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Hadron Production in Deep Inelastic Lepton Scattering*

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HADRON PRODUCTION IN DEEP INELASTIC LEPTON SCATTERING

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ABSTRACT

A short review is given on recent results on hadron production in deep inelastic lepton scattering concentrating mainly on the fragmentation process. New experimental data and refined methods in the analysis provide a better separation between different regimes of fragmentation and the possibility to determine distributions of pions, kaons and protons separately. Latest results on scale breaking in hadron production and the so called seagull effect are also briefly discussed.

1. Introduction

The purpose of this review is to summarize the results on hadron production in deep inelastic lepton scattering gained during the last year. The main emphasis is laid on the investigation of the fragmentation process. Other very interesting topics related to QCD are either mentioned only briefly (scale breaking, seagull effect) or left out completely (jets, high $p_\perp$ phenomena, planar events, φ asymmetry). The reason for this choice is that in these fields nothing strikingly new has been found recently but as work is going on at several institutes interesting results can be expected in the near future. As the most recent and complete review of hadron production in lepton scattering an article by P. Renton an W. S. C. Williams is recommended[1).

The main features of hadron production in lepton nucleon scattering are commonly described in the framework of the quark-parton model (fig. 1a). The production of hadrons is interpreted as a two step process: First the virtual photon (boson) is absorbed by a quark inside the nucleon and then this struck quark and the spectator 'diquark' (system left behind) fragment into hadrons. Besides for its own interest, to understand the fragmentation is therefore of great importance in order to be able to study the basic process at the parton level.

The following quantities are used to present the results on leptoproduction of hadrons. The variables are given in terms of the four momenta of the initial and final state particles (fig. 1a).

Event variables:

$Q^2 = -(l-l')^2$	mass squared of the virtual photon (boson)
$\nu = q \cdot N/m_N$	lab. energy of the virtual photon (boson)
$W^2 = s = (q+N)^2$	hadronic centre of mass energy squared
$x = Q^2/2m_N\nu$	fraction of the nucleon's momentum carried by the quark (Bjorken x)

Hadron variables:

$z = h \cdot N/q \cdot N = E/\nu$	fraction of the quark's momentum carried by the hadrons
$x_F = p_\parallel^*/p_{max}^* \approx 2p_\parallel^*/W$	Feynman x
$y = 0.5\log(E+p_\parallel)/(E-p_\parallel)$	rapidity
$p_\perp$	momentum perpendicular to the current direction

In the quark-parton model (QPM) the differential multiplicity of hadrons produced per event can be expressed by

$$1/\sigma \cdot dN^h/dz = \sum \varepsilon_i(x) \cdot D_i^h(z) \quad (1)$$

where the summation runs over all quarks and antiquarks. The structure of this formula reflects the picture of a process of two independent steps (factorization) where the fragmentation function $D_i^h(z)$ does not depend on the energy of the quark (scaling).

The differential probability for the scattering off quarks is given by

$$\varepsilon_i(x) = e_i^2 q_i(x) / \sum e_i^2 q_i(x) \quad (2)$$

in e or μ scattering. In ν ($\bar{\nu}$) scattering ε_d (ε_u) is equal to 1 all other ε_i being 0 if contributions from sea quarks and the production of s and c quarks (Cabbibo angle set to 0) are neglected.

The extension of the quark-parton model by taking into account gluons (fig. 1b) leads to a couple of clear predictions which differ from what is expected in the simple QPM picture. Among other effects scale breaking (i. e. Q^2 dependence of q_i and D_i^h) and the production of high $p_\perp$ hadrons (gluon bremsstrahlung) follow from perturbative QCD.

2. Fragmentation in lepton scattering

In deep inelastic lepton scattering three different kinds of fragmentation occur. Besides quark and gluon fragmentation which can also be studied in e^+e^- annihilation the investigation of 'diquark' fragmention is possible. This is one of several advantages of lepton scattering experiments compared with e^+e^- annihilation.

In lepton scattering the direction of the fragmenting quark is almost entirely determined by the current direction. Radiative effects and the influence of the primordinal $k_\perp$ of the quark (Fermi motion inside the target nucleon) lead to slight deviations. Above the sea region ($x > 0.1$) the flavour of the fragmenting quark is known to be u (d) in ν ($\bar{\nu}$) scattering and to be predominantly u (~ 90 %) in charged lepton scattering whereas in e^+e^- annihilation the flavour of the original quark is completely unknown. It should also be mentioned that higher statistics can be achieved more easily in e and μ experiments than in ν scattering or e^+e^- annihilation.

Besides these advantages of lepton scattering compared with e^+e^- annihilation there are certainly some disadvantages which are connected to the lower centre of mass energies reached so far in lepton scattering (≤ 20 GeV). This leads to a higher sensitivity to wrong mass assignments and to a spill over of hadrons between the target and the current hemispheres.

