

ARTICLES

Study of the orientation and energy partition of three-jet events in hadronic Z^0 decays

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We have measured the distributions of the jet energies in $e^+e^- \rightarrow q\bar{q}g$ events, and of the three orientation angles of the event plane, using hadronic Z^0 decays collected in the SLD experiment at SLAC. We find that the data are well described by perturbative QCD incorporating vector gluons. We have also studied models of scalar and tensor gluon production and find them to be incompatible with our data. [S0556-2821(97)00105-7]

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I. INTRODUCTION

The observation of e^+e^- annihilation into final states containing three hadronic jets [1], and their interpretation in terms of the process $e^+e^- \rightarrow q\bar{q}g$ [2], provided the first direct evidence for the existence of the gluon, the gauge boson of the theory of strong interactions, quantum chromodynamics (QCD) [3]. Following these initial observations, studies of the partition of energy among the three jets were performed at the DESY e^+e^- collider PETRA and SLAC e^+e^- storage ring PEP. Comparison of the data with leading-order QCD predictions, and with a model incorporating the radiation of spin-0 (scalar) gluons, provided qualitative evidence [4] for the spin-1 (vector) nature of the gluon, which is a fundamental element of QCD. Similar studies have since been performed at the CERN e^+e^- collider LEP [5,6].

An additional interesting observable in three-jet events is the orientation of the event plane with respect to the beam direction, which can be described by three Euler angles. These angular distributions were studied first by TASSO [7], and more recently by L3 [5] and DELPHI [8]. Again, the data were compared with the predictions of perturbative QCD and a scalar gluon model, but the Euler angles are less sensitive than the jet energy distributions to the differences between the two cases.

Here we present measurements of the jet energy and event plane orientation angle distributions from hadronic decays of Z^0 bosons produced by e^+e^- annihilations at the SLAC Linear Collider (SLC) and recorded in the SLC Large Detector (SLD). We used particle energy deposits measured in the SLD Liquid Argon Calorimeter, which covers 98% of the solid angle, for jet reconstruction. We compare our measured distributions with the predictions of perturbative QCD and a scalar gluon model. In addition, we make the first comparison [9] with a model which comprises spin-2 (tensor) gluons and discuss limits on the possible relative contributions of

scalar and tensor gluons to three-jet production in e^+e^- annihilation.

In Sec. II the observables are defined, and the predictions of perturbative QCD and of the scalar and tensor gluon models are discussed. We describe the detector, the event trigger, and the selection criteria applied to the data in Sec. III. The three-jet analysis is described in Sec. IV, and a summary and conclusions are presented in Sec. V.

II. OBSERVABLES AND THEORETICAL PREDICTIONS

A. Scaled jet energy distributions

Ordering the three jets in $e^+e^- \rightarrow q\bar{q}g$ according to their energies, $E_1 > E_2 > E_3$, and normalizing by the c.m. energy \sqrt{s} , we obtain the scaled jet energies

$$x_i = \frac{2E_i}{\sqrt{s}} \quad (i=1,2,3), \quad (1)$$

where $x_1 + x_2 + x_3 = 2$. Making a Lorentz boost of the event into the rest frame of jets 2 and 3, the Ellis-Karliner angle θ_{EK} is defined [10] to be the angle between jets 1 and 2 in this frame. For massless partons at the three level,

$$\cos \theta_{\text{EK}} = \frac{x_2 - x_3}{x_1}. \quad (2)$$

The inclusive differential cross section can be calculated to $O(\alpha_s)$ in perturbative QCD incorporating spin-1 (vector) gluons and assuming massless partons [11]:

$$\frac{1}{\sigma} \frac{d^2\sigma^V}{dx_1 dx_2} \propto \frac{x_1^3 + x_2^3 + (2 - x_1 - x_2)^3}{(1 - x_1)(1 - x_2)(x_1 + x_2 - 1)}. \quad (3)$$

One can also consider alternative ‘‘toy’’ models of strong interactions. For a model incorporating spin-0 (scalar) gluons, one obtains, at leading order at the Z^0 resonance [12],

