COMPARISON OF PLANAR FEATURES OF K^-p INTERACTIONS
WITH e^+e^- ANNIHILATIONS AND DEEP INELASTIC μ^-p SCATTERING

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ABSTRACT

The planar features of hadronic final states in K^-p interactions at 4.5, 5.6 and 14.3 GeV centre-of-mass energy are compared with data from e^+e^- annihilation and deep inelastic μ^-p scattering. Striking agreement is found between the K^-p data at 14.3 GeV and the e^+e^- data between 13-17 GeV in the variables $\frac{1}{\sigma} d\sigma/dp_t^2$, $\langle p_t^2 \rangle_{IN}$ and $\langle p_t^2 \rangle_{OUT}$ in the sphericity system. The distribution in the variable $\Sigma p_{t IN}^2$ with respect to the beam direction in the K^-p data at 14.3 GeV is similar to that observed in μ^-p scattering relative to the current direction. A strong energy variation of the distributions $\frac{1}{\sigma} d\sigma/dp_t^2$, $\langle p_t^2 \rangle_{IN}$ and $\Sigma p_{t IN}^2$ is observed from 4.5 to 14.3 GeV centre-of-mass energy.

1. INTRODUCTION

In a recent publication [1] we compared hadron production in 10, 16 and 110 GeV/c K^-p interactions with published results on e^+e^- annihilation and deep inelastic νN scattering. We pointed out that the variation with centre-of-mass energy, $E_{c.m.}$, of the average sphericity, $\langle S \rangle$, thrust, $\langle T \rangle$, and transverse momentum, $\langle p_t \rangle$, was similar in the leptonic and hadronic reactions. In this paper we extend the comparison to differential p_t^2 distributions, and to p_t^2 distributions in and out of the event plane. We present results on the energy dependence of these distributions for $4.5 < E_{c.m.} < 14.3$ GeV and compare them with e^+e^- data from the TASSO detector at PETRA [2] and with recent results on deep inelastic μ^-p scattering at the SPS from the European Muon Collaboration [3].

One feature of our analyses and similar meson-nucleon analyses (K^+p at 70 GeV/c [4] and K^+p at 147 GeV/c [5]) is that after the removal of the small diffractive component, all events are used in the analyses. These fully inclusive non-diffractive meson-nucleon reactions are then compared with e^+e^- data at the same total centre-of-mass energy or compared with μp or νN data with total hadronic c.m. energy, W , similar to the $E_{c.m.}$ of the meson-nucleon interactions. All these analyses claim striking similarities between the jet-like properties of the leptonic and hadronic interactions. In addition, the K^+p analysis at the single $E_{c.m.}$ of 11.5 GeV [4] points out that most of the distributions studied are well reproduced by a simple quark fragmentation model, or by a longitudinal phase space model.

A different approach has been taken for proton-proton reactions by two ISR groups, who apply more complicated criteria in order to eliminate the effect of leading protons. Breakstone et al. [6] use only events with two leading protons identified (using a kinematic algorithm). The leading protons are removed from these events and the remaining mesonic subsystem (with baryon number zero) is analysed in its own rest frame. The invariant mass of the mesonic subsystem, M_0 , is then taken as the energy for comparison with e^+e^- data. Basile et al. [7] perform a similar analysis, but using a mesonic subsystem in one hemisphere only. The conclusions of the two ISR analyses are contradictory. Ref. [7] claims agreement with e^+e^- data, whereas ref. [6] reports significant differences with respect to the e^+e^- data at the highest energies.

A review of these comparisons of jet-like features in leptonic and hadronic interactions can be found in ref. [8].

2. DATA SAMPLES AND SELECTION CRITERIA

The K^- data presented here come from 350 000 and 400 000 event exposures of the 1.5 m British National and 2 m CERN Bubble Chambers to 10 and 16 GeV/c K^- beams respectively, and from a 15 800 event exposure of BEBC to a K^- beam of 110 GeV/c nominal momentum. The K^-p centre-of-mass energies correspond to 4.5, 5.6 and 14.3 GeV respectively. Our data sample at 110 GeV/c has mean momentum error on the charged tracks $\langle \Delta p/p \rangle \approx 2\%$ (93% of the tracks have $\Delta p/p < 5\%$). Events in which any track has $\Delta p/p > 50\%$ were rejected and a small (multiplicity dependent) correction has been applied. Where tracks have been identified as protons by ionization, range or fitting they have been treated as protons. All other tracks are assumed to be pions.

