Fermilab Experiment E299.
Submitted to the Proceedings of the XIV International Symposium on Multiparticle Dynamics, Lake Tahoe, June 1983.

FERMILAB-CONF-83-122-E

PLANARITY AND JET-LIKE STRUCTURES IN LOW-P_t HADRON-PROTON INTERACTIONS AT 147 GeV/c

International Hybrid Spectrometer Consortium
Presented by

M. Kalelkar
Rutgers University, New Brunswick, New Jersey 08903

D. Brick, H. Rudnicka, A. M. Shapiro, M. Widgoff, Brown University; R. E. Ansorge, W. W. Neale, D. R. Ward, B. M. Whyman, University of Cambridge; R. A. Burnstein, H. A. Rubin, Illinois Institute of Technology; E. D. Alyea, Jr., Indiana University; L. Bachman, C. Y. Chien, P. Lucas, A. Pevsner, Johns Hopkins University; J. T. Bober, T. A. J. Frank, E. S. Hafen, P. Haridas, D. Huang, R. I. Hulsizer, V. Kistiakowsky, P. Lutz, S. H. Oh, I. A. Pless, T. B. Stoughton, V. Suchorebrow, S. Tether, P. C. Trepagnier, Y. Wu, R. K. Yamamoto, Massachusetts Institute of Technology; F. Grard, J. Hanton, V. Henri, P. Herquet, J. M. Lesceux, P. Pilette, R. Windmolders, Université de l'Etat, Mons; H. deBock, F. Crijns, W. Kittel, W. Metzger, C. Pols, M. Schouten, R. Van de Walle, University of Nijmegen and NIKHEF-H; H. O. Cohn, Oak Ridge National Laboratory; F. Carminati, R. Dolfini, S. Ratti, University of Pavia, Italy; R. DiMarco, P. F. Jacques, M. Kalelkar, R. J. Plano, P. E. Stamer, T. L. Watts, Rutgers University; E. B. Brucker, E. L. Koller, S. Taylor, Stevens Institute of Technology; L. Berny, S. Dado, J. Goldberg, S. Toaff, Technion; G. Alexander, O. Benary, J. Grunhaus, R. Heifetz, A. Levy, Tel-Aviv University; J. E. Brau, W. M. Bugg, G. T. Condo, T. Handler, E. L. Hart, A. H. Rogers, University of Tennessee; Y. Eisenberg, U. Karshon, A. Shapira, Weizmann Institute of Science; T. W. Ludlam, R. Steiner, H. D. Taft, Yale University.

ABSTRACT

We report on a study of jets in low p_t $\pi^{\pm}p$, $K^{+}p$ and pp collisions at 147 GeV/c. We show that certain categories of events are more planar than predicted by cylindrical phase space, but that 3-jet and 4-jet structures seen in the momentum flows are reasonably reproduced by the phase space Monte Carlo events subjected to the same mathematical handling as the data.

1. Introduction

Jets in multihadron final states have been observed in e^+e^- annihilation, in lepton-proton deep inelastic scattering, and in high p_t hadron-hadron collisions. Recently, low p_t hadron-hadron interactions have been compared[1-5] to these processes. In this paper we analyze data on hadron-proton collisions at 147 GeV/c to search for planar events, and to investigate jet-like structures within the plane. We also compare our results with the predictions of a simple cylindrical phase space model.

The data were obtained from two experiments at Fermilab using the 30-inch hydrogen bubble chamber and hybrid spectrometer. One experiment (E299) used a tagged positive beam at 147 GeV/c, yielding 9013 π^+p, 1164 K^+p and 9510 pp events. The other experiment (E154) yielded 6230 π^-p interactions at 147 GeV/c, for a grand total of 25917 events. For the present analysis the events were required to be well-measured and to have at least 6 charged prongs, reducing the sample to 14893 events. Our study of jets did not disclose any significant differences among the four beams, and so for the rest of this paper we report results from the combined sample of 14893 hadron-proton events at 147 GeV/c.

