HIGH p_T HADRONS AS LEADING PARTICLES IN JETS PRODUCED AT THE ISR

1. Momentum distribution of secondaries in the trigger jet

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ABSTRACT

The density of charged particles near a single high p_T trigger particle in proton-proton collisions has been studied with the SFM detector at the CERN-ISR. It is shown that:

- the secondaries cluster in a jet-like manner about the trigger particle
- the momentum distributions in this trigger jet can be unambiguously separated from the spectator background distributions
- the momentum component transverse to the jet direction is exponentially damped
- the width of the transverse distributions increases with the momentum component along the jet
- the fractional longitudinal momentum density depends strongly on the trigger transverse momentum and scales with $x_T = 2p_T/\sqrt{s}$.

All these findings support the hard constituent scattering origin of high p_T hadrons.

1. INTRODUCTION

The relatively abundant production of particles with large transverse momentum in hadronic interactions is a consequence of the hard scattering of hadron constituents. This has been pointed out a decade ago [1] and has been verified in a long series of experiments [2]. In particular, the detailed investigation of the phase space distribution of secondaries [3] revealed the dominance of four-jet events. These can be interpreted as resulting from the fragmentation of two hard-scattered constituents and of the non-interacting partons ("spectators") in the incident hadrons.

The present paper is the first in a series of publications that aim at a more quantitative study of the trigger jet in hadronic high p_T production. If the trigger particle does indeed originate from jet fragmentation, it must be a leading fragment which takes a major fraction of the jet energy. Its direction, energy and flavour will all be strongly correlated to those of the parent parton. The study of jets with leading particles can therefore reveal details of jet fragmentation concerning momentum, charge and flavour correlations as well as resonance production which are not easily accessible in other experimental approaches and which present a sensitive test of current ideas on parton fragmentation.

In the following we will study the distribution of charged particles ("secondaries") in the neighbourhood of single high transverse momentum trigger hadrons. We will present qualitative evidence for a jet-like correlation structure about these trigger particles. We will show that this jet structure can be unambiguously separated from the background which is due to the fragmentation of the constituents which do not participate in the hard collision. Longitudinal and transverse momentum distributions in the trigger jet will be discussed. We will show that the transverse component is exponentially damped. The fractional longitudinal momentum distribution depends strongly on the trigger transverse momentum (p_T^{TR}) and scales with $x_T = 2p_T^{TR}/\sqrt{s}$. All these results support the hard scattering of constituents as the source of high p_T hadron production.

2. EXPERIMENT

The experiment was performed at the CERN Intersecting Storage Rings (ISR) with the upgraded SFM detector [4]. Data were collected in pp collisions at centre-of-mass energies of $\sqrt{s} = 44$ GeV and 62 GeV. Hard scattering events were selected by triggering on particles with large transverse momentum (p_T^{TR}) in the range between 2 and 10 GeV/c. The rapidity of the trigger was $\langle y_{TR} \rangle \approx 0.7$, corresponding to a cms polar angle of about 50 degrees. In addition to the trigger particle, charged secondaries were recorded over 4π steradians and their charge and momenta were measured. The momentum resolution for the trigger particle was $\Delta p/p = 0.004 \cdot p$ (p expressed in GeV/c), while the uncertainty on the momenta of secondaries in the azimuthal angular region of the trigger was $\Delta p/p < 0.02 \cdot p$. The kinematical variables are defined in the proton-proton centre-of-mass system. Further details of the experimental set up and the analysis procedure are given in ref. [5].

Events were reconstructed with a standard chain of programs and corrected for geometrical acceptance and for track losses in the neighbourhood of the trigger track.

Detailed information about the different event samples used in our analysis is given in Table 1. The total number of events is close to $2.5 \cdot 10^5$.

Trigger particles have been identified by gas Cherenkov counters. However, since the flavour-dependences of the more general event features studied in this paper are small, we will use unseparated-particle data samples.

