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OBSERVATION OF JET STRUCTURE IN HIGH TRANSVERSE ENERGY EVENTS
AT THE CERN INTERSECTING STORAGE RINGS

CERN-Oxford-Rockefeller (COR) Collaboration

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ABSTRACT

The spectrum dN/dE_T^0 (E_T^0 = neutral transverse energy) has been measured with an electromagnetic calorimeter covering 90% of 2π in azimuth. The measurement, performed in pp collisions at $\sqrt{s} = 62$ GeV, covered the E_T^0 range from 10 to 30 GeV. Evidence is presented that a large fraction of these events are jet-like, the fraction increasing with E_T^0 .

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The search for jets in hadron-hadron collisions has a long history. Previous evidence for jets at Intersecting Storage Rings' (ISR) energies has come chiefly from the study of particles accompanying or recoiling from single triggering particles of high transverse momentum [1]. Studies at lower energies ($\sqrt{s} = 24$ GeV) removed the single-particle restriction by triggering on transverse energy deposition in large solid-angle calorimeters [2], but found that jet production is not dominant in this energy regime. However, similar investigations at higher energies ($\sqrt{s} = 540$ GeV) beyond the ISR range have seen copious jet production emerging at large transverse energies [3]. A recent ISR experiment with a calorimeter trigger but restricted solid angle has also seen evidence for jet production [4]. The present work extends the search with an electromagnetic calorimeter trigger covering 90% of 2π in azimuth, the aim being to see whether events with large transverse energy show jet-like structure even when the trigger places weak geometrical constraints on the events.

The apparatus, shown in Fig. 1, consisted of a superconducting solenoid providing a magnetic field of 1.4 T and enclosing a system of cylindrical drift chambers. Four modules of lead/scintillator shower counters were also located inside the magnet. Each module subtended 50° in azimuth and ± 1.1 units of rapidity y , centred on $y = 0$, and segmented azimuthally into eight counters equipped with phototubes at both ends. The detection of electromagnetic showers was completed by two lead-glass modules located outside the magnet in the angular region not covered by the shower counters. The angular acceptance of each lead-glass array was 57° in azimuth and ± 0.6 units of rapidity, also centred on $y = 0$. The thickness of the lead glass was 21 radiation lengths (r.l.) and that of the shower counters was 14 r.l. The r.m.s. energy resolutions were $(4.3/\sqrt{E} + 2)\%$ and $16\%/\sqrt{E}$, respectively, where E is measured in GeV. A hodoscope of 32 scintillation counters (A), also equipped with phototubes at both ends, was located between the first and second drift chamber modules. The apparatus has been described in more detail elsewhere [5].

To trigger the apparatus, all energies deposited in the shower counters and the lead glass were summed and the total was required to be above a threshold.

The threshold was applied again in the off-line analysis, using more detailed calibration information.

Events due to the occurrence of more than one interaction during the apparatus recording time were rejected. This requirement was necessitated by the high interaction rate at the ISR and the nature of the trigger, which purposely placed little requirement on the pattern of energy deposition. All shower counters were equipped with time-to-digital converters (TDCs). In addition, the scintillator hodoscope (A) which surrounded the interaction region had TDCs capable of recording up to 14 hits per counter end in a time range of 300 ns before and after the nominal event time. The time data from the shower counters and the A scintillators were searched in a range of ± 200 ns (the longest gate time used in the calorimeter). A time cluster was defined as two or more counters firing within a 12 ns interval. If more than one distinct cluster was found, the event was rejected. To test the method, data were taken at several values of instantaneous luminosity. Figure 2 shows the cross-section inferred for a typical energy bin, with and without this single interaction requirement. The highest instantaneous luminosity shown is that normal in our intersection region. The inferred cross-section is seen to be a strong function of the instantaneous luminosity, but this dependence is removed by the single interaction requirement. The data presented in this first publication were collected at an instantaneous luminosity of $1.5 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, the lowest of the values shown in Fig. 2.

For each shower counter the longitudinal position of the energy deposition was calculated from the time difference or the energy ratio between the two ends. The transverse energy in the pp centre-of-mass system was calculated for each shower counter and lead-glass block, assuming the energy was deposited by a massless neutral particle originating at the vertex position measured with the charged tracks. These energies were summed to give the total neutral transverse energy E_T^0 . The number of events per GeV of E_T^0 was divided by the integrated luminosity ($1.8 \times 10^{36} \text{ cm}^{-2}$) to give the spectrum dN/dE_T^0 shown in Fig. 3. This spectrum deviates from a simple exponential above E_T^0 of 20 GeV. The result of a fit to an exponential in E_T^0

over the range 10 to 20 GeV is shown $[\sim \exp(-0.89E_T^0)]$. No corrections have been applied for resolution, double hits within the same shower counter, or energy deposited by charged tracks in the shower counters or lead glass. These corrections will tend to increase the slope of the spectrum.

