BALANCE OF TRANSVERSE MOMENTUM OF HADRONS PRODUCED
IN DEEP INELASTIC MUON PROTON SCATTERING

The European Muon Collaboration

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ABSTRACT

Data are presented on the balance of transverse momenta of final state charged hadrons in 280 GeV muon-proton scattering. In particular the way in which the transverse momentum of either leading particles ($z > 0.5$) or high p_T particles ($p_T^2 > 2 \text{ GeV}^2$) is compensated by further hadrons in the forward hemisphere is studied. The results are consistent with a QCD based model. The agreement is achieved by including in the model the emission of soft gluons and assuming that the partons have a distribution of primordial transverse momentum with $\langle k_T^2 \rangle \approx 0.2 \text{ GeV}^2$, a value considerably less than found in previous analyses.

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We showed in previous publications on final state hadrons in muon proton scattering that the observed widening of p_T distributions with increasing W^2 [1] and the double jet structure in the forward hemisphere, observed in events containing high p_T particles [2], can be interpreted as being due to the emission of hard gluons. A further interesting feature of these results [1] is the strong rise of $\langle p_T^2 \rangle$ with the fractional hadron energy z ("seagull effect"). A broad distribution of primordial transverse parton momenta ($\langle k_T^2 \rangle = 0.6 \dots 0.8 \text{ GeV}^2$) was needed to describe these data [1,3] in the framework of first order QCD-matrix elements [4] for hard gluon emission and hadronisation according to the Field-Feynman [5] or the Lund model [3]. In this publication we present more detailed studies concerning the origin of these effects.

It was pointed out by Andersson et al. [3,6,7] that the leading particle might carry recoil p_T due to the emission of soft gluons by the struck quark and they predicted that the p_T of a high z particle is therefore balanced to a large extent in the central rapidity plateau. On the other hand the large p_T of high z particles could also be attributed to the effect of Fermi motion of the initial state partons (primordial k_T). In this case the p_T would be balanced by the target remnants in the backward hemisphere. The available muon-proton data on high p_T phenomena [1,2,8] are described well by either approach [3,7]. We aim to distinguish the two cases by selecting energetic hadrons ($z > 0.5$) and studying the balancing p_T of the remaining particles in the forward hemisphere.

As a further point we study, by selecting a particle of large p_T , whether this particle can indeed be interpreted as part of a quark or gluon jet emitted at finite angles with respect to the current direction as in our previous reports [1,2,8]. In this case the particle of large p_T should not be isolated in phase space but is expected to be accompanied by further particles. Recent νN [9] data show no clear evidence for such an effect.

The experiment was performed in the muon beam of the SPS at CERN with a mean muon energy of 280 GeV. The muons scattered in a 6 m long hydrogen target and the charged hadrons produced were measured in the EMC forward spectrometer [10]. The apparatus, trigger and track reconstruction criteria, are the same as described in [1]. To reduce the contamination of the hadron sample by reinteractions within the target we required, as in [1] and [2], the event vertex to be in the downstream two metres of the target.

Denoting the four-vector of the primary and secondary muon as p_μ, p_μ' , those of the target nucleon and a final state hadron as p_i and p_f , and the nucleon mass as M , we define the standard kinematic variables:

$$q = p_\mu - p_\mu', \quad -Q^2 = q^2 = (p_\mu - p_\mu')^2$$

$$\nu = (p_i \cdot q)/M = (E_\mu - E_\mu')_{lab}$$

$$W^2 = s = 2M\nu + M^2 - Q^2$$

$$z = (p_f \cdot p_i) / (q \cdot p_i) = E_h/\nu$$

where E_h is the hadron laboratory energy. The transverse and longitudinal momenta, p_T and p_L respectively, are measured relative to the virtual photon or current direction. We evaluate the rapidity of the observed hadrons

$$y^* = 0.5 \cdot \ln \frac{E^* + p_L^*}{E^* - p_L^*}$$

in the virtual photon-proton centre of mass frame, where the quantities E^* and p_L^* are energy and longitudinal momentum of secondary hadrons. The kinematic variables of hadrons are evaluated assuming pion masses, both in the analysis of the experimental data and in the theoretical Monte Carlo models with which we compare our results. There is little effect on the y^* distributions presented below if the correct particle masses are used in the models: $\langle y^* \rangle$ is reduced by ≈ 0.1 and the yield in balancing p_T is reduced by $\approx 4\%$.

All results presented below are corrected for acceptance losses, chamber inefficiencies and resolution effects by a Monte Carlo simulation of the experiment. This simulation includes electromagnetic radiation from the muons [11], which leads to corrections that are smaller than the experimental errors. The experimental yield in each bin of the distributions was corrected by the ratio of the yields for generated Monte Carlo events to those accepted by the apparatus in the simulation. The model [3] used represents most aspects of the data well. However we checked that the results are not model dependent by an alternative approach, correcting the hadron yields track by track using an acceptance table as function of laboratory momentum and angle. The results of both methods agree within errors.