3. QUALITATIVE FEATURES OF THE DATA

Our analysis starts from the observation that the trigger particle is accompanied by a jet of particles ("secondaries") which peaks at the azimuthal angle and rapidity of the trigger. This is shown in fig. 1, where the particle density

$$n = \frac{1}{N_{ev}} \frac{\Delta^2 N}{\Delta\phi\Delta Y}$$

is presented as a function of the rapidity and the azimuthal angle difference between secondaries and trigger particle.

Here, N_{ev} = number of events,

$$Y = y - y^{TR},$$

$$\phi = \varphi - \varphi^{TR}, \text{ and}$$

$\frac{\Delta^2 N}{\Delta\phi\Delta Y}$ is the number of charged secondaries in a given interval of transverse momentum, $\Delta\phi$ and ΔY .

A sharp correlation structure emerges which has the characteristic width in ϕ and Y of hadronic jet fragmentation [6]. At sufficiently high transverse momentum of secondaries (p_T^{sec}), this jet structure appears almost background-free (fig. 1(a)), whereas at lower p_T^{sec} (fig. 1(b)) it is superimposed on an important, relatively uniform background contribution. This background originates from the fragmentation of the non-participating constituents (spectators). Its height and shape are compatible with the particle density observed in unselected proton-proton interactions ("minimum bias" events).

Fig. 2 shows the rapidity projection of secondary particle density for different intervals of trigger transverse momentum. For secondaries with p_T^{sec} above 1 GeV/c (fig. 2(a)), the particle density increases with p_T^{TR} in the correlation peak, whereas the smooth spectator background remains almost constant.

This observation is in agreement with expectations from jet fragmentation, since the trigger jet energy is supposed to increase with p_T^{TR} and hence Σp_T^{sec} should increase as well. A quantitative study of the momentum flow into secondary particles should therefore allow the determination of jet energy as function of p_T^{TR} , or alternatively of the fraction of jet energy taken by the trigger particle, $z^{TR} = p^{TR}/p^{jet}$ $\sim p_T^{TR}/p_T^{jet}$. An interesting qualitative observation on this variable can already be made by presenting the particle density at fixed fractional transverse momentum, $x_E = p_T^{sec}/p_T^{TR}$ rather than at fixed p_T^{sec} . If we tentatively assume z^{TR} to be constant with p_T^{TR} , then the fractional energy into secondary particles $(p^{jet} - p^{TR})/p^{jet} = 1 - z^{TR}$ is constant as well. Cascade fragmentation models will therefore predict scaling of particle density in the variable $p_T^{sec}/(p_T^{jet} - p_T^{TR}) = [z^{TR}/(1 - z^{TR})] \cdot p_T^{sec}/p_T^{TR}$, which is

proportional to x_E if $z^{TR} = \text{const.}$ Rapidity distributions at fixed x_E are shown in fig. 2b for different p_T^{TR} intervals. It can be seen that the density of secondary particles decreases strongly with increasing p_T^{TR} . Evidently, z^{TR} is not constant but increases with trigger transverse momentum. Hence, although the jet energy itself is increasing, less energy is available for secondary particle production at any fixed x_E . We will explore this behaviour in more detail in the following sections.

4. MOMENTUM DISTRIBUTIONS OF SECONDARIES IN THE TRIGGER JET

For a quantitative discussion of the jet properties it is useful to present the data in the coordinate system of the trigger jet (see fig. 3 for the relevant geometrical configuration). Since we will show that the trigger direction itself is a good approximation to the jet axis, we refer the secondary particles to the trigger direction and to the event plane which is formed by the trigger particle and the incoming beam direction. Each particle is then characterized by three momentum components:

- (a) $p_{//}^{\text{sec}}$, the momentum parallel to the trigger direction;
- (b) u , the momentum component in the event plane and orthogonal to the trigger direction;
- (c) v , the momentum component orthogonal to the event plane.

We also define the dimensionless variable

$$z_f = p_{//}^{\text{sec}} / p^{TR}$$

as the fractional momentum of the secondaries along the jet axis.

If we now plot the secondary particle density

$$n = \frac{1}{N_{ev}} \frac{d^2 N}{du dv}$$

for a fixed interval of z_f (fig. 4) we see again a well defined jet structure about the trigger particle. The spectator background however is now visible as a clearly separated, second jet structure about the outgoing beam particle (see fig. 3).

