A STUDY OF MULTI-JET EVENTS IN e^+e^- ANNIHILATION

PLUTO Collaboration

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A multi-jet analysis of hadronic final states from e^+e^- annihilation in the energy range $27 < E_{cm} < 32$ GeV is presented. The analysis uses a cluster method to identify the jets in a hadronic event. The distribution of the number of jets per event is compared with several models. From the number of identified coplanar three-jet events the strong coupling constant is determined to be $\alpha_s = 0.15 \pm 0.03$ (stat. error) $\pm$ 0.02 (syst. error). The inferred energy distribution of the most energetic parton is in good agreement with the first-order QCD prediction. A scalar-gluon model is strongly disfavoured. Higher-twist contributions to the three-jet sample are found to be small.

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The two-jet structure observed in e^+e^- annihilation [1] has given strong support to the quark parton model [2]. In addition to this structure, the production of three-jet events has been observed recently at PETRA energies above ≈25 GeV [3–5]. The appearance of this new process is an essential premise for the validity of Quantum Chromodynamics (QCD) which predicts three-jet events due to hard gluon bremsstrahlung [6]. The theoretical predictions of QCD are made in terms of partons (quarks and gluons) disregarding their fragmentation to real hadrons. Thus for direct comparison of experiments and these predictions a method of analysis has to be applied which allows the reconstruction of the original parton configuration. In contrast to previously applied methods to analyse jet structures in e^+e^- annihilation [1,3–5,7–9], we use a new cluster method [10] which determines the number of jets exploiting only the angular collimation of the particles. This allows counting and measuring of the hard partons involved in the reaction. Of particular interest in this context are the determination of the strong coupling constant α_s and the measurement of the parton energy distributions in three-jet events. The latter can be used to test the matrix element of QCD in first order of α_s [6].

The cluster method used is a two-step algorithm. The first step associates all particles into preclusters irrespective of their charges and momenta. Preclusters are sets of at least one particle. If the angle between the directions of any two particles is less than a "collecting angle" α they belong to the same precluster. It is obvious that by this definition every particle of an event is assigned to exactly one precluster. The unit vector parallel to the sum of the momenta of the particles in a precluster defines its direction. In the second step the preclusters are merged to clusters if the momentum vectors of any two of them subtend an angle smaller than β. The sum of the energies of all particles assigned to a cluster i defines the cluster energy E_{Ci}. The number of clusters n_c is defined as the minimum number of clusters which fulfills the inequality

$$\sum_{i=1}^{n_c} E_{Ci} > E_{vis}(1-\epsilon) ,$$

for a given value of $\epsilon \ll 1$, thus allowing for a fraction ϵ of the visible energy E_{vis} to be outside of the accepted clusters. Finally, any of these clusters is called a jet if its energy E_{Ci} exceeds a predefined threshold energy E_{th}. All particles not attributed to a jet are neglected in the further analysis.

The parameters have been chosen in order to optimize the efficiency for recognizing two- and three-jet events using Monte Carlo simulations of different e^+e^--annihilation final states [10]. In our analysis we used $\alpha = 30°$, $\beta = 45°$, $\epsilon = 0.1$ and $E_{th} = 2$ GeV. The latter choice is motivated by low-energy results on jets [1]. E_{th} should be large compared to the typical transverse momentum of a hadron in a jet ($\langle p_t \rangle \approx 300$ MeV), in order to allow clear separation of jets originating from partons which are sufficiently separated in space. The results of this paper are rather insensitive to the actual choice of these parameters.

Applying this cluster analysis we obtain for each event the number of jets, n_j and for each jet i the energy E_{Ji} and the direction $\boldsymbol{n}_{Ji}$. The direction is defined by the unit vector parallel to the sum of the momenta of all particles assigned to the jet J_i. Assuming zero mass for the jet, its momentum is simply $\boldsymbol{P}_{Ji} = \boldsymbol{n}_{Ji}E_{Ji}$. All jets found are ordered according to their energies starting with the most energetic jet with energy E_{J1}. Due to fluctuations in the hadronisation process, n_j is not necessarily equal to the number of initial energetic ($E > E_{th}$) partons. To correct for this difference Monte Carlo simulations of various processes are used.

In this letter we report on the analysis of data with the PLUTO detector [11] at the e^+e^- storage ring PETRA in the energy range $27 < E_{cm} < 32$ GeV. Charged particles are measured in 13 cylindrical proportional chambers which cover 87% of 4π sr and which operate in an axial magnetic field of 1.65 T. Photons are measured in lead scintillator shower counters covering 97% of the full solid angle.

