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First Measurements of Hadronic Decays of the Z Boson

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We have observed hadronic final states produced in the decays of Z bosons. In order to study the parton structure of these events, we compare the distribution in sphericity, thrust, aplanarity, and number of jets to the predictions of several QCD-based models and to data from lower energies. The data and models agree within the present statistical precision.

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In this Letter we present studies of the decays of Z bosons to hadronic final states. The experiment was performed with the Mark II detector at the SLAC e^+e^- Linear Collider (SLC). We focus on measurables which relate to testing the partonic structure that underlies the observed hadrons, namely, sphericity, aplanarity, thrust, and jet multiplicity.

The Mark II detector has been described in detail elsewhere.[1] The momenta of charged tracks are measured with a 72-layer drift chamber in a 4.75-kG solenoidal magnetic field. The momentum resolution, $\sigma(p)/p^2 = 0.0046\ (\mathrm{GeV}/c)^{-1}$, is measured from Bhabha-scattering events at a center-of-mass energy of 29 GeV at the SLAC storage ring PEP. The energy and direction of photons are measured in two electromagnetic calorimeter systems of strip-readout geometry which cover the angular region $|\cos\theta| < 0.96$, where θ is measured relative to the incident beam direction. The calorimeters in the central region ($|\cos\theta| < 0.72$) are lead-liquid-argon sampling calorimeters with an energy resolution of $\sigma(E)/E = 0.14/\sqrt{E}$ (E in GeV) for electromagnetic showers below 10 GeV. In the forward and backward regions there are lead-proportional-tube calorimeters with an energy resolution of $\sigma(E)/E$

$=0.22/\sqrt{E}$ (E in GeV).

The trigger for hadronic Z decays in a combination of charged-particle and neutral-energy triggers and is described in detail in Ref. 1. Two charged tracks in the angular region $|\cos\theta| < 0.76$ are sufficient for an event trigger. The system has considerable redundancy and has an estimated efficiency of greater than 0.99 for hadronic events from Z decay.

Events are selected by requiring at least seven well-reconstructed charged tracks and that the sum of charged-particle energies and shower energies (E_{vis}) be greater than $0.5E_{\mathrm{c.m.}}$. This selection ensures that the events are well contained within the sensitive regions of the detector and eliminates lepton pairs from the data sample.

Charged tracks must originate from the region of the e^+e^- collision point defined by a cylinder around the nominal collision point of radius 1 cm and half-length 3 cm along the beam direction. This requirement reduces the number of background tracks due to secondary interactions in the material of the detector and reduces the number of tracks from beam-gas events. In order to ensure well-measured momenta and a high tracking efficiency, the tracks must be within the angular region $|\cos\theta| < 0.82$ and must have transverse momenta with respect to the beam axis of at least 150 MeV/c. In the central calorimeters, showers are selected within a fiducial volume bounded by $|\cos\theta| < 0.68$ and within the active volume of the calorimeter in the azimuthal angle ϕ. The total solid angle coverage of the central calorimeters is 63.5%. In the forward and backward calorimeters, showers are selected within a fiducial volume of $0.74 < |\cos\theta| < 0.95$. All showers in the fiducial volume of the calorimeters are retained if their energy exceeds 0.5 GeV, irrespective of any association with a charged track.

The data used in this analysis have been collected during a scan of center-of-mass energy ($E_{\mathrm{c.m.}}$) ranging from 89.2 to 93.0 GeV, corresponding to an integrated luminosity of 9.9 nb^{-1}. The criteria given above select 185 events. The selection efficiency is estimated using QCD-based Monte Carlo generators[2-5] (described in detail later) to be 0.78 ± 0.02, where the error is the systematic uncertainty from different Monte Carlo models. The events removed by this selection tend to have large undetected energy close to the beam line, and studies with the Monte Carlo models demonstrate their removal does not bias the Z decay characteristics presented in this paper.

Event backgrounds resulting from beam-gas scattering, lepton pairs, and two-photon production are small. The number of beam-gas events has been estimated to be less than 0.4 by searching for events with vertices outside the required region. The numbers of background events from lepton pairs and from two-photon production have been estimated from Monte Carlo simulations to be less than 0.05 and 0.01 event, respectively.

The characteristics of the selected events are described in terms of the event-shape parameters sphericity (S), aplanarity (A), and thrust (T), and these quantities are compared to the expectations of QCD models. These shape parameters are commonly used in the literature and their full descriptions can be found in Ref. 6. In addition, a cluster algorithm is used to estimate the number of jets (N_{jet}) observed in each event. The analysis method for calculating N_{jet} is described in detail elsewhere.[7,8] Briefly, in each event the quantities $y_{kl} = M_{kl}^2/E_{\mathrm{vis}}^2$ are calculated for all pairs of particles k and l, where M_{kl} is the invariant mass of k and l. The pair with the smallest invariant mass is replaced by a pseudoparticle with four-momentum $P_k + P_l$. The procedure is repeated until the smallest y_{kl} exceeds a threshold value y_{cut}. The clusters formed by this procedure are called jets.

