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We present a study of 4200 4-jet events from Z^0 boson decays. The measured angular correlations between jets are reproduced well by QCD. An alternative abelian model fails to describe the data.

1. Introduction

One of the essential features of quantum chromodynamics QCD [1] is the self-interaction of gluons, a consequence of the nonabelian nature of QCD. Several tests of QCD which are sensitive to the gluon self-coupling in $e^+e^- \to$hadrons events have been proposed, which are based on a study of angular correlations in 4-jet events [2–4]. Such tests become feasible at the Z^0 resonance since the hadronic cross section and thus the number of 4-jet events is large.

We report here on measurements of angular distributions for 4200 4-jet events observed at $\sqrt{s} \approx 91$ GeV in the L3 detector at LEP, and on a comparison to QCD. We use an alternative abelian model, QCD′, to demonstrate the sensitivity of this comparison.

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2. Theoretical basis

Perturbative QCD predicts two classes of 4-jet events which correspond to the processes

$$Z^0 \to q\bar{q}gg \tag{1}$$

and

$$Z^0 \to q\bar{q}q\bar{q}\,. \tag{2}$$

The corresponding generic Feynman diagrams are shown in fig. 1. The first graph for process (1) contains a "three gluon vertex", a consequence of the nonabelian nature of QCD.

Differential and total cross sections for processes (1) and (2) can be written as a linear combination of gauge invariant terms with "colour factors" N_C, C_F and T_R as coefficients [5]. In QCD the colour factors are $N_C=3$, $C_F=\frac{4}{3}$ and $T_R=\frac{1}{2}N_F=\frac{5}{2}$, where N_F is the number of quark flavours.

An alternative model QCD′ without self-coupling of the spin-1 gluons can be constructed with three

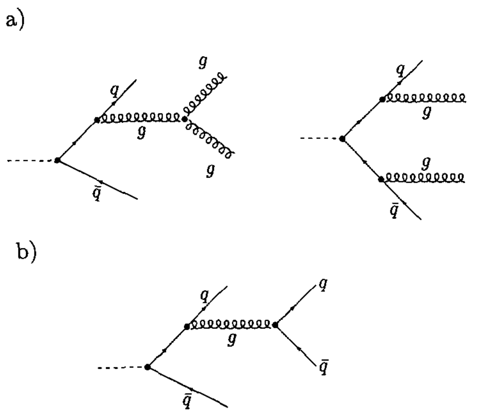

Fig. 1. Generic Feynman diagrams for production of four partons in second order perturbation theory for process (a) $Z^0 \to q\bar{q}gg$ and (b) $Z^0 \to q\bar{q}q\bar{q}$.

colour degrees of freedom for the quarks. In this abelian model the colour factors are $N'_C = 0$, $C'_F = 1$ and $T'_R = 3N_F = 15$ [3]. Choosing α'_s in this model to be $\frac{4}{3}\alpha_s$, the total cross section and 3-jet rates are the same in QCD and QCD′ up to first order for a given center of mass energy [6]. In QCD′ only the double bremsstrahlung diagrams contribute to process (1). The contribution of reaction (2) to the total 4-parton production cross section is about 34%, significantly larger than in QCD, where it is approximately 6% [7]. This difference in the rate of process (2) gives the main detectable difference between the models QCD and QCD′. Such an abelian model QCD′ is not compatible with various other measurements, for example the energy dependence of jet rates [8]. Its only purpose in this context is to provide a consistent theoretical alternative to QCD.

Three different variables have been proposed that are sensitive to the differences between QCD and QCD′. All of them are based on angular correlations between the four energy ordered jets. The most energetic jets 1 and 2 are likely to correspond to the "primary" quarks.

The variable proposed by Körner, Schierholz and Willrodt [2], Φ_{KSW}, is defined for events for which there are two jets in both hemispheres defined by the thrust axis. Φ_{KSW} is the angle between the normals to the plane containing the jets in one hemisphere and to the plane defined by the other two jets. Gluon alignment in the splitting process $g \to gg$ favours $\Phi_{KSW} \approx \pi$, whereas $g \to q\bar{q}$ prefers the planes to be orthogonal.

The Nachtmann–Reiter angle [3], Θ^*_{NR}, is the angle between the momentum vector differences of jets 1, 2 and jets 3, 4. Due to the different helicity structures, $\Theta^*_{NR} \approx 0$ is favoured by the process $g \to gg$ and $\Theta^*_{NR} \approx \frac{1}{2}\pi$ is favoured by $g \to q\bar{q}$.

