TOPOLOGY OF HADRONIC e^+e^- ANNIHILATION EVENTS AT 22 AND 34 GeV CM ENERGY

CELLO Collaboration

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The topology of hadronic e^+e^- annihilation events has been analysed using the sphericity tensor and a cluster method. Comparison with quark models including gluon bremsstrahlung yields good agreement with the data. The strong-coupling constant is determined in 1st order QCD to be $\alpha_s = 0.19 \pm 0.04$ (stat.) ± 0.04 (syst.) at 22 GeV and $\alpha_s = 0.16 \pm 0.02 \pm 0.03$ at 34 GeV. The differential cross section with respect to the energy fraction carried by the most energetic parton agrees with the prediction of QCD, but cannot be reproduced by a scalar gluon model. These results are stable against variations of the transverse momentum distribution of the fragmentation function within the quoted errors.

The occurrence of multijet events in high-energy e^+e^- annihilation [1] is usually attributed to quark pair production and colour-radiative processes as predicted by QCD [2]. The purpose of this paper is to check QCD predictions in hadronic events and to test the stability of the results against changes of the form of the transverse momentum distribution in the fragmentation chain.

We present an analysis of hadronic e^+e^- annihilation events recorded at 22 and 34 GeV c.m. energy using the CELLO detector [3] at PETRA. Charged particles are measured in cylindrical drift- and proportional chambers in a 1.3 T magnetic field yielding a momentum resolution of $\sigma_{p_\perp}/p_\perp \approx 2\% \cdot p_\perp$ ($p_\perp$ in GeV) over 92% of the solid angle. Photons are detected in a barrel lead liquid argon calorimeter in the angular range $|\cos\theta| < 0.86$. It offers an energy resolution of $13\%/\sqrt{E}$ and allows for fine lateral and longitudinal sampling.

Hadronic events are triggered if any of the following conditions are fulfilled: (1) at least 2 charged tracks with a transverse momentum above 200 MeV/c, or (2) an energy of more than 6 GeV deposited in the calorimeter, or (3) at least 1 charged track in the cylindrical wire chambers and more than 2 GeV in the calorimeter. In the analysis chain charged particles and neutral electromagnetic showers are taken into account if they exceed 200 MeV momentum or energy, respectively. Charged particles are assumed to carry the pion mass, neutral electromagnetic showers are assumed to originate from photons. Further requirements are imposed to remove background:
– more than 4 charged tracks originating from the interaction vertex with a total charge $\leqslant +6e$,
– at least 33% of the cm energy (E_{cm}) carried by these charged particles or at least 50% of E_{cm} carried by both charged and neutral particles.

Residual background from cosmic rays, beam gas, and QED processes (e, μ, τ-pair production) of $\lesssim 5\%$ is removed by visual scan of all hadronic candidates passing the above criteria. The remaining contaminations are $\lesssim 0.2\%$ from higher-order QED events and $\lesssim 2\%$ from two-photon scattering. The resulting statistics is 1477 events at 22 GeV and 2033 events at 34 GeV.

All particles are submitted to the following cluster algorithm [4]:

(1) Particles emitted close to each other are merged into preclusters. The procedure is started with the most energetic particle. The next energetic particle occurring within 30° is added. The procedure is iterated taking the sum of the momenta of all particles already merged in the precluster as the new starting direction.

(2) Preclusters are grouped into clusters if their axes are less than 45° apart.

(3) Clusters with more than 2 GeV total energy containing at least two particles (charged or neutral) are retained and treated as separate jets. The jets must contain $\geqslant 85\%$ of the visible energy.

Table 1 lists the number of three jet events found in this way at 22 and 34 GeV.

Data are compared to model calculations which include gluon bremsstrahlung. To describe the quark and gluon fragmentation we adapt the phenomenological model of ref. [5] assuming two types of transverse momentum distributions in the fragmentation chain:

(i) gaussian: $p_{\text{T}} \exp(-p_{\text{T}}^2/\sigma_{\text{q}})$,

(ii) exponential: $\exp(-p_{\text{T}}/\sigma_{\text{e}})$.