The results presented correspond to approximately $5 \cdot 10^{11}$ incident muons and are derived from 13k scattering events satisfying the conditions $100 < W^2 < 340 \text{ GeV}^2$, $Q^2 > 5 \text{ GeV}^2$, $\theta_\mu > 0.8^\circ$, $\nu < 260 \text{ GeV}$ and $E'_\mu > 20 \text{ GeV}$. Hadrons were only considered if they were produced in the forward hemisphere ($y^* > 0$) and if they had laboratory momenta $p_h > 6 \text{ GeV}$. The above cuts were applied to ensure good acceptance in the whole kinematic range for muons and hadrons and to avoid regions of poor resolution or having a significant background from pion decay leading to misidentification of the scattered muon.

To study how the transverse momentum of leading particles or high p_T particles is balanced we consider in what follows two classes of events defined by the property of a "trigger particle":

Class A contains 327 events for which the trigger particle has maximum p_T and satisfies $p_T^2 > 2 \text{ GeV}^2$. For these events $\langle W^2 \rangle = 228 \text{ GeV}^2$ and $\langle Q^2 \rangle = 26 \text{ GeV}^2$.

Class B contains 1008 events for which the trigger particle has $z > 0.5$ and thus carries at least half the available energy. For these events $\langle W^2 \rangle = 200 \text{ GeV}^2$ and $\langle Q^2 \rangle = 26 \text{ GeV}^2$.

There is some overlap between these two classes, as 29% of the high p_T triggers have $z > 0.5$.

Fig. 1a and 1b give distributions of fractional energy z for the two above event classes, separately for the trigger particle (maximal p_T or $z > 0.5$ respectively) and for the remaining particles in the event. The z distributions of these further particles in the event are similar in the two cases. The decrease below $z \approx 0.1$ is due to the fact that only particles with $p_h > 6 \text{ GeV}$ are considered in the analysis.

We compare these and further distributions with the predictions of the QCD based model of Andersson et al. [7]. This extended "Lund model" for lepto-production contains baryon production in addition to first order QCD matrix elements and the fragmentation of quarks and gluons to mesons, and it attempts to account for the effects of the emission of soft gluons on the observed hadrons. No parameters of the model were adjusted to the present results and we use the fragmentation parameters used in [7]. Parton distribution functions are taken

from Glück et al. [12]. The strong coupling constant is given by the four flavour expression $\alpha_s = 12\pi/(25 \ln Q^2/\Lambda^2)$ with $\Lambda = 300$ MeV, i.e. $\alpha_s = 0.27$ at $\langle Q^2 \rangle = 26 \text{ GeV}^2$.

The inclusion of the recoil effects due to soft gluon emission permits only a small amount of primordial transverse momentum k_T , the latter is simply treated by rotating the whole event with respect to the virtual photon direction [3]. The authors of [7] set the width of the k_T distribution equal to the width of the transverse momentum distribution ($\sigma_q = 0.31 \text{ GeV}$) of quarks generated in the fragmentation process, so that $\langle k_T^2 \rangle = 0.19 \text{ GeV}^2$. This model was shown [7] to represent well other aspects of our data. Without the assumption of soft gluon emission in the model a value of $\langle k_T^2 \rangle \approx 0.74 \text{ GeV}^2$ is needed to account for the p_T of high z particles, keeping all other parameters unchanged.

Fig. 2 shows how the transverse momentum of the particle with maximum p_T is balanced by further charged particles within our experimental cuts, where we plot the transverse momentum flow P_T defined by

$$P_T = 1/N_{ev} \int p_T \frac{dN}{dp_T} dp_T$$

with N_{ev} the number of events in the class. According to the Lund model $\sim 90\%$ of the events having a particle with $p_T^2 > 2 \text{ GeV}^2$ (class A) are multijet events containing either a quark and a gluon jet or a quark and an antiquark jet in the forward hemisphere. Such a high p_T particle, being part of a jet, should therefore be accompanied by further particles. Such behaviour is demonstrated in fig. 2a where the transverse momentum flow is plotted as function of ϕ_T , the azimuth of the particles relative to the virtual photon direction. $\phi_T = 0$ is defined by the particle with maximum p_T which is removed from the plot. The same side correlation ($|\phi_T| \sim 0$) shows that the large p_T particle is accompanied by other particles as expected in this picture and the behaviour is consistent with the Lund model (solid curve fig. 2a). A strong away side enhancement ($|\phi_T| \approx \pi$) is expected from momentum conservation. To show that the same side enhancement is not produced by decays of unstable particles the data in fig. 2a is compared with a pure quark parton model prediction obtained by switching off the QCD matrix elements in the model and choosing a broader distribution of p_T due to fragmentation

($\sigma_q = 0.47$ GeV). The agreement is poor (dash-dotted curve fig. 2a). We know, however, that such a model also fails to describe other aspects of the data [2]. The evidence for such a same side correlation in νN data is not conclusive [9].