Bengtsson and Zerwas [4] define χ_{BZ} as the angle between the plane containing jets 1, 2 and the plane containing jets 3, 4. Linear polarization of the gluon in $e^+e^- \to q\bar{q}g$ results in different distributions of χ_{BZ} for $g \to gg$ and $g \to q\bar{q}$.

QCD can thus be tested by comparing the measured distributions in the three above angular variables for 4-jet events to the theoretical predictions.

3. The L3 detector

The L3 detector covers 99% of 4π. The detector includes a central vertex chamber, a precise electromagnetic calorimeter composed of bismuth germanium oxide crystals, a uranium and brass hadron calorimeter with proportional wire chamber readout, a high accuracy muon chamber system, and a ring of scintillation trigger counters. These detectors are installed in a magnet with an inner diameter of 12 m. The magnet provides a uniform field of 0.5 T along the beam direction. The luminosity is measured with two small angle electromagnetic calorimeters. A detailed description of each detector subsystem, and its performance, is given in ref. [9].

The fine segmentation of the electromagnetic detector and the hadron calorimeter allows us to measure the axis of jets with an angular resolution of 2.5°, and to measure the total energy of hadronic events from Z^0 decay with a resolution of 12%.

For the present analysis, we used the data collected in the following ranges of polar angles:
- for the electromagnetic calorimeter, $42.4° < \theta < 137.6°$,
- for the hadron calorimeter, $5° < \theta < 175°$.

4. Selection of hadronic events

Events collected at center of mass energies $\sqrt{s} =$ 88.2–94.2 GeV from the 1990 (March–June) LEP running period are used for this analysis.

The primary trigger for hadronic events requires a total energy of 15 GeV in the central region of the calorimeters ($|\cos\theta| < 0.74$), or 20 GeV in the entire detector. This trigger is in a logical OR with a trigger using the barrel scintillation counters and with a charged track trigger. The total trigger efficiency for selected hadronic events exceeds 99.95%.

The selection of $e^+e^- \to$ hadrons events is based on the energy measured in the electromagnetic and hadron calorimeters:

$$0.6 < E_{vis}/\sqrt{s} < 1.4 ,$$

$$|E_{\parallel}|/E_{vis} < 0.40, \quad E_{\perp}/E_{vis} < 0.40 ,$$

$$N_{cluster} > 12 ,$$

where E_{vis} is the total energy observed in the detector, $E_{\parallel}$ is the energy imbalance along the beam direction, and $E_{\perp}$ is the transverse energy imbalance. An algorithm was used to group neighbouring calorimeter hits, which are most likely produced by the same particle, into clusters. Only clusters with a total energy above 100 MeV were used. The algorithm normally reconstructs one cluster for each particle produced near the interaction point. Thus the cut on the number of clusters rejects low multiplicity events ($Z^0 \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$).

In total 49 000 events were selected.

Applying these cuts to a sample of simulated events, we calculate an acceptance of 97% for hadronic decays of the Z^0.

The contamination from e^+e^- and $\tau^+\tau^-$ final states in the hadronic event sample is below 0.2% and can be neglected. The contribution to the event sample from the "two photon process" $e^+e^- \to e^+e^- +$ hadrons also has been found to be negligible.

All Monte Carlo distributions were generated by the parton shower program JETSET 7.2 [10] with $\Lambda_{LL} = 290$ MeV and string fragmentation. The b quark fragmentation function was adjusted to match our measured inclusive muon data [11]. The generated events were passed through the L3 detector simulation [12] which includes the effects of energy loss, multiple scattering, interactions and decay in the detector materials and beam pipe.

The simulated distributions in the cut quantities and in event shape variables agree very closely with the corresponding measured distributions [13].

5. Analysis of 4-jet events

Jets are reconstructed out of clusters in the calorimeters by using the JADE version [14] of an invariant mass jet algorithm. In this recombination scheme there is a close agreement between jet rates on parton and detector level. First the energy and direction of all clusters are determined. For each pair of clusters i and j the scaled invariant mass squared

$$y_{ij} = 2E_iE_j/E_{vis}^2 \cdot (1 - \cos\theta_{ij})$$

is then evaluated. E_i and E_j are the cluster energies and θ_{ij} is the angle between clusters i and j. The cluster pair for which y_{ij} is smallest is replaced by a pseudocluster k with four-momentum

$$p_k = p_i + p_j .$$

This procedure is repeated until all scaled invariant masses squared y_{ij} exceed the jet resolution parameter y_{cut}. The remaining (pseudo)clusters are called jets.