Monte Carlo (MC) generated events are passed through a realistic detector simulation and through the reconstruction chain. Initial-state radiative corrections are taken into account [6].

Different values for σ_{q} and σ_{e} have been tried within the range which gives a reasonable agreement between Monte Carlo simulation and data in the $p_\perp$ distribution of particles in the jets. The mean value of the experimental distribution is reproduced by $\sigma_{\text{q}} \approx 300$ MeV and $\sigma_{\text{e}} \approx 420$ MeV.

Table 1
Three-jet contributions from data and from $q\bar{q}$-Monte Carlo using different fragmentation models. (The number for $q\bar{q}$ are normalized to the number of accepted events in the data. The errors reflect the finite number of Monte-Carlo events processed through the analysis chain.)

	three-jet events		Data	$q\bar{q}$ gaussian	$q\bar{q}$ exponential
34 GeV					
2033 events accepted	no cut				
	in $\cos\theta_{jet}$	all	418		
		$T < 0.95$	314		
	$\lvert\cos\theta_{jet}\rvert < 0.8$	all	334	142 ± 8	230 ± 14
		$T < 0.93$	161	31 ± 4	61 ± 7
22 GeV					
1477 events accepted	$\lvert\cos\theta_{jet}\rvert < 0.8$	all	173	83 ± 9	
		$T < 0.91$	75	25 ± 5	

Recently it was claimed that the high-energy data on e^+e^- annihilation into hadrons might be explained without gluon Bremsstrahlung [7]. To study this we compare our data with pure $q\bar{q}$ Monte Carlo simulations. Fig. 1a shows the experimental $p_\perp$ distribution (i) and the results of two model predictions. The model with the gaussian distribution in the fragmentation (ii) underestimates the high-$p_\perp$ tails whereas

