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Evidence for Double-Jet Structure in pp Interactions at $\sqrt{s} = 62$ GeV.

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In e^+e^- physics the three-jet structure has recently been reported [1,2]. This peculiar structure is interpreted as the production, in e^+e^- annihilation, of two quark-induced jets plus a third jet induced by a gluon. The purpose of this paper is to investigate what happens in the pp case. According to our analysis, where only one half-hemisphere is studied, the three-jet structure would correspond to a two-jet in the pp case, both jets being in the same hemisphere as that of the « leading proton ». We have attempted to reveal this effect in our « minimum bias » sample of pp, low-p_T data at $\sqrt{s} = 62$ GeV.

The experiment has been done at the CERN Intersecting Storage Rings (ISR) using the Split Field Magnet facility (SFM).

For details we refer the reader elsewhere [3,4]. The sample of « minimum bias » events has been analysed according to the following criteria. Each event has been divided into two hemispheres, and each hemisphere has been first selected by requiring the presence of a « leading proton ». Moreover, at least four charged particles, besides the proton, are required. We define as the « leading proton » the fastest charged

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(2) JADE COLLABORATION (W. BARTEL *et al.*): *Phys. Lett. B*, **91**, 142 (1980).
(3) R. BOUCLIER, R. C. A. BROWN, E. CHESI, L. DUMPS, H. G. FISCHER, P. G. INNOCENTI, G. MAURIN, A. MINTEN, L. NAUMANN, F. PIUZ and O. ULLALAND: *Nucl. Instrum. Methods*, **125**, 19 (1975).
(4) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, L. FAVALE, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Phys. Lett. B*, **92**, 367 (1980); M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. SUSINNO, R. NANIA, G. VALENTI and A. ZICHICHI: *A new method to study particle production in* pp *interactions at high energy*, to be submitted to *Nucl. Phys. B* (1980).

particle in the hemisphere, when positive, with $\Delta p/p \leqslant 8\%$, and with $0.4 \leqslant x_F \leqslant 0.9$ ($x_F = 2p_L/\sqrt{s}$; p_L is the momentum component in the beam direction, and $\sqrt{s}$ is the total c.m. energy of the colliding protons). With this selection, the contamination from pions ranges from about 25% at $x_F = 0.4$ down to 1% at $x_F = 0.9$, being about 10% at $x_F = 0.5$ (5). To take into account how all selection criteria, including the above-quoted π contamination, could affect the results, we have used a Monte Carlo simulation program (6). The «leading proton» in Monte Carlo simulated events has been selected as specified above. The π contamination in simulated events ranges from 27% to 2%, and this agrees very well with the experimental findings quoted above. Moreover, the analysis has been repeated with the lower cut in x_F at 0.5, without any noticeable variation in the results.

In a previous paper (7) we have studied «planarity» effects in the multiparticle systems produced in pp interactions, following criteria that are as similar as possible to those used in e^+e^- data (2,8). In the pp case we must use a two-dimensional analysis and determine the jet axis as the missing momentum axis. In the e^+e^- case, a three-dimensional analysis is made in order to determine the jet axis also.

Following BJORKEN and BRODSKY (9), a two-dimensional momentum tensor, for the N particles accompanying the proton, has been evaluated for each event in the plane orthogonal to the missing momentum axis (*) in the pp rest system

$$M_{\alpha\beta} = \sum_{j=1}^{N} p_{j\alpha} p_{j\beta} \qquad (\alpha, \beta = 1, 2) .$$

The ordered eigenvalues Λ_1, Λ_2 ($\Lambda_1 < \Lambda_2$) are, respectively, the sum of the square of the momentum components, normal to the event plane (out) and in the event plane (in):

$$\langle p_T^2 \rangle_{out} = \frac{\Lambda_1}{N} = \frac{1}{N} \sum_{j=1}^{N} p_{j\,out}^2 , \qquad \langle p_T^2 \rangle_{in} = \frac{\Lambda_2}{N} = \frac{1}{N} \sum_{j=1}^{N} p_{j\,in}^2 .$$

In order to study the behaviour of «planar» events, we have imposed the condition

$$\langle p_T^2 \rangle_{in} \geqslant 3 \langle p_T^2 \rangle_{out} .$$

This condition selects 68% of the real event sample and 59% of simulated events.