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$$\frac{1}{\sigma} \frac{d^2\sigma^s}{dx_1 dx_2} \propto \left[\frac{x_1^2(1-x_1) + x_2^2(1-x_2) + (2-x_1-x_2)^2(x_1+x_2-1)}{(1-x_1)(1-x_2)(x_1+x_2-1)} - R \right], \quad (4)$$

where

$$R = \frac{10 \sum_j a_j^2}{\sum_j (v_j^2 + a_j^2)} \quad (5)$$

and a_j and v_j are the axial and vector couplings, respectively, of quark flavor j to the Z^0 . For a model of strong interactions incorporating spin-2 (tensor) gluons (see the Appendix), one obtains, at leading order,

$$\frac{1}{\sigma} \frac{d^2\sigma^T}{dx_1 dx_2} \propto \frac{(x_1+x_2-1)^3 + (1-x_1)^3 + (1-x_2)^3}{(1-x_1)(1-x_2)(x_1+x_2-1)}. \quad (6)$$

Singly differential cross sections for x_1 , x_2 , x_3 , or $\cos\theta_{EK}$ were obtained by numerical integrations of Eqs. (3), (4), and (6). These cross sections are shown in Fig. 1, the shapes are different for the vector, scalar, and tensor gluon cases.

It is well known that vector particles coupling to quarks in either Abelian or non-Abelian theories allow consistent and renormalizable calculations to all orders in perturbation theory. However, the scalar and tensor gluon models have limited applicability beyond leading order. In the scalar model no symmetry, such as gauge invariance, exists to prevent the gluons from acquiring mass. In the tensor case the model is nonrenormalizable (see the Appendix), so that higher-order predictions are not physically meaningful. Given these difficulties, we limit ourselves to the leading-order expressions for three-jet event production in these two cases. In the vector case we do consider the influence of higher-order corrections to the leading-order predictions. We

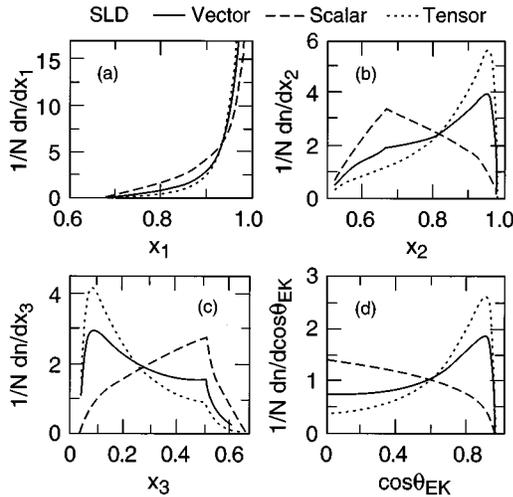


FIG. 1. Leading-order calculations, incorporating vector (solid lines), scalar (long dashed lines), and tensor (short dashed lines) gluons, of distributions of (a) scaled energy of the highest-energy jet, (b) scaled energy of the second-highest-energy jet, (c) scaled energy of the lowest-energy jet, and (d) the Ellis-Karliner angle.

also assume that the transformation of the partons in three-jet events into the observed hadrons is independent of the gluon spin.

B. Event-plane orientation

The orientation of the three-jet event plane can be described by the angles θ , θ_N , and χ illustrated in Fig. 2. When no explicit quark, antiquark, or gluon jet identification is made, θ is the polar angle of the most energetic jet with respect to the electron beam direction, θ_N is the polar angle of the normal to the event plane with respect to the electron beam direction, and χ is the angle between the event plane and the plane containing the electron beam and the most energetic jet. The distributions of these angles may be written [12]

$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha(T)\cos^2\theta, \quad (7)$$

$$\frac{d\sigma}{d\cos\theta_N} \propto 1 + \alpha_N(T)\cos^2\theta_N, \quad (8)$$

$$\frac{d\sigma}{d\chi} \propto 1 + \beta(T)\cos 2\chi, \quad (9)$$

where T is the thrust value [13] of the event. The coefficients $\alpha(T)$, $\alpha_N(T)$, and $\beta(T)$ depend on the gluon spin; they are shown in Fig. 16 for leading-order calculations incorporating vector, scalar, and tensor gluons. In perturbative QCD, $O(\alpha_s^2)$ corrections to the leading-order result have been calculated and are small [14].

In Z^0 decay events produced with longitudinally polarized electrons, an additional term $\beta_N S_Z \cos\theta_N$, representing a correlation between the event-plane orientation and the Z^0 spin direction, should be added to Eq. (8). For standard model processes the correlation parameter β_N is expected [15] to be of order 10^{-5} , which is well below our current experimental

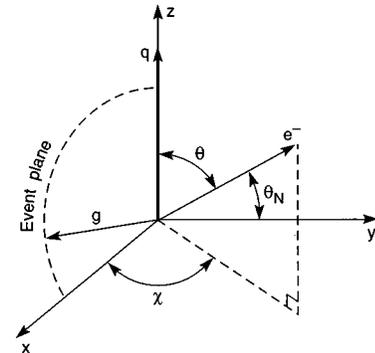


FIG. 2. Definition of the Euler angles θ , θ_N , and χ that describe the orientation of the event plane.

sensitivity [16]. In this analysis we have ignored information on the helicity of the electron beam and are hence insensitive to a term in Eq. (8) linear in $\cos\theta_N$.

