LEPTON PAIR PRODUCTION IN HADRONIC COLLISIONS

G. Altarelli
Istituto di Fisica dell'Università - Roma
Istituto Nazionale di Fisica Nucleare, Sezione di Roma

1. INTRODUCTION

In this talk I shall briefly summarize our present understanding of lepton pair production in hadronic collisions. I shall limit my discussion to continuum production (i.e. for lack of time I shall not consider Ψ and Υ production) and the main emphasis will be on recent progress with respect to the situation as it looked last year and was neatly reviewed by Lederman [1] at the Tokyo Conference.

Consider the inclusive production of a lepton-antilepton pair of total invariant mass Q in the collision of two hadrons H_1 and H_2 with total invariant mass $\sqrt{S}$. As usual one defines:

$$\tau = Q^2/S \tag{1}$$

The Drell-Yan [2] mechanism is the basis of our theoretical understanding of these processes in the deep inelastic region i.e. for $Q^2 \longrightarrow \infty$ with τ fixed. In this picture the lepton pair is produced via the pointlike, one photon, annihilation of a quark (antiquark) from H_1 and an antiquark (quark) from H_2. At the naive parton model level this corresponds to the simple Drell-Yan [2] formula:

$$Q^2\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3S}\frac{1}{3}\int\frac{dx_1dx_2}{x_1x_2}\left[\sum_i e_i^2\, q_i^{H_1}(x_1)\,\bar{q}_i(x_2) + 1\leftrightarrow 2\right]\delta\left(1-\frac{\tau}{x_1x_2}\right) \tag{2}$$

where the index i runs over flavors, $q_i^H(x)$ are the densities for a quark q_i with charge e_i in the hadron H, x is the fraction of longitudinal momentum carried by the quark, and a factor of $1/3$ arises from color. The cross section at fixed $x_F=2P_L/\sqrt{S}$, where P_L is the total longitudinal momentum of the pair in the overall center of mass, is given by a simpler formula that reads:

$$\frac{d\sigma}{dQ\,dx_F} = \frac{8\pi\alpha^2}{3Q^3}\frac{1}{3}\left[\sum_i \frac{e_i^2}{x_1+x_2}\, q_i^{H_1}(x_1)\,\bar{q}_i^{H_2}(x_2) + 1\leftrightarrow 2\right] \tag{3}$$

$$x_{1,2} = \frac{1}{2}\left[\pm x_F + \sqrt{x_F^2+4\tau}\right] \tag{4}$$

Leaving for the moment aside all corrections that perturbative QCD imposes on eqs.(2,3) we stress that the validity of the Drell-Yan mechanism implies a number of striking signatures that all seem to be well supported by the available experimental evidence. We recall here the main tests of the Drell-Yan mechanism.

a) Intensity rules. We know from deep inelastic scattering that in the nucleon valence quarks are dominant over sea quarks especially at large x. We have no reasons to doubt that this ought to be true for hadrons other than the nucleon. Thus the Drell-Yan formula predicts much larger cross sections for processes where the lepton pair can be produced by valence-valence annihilation ($\pi^{\mp}$ N, K^-N, $\bar{P}$N) than processes where only valence-sea annihilations are possible (PN,K+N). This should be more and more true the larger is τ , because the bulk of the production arises at small X_F and at $X_F=0$ we have $X_{1,2}=\sqrt{\tau}$ as follows from eq.(4). Thus for large enough τ where the sea can be neglected we also expect for example (on isoscalar targets) $\sigma(\pi^+N(I=0))/\sigma(\pi^-N(I=0)) \cong 1/4$. New data on $\pi^{\mp}$, $K^{\mp}$ and $\bar{P}$ cross sections have been collected over the last year by the CIP collaboration [3] at FNAL and, at CERN, by the NA3 [4] and the Goliath [5] groups. Also new results obtained at CERN-ISR by the CCOR [6] and the R209 [7] collaborations were reported. Most of these new data have been presented at this conference for the first time and added new evidence to the above mentioned intensity rules. All of them appear to be quite well supported by the data.

