Studies of Jet Fragmentation in Large p_T Events at the ISR

CERN-Collège de France-Heidelberg-Karlsruhe Collaboration

E. E. Kluge

Institut für Hochenergiephysik der Universität Heidelberg and CERN, Geneva, Switzerland

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Abstract

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In an experiment done with the SFM-facility at the CERN-ISR, we have studied events with a high p_T particle (π^+ , π^- , K^- , p) produced at $\theta = 20^\circ$ and $\theta = 45^\circ$. The distribution of leading fragments of the spectator jet in the same rapidity hemisphere as the trigger depends strongly on the kind of trigger particle involved. These distributions agree with predictions from dimensional counting rules, if parton scattering via vector gluon exchange is assumed for the large p_T process. The average charge of the fastest particle (jet leader) in the away jet is $\simeq 1/3$ independent of the trigger charge, a value expected if 3 valence quarks participate in the hard scattering process. For transverse momenta of $\simeq 2 \text{ GeV}/c$ the $\rho^0/\pi^\pm$ production ratio is near unity.

1. Introduction

It has become increasingly clearer recently that the scattering of constituents is the underlying process giving rise to large p_T secondaries in inelastic hadron interactions. In particular has the CCHK Collaboration [1], whose newest results are reported here, been able to describe the phase space structure of secondaries in inelastic pp interactions with a charged hadron of large p_T in terms of a simple parton scattering model [2]. There, their data obtained by triggering on a charged hadron of large p_T were explained by assuming elastic parton scattering with vector gluon exchange. The subsequent fragmentation of the active and the spectator partons gives rise to a four-jet structure of the event (more specifically twice two-jet systems like in e^+e^- annihilations). The new idea which had to be introduced to make the model work (as compared to earlier studies [3]) was the assumption that the partons have a substantial transverse motion with a average $\langle K_T \rangle$ of $\simeq 800 \text{ MeV}/c$. Clearly, this model is in a sense a first approximation to a description in terms of QCD.

Given the fundamental process of large p_T particle production a sketched in Fig. 1, specific quantum number correlation are expected to exist between the different jets in the event. This is so because no quantum numbers (flavour) are transferred by the exchanged gluon. In the following we are going to work out and test predictions by assuming that the flavour content of the jets (or of the quarks respectively) is remembered by the leading particles in the jet.

2. Experimental procedure

The Split Field Magnet (SFM) of the CERN Intersecting Storage Rings (ISR) was used in nearly the full solid angle to measure

charge and momenta of the particles produced in pp interactions at $\sqrt{s} = 52.2 \text{ GeV}$. An efficient trigger road through the chamber system containing the trajectories of charged particles with a large transverse momentum in a given polar angular region ($\theta = 20^\circ$ or $\theta = 45^\circ$) was set up, using the self-triggering properties of the Multiwire Proportional Chamber (MWPC) system. Details of the set-up, of the acceptance, resolution and data analysis procedure have been described in [2].

Threshold Cerenkov counters were used to separate charged pions with $p > 7 \text{ GeV}/c$ from heavier particles in the trigger for an event sample at $\theta = 20^\circ$. The remaining sample consists mainly of protons for the case of positive heavy particle and of K^- for the negative ones as known from other measurements [4, 5]. Properties of the trigger samples are given in Table I.

Kinematical quantities of the charged secondaries produced together with the triggering particle are given in the coordinate system of Fig. 2. The sample has been corrected for acceptance losses and a transverse momentum cut of $p_T > 0.25 \text{ GeV}/c$ has been applied.

3. Spectator jets

The two spectator jets in the large p_T process of Fig. 1 have approximately the directions of the two incident protons. Moreover, the trigger condition $\theta = 20^\circ$ favours a configuration where the trigger and its spectator jet tend to occupy the same rapidity hemisphere [2]. The other jet, associated to the jet away in azimuth with respect to the trigger, then is in the opposite rapidity hemisphere.

Having identified the triggering large p_T particle, we are going to study, in which way the longitudinal phase-space structure of the event depends on the trigger kind.

