

Talk given at the
XVII Rencontre de Moriond
Les Arcs, March 1982

ISTITUTO NAZIONALE DI FISICA NUCLEARE
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DRELL-YAN PROCESSES AND PERTURBATIVE QCD.

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ABSTRACT.

A brief account is given of our present understanding of the normalization factor of the total cross sections and of the transverse momentum properties in the Drell-Yan processes.

Impressive amount of data have been accumulated recently¹⁾ in support of the parton picture of the production of lepton pairs in hadronic collisions, which was proposed by Drell and Yan²⁾ more than ten years ago. The approximate scaling of $Q^4 d\sigma/dQ^2$ as a function of $\tau = Q^2/S$, the large magnitude of the cross sections for the valence dominated processes (π^+ , K^+ , \bar{p})N in comparison with the sea dominated ones (p , K^+)N, the angular distributions of the lepton pairs, the dependence on the atomic number of the nuclear target, are all crucial tests which have been successfully passed by the naive model.

It is by now well known that QCD predicts definite deviations from the parton model³⁾. Quite remarkably, the two most spectacular QCD predictions for the Drell-Yan process, i. e. the absolute normalization of the cross section and the transverse momentum properties of the dilepton pairs are now in impressive agreement with data. This conclusion is based upon a great deal of theoretical and experimental work which has been carried out recently.

In this talk I will present a short review of the theoretical aspects of this field and focus in particular the two items mentioned above.

The basic cross section in the naive parton model is given by

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9SQ^2} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \delta(x_1 x_2 - \tau) \sum_k e_k^2 \left\{ q_k(x_1) \bar{q}_k(x_2) + (1 \leftrightarrow 2) \right\}, \quad (1)$$

where \sqrt{S} is the invariant mass of the incoming hadronic system, Q is the invariant mass of the produced pair and $\tau = Q^2/S$. The parton densities $q_k(x_i)$ and $\bar{q}_k(x_i)$, which are measurable in deep inelastic scattering^(*), are supposed to depend only on the fractions x_i of the longitudinal momenta of the hadrons 1 and 2, neglecting the transverse momentum of the quarks. Eq. (1) predicts therefore scaling for $[Q^4 d\sigma/dQ^2](\tau)$, which is borne out by the data¹⁾ within the actual experimental accuracy.

The presence of $\log Q^2$ scale-breaking effects, as for any others deep inelastic process, is the most direct of the QCD expectations. These effects however are too tiny to be visible in the present data, also because of the very steep

(*) In the following factorization will be assumed, although a complete proof is still lacking for the Drell-Yan process. Possible failures⁴⁾ of factorization due to initial state interactions will be discussed by D. Soper in this meeting.

fall-off of the cross sections with Q^2 . Fortunately, QCD effects turn out to be quite relevant for the problem of the absolute normalization of the dilepton cross sections, the so called K factor problem. In fact the explicit evaluation⁵⁾ of the first order correction to eq. (1) leads to a surprisingly large result. More in detail one finds

$$\frac{d\sigma}{dQ^2} = \frac{4\pi\alpha^2}{9SQ^2} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \left\{ \sum_k e_k^2 q_k(x_1, Q^2) \bar{q}_k(x_2, Q^2) + (1 \leftrightarrow 2) \right\} \cdot \left\{ \delta(1-z) + \alpha_s(Q^2) \theta(1-z) \tilde{f}_q^{\text{DY}}(z) \right\} + (\text{qg contributions}), \quad (2)$$

where $z = \tau/x_1 x_2$ and

$$\tilde{f}_q^{\text{DY}}(z) = \frac{C_F}{2\pi} \left\{ 2(1+z^2) \left[\frac{\ln(1-z)}{1-z} \right]_+ + \pi^2 \delta(1-z) + \dots \right\}. \quad (3)$$

In the above eq. we have introduced the Q^2 dependence in the parton densities of deep inelastic scattering, and furthermore, the two main corrections to order α_s have been explicitly reported. At the presently accessible values of Q^2 and τ , the terms (3) give a large positive correction, of order of two, to the naive parton model, which is substantially independent of τ . The presence of such a large and almost constant factors has been impressively confirmed by the data in all observed channels^{1, 6)}.

