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Properties of Hadronic Events in e^+e^- Annihilation at $\sqrt{s} = 91 \text{ GeV}$

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Abstract

We report on properties of hadronic events from e^+e^- annihilation observed by the ALEPH detector at the Large Electron Positron Collider at CERN. The center-of-mass energy was $\sqrt{s} = 91.0\text{--}91.3$ GeV. Measured distributions of the global event-shape variables sphericity, aplanarity, thrust and minor value, and of the inclusive variables x_p , $p_\perp^{in}$, $p_\perp^{out}$ and y are presented. We measure a mean charged multiplicity in hadronic events of $\langle N_{ch} \rangle = 21.3 \pm 0.1$ (statistical) ± 0.6 (systematic). The data are in good agreement with QCD-based models which use the leading-logarithm approximation, and are less well described by a model using $O(\alpha_s^2)$ QCD.

In this paper we report on properties of hadronic events from e^+e^- annihilation observed by the ALEPH detector during the first three weeks of physics running at LEP. The measurements are based on a sample of 1491 hadronic events with center-of-mass energies in the range $\sqrt{s} = 91.0 - 91.3$ GeV, close to the peak of the Z resonance [1,2,3]. Measured distributions of several global event-shape and inclusive variables based on charged particles are presented. These are compared with the predictions of QCD-based hadron-production models which are in reasonable agreement with data at $\sqrt{s} = 29$ GeV. Extrapolating these models to a higher energy while retaining the same parameter values provides an important test of the hadron-production mechanism.

A detailed description of the apparatus is in preparation [4]. A brief description of the detector components crucial to this analysis is given here. The ALEPH detector measures the momenta of charged particles with an inner tracking drift chamber (ITC) and a time-projection chamber (TPC), situated in a 1.5 T magnetic field from a superconducting solenoid. The TPC measures for charged tracks up to 21 three-dimensional coordinates between radii of 40 and 170 cm, with a point resolution for radial tracks of approximately $200 \mu m$ in $r\phi$ and $1 - 2$ mm in the z direction. The momentum resolution presently achieved is typically $\Delta p/p^2 \approx 0.002 (GeV/c)^{-1}$ for $p > 4 (GeV/c)$. The track finding efficiency is estimated by Monte Carlo studies to be 96 ± 2 % for the momentum and angular range used in this analysis. Also located inside the solenoid is an e/γ calorimeter (ECAL) con-

sisting of 45 lead sheets interspersed with wire chambers. Outside the coil is a hadron calorimeter (HCAL) of 23 iron slabs interspersed with streamer tubes, which also serves as a magnetic-flux return. The triggers relevant for hadronic events are based on a minimum energy threshold from the ECAL anode-wire signals or on charged particle penetration through the HCAL in coincidence with corresponding track information from the ITC.

The track and event selection criteria are the following: Charged tracks are required to have at least four coordinates measured by the TPC, a polar angle in the range $20^\circ < \theta < 160^\circ$, a momentum $p \geq 200 \text{ MeV}/c$, and to extrapolate to within 3 cm of the beam axis and to within 5 cm of the origin in the direction parallel to the beam. Hadronic events are selected by requiring at least five charged tracks and a total charged energy of at least 15 GeV. In addition, it is required that the polar angle of the sphericity axis be in the range $35^\circ < \theta_s < 145^\circ$ so that the event is well contained in the detector. These cuts result in a sample of 1491 events. Varying the track- and event-selection criteria does not produce significant changes in the final results. The largest background is from the reaction $e^+e^- \rightarrow \tau^+\tau^-$. This is estimated to be 0.25% of the accepted events, which does not cause a significant systematic uncertainty in this analysis.