We therefore present in Figs. 3–5 the ratios of rapidity distributions of positive and negative secondaries respectively for a π^+ to a π^- trigger, a p to a π^+ trigger and a K^- to a π^- trigger.

As can be seen in the figures, no correlation exists between the trigger particle and the longitudinal phase space density in the opposite rapidity hemisphere. This is expected if vector gluon exchange mediates the hard scattering process of Fig. 1.

Table I. Trigger properties for sample with identified trigger

Trigger type	p_T	Purity
π^-	$> 2.0 \text{ GeV}/c$	$> 99\%$
π^+	$> 2.0 \text{ GeV}/c$	$> 99\%$
K^-	$> 1.4 \text{ GeV}/c$	$> 70\%$
p	$> 2.0 \text{ GeV}/c$	$> 80\%$

Fig. 1. Pictorial representation of the quark-quark scattering process leading to a four-jet structure in a large p_T event.

On the other hand, the particle ratios of Figs. 3–5 deviate from unity in the rapidity hemisphere of the trigger. Since the jet away in azimuth is restricted in rapidity to values $y < 2$ (Fig. 5 of [2]), we have evidence for correlations between the trigger particle and its spectator.

Triggering on single particles of large p_T we select trigger jets where a single particle takes nearly the full jet momentum [6]. Thus, an identification of the fragmenting quark is possible and we see that, e.g., π^+ stem from u -quarks, π^- from d -quarks and K^- mesons from sea quarks [7].

Taking into account the quark composition of the incident proton, we then know which quarks remain in the spectator system of the same rapidity hemisphere (Fig. 1). For the fragmentation of these quarks we can predict the scaling behaviour of particle densities, e.g., by quark counting rules and compare the expected distribution of fast particles with the observed ones. This allows to investigate the underlying hard scattering process of Fig. 1 further.

For this purpose we have to establish the proper scaling variable for the fragmentation of the spectator jet since in large p_T events the available energy of the spectator system is reduced when compared to the pp c.m. system energy. Hence the usual Feynman variable $x (=p_L/p_{L_{\max}})$ is not suitable to describe spectator fragmentations.

Instead we use a reduced energy $\sqrt{s'}$ (neglecting parton k_T) for the system of the two-spectator jets, which moves with a momentum p' in the proton-proton rest frame. Denoting by y_1 and y_2 the rapidities of the trigger jet and the away side jet, then the overall energy momentum and invariant mass of the spectator systems are

Fig. 2. Coordinate system, indicating the different kinematical regions.

Fig. 3. Ratio of the number of secondaries for a π^- trigger to secondaries for a π^+ trigger: (a) for positive secondaries, (b) for negative secondaries.

$$E' = \sqrt{s} - m_T(\cosh(y_1) + \cosh(y_2))$$

$$p' = -m_T(\sinh(y_1) + \sinh(y_2))$$

Here m_T is the transverse mass of the jet (i.e., $m_{T_1} = m_{T_2}$).

We use the following approximations for y_1 , y_2 and m_T :

$$y_1 = y^{\text{Tr}}, \quad (\text{Tr} = \text{Trigger})$$

Fig. 4. Same as Fig. 3 for p to π^+ trigger.

Fig. 5. Same as Fig. 3 for K^- to π^- trigger.

$$y_2 = 0, \quad (\text{experimentally: } \langle y_2 \rangle = 0.05)$$

$$m_T = 1.1 \times p_T^{\text{Tr}}$$

The resulting scaling variable is then

$$x' = 2p'_y/\sqrt{s'},$$

the reduced longitudinal momentum of a secondary in the spectator system.

Since inclusive particle spectra resulting from quark fragmentation are expected to show a power law behaviour $(1-x')^n$ for $x' \rightarrow 1$ [8], we present in Figs 6–10 the quantity $x' \cdot dN/dx'$ vs. $(1-x')$ (or ratios thereof respectively) with a double logarithmic scale.