The puzzling aspects of this close agreement between data and the first order QCD result lies on the fact that the size of the correction clearly casts doubt on the validity of the perturbative expansion in α_s . However, due to the particular structure of eq. (3) and the physical meaning associated to it, the resummation of those largest contributions has been suggested by various authors^{7, 8)}. In fact the first term in eq. (3) is clearly associated to phase space effects in the soft gluon emission from the initial (q, \bar{q}) pair, whereas the famous π^2 term in (3) arises from the continuation of the form factor from space like to timelike values of Q^2 . Resummation of these soft effects to all orders in α_s then gives⁹⁾

$$\frac{d\sigma}{dQ^2} \simeq \frac{4\pi\alpha^2}{9SQ^2} \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \left\{ \sum_k e_k^2 q_k(x_1, Q^2) \bar{q}_k(x_2, Q^2) + (1 \leftrightarrow 2) \right\} \cdot \exp \left\{ \frac{\alpha(Q^2)}{2} C_F \pi \right\} \tilde{f}(z, Q^2), \quad (4)$$

with

$$\tilde{f}(z, Q^2) = \frac{1}{2\pi} \int_{-\infty}^{\infty} db e^{ib(1-z)} \exp \left\{ \frac{C_F}{\pi} \int_0^1 dy \left(\frac{1+y^2}{1-y} \right) \cdot \int_{Q^2(1-y)}^{Q^2(1-y)^2} \frac{dk_{\perp}^2}{k_{\perp}^2} \alpha(k_{\perp}) \left[e^{-ib(1-y)} - 1 \right] \right\}. \quad (5)$$

Phenomenologically, eq. (4) leads⁹⁾ to an overall soft correction factor K to the parton model which is not significantly different, to the level of the actual experimental accuracy, from the first order result in the kinematical ranges explored so far. An improved accuracy in the next future experiments, particularly in πN collisions at large τ , could test the effect of higher orders. For the time being the question of the K factor can be considered to be satisfactory settled.

Among the most spectacular QCD effects are the p_{\perp} effects which are caused by gluon bremsstrahlung. These have been extensively studied in e^+e^- annihilation and Drell-Yan processes and can be very easily measured in the latter reaction by observing the transverse momentum distribution of the lepton pair. In particular one expects, for the average p_{\perp}^2 ,

$$\langle p_{\perp}^2 \rangle = \alpha_s(Q^2) S f(\tau, \alpha_s(Q^2)) + \dots, \quad (6)$$

where the dots indicate terms which are constant with S and may be ascribed to an intrinsic transverse momentum of the partons. The observation⁶⁾ of a linear increase with S of $\langle p_{\perp}^2 \rangle$, for fixed τ , is in qualitative agreement with first order results. However, to explain the data one requires quite a large value of the intrinsic transverse momentum $\langle p_{\perp}^2 \rangle_{\text{intr}} \sim 1 \text{ GeV}^2$, and furthermore, the τ dependence of $\langle p_{\perp}^2 \rangle$ with τ predicted by the theory is wrong⁶⁾.

The comparison of the absolute distributions from first order diagrams is shown¹⁰⁾ in Fig. 1 for pN and πN collisions. Apart from the low p_{\perp} region, where perturbation theory is supposed to break down (see below) and non perturbative intrinsic effects could be of importance, the p_{\perp} -distributions are consistent with the pN data at $p_{\perp} \gtrsim 3 \text{ GeV}$, but are substantially below the πN data. Even after the inclusion of a substantial intrinsic $\langle p_{\perp}^2 \rangle_{\text{intr}} \sim 1 \text{ GeV}^2$, the πN

