THE FOUR-JET STRUCTURE OF LARGE TRANSVERSE MOMENTUM EVENTS
IN pp INTERACTIONS AT THE ISR

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ABSTRACT

Deep inelastic proton-proton collisions have been recorded with the Split-Field-Magnet Detector (SFM) at the CERN Intersecting Storage Rings (ISR) by triggering on a single particle at high transverse momentum. Full reconstruction of the charged particles in these collisions was performed. In this paper we demonstrate the existence of a structure comprised of four jet-like clusters, two longitudinal and two transverse with respect to the beam, as would be expected from hard scattering of proton constituents.

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1. INTRODUCTION

Proton-proton interactions at high centre-of-mass energy and high momentum transfer are potentially a very rich field for the study of phenomena such as hard scattering of hadron constituents (partons). Thus information on the properties of partons, as they exist within the proton and fragment into observed hadrons after scattering, can be obtained [1]. These observations can be compared with a fundamental theory such as QCD.

In particular, within the parton model, the hard (i.e. large angle) scattering of constituents from the two protons is expected to produce a four-jet structure as the characteristic topology of the emerging hadrons. Two-jets in a transverse direction (with respect to the beam) result from the fragmentation of the partons involved in the hard scattering process. The other two jets, approximately in the beam directions, originate from the fragmentation of the proton remnants (spectator jets). Fig. 1 indicates the typical topology expected for such events.

Since the discovery of large transverse momenta processes in hadronic interactions [2], the subsequent experiments [3] have been interpreted in terms of hard scattering of hadron constituents and of their fragmentation into jets [4], as originally suggested [1]. Recently, more direct evidence for the presence of two transverse jets was obtained both at the CERN ISR [5] and the $\bar{p}p$ Collider [6] by selecting events with large transverse energy.

In contrast to these experiments, where one triggers on large transverse energy, we select events with a single charged particle of large transverse momentum. The detection and measurement of the accompanying charged particles in each large p_T event allows us to establish in addition to the two-jet structure in transverse direction the full four-jet structure expected.

These four-jet events are difficult to extract from the bulk of normal inelastic events. First, they constitute rare events since they result from hard parton scatterings. Second, the motion of the partons inside the nucleons causes the parton-parton rest frame to be different

from the overall proton-proton c.m. system. Thus, the observed jets will, in general, have undergone a Lorentz boost, and the jets originating from the two scattered partons will usually not be collinear.

In order to identify events of this type and provide a maximum of useful information, the following features have been incorporated into the configuration of the SFM Detector for this program at the ISR:

- (a) Events are selected in which one of the transverse jets goes into a limited angular region and, more important, fragments in such a way that a large fraction of its original momentum is taken up by one stable particle (π, K, p). Technically this is done by triggering on events with a charged particle of large transverse momentum within a limited angular range.
- (b) The trigger particle is required to be at a scattering angle θ away from 90° in order to provide a sense of forward and backward scattering.
- (c) Identification of trigger particles (separation of kaons and protons from pions) is provided. The combination of these features (high- p_T flavour-analyzed trigger with θ away from 90°) means that in a hard scattering event, the observed trigger hadron typically provides information on the scattered parton's flavour and its original incident direction.
- (d) The rest of the charged particles in the event are also momentum-analyzed with good efficiency and recorded over close to 4π steradians angular range.

This configuration provides the possibility to study many types of detailed phenomenological features relevant to parton-parton hard scattering processes: inclusive pion, kaon and proton differential cross sections; topological studies of jet-like structure; correlations between the quantum numbers and the momentum vector of the trigger particle with those of other particles in the same or different jets (fig. 1).

The phenomenological results in turn provide information on such fundamental physics questions as four-jet final states, hard quark

scattering, evidence for neutral gluon-like partons, gluon-gluon scattering and the triple gluon vertex, and the spin of the exchanged object [8] (which probes the non-Abelian nature of QCD).

In this introductory publication we present evidence for the four-cluster jet-like structure of events triggered on large transverse momentum charged particles. Whereas we restrict ourselves to present here a purely topological analysis, we shall in forthcoming publications deal with a more detailed analysis of quantum number correlations amongst the various particles and the information which this program provides in answer to physics questions such as those listed above.