Fig. 6. Particle density of positive secondaries in the spectator jet accompanying a triggering proton as a function of $(1-x')$, x' being the reduced longitudinal momentum in the jet. Fig. 7. Particle density of positive particles in the spectator jet accompanying the triggering pion as a function of $(1-x')$.

mic scale. The distributions are given for different combinations of trigger particle and charge of secondaries in the spectator jet. As can be observed in the figures, the distributions show marked differences and we shall try to explain these at least qualitatively.

For this purpose we make use of dimensional counting rules [8] to estimate the expected power behaviour of the fragmentation function. These state, that the inclusive distribution of hadrons from the fragmentation of a system of quarks is given by $x d\sigma/dx \simeq (1-x)^{2n-1}$, where n is the number of quarks remaining in the system after emission of the hadron under consideration. In Table II we give the expected power law behav-

Fig. 8. Particle density of negative particles in the spectator jet accompanying the triggering π^+ as a function of $(1-x')$.

Fig. 9. Ratio of particle densities of positive and negative secondaries for a π^- trigger to a π^+ trigger as a function of $(1-x')$.

four depending on the quantum number of the trigger and the associated secondaries. We add a slight modification though: counting rules yield identical results for the distribution functions $u(x)$ and $d(x)$ for u and d quarks and for their fragmentation into π^+ and π^- respectively. In inelastic pp collisions a reduced longitudinal momentum distribution of $(1-x)^3$ for

Fig. 10. Ratio of particle densities of positive and negative secondaries in the spectator jet for a K^- trigger to a π^- trigger vs. $(1-x')$.

Table II. Fragmentation functions for the same rapidity spectator jet for different trigger particles, derived from dimensional counting rules with vector gluon exchange

Trigger type	Spectator fragment type	Fragmentation function "counting rules"
p	π^+	$(1-x)$
p	π^-	$(1-x)^2$
π^+	p	$(1-x)$
π^+	π^-	$(1-x)^4$
π^-	p	$(1-x)$
π^-	π^-	$(1-x)^7$
K^-	p	$(1-x)$
K^-	π^-	$(1-x)^8$

π^+ and $(1-x)$ for π^- is observed [9]. Therefore, we increase the predicted power by one, whenever a valence d quark is fragmenting. Moreover, for the cases of meson triggers and positive secondaries in the spectator jet the latter are taken to be protons. Counting rule predictions for different combinations of trigger particle and spectator fragment type are given in Table II. The counting rule predictions should not be taken too literally, because of the choice of the variable x' . Furthermore, with increasing power n , the experimental distributions fall quite rapidly for $x' \rightarrow 1$ and hence the statistical accuracy becomes rather limited.

As a first example we display in Fig. 6 for the case of a proton trigger the x' distribution of positive secondaries in the spectator jet. Also shown is the fragmentation function $x'D_u^+(x')$ [10], which is seen to describe the experimental x' dependence quite well. Dimensional counting rules yield a prediction very similar to the function $x'D_u^+(x')$, namely $(1-x')$, if we assume that the spectator consists of a single quark (i.e., the trigger proton taking two quarks from the incident proton).

The next example in Fig. 7 shows for the case of a pion trigger (π^+ and π^-) the x' distribution of positive secondaries in the spectator jet, which we can safely assume to be mainly protons. The distribution is quite similar to the one in Fig. 6, in fact dimensional counting rules predict also a behaviour $(1-x')$ for the fragmentation of an (ud) diquark system fragmenting into a proton. Thus, we compare the data with the same fragmentation function $x'D_u^+$ as in the previous case.

Fig. 8 is the x' distribution of negative secondaries for a π^+ trigger and is quite different from the previous two fragmentation distributions. Here, we have the case of a diquark system fragmenting into a pion and no fragmentation functions are available to compare with. Thus, we make use of the modified dimensional counting rules of Table II, giving a $(1-x')^4$ behaviour for a π^- in the spectator jet, which is seen to reproduce the data.

Similarly in Fig. 9 ratios of rapidity distributions for secondaries in the spectator jet associated to a π^- trigger and to a π^+ trigger are shown. Again a comparison is made with counting rules and good agreement is observed.