b) Angular distribution of the leptons. On general grounds the angular distribution of the lepton in their center of mass for production through one photon exchange must be of the form:

$$\frac{d\sigma}{dQ\,d\cos\theta} = W_T(Q)\left(1+\cos^2\theta\right) + W_L(Q)\sin^2\theta \qquad (5)$$

The Drell-Yan mechanism predicts the longitudinal component W_L to be absent because the quark spin is 1/2. For non vanishing transverse momentum of the pair there is some ambiguity in the choice of the reference axis that defines θ. Apart from detailed QCD effects [8][9] this ambiguity can only be important at finite energies. In fact within the present error bars it makes no difference whether for example the Gottfried-Jackson (G.J.) or the Collins-Soper [10] (C.S.) definitions for the angle are adopted. The available data are in fair agreement with the expected angular distribution. New data have been presented. The results can be summarized by giving the measured value of λ obtained by fitting the observed angular distribution with a form $1+\lambda\cos^2\theta$. In πN collisions the reported values are (pion energies $\sim$ 200 GeV, $3.5 < Q < 9$ GeV)

CIP [3]	$\lambda = 1.30 \pm 0.23$	(C.S.)	
NA3 [4]	$\lambda = 0.80 \pm 0.16$	(G.J.)	(6)
	$= 0.85 \pm 0.17$	(C.S.)	

In PP collisions a value for λ was obtained at ISR by the R209 [5] collaboration:

$$\lambda = 1.6 \pm 0.7 \qquad \text{(C.S.)}$$

c) Atomic number dependence. Since the cross section is proportional to the number of quarks or antiquarks in the target one expects a linear A dependence in the Drell-Yan domain of validity. This is well supported by the data on PN collisions and to a lesser extent also for πN collisions. Precisely by introducing a parameter α defined from $\sigma \simeq A^{\alpha}$ one obtains (above the ψ' region):

CFS [11]	$\alpha = 1.02 \pm 0.018 \pm 0.059$	(P N)	
CIP [3]	$\alpha = 1.12 \pm 0.05$	(π N)	(8)
NA3 [4]	$\alpha = 1.02 \pm 0.03$	(π N)	

It is important in the following to keep in mind that taking $A^{1.12}$ as opposed to A^1 makes a difference of about a factor of 2 when the cross section per nucleon is derived from data on a tungsten target, as is the case for the CIP experiment.

d) Approximate scaling. The adimensional quantity $Q^3 \frac{d\sigma}{dQ}$ can only be a function of τ in the naive parton limit. A rather good evidence in support of this approximate scaling law is obtained by comparing the FNAL data in the range $\sqrt{S} \simeq 20 \div 27$ GeV among themselves and with the ISR data at $\sqrt{S} \simeq 62$GeV. Unfortunately there is only a limited overlap in the τ ranges at FNAL and ISR. Further evidence for the approximate scaling law is obtained from the π-N data of CIP, NA3 and Goliath, provided of course the same A dependence is used.

We can therefore conclude that the Drell-Yan mechanism seems to be a firm starting point for the analysis of lepton pair production. As for other processes we think the naive parton model to be only a rough approximation, to be implemented with scaling violations and other effects that are computable if QCD is right.

2. THE PION STRUCTURE FUNCTION

I make at this point a digression to discuss the recent important results on the pion structure function as measured in lepton pair production from π beams. Three experimental groups have reported results on this. They are CIP [3] (FNAL) with about 2000 events analyzed from 225 GeV/c π^- on tungsten, NA3 [4] (CERN) with 8000 events on platinum from both π^- and π^+ at 200 GeV/c, plus over 3000 π^- at 280 GeV/c, Goliath [5] (CERN) with 500 events from π^- on berillium at 150 and 175 GeV/c. The measured values at different τ and X_F are analyzed in terms of eq.3 and the following quantity is determined for an array of different X_1 and X_2 values:

$$\sigma(x_1,x_2) = V_\pi(x_1)\,Q_N(x_2) + S_\pi(x_1)\,H_N(x_2) \qquad (9)$$

where $V_\pi(x)$ and $S_\pi(x)$ are the valence and the sea densities in the pion and $Q_N(x)$ and $H_N(x)$ are combinations of valence and sea distributions in the nucleon. CIP and Goliath neglect $S_\pi(x)$, while the π sea is also determined in the NA3 analysis that includes both π^- and π^+ results. The fitted forms for $V_\pi(x)$ are given by:

$$\begin{array}{lll} \text{NA3 [3]} & xV_\pi(x) \simeq x^{0.4\pm0.06}\,(1-x)^{0.90\pm0.06} & \\ \text{CIP [4]} & \simeq \sqrt{x}\,(1-x)^{1.27\pm0.06} & (10) \\ \text{Goliath [5]} & \simeq \sqrt{x}\,(1-x)^{1.56\pm0.18} & \end{array}$$