2. APPARATUS AND EXPERIMENT

The experiment was performed at the CERN Intersecting Storage Ring (ISR) with the upgraded SFM Detector [7]. Data were collected at a centre-of-mass energy of $\sqrt{s} = 62$ GeV. Hard scattering events were selected by triggering on particles with high transverse momentum [8]. Samples of data were obtained with transverse momenta p_T^{tr} of the triggering particle above 2 GeV/c, 4 GeV/c and 6 GeV/c. The rapidity of the trigger was $\langle y_{tr} \rangle \approx 0.7$ corresponding to a c.m.s. polar angle of $\approx 50^\circ$. Cherenkov counters provided separation of pions from kaons and protons. In addition to the trigger particle, charged particles were recorded in 4π steradians and their momenta were measured. The momentum resolution for the trigger particles was $\Delta p/p = 0.004 p$ (p in units of GeV/c). The kinematical variables are defined in the proton-proton c.m.s. Further details of the experimental set-up and the analysis procedure are given in ref. [9].

The data sample contains 10^5 events with trigger transverse momentum between 4 and 6 GeV/c, 6000 events above 6 GeV/c, and a comparison sample of 20 000 events with p_T between 2 and 3 GeV/c.

3. RESULTS

In order to demonstrate that a pronounced jet structure does occur in events with a large transverse momentum particle, we present in fig. 2 (in a polar diagram) the normalized momentum F flow per event projected onto

the scattering plane as a function of the polar angle averaged over many events. The scattering plane is defined by the momentum of the incoming protons and the trigger particle. The normalization was done by scaling the projected momenta Q in each angular bin $\Delta\theta$ by the corresponding average projected momentum per particle $\langle q \rangle$ observed in normal inelastic events in the same bin

$$F(\theta) = 1/\langle q \rangle \frac{1}{N} \sum_{i=1}^N \sum_{j=1}^{n_i} Q_j ,$$

where N is the total number of events and n_i the number of tracks in event i which points at the angle θ within $\Delta\theta$. No acceptance correction was used for this plot, so the scale was left arbitrary (in particular $\Delta\theta$ is not mentioned in the formula defining $F(\theta)$). The distribution for normal inelastic events is displayed in fig 2(a): it represents, up to a constant factor, the inclusive angular distribution.

In fig. 2(b), a sample of events with a particle of large transverse momentum $p_T > 6$ GeV/c at $\theta = 50^\circ$ has been used. The plot exhibits the following features: although the triggering large p_T particle has not been included in the diagram, one observes a pronounced increase of the momentum flow in the angular region of the trigger due to clustering of secondary particles in this region.

The spectator jets are shown by large the excess in normalized momentum flow at $\theta = 0^\circ$ and at $\theta = 180^\circ$. Note however, that fig. 2(b) exhibits no jet-like behaviour on the side opposite to the trigger, although a general increase of momentum flow per event can be recognized extending over a wide range of polar angle. This is exactly what is expected, since the structure function of the protons will cause the polar angle of the fourth jet to vary widely from event to event (the small value of $F(\theta)$ at $\sim 270^\circ$ reflects incomplete cancellation of acceptance effects along the quadrupole axis of the SFM magnetic field).

In order to reveal the presence of this fourth jet, we impose via software a condition on the "away" side similar to that on the trigger side; i.e., we select only events with a particle of large transverse momentum in a limited polar angle region on the "away" side. In particular, in fig. 2(c) we have demanded such a "pseudo-trigger" of

$p_T > 2$ GeV/c in the "back-to-back" configuration with $\theta \approx 230^\circ$ - 260° (indicated by the arrow). As in the case of the trigger particle, this "pseudo trigger" particle is excluded when the momentum flow is calculated. The structure of four jet-like clusters is clearly evident in fig. 2(c).

Similary, in fig. 2(d) we show the normalized energy flow for events with a "pseudo trigger" on the away side in the "back-to-antiback" configuration with $\theta \approx 280^\circ$ - 310° . Even in this extreme case, the away-side secondaries cluster about the pseudo-trigger, rather than populating the kinematically favored back-to-back region.