III. APPARATUS AND HADRONIC EVENT SELECTION

The e^+e^- annihilation events produced at the Z^0 resonance by the SLD in the 1993 run were recorded using the SLD. A general description of the SLD can be found elsewhere [17]. The analysis presented here used particle energy deposits measured in the Liquid Argon Calorimeter (LAC) [18], which contains both electromagnetic and hadronic sections, and in the Warm Iron Calorimeter [19]. The trigger for hadronic events required a total LAC electromagnetic energy greater than 12 GeV.

Clusters were formed from the localized energy depositions in the LAC; energy depositions consistent with background muons produced upstream in the accelerator were identified and removed [20]. The measured cluster energies were then corrected [9] for the response of the LAC, which varies with polar angle θ due to the material of the inner detector components as well as the thinner calorimeter coverage at the end-cap–barrel interface, using a detailed Monte Carlo simulation of the detector. We first verified that the measured energy of clusters in each polar-angle bin, integrated over all selected clusters in all selected hadronic events, was well described by the simulation. Next, the ratio of simulated cluster energy to generated particle energy was calculated for each cluster. This ratio was averaged over all clusters in each polar-angle bin to yield the response function $r(\theta)$. Finally, the measured energy of each cluster in the data was weighted by $1/r(\theta)$. The normalized rms deviation of the distribution of the total cluster energy in hadronic events was 21% before, and 16.5% after, application of this procedure [9].

Corrected clusters were then required to have a nonzero electromagnetic energy component and a total energy E_{cl} of at least 100 MeV. For each event the total cluster energy E_{tot} , energy imbalance $\Sigma|\vec{E}_{cl}|/E_{tot}$, and thrust axis polar angle θ_T [13] were calculated from the selected corrected clusters. Events with $|\cos\theta_T| \leq 0.8$ ($|\cos\theta_T| \geq 0.8$) were then required to contain at least 8 (11) such clusters, to have $E_{tot} > 15$ GeV, and to have $\Sigma|\vec{E}_{cl}|/E_{tot} < 0.6$. From our 1993 data sample, approximately 51 000 events passed these cuts. The efficiency for selecting hadronic events was estimated to be $(92 \pm 2)\%$, with an estimated background in the selected sample of $(0.4 \pm 0.2)\%$ [21], dominated by $Z^0 \rightarrow \tau^+ \tau^-$ and $Z^0 \rightarrow e^+ e^-$ events.

IV. DATA ANALYSIS

Jets were reconstructed from selected LAC clusters in selected hadronic events. The JADE jet-finding algorithm [22] was used, with a scaled invariant mass cutoff value $y_c = 0.02$, to identify a sample of 22 114 three-jet events. This y_c value maximizes the rate of events classified as three-jet final states; other values of y_c were also considered and found not to affect the conclusions of this study. A nonzero sum of the three-jet momenta can be induced in the selected events by particle losses due to the acceptance and inefficiency of the detector, and by jet energy resolution effects. This was cor-

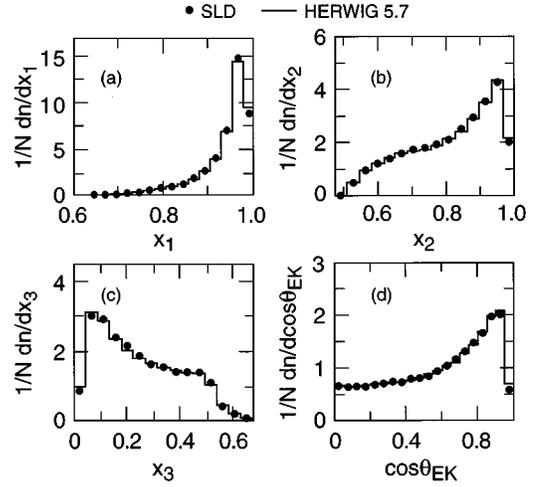


FIG. 3. Measured distributions (dots) of (a) scaled energy of the highest-energy jet, (b) scaled energy of the second-highest-energy jet, (c) scaled energy of the lowest-energy jet, and (d) the Ellis-Karliner angle. The errors are statistical only. The predictions of a Monte Carlo simulation are shown as solid histograms.