Fig. 10 is the ratio of x' distributions for secondaries in the spectator jet associated to a K^- and a π^- trigger. Again experimental distributions agree with counting rule predictions, if we assume the triggering K meson to originate from a scattered sea quark.

Finally, in Fig. 11 the experimental negative to positive spectator particle ratio for a proton trigger is shown as a function of x' and compared to counting rule predictions.

It should be pointed out, that in the case of the proton

Fig. 11. Ratio of particle densities of negative to positive secondaries in the spectator jet accompanying a triggering proton versus $(1-x')$.

trigger, the inclusive distributions of particles in the spectator jet are in agreement with simple predictions only if single quark fragmentation is assumed. Diquark and gluon fragmentation are excluded by the data. We are therefore led to conclude, that the triggering proton contains two quarks from the incident proton. Hence, one would speculate that either two quarks are affected by the hard scattering process or our forward trigger condition, $\theta = 20^\circ$, in the p_T range under consideration, is fulfilled by a proton coming from a spectator jet (which recoils with transverse momentum k_T [2]).

4. Trigger jet

It has been observed in deep inelastic electron scattering [11], that quarks fragment with equal probability into pions and rho

mesons. We therefore determine the ratio of rho mesons to pions of same transverse momentum in the trigger jet, since we expect a value near unity if the assumed picture of Fig. 1 holds. Note however, that even for a rho/ π ratio of one, only a small fraction of the observed triggering pions stem from rho decay due to the steep fall off in transverse momentum.

To measure the rho/ π ratio, the invariant mass of the trigger with any particle of opposite charge in an azimuthal range of $\Delta\phi = 40^\circ$ is determined. A sample of events is used with a triggering pion at $\theta = 20^\circ$ identified by the Cerenkov counters.

Figs. 12(a) and (b) show the resulting $\pi^+ - \pi^-$ mass spectra, exhibiting a peak in the mass region of the rho meson. Background distributions are obtained in two different ways: (i) by replacing the component of the trigger momentum in the beam direction by its negative value and (ii) by randomly combining normal inelastic events with the trigger particles of the large p_T sample. Both methods yield nearly identical background distributions.

To determine the rho signal exceeding the background, a relativistic P -wave Breit-Wigner function was used to parametrize the mass distribution in the rho region and the decay angular distribution was taken to be isotropic. The resulting distribution, obtained by simulation methods and by imposing acceptance conditions, when added to the background, describes the experimental mass spectrum quite adequately, as can be seen in the Fig. 12.

In order to obtain the amount of directly produced pions as compared to those from rho decay in the trigger, the acceptance for single pions was also computed by the Monte-Carlo method. We thus obtain the relative production yields of rho mesons to charged pions of the same p_T as given in Table III.

The observed rho/ π ratio near unity is consistent with the hard scattering picture of Fig. 1. Although the fragmentation of the quarks yields nearly equal numbers, the trigger bias on the other hand then favours the detection of directly produced pions.

5. Away jet

Assuming that the leading particle of the quark fragmentation reflects the original quantum numbers, we have a possibility to

Fig. 12. Invariant $\pi^+\pi^-$ mass spectrum for the trigger jet (full line): (a) π^+ is a large p_T trigger and (b) π^- is a large p_T trigger. The dotted curve is an

estimate of the background; the hatched is the sum of background and Breit-Wigner distribution for the ρ meson.

Table III. Properties of trigger jet sample used for determination of the ρ/π ratio

Trigger type	π^-	π^+
Number of triggers	14 000	28 000
$\langle p_T \rangle$	1.7 GeV/c	2.5 GeV/c
Number of ρ^0 observed	313 $\pm$ 44	1164 $\pm$ 64
ρ^0/π^- resp. π^+	0.82 $\pm$ 0.15	1.34 $\pm$ 0.15

connect the average charge of the jet leader in the away jet with the average charge of the scattered partons.