Note that events shown in figs 2(c) and 2(d) may have significantly different origins: whereas the distribution of fig. 2(c) results from the scattering of partons of approximately equal fractional parton momentum x , in fig. 2(d) the scattered partons involved must have different values of reduced longitudinal momentum x , such that the Lorentz boost causes both jets to be in the same polar hemisphere. In QCD models, where gluons have "softer" structure functions than valence quarks, fig. 2(c) would tend to contain events predominatly from quark-quark scattering, whereas fig. 2(d) would tend to be populated predominantly by quark-gluon scattering events. Such correlations will be explored in fourthcoming publications.

The distributions of secondary particles with $p_T > 1.0$ GeV/c as a function of rapidity for events with trigger transverse momentum $p_T^{tr} > 4$ GeV/c and two different away-side pseudo-trigger requirements also shown in fig. 3(a-c). The secondaries are restricted to wedges in azimuthal angle of $\phi = 0^\circ \pm 25^\circ$ for "towards" and $\phi = 180^\circ \pm 25^\circ$ for "away" side particles. Note that trigger and pseudo-trigger particles have not been included in the distributions. Fig. 3(b) shows all events (with no pseudo-trigger requirement). Fig. 3(a) requires a pseudo-trigger, with $y = -.8$ to $-.4$ and $x_E = p_T^{pseudo-tr}/p_T^{tr} > 0.3$. Similarly, fig. 3(c) requires a pseudo-trigger of $y = +.4$ to $+.8$. Again we see that the transverse secondaries follow the triggers and pseudo-triggers. The widths in rapidity of these clusters are $\Delta y \approx 1.0$, the scale expected from quark fragmentation at the observed jet momenta [4].

Thus far, we have shown evidence for jet-like structure in large p_T events by analyzing the particle density as a function of polar angle

(or y) projected onto the scattering plane. In order to demonstrate the occurrence of particle clustering in the other dimension, the azimuthal angle, we present in figs 4(a)-(c) the density distributions for secondary particles as a function of both rapidity y and azimuthal angle ϕ for events with trigger $p_T > 4$ GeV/c. These distributions were obtained by normalizing the particle density distribution of large p_T events to the density distribution of normal inelastic events. The position of the trigger particle (which is excluded from the graph) is indicated by the arrow which defines $\phi = 0^\circ$; the distribution is folded to include both intervals $\phi = 0^\circ \pm 180^\circ$. The distributions are given for three different intervals of p_T . Whereas at low transverse momenta only a slight deviation from uniformity is observed, the distributions show clear particle clustering and a very strong increase in particle density at $\phi = 0^\circ$ and at $\phi = 180^\circ$ as the transverse momentum increases. Note that the particle ratio is larger than unity, indicated by the dashed line, in the region between the two jets at $\phi \sim 90^\circ$. Although the increased clustering in the $\phi = 180^\circ$ region can have a kinematical component, the clustering at high p_T about the trigger is in a kinematically unfavoured region. Further, the widths of the distributions on the trigger side in both y and ϕ indicate average transverse momenta relative to the trigger of a few hundred MeV, which is the scale expected from quark fragmentation. On the away side, the rapidity distribution is broad, as the particles come from jets originating at various polar angle directions. The away side ϕ distribution is somewhat broader than the trigger side distribution, which is compatible with quark fragmentation smeared by intrinsic transverse momentum of the incident partons before scattering.

We next attempt to answer the often asked question: how much of a role does simple momentum conservation play in creating the jet structures seen in high p_T hadron-hadron scattering? Evidently, the transverse momentum of the triggering high p_T particle must be balanced by that of the other particles, but this could be done in many different ways.

It is rather involved to disentangle the global constraint of four-momentum conservation from any additional multiparticle correlations, so that a definite disproof of a "simple" explanation is outside the scope of this paper. We rather restrict ourselves to a straightforward check.

Specifically, we study an azimuthal distribution which is sensitive to the question, and compare it with the predictions of a "minimal model". An observed disagreement would show that a minimal model embedding little more than four-momentum conservation and the additional correlations introduced by longitudinal phase space is inadequate to explain the data.