The two groups of particles are merged together at low z_f and separate more and more with increasing z_f . This is demonstrated in fig. 5(a), where the particle density in the u coordinate is shown for different z_f intervals, for p_T^{TR} between 4 and 6 GeV/c and at $\sqrt{s} = 62$ GeV.

Although the spectator background can be well estimated and subtracted at large z_f values, it is interesting to increase the useful range of z_f by a more direct and independent background determination. This is possible since the spectator jets are expected to show a rather close resemblance to normal inelastic pp collisions. This should also be true quantitatively if the corresponding cms energy is reduced to take into account the energy transferred to the two high p_T jets. Parton model calculations [7] predict a spectator energy of about 42 GeV for $\langle p_T^{TR} \rangle = 4.6$ GeV/c and $\sqrt{s} = 62$ GeV. We have therefore used "minimum bias" events, i.e. inelastic interactions observed without specific trigger conditions in the SFM detector at $\sqrt{s} = 44$ GeV, to perform this background estimation. Trigger particles with a phase space distribution as observed in our high p_T experiment were superimposed on minimum bias events in order to obtain projected particle density distributions as shown in fig. 5(b). These distributions describe the spectator background rather well both in shape and in absolute normalisation, which becomes more evident if we subtract them from the high p_T event densities as shown in fig. 5(c).

We thus obtain cleanly separated towards-jet momentum distributions even at low values of fractional momentum, z_f .

The separation at fixed z_f is even better at larger p_T^{TR} , as is shown in fig. 6 for p_T^{TR} above 6 GeV/c.

We wish to stress however that independent of the method of background subtraction, two features are clearly visible in the towards-jet momentum distributions: The distributions are asymmetrical with respect to the trigger direction and their width increases with z_f . In the next section we discuss these features more quantitatively.

4.1 Asymmetry of secondaries with respect to the trigger direction

Although the particle density is peaked close to the trigger direction, its distribution develops a distinct asymmetry in u , the momentum component in the trigger plane (figs 5 and 6). This asymmetry increases with $p_{//}^{\text{sec}}$ (or z_f). It can be computed as the mean of the u distribution directly at large z_f values, where the background contributions are small. At lower z_f we have used the background subtraction described above to obtain quantitative results.

The asymmetry $\langle u \rangle$ is shown in fig. 7 for different intervals of p_T^{TR} and for two cms energies.

The almost linear dependence of $\langle u \rangle$ on z_f and the substantial values of up to 500 MeV/c reached at large z_f carry interesting consequences in terms of parton model interpretation.

Firstly, one has to check to which extent the observed asymmetry can be a consequence of Lorentz transformations between the rest frame of the fragmenting parton and the proton-proton rest frame in which the analysis is performed. This question is particularly relevant in the case of colour-string fragmentation schemes, where certain string configurations involve extreme Lorentz factors up to $\beta = 0.9$ and above. We will study this point in a subsequent publication.

A second consequence concerns the transverse degree of freedom of the trigger particle with respect to its parent parton direction. Since in hard scattering processes the resulting jet-axis distribution is a steeply falling function of polar angle (i.e. momentum transfer), the trigger particles at a given forward trigger angle tend to come from parent jets produced at slightly smaller angle; the polar angle difference being made up by the transverse momentum in the fragmentation process. This results in an alignment of the trigger particle with the event plane and a corresponding recoil of the secondaries in the trigger jet to smaller angles (negative u) as seen in the data. Invoking local transverse momentum balance as expected in cascade fragmentation models, this would yield the observed dependence of $\langle u \rangle$ on z_f .

We may in fact use the asymmetries shown in fig. 7 to estimate the average polar angle difference between trigger and jet axis.

