EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/EP 80-66
13 May 1980

TRANSVERSE MOMENTUM OF HADRONS PRODUCED IN
 ν AND $\bar{\nu}$ INTERACTIONS ON AN ISOSCALAR TARGET IN BEBC

Aachen-Bonn-CERN-Demokritos Athens-I.C. London-Oxford-Saclay Collaboration

H. Deden, P. Fritze, H. Grässler, F.J. Hasert, J. Morfin and R. Schulte
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

K. Böckmann, C. Geich-Gimbel, T.P. Kokott, B. Nellen, R. Pech and
H. Saarikko
Physikalisches Institut der Universität Bonn, Bonn, Germany

P.C. Bosetti¹, D.C. Cundy, A.L. Grant, P.O. Hulth, L. Pape, W.G. Scott and
O. Skjeggstad²
CERN, European Organization for Nuclear Research, Geneva, Switzerland.

M. Mermikides, E. Simopoulou and A. Vayaki
Nuclear Research Centre Demokritos, Athens, Greece

K.W.J. Barnham, I. Butterworth, J.S. Chima, E.F. Clayton, D.B. Miller,
M. Mobayyen, C. Penfold and K.J. Powell
Imperial College of Science and Technology, London, U.K.

J.R. Batley, R. Giles, P. Grossmann, J.L. Lloyd, G. Myatt, D.H. Perkins,
D. Radojicic, P. Renton and B. Saitta
Department of Nuclear Physics, Oxford, U.K.

M. Bloch, T. Bolognese, B. Tallini, J. Velasco and D. Vignaud
Centre d'Etudes Nucléaires, Saclay France

¹ CERN fellow from III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany.

² On leave from University of Bergen, Norway.

Submitted to Physics Letters B

ABSTRACT

The average transverse momentum squared, $\langle p_{\perp}^2 \rangle$, of hadrons is studied as a function of W^2 and of Q^2 for ν and $\bar{\nu}$ interactions on an isoscalar target. An increase of $\langle p_{\perp}^2 \rangle$ with W^2 is observed for the hadrons emitted forward in the hadronic c.m.s. The $p_{\perp}$ dependence of the fragmentation function is found to factorise from the structure function at fixed W , but does not factorise at fixed Q^2 . Unlike the case of forward going particles, the $\langle p_{\perp}^2 \rangle$ of hadrons going backward in the c.m.s. shows no strong dependence on W^2 .

In this letter we present a study of the transverse momentum distributions of charged hadrons, produced in deep inelastic charged current ν and $\bar{\nu}$ interactions in BEBC. Preliminary results based upon about one third of the present statistics have been published earlier [1].

Experimental details. The bubble chamber BEBC, exposed to the 200 GeV CERN narrow band beam, was filled with a 73% molar Ne/H₂ mixture with a density of 0.68 g/cm³, corresponding to a radiation length of ~ 40 cm. The scanning and measuring procedure was the same as that described in ref. [1], in particular all tracks, including associated gamma's and neutral stars, were measured in all events.

Muons with momentum ≥ 5 GeV/c are identified by a 2-plane EMI with an efficiency of $\sim 98\%$. The hits in the EMI proportional chambers have been used to improve the momentum measurement of muons with short track length in the bubble chamber, giving for example $\Delta p_{\mu}/p_{\mu} \lesssim 10\%$ for $p_{\mu} \approx 100$ GeV/c.

For the study of the production of charged hadrons, the nuclear evaporation protons have been removed by rejecting identified protons if they have momentum less than 300 MeV/c or go backwards in the laboratory frame. Furthermore, it was found that badly measured tracks, mainly due to interactions close to the primary vertex, introduce considerable tails in the $p_{\perp}$ distributions. Hence charged tracks with momentum uncertainties $\Delta p/p > 30\%$ have been removed from the events and, when such a track carried $\geq 30\%$ of the total hadronic energy, the event has been completely rejected.