The above shapes obtained by the three groups are in fair agreement (the smaller exponent of (1-x) obtained by NA3 is compensated by the smaller exponent of X). We shall discuss the important issue of normalization later in this talk. The sea distribution obtained by NA3 is given by

$$xS_\pi(x) \simeq (0.09\pm0.06)\,(1-x)^{4.4\pm1.9} \qquad (11)$$

which confirms the expectations that the sea in the pion is of the same order as in the nucleon. The flatter x dependence of the π sea in comparison with the nucleon sea is also reasonable in view of the similar difference in the valence x distributions.

On the theoretical side an interesting prediction for the behavior of the π structure function near x=1 was made by Berger and Brodsky [12]. On the same lines as for the quark counting rules [13], they make a QCD model for the higher twist operators that we know must be important in the region near x=1. In this limit almost all of the π momentum is carried by one of its constituent quarks (all non valence parton densities can be neglected near x=1). That requires a large momentum transfer between the two constituent legs. It is argued that this interaction is well approximated by a single hard gluon exchange. Neglecting all normal gluon radiative corrections that lead to scaling violations (which however may be large near x=1), the resulting predictions for the lepton pair cross section near x=1 is of the form:

$$\sigma_{\ell^+\ell^-} \cong (1-x)^2 (1+\cos^2\theta) + \frac{4}{9}\frac{\langle k_T^2\rangle}{Q^2} \sin^2\theta \tag{12}$$

It has been checked by the CIP [14] collaboration that eq.(12) provides a good fit to the data on the π structure function for $x > 0.5$ with $\langle k_T^2\rangle = 1.1 \pm 0.2\ (\mathrm{GeV}/c)^2$. Also clear evidence is indicated by the data[14] for the predicted shift of the angular distribution toward a $\sin^2\theta$ angular dependence near x=1. This is not in contradiction with the previously mentioned test of the Drell-Yan mechanism which predicts $1+\cos^2\theta$, because only a small fraction of events is at large values of X_F.

3. QCD EFFECTS IN DRELL-YAN PROCESSES

We have seen that the Drell-Yan formula is well supported by the data at the naive parton model level. We now consider the corrections to it implied by our present understanding of QCD [15] and the related tests that can be checked in the data.

The first of these effects is the replacement in the Drell-Yan formula of the scaling quark densities with effective Q^2 dependent densities. These are the same as in leptoproduction and satisfy the same Q^2 evolution equations in spite of q^2 being spacelike in one process and timelike in the other. Thus in the leading approximation in QCD (i.e. when additional terms of order $\alpha_s(Q^2)$ can be neglected as well as terms down by powers of Q^2) the Drell-Yan formula is replaced by:

$$Q^2\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{3S}\,\frac{1}{3}\int\frac{dx_1dx_2}{x_1x_2}\left[\sum_i e_i^2\, q_i^{H_1}(x_1,Q^2)\,\bar{q}_i^{H_2}(x_2,Q^2) + 1\leftrightarrow 2\right]\delta\!\left(1-\frac{\tau}{x_1x_2}\right) + o(\alpha_s(Q^2)) \tag{13}$$

This is a consequence of a general factorization theorem [16] that was recently extended by diagrammatic techniques also to processes where the operator expansion method [17] cannot be applied.

