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Physical Review Letters, 64(12)

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1990

10.1103/PhysRevLett.64.1334

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Measurements of Charged-Particle Inclusive Distributions in Hadronic Decays of the Z Boson


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(Received 18 December 1989)

We have measured inclusive distributions for charged particles in hadronic decays of the Z boson. The variables chosen for study were charged-particle multiplicity, scaled momentum, and momenta transverse to the sphericity axes. The distributions have been corrected for detector effects and are compared with data from \(e^+e^-\) annihilation at lower energies and with the predictions of several QCD-based models. The data are in reasonable agreement with expectations.

PACS numbers: 13.38.+e, 13.65.+i, 13.87.Fh

In this Letter we present measurements of charged-particle inclusive distributions in hadronic decays of the Z boson. These distributions allow us to study hadron production at higher energies than were previously available in \(e^+e^-\) annihilation. The leading theory of the strong interactions, QCD, predicts that many hadronization properties will have a logarithmic dependence on the center-of-mass energy (\(E_{\text{c.m.}}\)). Hence, comparisons of data from a wide range of \(E_{\text{c.m.}}\) values are of interest for testing these predictions. The data presented here were taken with the Mark II detector at the SLAC \(e^+e^-\) Linear Collider (SLC) running at several \(E_{\text{c.m.}}\) values near the Z-boson resonance peak at 91.1 GeV.\(^1\) These data correspond to a total integrated luminosity of 19.7 nb\(^{-1}\). Comparisons with lower-energy data are presented, in particular, with measurements at 29 GeV taken with the same detector.

The Mark II detector has been described in detail elsewhere.\(^2\) Charged particles are measured for \(|\cos\theta| < 0.92\), where \(\theta\) is the polar angle relative to the beam direction, with a 72-layer cylindrical drift chamber in a 4.75-kG solenoidal magnetic field. The momentum (\(p\)) resolution was determined from Bhabha-scattering events at 29 GeV \(E_{\text{c.m.}}\) to be \(\sigma(p)/p = 0.0046p\) (\(p\) in GeV/c). When the charged tracks are constrained to originate at the \(e^+e^-\) interaction point (IP), the momentum resolution improves to \(\sigma(p)/p = 0.0031p\). The energy and direction of photons are measured in two
electromagnetic calorimeter systems which together cover the angular region $|\cos\theta| < 0.96$. The trigger system is described in detail in Ref. 2. It includes charged-particle and neutral-energy triggers and has an estimated efficiency of greater than 99% for hadronic $Z$ decays.

Events were selected for this analysis on the basis of the reconstructed charged tracks and electromagnetic showers. The charged tracks were required to pass through a cylinder around the measured IP of radius 1 cm and half-length 3 cm along the beam direction. This reduced the number of beam-gas events and tracks from secondary interactions. The polar angles had to satisfy $|\cos\theta| < 0.82$, in order that the tracks traverse a sufficient number of drift chamber layers to have well-measured momenta. The momenta transverse to the beam direction were required to exceed 0.3 GeV/c, so that the tracking efficiency be well understood. For particles with momenta greater than 10 GeV/c, the tracks were refit using the IP as a constraint. This is not a useful procedure for lower-momentum particles because of systematic uncertainties in the amount of multiple scattering.

Electromagnetic showers in the central calorimeter were required to satisfy $|\cos\theta| < 0.68$ and to be within the fiducial volume of the calorimeter in azimuth, a total of 63.5% of the solid angle. The fiducial volume for the end-cap calorimeter was defined to be $0.74 < |\cos\theta| < 0.95$. An energy greater than 0.5 GeV was required for all showers in order to ensure high detection efficiency and reduce accelerator-related backgrounds. Showers were retained regardless of any association with a charged track.