We have used $y_{cut} = 0.02$ for our study, which corresponds to jet pair masses of 13 GeV or more. This cut is sufficiently hard to be insensitive to the details of hadronization and heavy quark decays and at the same time leaves a large fraction of 4-jet events of about 9%. A total of 4200 4-jet events was selected.

Fig. 2 shows the measured energy distributions of the four energy ordered jets. The simulated distributions are in good agreement with the experimental ones.

For the Φ_{KSW} analysis only those events were used for which there are two jets in both hemispheres defined by the thrust axis. This requirement eliminates about 30% of all 4-jet events.

χ_{BZ} can be measured only for events for which the planes spanned by each jet pair are well defined. We required the angle between jets 1 and 2 and the angle between jets 3 and 4 to be less than 160°. This cut reduces the number of 4-jet events by 40%.

For the study of the $\cos\Theta^*_{NR}$ distribution all 4200 events were used.

To be able to compare the experimental 4-jet angular distributions to those predicted by the two theoretical models, we have corrected our data for de-

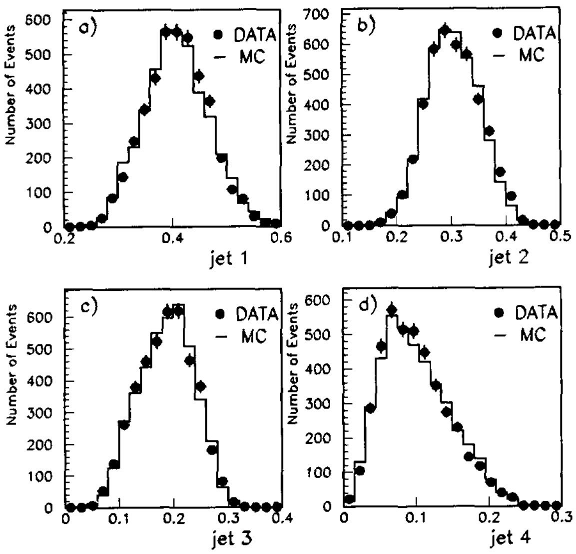

Fig. 2. Measured distributions of $E_{\rm jet}/E_{\rm vis}$ for energy ordered jets in 4-jets events in comparison with the Monte Carlo prediction (parton shower, $\Lambda_{\rm LL}=290$ MeV).

tector effects, acceptance and resolution. We used the JETSET 7.2 Monte Carlo program as described before. The RMS resolutions in the angular variable $\Phi_{\rm KSW}$, $\Theta^*_{\rm NR}$ and $\chi_{\rm BZ}$ are found to be 12°, 6° and 6°, respectively. We have corrected our measurements for resolution effects by applying the method of regularized unfolding described in ref. [15]. We subdivide the range of the allowed values for the three angular variables into four bins of equal size. The corrections due to the finite detector resolution and acceptance for the two outer bins is below 2% for $\Phi_{\rm KSW}$, less than 7% for $\cos\Theta^*_{\rm NR}$ and at most 10% for $\chi_{\rm BZ}$. The corrections for the two central bins are smaller.

Our data sample contains a background of 30% from 3-jet events on the generator level which are classified as 4-jet events after all particles have been passed through the full detector simulation and reconstruction. We also lose a fraction of 4-jet events on the generator level since they have jet multiplicities different from 4 on the detector level. However, this number is close to the number of background events. Furthermore, the difference in the angular distributions for these event classes is small and the total correction per bin is below 3%.

The uncertainties in the detector correction were studied by changing the energy response in different detector components in the Monte Carlo simulation by up to 10%. Larger variations are incompatible with the measured energy distributions in the calorimeters. We find a systematic uncertainty in the angular distribution of 2–5% for different bins.

6. Comparison to theoretical models

Figs. 3–5 show the corrected normalized distributions for the variables $\Phi_{\rm KSW}$, $\cos\Theta^*_{\rm NR}$ and $\chi_{\rm BZ}$ in comparison to the Monte Carlo predictions for both QCD and QCD′. To generate the theoretical predictions we used two different options in the JETSET 7.2 Monte Carlo program:

(a) Matrix elements, calculated to second order in QCD [5,16].