If we consider the case (see fig. 8) that the transverse momentum of the trigger particle at its mean fractional momentum $\langle z^{TR} \rangle$, is balanced by one secondary particle at the maximum available momentum $z_f^{max} = (1 - \langle z^{TR} \rangle) / \langle z^{TR} \rangle$, we can write

$$\Delta\theta \sim \frac{\langle z^{TR} \rangle}{p^{TR}} \cdot \langle u \rangle_{z_f^{max}}.$$

Inserting known $\langle z^{TR} \rangle$ values (see e.g. ref. [8] and also a forthcoming publication for a more detailed study of z^{TR}), we obtain the angle difference presented in fig. 8 as a function of p_T^{TR} . It is in good agreement with parton model predictions [7] and shows that the trigger direction is still a good approximation (within a few degrees) of the jet direction.

It is interesting to note that this result disagrees with the simple dimensional counting arguments used to predict the scaling behaviour of high p_T inclusive cross sections. These arguments neglect the transverse momentum both of the incoming partons ("intrinsic k_T " within the beam protons) and of the trigger jet fragmentation in order to derive a p_T^{-4} behaviour of the inclusive cross section from parton-parton scattering. Our data show that transverse momentum effects in the trigger jet are indeed important and observable over the p_T^{TR} range of our experiment.

4.2 Transverse momentum distributions in the trigger jet

Due to the fact that we are dealing with a "biased" jet, i.e. a jet that has already produced a leading trigger particle, the behaviour of the secondary particle density perpendicular to the trigger direction may be rather intricate; e.g. effects like angular asymmetries of the trigger (as shown above) and local transverse momentum conservation may play a rôle. Nevertheless we expect at least a strong bound on the transverse dimension of the trigger jet as in all hadronic fragmentation processes.

This bound is indeed visible already in the projected density distributions of figs 5 and 6. If we plot the variance of the density distributions in the u and v coordinates, fig. 9, we observe values typical of jet fragmentation [6], with a marked increase with z_f and somewhat larger values in the event plane (u coordinate) than orthogonal to the plane (v coordinate). The latter effect is expected from momentum conservation, as the trigger particle develops a transverse component in the event plane as discussed above.

In order to inspect the transverse momentum distributions in the trigger jet, we define the variable

$$p_{\text{perp}} = ((u - \langle u \rangle)^2 + v^2)^{1/2}.$$

In view of the spectator background (figs 5 and 6) which tends to contribute at large p_{perp} and negative values of u , we plot in fig. 10 particle density against p_{perp} only for particles with $(u - \langle u \rangle) > 0$, i.e. for the "half jet" pointing away from the spectator background. The resulting distributions have less than 10% background contributions and show exponential damping of particle density with transverse momentum as expected from jet fragmentation. The average p_{perp} increases however clearly with fractional longitudinal momentum, as shown in fig. 11. This has been observed earlier in the study of high p_T jets [9]. Measurements from e^+e^- annihilation [10] for biased jets (one charged particle with more than half the beam energy) are also plotted in fig. 11. They show a very similar behaviour over the limited z_f range available.

Given the systematic transverse deviation of the trigger particle from the jet direction and the fact that the fraction of jet energy z^{TR} taken by the trigger particle changes with p_T^{TR} , it is not a priori evident that the average transverse momentum $\langle p_{\text{perp}} \rangle$ should scale with z_f . Indeed some increase of $\langle p_{\text{perp}} \rangle$ with p_T^{TR} (at fixed z_f) is visible in fig. 11. This indicates that the same (limited) transverse momentum given to the trigger particle is balanced by secondaries at different fractional momentum z_f for different p_T^{TR} values. In fact it turns out that plotting $\langle p_{\text{perp}} \rangle$ against the secondary momentum parallel to the trigger direction, $p_{\text{sec}}^{\text{perp}}$, we obtain a universal curve for the complete range of p_T^{TR} and $\sqrt{s}$ covered by our experiment, which is shown in fig. 12.

4.3 Longitudinal momentum distributions

We have seen that the production of the trigger particle influences the trigger jet only slightly in the transverse dimension, namely by an asymmetry of secondaries and eventually by an increased transverse momentum spread in the event plane at large z_f .