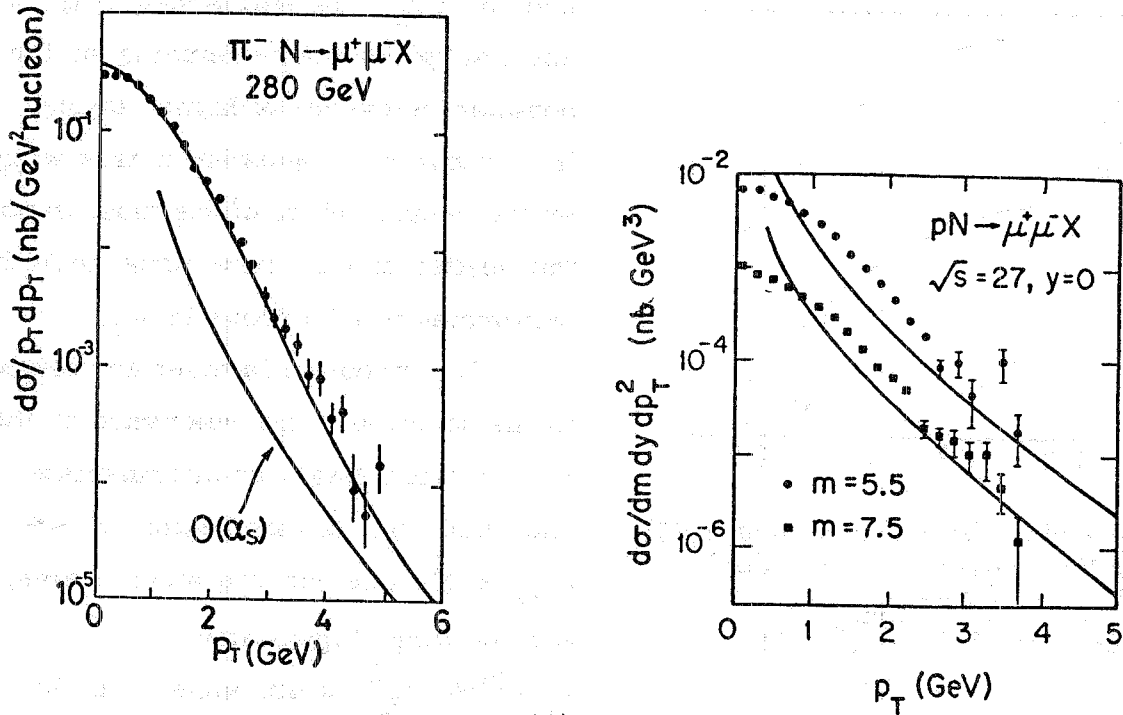


FIG. 1 - $O(\alpha_s)$ p_T -distributions¹⁰⁾ for pN and π N collisions. The fit to the π N data is obtained from the $O(\alpha_s)$ calculation, regularized with $\langle p_{\perp}^2 \rangle_{\text{intr}} = 1 \text{ GeV}^2$ and renormalized by a constant factor 2.4.

lie by a factor $K' \approx 2$ above the theoretical predictions. This result suggests the possible relevance of α_s^2 correction also at large p_{\perp} .

Indeed this has been found recently in ref. (11) by studying the non singlet cross sections $(\pi^+ - \pi^-)N$. The $O(\alpha_s^2)$ correction factor

$$K'(p_{\perp}) = \frac{\frac{1}{p_{\perp}} \frac{d}{dQ} \frac{dQ}{dp_{\perp}} \Big|_{O(\alpha_s^2)}}{\frac{1}{p_{\perp}} \frac{d}{dQ} \frac{dQ}{dp_{\perp}} \Big|_{O(\alpha_s)}} \quad (7)$$

is shown¹¹⁾ in Fig. 2. Although this large correction is welcomed by the data it does not solve all the problems. In fact one still needs a large value for $\langle p_{\perp}^2 \rangle_{\text{intr}}$, the τ depend-