The available data are not precise enough to establish the existence of the predicted scaling violations directly. Some indirect evidence is obtained by analyzing the PN data in the FNAL energy range [1]. If the nuclear structure function as measured at a fixed value of Q^2 ($Q^2 \simeq 10 GeV^2$) is taken as an input then the resulting sea distribution that one obtains by fitting the data with the Drell-Yan formula is definitely steeper in X than the sea distribution as measured in leptoproduction. Typically one obtains [1] $(1-x)^n$ with $n \simeq 10$. On the other hand, by using as an input $F_2(x,Q^2)$ as measured in leptoproduction Q^2 by Q^2, then the sea x dependence turns out to be $S(x) \simeq (1-x)^{8.5 \pm 0.1}$ (in the SU(3) symmetric case) in fair agreement with the CDHS extimate of $(1-x)^{8.4 \pm 0.7}$ from ν scattering [18].

A more practical way of detecting a sign of QCD effects is provided by a study of the transverse momentum distribution of the lepton pairs. Most of the lepton pairs are produced with small transverse momentum together with two hadronic jets opposite in momentum arising from the fragments of the two incoming hadrons. However a small fraction of events of order $\alpha_s(Q^2)/\pi$ should contain a pair with large $P_\perp \sim \sqrt{Q^2}$ with three accompanying hadronic jets, i.e. the two hadron fragmentation jets plus a third parton jet. These events arise from the possibility that the incoming quark or antiquark radiates a hard gluon with large $p_\perp$ before annihilating. Alternatively a quark or antiquark may interact with a gluon from the other hadron to produce a massive photon and a final, high $p_\perp$, quark or antiquark. Notice that the lepton pair directly measures the sum of the transverse momenta of the interacting partons. So the actual $P_\perp$ distribution is a superposition of the intrinsic $P_\perp$ distribution of the partons inside the hadrons and of gluon effects including a long tail (up to $P_\perp \sim Q$) arising from hard parton interactions. The tail of $\frac{d\sigma}{dP_\perp^2}$ can be computed [19] in perturbation theory and it behaves at large $P_\perp$ as $1/P_\perp^2$. It is precisely this same effect that leads to the scaling violations in the cross section. We understand that its importance is enhanced if we look at the average $P_\perp$ ($\langle P_\perp \rangle$) or better at higher $P_\perp$ moments. A general and unambiguous prediction of QCD in the increase [19] of $\langle P_\perp \rangle$ with energy at fixed τ :

$$\langle P_\perp \rangle = \alpha_s(Q^2)\sqrt{S}\, f(\tau, \alpha_s(Q^2)) + \text{const.} \qquad (14)$$

The linearly rising term is computable in perturbation theory while the constant term is affected by wave function effects from the intrinsic $P_\perp$ and is mainly non perturbative.

The available data on PN collisions for $\langle P_\perp \rangle$ are shown in Fig.1. Notice that at fixed S the dependence of $\langle P_\perp \rangle$ with Q is flat at not too small Q. That is no evidence against eq.(14) because a meaningful comparison independent of the shape of $f(\tau,\alpha_s)$ (apart from the log dependence on Q^2 though $\alpha_s(Q^2)$) must be done at fixed τ. It is clear for example that at $\tau = 0$ and $\tau = 1$ $\langle p_\perp \rangle$ must go to zero because of phase space, and therefore $f(\tau,\alpha_s)$ cannot be monotonic. The τ value of the ISR point at the highest Q is the same as the points at FNAL energies for $Q \simeq 4 \div 5$ GeV. If we take advantage of the empirical flatness of $\langle p_\perp \rangle$ in τ at fixed S for making some averaging in τ, we obtain a plot as in Fig.2 for the observed rise of $\langle p_\perp \rangle$ with energy. The observed slope is well consistent with theoretical estimates [20] within the uncertainties in the calculation due to the lack of knowledge of the gluon density, the ambiguity on the value of α_s ($\alpha_s(Q^2)$, $\alpha_s(S)$ etc.), the non leading terms. All this taken into account the increase of $\langle p_\perp \rangle$ with $\sqrt{S}$ appears to be the clearest evidence so far for QCD effects in Drell-Yan processes.