The quantities have been corrected for detector acceptance inefficiencies and for machine-related backgrounds using the following procedure. Simulated events have been generated using five-flavor QCD fragmentation models which were adjusted to fit the Mark II data at a center-of-mass energy of 29 GeV.[6] The models are the Lund parton shower model (Lund 6.3 shower),[2] the Webber-Marchesini parton shower model (Webber 4.1),[3] the parton shower model of Gottschalk and Morris (Caltech-II 86),[4] and the Lund model based on the second-order QCD matrix element calculated by Gottschalk and Shatz (Lund 6.3 M.E.).[2,5] The generated particle four-momenta are then used in a simulation of the responses of the Mark II detector components.

In addition, the contamination of the data arising from machine-related backgrounds is included. These backgrounds include soft phonons which are absorbed in the drift-chamber gas and result in spurious, saturated drift-chamber signals, and muons produced near the final focus of the SLC which deposit energy in the calorimeters. These backgrounds have been taken into account with a technique in which signals recorded in the detector during random beam crossings have been mixed with Monte Carlo simulated events. These mixed, simulated events have then been subjected to the same reconstruction and analysis procedures as the data.

The corrected distribution $dn_{\mathrm{cor}}(x)$ in a shape parameter x is obtained from the measured distribution $dn_{\mathrm{meas}}(x)$ using a bin-by-bin correction function $C(x)$:[6]

$$dn_{\mathrm{cor}}(x) = C(x)\,dn_{\mathrm{meas}}(x)\,.$$

$C(x)$ is calculated by

$$C(x) = \frac{n_{\mathrm{gen}}(x)/N_{\mathrm{gen}}}{n_{\mathrm{det}}(x)/N_{\mathrm{det}}}\,,$$

where N_{gen} and N_{det} are the generated and detected numbers of events and $n_{\mathrm{gen}}(x)$ and $n_{\mathrm{det}}(x)$ are the generated and detected numbers of events in the specified x

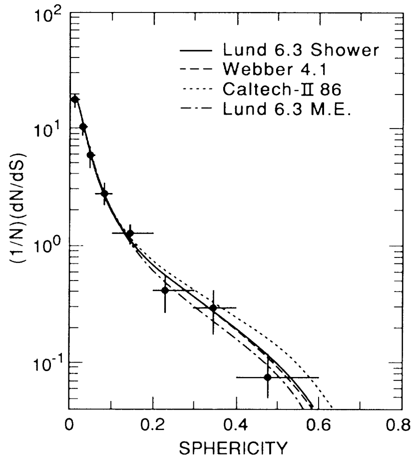

FIG. 1. Event sphericity for data (circles, with statistical errors) and four QCD Monte Carlo models (curves). Data points are plotted at the mean data value within each range and the horizontal bars show the extent of the range.

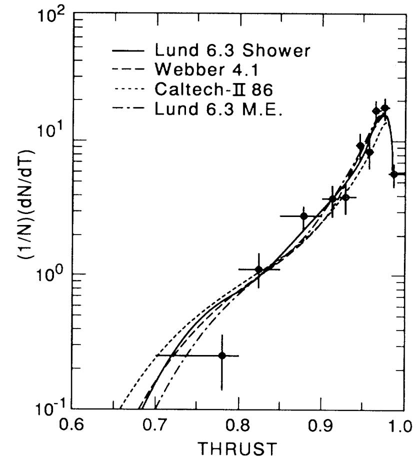

FIG. 3. Event thrust for data (circles, with statistical errors) and four QCD Monte Carlo models (curves).

bin as calculated using the Monte Carlo simulations. The correction factors varied within the range of 0.7 to 1.2.

The corrected distributions for the shape parameters sphericity, aplanarity, and thrust are shown in Figs. 1–3. Also shown are the predictions from several five-flavor QCD models for these quantities. These QCD-model predictions are in good agreement with the data. The mean values of the shape quantities have been measured to be $\langle S\rangle = 0.070 \pm 0.007$, $\langle A\rangle = 0.0110 \pm 0.0009$, and $\langle T\rangle = 0.935 \pm 0.004$, where the corrections for detector acceptance have been applied and the errors are statistical only.