The data sample satisfying these criteria corresponds to

$$\begin{array}{ll} \nu N \rightarrow \mu^{-} h^{\pm} X & 2700 \text{ events,} \\ \bar{\nu} N \rightarrow \mu^{+} h^{\pm} X & 680 \text{ events.} \end{array}$$

As some of the neutral hadrons ($\sim 20\%$ of the total hadronic energy) are not observed in the bubble chamber, the hadronic energy E_H^{vis} has been corrected (E_H) by using a method based on transverse momentum balance [2]. It should be noted that such a method not only corrects the energy for unobserved neutrals, but also for the charged particles which have been rejected for reasons given above. Energy corrections based on other methods (for example a global correction of $1.2 \times E_H^{\text{vis}}$) have

also been tried and they show that the results presented here are not sensitive to the type of energy correction used.

The corrected neutrino beam energy spectrum $E_\nu = E_\mu + E_H$ is in good agreement with the nominal ν energy expected for the narrowband beam.

Definition of the variables used. The four-momentum transfer, q , is defined from p_ν , the corrected neutrino, and p_μ , the muon four-vectors by

$$q = p_\nu - p_\mu \quad (1)$$

giving

$$\begin{aligned} Q^2 &= -|q|^2 = 2E_\nu(E_\mu - p_{\mu x}) - m_\mu^2, \\ \nu &= E_\nu - E_\mu = E_H - M. \\ W^2 &= M^2 + 2M\nu - Q^2. \\ x &= Q^2/2M\nu. \end{aligned} \quad (2)$$

where $p_{\mu x}$ is the component of the muon momentum in the neutrino beam direction, W^2 the mass squared of the hadronic system, and x the Bjorken variable.

The component of the transverse momentum of individual hadrons perpendicular to the plane defined by the incident neutrino and the muon, is called $p_\perp^{\text{out}}$, the transverse momentum with respect to the observed direction of the hadronic system is called $p_\perp$. The quantity $p_\perp^{\text{out}}$ does not depend on the detection of neutrals, whilst $p_\perp$ may. If the measurement of $p_\perp$ is unbiased, and there is no dynamical azimuthal dependence, then the average values satisfy the relation

$$\langle p_\perp^2 \rangle = 2 \langle p_\perp^2 \rangle_{\text{out}}. \quad (3)$$

Finally, the longitudinal properties of the fragmentation into hadrons is described here by the variable

$$z = \frac{E_h}{E_H} \quad (4)$$

where E_h represents the energy of individual hadrons in the laboratory frame.

Separation between forward and backward jets. The hadrons are assigned to a forward or backward jet according to whether they are produced forward or backward in the hadronic c.m.s. Such a criterion is supported by a change in the distribution of the mean charge as a function of y_{cms} , the c.m.s. rapidity, at $y_{\text{cms}} = 0$, provided W is sufficiently large. Fig. 1(a) shows the data for incident neutrinos and fig. 1(b) the antineutrino data, where one observes a change in sign of the mean charge at $y_{\text{cms}} = 0$, in qualitative agreement with the quark parton model, as already observed in previous experiments [3]. Hence, the forward-backward separation of the hadrons in the c.m.s. seems to correspond reasonably well to the separation into jets, although for $W < 6$ GeV the distinction is not so clear.

Fragmentation of forward hadrons. The average values $\langle p_{\perp}^2 \rangle$ for the charged hadrons going forward in the c.m.s. are displayed in fig. 2 and given in table 1 as a function of W^2 and Q^2 . A significant rise of $\langle p_{\perp}^2 \rangle$ with W^2 is visible in the ν data, confirming the results of ref. [1]. The same rate of increase is observed in the $\bar{\nu}$ data, whereas in ref. [1] the smaller number of $\bar{\nu}$ events available did not allow any firm conclusions to be drawn. It is also seen that $\langle p_{\perp}^2 \rangle$, to within 10%, is twice as large as $\langle p_{\perp}^2 \rangle_{\text{out}}$, in agreement with relation (3).

The average momentum of the tracks is larger at high W^2 and it is thus important to ensure that the observed rise in $\langle p_{\perp}^2 \rangle$ is not due to the correspondingly larger measurement errors. In order to investigate such effects, a test was made in which the events were randomized according to the measurement errors on the neutrino direction and the muon and hadron momenta and angles. Further, in order to check the sensitivity of $\langle p_{\perp}^2 \rangle$ to the way in which missing neutrals are corrected for, a test was made in which all measured gamma's and neutral stars were eliminated and corrected by the method described above (e.g. the average correction factor increased from ~ 1.2 to ~ 1.45). The possibility of such systematic effects has also been investigated using Monte-Carlo generated events, which simulated as closely as possible all the relevant experimental distributions. All of these methods show that the resultant $\langle p_{\perp}^2 \rangle$ values did not increase by more than 10% in the highest W bins, so that the rise cannot be assigned to measurement uncertainties.