2. Planarity

To describe the events in momentum space, we use the principal axis reference frame.[5] The thrust axis $\hat{u}_1$ is the direction along which the projected momentum flow is maximized. The major axis $\hat{u}_2$ is perpendicular to $\hat{u}_1$ and is the direction along which the projected momentum flow in the plane perpendicular to $\hat{u}_1$ is maximized. Finally, the minor axis $\hat{u}_3 = \hat{u}_1 \times \hat{u}_2$.

$$T = \frac{\max \Sigma\ |\vec{P}_i \cdot \hat{u}_1|}{\Sigma\ |\vec{P}_i|} \qquad F_{major} = \frac{\max \Sigma\ |\vec{P}_i^t \cdot \hat{u}_2|}{\Sigma\ |\vec{P}_i^t|}$$

In this reference frame the beam direction is given by two Euler angles, as shown in Fig. 1a. Fig. 1b displays the distribution of the cosine of the polar angle θ_B, indicating that the events have the thrust predominantly aligned with the beam direction. To search for planarity, we look for departures from isotropy in the distribution of the azimuthal angle ϕ_B. Fig. 2a is a plot of ϕ_B for those events where the beam is aligned with the thrust axis ($\cos\theta_B > 0.9$), while Fig. 2b is the corresponding plot for non-aligned events ($\cos\theta_B < 0.9$). Neither plot is isotropic, and the non-aligned events

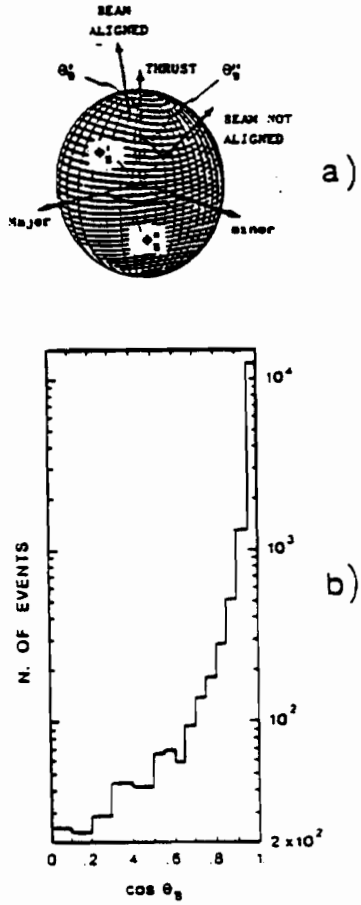

Fig. 1. a) Definition of the Euler angles in the principal axis reference frame.
b) Distribution of the cosine of the polar angle of the beam with respect to the thrust axis.

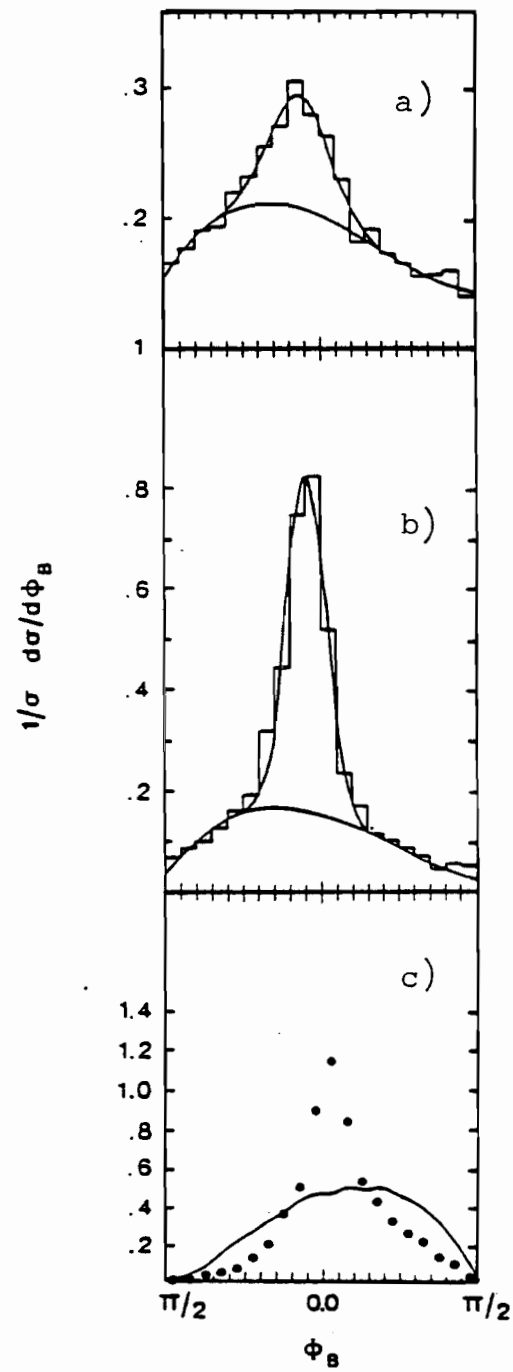

Fig. 2. Distributions of the azimuthal angle of the beam in the principal axis reference frame.
a) 13809 aligned events ($\cos\theta_B > 0.9$),
b) 1537 non-aligned events;
c) 5241 central clusters; the solid line is the prediction of cylindrical phase space.

exhibit a pronounced peak near $\phi_B = 0$. We conclude that when the beam is not aligned with the thrust direction, the events are particularly planar.

