesting to note that because of $\Delta\tau \approx x_i \Delta\bar{x}_i$, at small τ , the function $F(\tau)$, experimentally measured, offers a direct picture of the sea quark fall-off, and any new point at smaller τ is, for that reason, quite important:

$$F(\tau) \propto \bar{x}S(\bar{x}) \quad \text{for small } \tau.$$

A very important and unique contribution of dilepton production concerns the quark distribution in pions. This is the only way of getting such distributions, and new data¹³ in $\pi p \rightarrow \mu^+ \mu^- X$ make the method possible. The result (Fig. 15) shows that the valence-quark distribution in the π is substantially flatter than that of the proton.

6. PROBLEMS OF THE BASIC MODEL

Qualitative predictions of the Drell-Yan model agree very well with the data. It is a little surprising, considering that hadrons are supposed to be made of quarks, antiquarks, and gluons, to witness that the hadron-hadron interaction takes place almost totally through quark-antiquark annihilation. In QCD other interactions may occur; their diagrams are shown in Fig. 16. In first order they all give the same scaling law $m^3(d\sigma/dm) = F(\tau)$ ²² and their relative effect must be searched for elsewhere.

In the basic model the dilepton system gets no transverse momentum p_T , as the quarks are supposed to have no intrinsic p_T in the hadron. It seems obvious that the constituents carry some p_T because of their confinement in a region of small transverse size. One then expects an intrinsic p_T of the order of 300-500 MeV/c independent of the beam energy.

Experimental results^{10,13} are shown in Fig. 17; p_T first increases with mass then levels off, but this plateau varies with beam energy, in clear contradiction with the naïve prediction. Hard-scattering bremsstrahlung diagrams shown in Fig. 16 can give rise to transverse momentum for the dilepton even without assuming an intrinsic p_T to the constituents: the p_T of the intermediate photon is balanced by a jet of hadrons. Large p_T pairs seem to have an origin that is different from the pure annihilation diagram, and the detailed study of this new kinematical region will be necessary to better understand the dynamics of the quarks inside the hadrons.

Many theoretical papers²³ have appeared on this subject of surprisingly high p_T . Present judgement is that the p_T behaviour may be interpreted in a QCD framework, taking into account the full series of constituent scattering diagrams. This should generate q^2 dependences of the quark distributions and consequently a violation of scaling. The present results are not accurate enough to test scaling to better than 20%, and nobody would be surprised by such violation, considering the scaling violation in deep inelastic scattering which already forces us to include q^2 -dependent structure functions. These two scaling violations are not independent, and if we insert the q^2 dependent structure functions measured in deep inelastic

scattering into the dilepton function, for the same q^2 , then the effects of higher-order graphs are automatically included¹⁹, and the connection between the two phenomena is preserved. This obviously means that theorists give a recipe for going from a space-like photon to a time-like photon.

Despite these difficulties, dilepton production gives a new support to the idea of hadron constituents carrying the quantum number of the quarks. It also stresses the difference between valence quarks and sea quarks.

The future of dilepton production points, as usual, towards better data, especially at higher energies, but also towards a better understanding of a QCD formulation. This new formulation must retain the striking successes of the Drell-Yan model but also explain the discrepancies that we underlined. In the last two years the sensitivity of dilepton production has been improved by several orders of magnitude, and, if the trend continues, all questions still pending may find an answer very quickly.

In particular, within the next two years CERN will have a $p\bar{p}$ collider with a total c.m. energy of 540 GeV²⁴. This represents a jump in $\sqrt{s}$ of almost a factor of 10 with respect to the ISR. It will be interesting to see if the scaling formula still holds. The result of this exercise is shown in Fig. 18: it shows the number of events detected in 1000 hours of running time in an apparatus which covers a 4π solid angle. I have taken into account a reduction in luminosity with respect to the ISR (it is expected to be 10^{30} cm⁻² s⁻¹ at the $p\bar{p}$ collider) and also the advantage of using $\bar{p}$ which offer their valence antiquarks²⁵. The expected rate is dramatically low. Fortunately the intermediate vector boson Z^0 is expected to be produced with a cross-section 3-4 orders of magnitude above the continuum, thus giving semi-comfortable rates, as is also seen in Fig. 18.

Will this curve be what experimentalists find at the $p\bar{p}$ collider? In less than 3 years we will know if this prediction comes true.

I wish to thank Professors Ting and Fries for the opportunity of preparing this study and Professor Jacob for reading the manuscript.