2.1 Separation between forward and backward fragmentation

In order to achieve a clean separation between the forward and backward hemispheres the masses of the hadrons must be known and the energy must be sufficiently high. In recent analyses of νH_2 and $\bar{\nu} H_2$ scattering[2] in BEBC both effects have been studied. To correct for wrong mass assignments the following procedure was applied using Monte Carlo techniques: Events have been created with the experimental energy distribution of the neutrinos. The hadronic final state was simulated according to the so called Lund model[3] but with some parameters different from their default values (e. g. V/P = 3) in order to achieve perfect agreement between experimental and Monte Carlo distributions. These events have been modified by smearing, removing neutral particles and treating all hadrons as pions. The correction for wrong mass assignments was then determined from a comparison between the initial and modified Monte Carlo events.

In fig. 2 the mean multiplicities of charged hadrons in the forward (positive x_F) and backward (negative x_F) hemispheres are shown as function of W^2 after the corrections just mentioned have been applied. The solid and the dashed lines represent earlier results from this[4] and other experiments[5] which agreed well among each other but had not been corrected for wrong mass assignments to kaons and baryons. One can see that as expected the corrections are most important for positive hadrons at low W^2, i. e. where the influence of slow protons (target fragments) is strongest. The effect of wrong mass assignments gets weaker with increasing W^2 and is in general smaller for negative hadrons mainly because there are fewer slow antiprotons than slow protons.

From this it becomes obvious that the identification of hadrons is important if one wants to draw firm conclusions from a comparison between results on the production of positive and negative hadrons in the forward and backward direction separately. As can be concluded from fig. 2 in νp scattering $\langle n_B^+ \rangle$ is greater

than $\langle n_F^+ \rangle$ over the whole W^2-range. This may be expected since the forward hadrons are fragments of a u-quark whereas a uu-system is emitted backward. Previous analyses led to opposite results namely $\langle n_B^+ \rangle < \langle n_F^+ \rangle$ with the interpretation that the high mass of the proton reduces $\langle n_B^+ \rangle$ significantly.

Besides mass effects insufficient energy can also cause spill over of hadrons between the current and the target hemispheres. This problem was investigated in νp and $\bar{\nu} p$ scattering[2] in terms of forward-backward multiplicity correlations. They have been found to disappear for $W \gtrsim 7$ GeV.

2.2 Quark and diquark fragmentation into π's, K's and baryons

From basic principles and generally accepted assumptions the following relations between fragmentation functions of charged pions are expected to be valid:

$$D_u^{\pi+} = D_d^{\pi-} \quad (3)$$
$$D_u^{\pi-} = D_d^{\pi+} \quad \text{isospin symmetry} \quad (4)$$
$$D_{ud}^{\pi+} = D_{ud}^{\pi-} \quad (5)$$

$$D_u^{\pi+} > D_u^{\pi-} \quad \text{favoured > unfavoured} \quad (6)$$

$$D_{uu}^{\pi+} > D_{uu}^{\pi-} \quad \text{if breakup and/or resonance production is important} \quad (7)$$

The best place to test these relations is ν ($\bar{\nu}$) scattering off protons where the flavours of the fragmenting quark and 'diquark' are well defined. Results on charged pion production[6] are shown in fig. 3. The validity of equations (3), (4) and (5) is clearly demonstrated in figures 3a, 3b and 3d respectively. By comparing fig. 3a and fig. 3b it becomes obvious that relation (6) is also fulfilled. Fig. 3c shows a much more copious π^+ than π^- production in the backward hemisphere as expected from relation (7).

A more specific prediction for the relation between D_{uu}^{π} and D_{ud}^{π} of charged pions is possible when using the diquark model of S. Fredriksson et al.[7]. The essential point in this model is that diquarks with isospin and spin I = S = 0 are less massive than those with $I = S = 1$. Therefore $(ud)_0$ is expected to have a lower breakup probability than for instance $(uu)_1$ and $(ud)_1$. Assuming maximum SU(6) breaking (uu) will always fragment like two single quarks whereas (ud) will hadronise like two quarks in 50 % of the cases and like one quark in the other 50 %. The creation of pions in the force field stretched by the backward going object is expected to be independent of the fact whether this is a coloured quark or an anticoloured diquark. These arguments lead to the following simple prediction

$$D_{uu}^{\pi}/D_{ud}^{\pi} \approx 2 \cdot D^{\pi}/(0.5 \cdot D^{\pi} + 0.5 \cdot 2 \cdot D^{\pi}) = 4/3 \qquad (8)$$

which is expected to be valid for $x_F < -0.5$. Fig. 4 shows that the data on charged π production in $\nu(\bar{\nu})p$ scattering[6] agree with relation (8) for $x_F < -0.15$. But it should be noted that the creation of baryon resonances and their subsequent decay into charged pions will also lead to $D_{uu}^{\pi}/D_{ud}^{\pi}$ being greater than 1.

As already mentioned, in order to study the basic lepton parton scattering one must understand the influence of the fragmentation process on the production of the hadrons in the final state. This is true not only in terms of momentum distributions but also with respect to quantum numbers. Especially when comparing quark and gluon jets the knowledge of the particle types may be of great importance.

