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CHARGE AND TRANSVERSE MOMENTUM CORRELATIONS IN DEEP INELASTIC MUON-PROTON SCATTERING

The European Muon Collaboration

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Abstract

Correlations between charged hadrons are investigated in a 280 GeV muon-proton scattering experiment. Although most of the observed particles are decay products it is shown that the correlations found originate in the fragmentation process and are not due simply to resonance production. Correlations are demonstrated between hadrons close in rapidity with respect to their charges and to the directions of their momentum components perpendicular to the virtual photon axis. Such short range correlations are predicted by the standard hadronization models.

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For footnotes see next page

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1. Introduction

This paper is devoted to a study of the correlations between hadrons created in a deep inelastic muon-proton scattering experiment. Correlation studies have a rather long tradition in pp physics whereas in e^+e^- annihilation and particularly in lepton-nucleon scattering they have not played an important role up to now [1]. This is mainly due to the fact that correlation studies require that final state particles are detected over a large fraction of the phase space. In fixed target experiments this is usually only achieved in bubble or streamer chamber experiments.

The motivation for correlation studies stems mainly from the interest in a detailed understanding of the hadronization process. In order to describe this process in deep inelastic scattering it is generally assumed that the energy density in the space region between the scattered quark and the remaining system increases to the point where the virtual quarks and antiquarks from the vacuum polarization are combined to produce real primary hadrons. Such a process, which is described schematically in fig. 1, predicts short range correlations between certain quantities; for example charge, strangeness, baryon number or transverse momentum of neighbouring primary hadrons. The observation of these correlations tends to be obscured by the decays of the primarily produced resonances. Therefore care must be taken when interpreting the short range correlations found in terms of local quantum number or momentum compensation within the fragmentation process.

This paper deals specifically with charge and $p_\perp$ correlations. Other correlation studies from this experiment have either already been published [2] (backward-forward multiplicity correlation) or will be published in subsequent papers (Bose-Einstein interference, global rapidity correlation function, $p\bar{p}$ correlations and correlations between strange particles).

2. The experiment

The data used in this analysis were taken in the muon-proton scattering experiment performed by the European Muon Collaboration using a 280 GeV beam of positive muons at CERN. A detailed description of the apparatus and of the experimental method can be found in reference [3]. The apparatus achieves an almost complete coverage of the solid angle for hadrons with momentum larger than 200 MeV/c. Good particle identification is achieved by means of several Cerenkov detectors with different gas fillings and an array of time-of-flight counters. In order to restrict the sample of events used in the analysis to kinematical regions where the corrections for acceptance, smearing effects from resolution and radiative effects are relatively small ($\lesssim 20\%$) the following cuts on the usual kinematic quantities [2] were adopted:

$Q^2 > 4\ \mathrm{GeV}^2$	($-Q^2$: mass of the virtual photon squared)
$40\ \mathrm{GeV}^2 < W^2 < 400\ \mathrm{GeV}^2$	(total hadronic cms energy squared)
$y < 0.9$	($y = \nu/E_{\mathrm{beam}}$)
$E_\mu' > 20\ \mathrm{GeV}$	(energy of scattered muon)
$\nu < 260\ \mathrm{GeV}$	($\nu = E_{\mathrm{beam}} - E_\mu'$)
$\Theta_\mu' > 0.75^\circ$	(muon scattering angle)

The number of events remaining after these cuts is about 21000.

All the data presented below have been corrected for the effects of acceptance, the finite resolution of the apparatus and for radiative effects. The correction factors are calculated using a detailed Monte Carlo simulation of the experiment as described in reference [4]. The results presented below refer to charged hadrons only. Only the statistical errors are shown. The systematic errors will be discussed in the text.

3. Ordering of the hadrons

In order to study correlations between hadrons one has to choose an appropriate variable in which the degree in neighbourhood between two hadrons can be described. There exists, besides the azimuthal angle around the direction of the virtual photon, two independent variables for each hadron namely the components $p_\parallel$ and $p_\perp$ of the momentum in the hadronic centre-of-mass system parallel and transverse to the current direction. Based on $p_\parallel$, $p_\perp$ and using E or E_{lab} (these being the energy of the hadron in the centre-of-mass or the laboratory system) the following variables can be defined which are frequently used to describe hadron production in lepton-nucleon scattering:

$x_F = 2 \cdot p_\parallel / W$	(Feynman variable)
$y = 0.5 \cdot \log[(E+p_\parallel)/(E-p_\parallel)]$	(rapidity)
$z = E_{\mathrm{lab}}/\nu$	(energy fraction of hadron from quark)
$\lambda = p_\parallel / p_\perp$	

One might expect that a merely longitudinal quantity such as the Feynman variable x_F would be appropriate to study charge correlations. The rapidity y is usually preferred in this context since in the centre-of-mass system the hadrons are equally distributed in this variable, but in contrast to x_F it depends also on $p_\perp$.

In order to differentiate between all these variables and to select the optimum one a 'distance' between two variables is defined in the following way: the particles in each event are ordered according to a certain variable and then re-ordered taking another variable. The number of permutations necessary to convert one ordering into the other is taken as a quantitative measure of the difference between the two orderings. By taking the average over all events the values listed in table 1 are obtained. In addition to the already mentioned variables x_F, y, z and λ the effect of random ordering was also investigated. From table 1 it can be seen that there is little difference between y and λ but some difference between x_F and y (or λ) is observed. From the fact that significantly different orderings are obtained by using different variables the determination of charge correlations can be expected to depend on the variable chosen to order the hadrons. As discussed below the charge correlations observed are largest in terms of the variable x_F.