This analysis uses both charged particles and photons. The masses of the charged particles are assumed to be the pion mass. In order to discriminate hadronic events from background (mainly from beam–gas interactions, QED and $\gamma\gamma$ physics) and to suppress incompletely measured events we apply the following cuts: (i) the visible energy E_{vis} must exceed half of the center of mass energy E_{cm}, (ii) at least four charged particles must belong to a common vertex, (iii) the possible charge excess must be less than 2 if the observed charged multiplicity is smaller than 7, (iv) the missing transverse momentum with respect to the most energetic jet must be smaller than $0.2\,E_{vis}$, and (v) the angles ϑ_1 and ϑ_2 of the two most energetic jets with respect to the e^+-beam direction have to fulfill the condition $(|\cos\vartheta_1| + |\cos\vartheta_2|)/2 < 0.75$.

The selected events were visually inspected to reduce the contamination of higher-order QED processes and cosmic showers. After these cuts we obtain 859 events for the further analysis. It is estimated that this sample contains a maximum of 0.2% of beam–gas events, 0.2% of the events are expected from higher-order QED and less than 1.2% from $\gamma\gamma$ interactions.

We compare our data to Monte Carlo events generated according to four different models:

(1) A two-jet model ($q\bar{q}$) [12] including c- and b-quark production. The fragmentation parameters were fixed to the values of ref. [10] with the exception of σ_q, the transverse momentum spread of the primary mesons. For the c- and b-quark fragmentation standard assumptions were made [13].

(2) A gluon bremsstrahlung model ($q\bar{q}g$) based on the first-order QCD matrix element [14]. Gluons are assumed to fragment like quarks. The singularities of the matrix element are suppressed by a cut in the normalized energy of the fastest parton P_1 requiring $x_1 = 2E_{P1}/E_{cm} < 0.95$.

(3) A model to describe a hypothetical heavy $q\bar{q}$ resonance (M_{res} = 30 GeV) decaying into three gluons (ggg) [15].

(4) An isotropic multiparticle phase space (PS). It provides an extreme model with no dynamics and can be used to simulate the decay of two heavy objects which are generated almost at rest.

Radiative corrections of the initial state are included for models (1) and (2). All Monte Carlo events were passed through a complete detector simulation program, using the same pattern recognition and analysis chain as used for the data.

First we consider the distribution of the observed numbers of jets per event (n_j) shown in fig. 1. The two-jet structure is dominant. However, about 30% of the events are classified as three-jet events. In table 1 the data are compared with the Monte Carlo expectations from models (1), (2), (4) and a linear combination of $q\bar{q}$ and $q\bar{q}g$. Model (1) with a quark fragmentation parameter σ_q = 290 MeV does not describe our data, in particular the number of three-jet events is much too small. This model does not fit the data even if σ_q is increased to 350 meV, a value which is excluded by the experimental value of $\langle p_{out}\rangle$ [3].

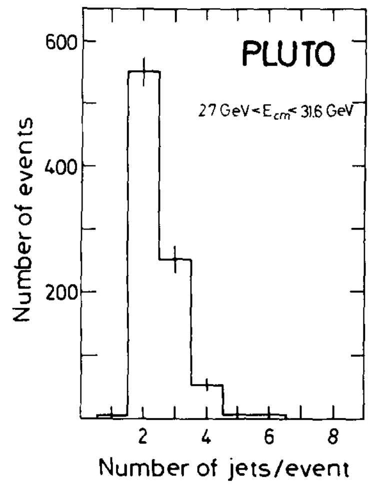

Fig. 1. Distribution of the observed number of jets per event.

Moreover, the experimental fraction of three-jet events cannot be explained by any combination of isotropic phase space events [model (4)] and $q\bar{q}$ events. However, if we mix model (1) and (2) according to first-order QCD we obtain good agreement for all n_j classes. In particular all observed four-jet events are explained by this model. Thus there is no sizeable production of events with four energetic partons. Such events are expected from higher-order QCD effects at a rather low rate but sufficiently detailed calculations are not yet available [16].

Comparing the experimental n_j distribution with the distribution of the phase space model (4), given in the last line of table 1, we can obtain upper limits on

Table 1
Distributions of the observed numbers of jets per event (n_j) for data and different models, all normalized to the number of observed events. For the $q\bar{q}$ + $q\bar{q}g$ model α_s = 0.15 is assumed.

	n_j = 1	2	3	4	5	6	7
data	2	551	249	53	3	1	
$q\bar{q}$	3	680	152	23	1		
$q\bar{q}g$	2	229	509	113	5	1	
$q\bar{q}$ + $q\bar{q}g$	3	567	247	46	2		
PS	1	30	154	306	268	86	14

processes generating heavy new particles [17] nearly at rest if they have an isotropic decay structure. We conclude from the $n_j > 4$ classes that the total isotropic contribution in our data is smaller than 3% at 99% c.l.