The reason why this is not a strong condition, also for Monte Carlo simulated events, is due to the choice of the «out» axis. This is the axis where the sum of the square of the momentum components is minimal. This condition is applied in the analysis to separate out those events that are symmetric in the orthogonal plane and to study the different behaviour of «planar» and «nonplanar» events.

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(5) J. W. CHAPMAN, J. W. COOPER, N. GREEN, A. A. SEIDL, J. C. VENDER VELDE, C. M. BROMBERG, D. COHEN, T. FERBEL and P. SLATTERY: *Phys. Rev. Lett.*, **32**, 257 (1974); P. CAPILUPPI, G. GIACOMELLI, A. M. ROSSI, G. VANNINI and A. BUSSIÈRE: *Nucl. Phys. B*, **70**, 1 (1974).
(6) D. C. CAREY and D. DRIJARD: *J. Comput. Phys.*, **28**, 327 (1978).
(7) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, R. NANIA, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **29**, 491 (1980).
(8) TASSO COLLABORATION (R. BRANDELIK *et al.*): *Phys. Lett. B*, **86**, 243 (1979); PLUTO COLLABORATION (CH. BERGER *et al.*): *Phys. Lett. B*, **86**, 418 (1979).
(9) J. D. BJORKEN and S. J. BRODSKY: *Phys. Rev. D*, **1**, 141 (1970).
(*) This axis is always within few degrees with respect to the sphericity axis. On the other hand, we prefer to use the «missing momentum» axis, because this is not biased by loss of charged particles. Moreover, this is the best approximation to the real jet axis.

To sum up all conditions:

1) $\Delta p/p \leqslant 8\%$
2) $0.4 \leqslant x_F \leqslant 0.9$

} for the « leading proton »,

3) $n_{\text{charged}} \geqslant 4$
4) $\langle p_T^2 \rangle_{\text{in}} \geqslant 3 \langle p_T^2 \rangle_{\text{out}}$

} for the particles accompanying the proton.

The total number of selected events was 3614. The average charged multiplicity of these events is $\langle n_{\text{charged}} \rangle = 4.9$. The average $\langle p_T^2 \rangle_{\text{out}}$ is 0.023 $(\text{GeV}/c)^2$, and the average $\langle p_T^2 \rangle_{\text{in}}$ is 0.170 $(\text{GeV}/c)^2$. In order to analyse the structure of these events, the thrust $\mathcal{T}$ was first evaluated in the pp c.m. system (*). Then, for each event, a thrust $\mathcal{T}^*$ in the rest system of the charged particles (2) was calculated. This system corresponds to the c.m. system of the jet, under the hypothesis that the nonobserved particles (neutrals plus those escaping from the detector) are evenly distributed in the c.m. The thrust in the c.m. system, $\mathcal{T}^*$, is defined as

$$\mathcal{T}^* = \max \frac{\sum_i |p^*_{Li}|}{\sum_i |p^*_i|},$$

where p^*_{Li} is the component along a given axis of the momentum p^*_i of the particle i in the rest system of the charged particles observed. The thrust quantity is 1 when all the particles in the event have exactly the same direction, and approaches 0.5 when symmetrically distributed in a sphere. In the case of perfectly « planar » events, *i.e.* with particles symmetrically distributed in the plane, the thrust approaches the value of $2/\pi$.

In fig. 1 the average values of $\mathcal{T}^*$ *vs.* $\mathcal{T}$ are reported for experimentally observed « planar » events and for Monte Carlo simulated events. The Monte Carlo simulation

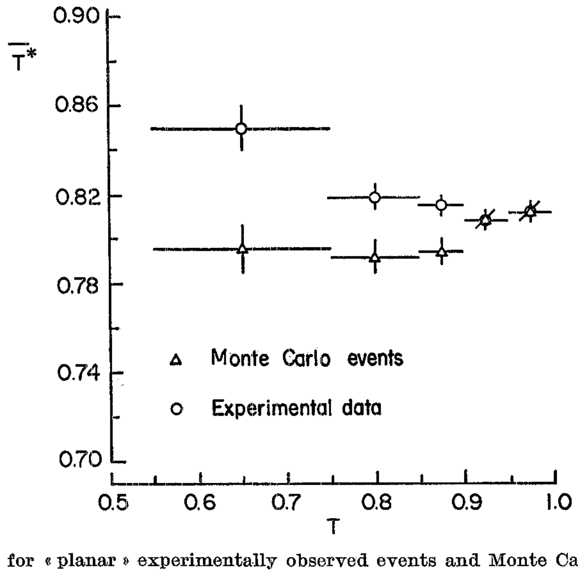

Fig. 1. – $\bar{\mathcal{T}}^*$ *vs.* $\mathcal{T}$ for « planar » experimentally observed events and Monte Carlo simulated events.