A more difficult theoretical problem is the prediction of $\frac{d\sigma}{dp_\perp^2}$ at smaller $P_\perp$. An important step in this direction was achieved by extending the calculable domain from the case of a single large scale (i.e. $P_\perp^2 \sim Q^2$) to the case of two large scales ($M^2 \ll P_\perp^2 \ll Q^2$). This involves keeping track to all orders of terms in log $P_\perp^2/Q^2$ that could be neglected in the previous case. The result is the famous DDT formula [21]:

$$\frac{Q^2 d\sigma}{dQ^2 dp_\perp^2 dy} = \frac{4\pi\alpha^2}{9S p_\perp^2} \frac{\partial}{\partial \ln p_\perp^2} \sum_i \left[e_i^2\, q_i^{H_1}(x_1, p_\perp^2)\, \bar{q}_i^{H_2}(x_2, p_\perp^2) + 1 \leftrightarrow 2 \right] T^2\left(\frac{Q^2}{p_\perp^2}\right) \tag{15}$$

with

$$T(\lambda) = \int_1^Z dz \exp - \frac{1}{z^2} \frac{2}{3\pi} \alpha_s \ln^2 \lambda \tag{16}$$

In the available data the applicability of this formula is only marginal due to the limited Q and $P_\perp$ range explored so far. Actually perhaps the most important quantitative difference in practice is the realization that the use of $\alpha_s(p_\perp^2)$ rather than $\alpha_s(Q^2)$ is more appropriate in the calculation of the $P_\perp$ moments. The result is a reduction of the amount of intrinsic $P_\perp$ needed to reproduce the actual distribution [22]. Last year it was thought to be around $p_\perp \sim 600$ MeV (intrinsic per parton). Now it is considerably lower [22]: $P_\perp \sim 400$ MeV.

We now turn to a third effect of QCD that has to do with the calculation of non leading corrections. In eq.(13) all terms down by a power of $\alpha_s(Q^2)$ were neglected. To evaluate the first order corrections it is preliminarly necessary to precisely specify what we mean by quark densities. This can be done [23] by specifying that the quark densities are to be measured from the structure function F_2 in leptoproduction. That is F_2 is related to the quark densities by the familiar parton formula valid by definition with no corrections of order $\alpha_s(Q^2)$. The advantage of choosing F_2 as a standard is that it turns out that quark densities so defined satisfy [13] the valence sum rules:

$$\int_0^1 dx\,\left[u(x,Q^2) - \bar{u}(x,Q^2)\right] = 2 \tag{17}$$

etc., with no corrections of order $\alpha_s(Q^2)$. Once the quark densities are so defined one can compute in a non ambiguous way the corrections of order $\alpha_s(Q^2)$ to the parton formulae for all other processes. In the Drell-Yan case the improved formula is as follows: [23][24][25]

$$Q^2\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9S}\int\frac{dx_1\,dx_2}{x_1 x_2}\Big\{\Big[\sum_i e_i^2\, q_i^{H_1}(x_1,Q^2)\,\bar{q}_i^{H_2}(x_2,Q^2) + 1\leftrightarrow 2\Big]\Big[\delta(1-z) + \alpha_s(Q^2)\,\theta(1-z)\,f_q(z)\Big] + \Big[\frac{1}{x_1}F_2^{H_1}(x_1,Q^2)\,G^{H_2}(x_2,Q^2) + 1\leftrightarrow 2\Big]\alpha_s(Q^2)\,\theta(1-z)\,f_G(z)\Big\} \tag{18}$$

where $z = \frac{\tau}{x_1 x_2}$, $\quad F_2^H(x,Q^2) = x\sum_i e_i^2\left[q_i^H(x,Q^2) + \bar{q}_i^H(x,Q^2)\right]$ and

$$\alpha_s f_q(z) = \frac{4}{3}\frac{\alpha_s}{2\pi}\left[\left(1+\frac{4\pi^2}{3}\right)\delta(1-z) + 2(1+z^2)\left(\frac{\ln(1-z)}{1-z}\right)_+ + \frac{3}{(1-z)_+} - 6 - 4z\right]$$

$$\alpha_s f_G(z) = \frac{1}{2}\frac{\alpha_s}{2\pi}\left[\left(z^2+(1-z)^2\right)\ln(1-z) + \frac{9}{2}z^2 - 5z + \frac{3}{2}\right] \tag{19}$$