Another measure of planarity can be obtained from the eccentricity of the momentum flow in the plane perpendicular to the thrust direction. The eccentricity R is the ratio of the maximum expansions of the momentum flow along the minor and major axes. For the aligned events the eccentricity is $R = 0.84 \pm 0.03$, which is essentially the same as that for all events (0.80 ± 0.02). However, for non-aligned events, we measure $R = 0.51 \pm 0.02$, indicating that these events lie in the thrust-major plane.

3. Jet-like structures

A characteristic feature of low p_t hadron-hadron collisions is the "leading effect". If the interaction occurs between two quarks, the remains of the two incident hadrons continue their path along the original collision axis, eventually fragmenting into hadrons. In order to study jet-like structures it is important to remove the leading effect and isolate a central fireball or cluster of particles which is then similar to the hadron system produced in e^+-e^- annihilation. One approach[3] is to remove simply the fastest and slowest charged particles. However, in some cases (typically nucleon isobars) the leading hadron may decay into several particles in the final state. Our approach, therefore, is to try to subtract leading clusters of particles. We calculate a charge transfer function[6] along the rapidity axis, and by looking for two zeroes of the function we define clusters of particles. Subtracting the fastest and slowest clusters leaves us with 7037 events with a central fireball, and a further requirement of at least four charged particles in the fireball reduces the sample to 5241 events. We transform to the center of mass of the central clusters, and define principal axes as before. Fig. 2c shows the azimuthal angle of the beam for these central cluster events, indicating again that the events are highly planar.

We turn next to the momentum flows within the three planes defined by the principal axes. Recently, DeRujula et al. have pointed out[7] the importance of defining not only the directions of the principal axes but also their orientations. We have adopted their prescription, which is as follows:

a) The thrust axis is oriented so that the sum of the transverse momenta having a positive component along this

axis is smaller than the sum of the transverse momenta having negative component. This implies that the narrow jet is always oriented along the positive thrust direction.

b) The major axis is oriented so that, amongst the particles having negative components along the thrust axis, the sum of the momenta in the thrust-major plane for those having negative projection along the major axis is smaller than the corresponding sum for those having positive projection along the major axis. This implies that if there are two jets with negative thrust components, the larger one will be oriented along the positive major axis.

We have applied this orienting scheme to our sample of 2672 events having a central cluster which contains at least 6 charged particles. We show polar displays of the momentum flows (in 10° bins) in the thrust-major plane (Fig. 3a) and the thrust-minor plane (Fig. 3b). The former plot shows a 3-jet-like structure very similar to that in e^+e^- annihilation. The latter plot shows that the events are very planar; from the momentum flow in the major-minor plane (not shown) we measure an eccentricity of $R = 0.41 \pm 0.02$.

In view of the apparent similarities of our data to jets in e^+e^- annihilation, we have applied further selection criteria similar to the cuts used in e^+e^- experiments. Specifically, we require: a) Oblateness $O = F_{major} - F_{minor} > 0.03$; b) Thrust $T > 0.8$; c) Effective mass of clusters $> 0.5\sqrt{s}$; d) Cluster multiplicity ≥ 6. We are then left with 461 events, about 9% of the original cluster sample. Fig. 4 shows the momentum flows for these events in the three planes. In the thrust-major plane (Fig. 4a) a clear 4-jet-like structure is seen; the thrust-minor plot (Fig. 4b) shows that the events are extremely planar; and the major-minor plot (Fig. 4c) yields an eccentricity of $R = 0.18 \pm 0.01$.

4. The behavior of phase space

At this point it is obviously important to check whether the jet-like structures in our data can be predicted by phase space. Recently, Clegg and Donnachie[8] have shown that P_t^{in} and P_t^{out} distributions in soft multihadron production are reproduced by longitudinal phase space.