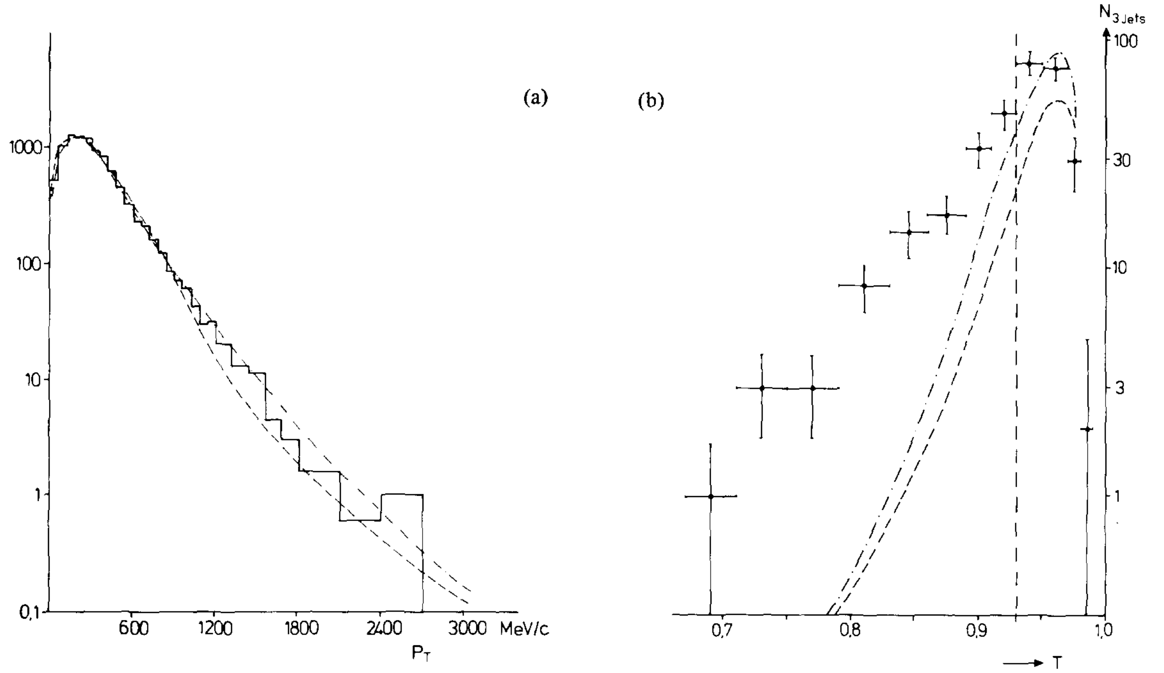

Fig. 1. Comparison of data with different $q\bar{q}$ fragmentation models. (a) Distribution of p_T in a jet for charged particles in the 2 jet sample, (i) (histogram) experimental distribution, (ii) (dashed curve) gaussian dependence in the fragmentation process with σ_q = 300 MeV/c, (iii) (dashed–dotted) exponential dependence with σ_e = 420 MeV/c. High $p_\perp$ values are overestimated. (b) Distribution of thrust T calculated from the jet momenta in 3 jet events. Experimental distribution and $q\bar{q}$ model calculations (dashed and dashed–dotted curves) using the $p_\perp$ distribution (ii) and (iii) described in (a). Both models fail to describe the data.

the exponential model (iii) is systematically higher at large $p_\perp$. The neutral tracks show analogue behaviour.

Both $q\bar{q}$ model calculations yield three jet events due to statistical fluctuations, however, their number cannot explain the data (table 1). To quantify this further we study the event thrust of the three-jet events which is defined by the jet momenta p_i [8]

$$T = \max\left(\sum_{i=1}^{3} |p_{\parallel i}| \Big/ \sum_{i=1}^{3} |p_i|\right) .$$

The data shown in fig. 1b are compared to model calculations (i) and (ii) normalized to the observed number of events. Neither of them can reproduce the data. Using the number of events with $T < 0.93$ in table 1 the hypothesis $q\bar{q}$ for both transverse momentum distributions is ruled out by 7 s.d.. This confirms results of other PETRA experiments [9].

The three-jet sample at 34 GeV is finally analysed to study the dynamics of the proposed underlying QCD process and to determine the value of the strong-coupling constant α_s.

For vector gluons the differential cross section with respect to the energy fraction x_1 of the most energetic parton is given by [2]

$$\frac{1}{\sigma_t}\frac{d\sigma}{dx_1} = \frac{2}{3}\frac{\alpha_s}{\pi}\frac{1}{1+\alpha_s/\pi}\frac{1}{1-x_1} \times \left(\frac{2(3x_1^2-3x_1+2)}{x_1}\ln\frac{2x_1-1}{1-x_1} - 3(3x_1-2)(2-x_1)\right) . \qquad (1)$$

The event thrust T calculated from the three-jet momenta turns out to measure x_1 (fig. 2a) to a very good approximation. MC studies show that in our detector T determines x_1 with an error of ≈ 0.02 and the efficiency is $(45 \pm 3)\%$ in the region $x_1 \geqslant 0.91$, dropping smoothly to about 38% at 0.95 (fig. 2b). If we restrict ourselves to the region $T \leqslant 0.95$ we retain 314 events. The migration of genuine two-jet events into the three jet class is determined by the MC simulation. It is 17% of the three-jet sample, contributing mainly to the region $T > 0.9$.

The resulting x_1 distribution corrected for two-jet contribution, efficiency and radiation is shown in fig. 3. A comparison with (1) yields good agreement with vector gluon bremsstrahlung as shown in fig. 3 (solid curve). The distribution for a hypothetical scalar gluon [2] does not reproduce the data (fig. 3, dashed curve) which agrees with the results of other PETRA groups [10,11].