Our model (see Appendix), which conserves four-momentum, is tailored to reproduce the experimental single particle distributions in high p_T events. This is taken as a minimal requirement for a plausible model. From events generated according to this model, we can compare distributions to those of the real data. We first considered the azimuthal distribution about the beam direction. However, in order to remove the strong asymmetry in angle due to the recoil against the trigger particle, we transform to the rest frame of all outgoing particles excluding the trigger itself. We do not observe neutral particles, however this Lorentz transformation is uniquely determined by the beam momenta and the trigger momentum. We take as the axis of the transformed azimuthal distribution the difference of the beams' three-momenta in this Lorentz frame.

The distribution of secondaries in ϕ' , the azimuthal angle in the new system, is shown in fig. 5 for all p_T and for $p_T > 1$ GeV/c, restricted to the region $|y| < 1$. The trigger particle, excluded from the distribution, defines $\phi' = 0^\circ$. The results of the model are shown by two curves: one of them is normalized to the integrated distribution, the other to $dn/d\phi'$ at $\phi' = \pi/2$. The data show a clear peak at $\phi' = 0^\circ$ which corresponds to the trigger jet, essentially on the trigger side ($y > 0$), with some leakage in the opposite hemisphere ($y < 0$). The away jet is clearly seen at $\phi' = \pi$. The model curves show an enhancement around $\phi' = \pi$ (but none at $\phi' = 0$), a remnant of the p_T balance which has not been completely removed by the change of reference frame. However, such an enhancement is clearly far from reproducing the strong effect seen in the data and we therefore conclude that the trigger and away side jets cannot be explained from such a single kinematical model.

In fig. 6 we present another topological observation suggestive of the presence of different parton-parton subprocesses in large p_T events. We show the rapidity distribution of secondary particles with $p_T > 1$ GeV/c in an azimuthal region $\Delta\phi = \pm 30^\circ$ around the triggering large

transverse momentum particle, "towards side", plotted upwards and of particles at $\Delta\phi = 180^\circ \pm 40^\circ$, "away side", plotted downwards in the figure. Moreover, these distributions are given for three different intervals of trigger momentum, as indicated. We observe that the average direction of the away particles shifts from a symmetric configuration to a collinear configuration, "back-to-back", in polar angle as the trigger momentum increases. Again, although momentum conservation could shift particles in this direction, this shift can also occur as a consequence of the change of relative importance of possible parton subprocesses: whereas at moderate trigger momenta the away side particles would be predominantly gluon fragments, the relative contribution from quark-quark scattering would increase with trigger momentum. This would also shift the observed away-side particles toward negative rapidity as the p_T of the trigger increases.

4. CONCLUSIONS

The events obtained in this experiment by triggering on a charged particle of large transverse momentum exhibit a topological structure very much like the four-jet structure expected from hard parton-parton scattering in which there would be two longitudinal jets from the proton remnants and two transverse jets from the fragmentation of the scattered partons. Specifically, we find that:

- (i) The data contain two jet-like clusters along the beam direction from the remnants of the incident protons.
- (ii) There are secondary particles clustered around the trigger particle. Their distributions in y (or θ) and ϕ relative to the trigger resemble those of parton fragmentation.
- (iii) The particle density as a function of y (or θ) shows a broad enhancement for secondaries on the away side compatible with jets recoiling at varying polar angle due to different "balances" in the incident partons' momenta. The width of the enhancement in ϕ resembles quark fragmentation expectations. Moreover, the distribution of particles in ϕ is not compatible with a longitudinal phase space model.

- (iv) When a "pseudo-trigger" (an additional particle of large p_T and in a limited region of y or θ) is demanded on the away side, then the away-side particles cluster in y or θ about the pseudo-trigger, again with distributions similar to those of quark fragmentation. This holds for pseudo-triggers selected both in the back-to-back and back-to-antiback configuration.

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APPENDIX

We intended for this study to construct a model with minimal dynamical correlations, adjusted to reproduce the global features of single particle distributions as we observe them in high p_T events.

