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TRANSVERSE MOMENTUM OF CHARGED HADRONS OBSERVED
IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration

CERN¹- DESY(Hamburg)²-Freiburg³-Kiel⁴-Lancaster⁵-LAÏP(Annecy)⁶-Liverpool⁷-
Oxford⁸-Rutherford⁹-Sheffield¹⁰-Turin¹¹ and Wuppertal¹².

J.J. Aubert⁶, G. Bassompierre⁶, K.H. Becks¹², C. Best⁹, E. Böhm⁴, X. de Bouard⁶,
F.W. Brasse², C. Broll⁶, S. Brown⁷, J. Carr⁹, R.W. Clifft⁹, J.H. Cobb⁵,
G. Coignet⁶, F. Combley¹⁰, G.R. Court⁷, J.M. Crespo⁶, P.F. Dalpiaz¹¹,
P. Dalpiaz¹¹, W.D. Dau⁴, J.K. Davies⁸, Y. Déclais⁶, R.W. Dobinson¹,
U. Dosselli¹¹, J. Drees¹², A. Edwards⁷, M. Edwards⁹, J. Favier⁶, M.I. Ferrero¹¹,
W. Flauger², E. Gabathuler¹, R. Gamet⁷, J. Gayler², V. Gerhardt², P. Ghez⁶,
C. Gössling², P. Gregory¹, J. Haas³, U. Hahn^{3†}, K. Hamacher¹², P. Hayman⁷,
M. Henckes¹², H. Jokisch⁴, V. Korbel², U. Landgraf³, M. Leenen¹, M. Maire⁶,
L. Massonnet⁶, W. Mohr³, H.E. Montgomery¹, K. Moser³, R.P. Mount⁸, P.R. Norton⁹,
J. McNicholas⁸, A.M. Osborne¹, P. Payre⁶, C. Peroni¹¹, H. Pessard⁶, U. Pietrzyk¹²,
K. Rith³, E. Schlösser³, M. Schneegans⁶, T. Sloan⁵, H.E. Stier³, W. Stockhausen¹²,
J.M. Thénard⁶, J.C. Thompson⁹, L. Urban^{6#}, H. Wahlen¹², D. Williams⁷,
W.S.C. Williams⁸, S.J. Wimpenny¹⁰.

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Abstract

The transverse momenta of charged hadrons produced in high energy muon-proton scattering have been studied. The average squared transverse momentum $\langle p_{\perp}^2 \rangle$ shows a strong dependence on $z = E_h/\nu$ characteristic of intrinsic momentum effects and a significant rise as a function of $s = W^2$. The W^2 , q^2 , x and z dependencies of the data are compared with the predictions of a perturbative QCD model.

† now at Rheinmetall, Düsseldorf, Germany

now at Central Research Institute for Physics of the Hungarian Academy of Sciences, Budapest, Hungary.

The transverse momentum spectra of charged hadrons produced in the scattering of high energy muons on a proton target have been measured.

The experiment was performed in the M2 muon beam line of the SPS at CERN. The μ^+ beam had a mean energy of 280 GeV with a momentum bite of 8% FWHM. The muons scattered in a 6 metre long hydrogen target and the hadrons produced in the downstream 2 metres were measured in the EMC forward spectrometer consisting of a 4 Tm dipole magnet and a system of drift and proportional chambers. An iron absorber followed by more drift chambers further downstream was used to identify muons. The apparatus was triggered by scattered muons which satisfied a set of coincidence conditions between two scintillator hodoscope planes immediately downstream of the magnet and three downstream of the absorber. This trigger imposed an angle cut of 0.5 degrees on the scattered muon. The apparatus was the same as that used for recent multi muon studies [1] except for the target. A full technical report is given in [2].

In the present analysis hadron tracks were required to link from the drift chambers downstream of the magnet to the proportional chambers in the magnet and drift chambers in front of it or to the proportional chambers in the beam in front of the magnet. Further they had to fit to the vertex reconstructed from the measured beam trajectory and the scattered muon. This vertex was required to be in the downstream two metres of the target to reduce the contamination of the hadron sample by reinteractions within the target.

Defining p_μ , p_μ' as the four vectors of the primary and secondary muon and p_i and p_f as those of the target proton and the measured final state hadron we use in the following:

$$\begin{aligned} q &= p_\mu - p_\mu' \\ -Q^2 &= q^2 = (p_\mu - p_\mu')^2 \\ \nu &= (p_i \cdot q)/M = (E_\mu - E_\mu')_{\text{lab}} \\ W^2 &= s = 2M\nu + M^2 - Q^2 \\ x &= Q^2/2M\nu \\ z &= (p_f \cdot p_i)/(q \cdot p_i) = E_h/\nu \end{aligned}$$

where E_h is the hadron laboratory energy. The transverse momentum $p_\perp$ of the hadrons is measured with respect to the current direction $\vec{q}$.

The acceptance of the apparatus was determined by a Monte Carlo calculation which simulated the whole apparatus taking into account chamber inefficiencies and the resolution of $p_{\perp}$. The physics model used in this calculation was a quark to hadron cascade model [3] based on that of Feynman and Field [4]. The quark distribution functions were chosen according to ref. 5.