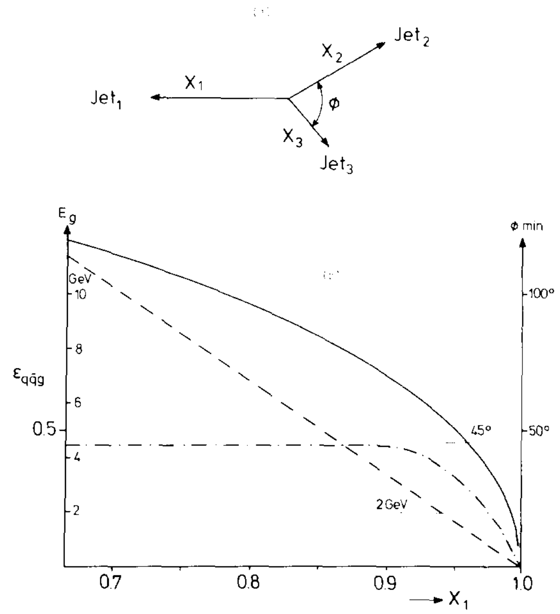

Fig. 2. Illustration of the cluster formalism. (a) Definition of parton variables. (b) Evaluation of x_1 distributions. (i) (full curve): x_1 dependence of jet separation described by the minimum opening angle ϕ_{min} between the two less energetic jets, (ii) (dashed) minimum energy of the gluon jet for given x_1 (for E_{cms} = 34 GeV), (iii) (dashed–dotted): x_1 dependence of the efficiency $\epsilon_{q\bar{q}g}$ for three jet detection (for E_{cms} = 34 GeV).

The only free parameter in comparing data and theory in fig. 3 is the strong-coupling constant α_s, which is 1st order QCD is directly related to the normalisation of the curve. For this comparison we consider only those events in which all jets have $|\cos\theta_{jet}| < 0.8$ to guarantee that the jets are well inside the cylindrical part of our detector. A best fit to the data in the region $T \leqslant 0.93$ where the two-jet contamination is small, yields an $\alpha_s = 0.15 \pm 0.02 \pm 0.03$ at 34 GeV. The systematic error of 0.03 reflects the uncertainties between data and Monte Carlo due to background of two-jet and > three-jet events, absolute normalisation and choice of the parameters in the fragmentation chain.

A similar analysis is carried out with the 22 GeV data. The number of genuine three-jet events is smaller (table 1) and the corrections from migrating two-jet events are more important. Within the re-

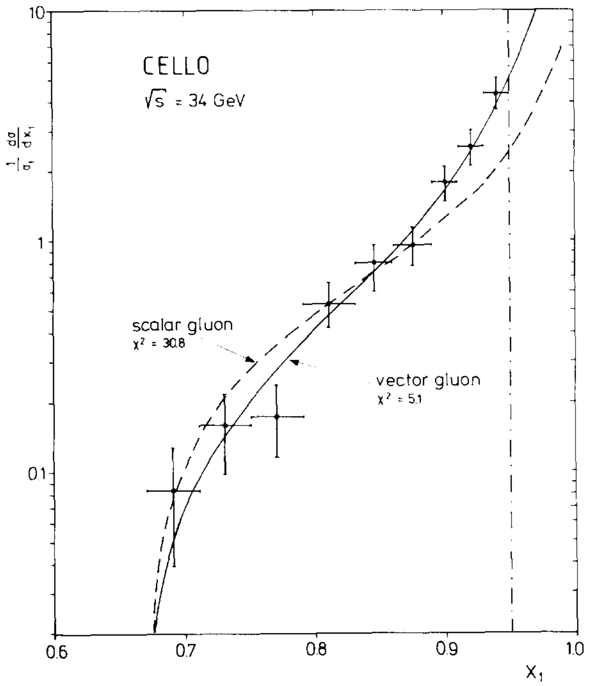

Fig. 3. Differential cross section of three jet events with respect to the energy fraction x_1 carried by the most energetic parton. Data are compared to the QCD prediction of vector gluons (full curve) and a scalar gluon model (dashed curve).

sulting large errors we find good agreement with QCD, in particular in the x_1 distribution. The value of α_s is $\alpha_s = 0.19 \pm 0.04 \pm 0.04$ at 22 GeV.

In addition we performed a standard topology analysis using the sphericity tensor [12]. From the number of planar events, i.e. events with a sphericity larger 0.25 and an aplanarity smaller 0.08 in our data and in the Monte Carlo simulation we deduce a value of $\alpha_s = 0.17 \pm 0.03 \pm 0.03$ at 34 GeV and $\alpha_s = 0.20 \pm 0.04 \pm 0.04$ at 22 GeV.