In contrast, the longitudinal momentum distributions are expected to display a strong correlation with the trigger particle if the trigger results from the fragmentation of a parton in an incident hadron. Since the trigger takes a fraction $z^{TR} = p^{trig}/p^{jet}$ of the parton energy, secondaries should be constrained by energy-momentum conservation to momentum fractions $z = p^{sec}/p^{jet}$ smaller than the limit $z^{lim} = 1 - z^{TR}$. A schematic representation of the kinematics is shown in fig. 13.

As the value of p^{jet} is not readily accessible in our experiment, we can re-express the momentum limit by the experimental quantity $z_f = p^{sec}/p^{TR}$ by the relation $z_f^{lim} = 1/z^{TR} - 1$.

In reality z^{TR} is not sharply defined but has a distribution around an average $\langle z^{TR} \rangle$. This will somewhat smear out the kinematical limit z_f^{lim} . Nevertheless the secondary particle distribution in z_f remains a well-defined measure of the value of $\langle z^{TR} \rangle$.

Experimental longitudinal momentum distributions are shown in fig. 14(a) as functions of z_f for different intervals of p_T^{TR} . Contributions from spectator fragmentation have been subtracted using the background estimation from "minimum bias" events as outlined above. In order to check our sensitivity to this background evaluation, density distributions in the "half-jet" defined by the condition $(u - \langle u \rangle) > 0$ are displayed in fig. 14(b). This selection limits the secondaries to the jet component pointing away from the spectator limits and thereby eliminates most of the background (see also figs 5 and 6).

Comparison of figs 14(a) and (b) shows that the corresponding z_f distributions are equal within errors, with the exception of the lowest p_T^{TR} bin which is most affected by spectator background.

A first qualitative conclusion to be drawn from the data is based on the fact that secondaries in the trigger jet occasionally reach values of z_f near 1, i.e. the momentum of the secondaries is comparable to that of the trigger particle. This means that z^{TR} must sometimes be appreciably smaller than unity to allow for these high-momentum secondaries in the jet.

A second observation concerns the marked decrease of particle density with increasing trigger transverse momentum apparent in fig. 14. This fact can be interpreted as a substantial increase with p_T^{TR} of the average fraction of parton energy $\langle z^{TR} \rangle$ taken by the trigger particle.

A third conclusion may be drawn from the z_f distributions at $\sqrt{s} = 44$ GeV shown in fig. 15. We note that the secondary distributions recorded at this energy for $\langle p_T^{TR} \rangle = 3.2$ GeV/c coincide with those at $\sqrt{s} = 62$ GeV and $\langle p_T^{TR} \rangle = 4.6$ GeV/c. This implies that the measured z_f distributions do not separately depend on the cms energy and the trigger transverse momentum, but rather on their ratio $x_T^{TR} = 2 p_T^{TR} / \sqrt{s}$. This scaling behaviour is displayed in more detail in fig. 16, where the particle density for several z_f bins is plotted against x_T^{TR} .

All three qualitative results follow in a natural way if the high p_T trigger particle stems from a fragmenting constituent. This is in agreement with parton model calculations [1], especially with the work of Alonso et al. on the trigger jet [11]. Simple CIM models [12] where the trigger particle is produced directly in the hard scattering process, are not compatible with the observed fragmentation behaviour, although we cannot exclude a small contribution from such mechanisms at this stage.

5. CONCLUSIONS

We have investigated the distribution of charged particles in the vicinity of single high transverse momentum hadrons, with a high statistics data sample of $2.5 \cdot 10^5$ events obtained at the CERN-ISR. Since the polar angle of the triggering hadrons is away from 90° , the soft hadronic background can be subtracted and we obtain a correlation structure which is in general agreement with expectations from parton fragmentation. The

high transverse momentum hadron is a leading fragment in this fragmentation process. The transverse momentum of the secondary particles with respect to the trigger direction is sharply limited. Its mean value is increasing with the longitudinal momentum along the jet direction.

The fractional longitudinal momentum density decreases strongly with increasing trigger momentum. It scales in the variable $x_T^{TR} = 2p_T^{TR}/\sqrt{s}$ as expected in constituent scattering models.