We now proceed to analyse the identified two-jet and three-jet events in order to obtain quantitative results related to the first-order QCD predictions, addressing ourselves specifically to
– the determination of the strong coupling constant α_s and
– a study of the energy distribution of the partons to obtain information on the gluon spin.

In principle, α_s is determined to first order directly from the three-jet to two-jet ratio, fully corrected for detector efficiency. However, since the model predictions of this ratio slightly depend on the fragmentation parameters, in particular on σ_q, we first determine σ_q from the p_t distribution of the two-jet class which contains predominantly $q\bar{q}$ events. The small contamination expected from degraded three-parton events (≈11%) is subtracted. The comparison with the $q\bar{q}$ model (using different values of σ_q) yields σ_q = (290 ± 20) MeV in good agreement with other experimental results at these energies [18].

To obtain a cleaner three-jet event sample we impose more severe cuts, namely (i) the sum of the energy of the three jets must exceed 0.9 E_{vis}, (ii) each jet must contain more than one particle, and (iii) the events must be planar with 45°, more precisely

$$\cos\gamma = (\boldsymbol{n}_{J2} \times \boldsymbol{n}_{J3}) \cdot (\boldsymbol{n}_{J3} \times \boldsymbol{n}_{J1}) > \cos 45°$$

($\boldsymbol{n}_{Ji}$ are the unit vectors of the jet direction). 196 events are kept in the three-jet class after these cuts. For these events we define a thrust variable T_J by maximizing the longitudinal momenta of the three jets instead of the particles,

$$T_J = \max\left(\sum_{i=1}^{3} |\boldsymbol{P}_{Ji}^{\parallel}| \Big/ \sum_{i=1}^{3} |\boldsymbol{P}_{Ji}|\right),$$

where $\boldsymbol{P}_{Ji}^{\parallel}$ is the momentum component of the jet i parallel to the thrust axis. We found by Monte Carlo studies that T_J is a very good approximation of the normalized energy x_1 of the most energetic parton. Thus we can consider T_J as a direct measure of x_1. We restrict our three-jet sample to $T_J \leqslant 0.925$, which leaves 114 events. From the $q\bar{q}$ model we expect 34 events which are statistically subtracted for the further analysis.

From the following investigations we conclude that the remaining events are consistent with a three-parton process. The events are planar with $\langle\gamma\rangle = 13°$. The multiplicity of the events is nearly independent of T_J in accordance with the model. The energy dependence of the multiplicity of the least energetic jet is "parton-like", i.e. is increasing logarithmically with energy [2]. In fig. 2 the average observed charged multiplicity $\langle n_{ch}\rangle$ of the least energetic jet is shown as a function of the jet energy squared. The data show the typical logarithmic increase. Furthermore the absolute observed values are in good agreement with the predictions from the $q\bar{q}g$ model (full curve in fig. 2). Finally a detailed Monte Carlo study yields the result that the measured directions and energies of the jet are strongly correlated to those of the partons [10].

This sample of three-jet events is now used to determine α_s. Correcting for detector efficiencies, radiation and fragmentation we obtain:

$$\alpha_s = 0.15 \pm 0.03 \text{ (stat. error)} \pm 0.02 \text{ (syst. error)}.$$

The systematic error reflects the uncertainties introduced by cuts and the models, but does not take into account next-order QCD effects. This result is consistent with other determinations [5,18,19]. The correlation between α_s and σ_q is particularly small. Even assuming extreme values for σ_q such as 250 MeV and

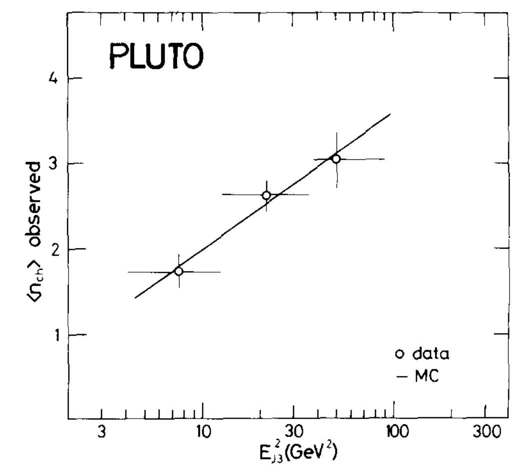

Fig. 2. Observed mean charged multiplicity for the least energetic jet in identified three-jet events at $E_{cm} \approx 30$ GeV (points) and Monte Carlo prediction for the $q\bar{q}g$ model.