The rise of $\langle p_{\perp}^2 \rangle$ for $W^2 \lesssim 25 \text{ GeV}^2$ (fig. 2) may be attributed to the increase in phase space, and is well reproduced by a Monte-Carlo calculation based on longitudinal phase space. The data for larger W^2 suggest a linear dependence of $\langle p_{\perp}^2 \rangle$ on W^2 . A linear least squares fit for $W > 4 \text{ GeV}$ was performed, giving values of $(3.7 \pm 0.8)10^{-4}$ and $(5.4 \pm 1.9)10^{-4}$ for the slope of ν and $\bar{\nu}$ data respectively. A similar fit for the ν data, restricted to the region $z \geq 0.2$, gives $(8.1 \pm 2.4)10^{-4}$. The slope is significantly different from zero and the ν and $\bar{\nu}$ data are in quantitative agreement with each other. It should be noted, however, that the systematic effects have not been unfolded in the fits.

The $\langle p_{\perp}^2 \rangle$ also shows a variation with Q^2 (fig. 2 b,d). An increase is visible for the ν data, but the large errors allow no similar conclusion to be drawn for the $\bar{\nu}$ data, which span, however, a much smaller range in Q^2 and are in good agreement with the data inside this range.

The $\langle p_{\perp}^2 \rangle$ has been computed separately for positive and negative hadrons in the forward direction and no significant difference between them was found.

It follows from eq. (2) that W^2 is related to Q^2 by

$$W^2 = M^2 + Q^2(1/x - 1) \quad (5)$$

which implies that $\langle p_{\perp}^2 \rangle$ could also depend on x for fixed Q^2 or W^2 . A systematic difference is indeed observed between the Q^2 dependence of $\langle p_{\perp}^2 \rangle$ for events with $x < 0.2$ and $x > 0.2$, mainly in the region of $Q^2 \lesssim 10 \text{ GeV}^2$ (not shown). When plotted versus W^2 , no such difference exists. This effect is seen in fig. 3, which displays the x dependence of $\langle p_{\perp}^2 \rangle$ for given intervals of Q^2 or of W^2 . In the region of low Q^2 , a marked dependence of $\langle p_{\perp}^2 \rangle$ on x is visible when no cut in W is applied. Since high x corresponds to low W^2 , at fixed Q^2 , the possible dependence from phase space limitations has been reduced by applying a cut at $W > 4 \text{ GeV}$, which limits the x range to $x < 0.4$. Within this range, the decrease of $\langle p_{\perp}^2 \rangle$ with x is still apparent, although its statistical significance is reduced. At high Q^2 , no comparable dependence is

found. A selection of events with high or low values of W does not produce an x dependence in $\langle p_{\perp}^2 \rangle$. The data therefore indicate that the fragmentation function in $p_{\perp}$ does not factorise at fixed values of Q^2 (at least for $Q^2 \lesssim 10 \text{ GeV}^2$) but are compatible with factorisation at fixed W .

An increase of $\langle p_{\perp}^2 \rangle$ as a function of W^2 is not expected to arise at high W^2 in the naive quark parton model, whereas QCD predicts such an effect from the emission of hard gluons by the fragmenting quark. This should, to first order in the effective strong coupling constant α_s , behave like [4]

$$\langle p_{\perp}^2 \rangle_{\text{QCD}} \propto Q^2 \alpha_s(Q^2) g(x, y), \quad (6)$$

where the function $g(x, y)$ is almost independent of y and is expected to depend on x in such a way that the variation of $\langle p_{\perp}^2 \rangle$ with W^2 is in fact close to linear. This is thus in qualitative agreement with the data. A model calculation, made by Mazzanti, Odorico and Roberto [5] for the region of $z \geq 0.2$, is compared to our neutrino data in fig. 2(e) and (f). The non-perturbative contribution, including the effect of primordial and fragmentation $p_{\perp}$, is a free parameter supposedly independent of W and Q^2 . The curves of fig. 2 have been obtained by putting this contribution at 0.20 GeV^2 , i.e.

$$\langle p_{\perp}^2 \rangle = 0.20 + \langle p_{\perp}^2 \rangle_{\text{QCD}}. \quad (7)$$

The dependence of $\langle p_{\perp}^2 \rangle$ on W^2 is reproduced reasonably well. However, it seems that the data exhibit a slightly stronger Q^2 dependence than predicted by this QCD calculation.