(b) Parton shower evolution, obtained from leading log approximations.

The differences between these two approaches can be considered as theoretical uncertainties [7,17]. For (a) we used the value $\Lambda_{\overline{\rm MS}}=190$ MeV [8] and a renormalisation scale $\mu^2=0.08s$ for the QCD prediction. For the abelian model the strong coupling constant was increased with respect to QCD by a factor of $\frac{4}{3}$. The parton shower calculations (b) were performed with $\Lambda_{\rm LL}=290$ MeV for QCD. For the abelian shower mode we used the JETSET parameters as suggested in ref. [7].

Fragmentation parameters were determined from a comparison between measured and predicted distributions for several event shape variables both for the QCD parton shower MC and the second order matrix element generator. The uncertainty due to hadronization was estimated by changing the fragmentation parameters. Replacing the measured ones by the JETSET default values (for parton shower) modifies the distributions by at most 5% per bin. We have assumed the same fragmentation parameters for the abelian model as for QCD.

In addition, a small correction for initial and final state radiation was applied, which changes the angular distributions by about 2% per bin.

The two bands in figs. 3–5 indicate the theoretical uncertainties coming from the difference between the matrix element and parton shower approaches and from hadronization uncertainties.

Fig. 3 shows that the differences between QCD and QCD′ are small in the Φ_{KSW} distribution. The measurements are consistent with either prediction.

The measured $\cos\Theta^*_{\mathrm{NR}}$ distribution clearly favours QCD and is incompatible with the abelian model, as can be seen in fig. 4. We obtain for three degrees of freedom $\chi^2(\mathrm{QCD}) = 5.0$ and $\chi^2(\mathrm{QCD}') = 39.8$ for the matrix element predictions, and $\chi^2(\mathrm{QCD}) = 0.7$ and $\chi^2(\mathrm{QCD}') = 33.2$ for the parton shower approach. In the calculation of the χ^2 values a theoretical error due to fragmentation of (2–5)% per bin was included.

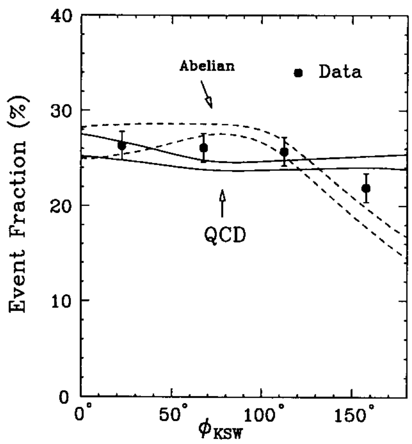

Fig. 3. Measured distribution of Φ_{KSW}. The predictions for QCD and the abelian model QCD′ are shown as bands indicating the theoretical uncertainties, see text.

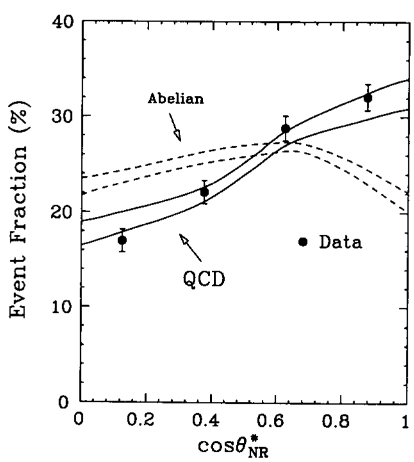

Fig. 4. Measured distribution of $\cos\Theta^*_{\mathrm{NR}}$. The predictions for QCD and the abelian model QCD′ are shown as bands indicating the theoretical uncertainties, see text.

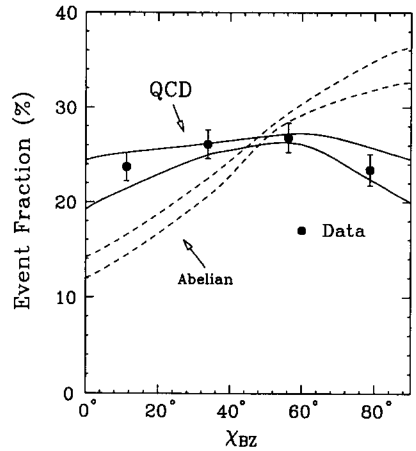

Fig. 5. Measured distribution of χ_{BZ}. The predictions for QCD and the abelian model QCD′ are shown as bands indicating the theoretical uncertainties, see text.