As shown in table 1 the orderings according to z and especially according to $p_\perp$ and the random ordering are grossly different from those according to y, λ and x_F. Since the latter three variables seem to be more appropriate than z (which is not well suited to describe the target fragments) and $p_\perp$ (being similar to random ordering) to describe the fragmentation process which is supposed to proceed along the photon direction, these variables will not be considered further.

4. Charge correlation

Since neighbouring primary hadrons share a quark line the charges of the mesons (if baryons are ignored) as one goes down the chain in fig. 1 will be a succession of values (q_0-q_1), (q_1-q_2), (q_2-q_3), ... where $q_i = 2/3$ or $-1/3$. One immediately notices that the charges alternate between 1 and -1 no matter how many neutrals appear between charged hadrons. This prediction about the charges of primary hadrons may no longer hold for the observed hadrons because resonance decays can disturb the ordering. Furthermore, the ordering implied by the chain fragmentation picture of fig. 1 does not necessarily mean that the primary particles have this order in any longitudinal variable although such a correlation is expected on average [5]. However we will see later that, although most observed charged hadrons are decay products, some remnant of the charge correlation of the primary hadrons can be observed.

4.1 Random charge model

The overall charge per event in conjunction with a finite hadron multiplicity will produce charge correlations. To calculate the influence of this constraint on charge correlations one needs to know the probability of randomly picking up a pair of particles with different charges from an event with total charge Q and charged multiplicity N (ignoring neutral hadrons). This probability is given by

$$p_{dif} = \frac{1}{2} \frac{N^2 - Q^2}{N \cdot (N-1)} . \tag{1}$$

In order to estimate the influence of charge conservation on the experimentally observed charge correlations the following procedure was adopted: a sample of events generated by the Lund Monte Carlo model [6] was selected applying the same criteria (cuts on kinematic variables and minimum multiplicity of charged hadrons) as for the data. From each of these Monte Carlo events the charged hadron multiplicity was taken to calculate p_{dif} (equation(1)). By averaging p_{dif} over the chosen sample of Monte Carlo events the random value of the fraction of unlike charged pairs among all possible hadron pairs is obtained. This will be referred to as the random charge model (RCM) value. Any 'non-trivial' correlations are expected to appear as a departure of the experimental results from the corresponding RCM values.

4.2 Results on charge correlations

In the subsequent analysis all charged particles of an event are ordered according to a certain variable. Using the definition of the degree in neighbourhood depicted schematically in fig. 2 the ratio of the number of pairs of a given degree in neighbourhood with different charges divided by the total number of pairs of the same degree in neighbourhood is calculated for each event. By taking the average of this ratio over all events the values of R_n (n denotes the degree in neighbourhood) as presented in figures 3 to 7 are obtained. The systematic errors on the values of R_n are due to the uncertainties in the determination of the charged hadron multiplicity and the total charge per event. Their absolute values are less than 0.01.

In fig. 3, R_1, the probability that hadrons which are adjacent in x_F have opposite charges, is shown as a function of W^2. It can be seen that R_1 decreases with increasing W^2 but the RCM value follows the same trend. This decrease is due to the increasing hadron multiplicity at higher W^2 [2], which leads to a weaker influence of the overall charge conservation on R_1. The difference between the experimental and RCM values is almost independent of W^2. From this it can be concluded that the observed charge correlation is of a short range nature since the net effect is independent of the total energy of the event and therefore also of the mean hadronic multiplicity. Furthermore it is found in this experiment (not shown here) that R_1(data) - p_{dif} (see equation (1)) does not depend on the multiplicity.

For comparison, the results on $\langle -Q_1 \cdot Q_2 \rangle$ obtained by the Pluto collaboration [7] have been transformed by the relation $\langle -Q_1 \cdot Q_2 \rangle = 2R_1 - 1$ and are also presented in fig. 3. They confirm, at high W^2, the observations made by this experiment at lower W^2. One should note however that the experimental data of the Pluto collaboration are not corrected for inefficiencies of the apparatus, in contrast to the data presented in this paper.

In fig. 4 the values of R_n for the data and for the random charge model taking x_F to order the hadrons are shown as a function of the degree in neighbourhood, integrated over the complete range of W^2. As already seen in fig. 3, R_1 for the data lies well above the RCM value whereas at high degrees in neighbourhood the experimental values of R_n are systematically below the corresponding values from the random charge model. This effect can be understood in terms of a long range charge correlation. It has been observed in this experiment [4] that the charge is not uniformly distributed between the forward and the backward regions. Since at high degrees in neighbourhood the hadrons of a pair will most probably come from different hemispheres the positive net charge observed in either hemisphere will lead to a long range anticorrelation between charges. This is confirmed by the results shown in fig. 5 which are obtained by omitting pairs of hadrons belonging to different hemispheres. Almost no discrepancy between the data and the random charge model then remains at high degrees in neighbourhood. A similar conclusion was drawn from studies of the long range charge compensation probability in e^+e^- annihilation [8]. Both findings support the idea that the partons involved in the basic scattering or annihilation process are charged.