rected by rescaling the measured jet momenta \vec{P}_i ($i=1,2,3$) according to

$$P_i^{j'} = P_i^j - R^j |P_i^j|, \quad (10)$$

where P_i^j is the j th momentum component of jet i , $j=x, y, z$, and

$$R^j = \frac{\Sigma_{i=1}^3 P_i^j}{\Sigma_{i=1}^3 |P_i^j|}. \quad (11)$$

The jet energy components were then rescaled according to

$$E_i' = \frac{|\vec{P}_i^{j'}|}{|P_i^j|} E_i. \quad (12)$$

This procedure resulted in a slight improvement in the experimental resolution of the scaled jet energies x_i [9].

A. Scaled jet energy distributions

The measured distributions of the three scaled jet energies x_1, x_2 , and x_3 , and the Ellis-Karliner angle θ_{EK} , are shown in Fig. 3. Also shown in Fig. 3 are the predictions of the HERWIG 5.7 [23] Monte Carlo program for the simulation of hadronic decays of Z^0 bosons, combined with a simulation of the SLD and the same selection and analysis cuts as applied to the real data. The simulation describes the data well.

For each observable X , the experimental distribution $D_{SLD}^{data}(X)$ was then corrected for the effects of selection cuts, detector acceptance, efficiency, resolution, particle decays, and interactions within the detector, and for initial state photon radiation, using bin-by-bin correction factors $C_D(X)$:

$$C_D(X)_m = \frac{D_{hadron}^{MC}(X)_m}{D_{SLD}^{MC}(X)_m}, \quad (13)$$

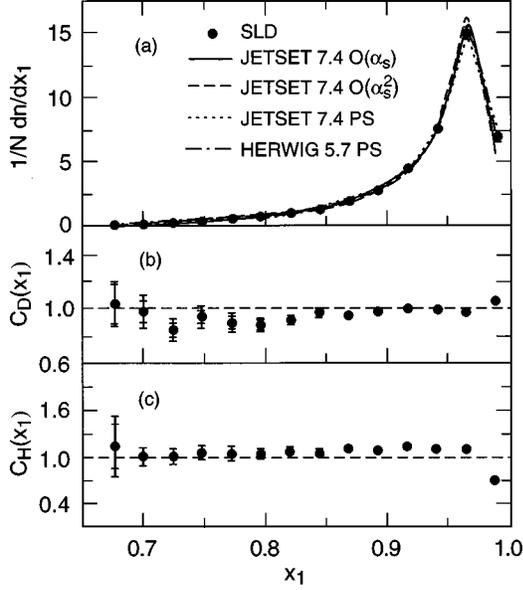


FIG. 4. (a) The measured distribution (dots) of the scaled energy of the highest-energy jet, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

where m is the bin index, $D_{\text{SLD}}^{\text{MC}}(X)_m$ is the content of bin m of the distribution obtained from reconstructed clusters in Monte Carlo events after simulation of the detector, and $D_{\text{hadron}}^{\text{MC}}(X)_m$ is that from all generated particles with lifetimes greater than 3×10^{-10} s in Monte Carlo events with no SLD simulation and no initial state radiation. The bin widths were chosen from the estimated experimental resolution so as to minimize bin-to-bin migration effects. The $C_D(X)$ were calculated from events generated with HERWIG 5.7 using default parameter values [23]. The *hadron level* distributions are then given by

$$D_{\text{hadron}}^{\text{data}}(X)_m = C_D(X)_m D_{\text{SLD}}^{\text{data}}(X)_m. \quad (14)$$

Experimental systematic errors arising from uncertainties in modeling the detector were estimated by varying the event selection criteria over wide ranges¹ and by varying the cluster energy response corrections in the detector simulation [9]. In each case the correction factors $C_D(X)$ and, hence, the corrected data distributions $D_{\text{hadron}}^{\text{data}}(X)$ were rederived. The correction factors $C_D(X)$ are shown in Figs. 4(b), 5(b), 6(b), and 7(b); the errors comprise the sum in quadrature of the statistical component from the finite size of the Monte Carlo event sample and the systematic uncertainty. It can be seen

¹The total cluster energy E_{tot} requirement was varied in the range $10 \leq E_{\text{tot}} \leq 25$ GeV, the energy imbalance I requirement was varied in the range $0.3 \leq I \leq 0.8$, and the number of clusters, N_{cl} , requirement was varied in the ranges $6 \leq N_{\text{cl}} \leq 10$ ($\cos\theta_T \leq 0.8$) and $9 \leq N_{\text{cl}} \leq 13$ ($\cos\theta_T > 0.8$).