As in our previous analysis, to avoid the effect of the diffractive component in hadronic reactions we remove all events with any track that has Feynman-x, $|x_F| > .85$. This cut removes essentially all the diffraction dissociation events and a negligible proportion of non-diffractive events.

The only additional cuts applied to our data are those required to reproduce the acceptance criteria or other selections applied to the data of the lepton experiments.

3. COMPARISONS WITH e^+e^- DATA

In e^+e^- reactions various algorithms are applied to determine the jet axis. For these comparisons we take the jet axis to be the sphericity axis, as was done for the TASSO data [2]. To be consistent with TASSO we have only used events with 4 or more charged tracks. For each event we construct the second rank tensor from the N charged hadron momenta

$$M_{\alpha\beta} = \sum_{i=1}^N p_{i\alpha} p_{i\beta} \quad (\alpha, \beta = x, y, z) \quad (1)$$

If $\hat{n}_1$, $\hat{n}_2$ and $\hat{n}_3$ are the unit eigenvectors of this tensor associated with the eigenvalues λ_1 , λ_2 and λ_3 , such that $\lambda_1 > \lambda_2 > \lambda_3$, then $\hat{n}_1$ is the sphericity axis, and the plane defined by $\hat{n}_1$ and $\hat{n}_2$ is known as the event plane.

In fig. 1 we present the normalised transverse momentum distribution, $\frac{1}{\sigma} d\sigma/dp_t^2$, with respect to the sphericity axis for our K^-p data and compare it with the corresponding distributions from e^+e^- interactions. The $\frac{1}{\sigma} d\sigma/dp_t^2$ distribution in K^-p interactions at 14.3 GeV is remarkably similar to that of the TASSO data for $13 < E_{c.m.} < 17$ GeV over the entire range of p_t^2 studied. In addition the shape of this distribution shows a strong energy dependence between 4.5 and 14.3 GeV in K^-p interactions. In particular the tail of this distribution rises rapidly with $E_{c.m.}$.

The TASSO Collaboration points out [2] that to fit both the 13-17 GeV and the 27-32 GeV e^+e^- data with a simple quark fragmentation model [9] without hard gluons, it is necessary to increase significantly the parameter σ_q , which determines the transverse momentum distributions. The strong energy dependence of the K^-p distributions observed in fig. 1 indicates that simple quark fragmentation models with a fixed σ_q would not describe these hadron data below 14.3 GeV either.

The planar features of the e^+e^- data at PETRA have aroused considerable interest. As was done in the e^+e^- analyses, we have determined the mean transverse momentum squared in the event plane, $\langle p_t^2 \rangle_{IN}$, and perpendicular to the event plane, $\langle p_t^2 \rangle_{OUT}$, where

$$\langle p_t^2 \rangle_{IN} = \frac{1}{N} \sum_{i=1}^N (p_i \cdot \hat{n}_2)^2 \quad (2)$$

$$\langle p_t^2 \rangle_{OUT} = \frac{1}{N} \sum_{i=1}^N (p_i \cdot \hat{n}_3)^2 \quad (3)$$

and all other quantities have the same meaning as in eq. (1).

In fig. 2 we show the distributions of $\langle p_t^2 \rangle_{OUT}$ and $\langle p_t^2 \rangle_{IN}$ for the K^-p data at 4.5, 5.6 and 14.3 GeV together with the e^+e^- data of TASSO [2,10] at 13-17 GeV and 27-32 GeV. The $\langle p_t^2 \rangle_{OUT}$ distribution in K^-p interactions at 14.3 GeV has a very similar shape to that in e^+e^-

interactions at 13-17 GeV. In addition there is little energy dependence in the shape in K^-p interactions below 14.3 GeV as is also the case for e^+e^- interactions above 13-17 GeV. On the other hand the $\langle p_t^2 \rangle_{IN}$ distribution shows a marked energy variation in K^-p interactions below 14.3 GeV over the whole range of $\langle p_t^2 \rangle_{IN}$ values studied. The 14.3 GeV K^-p data are in good agreement with the statistically rather weak e^+e^- data at 13-17 GeV. It is clear that there is a tail of events with large values of $\langle p_t^2 \rangle_{IN}$ in the K^-p data at 14.3 GeV. A similar broadening of the jet in the event plane in e^+e^- annihilations at the highest energies is attributed to the increasing hard gluon contribution.