The set-up of the European Muon Collaboration (EMC) at CERN has been upgraded recently and particle identification of charged hadrons as well as the detection of π^0, K_s^0 and Λ ($\bar{\Lambda}$) is possible now over a wide range of momenta[8]. Preliminary results[9] on the normalised distributions in x_F for π^+, K^+, p and also π^-, K^-, $\bar{p}$ are shown in figs. 5a and 5b respectively. The pion yield is clearly dominating in the central region whereas in the current fragmentation region the rate of production of the various particles becomes less different. In the backward hemisphere ($x_F \lesssim 0.2$) the proton is much more frequently produced than the antiproton. From this one can conclude that the backward protons stem mainly from the target remnants (qq or qqq + sea quark/antiquark). The data are compared with the predictions from the Lund model. Keeping in mind that the data are still preliminary with a sytematic error of about 20 % the agreement

between data and Monte Carlo simulation is rather good. There may be a slight tendency that the pion yields in the forward region are overestimated by the Lund model, a fact which was also observed by a νD_2 experiment[10].

In the original versions of quark fragmentation models[11,12] baryon production was neglected; baryons were only considered as target remnants. The observation of fast baryons and antibaryons in deep inelastic lepton scattering[13] and e^+e^- annihilation[14] led to modifications of the fragmentation models now incorporating baryon-antibaryon production in the fragmentation chain. In addition to that the question arose whether at least a fraction of the baryons (antibaryons) came from gluon fragmentation.

Results on forward proton and antiproton production with high statistics became available recently[15] from the EMC. The data are presented as ratios of the proton and antiproton yields over the number of all positive and negative hadrons respectively within the momentum range where proton identification is possible. In fig. 6 the ratios p/h^+ and $\bar{p}/h^-$ are shown as function of z in different kinematic ranges. At lower values of W^2 the ratio p/h^+ is steeply decreasing with z in contrast to the behaviour of $\bar{p}/h^-$ thus indicating sizeable contributions from target remnants to the yield of forward protons (see fig. 6a).

If in the fragmentation chain baryons and antibaryons are created from diquark-antidiquark pairs like mesons are produced from quark-antiquark pairs the proton is expected to have a harder spectrum than the antiproton since it can contain the initial quark, preferentially a u quark, more often. Taking also into account that the distribution of π^+ is harder[9] than the corresponding one of π^- p/h^+ should be larger than $\bar{p}/h^-$ (see fig. 6b). At low x where no flavour dominates p/h^+ and $\bar{p}/h^-$ are expected to be equal (fig. 6c). From fig. 6d which shows p/h^+ and $\bar{p}/h^-$ at high W^2 (to suppress contamination from target remnants) and at $x > 0.2$ (u quark fragmentation dominates) one can conclude that protons contain the parent quark with a higher probability than charged pions and kaons since protons are faster than the other positive and negative hadrons.

The $p_\perp^2$ dependence of p/h^+ and $\bar{p}/h^-$ is shown in fig. 7. For $W^2 > 200$ GeV^2 one observes an increase of both ratios with $p_\perp^2$ (fig. 7b) in contrast to the behaviour for $W^2 < 200$ GeV^2. As large transverse momenta especially at high W^2 are expected to reflect the occurence of gluon emission the increase of p/h^+ and $\bar{p}/h^-$ with $p_\perp^2$ can be interpreted as indication of a more copious yield of protons and antiprotons in gluon fragmention.

3. QCD effects

Although the main emphasis of this review is laid on the fragmention process a few selected topics studying QCD effects are discussed briefly.

3.1 Scale breaking

From strict Feynman scaling (predicted by QPM plus fragmentation) one expects that the fragmentation functions determined in lepton scattering do not depend on the variables of the scattered lepton, e. g. the x_F distributions of hadrons should be independent of W. QCD effects like gluon bremsstrahlung will change this and will introduce additional dependencies on x or W.

Evidence for scaling violation was found in several experiments, in e^+e^- annihilation[16], in μp scattering[17] and in νD_2 reactions[18] where spectra of all charged hadrons without identification were studied. The new experimental data from the EMC[9] are used to investigate scale breaking in pion production over the full x_F range. Particles were identified using Cherenkov and time-of-flight counters only in a limited range of the full acceptance in this experiment. To use the highest statistics possible in particular studies, kaons and protons are subtracted by applying a method based on the Lund model which is similar to that used in ν scattering (see 2.1). The π-spectra gained in this way agree almost perfectly with the corresponding ones resulting from particle identification.