These results show a striking similarity to the behaviour of the fragmentation functions in terms of the variable z [6,7]. It thus seems that the main features of the scale-breaking in the fragmentation process are more easily studied experimentally in terms of W^2 than of Q^2 . It should, however, be stressed that this behaviour of the fragmentation functions is a direct consequence of the particular form of the non-factorisation expected in the framework of QCD [4,8].

The $\langle p_{\perp}^2 \rangle$ of charged particles produced forward in the c.m.s. has been studied for various intervals of the fragmentation variable z (eq. (4)). As seen in fig. 4(a), the $\langle p_{\perp}^2 \rangle$ increases rapidly with z (the seagull effect). Furthermore, an increase of $\langle p_{\perp}^2 \rangle$ with W^2 is also observed for fixed values of z . Except from the first bin $0 \leq z \leq 0.1$, where the increase is slower, it seems that, within the uncertainties of our data, the rate of increase is roughly the same for all values of z .

Fragmentation of backward hadrons. The $\langle p_{\perp}^2 \rangle$ of negative hadrons, produced backward in the c.m.s. is plotted in fig. 4(b), and compared with the forward negative hadrons. Positive hadrons have not been included, as they may be contaminated in the backward hemisphere by nuclear evaporation products. Although most of these are removed by the cuts which have been applied, the $\langle p_{\perp}^2 \rangle$ of the backward positives is less reliable, than for negatives. A clear difference between the forward and the backward hadrons is visible in fig. 4(b). The $\langle p_{\perp}^2 \rangle$ of the backward hadrons is the same as for the forward hadrons in the region of $W^2 \lesssim 50 \text{ GeV}^2$, but no significant increase with W^2 is observed for the backward hadrons.

Conclusions

- The $\langle p_{\perp}^2 \rangle$ of the charged hadrons produced forward in the hadronic c.m.s. shows an increase with W^2 in both the v and $\bar{v}$ data. An increase as a function of Q^2 is also visible. No difference is observed between positives and negatives.
- In the region of $z > 0.2$, the W^2 and Q^2 dependence is in reasonable agreement with the QCD calculation of ref. [5], assuming that non perturbative effects are independent of W^2 and Q^2 .
- Factorization is observed between the x dependence of the structure function and the $\langle p_{\perp}^2 \rangle$, at fixed W^2 . On the other hand, the $\langle p_{\perp}^2 \rangle$ shows a significant x dependence at fixed Q^2 , which is strongest in the region of low Q^2 ($\lesssim 10 \text{ GeV}^2$). This type of non-factorisation is in qualitative agreement with the predictions of QCD.

- The $\langle p_{\perp}^2 \rangle$ shows both a rapid rise with z at fixed W^2 (seagull effect) and an increase with W^2 at fixed z .
- The behaviour of the particles produced backward in the c.m.s. is strikingly different from those produced forward. The $\langle p_{\perp}^2 \rangle$ of the backward hadrons is in fact compatible with being independent of W^2 .

It is a pleasure to acknowledge the work of the scanning and measuring teams at the several laboratories and the staff at CERN for the operation of the SPC, BEBC and EMI. We are also indebted to R. Odorico for providing us with the results of his calculation.