The measured distributions were corrected using Monte Carlo programs for effects of geometrical acceptance, detector efficiency and resolution, decays, particle interactions with the material of the detector, initial state photon radiation and effects of event and track selection. First, hadronic

events with u, d, s, c and b quarks were generated using the Lund Parton-Shower model [5] (program JETSET version 6.3) including initial state photon radiation. The events were processed through the detector simulation program to produce simulated raw data, which were then processed by the same reconstruction and analysis programs as used for the real data. A second set of Monte Carlo data was generated, but here with all particles having mean lifetimes less than 10^{-9} seconds required to decay, all others treated as stable, and with initial state radiation turned off. A correction factor for each data point was obtained by comparing the bin occupancy of a Monte Carlo distribution from the second data set (event generator alone) to that obtained from the first (with detector simulation, decays, reconstruction and analysis cuts included). These factors are typically in the range 0.8 to 1.2, and are in all cases between 0.6 and 1.8.

Systematic errors due to uncertainties in the correction factors are dominated by discrepancies between the actual detector performance and that described by the simulation program. To estimate these errors, the simulated data were varied to introduce a number of possible systematic effects, such as shifts in track angles and momenta, increased momentum smearing and loss of track coordinates. Systematic uncertainties due to the resulting changes in the correction factors are in all cases smaller than or comparable to the statistical errors. (For example, studies with straight tracks in the TPC from a laser calibration system indicate that systematic errors in the track curvature, $c = 1/\sqrt{p_x^2 + p_y^2}$, are less than $0.001 \text{ (GeV/c)}^{-1}$).

This would imply a 12 % shift in the inclusive distribution of scaled track momentum, $x_p = p/p_{beam}$, for $0.6 \leq x_p \leq 0.8$, while the statistical error for this bin is 17 %. This effect produces negligible errors for lower momentum tracks.) Different event generators (Lund PS [5] and Lund ME [6], see below) were investigated for computing the correction factors, and the systematic error due to the choice of generator was found to be small compared to the statistical errors. Unless otherwise stated, the error bars shown on the plots for ALEPH data are statistical only.

The measured distributions are compared with the predictions of several QCD-based hadron-production models: the Lund Parton-Shower (PS) model [5,9], the Lund Matrix-Element (ME) model [6,9] (both from the program JETSET version 6.3) and the Webber-Marchesini model as implemented in the program HERWIG version 3.4 [7,8,9]. It is assumed for the model predictions that only u, d, s, c and b quarks are produced. In both Lund PS and HERWIG, the quark-antiquark pair resulting from the Z decay evolves into a system of quarks and gluons according to the leading-logarithm approximation of QCD. In this approach, successive branchings of the type $q \rightarrow qg$, $g \rightarrow gg$, $g \rightarrow q\bar{q}$ are repeated until the invariant mass of the resulting two-parton system falls below a specified cut-off. In Lund ME, the parton level is described by exact $O(\alpha_s^2)$ matrix elements and hence produces a maximum of four final state partons. In Lund PS and Lund ME, the transformation of the quarks and gluons into observable hadrons is described by string fragmentation [10] and in HERWIG using

cluster fragmentation. The parameters used in Lund ME and Lund PS were determined by fitting to data from the Mark II experiment at $\sqrt{s} = 29$ GeV [11]. For HERWIG, the default parameters have been derived from its predecessor, BIGWIG [8], which is in reasonable agreement with the data at lower energies [11,12].

We have measured the distributions of the global event shape variables sphericity, aplanarity, thrust and minor value. Sphericity and aplanarity are obtained from the eigenvalues of the momentum tensor $M_{\alpha\beta} = \sum_j p_{\alpha j} p_{\beta j}$, where α and β refer to the x , y and z directions, and the sum is carried out over all of the charged particles in the event. Normalizing the eigenvalues, Q_i , such that $Q_1 + Q_2 + Q_3 = 1$, and ordering them such that $0 < Q_1 < Q_2 < Q_3$, one defines the sphericity as $S = \frac{3}{2}(Q_1 + Q_2)$ and the aplanarity as $A = \frac{3}{2}Q_1$. The eigenvector $\mathbf{n}_3$ defines the sphericity axis, and $\mathbf{n}_2$ and $\mathbf{n}_3$ define the event plane. The sphericity ($0 \leq S \leq 1$) approaches zero for extreme two-jet events and one for spherical events. The aplanarity ($0 \leq A \leq 0.5$) is a measure of event flatness, approaching zero for planar events. Measured distributions of sphericity and aplanarity are shown in Figures 1(a) and 1(b) respectively. Also shown on the plots are data from the Mark II experiment at $\sqrt{s} = 29$ GeV [11]. One observes a large increase in the fraction of low sphericity and low aplanarity events at higher energy, indicating an increased jet-like structure. Also shown are predictions at $\sqrt{s} = 91$ GeV of the three previously discussed models, all of which are in reasonable agreement with the measured sphericity distribution. The aplanarity