It turns out that the gluon correction is normal, i.e. it can be neglected at not too larger values of τ in all processes where the quark term is of valence-valence type, while it makes a non negligible correction for valence-sea processes [23][26]. On the other hand the quark correction is quite large at present energies with currently accepted values for $\alpha_s(Q^2)$. The most dangerous term is the δ function term that renormalizes the point like cross section. It arises mainly from the continuation from spacelike q^2 in leptoproduction to timelike q^2 in Drell-Yan processes. The other terms in f_q are rapidly increasing with τ and arise from the difference in phase space between leptoproduction (the heavy photon in the initial state) and Drell-Yan processes (the heavy photon in the final state). The situation is summarized in Fig.3 for πN collisions at $\sqrt{S} \simeq 21$ GeV. The gluon correction is in this case negligible and it is not displayed. It is important to notice that in the τ range of the data the result amounts essentially to a large change in the over all normalization in the cross section in excess with respect to the naive prediction. Of course being the first order correction so large we cannot trust the present approximation beyond a semi quantitative level.

Note that all tests of the Drell-Yan mechanism discussed in the first part of this talk are essentially unaffected by the above results. In fact the predictions of a linear A dependence, approximate scaling, linear rise of $\langle p_\perp \rangle$ at fixed τ are not changed. The intensity rules are not qualitatively altered. Also the $1+\cos^2\theta$ angular distribution is not changed, because it turns out that the large corrective terms are not in the longitudinal part but only in the transverse part.

In view of this large non leading terms it is interesting to inquire whether the experiments allow to draw some conclusion on the measured scale of the cross section in comparison with the prediction of the naive Drell--Yan formula. It is remarkable that actually there are consistent indications in the data for a cross section larger than expected. We consider first the new data on πN collisions. Let us introduce a scale factor defined as

$$\left(\frac{d\sigma}{dQ^2}\right)_{EXP} = K \left(\frac{d\sigma}{dQ^2}\right)_{NAIVE\ D.Y.} \tag{20}$$

The parton densities can be normalized by requiring the validity of the valence sum rules:

$$\int_0^1 V_\pi(x)\, dx = 1 \tag{21}$$

for the pion and similarly for the nucleon (see eq.(17)). Then the situation appear to be as follows. The Goliath group takes the nucleon structure functions from Buras-Gaemers [27] and obtains $K \simeq 3$. The NA3 [4] collaboration finds $K \simeq 2.2 \div 2.5$ if the CDHS [18] nucleon densities are taken and $K \simeq 1.4$ if they take the nucleon densities from their own fit (which however contains a large sea component, so that only 20÷30 % of the momentum is left for gluons in the nucleon). The CIP [3] collaboration finds $K \simeq 1$ if the cross section per nucleon is extracted from the data on tungsten by using the measured $A^{1.12}$ dependence. That means they would end up with

$K \simeq 2$ for a linear A dependence.

Finally in PN collisions we learn from refs.(1,11) that the CFS group finds the amount of sea required to fit the Drell-Yan data to correspond to a fraction of momentum as high as 6% (per species). In ν scattering CDHS[18] only finds about 2.5 °/₀ . This is also illustrated by a study of Berger [28] who compares at correspondent values of Q^2 and x the CDHS sea with the Drell-Yan sea. In the overlap region a discrepancy of about a factor of two is observed (see Fig.4).

Note that the predicted departures from the naive Drell-Yan formula should dramatically increase when τ approaches 1, where prominent factorization breaking effects should also be present. Finally we recall that instanton effects are also possibly dangerous for the Drell-Yan picture [29].

4. CONCLUSIONS

The data accumulated so far are enough to conclude that the Drell-Yan mechanism for leptoproduction appears to be physically correct. The problem is now to go beyond the naive parton model and establish or disproof the presence of the departures from this first approximation as predicted by QCD. The only reasonably verified signature so far is the rise of $\langle P_\perp \rangle$ with $\sqrt{s}$ at fixed τ . The normalization issue seems to be a crucial point to be checked. πN collisions are promising in this respect, but the problem of the A dependence must be settled before one can derive firm conclusions.