The TASSO Collaboration pointed out that the simple quark fragmentation model could not reproduce the $\langle p_t^2 \rangle_{IN}$ distribution at 27-32 GeV even if σ_q was varied. We show the shapes predicted by the model used in ref. [2] on fig. 2 and it can be seen that varying σ_q merely changes the slope of the exponential fall-off of the $\langle p_t^2 \rangle_{IN}$ distribution. We note that the shape of the $\langle p_t^2 \rangle_{IN}$ distribution in the 14.3 GeV data is not consistent with the simple quark fragmentation model prediction of a single exponential fall-off. This is also true for the lower energy data.

It is important to find out if the rise in the tail of $\frac{1}{\sigma} d\sigma/dp_t^2$ and the broadening of the $\langle p_t^2 \rangle_{IN}$ distribution in meson-nucleon reactions continues above 14.3 GeV, or whether a saturation effect sets in. The evidence from the ISR analyses of the mesonic subsystem from pp interactions with leading protons removed is confusing. An energy dependence in the $\langle p_t^2 \rangle_{IN}$ tail has been claimed in ref. [7] but this was using only one hemisphere and full p_t^2 minimisation was not performed. On the other hand Breakstone et al. [6] perform a sphericity analysis using data in both hemispheres and claim no variation of the $\langle p_t^2 \rangle_{IN}$ or $\frac{1}{\sigma} d\sigma/dp_t^2$ distributions between $11 < M_0 < 18$ GeV and $30 < M_0 < 35$ GeV. However the properties of these mesonic subsystems could be different from the properties of non-diffractive meson-nucleon reactions. Indeed we note that the $\frac{1}{\sigma} d\sigma/dp_t^2$ distributions from the analysis of the mesonic subsystems with M_0 between 11 and 18 GeV from ref. [6] lie significantly above the corresponding distribution for K^-p interactions at 14.3 GeV c.m. energy. This emphasises the need to continue the meson-nucleon analyses to higher c.m. energies to clarify the situation.

4. COMPARISON WITH μ^-p DATA

We now compare the planar features of our data with those observed in a recently published study of μ^-p scattering [3]. In the case of deep inelastic lepton scattering there is a natural direction that can be used as the jet axis in the search for hard gluon effects, namely the current direction. We compare distributions of transverse momentum with respect to the current direction in μ^-p interactions with the corresponding hadron distributions with respect to the incident K^- direction. It should be pointed out that in our previous study the only significant discrepancy we observed between distributions from leptonic reactions and the corresponding K^- distributions was that $\langle p_t^2 \rangle$ relative to the K^- direction did not rise as fast with $E_{c.m.}$ as $\langle p_t^2 \rangle$ relative to the "current" direction in deep inelastic νN scattering.

Our 14.3 GeV K^-p data ($s = 205 \text{ GeV}^2$) is comparable with the EMC data which has a range of hadronic invariant masses $100 \leq W^2 \leq 460 \text{ GeV}^2$ with $\langle W^2 \rangle = 310 \text{ GeV}^2$. The EMC data were presented in terms of variables

$$\sum p_{t \text{ IN}}^2 = \sum_{i=1}^N (\underline{p}_i \cdot \hat{n}_2')^2 \quad (4)$$

$$\sum p_{t \text{ OUT}}^2 = \sum_{i=1}^N (\underline{p}_i \cdot \hat{n}_3')^2 \quad (5)$$

where $\hat{n}_2'$ and $\hat{n}_3'$ are unit vectors perpendicular to the current direction such that $\sum p_{t \text{ IN}}^2$ is maximised and $\sum p_{t \text{ OUT}}^2$ is minimised. In the case of the K^-p data we take the beam direction as equivalent to the current direction and obtain $\hat{n}_2'$ and $\hat{n}_3'$ by diagonalising the tensor

$$M'_{\alpha\beta} = \sum_{i=1}^N p_{i\alpha} p_{i\beta} \quad (\alpha, \beta = y, z) \quad (6)$$