Figures 4 and 5 do not show any oscillation of the values of R_n for the data around the corresponding values for the random charge model as one would expect if only primarily produced particles were observed. In this case pairs of odd (even) degree in neighbourhood would have a higher (lower) probability of having different charges than in the random charge model. Of course the reason for not observing such oscillations is that the decays of unstable primary hadrons confuse the charge correlations between primaries. In order to find some remnant of the primary correlation one must look at R_2, because a value of this quantity lower than the corresponding value in the random charge model is uniquely due to primary correlations and cannot be produced by decays, as is the case for R_1. For this reason R_2 is a more sensitive quantity than R_1 for looking at charge correlations between primaries.

In order to see such an effect a sample of pairs predominantly made up from primary particles must be selected. A guide as to how to achieve this enrichment may be obtained from the Lund Monte Carlo model [6]. In this model most particles in the central region are decay products. At high values of $|x_F|$ the primary particles dominate. A further enrichment can be obtained by requiring a certain minimum difference between the values of the variable used to order the hadrons. It can be demonstrated by Monte Carlo simulation that, by requiring a larger separation between the particles of a pair, primary pairs are selected with increasing probability. This behaviour is not surprising since the decay products will tend to stay near to each other in x_F.

Thus the Lund Monte Carlo predicts that the charge correlation effect in R_2 which is defined as

$$C_2 = -\left[\ R_2(\text{Data}) - R_2(\text{RCM})\ \right], \qquad (2)$$

will increase as both the width of the excluded central gap and the cut on the minimum separation required between the particles forming the pairs are increased. The results obtained when using these criteria are shown in fig. 6, where R_n is presented for the data and the random charge model, using x_F to order the hadrons in the events. Long range correlations are avoided by excluding pairs of hadrons from different hemispheres. A separation in x_F larger than 0.10 is demanded and the width of the excluded central x_F region is 0.16. In this figure a slight indication of the expected oscillation of the value of R_n for the data around the corresponding value for the random charge model can be seen (at least for R_1 and R_2). This effect gets weaker if the cuts mentioned above are not applied and is not observed for any other variable than x_F.

In order to investigate the charge correlations of hadrons going forward in the hadronic centre-of-mass system, data from a previous stage of this experiment [9] have been combined with the data presented here. This allows a study of charge correlations in the forward region with higher statistical precision. The investigation is limited now to the leading pair of hadrons of first degree in neighbourhood. Leading means that the pair is made out of the two charged hadrons with the highest x_F. Furthermore it is also required that each hadron of the pair has $x_F>0.1$. Using this stronger charge correlations are expected as the leading pairs at high values of x_F should be less sensitive to resonance decays (see also the discussion in connection with fig. 6). This behaviour is in fact observed as demonstrated in fig. 7 where the value of R_1 for the leading pair is plotted as a function of the sum $x_{F1}+x_{F2}$. The data agree very well with the prediction of the standard Lund Monte Carlo (solid line) but deviate significantly from the prediction obtained if the charge ordering is taken at random (dashed line). Resonance decays diminish (but do not destroy) the short range charge correlation at low $x_{F1}+x_{F2}$ as can be seen in fig. 7 from the difference between the prediction of the standard Lund model (solid line) and of the Lund model without resonance decays (dot-dashed line). At high $x_{F1}+x_{F2}$ resonance decays have little effect.

5. Correlations in $p_\perp$

In hadronization models of the type sketched in fig. 1, primary first degree neighbours will share a common quark (or diquark) line. The quark-antiquark pair associated with this line will have equal and opposite momentum transverse to a direction which is approximately the current direction. Neighbouring hadrons are therefore expected to have transverse momenta of preferentially opposite direction. This corresponds to a difference of π in the azimuthal angle φ with respect to the photon direction.

It is well known from investigations in e^+e^- annihilation and hadron-hadron reactions [1], and from preliminary studies of this experiment [10], that short range correlations in rapidity exist with a correlation length of about two units of rapidity. Therefore, in order to select preferentially pairs of hadrons which share one quark line, only pairs of particles separated by less than one unit of rapidity are considered.

It was shown in the first part of this paper that two charged neighbouring hadrons tend to have opposite charges. So, in order to enrich the sample of pairs of hadrons sharing a quark line even further, pairs of oppositely charged hadrons are selected. Primary charged mesons with the same charge cannot share the same quark line. A comparison between the distributions of $\Delta\varphi$ for oppositely and equally charged pairs with $|\Delta y|<1$ should thus show an enhancement near $\Delta\varphi=\pi$ for oppositely charged hadrons over that for pairs of equal charges.

In the following discussion one has to keep in mind that, due to systematic errors in the determination of the corrections for track losses and contaminations, the slopes of the experimental $\Delta\varphi$ distributions are uncertain within ±5% [11]. This estimate was obtained by varying the quality criteria for accepting tracks within reasonable limits.