arity distribution, however, is well described by Lund PS, somewhat less well by HERWIG, and is in significant disagreement with Lund ME. The deficit of high aplanarity events in Lund ME has already been observed at lower energies [11,12,13] and can be qualitatively explained by the absence of five- and higher-parton final states in $O(\alpha_s^2)$ QCD.

Alternatives to sphericity and aplanarity are the variables thrust and minor value. The thrust of an event is defined as $T = \max(\sum_j |p_{||j}| / \sum_j |p_j|)$ where the sum is over all charged particles in the event and $p_{||}$ refers to the momentum component along the axis for which T is maximum (the thrust axis). The direction perpendicular to the thrust axis relative to which the corresponding sum of parallel momenta is maximized is called the major axis, and the axis perpendicular to the thrust and major axes is the minor axis. The minor value is defined as $M = \sum_j |p_{||j}| / \sum_j |p_j|$ where $p_{||}$ is the momentum component along the minor axis. The thrust approaches one for extreme two-jet events, and the minor value approaches zero for planar events. Since they are linear in momentum, thrust and minor value are more sensitive to low momentum particles and less sensitive to decays than sphericity and aplanarity. Measured distributions for thrust and minor value are shown in Figures 1(c) and 1(d) respectively, along with the lower energy Mark II data and the model predictions. As is the case for sphericity and aplanarity, the measured thrust and minor value distributions show increased jet-like structure at higher energy and more aplanar events than predicted by Lund ME.

The single particle inclusive distributions of transverse momentum in and out of the event plane provide an additional measure of the overall event shape. These are defined as $p_{\perp}^{in} = |\mathbf{p} \cdot \mathbf{n}_2|$ and $p_{\perp}^{out} = |\mathbf{p} \cdot \mathbf{n}_1|$ where $\mathbf{n}_1$ and $\mathbf{n}_2$ are normalized eigenvectors of the momentum tensor. Measured distributions of $p_{\perp}^{in}$ and $p_{\perp}^{out}$ are shown in Figures 2(a) and 2(b) respectively. The larger number of particles with high $p_{\perp}^{in}$ at higher energy indicates an increase in the number of three-jet events, as predicted by all three of the models. The Lund ME model, however, fails to predict enough particles with high $p_{\perp}^{out}$, corresponding to a deficit of four- and higher-jet events.

Figure 2(c) shows the inclusive distribution of $x_p = p/p_{beam}$, where p is the particle's momentum. The ALEPH data at high x_p lie below the 29 GeV data. Such an effect is predicted by QCD because of the increased gluon radiation at higher energy, suppressing the production of high- x_p particles. Energy dependence of the x_p distribution is also expected from the change in quark-flavor content from the Z decay as opposed to the virtual photon decay at lower energy. The Lund ME prediction at high x_p is above both the ALEPH data and the other models. This stems from the smaller amount of gluon radiation in $O(\alpha_s^2)$ QCD relative to that obtained from the leading-logarithm approach.

An additional inclusive variable is the rapidity, $y = \frac{1}{2} \ln \left(\frac{E+p_{\parallel}}{E-p_{\parallel}} \right)$. Here, $p_{\parallel}$ refers to the component of the momentum parallel to the thrust axis, and the energy, E , is obtained from the particle's momentum assuming the pion mass. The ALEPH data, model predictions and lower energy data

are shown in Figure 2(d) (folded around $y = 0$). The rapidity distributions predicted by Lund PS and HERWIG are in good agreement with the data, whereas the Lund ME prediction is not. The smaller area under the Mark II rapidity distribution corresponds to the smaller mean charged multiplicity at lower energy.