Fig. 5 exhibits the measured and predicted distributions for χ_{BZ}. Again we find that the QCD′ model fails to describe our data while QCD reproduces our measurements well. We obtain for three degrees of freedom $\chi^2(\mathrm{QCD}) = 3.0$ and $\chi^2(\mathrm{QCD}') = 33.8$ for the matrix element case, and $\chi^2(\mathrm{QCD}) = 0.9$ and $\chi^2(\mathrm{QCD}') = 61.6$ when using the parton shower evolution.

We have studied the dependence of the theoretical predictions on the value of y_{cut} in the range 0.02–0.04. QCD can reproduce all measured angular distributions for all those values of the jet resolution parameter.

The distributions of the variable $\cos\Theta^*_{\mathrm{NR}}$ and χ_{BZ} have been measured also by the AMY Collaboration [18].

7. Conclusions

We have studied the angular correlations between jets in 4200 4-jet events from Z^0 decays. The measured distributions in the angular variables $\cos\Theta^*_{\mathrm{NR}}$ and χ_{BZ} are reproduced by QCD, while the predictions of an alternative abelian model are found to be incompatible with our data. The main difference comes from the large rate of $q\bar{q}q\bar{q}$ final states in the abelian model.

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References

[1] M. Gell-Mann, Acta Phys. Austr. Suppl. IX (1972) 733;
H. Fritzsch and M. Gell-Mann, XVI Intern. Conf. on High energy physics (Batavia, 1972) Vol. II, p. 135;
H. Fritzsch, M. Gell-Mann and H. Leutwyler, Phys. Lett. B 47 (1973) 365;
D.J. Gross and F. Wilczek, Phys. Rev. Lett. 30 (1973) 1343; Phys. Rev. D 8 (1973) 3633;
H.D. Politzer, Phys. Rev. Lett. 30 (1973) 1346.

[2] J.G. Körner, G. Schierholz and J. Willrodt, Nucl. Phys. B 185 (1981) 365.

[3] O. Nachtmann and A. Reiter, Z. Phys. C 16 (1982) 45.

[4] M. Bengtsson and P.M. Zerwas, Phys. Lett. B 208 (1988) 306.

[5] R.K. Ellis, D.A. Ross and E.A. Terrano, Nucl. Phys. B 178 (1981) 421.

[6] K.J.F. Gaemers and J.A.M. Vermaseren, Z. Phys. C 7 (1980) 81.

[7] S. Bethke, A. Ricker and P.M. Zerwas, Four-jet decays of the Z^0: prospects of testing the triple gluon coupling, Z. Phys., to be published.

[8] L3 Collab., B. Adeva et al., Phys. Lett. B 249 (1990) 000.

[9] L3 Collab., B. Adeva et al., Nucl. Instrum. Methods A 289 (1990) 35.

[10] T. Sjöstrand, Comput. Phys. Commun. 39 (1986) 347; in: Z physics at LEP 1, CERN report CERN-89-08, Vol. III, p. 143;
T. Sjöstrand and M. Bengtsson, Comput. Phys. Commun. 43 (1987) 367.

[11] L3 Collab., B. Adeva et al., Phys. Lett. B 241 (1990) 416.

[12] GEANT Version 3.13 (September 1989):
see R. Brun et al., "GEANT 3", CERN DD/EE/84-1 (Revised) (September 1987);
to simulate hadronic interactions the program GHEISHA is used: see H. Fesefeldt, RWTH Aachen preprint PITHA 85/02 (1985).

[13] L3 Collab., B. Adeva et al., Phys. Lett. B 231 (1989) 509; B 237 (1990) 136; B 249 (1990) 000.

[14] JADE Collab., W. Bartel et al., Z. Phys. C 33 (1986) 23;
JADE Collab., S. Bethke et al., Phys. Lett. B 213 (1988) 235.

[15] V. Blobel, DESY report 84-118 (1984); RUN, general program for regularized unfolding (1984).

[16] F. Gutbrod, G. Kramer and G. Schierholz, Z. Phys. C 21 (1984) 235.

[17] Z. Kunszt and P. Nason, in: Z physics at LEP 1, CERN report CERN-89-08, Vol. I, p. 373.

[18] AMY Collab., I.H. Park et al., Phys. Rev. Lett. 62 (1989) 1713.