Figures 8a and 8b show the distributions (normalized to 1) of $\Delta\varphi$ for pairs satisfying $|\Delta y|<1$; fig. 8a presents unlike sign pairs and fig. 8b like sign pairs. In the latter case a cut on $|\vec{p}_1-\vec{p}_2|$ of greater than 200 MeV/c in the cms is applied in order to suppress the contributions from the Bose-Einstein correlation [12], which is not incorporated in the model calculations also shown in the same figure. The experimental distributions in figures 8a and 8b show similar trends, but the data rise less steeply for like sign charges. This conclusion holds in spite of the fact that the suppression of the Bose-Einstein effect increases the slope of the distribution, since the cut mentioned above preferentially removes pairs with $\Delta\varphi$ near 0. The observed difference in behaviour is just as expected from local $p_\perp$ compensation as discussed in the preceding paragraph. This effect is somewhat more pronounced in the data than that predicted by the Lund model (solid lines).

The slope of the experimental distribution shown in fig. 8a (unlike charges, $|\Delta y|<1$) is steeper than that in fig. 8c (unlike charges, $|\Delta y|>1$) which is again steeper than that in fig. 8d (equal charges, $|\Delta y|>1$). This observation can be explained by the stepwise suppression of local correlations in $p_\perp$ when going from fig. 8a via fig. 8c to fig. 8d. However, this interpretation is, like in the case of the comparison between figures 8a and 8b, not unambiguous since the influences from other sources of correlations in $p_\perp$ are also affected by using different Δy cuts and charge combinations. To clarify the situation model calculations are necessary.

In fig. 8 the predictions of a randomized $p_\perp$ model (dashed lines) are also included. This model is based on the Lund model but the directions of the particles perpendicular to the virtual photon direction are randomized in the following way: In the first step the azimuthal angles φ of the hadrons are chosen randomly from a flat distribution, keeping x_F and the absolute value of $p_\perp$ fixed. After this $\sum\vec{p}_\perp$ will in general no longer be zero. Therefore, in order to restore momentum conservation, in the next step the resultant vector for the $p_\perp$ imbalance is distributed among the hadrons proportional to the $p_\perp$ of each particle. Thereafter energy conservation is checked and if it is violated by more than 6% of the total hadronic energy or by more than 350 MeV the procedure is restarted at the first step.

The effects which may influence the shape of the $\Delta\varphi$ distributions are the momentum balance due to soft gluon emission [9], φ asymmetry [13], vector meson decays and global momentum conservation. Among these effects momentum conservation turns out to be of greatest importance. This is demonstrated in fig. 8d, where all short range correlations are suppressed by demanding pairs of equally charged hadrons which are separated by more than one unit in rapidity. In fig. 8d the data points and the predictions of the random $p_\perp$ model agree well with each other, both showing a strong increase towards $\Delta\varphi=\pi$. Randomizing φ only (step 1 in the procedure outlined above) without demanding momentum conservation would lead to a completely flat $\Delta\varphi$ distribution in contradiction to the data.

Suppression of soft gluon emission and the φ asymmetry in the Lund model has no significant influence on the predicted curves. Only different assumptions for the ratio of vector to pseudoscalar meson production lead to significantly different predictions, but with somewhat poorer agreement with the data [11] than the result of the standard Lund model shown in fig. 8. Choosing different values of the vector to pseudoscalar meson production ratio in the random $p_\perp$ model leads to the same relative changes of the predicted curves as for the Lund model and does not result in a better agreement with the data. From this it can be concluded that the shape of the experimental $\Delta\varphi$ distribution cannot be explained by vector meson decays alone in the absence of local $p_\perp$ compensation. Furthermore a measurement of the ratio of ρ^0/π^0 in this experiment [14] is consistent with equal production of primary vector and pseudoscalar particles which is assumed in the standard Lund and random $p_\perp$ model shown in fig. 8.

To summarize, the previous discussion has demonstrated that the data provide some evidence for short range $p_\perp$ correlations. Although the differences between the data and the model curves in figures 8a and 8b are not large they are, nevertheless, significant. These differences are based on the well determined slopes of the experimental distributions and model predictions. From comparing the different slopes it can also be concluded that the random $p_\perp$ model is not adequate to describe the data. On the other hand the standard Lund model which incorporates short range $p_\perp$ correlations gives a clearly better representation of the experimental results.

6. Summary

Correlations between the charges and the directions of the transverse momenta of hadrons which are close in rapidity (or x_F) have been observed in deep inelastic muon-proton scattering. It has been shown by comparing with various models (Lund model with different parameter settings, random charge model and random $p_\perp$ model) that these short range correlations are not simply due to the effects of charge or momentum conservation or vector meson decays. Thus the results presented give confidence in the picture that the hadronization process may well be described by chain or string fragmentation models.

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	x_F	y	λ	z
y	1.94	0		
λ	2.70	0.82	0	
z	3.06	3.29	3.34	0
$p_\perp$	10.8	11.1	11.1	8.34
random	11.2	11.2	11.2	11.2

Table 1: Average number of permutations necessary to convert the ordering according to one variable into the ordering according to another variable.

Figure captions

Fig. 1: Diagram of the fragmentation process in deep inelastic muon-proton scattering.

Fig. 2: Definition of the degree in neighbourhood.

Fig. 3: Fraction of oppositely charged pairs adjacent in x_F as a function of W^2. The data (circles) are compared to the random charge model (squares). The full symbols refer to this experiment, the open symbols to results from the Pluto collaboration [7].

Fig. 4: Fraction of oppositely charged pairs as a function of the degree in neighbourhood. The data (circles) are compared to the random charge model (squares). The hadrons are ordered according to x_F.