The transverse energy carried by the charged particles E_T^C was measured using the drift chambers. The ratio E_T^C/E_T^0 decreased from 0.50 to 0.25 over the E_T^0 range. The smallness of these values is the result of triggering on only the electromagnetic energy rather than the total energy.

To investigate the structure of the events, the neutral energies were first clustered. In the shower counters, clusters were based upon counters containing at least 400 MeV of energy, adding energies over 100 MeV in neighbouring counters if these energies lay within ± 20 cm longitudinally. In the back arrays of lead glass, a 3×3 matrix centred on each block containing at least 100 MeV was considered. Within each matrix, energies over 20 MeV were added together, and overlapping clusters were combined to a maximum size of 5×5 blocks. The front arrays of lead glass were clustered by first associating energy with the back glass clusters, and then clustering any remaining energy according to the same energy criteria. The glass cluster energies were corrected for angle of incidence and energy loss in the coil of the magnet (~ 1 r.l. of Al) and iron magnetic shielding (0.3 r.l.). These corrections typically amounted to 15% of the glass cluster energy. The fraction of the neutral energy which appeared in clusters was essentially constant, at about 93%, over the E_T^0 range.

From the neutral energy clusters in each event the two with highest transverse energy were chosen, and the ratio of their sum to the E_T^0 in the event was formed. The mean value of this ratio is shown as a function of E_T^0 in Fig. 4. The rise to a value of ~ 0.8 is striking evidence that two-jet structure becomes predominant at high E_T^0 . Also shown in Fig. 4 is the mean value of the ratio of the highest transverse energy to E_T^0 , which shows that the rise of the two-cluster sum is not due to one-cluster dominance. The production of π^0 pairs [6] at $\sqrt{s} = 62$ GeV is a factor of about 10^{-3} lower than that for these events, so that the two-jet nature

of the events cannot be mainly due to two single π^0 's. The larger angular size of these clusters compared to those caused by π^0 's substantiates this argument. The mean number of shower counters per cluster increased linearly from 2.7 to 3.8 over the E_T^0 range, whereas a cluster size of 1.5 would be expected from a single π^0 .

Examination of individual events with E_T^0 over 24 GeV confirmed the jet-like structure, so a simple jet analysis was performed on each event. Momentum vectors were obtained for each charged track of $p_T > 300$ MeV/c and for each counter containing neutral energy. The event was divided into two spatial hemispheres, and the momenta within each were combined vectorially. The normal to the larger momentum sum was used to define another split into two hemispheres. This procedure was iterated until the vector momentum sums in the two hemispheres stabilized, and these sums then defined two jet axes, not necessarily back-to-back. All particles in the same hemisphere as the larger of the momentum sums were assigned to the larger jet. The remaining particles were assigned to the other jet. The azimuthal angle distribution between the jet axes obtained is displayed in Fig. 5. The back-to-back nature of the jets is clearly demonstrated.

A variable similar to sphericity, used in e^+e^- jet physics, was defined for each event by: $S = S_1 + S_2$, where $S_n = 3 \sum j_{Ti}^2 / 2 \sum p_i^2$, where $n = 1, 2$ labelled the two axes in each event, p_i was the magnitude of the momentum of particle i , j_{Ti} its transverse component relative to its jet axis, and the sums were over all charged and neutral particles associated with axis n . Figures 6a and 6b show the distributions of S for two samples of events, one with E_T^0 between 10 and 11 GeV and the other with E_T^0 between 24 and 28 GeV. The evident trend towards small values of S at higher E_T^0 values is confirmed by Fig. 6c, in which the mean value of S is plotted as a function of E_T^0 . The implication of this plot is that $\sum j_T^2$ does not grow as fast as $\sum p^2$, again demonstrating the jet structure of the events [7]. The actual values of $\langle S \rangle$ attained are not directly comparable with those in e^+e^- jets, because they are affected by the granularity of the detector.

From the evidence shown in this letter, we conclude that jets form a dominant component of events triggered in a geometrically unbiased way at high neutral transverse energies in pp collisions at $\sqrt{s} = 62$ GeV. The properties of these jets will be studied in a later paper.

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Figure captions

- Fig. 1 : The apparatus viewed along the beam axis.
- Fig. 2 : Events/Integrated Luminosity for a typical E_T^0 interval versus instantaneous luminosity. Open circles are for data without the single interaction criterion, and closed circles are for data after the selection.
- Fig. 3 : The spectrum Events/Integrated Luminosity versus E_T^0 at $\sqrt{s} = 62$ GeV.
- Fig. 4 : The mean fraction of neutral transverse energy contained in the two most energetic clusters (closed circles) and the mean fraction of neutral transverse energy contained in the most energetic cluster (open circles), versus E_T^0 .
- Fig. 5 : The azimuthal angle between the two jet axes defined in the text.
- Fig. 6 : The distribution of the sphericity variable S (defined in the text). Figure 6a is for events with E_T^0 in the range 10 to 11 GeV; Fig. 6b is for E_T^0 in the range 24 to 28 GeV; Fig. 6c shows the mean value of S as a function of E_T^0 .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6