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TABLE 1

Summary of kinematical intervals and event numbers for the different samples of high p_T events used in the present analysis

$\sqrt{s}$		44.5		62.2			GeV
p_T^{TR}	range average	(2.8,4) 3.2	(4,6) 4.5	(2,3) 2.4	(4,6) 4.6	(6,10) 6.7	GeV/c GeV/c
x_T^{TR}	average	0.144	0.202	0.077	0.148	0.215	$x_T^{TR} = \frac{2p_T^{TR}}{\sqrt{s}}$
no of events		105 K	19 K	24 K	92 K	5.2 K	
θ^{TR}	range average	negative charge (45.9, 61.2) 52.9			positive charge (41.4, 57.6) 49.0		degrees
y^{TR}	range average	(0.52, 0.88) 0.71			(0.60, 1.00) 0.80		
ϕ^{TR}	range	(-10.5, +10.5)					degrees

FIGURE CAPTIONS

Fig. 1 Particle density as function of $Y = y - y^{TR}$ and $\phi = \varphi - \varphi^{TR}$ for $\langle p_T^{TR} \rangle = 4.6$ GeV/c and two intervals of secondary particle transverse momentum,

(a) $p_T^{sec} \in (1.6-2.0)$ GeV/c

(b) $p_T^{sec} \in (0.4-0.8)$ GeV/c.

The trigger particle itself is not plotted.

Fig. 2 Rapidity projection of secondary particle density for different intervals of p_T^{TR} ,

(a) at fixed p_T^{sec}

(b) at fixed fractional transverse momentum $x_E = p_T^{sec}/p_T^{TR}$.

Fig. 3 Definition of momentum components relative to the trigger direction and event plane.

Fig. 4 Secondary particle distribution in the variables u and v relative to the trigger direction, for $z_f > 0.5$ and $\langle p_T^{TR} \rangle = 4.6$ GeV/c. The trigger particle itself is not plotted.

Fig. 5 Secondary particle density as a function of u , the momentum component in the event plane and orthogonal to the trigger direction, for different z_f intervals:

(a) for high p_T events with $\langle p_T^{TR} \rangle = 4.6$ GeV/c and $\sqrt{s} = 62$ GeV;

(b) for minimum bias events (background);

(c) background subtracted.

Fig. 6 Same as fig. 5 but $\langle p_T^{TR} \rangle = 6.7$ GeV/c.

FIGURE CAPTIONS (Cont'd)

- Fig. 7 Mean value $\langle u \rangle$ as function of z_f for different intervals of p_T^{TR} and two values of $\sqrt{s}$.
- fig. 8 Angle difference between trigger direction and jet axis as extracted from u-asymmetry and compared to model calculation [7].
- Fig. 9 Variance of transverse momentum components in the event plane (u) and vertical to the event plane (v) as function of z_f , for various $\langle p_T^{TR} \rangle$.
- Fig. 10 Transverse momentum distributions of secondaries in the trigger jet for different z_f intervals.
- Fig. 11 Average transverse momentum $\langle p_{perp} \rangle$ as function of z_f for different values of $\langle p_T^{TR} \rangle$ and $\sqrt{s}$.
- Fig. 12 Average transverse momentum $\langle p_{perp} \rangle$ as function of $p_{//}^{sec}$, the parallel momentum of secondaries with respect to the trigger particle.
- Fig. 13 Schematic representation of kinematical limits for secondary particle momenta at given z_f^{TR} .
- Fig. 14 z_f distributions, after background subtraction, for different $\langle p_T^{TR} \rangle$ values at $\sqrt{s} = 62$ GeV,
 (a) including the full u-range
 (b) for the "half cylinder" $u > \langle u \rangle$
- Fig. 15 z_f distributions at $\sqrt{s} = 44$ GeV.
- Fig. 16 Dependence of particle density on $x_T^{TR} = 2p_T^{TR}/\sqrt{s}$, for different z_f intervals.

fig. 1a

fig. 1b

fig. 2

fig. 3

fig. 4

fig. 5

fig. 6

fig. 7

fig. 8

fig. 9

fig.10

fig. 11

fig. 12

fig. 13

fig.14a

fig.14b

fig. 15

fig.16