Fig. 5: Fraction of oppositely charged pairs as a function of the degree in neighbourhood. Pairs of hadrons from different hemispheres are excluded. The data (circles) are compared to the random charge model (squares). The hadrons are ordered according to x_F.

Fig. 6: Fraction of oppositely charged pairs as a function of the degree in neighbourhood. Pairs of hadrons from different hemispheres are excluded and for all hadrons $|x_F|>0.08$ is required. The separation of the hadrons in x_F is greater than 0.10. The data (circles) are compared to the random charge model (squares). The hadrons are ordered according to x_F.

Fig. 7: Fraction of oppositely charged leading pairs of hadrons adjacent in x_F as a function of $x_{F1}+x_{F2}$ ($x_{F1},x_{F2}>0.1$). For comparison the predictions from the standard Lund Monte Carlo model (solid line), the Lund model with random charge ordering (dashed line) and the Lund model without resonance decays (dot-dashed line) are also shown.

Fig. 8: Normalized distribution of $\Delta\varphi$ for (a,c) oppositely and (b,d) equally charged pairs of hadrons with $|\Delta y| < 1$ (a,b) and with $|\Delta y| > 1$ (c,d). The predictions of the Lund model (solid lines) and of the randomized $p_\perp$ model (dashed lines) are also shown.

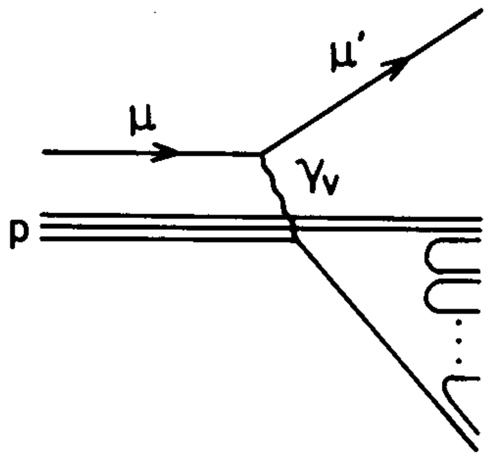
μ
μ′
γ_v
p

FIG. 1

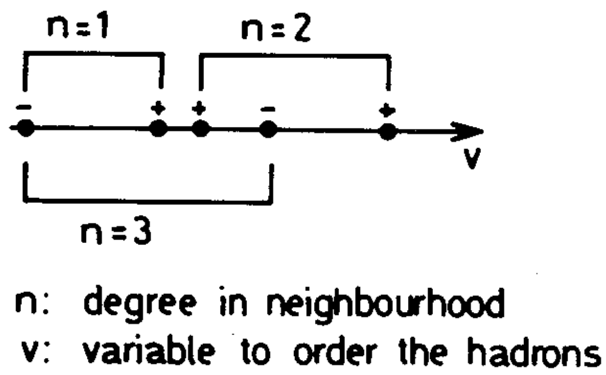
n=1
n=2
n=3
v
n: degree in neighbourhood
v: variable to order the hadrons

FIG. 2

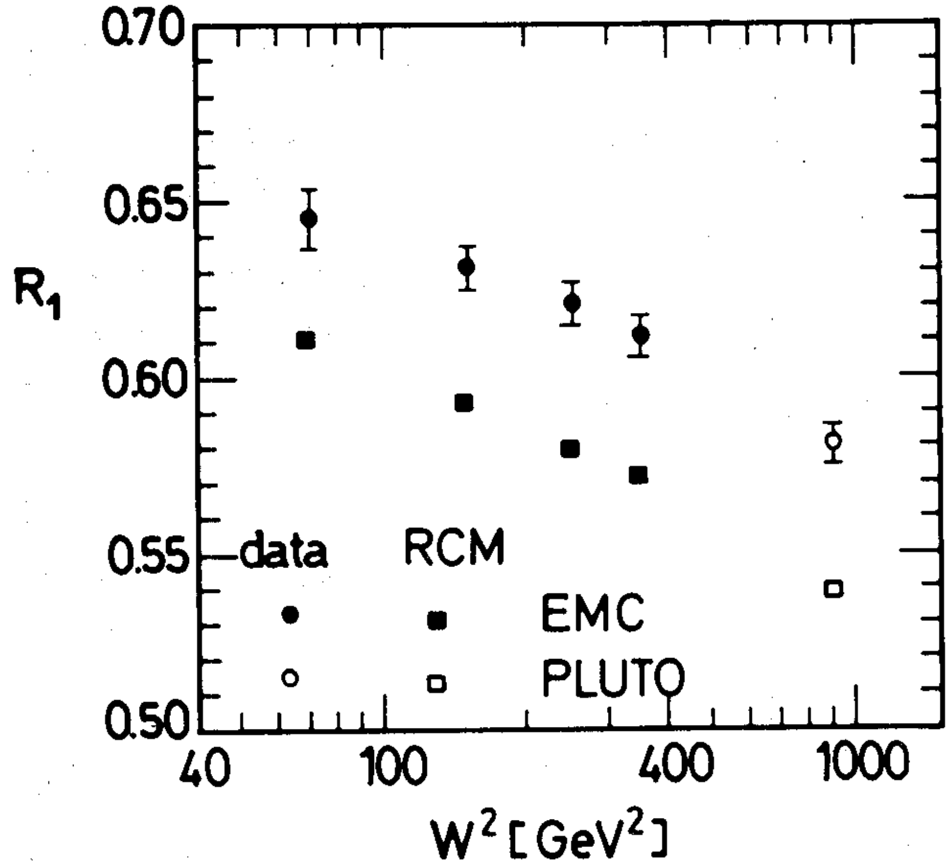
0.70
0.65
0.60
0.55
0.50
R1
data
RCM
EMC
PLUTO
40
100
400
1000
W2 [GeV2]