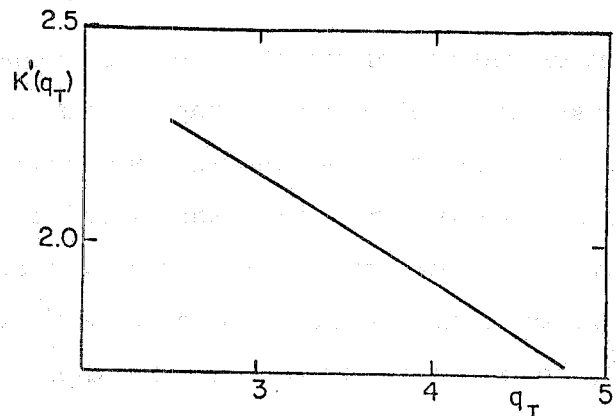


FIG. 2

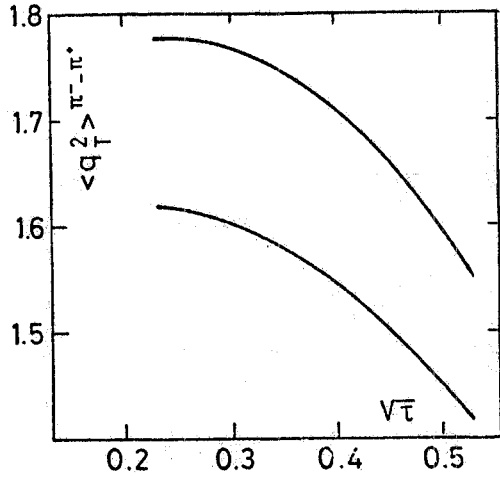


FIG. 3 - $O(\alpha_s)$ (lower line) and $O(\alpha_s^2)$ (upper line) results¹¹⁾ for $\langle p_{\perp}^2 \rangle = \langle p_{\perp}^2 \rangle_{\text{QCD}} + [\langle p_{\perp}^2 \rangle_{\text{int}} = 1 \text{ GeV}^2]$, as a function of $\sqrt{\tau}$ at $\sqrt{S} = 19.4 \text{ GeV}$.

ence of $\langle p_{\perp}^2 \rangle$ is still wrong (Fig. 3) and finally the worry remains of the possible relevance of higher orders. In particular the question arises whether the resummation of the most important higher order corrections could be performed to all orders in α_s .

This problem is directly related to the question of the relevance of the perturbation theory at intermediate and small p_{\perp} . In this region ($\Lambda^2 \ll \ll p_{\perp}^2 \ll Q^2$) one has two mass scales, and the large logarithms

$$\alpha_s^n \ln^{2n}(Q^2/p_{\perp}^2)$$

which appear in the perturbative parton cross sections have to be resummed to all orders. The so called double leading logarithmic approximation (DLLA), which resums in each order only the dominant terms of the expansion

$$\frac{1}{\sigma_0} \frac{d\sigma}{dp_{\perp}^2} \sim \frac{\alpha_s}{p^2} \ln \frac{Q^2}{p_{\perp}^2} \left\{ A + \alpha_s (B_1 \ln^2 \frac{Q^2}{p_{\perp}^2} + B_2 \ln \frac{Q^2}{p_{\perp}^2}) + \alpha_s^2 (C_1 \ln^4 \frac{Q^2}{p_{\perp}^2} + C_2 \ln^3 \frac{Q^2}{p_{\perp}^2} + C_3 \ln \frac{Q^2}{p_{\perp}^2} + \dots) + \dots \right\} \quad (8)$$

then gives¹²⁾, for fixed α_s ,

$$\frac{1}{\sigma_0} \frac{d\sigma}{dp_{\perp}^2} \sim \frac{\alpha_s}{p_{\perp}^2} \ln \frac{Q^2}{p_{\perp}^2} \exp \left\{ - \frac{C_F \alpha_s}{2\pi} \ln^2 \frac{Q^2}{p_{\perp}^2} \right\}. \quad (9)$$

The exponential in the above eq. corresponds to an effective quark form factor. It essentially gives the probability that the massive lepton pair is produced without emission of gluons having transverse momenta $k_{\perp} > p_{\perp}$. When $p_{\perp}^2 \ll Q^2$ this probability is very small, and indeed the DLLA⁹⁾ predicts a dip at $p_{\perp} = 0$, which however is quite fictitious. In fact at small p_{\perp}^2 , the subleading contributions from multigluon emission with $k_{\perp i}^2 > p_{\perp}^2$ and which add vectorially to give a small p_{\perp}^2 , become dominant and fill that dip.

It is therefore relevant to keep trace of exact momentum conservation. This can be most easily done by working in the impact parameter space and one finds¹³⁾

$$\frac{1}{\sigma_0} \frac{d\sigma}{dp_{\perp}^2} = \frac{1}{2} \int_0^{\infty} b db J_0(b p_{\perp}) \exp\left[\Delta(b, q_{\perp \max})\right], \quad (10)$$

with

$$\Delta(b, q_{\perp \max}) = \frac{4C_F}{\pi} \int_0^{q_{\perp \max}} \frac{dq_{\perp}}{q_{\perp}} \ln\left(\frac{Q}{q_{\perp}}\right) \alpha(q_{\perp}) \left[J_0(bq_{\perp}) - 1\right], \quad (11)$$

and $q_{\perp \max} \sim Q$ is the phase space limit for the emitted gluons.