It is convenient to obtain the mean charged multiplicity, $\langle N_{ch} \rangle$, by integrating the rapidity distribution since it is smoothly varying over the entire kinematic range. Doing so for the ALEPH data one obtains $\langle N_{ch} \rangle = 21.3 \pm 0.1$ (statistical) ± 0.6 (systematic). The systematic error is dominated by uncertainties in the track finding efficiency. The mean charged multiplicity in Lund ME rises from 12.8 at $\sqrt{s} = 29$ GeV to only 18.1 at 91 GeV. For Lund PS, the corresponding increase is from 12.9 to 21.2, and for HERWIG from 12.8 to 20.8. Mean charged multiplicities measured by ALEPH and by other experiments at lower energies [14] along with model predictions are shown in Figure 3.

The measurements presented here are in agreement with results recently reported by the Mark II collaboration at the SLC [16]. Because of the larger data sample, the ALEPH measurements provide a more sensitive discrimination between different hadron-production models. The overall level of agreement between the data and model predictions is summarized by the χ^2 values shown in Table 1. Lund PS agrees with the data remarkably well given that the parameters were fit to data at $\sqrt{s} = 29$ GeV. Although the Webber-Marchesini model as implemented in the program BIGWIG

is in fairly good agreement with the data at lower energy, the parameters in HERWIG have not been tuned, which could account for its somewhat worse agreement with the ALEPH measurements. We observe significantly more aplanar events than predicted by Lund ME, in confirmation of measurements at lower energies [11,12,13,15]. We find in addition that the mean charged multiplicity predicted by Lund ME does not increase rapidly enough with center-of-mass energy to describe the data, whereas Lund PS and HERWIG accurately predict this quantity. It should be noted that the evidence against Lund ME may not apply if the renormalization point of the perturbation series is optimized. In this case, recent studies have indicated that one may be able to achieve agreement with experiment [17,18].

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Figure 1: Distributions of event-shape variables from this analysis ($\sqrt{s} = 91$ GeV, statistical errors only), Mark II ($\sqrt{s} = 29$ GeV [11], error bars statistical and systematic) and predictions of hadron-production models: Lund Parton-Shower, Lund Matrix-Element and HERWIG: a) sphericity; b) aplanarity; c) thrust; d) minor value.

Figure 2: Distributions of inclusive variables from this analysis ($\sqrt{s} = 91$ GeV, statistical errors only), Mark II ($\sqrt{s} = 29$ GeV [11], error bars statistical and systematic) and predictions of hadron-production models: Lund Parton-Shower, Lund Matrix-Element and HERWIG: a) transverse momentum in the event plane, $p_{\perp}^{in}$; b) transverse momentum out of the event plane, $p_{\perp}^{out}$; c) $x_p = p/p_{beam}$; d) rapidity, y (folded around $y = 0$).

Figure 3: The mean charged multiplicity, $\langle N_{ch} \rangle$, as a function of center-of-mass energy from this analysis and from experiments at lower energies [14] with the predictions of hadron production models: Lund Parton-Shower, Lund Matrix-Element and HERWIG. The error bars represent the quadratic sum of statistical and systematic uncertainties, except for the TOPAZ and ADONE errors, which are statistical only.

Distribution	Degrees of freedom	χ^2		
		Lund PS	Lund ME	HERWIG
sphericity	12	12.4	82.0	53.7
aplanarity	11	5.9	311.7	59.2
thrust	12	18.7	111.8	51.3
minor	12	6.2	357.4	37.3
x_p	20	20.6	632.9	50.8
y	21	19.2	878.2	51.5
$p_{\perp}^{in}$	24	61.7	619.9	293.7
$p_{\perp}^{out}$	20	25.2	775.9	295.2

Table 1: χ^2 values for the hadron-production models: Lund Parton-Shower, Lund Matrix-Element and HERWIG.

Figure 1(a)

Figure 1(b)

Figure 1(c)

Figure 1(d)

Figure 2(a)

Figure 2(b)

Figure 2(c)

Figure 2(d)

Figure 3