REFERENCES

- [1] P.C. Bosetti et al., Nucl. Phys. B149 (1979) 13.
- [2] G. Myatt, Report CERN/ECFA 72-4, Vol. II (January 1973).
H. Heilmann, Int. Report Bonn University (11.09.1978).
- [3] B. Musgrave, Int. Conf. Neutrino 79, Bergen, June 1979, p. 556;
N. Schmitz, 1979 Int. Symposium on Lepton and Photon Interactions at
High Energies, Fermilab, August 1979.
- [4] G. Altarelli and G. Martinelli, Phys. Lett. 76B (1978) 89.
- [5] P. Mazzanti, R. Odorico and V. Roberto, Phys. Lett. 81B (1979) 219; the
numbers used here were obtained from R. Odorico, private
communication.
- [6] J. Blietschau et al., Phys. Lett. 87B (1979) 281.
- [7] B. Tallini, Rapporteur's Talk at the EPS Int. Conf. on High Energy
Physics, Geneva 1979.
- [8] W.G. Scott, Int. Conf. Neutrino 79, Bergen, June 1979, p. 533.

TABLE 1

Values of $\langle p_{\perp}^2 \rangle$ and $\langle p_{\perp}^2 \rangle_{\text{out}}$ in units of GeV^2 for forward hadrons in the c.m.s. as a function W^2 and Q^2 for the neutrino and the antineutrino data. The errors are statistical only.

$\nu + \text{Ne}$			$\bar{\nu} + \text{Ne}$		
$\langle W^2 \rangle$	$\langle p_{\perp}^2 \rangle$	$\langle p_{\perp}^2 \rangle_{\text{out}}$	$\langle W^2 \rangle$	$\langle p_{\perp}^2 \rangle$	$\langle p_{\perp}^2 \rangle_{\text{out}}$
4	0.116 ± 0.009	0.060 ± 0.005	5	0.112 ± 0.010	0.073 ± 0.008
25	0.153 ± 0.007	0.072 ± 0.005	20	0.157 ± 0.009	0.087 ± 0.007
50	0.177 ± 0.008	0.088 ± 0.005	40	0.177 ± 0.012	0.086 ± 0.008
80	0.181 ± 0.006	0.090 ± 0.005	70	0.181 ± 0.014	0.107 ± 0.012
120	0.201 ± 0.009	0.106 ± 0.007	150	0.230 ± 0.075	0.119 ± 0.016
200	0.232 ± 0.012	0.117 ± 0.008			
$\langle Q^2 \rangle$	$\langle p_{\perp}^2 \rangle$	$\langle p_{\perp}^2 \rangle_{\text{out}}$	$\langle Q^2 \rangle$	$\langle p_{\perp}^2 \rangle$	$\langle p_{\perp}^2 \rangle_{\text{out}}$
2	0.162 ± 0.006	0.087 ± 0.005	2	0.178 ± 0.012	0.099 ± 0.009
6	0.161 ± 0.007	0.086 ± 0.005	6	0.153 ± 0.010	0.091 ± 0.008
10	0.201 ± 0.011	0.095 ± 0.006	10	0.165 ± 0.016	0.087 ± 0.010
16	0.178 ± 0.008	0.082 ± 0.004	16	0.166 ± 0.021	0.082 ± 0.009
30	0.197 ± 0.008	0.094 ± 0.005	28	0.189 ± 0.021	0.102 ± 0.016
50	0.196 ± 0.013	0.112 ± 0.010	50	0.206 ± 0.035	0.081 ± 0.019
70	0.232 ± 0.020	0.120 ± 0.015			
110	0.230 ± 0.020	0.105 ± 0.014			

FIGURE CAPTIONS

- Fig. 1 Distribution of the total charge per event as a function of the c.m.s. rapidity y_{cms} , in bins of unit rapidity. The data are given for various intervals of W .
- Fig. 2 $\langle p_{\perp}^2 \rangle$ and $\langle p_{\perp}^2 \rangle_{\text{out}}$ shown as function of W^2 and Q^2 for the ν and $\bar{\nu}$ data (a-d). In (e) and (f), the curve corresponds to the QCD calculation of ref. [5] for charged hadrons with $z \geq 0.2$ and $W \geq 4$ GeV.
- Fig. 3 $\langle p_{\perp}^2 \rangle$ displayed as a function of x for low and high values of Q^2 and of W . The open circles in (a) correspond to a selection of events with $W \geq 4$ GeV.
- Fig. 4 Dependence of $\langle p_{\perp}^2 \rangle$ versus W^2 for several intervals of z for hadrons forward in the c.m.s. (a) and comparison of forward and backward negatives (b).

Fig. 1

Fig. 2

Fig.3

Fig. 4