I think it is clear by now that a solid confirmation of QCD can only arise from a patient work exploring at the same time different processes where the same basic quark gluon interactions are at work. In this respect Drell-Yan processes will play an important role.

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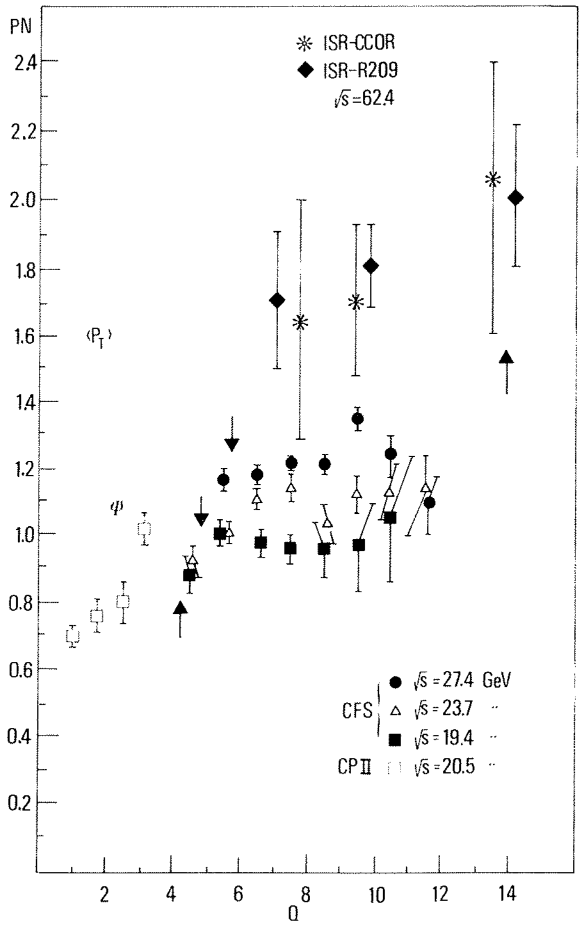

Fig. 1 Average $\langle P_\perp \rangle$ for PN lepton pair production. The arrows indicate points with same τ.

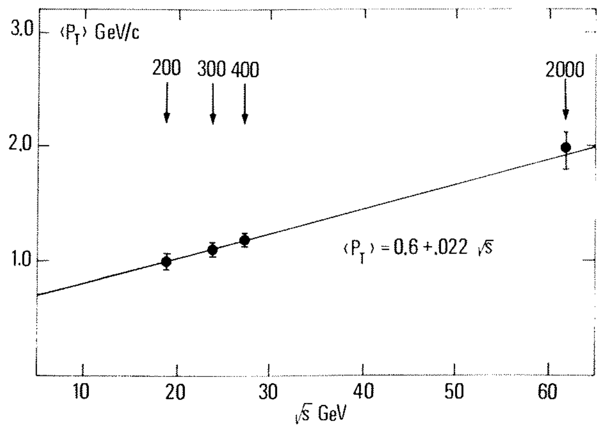

Fig. 2 Average $\langle P_\perp \rangle$ VS $\sqrt{S}$. The point at $\sqrt{S}$ = 62 is from ISR CCOR and R209 collaborations.