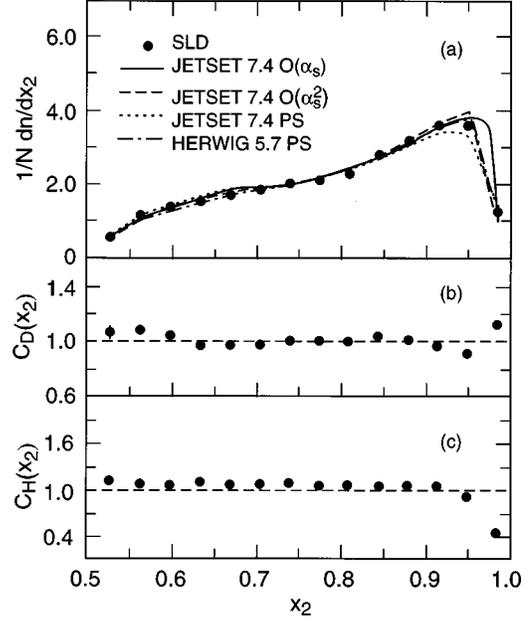


FIG. 5. (a) The measured distribution (dots) of the scaled energy of the second-highest-energy jet, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

that the $C_D(X)$ are close to unity and slowly varying, except near the boundaries of phase space. The hadron level data are listed in Tables I–IV, together with statistical and systematic errors; the central values represent the data corrected by the central values of the correction factors.

Before they can be compared with parton level predictions, the data must be corrected for the effects of hadronization. In the absence of a complete theoretical calculation, the phenomenological models implemented in JETSET 7.4 [24] and HERWIG 5.7 represent our best description of the hadronization process. Although these models are defined independent of any *a priori* assumption of the gluon spin, they have been tuned to $e^+e^- \rightarrow \text{hadrons}$ data at the Z^0 resonance [25], as well as data at $W \sim 35$ GeV from the PETRA and PEP storage rings [26]. We find that they provide a good description of our data in terms of the observables presented here (Fig. 3) and other hadronic event shape observables [27], and we hence employ them to calculate hadronization correction factors. It will be shown that our conclusions do not depend on the details of the calculation of these factors. The HERWIG parameters were left at their default values. Several of the JETSET parameters were set to values determined from our own optimization to hadronic Z^0 data; these are given in Table V.

The hadronization correction procedure is similar to that described above for the detector effects. Bin-by-bin correction factors

$$C_H(X)_m = \frac{D_{\text{parton}}^{\text{MC}}(X)_m}{D_{\text{hadron}}^{\text{MC}}(X)_m}, \quad (15)$$

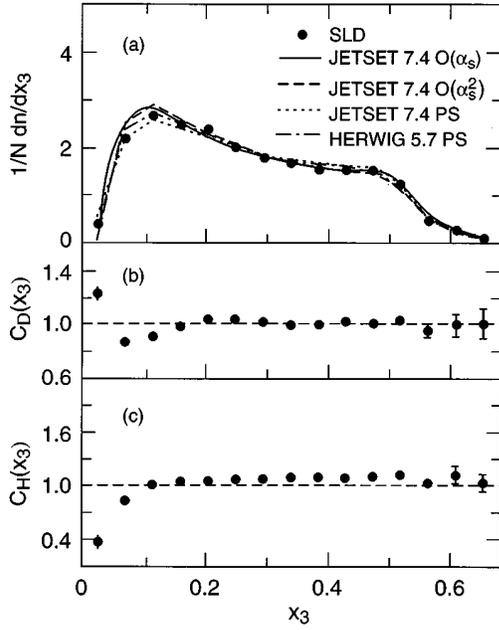


FIG. 6. (a) The measured distribution (dots) of the scaled energy of the lowest-energy jet, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