and taking $\hat{n}_2'$ as the eigenvector corresponding to the larger eigenvalue. For the μ^-p analysis only charged tracks with $p_{lab} > 6 \text{ GeV}/c$ were considered and events were required to have at least 4 such tracks. We have tried to impose a similar cut on our data allowing for the lower $E_{c.m.}$ values, by only using charged tracks with $x_F > 0.036$. This approximately corresponds to a cut of $p_{lab} = 6 \text{ GeV}/c$ at $\langle W^2 \rangle = 310 \text{ GeV}^2$ and

to a cut of $p_{\text{lab}} = 4 \text{ GeV}/c$ in our 14.3 GeV data. The requirement of 4 tracks with $x_F > 0.036$ is a very severe cut for the 4.5 and 5.6 GeV data.

Fig. 3 compares the $\Sigma p_t^2 \text{ IN}$ and $\Sigma p_t^2 \text{ OUT}$ distributions from the K^-p data with those from the μ^-p data. Both the $\Sigma p_t^2 \text{ OUT}$ and $\Sigma p_t^2 \text{ IN}$ distribution for K^-p at $W^2 = 205 \text{ GeV}^2$ are in reasonable agreement with the μ^-p data, although the K^-p data tend to lie below the μ^-p data at $\Sigma p_t^2 \text{ IN}$ above about 3 GeV^2 . The data at lower K^-p energies show a strong energy dependence in both distributions, but this to a large extent reflects the increase in average multiplicity of the samples used at the various energies. Since each selected track enters into the summation considerable energy dependence is inherent in the definition of these variables. The multiplicity dependence of these variables (remembering that the EMC data have higher $\langle W^2 \rangle$ than 205 GeV^2 and extend to significantly higher values) could account for much of the difference between the highest energy K^-p data, and the μ^-p data.

In fig. 3 we also show the predictions of the two models with which the EMC compared their data, taken directly from fig. 2 in ref. [3]. These are a simple quark fragmentation model with two values of σ_q and a first order QCD calculation of Andersson et al. [11]. As in the case of the TASSO calculations for $\langle p_t^2 \rangle \text{ IN}$, the quark fragmentation model predicts a simple exponential fall-off at high p_t whatever the value of σ_q . Hence the shape of the $\Sigma p_t^2 \text{ IN}$ distribution in K^-p interactions at 14.3 GeV is not consistent with simple quark fragmentation model predictions whatever the value of σ_q , as the fall-off deviates from a single exponential fall-off for $\Sigma p_t^2 \text{ IN}$ values above 3 GeV^2 . In fact the K^-p data at $E_{\text{c.m.}} = 14.3 \text{ GeV}$ lie closer to the curve predicted by QCD quark plus gluon production in leptonic data, particularly at the highest values of $\Sigma p_t^2 \text{ IN}$.

5. CONCLUSIONS

Using the fully inclusive non-diffractive events from K^-p data at 4.5, 5.6 and 14.3 GeV centre-of-mass energy we have compared momentum distributions transverse to the jet axis (in particular those distributions relating to the planar properties of the events) with the corresponding

distributions from e^+e^- interactions at the closest available c.m. energy, and μ^-p scattering at similar hadronic energies. We make the following observations:

- (a) The $\frac{1}{\sigma} \frac{d\sigma}{dp_t^2}$ distribution with respect to the sphericity axis in K^-p interactions at $E_{c.m.} = 14.3$ GeV is in good agreement with that of the TASSO e^+e^- data at $13 < E_{c.m.} < 17$ GeV over the entire range of p_t^2 studied. The shape of this distribution shows a very significant energy dependence between 4.5 and 14.3 GeV in K^-p interactions. In particular the tail rises strongly with $E_{c.m.}$. The energy dependence is such that simple quark fragmentation models could not reproduce the K^-p data up to 14.3 GeV without a significant increase of the parameter σ_q with energy.
- (b) The $\langle p_t^2 \rangle_{OUT}$ distribution in K^-p interactions at 14.3 GeV is similar to that in e^+e^- annihilations at $13 < E_{c.m.} < 17$ GeV. Its shape shows little energy dependence below 14.3 GeV. The e^+e^- data show little energy dependence in this variable above 13-17 GeV. The $\langle p_t^2 \rangle_{IN}$ distribution, however, shows strong energy variation in K^-p interactions up to 14.3 GeV, over all values of $\langle p_t^2 \rangle_{IN}$ studied. At 14.3 GeV the K^-p distribution agrees well with the statistically weak e^+e^- data of TASSO between 11-17 GeV. The $\langle p_t^2 \rangle_{IN}$ distribution in K^-p interactions at 14.3 GeV is not consistent with the predictions of a simple quark fragmentation model as the shape is not compatible with a single exponential fall-off.
- (c) The behaviour of the $\Sigma p_t^2_{IN}$ distribution in K^-p interactions at $W^2 = 205 \text{ GeV}^2$ is similar to that in μ^-p data with $\langle W^2 \rangle = 310 \text{ GeV}^2$, although at the highest values of $\Sigma p_t^2_{IN}$ the K^-p data lie systematically below the leptonic data. However, the strong energy dependence inherent in the $\Sigma p_t^2_{OUT}$ and $\Sigma p_t^2_{IN}$ variables may account for some of the discrepancy. On the other hand it could be that the comparison of distributions from leptonic data with respect to the current direction with the corresponding distributions in hadronic reactions with respect to the beam direction are more sensitive to differences than are comparisons of distributions with respect to the sphericity or thrust axis, as the results in ref. [1] suggest.

Irrespective of the comparison with μ^-p data we note that, as for $\langle p_t^2 \rangle_{IN}$, the $\Sigma p_t^2_{IN}$ distribution in K^-p interactions at 14.3 GeV is not consistent with simple quark fragmentation models as the shape is incompatible with a single exponential fall-off.

The results presented here show that a number of the effects observed in e^+e^- and in μ^-p scattering, which at higher energies are considered to be good evidence for hard gluon effects as they do not appear in simple quark fragmentation models, such as strong energy variation in the tail of the $\frac{1}{\sigma} d\sigma/dp_t^2$ and $\langle p_t^2 \rangle_{IN}$ distributions, and the complexity of the shape of the $\langle p_t^2 \rangle_{IN}$ and $\Sigma p_t^2_{IN}$ distributions, are also present at lower energies in K^-p interactions up to around 15 GeV centre-of-mass energy.

It is possible that saturation effects will set in above these energies in hadron reactions as, for example, is suggested by a longitudinal phase space model presented in ref. [12] and claimed in one of the ISR analyses of the mesonic subsystem [6]. It is therefore important to see if these striking similarities between lepton data and fully inclusive non-diffractive meson-proton persist at higher energies.

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FIGURE CAPTIONS

- Fig. 1 The distribution of the transverse momentum of charged tracks with respect to the sphericity axis for K^-p interactions at $E_{c.m.}$ values 4.5 GeV, 5.6 GeV and 14.3 GeV, and for e^+e^- interactions from TASSO at $13 < E_{c.m.} < 17$ GeV and $27 < E_{c.m.} < 32$ GeV [2]. The curves are the predictions from the simple quark fragmentation model for $e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}$ taken from ref. [2].
- Fig. 2 The distributions of (a) $\langle p_t^2 \rangle_{OUT}$ and (b) $\langle p_t^2 \rangle_{IN}$ for K^-p interactions at $E_{c.m.}$ values 4.5 GeV, 5.6 GeV and 14.3 GeV, and e^+e^- interactions from TASSO at $13 < E_{c.m.} < 17$ GeV, $27 < E_{c.m.} < 32$ GeV [2,10]. The curves are the predictions as in fig. 1.
- Fig. 3 Distributions of (a) $\Sigma p_t^2_{OUT}$ and (b) $\Sigma p_t^2_{IN}$ from events with ≥ 4 charged tracks with $x_F > 0.0364$ for K^-p interactions with $W^2 = 20.3 \text{ GeV}^2, 31.4 \text{ GeV}^2$ and 205 GeV^2 , and for μ^-p interactions from events with ≥ 4 charged tracks with $p_{lab} > 6 \text{ GeV}/c$ with $100 \leq W^2 \leq 460 \text{ GeV}^2$ [3]. The curves are the predictions for the leptonic reactions taken from ref. [3] for single quark jet fragmentation with $\sigma_q = 310$ (dashed line), $\sigma_q = 470 \text{ MeV}$ (dash-dotted line) and for the QCD model including hard gluon effects [11] (solid line).

Fig. 1

Fig. 2

Fig. 3