(*) As usual the quantity $\mathcal{T}$ is given by $\mathcal{T} = \max \sum_i |p_{Li}| / \sum_i |p_i|$.

is based on « limited p_T » ($\langle p_T \rangle = 0.300$ GeV/c) phase-space events ([6]), with the same analysis conditions as for the data (1), 2), 3), 4) above). After these selections the average charged multiplicity of generated events is $\langle n_{\text{charged}} \rangle = 4.8$, the average $\langle p_T^2 \rangle_{\text{out}}$ is 0.02 (GeV/c)^2, and the average $\langle p_T^2 \rangle_{\text{in}}$ is 0.113 (GeV/c)^2. The experimental data show increasing $\mathcal{T}^*$ values when $\mathcal{T}$ decreases. The « nonplanar » events (defined by $\langle p_T^2 \rangle_{\text{in}} < 3 \langle p_T^2 \rangle_{\text{out}}$) do not show this effect, as can be seen in fig. 2.

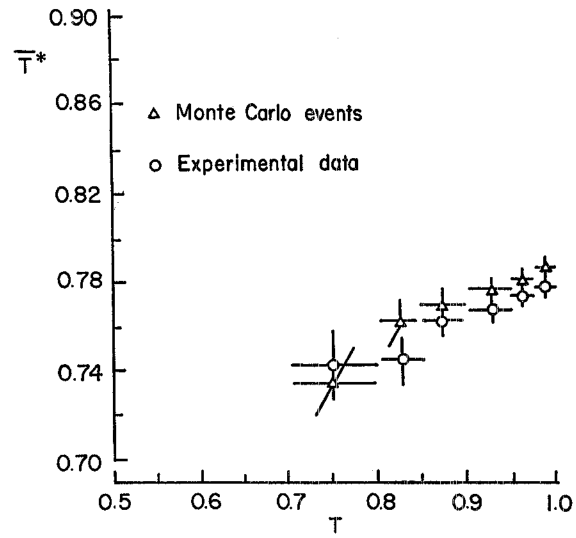

Fig. 2. – $\bar{\mathcal{T}}^*$ *vs.* $\mathcal{T}$ for « nonplanar » experimentally observed events and Monte Carlo simulated events.

Monte Carlo « planar » events, with low thrust, *i.e.* broad events, show no correlation with high-$\mathcal{T}^*$ events, as shown in fig. 1. The fraction of « planar » events with $\mathcal{T} < 0.85$ is, respectively, $(9.8 \pm 0.6)\%$ in real data and $(4.8 \pm 0.4)\%$ in the Monte Carlo simulated events. The two-jet effect in the $\mathcal{T} < 0.85$ range is, therefore, at the $\sim 5\%$ level.

The Monte Carlo events, by definition, do not have a two-jet structure, and the behaviour of $\mathcal{T}^*$ *vs.* $\mathcal{T}$, reported in fig. 1 and 2, is as expected. For high-$\mathcal{T}$, single-jet low-p_T events in the c.m. of the particles, a back-to-back jet structure is expected, aligned with the line of flight of the c.m. itself. When $\mathcal{T}$ decreases, the jet is broader, and a broadening in the c.m. of the particles is also expected. The Monte Carlo results (fig. 1) show a decrease of $\mathcal{T}^*$ with decreasing $\mathcal{T}$, as expected.

The $\mathcal{T}^*$ *vs.* $\mathcal{T}$ trend, obtained for real events (fig. 1), could be the consequence of some bias due to the apparatus or to the analysis. However, this has been proved not to be the case, because Monte Carlo simulated events, reconstructed through the apparatus and analysed following the same chain, do not show this behaviour (fig. 1 and 2). Thus the correlation observed in fig. 1 must be a genuine effect: the wider a « planar » jet is in the pp c.m. system, the narrower it is in the jet rest system. This constitutes evidence that events with low $\mathcal{T}$ derive from two back-to-back jets in the c.m. system (high value of $\mathcal{T}^*$), not aligned with the line of flight of the c.m. system itself.

As mentioned earlier, this two-jet structure is a further analogy between the two ways, e^+e^- and pp, of producing multiparticle hadronic systems.