FIG. 3

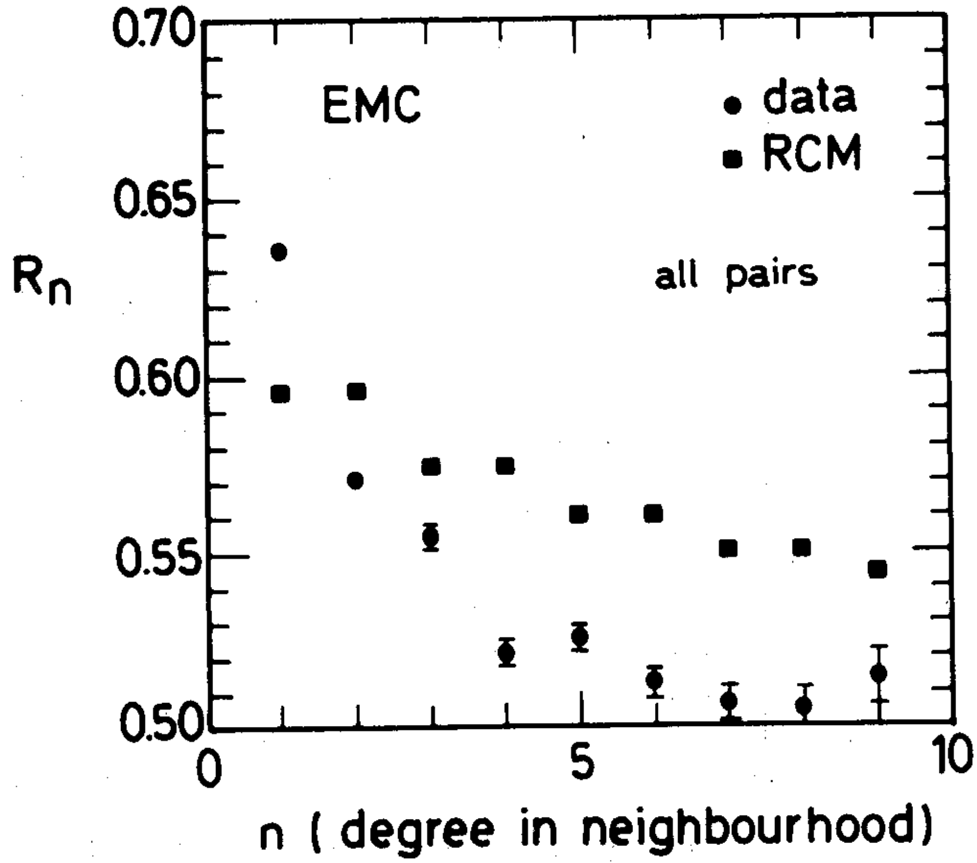
0.70
0.65
0.60
0.55
0.50
Rn
EMC
data
RCM
all pairs
0
5
10
n (degree in neighbourhood)

FIG. 4

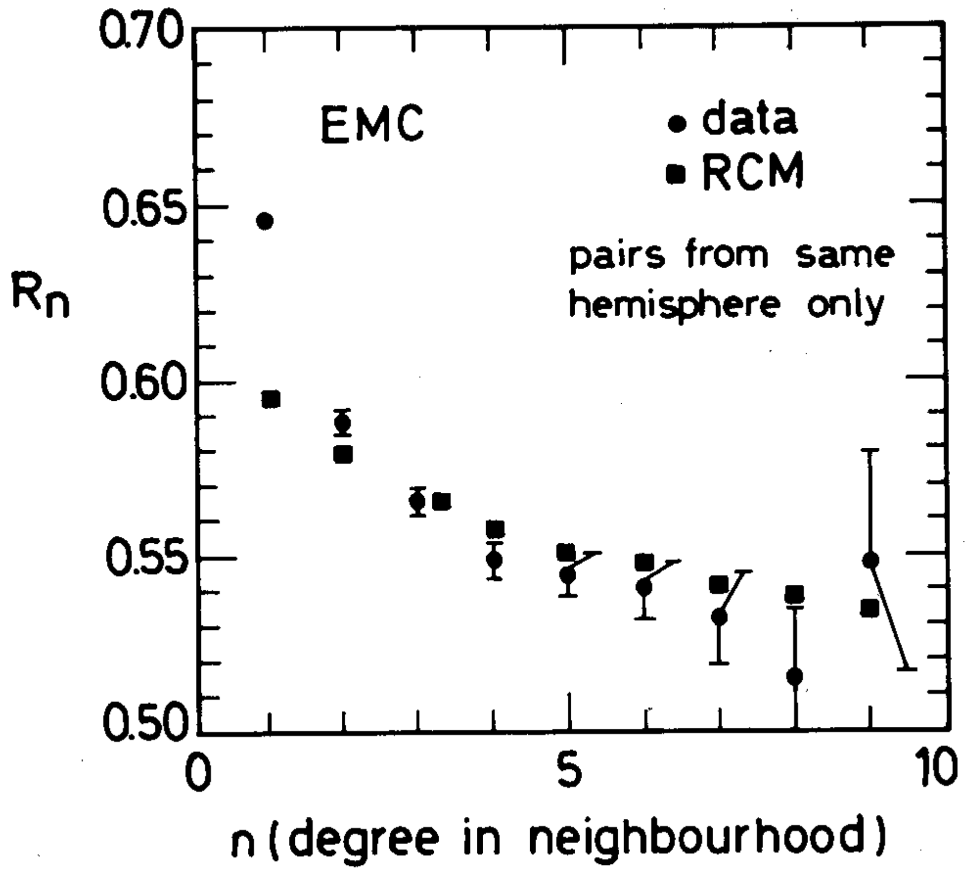
0.70
0.65
0.60
0.55
0.50
R_n
EMC
• data
▪ RCM
pairs from same
hemisphere only
0
5
10
n (degree in neighbourhood)