Radiation of the muons and its influence on the measured $p_{\perp}$ distribution were studied by a Monte Carlo simulation. This led to corrections of the order of $\leq 0.02 \text{ GeV}^2$ in $\langle p_{\perp}^2 \rangle$.

Extensive systematic studies have been made on the effects on the resulting $\langle p_{\perp}^2 \rangle$ of different criteria for the track selection. In particular stronger requirements on the number of detector planes per track, reducing the data sample by about 12%, led to changes of $\langle p_{\perp}^2 \rangle$ which were smaller than the statistical error.

The results presented below correspond to an incident flux of $3 \cdot 10^{11}$ muons and are derived from 23,000 events satisfying the conditions $20 < \nu < 260 \text{ GeV}$, $W^2 > 40 \text{ GeV}^2$, $E_{\mu} > 20 \text{ GeV}$ and $Q^2 > 1 \text{ GeV}^2$. Hadrons were only considered if they were produced in the forward hemisphere of the hadronic centre of mass system.

Measured $p_{\perp}^2$ spectra, corrected for acceptance, are shown in fig. 1 for two different ranges of z and three different ranges of W^2 . The distributions in $p_{\perp}^2$ are on average flatter both in the higher z and in the higher W^2 ranges, the dominant dependence being upon z .

Averaging over all events with $Q^2 > 5 \text{ GeV}^2$ we show in fig. 2 the W^2 dependence of $\langle p_{\perp}^2 \rangle$ for four different ranges of z . The mean accepted Q^2 of the individual data points is in the region of 20 GeV^2 but drops to 11 GeV^2 at the highest W^2 . The mean accepted z falls with increasing W^2 from 0.35 to 0.28 and 0.56 to 0.52 for $0.2 \leq z < 1$ and $0.4 \leq z < 1$ respectively. Also shown are the data from a neutrino experiment [6]. A clear rise of $\langle p_{\perp}^2 \rangle$ with W^2 is visible. In an earlier muon experiment [7] considerably lower values of $\langle p_{\perp}^2 \rangle$ had been obtained, which probably was mainly due to experimental cuts in those data. The excellent agreement with the neutrino data [6] at low W is remarkable as the relative contribution of the individual quark flavours and the spectrum of virtual bosons is much different.

If $\langle p_{\perp}^2 \rangle$ is studied as function of x and Q^2 , a rise at small x and with increasing Q^2 is observed (fig. 3). The available data are approximately independent of x for $x \geq 0.1$. This behaviour is grossly consistent with $\langle p_{\perp}^2 \rangle$ being mainly a function of W^2 . And indeed for a fixed range of W^2 the Q^2 dependence is small as shown in fig. 4a.

Contrary to the simple quark parton model, QCD predicts a rise of $\langle p_{\perp}^2 \rangle$ with W^2 [8] as a consequence of gluon emission. We therefore make the simple ansatz

$$\langle p_{\perp}^2 \rangle = \langle p_{\perp}^2 \rangle^{\text{NP}} + \langle p_{\perp}^2 \rangle^{\text{QCD}} \quad (1)$$

assuming that in the kinematic range covered the non-perturbative part, $\langle p_{\perp}^2 \rangle^{\text{NP}}$, is a function of z only. The perturbative part $\langle p_{\perp}^2 \rangle^{\text{QCD}}$ is calculated to first order in $\alpha_s(Q^2)$, the effective strong coupling constant. We use for this calculation a program of Kroll [9], based on the work of Altarelli and Martinelli and others [8], adapted to our kinematic range. The parton distribution functions and quark and gluon fragmentation functions were parametrized according to ref. [10]. The parameter Λ determining the q^2 dependence of $\alpha_s(Q^2)$ was set to 0.5 GeV.

For each of the four different ranges of z in fig. 2 we determine $\langle p_{\perp}^2 \rangle^{\text{NP}}$ in eq. (1) by a fit and obtain the results:

$$\begin{aligned} \langle p_{\perp}^2 \rangle^{\text{NP}} &= 0.25 \pm 0.01 \text{ GeV}^2 & \text{for } z > 0.2 \\ &0.14 \pm 0.01 & \text{" } 0.1 \leq z \leq 0.2 \\ &0.185 \pm 0.010 & \text{" } 0.2 \leq z \leq 0.4 \\ &0.41 \pm 0.03 & \text{" } z \geq 0.4 \end{aligned}$$

The remaining contribution, $\langle p_{\perp}^2 \rangle^{\text{QCD}}$, describes well the W^2 dependence as can be seen from the curves in fig. 2.

Using the derived values given above for $\langle p_{\perp}^2 \rangle^{\text{NP}}$ we compare the predicted Q^2 dependence with the data (fig. 4a). Again there is good agreement. The predicted Q^2 - x dependence is shown in fig. 3. The general trend of the data is reasonably well represented.