In order to exclude cases where an undetected neutral particle is the leading particle in the away jet, we check the transverse momentum balance. For this purpose we calculate the quantities p_x^{tow} and p_x^{away} , which are the sum of transverse momenta in the trigger plane for charged particles in the towards and away azimuthal range respectively (Fig. 2). The summation is restricted on the towards side to particle within $\Delta y = \pm 0.7$ around the trigger, in the away hemisphere around the charged secondary with largest p_x (jet leader). Defining $x_J = \Sigma p_x^{\text{away}} / \Sigma p_x^{\text{tow}}$ we obtain a measure for the fraction of the trigger jet transverse momentum compensated by the away side charged particles. Here we use the sample of events with a charged particle trigger at $\theta = 45^\circ$.

We determine the average charge $\langle q_F \rangle$ of the jet leaders in our sample as a function of x_J . The resulting distributions are shown in Fig. 13.

As can be seen in Fig. 13(a), the average charge of the largest momentum charged particle increases with x_J and reaches a value of 1/3 for $x_J \rightarrow 1$, i.e., when the trigger jet is balanced by the charged particles of the away jet. Fig. 13(a) contains data for the sum of negative and positive trigger particles and also the

separate distributions. We observe, that the behaviour of $\langle q_F \rangle$ on x_J does not depend on the trigger charge.

To Fig. 13(a) only events with a back-to-back configuration contribute, i.e., where the jet leader with rapidity y_F is in the rapidity hemisphere opposite to the trigger ($y^{\text{Tr}} \approx 0.8$).

In a simple valence quark parton model a value of $\langle q_F \rangle = 1/3$ is expected, since the average quark charge in a proton is $\langle q \rangle = \Sigma q_i / \text{number of quarks in proton} = 1/3$. The independence of the result from the trigger charge then is an indication for gluon exchange mediating the large p_T process.

Resulting distributions for events, where the jet leader of the away jet and the trigger are in the same rapidity hemisphere are displayed in Fig. 13(b).

The behaviour of $\langle q_F \rangle$ in the Fig. 13(b) is possibly due to the fact that this configuration results from the participation of partons of low x in the hard scattering process. Hence, the inclusion of sea quarks and gluons in addition to valence quarks will alter and decrease the simple prediction $\langle q_F \rangle = 1/3$.

6. Conclusions

We have studied the behaviour of the four jets in large p_T events. This we do by analyzing properties of leading particles in the jet, since in a sense they reflect the quantum numbers of the original jet. Thus, we can test, whether a simple picture for the origin of large p_T events, developed previously, also explains quantum number correlations in large p_T events. This model, which is elastic scattering of constituents with vector gluon exchange, predicts well defined correlations between the different jets, since no quantum numbers are exchanged between the incident protons.

Triggering on a charged particle of large p_T at $\theta = 20^\circ$, we observe that the charge composition of the spectator in the

Fig. 13. Mean charge of the jet leader in the away jet as a function of x_J , the fraction of transverse momentum compensated by charged particles: (a) trigger jet and away jet back-to-back in rapidity, for positive and neg-

ative trigger particles and for the combined sample; (b) trigger jet and away jet back-anti-back in rapidity, for positive and negative trigger particles and for the combined sample.

opposite rapidity hemisphere does not depend on the quantum numbers of the trigger particle, in contrast to the behaviour of the spectator jet in the same rapidity hemisphere. For this jet, we measure the fragmentation functions of charged particles for every kind of identified trigger. We find that all distributions agree with fragmentation functions, where known, or with dimensional counting rule predictions obtained by assuming vector gluon exchange in the large p_T process.

Analyzing the trigger jet, we find that as many neutral ρ mesons as π^+ respectively π^- of the same transverse momentum are produced. Since quarks are known (from deep inelastic electron scattering) to fragment into both particle kinds with equal strengths, our observation again indicates, that the trigger pions originate from scattered quarks.

Finally, the average charge of the jet leader in the away side jet equals the average charge of the valence quarks in the proton and is found to be independent of the trigger charge. This is the case in an event configuration where scattering of valence quarks is expected to dominate the large p_T process.

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