The normalised x_F distributions of charged pions in two different intervals of W are shown in fig. 8a. It is quite obvious that the two distributions do not agree. The trends in the various regions of x_F as a function of W can be seen more clearly in

fig. 8b. There is no dependence on W in the target hemisphere ($-1.0 \leq x_F \leq -0.3$) whereas in the central region ($-0.3 < x_F \leq 0.3$) a strong increase can be observed. In the current fragmentation region ($0.3 < x_F \leq 1.0$) the pion yield decreases with W. These findings are expected from QPM plus first order QCD effects. Scale breaking induced by gluons should manifest itself as a function of W. The increase of the multiplicity is expected to occur essentially in the central region whereas the target remnants stay uneffected by variations of the energy of the virtual photon.

In the QPM a linear rise of the multiplicity of charged hadrons with log(W) is expected which corresponds to an increase of the width of the rapidity distribution. In e^+e^- annihilation a stronger rise of the multiplicity than proportional to log(W) is observed[19]. This means that besides the width also the height of the rapidity plateau increases with W which can be only partially contributed to the fragmentation of heavy quarks.

In lepton scattering up to $W^2 = 200$ GeV^2 no deviation from a log(W) behaviour of the multiplicity[2,5] has been observed. This is confirmed by results from μp scattering[9] which indicate that this trend continues up to $W^2 = 400$ GeV^2. In fig. 9 one can see that the height of the plateau of the normalised distribution in cms rapidity of charged pions does not significantly change with W whereas the width at half-height increases from about 2.5 to 4.0 as W increases from 6 to 18 GeV. This is in agreement with the expectations of the QPM. It seems that at the energies reached so far QCD effects are not reflected in the development of the pion multiplicity with W.

3.2 Gluon bremsstrahlung

It is a well known fact seen in many different experiments[20] that hard gluon bremsstrahlung leads to an enhancement of hadrons at high $p_\perp^2$ which is equivalent to a rise of $\langle p_\perp^2 \rangle$ with W. As in the QPM the diquark system acts only as a spectator no such gluon bremsstrahlung should occur in the target fragmentation region. This means that $\langle p_\perp^2 \rangle$ at $x_F < 0$ is expected to be independent of W. In fig. 10 $\langle p_\perp^2 \rangle$ is shown as a function of x_F for different W regions for K^0 as well as for

$h^+ + h^-$. In both cases in agreement with the expectations $\langle p_\perp^2 \rangle$ rises with W in the forward hemisphere and stays constant in the backward region.

4. Summary

Higher energies and statistics as well as greatly improved particle detection and identification became available during the last year in deep inelastic lepton scattering. In conjunction with refined methods used in the analysis this led to a considerable increase of the knowledge about the fragmentation process especially in terms of quantum numbers and of a better separation between the different regimes. The Lund model is widely used as a kind of standard prescription to calculate in detail the predictions of the QPM including first order QCD and fragmentation. This model describes the experimental data rather well but some modifications are clearly necessary especially in the fast forward region. The evidence for QCD effects like scale breaking and the increase of high $p_\perp$ hadrons with W in the forward direction has been confirmed. At the presently available energies these effects are visible only in specific kinematic regions (e. g. high $p_\perp$), the production of the bulk of the hadrons can sufficiently be described by the QPM alone.

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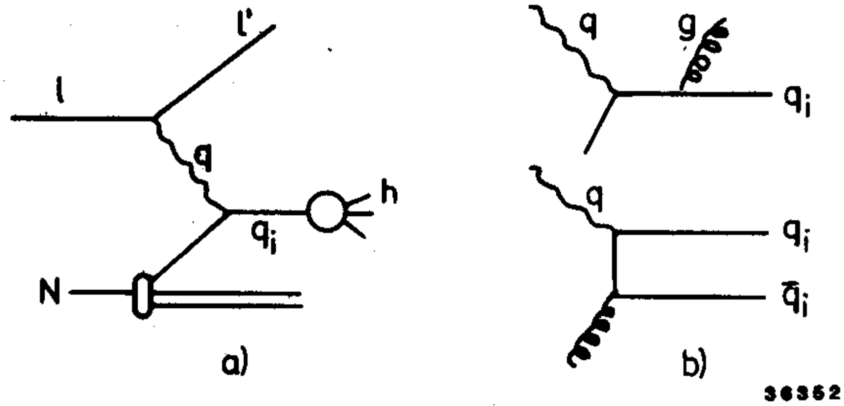

Fig. 1. Graphs for lepton nucleon scattering a) in the QPM and b) first order QCD corrections.