The above result explicitly shows the relevance of a detailed understanding of the subleading corrections to eq. (9). Thus a systematic investigation of such terms has been carried out recently¹⁴⁾. The result¹⁵⁾ is essentially given by a formula like (10), with next to leading corrections evaluated for the integrand of (11). On the other hand, from a more phenomenological point of view, it has been shown¹⁶⁾ the relevant role played by the appropriate use of the exact kinematics in evaluating in eq. (11) the emission of soft gluons. This observation has been motivated by analogous results obtained in deep inelastic scattering, and for the K factor itself, where a careful treatment of the kinematics in multi gluon emission accounts for the most important next to leading corrections. More explicitly, with $z = \tau/x_1 x_2$ and y the dilepton rapidity, one gets for $q_{\perp \max}$ in eq. (11)

$$q_{\perp \max} \approx \frac{Q(1-z)}{2\sqrt{z}} \frac{1}{\sqrt{1+z \sin^2 y}}. \quad (12)$$

Then a simultaneous analysis¹⁶⁾ of the soft effects to all orders in α_s (eqs. (10, 11, 12)) for $p_{\perp} \leq \bar{p}_{\perp}$ and the hard terms to first¹⁷⁾ and second order (eq. 7) in α_s for $p_{\perp} \geq \bar{p}_{\perp}$, with $\bar{p}_{\perp} \sim 3$ GeV, gives an excellent description of all data available so far, both in πN and pN collisions, after inclusion of an intrinsic $\langle p_{\perp}^2 \rangle_{\text{intr}} \sim 0.4$ GeV². This is shown in Figs. 4 and 5. Thus the inclusion of multi gluon effects improves considerably the agreement of the theory with the data at low p_{\perp} , without the need for an unnaturally large intrinsic p_{\perp} . The same analysis also suggests a sizeable α_s^2 corrections for the Compton term at large p_{\perp} in case of pN collisions.