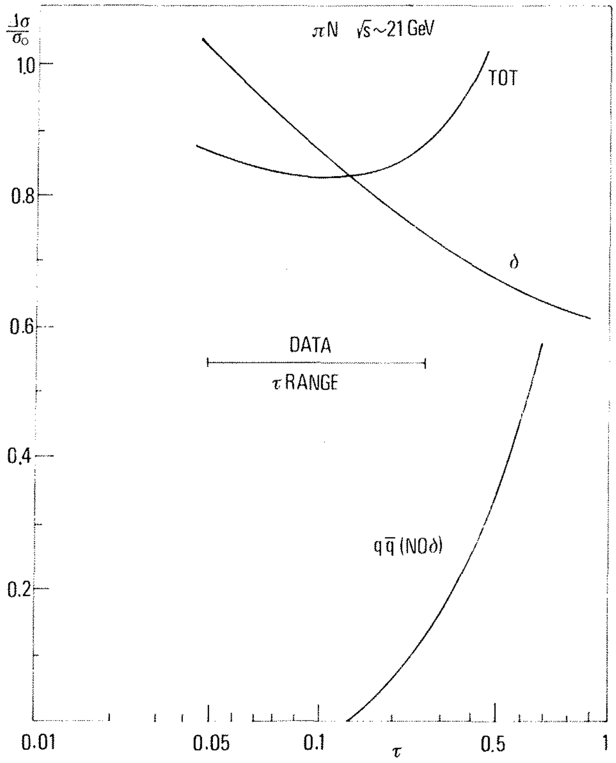

Fig. 3 Effect of non leading corrections to the π^-N cross section. A similar result also holds for PN collisions.

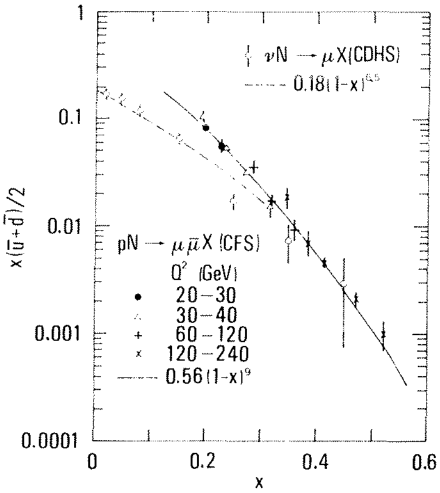

Fig. 4 The sea from ν scattering VS the sea extracted from PN Drell-Yan processes. At same values of x and Q^2 we note a factor two discrepancy. (Figure taken from ref. 28.)

DISCUSSION

Chairman: S.C.C. Ting

Sci. Secretaries: C. Best and H. Gennow

E.L. Berger: For the next to leading 1/log Q^2 corrections to the Drell-Yan formula, do the corrections due to the initial g + q diagrams dominate, or are the $q\bar{q}$ diagrams more significant? I am thinking of the possibility of subtracting π^+N from π^-N cross-sections to remove the higher order, non-leading 1/log Q^2 terms. If the qq set wins, this subtraction could be motivated.

G. Altarelli: In general the gluon term is completely negligible for valence dominated processes unless you go to very large τ.

R.C. Hwa: A year ago CP data showed no significant dependence of $\langle p_T \rangle_{\mu^+\mu^-}$ on x_F. That ruled out QCD contributions as an important effect because the large p_T of $\mu^+\mu^-$ accompanied by a gluon recoil in $q+q \to (\mu^+\mu^-) + g$ should be seen mainly at low x_F, not large x_F. Have the data changed since then at higher energies?

G. Altarelli: No, the data did not change at that energy.

A. Bodek: Do you see any mechanism for making the Drell-Yan cross-section bigger than $A^{1.0}$? Normally an A-dependence bigger than 1.0 can be obtained by multiple scattering of the final state. However, here the final state is two muons. Interaction of the initial state hadron in the nucleus, losing energy and re-interacting again tends to make the A-dependence smaller than 1.0.

G. Altarelli: Well, the final state is not only leptons, there are also hadron fragments which could contribute. I do not know however of any detailed theory for an A-dependence.

S.J. Brodsky: Regarding the A-dependence of the massive lepton-pair cross-section: an effect that seems reasonable physically is that one expects the incoming hadron to lose energy in the nucleus by standard particle production (Glauber) processes. The energy loss and re-arrangement of the Fock space of the incident hadron before the $q\bar{q}$ annihilation evidently destroys simple factorization arguments. Should not such effects be taken into account at some level?

G. Altarelli: I would not be so impressed by finding $A^{1.12}$. I only pointed out this fact because it is very important for knowing our cross-sections per nucleon. I would not expect more than, say, a 10% departure from a linear A-dependence because otherwise I would conclude that the parton model cannot be the full story, since the cross-section is not proportional to the number of partons you have around. So if you see a large effect, this is not impossible to imagine, but certainly a blow against the parton approach.

The experimental evidence is contradictory because from proton beams we would say it is perfectly linear. From pion-nucleus collisions there is contradictory evidence from different groups, so the situation is more confused on a measurement point level than for theory to worry about.