We have used the standard program FOWL to generate uncorrelated phase space Monte Carlo events. We impose the experimentally observed distributions of cluster energy and multiplicity. The cylindrical character of the

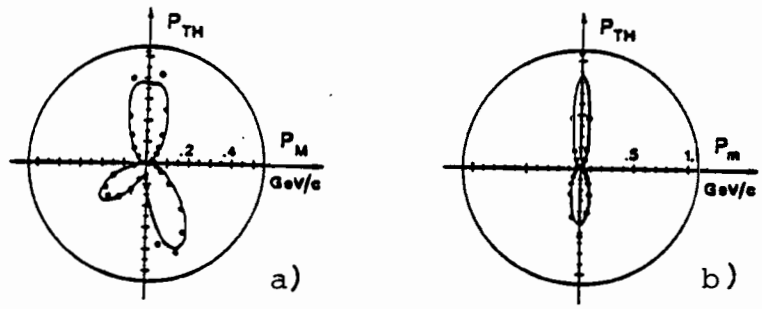

Fig. 3. Momentum flows in the two planes containing the thrust direction, for 2672 central clusters. a) Thrust-major plane; b) Thrust-minor plane. The solid lines are the predictions of cylindrical phase space.

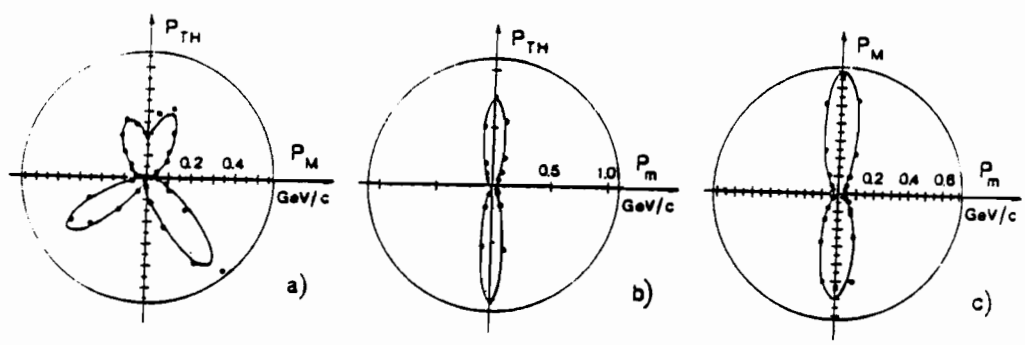

Fig. 4. Momentum flows for 461 central clusters obtained after imposing "e^+e^- type" cuts on oblateness, thrust and cluster energy. a) Thrust-major plane; b) thrust-minor plane; c) major-minor plane. The solid lines are the predictions of cylindrical phase space.

production is preserved by adopting the marginal distributions given by $d\sigma/dp_\ell$ and $d\sigma/dp_t^2$. This weighting does not introduce any correlation between p_t^{in}, p_t^{out}, etc. Then the Monte Carlo events have been subjected to the same mathematical handling as the real data, including the ordering scheme described in the previous section.

The predictions of this cylindrical phase space model are shown as solid lines in Figs. 2, 3 and 4. The agreement with the real data is very striking. The only distribution which is not reproduced is the azimuthal angle ϕ_B of Fig. 2c. The correlation of the beam direction with the thrust-major plane is much stronger than predicted by phase space. All other aspects are reasonably reproduced, including the 3-jet and 4-jet structures of Figs. 3a and 4a. When we impose on the Monte Carlo events the "e^+e^- cuts" described in the previous section, we find that 10.5% of the events survive, which is very close to the fraction (9%) of the real data that survives. The momentum flows (Fig. 4) also agree very well with the data.

5. Conclusions

Our primary conclusion is that the mathematical handling of the kinematic variables, including the ordering scheme of DeRujula et al., forces the appearance of multi-jet configurations. Central clusters free from leading effects (and with at least 6 charged particles) appear to be more planar than predicted by phase space, if the azimuthal angle of the beam can be taken as a measure of planarity. But jet-like structures in the thrust-major plane are primarily a consequence of the mathematical handling. Standard cuts on oblateness, thrust, and cluster energy select about 10% of the data as well as the phase space events.

REFERENCES

1. S. P. Ratti, High Energy Physics-1980, Ed. by L. Durand and L. G. Pondrom (A.I.P. New York 1981), p. 84.
2. D. Brick et al., Zeit. für Phys. C15, 1 (1982).
3. M. Basile et al., N. Cim. 66A, 129 (1981).
4. G. Valenti, XII Int. Symp. Multiparticles (Notre Dame 1982), p. 717.
5. S. P. Ratti et al., XII Int. Symp. Multiparticles (Notre Dame 1982), p. 67.
6. J. E. Brau, Ph.D. Thesis, M.I.T. (1978); D. Brick et al., Nucl. Phys. B152, 45 (1979).
7. A. DeRujula et al., Nucl. Phys. B138, 387 (1978).
8. A. B. Clegg and A. Donnachie, Zeit. für Phys. C13, 71 (1982).