The corrected fractions of two-, three-, four-, and five-jet events are shown in Fig. 4 as a function of y_{cut}. In Fig. 4 each event contributes at all values of y_{cut} and hence the statistical errors for different values of y_{cut} are not independent. As illustrated in Ref. 8, the corrected jet multiplicity is expected to reproduce rather closely the produced jet (parton) multiplicity. At a standard value of $y_{\text{cut}} = 0.08$, the fraction of three-jet events in hadronic events is 0.22 ± 0.03. For a high value of $y_{\text{cut}} = 0.14$, eight three-jet events are observed while the model expectation is fourteen events. This difference is not significant with the current statistics.

Statistical errors are the dominant uncertainties in these studies. One source of systematic error is the correction for machine-related backgrounds determined using the mixing technique described above. The effects of these backgrounds are increase in mean sphericity of

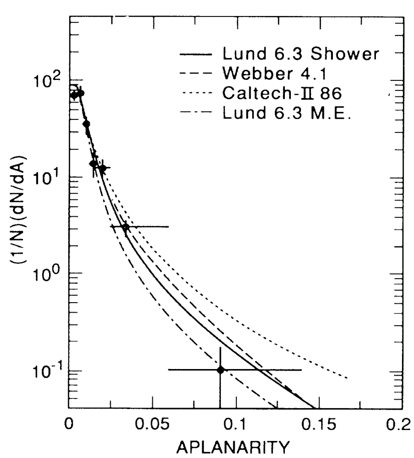

FIG. 2. Event aplanarity for data (circles, with statistical errors) and four QCD Monte Carlo models (curves).

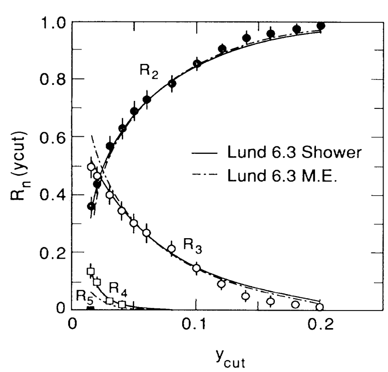

FIG. 4. The observed two-, three-, four-, and five-jet fractions for different values of y_{cut} (symbols, with statistical errors) and two QCD Monte Carlo model predictions (curves). For reasons of clarity, the other two models are not shown, but are also consistent with the data. Note that each event contributes at all values of y_{cut} and hence the statistical errors for different values of y_{cut} are not independent.

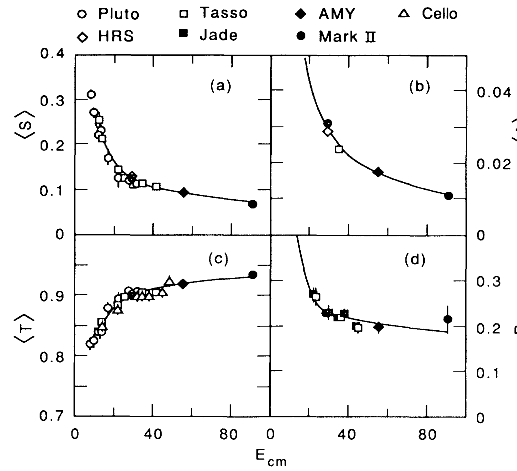

FIG. 5. The mean values of (a) sphericity, (b) aplanarity, (c) thrust, and (d) the three-jet fraction for a y_{cut} of 0.08 compared to data from several center-of-mass energies. The errors are statistical only. The only curves are the predictions from the Lund parton shower model.

7% and mean aplanarity of 12% and a decrease in mean thrust of 0.6%. The fraction of three-jet events is increased by less than 4% for the range of y_{cut} values used. The uncertainties in these corrections are small compared to the statistical errors.

The mean values of the corrected quantities are compared in Fig. 5 to mean values from other experiments[9] at different center-of-mass energies and to the values from this experiment at 29 GeV.[6,8] As the energy increases, the mean values of sphericity and aplanarity decrease and the mean value of thrust increases. These trends can be interpreted as evidence that the underlying parton kinematics are more distinct at higher center-of-mass energies due to the lessened importance of soft fragmentation effects. For comparison, the solid curves show the expectations from the Lund parton shower model which follows the data over a wide range of energies.

With the current statistical precision, all four QCD-based models account well for the data. No significant anomalies are seen and the global properties of the Z hadronic decays appear to be correctly predicted by QCD-based fragmentation models. Until higher statistics tests are available at these energies, it is reasonable to use the standard Monte Carlo models as a guide to the partonic properties of Z decays.

In conclusion, we have presented the first study of the global properties of the decays of Z bosons to hadrons. The data are in agreement with the predictions of the QCD-based fragmentation models optimized at lower energies at the SLAC storage ring PEP using the same detector.

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