FIG. 5

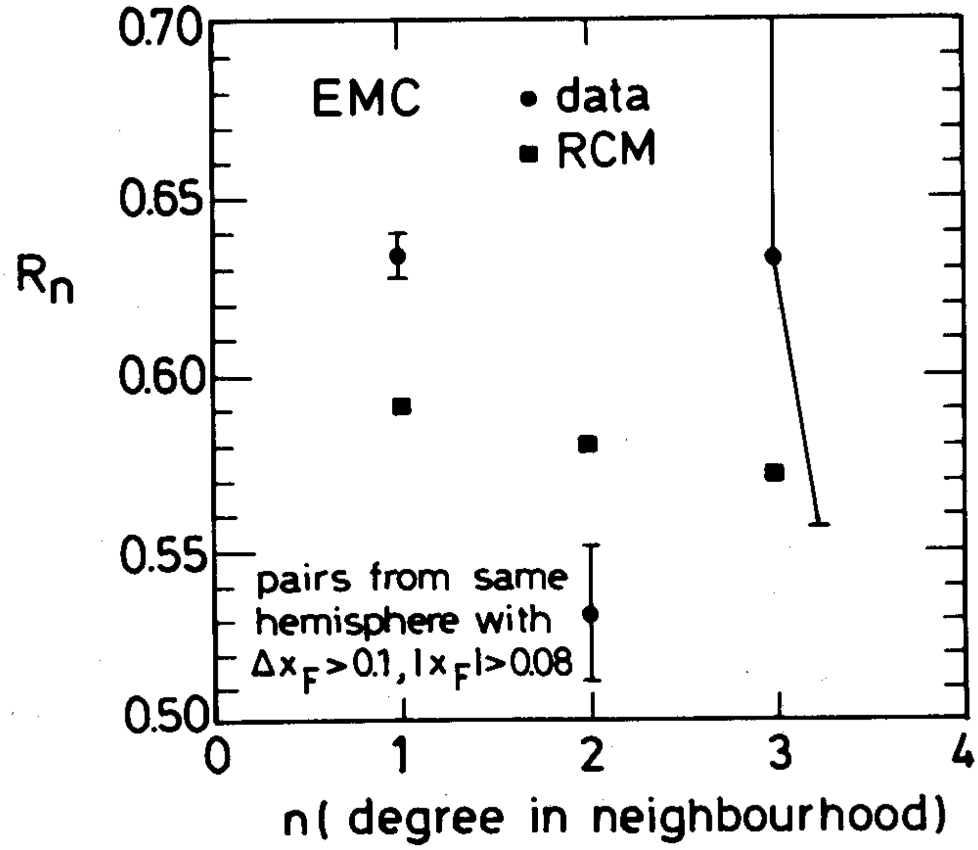
0.70
0.65
0.60
0.55
0.50
R_n
EMC
• data
▪ RCM
pairs from same
hemisphere with
$\Delta x_F > 0.1, |x_F| > 0.08$
0
1
2
3
4
n (degree in neighbourhood)