Events were required to have at least seven charged tracks passing these cuts in order to reduce contamination from backgrounds, in particular, $Z \rightarrow \tau^+ \tau^-$. The visible energy was defined to be the sum of the energies of the selected charged particles, calculated assuming pion masses, and the energies of the showers passing the cuts. Events were selected if the visible energy was greater than $0.5E_{\text{c.m.}}$, to ensure the event was well contained. The number of events passing all selection criteria was 381. The efficiency for detecting events was estimated from Monte Carlo simulations to be $0.77 \pm 0.01$, where the error represents the systematic uncertainty due to differences in the fragmentation models used. Backgrounds from beam-gas scattering, $Z$ decays into lepton pairs, and two-photon scattering were estimated to be less than 0.5 event. Contamination from accelerator-related backgrounds was included by superimposing data from random beam crossings onto Monte Carlo events with detector simulation.

The data are compared with events simulated by three QCD-based Monte Carlo event generators. The models used are the Lund parton-shower model with string fragmentation (LUND 6.3 SHOWER), the Marchesini-Webber parton-shower model with cluster fragmentation (WEBBER 4.1), and the parton-shower model of Gottschalk and Morris (CALTECH-II 86) with a combined fragmentation method. The parameters of these models were tuned to fit Mark II data at 29 GeV. The Lund model based on the second-order QCD matrix element calculated by Gottschalk and Schatz, again with string fragmentation, was not used because an extrapolation to 91 GeV is not possible without changing parameters which should be kept constant.

The variables studied were the charged-particle multiplicity distribution, the inclusive charged-particle distributions in the scaled momentum ($x = 2p/E_{\text{c.m.}}$), and the momentum transverse to the axes of the sphericity tensor both in the event plane ($p_{\perp,\text{in}}$) and out of the event plane ($p_{\perp,\text{out}}$). The sphericity axes were calculated using all charged tracks and calorimeter showers passing the selection criteria.

The data were corrected for detector inefficiencies, resolutions, and machine backgrounds using bin-by-bin correction factors derived from the LUND 6.3 SHOWER Monte Carlo program with full detector simulation. Charged particles from all $K_S^0$, $K_L^0$, and $\Lambda$ decays were included in the corrected distributions. Typical correction factors were $\sim 1.2$, with a spread of $\sim 30\%$ for the different bins in each distribution. The correction factors were compared with those derived from the other QCD models and the differences were included in the systematic errors. Corrections for QED radiative effects were included but were less than 2% for these data. All errors shown for these data, except for the first figure, have statistical and systematic uncertainties added in quadrature.

The multiplicity distribution was not corrected using this bin-by-bin method because the correlations between bins are large. An unfold procedure was used to measure the mean corrected charged-particle multiplicity to

![Graph](image-url)

**FIG. 1.** Mean corrected charged-particle multiplicity vs $E_{\text{c.m.}}$ for various $e^+e^-$ experiments. The solid line is the Lund-shower-model prediction.
be $20.1 \pm 1.0 \pm 0.9$. The major systematic-error contribution arises from uncertainties in the drift-chamber efficiency. Figure 1 shows the mean charged-particle multiplicity versus $E_{c.m.}$ for several $e^+e^-$ experiments.\textsuperscript{11,12} For data where the systematic error was not published, note that only the statistical error is shown here. The solid line is the prediction of the Lund shower model, which has a value of 21.4 at 91.2 GeV. Only one model is shown for clarity; for comparison, the Webber model predicts a mean charged multiplicity of 20.1 and the Caltech-II model predicts 22.5.

Figure 2(a) shows the corrected inclusive distribution $(1/\sigma_{\text{had}})d\sigma_{\text{trk}}/dx$ compared with the predictions of the models, where $\sigma_{\text{had}}$ and $\sigma_{\text{trk}}$ are the total hadronic and charged-particle inclusive cross sections, respectively.

![Figure 2](image1)

**FIG. 2.** (a) Corrected charged-particle inclusive distribution $(1/\sigma_{\text{had}})d\sigma_{\text{trk}}/dx$, where $x = 2p/E_{c.m.}$, compared with several models. (b) Comparison between charged-particle inclusive distribution in $x$ for hadronic $Z$ decays and various $e^+e^-$ experiments at lower $E_{c.m.}$ The solid lines are the Lund-shower-model predictions.