Fig. 2b gives the distribution of the transverse momentum flow $P_T = 1/N_{ev} \int p_T \frac{dN}{dp_T} dp_T$ per unit of rapidity for the trigger particle with $p_T^2 > 2$ GeV² and the flow of the balancing transverse component p_T^{bal} of the other particles in the event, where $p_T^{bal} = -\cos\phi_T p_T$. This balancing component is plotted as function of y^* of the corresponding particles. The drop of the distributions at $y^* = 0$ is due to the applied cut $p_h > 6$ GeV. The Lund model is in reasonable agreement with these data. This is also true for the calculation without soft gluon emission but large k_T (not shown).

Fig. 3 shows how the transverse momentum of particles with $z > 0.5$ (class B events above) is balanced. The Lund model predicts that more than 90% of these events have a single forward jet and that there is no same side correlation. Fig. 3a, the azimuthal distribution of the transverse momentum flow, shows that the same side correlation ($|\phi_T| \sim 0$) is absent in the data in agreement with this picture. Fig. 3b shows the rapidity distribution of p_T^{bal} which is shifted by around -1.5 units with respect to that of the trigger particle. Again the drop at $y^* \approx 0$ is due to the applied cut $p_T > 6$ GeV. The data is well represented by the Lund model (full curve) assuming a small primordial k_T ($\langle k_T^2 \rangle = 0.19$ GeV²), but taking account of effects of the emission of soft gluons on the observed hadrons. The alternative approach, to interpret the large p_T of the trigger particle mainly as the result of large primordial k_T ($\langle k_T^2 \rangle = 0.74$ GeV²) and switching off the soft gluon emission, predicts less p_T^{bal} in the forward hemisphere than measured (dashed curves in fig. 3). The rapidity distribution of p_T for the trigger particle, however, is described equally well by either approach (not shown). Due to the fact that we observe neither charged hadrons with $p_h < 6$ GeV and $y^* < 0$ nor neutral hadrons, a large part of the balance of the p_T of the trigger particle is missing. We measure within our cuts $\langle \sum p_T^{bal} \rangle / \langle p_T^{trg} \rangle = 0.13 \pm 0.02$ (stat.) ± 0.02 (syst.). This is to be compared with the predictions 0.16 and 0.08 of the two models with small or large k_T respectively.

To conclude, we have presented several distributions selecting events with either a charged hadron with high p_T ($p_T^2 > 2 \text{ GeV}^2$) or with one carrying more than half of the available energy ($z > 0.5$). The general behaviour of the data in all these detailed distributions is reproduced rather well by the Lund model that not only contains first order QCD matrix elements but includes the effects of the emission of soft gluons on the observed hadrons. The distributions for events with a high p_T particle give further support to the hypothesis of a multi jet structure as predicted by perturbative QCD models. A considerable amount of the transverse momentum of energetic particles ($z > 0.5$) is balanced by other particles in the forward hemisphere. This suggests that the large observed p_T at high z is not due to a kind of Fermi motion of initial state partons, but rather that it is the result of gluon emission in the interaction.

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FIGURE CAPTIONS

Fig. 1 - z-distributions of trigger particle (open symbol) and remaining particles (closed symbol) in the events.

Curves: Lund model [7]

a) trigger: $p_{T \max}$ with $p_{T \max}^2 > 2 \text{ GeV}^2$ (Class A)

b) trigger: $z > 0.5$ (Class B).

N_{ev} is the total number of events in the appropriate class.

Fig. 2 - Events with $p_{T \max}^2 > 2 \text{ GeV}^2$ (Class A).

a) Azimuthal distribution of transverse momentum flow P_T . The azimuth is measured relative to the hadron with $p_{T \max}$, which is not included in the plot.

Solid line: Lund model [7]

Dash-dotted line: Lund model without the QCD matrix elements but

$\sigma_q = 0.47 \text{ GeV}$.

b) Distribution of the transverse momentum flow P_T^{trg} of the particle with $p_{T \max}$ (open symbols) and of the balancing component P_T^{bal} of further particles (closed symbols) as a function of rapidity.

Curves: Lund model [7].

Fig. 3 - Events with $z > 0.5$ (Class B).

a) Azimuthal distribution of transverse momentum. The azimuth is measured relative to the trigger hadron ($z > 0.5$), which is not included in the plot.

Solid line: Lund model [7].

Broken line: Lund model [7], with no emission of soft gluons and $\langle k_T^2 \rangle = 0.74 \text{ GeV}^2$.

b) Distribution of the transverse momentum flow P_T^{trg} of the particle with $z > 0.5$ (open symbols) and of the balancing component P_T^{bal} of further particles (closed symbols) as a function of rapidity.

Solid line: Lund model [7].

Broken line: Lund model [7], with no emission of soft gluons and $\langle k_T^2 \rangle = 0.74 \text{ GeV}^2$.

FIG. 1

FIG. 2

FIG. 3