We have chosen a model of the "independent emission" class in which the matrix element is the product of factors, each of which depends on only one single particle four-momentum p (apart from the overall $P = (\sqrt{s}, 0, 0, 0)$ in the c.m.s.). The formula used for the n -particle differential cross section (expressed in c.m.s. variables $E, p_T, p_\perp$) is

$$d\sigma_n = k_n E_1 E_2 \prod_{i=1}^n [f(p_T^2) \frac{dp_{\perp i} dp_{Ti}^2}{E_i}] \delta^4(p - \sum_{i=1}^n p_i)$$

The constants k_n were adjusted to reproduce the experimental charged multiplicity distribution observed in high p_T events. Apart from the two nucleons, we assumed all particles to be pions equally distributed, in the mean, between the three charges (subject to overall charge conservation). We assumed that the modest check under study would not have been fundamentally modified if resonances and strange particles had been introduced.

The function $f(p_T^2)$ was adjusted to reproduce both high p_T and low p_T observations. We found a reasonable agreement with the data when using the formula $f(p_T^2) = (p_T^2 + a)^b$ with $a = 0.25$ and $b = -2.0$.

We took account of leading baryon effects by the introduction of the factor $E_1 E_2$ ($i = 1, 2$ labels of the outgoing nucleons) so we have for each of these particles a factor $f(p_T^2) dp_{\perp} dp_T^2$ which gives rise to a uniform $p_{\perp}$ distribution. By contrast, $f(p_T^2) dy dp_T^2$ implies for the pions a uniform distribution in the rapidity y . These asymptotic expectations are seriously affected by four-momentum conservation.

We have generated a sample of events using the Monte-Carlo technique described in ref. [10]. The charged particle acceptance for the SFM Detector was then used to simulate particle losses from geometric acceptance, hardware recording, and software analysis. The resulting single particle distributions are in agreement with the observations, but correlations with the high p_T trigger particle fail to reproduce the data, as described in the text.

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FIGURE CAPTIONS

Fig. 1 Schematic representation and nomenclature for hard parton-parton collisions.

Fig. 2 Projection into the scattering plane of the normalized momentum flow as a function of the polar angle θ for:

(a) Inclusive angular distribution for normal inelastic events.

(b) Deep inelastic events triggered on a charged particle of $p_T^{tr} > 6$ GeV/c at $\theta \approx 50^\circ$ (trigger momentum flow not included in the figure).

(c) Same as (b) and the additional (pseudo trigger) requirement of a charged particle with $p_T > 2$ GeV/c at $\theta \approx 230^\circ$ - 260° (θ range indicated by the arrow). Momentum of pseudo trigger is not added in. The trigger momentum is $p_T^{tr} > 4$ GeV/c.

(d) Same as (c) with $\theta \approx 280^\circ$ - 310° .

Fig. 3 Particle density as a function of rapidity with the requirement of an additional large p_T particle (T') in the "away" azimuthal area in a rapidity interval of ± 0.4 around the value indicated by the arrow T' . Particles in the azimuthal region near the trigger $\phi = 0^\circ \pm 25^\circ$, "towards", are plotted upwards, those at $180^\circ \pm 25^\circ$, "away", to the trigger downwards. The particles included have $p_T > 1.0$ GeV/c. In the distribution 3(b) no additional particle T' is required.

Fig. 4 Relative increase of particle density with respect to normal inelastic events as a function of rapidity y and azimuth ϕ for different intervals in p_T (trigger particle again not included, $p_T^{tr} > 4$ GeV/c). Dashed line indicates unit ratio.

Fig. 5 Azimuthal angle distribution (excluding the triggering particle) - for different cuts in the transverse momentum p_T and rapidity y . The solid curves are predictions from a LPS model, normalized to the same area as the data and normalized to the data at $\phi = 90^\circ$.

FIGURE CAPTIONS (Cont'd)

Fig. 6 Particle density as a function of rapidity for 3 different trigger momenta $p_T > 2, 4$ and 6 GeV/c. The rapidity of the triggering particle is indicated by the arrow T. Particles in the azimuthal region near the trigger $\phi = 0^\circ \pm 25^\circ$, "towards", are plotted upwards, those at $180^\circ \pm 25^\circ$ to the trigger, "away", downwards. Particles included have transverse momenta > 1 GeV/c.

Fig. 1

Fig. 2

Fig. 2

Fig. 3

Fig. 4

NUMBER OF TRACKS

Fig. 5

Fig. 6