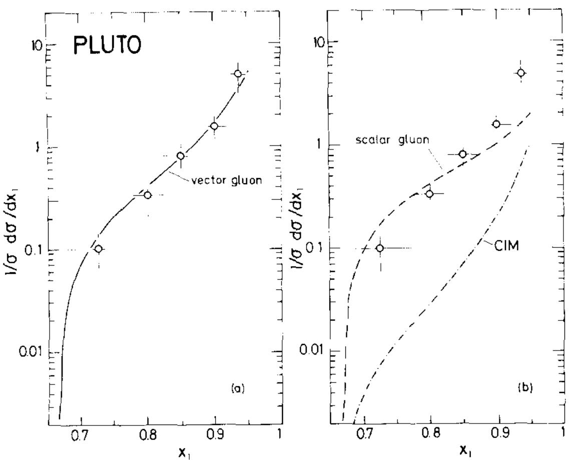

Fig. 3. Distribution of the relative energy of the fastest parton (x_1). The data points are corrected for detector acceptance, radiation and hadronisation. The curves are (a) first-order QCD, (b) dotted: scalar-gluon hypothesis and dashed–dotted: CIM.

350 MeV changes α_s only by +0.004 and −0.009, respectively.

The x_1 distribution up to $x_1 = 0.95$ is shown in fig. 3a together with the prediction from first-order QCD ($\alpha_s = 0.15$):

$$(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}x_1)$$

$$= (\alpha_s/3\pi)[1/(1+\alpha_s/\pi)]\,[1/(1-x_1)]F(x_1)\,, \qquad (1)$$

where [8]

$$F(x_1) = [4(3x_1^2 - 3x_1 + 2)/x_1]\ln[(2x_1-1)/(1-x_1)]$$
$$- 6(3x_1 - 2)(2 - x_1)\,,$$

which, of course, implies vector gluons. The experimental points of fig. 3 have been fully corrected for each bin separately. We find the x_1 distribution to be in excellent agreement with the theoretical prediction. The experimental x_1 distribution turns out to be insensitive to the specific model used to correct for detector effects and for efficiencies of the cluster algorithm. Using model (3) as an extreme example compared to model (2) we found the relative variations to be less than 15%. Furthermore the x_1 distribution is nearly independent of the actual choice of the fragmentation parameter σ_q. For $250 \leqslant \sigma_q \leqslant 350$ MeV we do not see any significant change of the slope, although the absolute normalisation varies according to α_s as mentioned above.

Formula (1) contains a $1/(1-x_1)$ pole which controls the steep rise of $(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}x_1)$ for $x_1 \to 1$. This term is characteristic of vector gluons. Hence it is of interest to check whether our data agree with the QCD pole behaviour. If we fit the exponent a of the term $[1/(1-x_1)]^a$ introduced into formula (1) and α_s simultaneously we get $\alpha_s = 0.08 \pm 0.05$ and $a = 1.3 \pm 0.3$, in good agreement with vector gluons.

Although scalar gluons can not be incorporated into an asymptotically free theory [20] the x_1 distribution has been predicted [6,8]. A fit of this scalar gluon prediction to the data points yields a $\chi^2/\mathrm{ND} = 9.1/4$ as shown in fig. 3b (dashed curve) and we obtain $\alpha_s^{\mathrm{scalar}} = 0.77 \pm 0.10$. If we average the x_1 distribution for $2/3 < x_1 < 0.95$, the predictions for vector and scalar gluons are 0.891 and 0.871, respectively. For the data we obtain $\langle x_1 \rangle = 0.893 \pm 0.005$. Hence the hypothesis of scalar gluons is strongly disfavoured in agreement with earlier conclusions from Υ(9.46) decays [9,21] and a recent study of three-jet events [22].

Finally we compare the x_1 distribution to the constituent interchange model (CIM) [23] which incorporates the characteristics of higher-twist terms. The dashed–dotted curve in fig. 3b is the absolute prediction of this model where the theoretical estimate of the coupling constant is $(g/4\pi)^2 \approx 220\ \mathrm{GeV}^2$. Clearly only a fraction of our three-jet events could be explained by higher-twist contributions. Furthermore we find only very few events, where one jet consists of a single π or ρ meson.

In conclusion we have analysed high-energy e^+e^- annihilation data by a cluster method which determines the observed number of jets in an event (n_j). Besides the dominating two-jet events a fraction of three-jet events is found, which cannot be explained by misidentified two-parton events nor by heavy-particle production. However, the observed n_j distribution is well reproduced by first-order QCD predictions. A limit on the production of heavy new particles which decay according to phase space is given. We determine the quark fragmentation parameter $\sigma_q = (290 \pm 20)$ MeV by analysing our two-jet events. From the fraction of three-jet events we obtain for the strong coupling constant $\alpha_s = 0.15 \pm 0.03 \pm 0.02$. The reconstructed x_1 distribution is in excellent agreement with predictions from first-order QCD. A hypothetical scalar-gluon model is strongly disfavoured and only a small fraction of our events can be explained by the CIM mechanism.

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