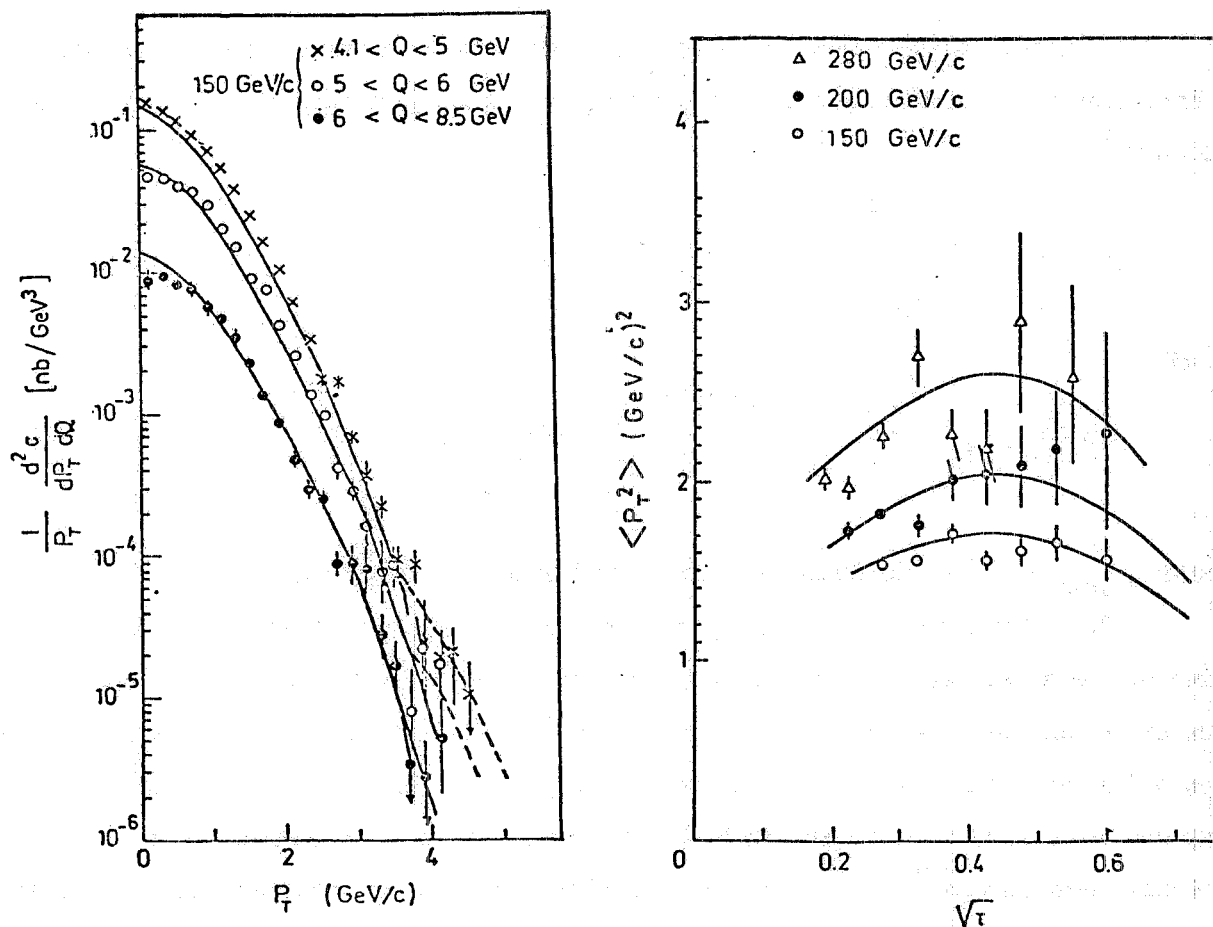


FIG. 4 - p_{\perp} -distributions¹⁶⁾ for πN collisions : the full line represents the soft contribution including an intrinsic $\langle p_{\perp}^2 \rangle_{\text{int}} = 0.4 \text{ GeV}^2$ and the dashed one the annihilation hard term. The $\langle p_{\perp}^2 \rangle$ curves are directly obtained from the distributions.

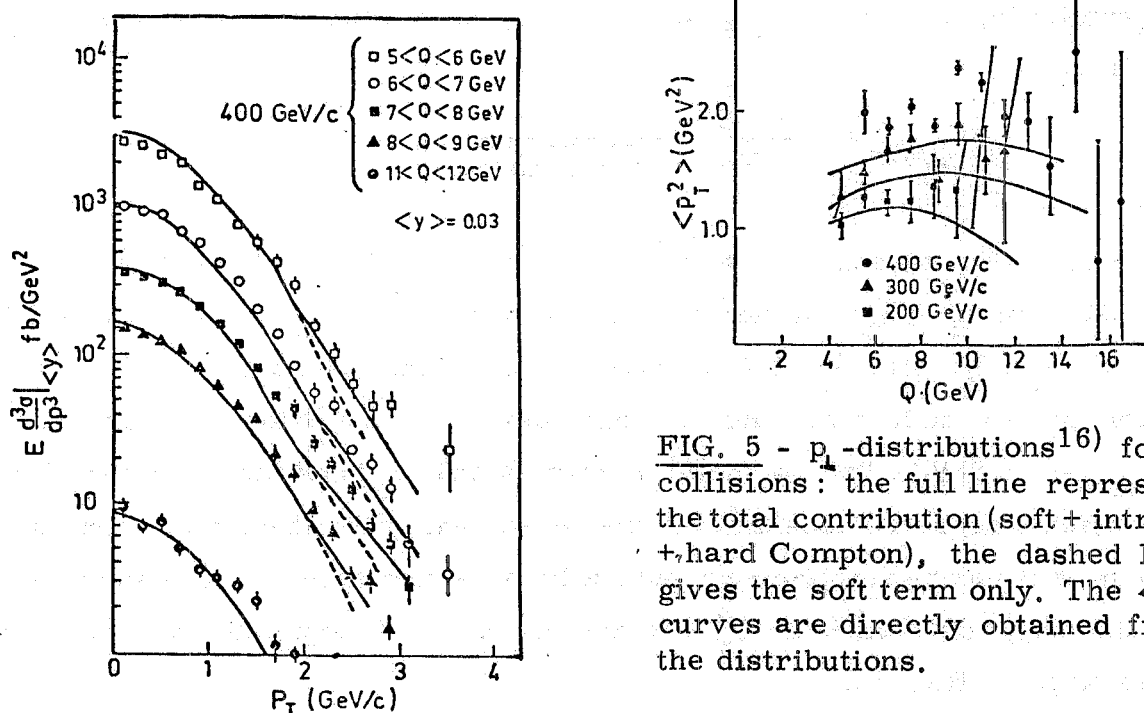


FIG. 5 - p_{\perp} -distributions¹⁶⁾ for pN collisions : the full line represents the total contribution (soft + intrinsic + hard Compton), the dashed line gives the soft term only. The $\langle p_{\perp}^2 \rangle$ curves are directly obtained from the distributions.

In summary it seems that a lot of progress has been made towards the understanding in QCD of the various features observed in the Drell-Yan processes. It is crucial, therefore, to check whether possible diseases of non factorization, as discussed in ref. (4), do not spoil the general framework reported here.

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