We made sure that this result is stable against variation of the cuts within the quoted statistical errors. We also checked the sensitivity of this α_s-evaluation to the shape of the Monte Carlo $p_\perp$ distribution used. Contrary to the cluster method all measured particles enter this analysis. Hence the method is more sensitive to tails in the $p_\perp$ distribution. Still the variation of α_s for different $p_\perp$ distributions (i) and (ii) stays within the quoted systematic errors (≈20%).

All these results are obtained using a Hoyer type

Table 2
Effective strong-coupling constant α_s measured at $E_{cm} \approx 30$ GeV from the rate of the multijet e^+e^--annihilations (first order QCD).

Experiment	α_s ± stat. ± syst. error
CELLO	0.16 ± 0.02 ± 0.03
JADE [13]	0.18 ± 0.03 ± 0.03
MARK J [14]	0.23 ± 0.02 ± 0.04
PLUTO [10]	0.15 ± 0.03 ± 0.02
TASSO [15]	0.17 ± 0.02 ± 0.03

[5] Monte Carlo simulation. The systematic errors quoted do not include different assumptions for the hadronization of the partons.

In conclusion we have studied hadronic e^+e^- annihilation at 22 and 34 GeV cm energy. We find good agreement with vector gluon bremsstrahlung of QCD and obtain as an average α_s value $\alpha_s = 0.19 \pm 0.04 \pm 0.04$ at 22 GeV and $\alpha_s = 0.16 \pm 0.02 \pm 0.03$ at 34 GeV. These α_s values are in good agreement with the ones measured by the other PETRA groups (table 2) [13, 14,10,15]. A scalar gluon model does not reproduce the data. The results are insensitive to the special choice of the transverse momentum distribution of the fragmentation function.

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References

[1] TASSO Collab., R. Brandelik et al., Phys. Lett. 86B (1979) 243;
MARK J Collab., D.P. Barber et al., Phys. Rev. Lett. 43 (1978) 830;
PLUTO Collab., Ch. Berger et al., Phys. Lett. 86B (1979) 418;

JADE Collab., W. Bartel et al., Phys. Lett. 91B (1980) 142.
[2] J. Ellis, M.K. Gaillard and G.L. Ross, Nucl. Phys. B111 (1976) 253.
[3] CELLO Collab., H.-J. Behrend et al., Phys. Scr. 23 (1981) 610.
[4] H.J. Daum, H. Mayer and J. Bürger, Z. Phys. C8 (1981) 167;
H.J. Daum, PhD thesis (1981), unpublished;
J. Dorfan, Z. Phys. C7 (1981) 349;
K. Lanius, H.E. Roloff and H. Schiller, Z. Phys. C8 (1981) 251.
[5] R.D. Field and R.P. Feynmann, Phys. Rev. D15 (1977) 2590; Nucl. Phys. B136 (1978) 1;
P. Hoyer et al., Nucl. Phys. B161 (1979) 349;
A. Ali et al., Z. Phys. C1 (1979) 203.
[6] F.A. Berends and R. Kleiss, DESY-report 80/66 (1980);
F.A. Berends et al., Phys. Lett. 63B (1976) 432.
[7] C.K. Chen, Purdue University preprint.
[8] S. Brandt et al., Phys. Lett. 12 (1964) 57;
E. Farhi, Phys. Rev. Lett. 39B (1977) 1587.
[9] MARK J Collab., D.F. Barber et al., MIT-LNS report No. 115 (1981);
TASSO Collab., in: W. Braunschweig, rapporteur talk 1981 Intern. Symp. on Lepton and photon interactions at high energies.
[10] PLUTO Collab., Ch. Berger et al., Phys. Lett. 97B (1980) 459;
[11] TASSO Collab., R. Brandelik at al., Phys. Lett. 97B (1980) 453.
[12] J.D. Bjorken and S. Brodsky, Phys. Rev. D1 (1970) 1416;
G. Hanson et al., Phys. Rev. Lett. 35 (1975) 1609.
[13] JADE Collab., W. Bartel et al., Phys. Lett. 91B (1980) 142.
[14] MARK J Collab., D.P. Barber et al., Phys. Lett. 89B (1980) 139.
[15] TASSO Collab., R. Brandelik et al., Phys. Lett. 94B (1980) 437.