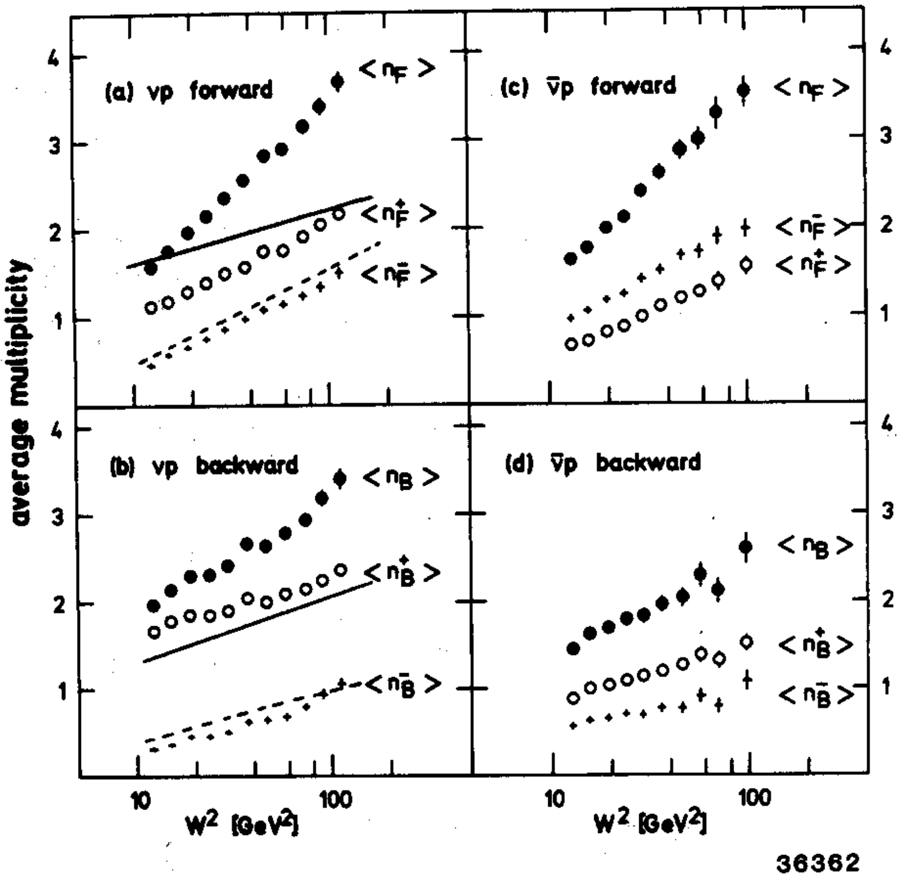

Fig. 2. Average multiplicities of charged hadrons from $\nu(\bar{\nu})$p scattering[2)] in the forward and backward hemispheres as fuctions of W^2 compared with previous results[4,5)] (solid lines: $\langle n^+ \rangle$, dashed lines: $\langle n^- \rangle$) which are not corrected for wrong mass assignments.

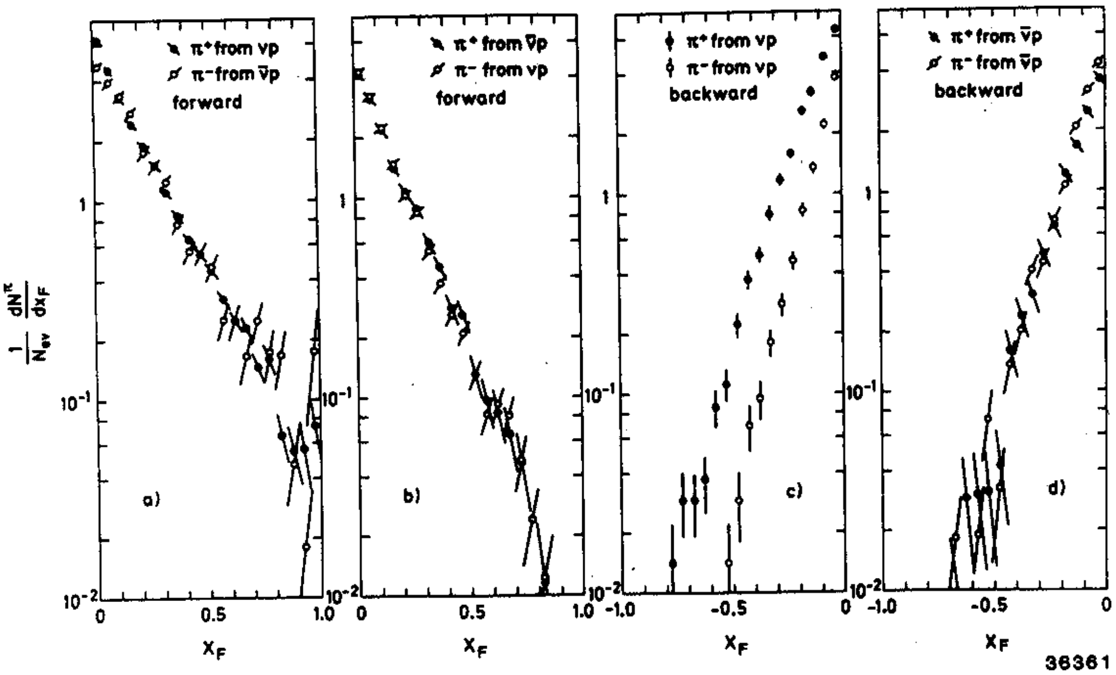

Fig. 3. Normalised x_F distributions of π^+ and π^- in the forward and backward hemispheres measured in $\nu(\bar{\nu})$p scattering[6]. The full and open circles represent in a) $D_u^{\pi+}$ and $D_d^{\pi-}$, in b) $D_d^{\pi+}$ and $D_u^{\pi-}$, in c) $D_{uu}^{\pi+}$ and $D_{uu}^{\pi-}$, in d) $D_{ud}^{\pi+}$ and $D_{ud}^{\pi-}$, respectively.