![Figure 3](image2)

**FIG. 3.** (a) Corrected charged-particle inclusive distribution $(1/\sigma_{\text{had}})d\sigma_{\text{trk}}/dp_{\text{in}}$ compared with the predictions of several models and with Mark II data at 29 GeV. (b) Corrected charged-particle inclusive distribution $(1/\sigma_{\text{had}})d\sigma_{\text{trk}}/dp_{\text{out}}$ compared with the predictions of several models and with Mark II data at 29 GeV. (c) Comparison between means of charged-particle inclusive distributions in $p_{\text{in}}$ and $p_{\text{out}}$ for hadronic $Z$ decays and various $e^+e^-$ experiments at lower $E_{c.m.}$ The solid lines are the Lund-shower-model predictions.
All of the models predict a spectrum consistent with the observed distribution. Figure 2(b) shows \( \frac{1}{\sigma_{91}} \frac{d\sigma_{91}}{dx} \) vs \( E_{\text{c.m.}} \) for several \( x \) bins, comparing the results of this analysis with data from other \( e^+e^- \) experiments at lower \( E_{\text{c.m.}} \). The solid line is the prediction of the Lund shower model. Small scaling violations, in agreement with this model and qualitatively expected from QCD, are seen in the higher-\( x \) bins. The scaling violations in the lower-\( x \) bins are due to the increase in available phase space for particle production.

Figures 3(a) and 3(b) show the distributions of \( p_{\perp,\text{in}} \) and \( p_{\perp,\text{out}} \) together with the model predictions at 91 GeV and the Mark II data taken at 29 GeV. The 91-GeV data agree with the predictions of the models, within errors, over the range shown. A clear increase in transverse momentum at 91 GeV compared with 29 GeV is seen for both \( p_{\perp,\text{in}} \) and \( p_{\perp,\text{out}} \) in the perturbative region (\( p_\perp \geq 1 \) GeV/c). In contrast, the distributions show little difference in the low-\( p_\perp \) region, where \( E_{\text{c.m.}} \)-independent fragmentation effects are expected to dominate. The corrected mean-square values were measured to be \( \langle p_{\perp,\text{in}}^2 \rangle = 0.70 \pm 0.05 \) (GeV/c)\(^2 \) and \( \langle p_{\perp,\text{out}}^2 \rangle = 0.121 \pm 0.005 \) (GeV/c)\(^2 \), and these are compared with the results from other experiments in Fig. 3(c).

The solid lines show the Lund-shower-model predictions, which are slightly below our measured values for both \( \langle p_{\perp,\text{in}}^2 \rangle \) and \( \langle p_{\perp,\text{out}}^2 \rangle \). The differences arise mainly from the tails of the data distributions which are broader than the Monte Carlo predictions.

The charged-particle inclusive distributions presented here for hadronic decays of \( Z \) bosons are consistent with our extrapolations of the three models and lower-energy data. These models also described the detected event shapes, such as sphericity, thrust, aplanarity, and number of jets. The small differences observed when compared with the data, e.g., in the momenta transverse to the sphericity axes, are not indicative of significant inadequacies in the models.

This work was supported in part by Department of Energy Contracts No. DE-AC03-81ER40050 (California Institute of Technology), No. DE-AM03-76SF00010 (University of California, Santa Cruz), No. DE-AC02-86ER40253 (University of Colorado), No. DE-AC03-83ER40103 (University of Hawaii), No. DE-AC02-84ER40125 (Indiana University), No. DE-AC03-76SF00098 (LBL), No. DE-AC02-76ER01112 (University of Michigan), and No. DE-AC03-76SF00515 (SLAC), and by the National Science Foundation (Johns Hopkins University).

\(^9\)T. Sjöstrand, Int. J. Mod. Phys. A 3, 751 (1988), see p. 764. When changing energies in the Lund second-order matrix-element model, the parameter specifying the minimum invariant mass \( m_{\text{min}} \) between two partons should be kept constant. However, the value used in Ref. 7 at 29 GeV, \( m_{\text{min}} = 3.5 \) GeV, gives a negative two-parton cross section at 91 GeV. The smallest value which could be used at both energies is \( m_{\text{min}} = 9.3 \) GeV, but this value would not allow sufficient soft gluon radiation at 29 GeV.
\(^13\)Y. Li (private communication); KEK Report No. 89-149 (to be published).