REFERENCES

- 1) J. Christenson et al., Phys. Rev. Letters 25, 1523 (1970).
- 2) J.J. Aubert et al., Phys. Rev. Letters 33, 1404 (1974).
- 3) S.N. Herb et al., Phys. Rev. Letters 39, 252 (1977).
- 4) D. Antreasyan et al., Measurement of high-mass muon pairs at very high energies, 19th Internat. Conf. on High-Energy Physics, Tokyo, 1978.
- 5) Workshop on Future ISR Physics (ed. M. Jacob) ISR workshop 12-8, CERN, 1977.
- 6) S.D. Drell and T.M. Yan, Phys. Rev. Letters 25, 316 (1970).
- 7) T.M. Yan *in* Workshop on Future ISR Physics (ed. M. Jacob) ISR workshop 12-8, CERN, 1977.
- 8) D.C. Hom et al., Phys. Rev. Letters 37, 1274 (1976).
- 9) D. Antreasyan et al., Phys. Rev. Letters 37, 1451 (1976).
- 10) J.G. Branson et al., Phys. Rev. Letters 38, 457 and 1334 (1977).
- 11) F. Renard, Proceedings, Ecole d'été de Gif, Sept. 1977.
- 12) M.J. Corden et al., Phys. Letters 76B, 226 (1978).
- 13) K.J. Anderson et al., Hadronic production of high-mass muon pairs, 19th Internat. Conf. on High-Energy Physics, Tokyo, 1978.
- 14) J.K. Yoh et al., Phys. Rev. Letters 41, 684 (1978).
- 15) L.M. Lederman and B.G. Pope, Phys. Letters 66B, 486 (1977).
- 16) K. Kinoshita, H. Satz and D. Schildknecht, BI-TP 77/74 (1977).
- 17) C. Kourkoumelis et al., Electron pair production at the ISR, 19th Internat. Conf. on High-Energy Physics, Tokyo, 1978.
- 18) R.D. Field and R.P. Feynman, Phys. Rev. D 15, 2590 (1977).
- 19) E.L. Berger, report ANL-HEP-PR 78-12 (1978).
- 20) D.M. Kaplan et al., Phys. Rev. Letters 40, 435 (1978).
- 21) F.T. Dao et al., Phys. Rev. Letters 39, 1388 (1977).

- 22) C.T. Sachradja, preprint CERN TH-2416 (1977).
- 23) R.C. Hwa, report RL 78-044, and references therein.
- 24) C. Rubbia, P. McIntyre and D. Cline, Proc. Internat. Neutrino Conf., Aachen, 1976, p. 683.
- 25) R.F. Peierls et al., Phys. Rev. Letters 16, 1397 (1977).

Fig. 1 : Detector of the experiment R209 at the ISR

Fig. 2 : One dimuon event as seen in the detector

Fig. 3 : Three generations of dimuon measurements

Fig. 4 : Schematic of the Drell-Yan mechanism

Fig. 5 : A dependence of dimuon production

Fig. 6 : Ratio of $\mu^+\mu^-$ production cross-sections in π^+ and π^- induced reactions

Fig. 7 : Ratio of $\mu^+\mu^-$ production cross-sections in π^- and p induced reactions

Fig. 8 : Angular distribution of one lepton in the dilepton c.m. frame. The reference axis of the sets of distributions are the recoil, the beam, and the target directions, respectively.

a) Dimuon mass spectra with incident proton energies of 200, 300, and 400 GeV

b) $s \frac{d^2 \sigma}{dV \sqrt{T}} dy$ plotted versus $\sqrt{T}$ for the same data

Fig. 9

Fig. 10 : The quantity $m^3(d\sigma/dm)$ plotted versus $\sqrt{\tau}$ for the CFS data. The full line represents the fit:

$$F_1(\tau) = 13 \exp(-18.6\sqrt{\tau}) 10^{-32} .$$

The dashed line represents the other fit:

$$F_2(\tau) = 5.23 \left[(1-\sqrt{\tau})^{10} / \sqrt{\tau} \right] \times 10^{-33} .$$

Fig. 11 : ISR mass spectrum with the scaling predictions based on $F_1(\tau)$ (full line) and $F_2(\tau)$ (dashed line)

Fig. 12 : The experimental function $F(\tau)$ versus $\sqrt{\tau}$

Fig. 13 : R_{DY} and $R_{e^+e^-}$ as a function of $m_{\mu\mu}$

Fig. 14 : Fit of the CFS data with different sea-quark distributions

Fig. 15 : Valence quark distribution in pions as found in $\pi p \rightarrow \mu^+ \mu^- + X$

Fig. 16 : QCD constituent scattering diagrams for dimuon production

Fig. 17 : $\langle p_T \rangle$ distribution as a function of the dimuon mass

Fig. 18 : Expectations for dimuon production in 1000 hours of running at the $p\bar{p}$ collider. The Z^0 signal is shown as predicted for a mass of 90 GeV/c² and a width of 2 GeV/c².