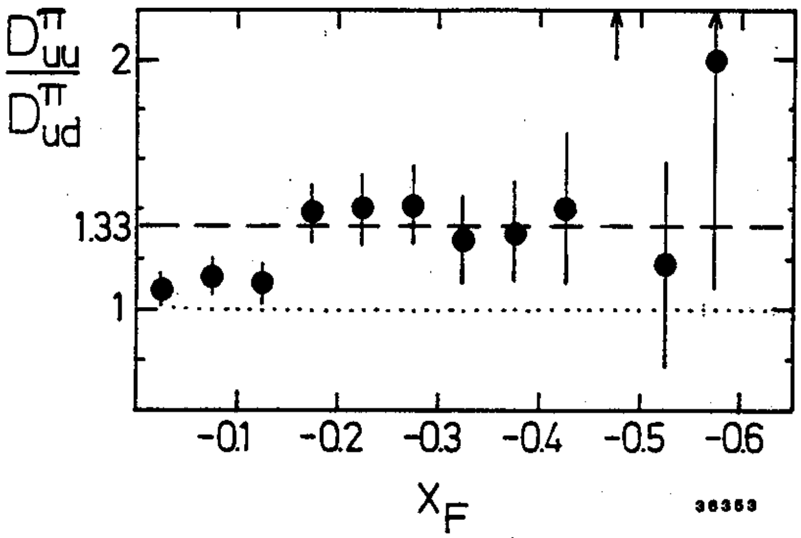

Fig. 4. Comparison of the prediction $D_{uu}^{\pi}/D_{ud}^{\pi} \approx 4/3$ from a diquark model[7] with the experimental results from $\nu(\bar{\nu})$p scattering[6].

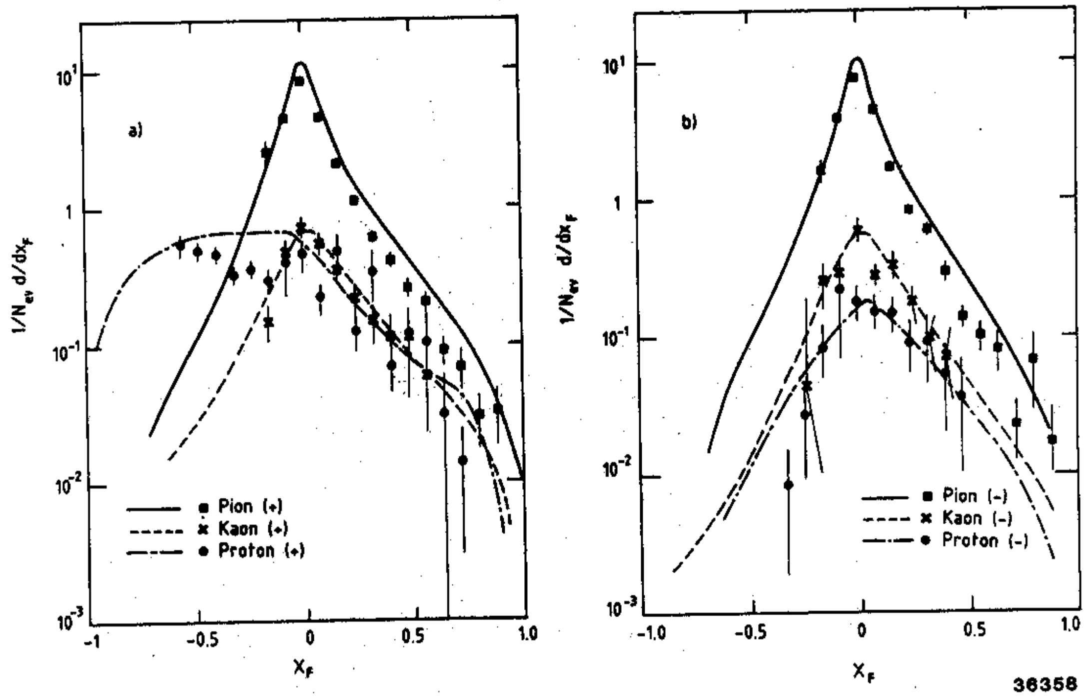

Fig. 5. Normalised x_F distributions for identified a) positive and b) negative hadrons[9]. The curves are predictions of the Lund model.