The sensitivity of these measurements to Λ is diluted by the uncertainties in the description of the parton distribution and fragmentation functions and in the detailed description of the non-perturbative part. Nevertheless, the value of $\Lambda = 0.5 \text{ GeV}$ gives an acceptable fit to these data, which are mainly at $x < 0.3$. This value of Λ corresponds to

$\alpha_s(Q^2) = 0.34$ (4 flavours) at $Q^2 = 20 \text{ GeV}^2$, which is about the average Q^2 of the data, and is, if naively extrapolated to $Q^2 = 900 \text{ GeV}^2$, consistent with the results obtained in e^+e^- interactions [11].

The z dependence of $\langle p_{\perp}^2 \rangle$ in principle contains information on the intrinsic transverse momenta $k_{\perp}$ [12]. The measured z dependence is explicitly displayed in fig. 4b. A strong rise with z^2 ('seagull') is visible. We compare the data with $\langle p_{\perp}^2 \rangle^{\text{frag}}$ (curve I) as obtained from the non perturbative quark to hadron cascade model [3], in which the $p_{\perp}^2$ distribution of the primary mesons in the cascade is assumed to be $\propto \exp(-p_{\perp}^2/2\sigma^2)$ with $\sigma = 0.35 \text{ GeV}$ and which does not contain an intrinsic $k_{\perp}$. The sum (curve III) of $\langle p_{\perp}^2 \rangle^{\text{frag}}$ (curve I) and the contribution from the perturbative QCD model (curve II) does not yield the large $\langle p_{\perp}^2 \rangle$ observed at high z .

If instead we parameterize [12]

$$\langle p_{\perp}^2 \rangle = \langle p_{\perp}^2 \rangle^{\text{frag}} + \langle k_{\perp}^2 \rangle \cdot z^2 + \langle p_{\perp}^2 \rangle^{\text{QCD}} \quad (2)$$

where now $\langle p_{\perp}^2 \rangle^{\text{NP}}$ is written as the sum of $\langle p_{\perp}^2 \rangle^{\text{frag}}$, the contribution from the fragmentation process plus $z^2 \langle k_{\perp}^2 \rangle$, that from intrinsic $k_{\perp}$, the data at $z^2 \geq 0.2$ are well represented by $\langle k_{\perp}^2 \rangle = (0.63 \pm 0.10) \text{ GeV}^2$ where the error is statistical only, as obtained from a fit according to eq. (2) to the measured $\langle p_{\perp}^2 \rangle$ shown in fig. 4b. The three data points at small z^2 are not included in this fit as they depend strongly on the unknown details of the fragmentation process, for instance the fraction of directly produced pions and kaons as compared to hadron resonances. The result for $\langle k_{\perp}^2 \rangle$ compares well with a result of the DECO experiment [13], $\langle k_{\perp} \rangle = 0.7 \pm 0.2 \text{ GeV}$, which was obtained at lower energies by studying the angle between the sphericity axis and $\vec{q}$.

In conclusion the general behaviour of $\langle p_{\perp}^2 \rangle$ of hadrons produced in high energy muon scattering is consistent with perturbative QCD which accounts rather well for the observed rise with W^2 . The measured rise of $\langle p_{\perp}^2 \rangle$ at large z can be parameterized by an intrinsic $\langle k_{\perp}^2 \rangle$ of order 0.6 GeV^2 .

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Figure Captions

Fig. 1 $p_{\perp}^2$ distributions for different ranges of W^2 and z , $Q^2 > 5 \text{ GeV}^2$.

Fig. 2a) $\langle p_{\perp}^2 \rangle$ of hadrons vs. W^2 for $0.1 \leq z < 0.2$, $0.2 \leq z < 0.4$,
 $0.4 \leq z < 1$ for μp , $Q^2 > 5 \text{ GeV}^2$ and νNe [6].

The curves represent: $\langle p_{\perp}^2 \rangle^{\text{QCD}} + \langle p_{\perp}^2 \rangle^{\text{NP}}$ (see text)

b) as a) for $0.2 \leq z < 1$

Fig. 3 $\langle p_{\perp}^2 \rangle$ vs. x for different ranges of Q^2 , $z \geq 0.2$

The curves represent: $\langle p_{\perp}^2 \rangle^{\text{QCD}} + \langle p_{\perp}^2 \rangle^{\text{NP}}$ (see text)

Fig. 4a) $\langle p_{\perp}^2 \rangle$ vs. Q^2 at $100 \leq W^2 \leq 340 \text{ GeV}^2$ for $0.1 \leq z < 0.2$, $0.2 \leq z < 0.4$,
 $0.4 \leq z < 1$

The curves represent: $\langle p_{\perp}^2 \rangle^{\text{QCD}} + \langle p_{\perp}^2 \rangle^{\text{NP}}$ (see text)

b) $\langle p_{\perp}^2 \rangle$ vs. z^2 at $100 \leq W^2 < 340 \text{ GeV}^2$, $Q^2 > 5 \text{ GeV}^2$

The curves represent:

I: non perturbative cascade model [3] with $k_{\perp} = 0$

II: $\langle p_{\perp}^2 \rangle^{\text{QCD}}$, III: I + II

IV: I + II + $0.63 (\text{GeV}^2) \cdot z^2$

Fig. 1

Fig. 2 a)

Fig. 2 b)

Fig. 3

Fig. 4

a)

b)