FIG. 6

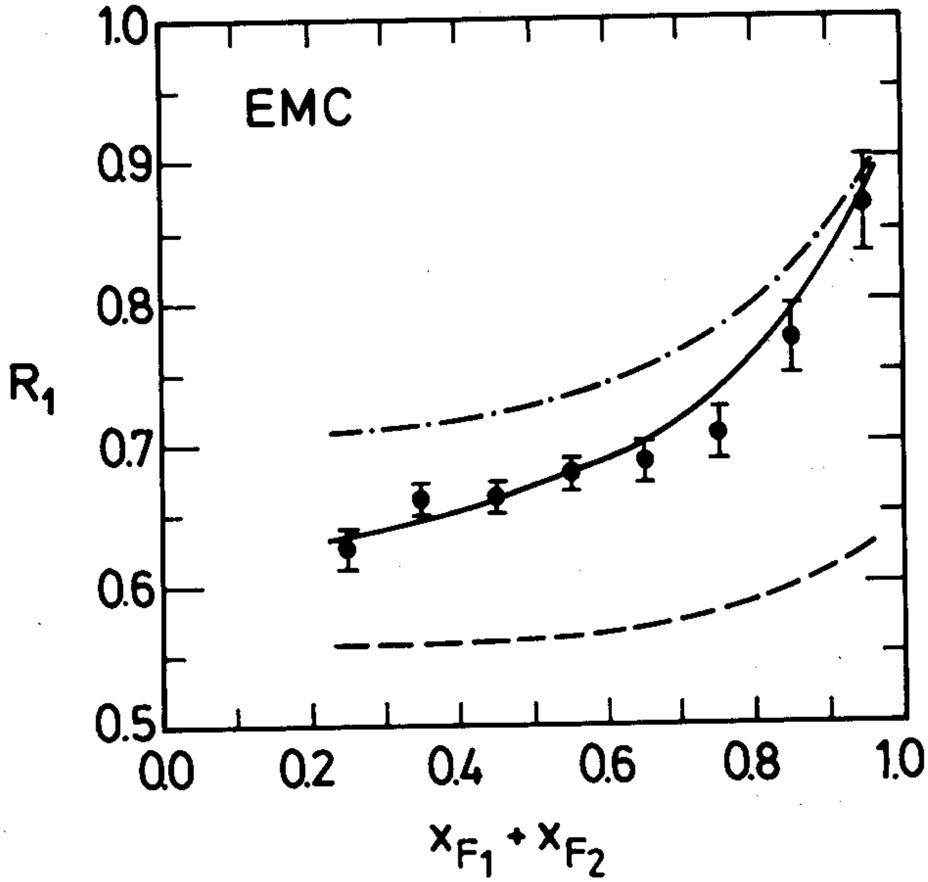

FIG. 7

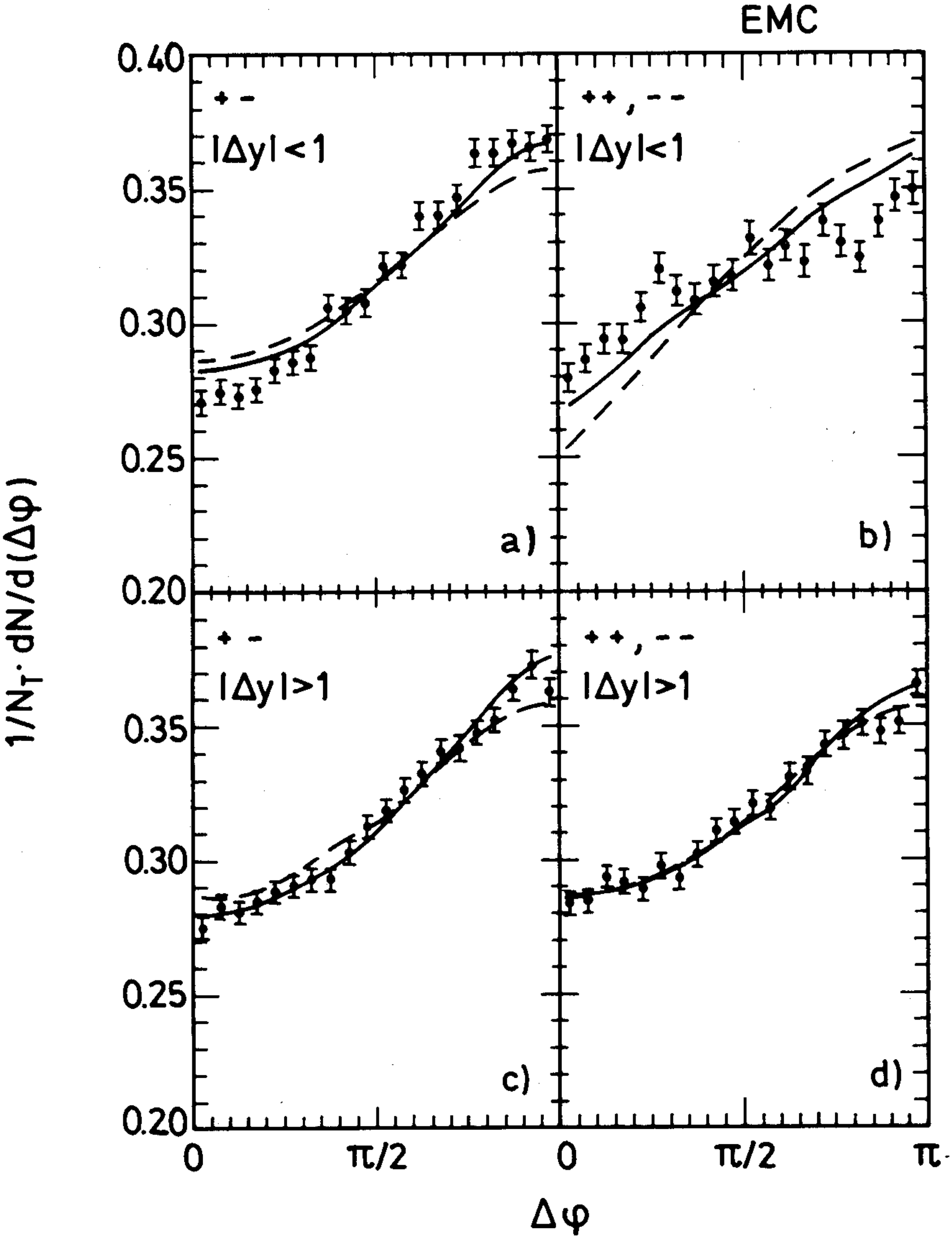

FIG. 8