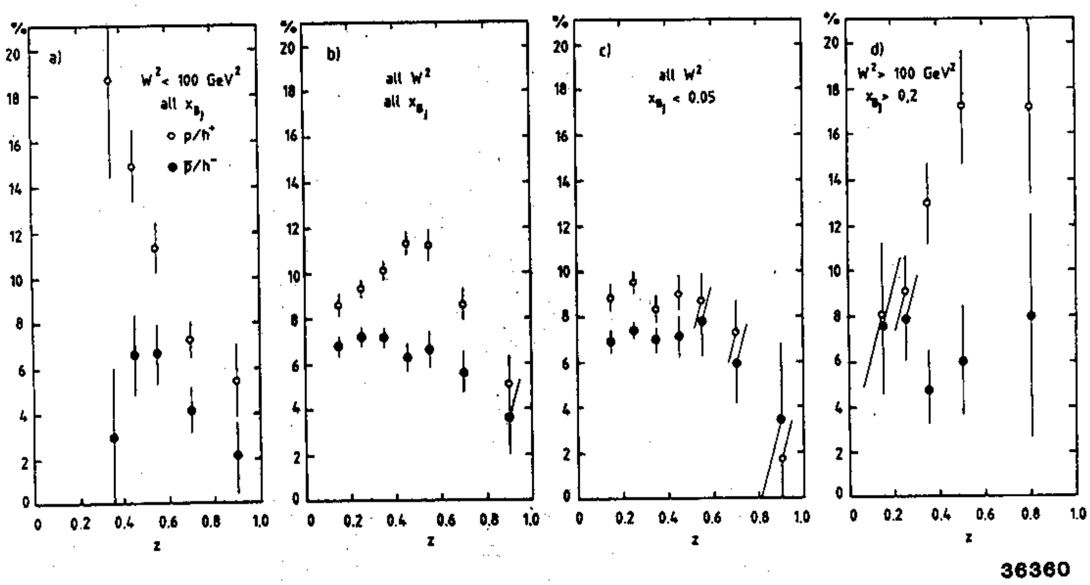

Fig. 6. Ratio of the yield of protons over that of all positive hadrons (open circles) and of the yield of antiprotons over that of all negative hadrons (full circles) as a function of z in different ranges of W^2 and x[15].

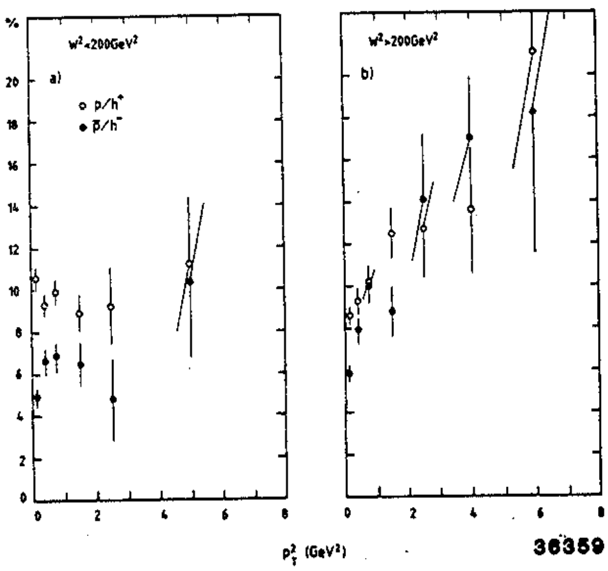

Fig. 7. Ratio of the yield of protons over that of all positive hadrons (open circles) and of the yield of antiprotons over that of all negative hadrons (full circles) as a function of $p_\perp^2$ in different W^2 regions[15].

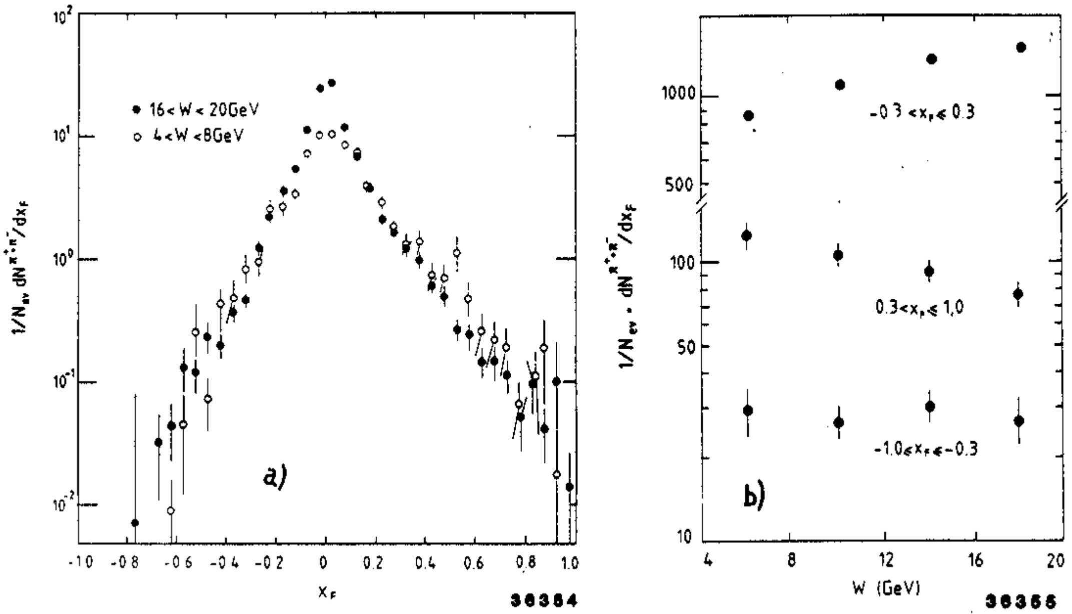

Fig. 8. a) Normalised x_F distributions for $\pi^+ + \pi^-$ at low (4 - 8 GeV) and at high W (16 - 20 GeV).
b) Multiplicity of charged pions as a function of W in different x_F intervals (backward, central, forward)[9].

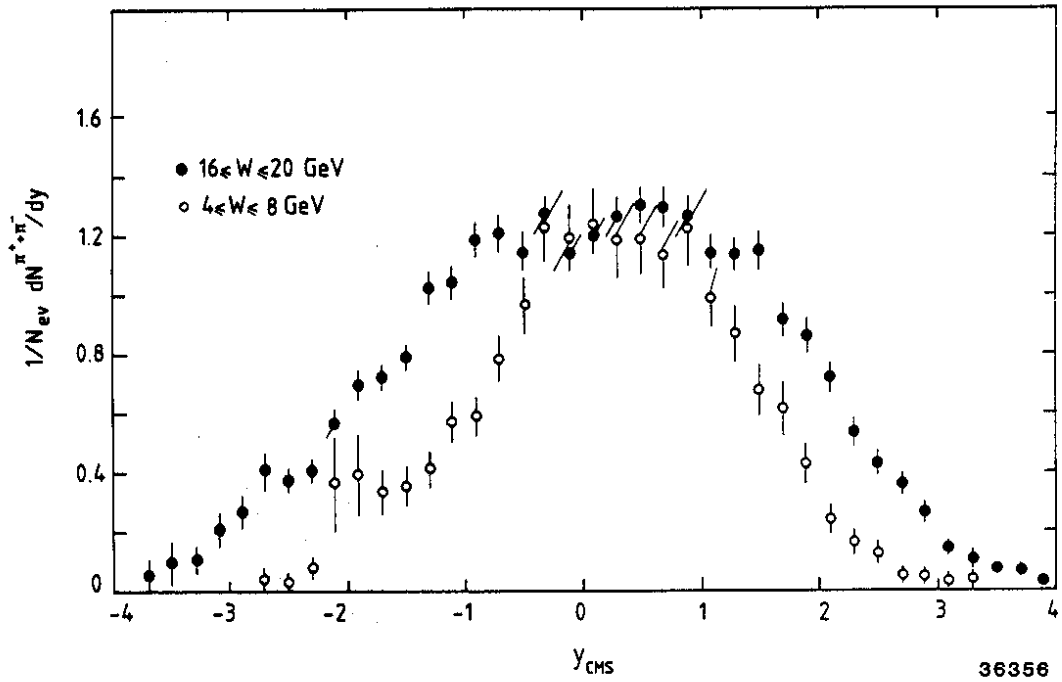

Fig. 9. Normalised cms rapidity distributions for $\pi^+ + \pi^-$ at low (4 - 8 GeV) and at high W (16 - 20 GeV)[9].

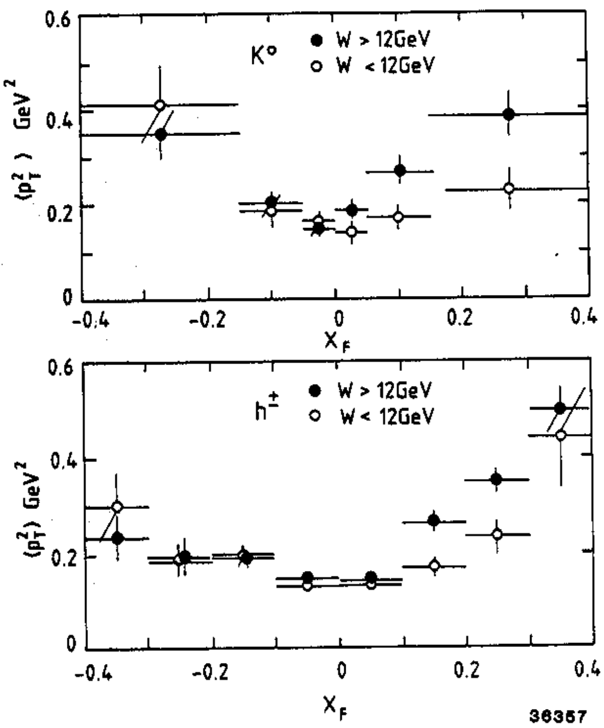

Fig. 10. Mean values of $p_\perp^2$ for K^0 and for the sum of all charged hadrons in different W regions[9].