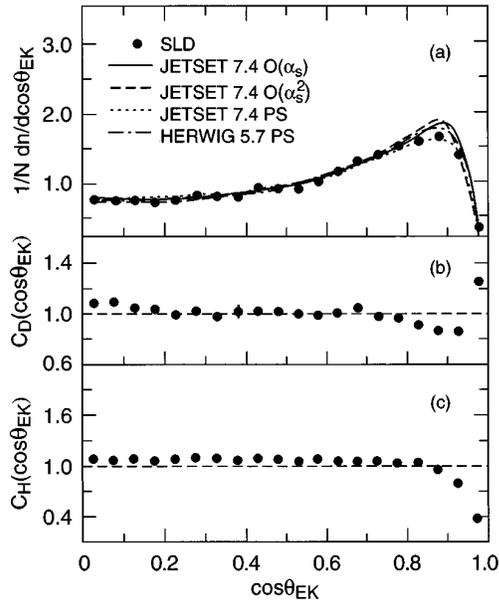


FIG. 7. (a) The measured distribution (dots) of the Ellis-Karliner angle, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

TABLE I. Measured scaled jet energy of the highest-energy jet in three-jet events. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

x_1	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{dx_1}$	Stat.	Expt. syst.
0.676	0.025	0.007	0.008
0.700	0.072	0.016	0.018
0.724	0.133	0.018	0.022
0.748	0.260	0.025	0.033
0.772	0.423	0.028	0.044
0.796	0.530	0.032	0.044
0.820	0.749	0.039	0.048
0.844	1.065	0.048	0.061
0.868	1.603	0.056	0.071
0.892	2.351	0.069	0.088
0.916	3.83	0.09	0.11
0.940	6.74	0.11	0.14
0.964	13.80	0.17	0.27
0.988	9.08	0.13	0.17

where $D_{\text{parton}}^{\text{MC}}(X)_m$ is the content of bin m of the distribution obtained from Monte Carlo events generated at the parton level, were calculated and applied to the hadron level data distributions $D_{\text{hadron}}^{\text{data}}(X)_m$ to obtain the *parton level* corrected data:

$$D_{\text{parton}}^{\text{data}}(X)_m = C_H(X)_m D_{\text{hadron}}^{\text{data}}(X)_m. \quad (16)$$

For each bin the average of the JETSET- and HERWIG-derived values was used as the central value of the correction factor, and the difference between this value and the extrema was

TABLE II. Measured scaled jet energy of the second highest-energy jet in three-jet events. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

x_2	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{dx_2}$	Stat.	Expt. syst.
0.5275	0.490	0.024	0.031
0.5625	1.031	0.039	0.050
0.5975	1.267	0.043	0.050
0.6325	1.356	0.044	0.051
0.6675	1.546	0.048	0.058
0.7025	1.689	0.048	0.057
0.7375	1.815	0.051	0.068
0.7725	1.938	0.053	0.061
0.8075	2.089	0.055	0.063
0.8425	2.619	0.060	0.071
0.8775	2.966	0.063	0.074
0.9125	3.391	0.064	0.082
0.9475	3.813	0.062	0.079
0.9825	2.205	0.056	0.075

TABLE III. Measured scaled jet energy of the lowest-energy jet in three-jet events. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

x_3	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{dx_3}$	Stat.	Expt. syst.
0.0225	1.095	0.037	0.050
0.0675	2.622	0.044	0.059
0.1125	2.632	0.048	0.069
0.1575	2.340	0.049	0.060
0.2025	2.228	0.049	0.060
0.2475	1.878	0.046	0.054
0.2925	1.645	0.043	0.052
0.3375	1.502	0.040	0.051
0.3825	1.386	0.040	0.049
0.4275	1.400	0.039	0.048
0.4725	1.356	0.038	0.045
0.5175	1.090	0.035	0.043
0.5625	0.378	0.022	0.028
0.6075	0.188	0.016	0.022
0.6525	0.037	0.008	0.009

assigned as a symmetric hadronization uncertainty. The correction factors $C_H(X)$ are shown in Figs. 4(c), 5(c), 6(c), and 7(c); the errors comprise the sum in quadrature of the statistical component from the finite size of the Monte Carlo event sample and the systematic uncertainty. It can be seen that the $C_H(X)$ are within 10% of unity and are slowly varying, except near the boundaries of phase space. The fully corrected data are shown in Figs. 4(a), 5(a), 6(a), and 7(a); the data points correspond to the central values of the correction factors, and the errors shown comprise the statistical and total systematic components added in quadrature. These results are in agreement with an analysis of our 1992 data sample using charged tracks for jet reconstruction [28]. From comparison of the raw data (Fig. 3) with the fully corrected data [Figs. 4(a), 5(a), 6(a), and 7(a)], it is apparent that the shapes of the distributions are barely affected by the detector and hadronization corrections.

We first compare the data with QCD predictions from $O(\alpha_s)$ and $O(\alpha_s^2)$ perturbation theory and from parton shower (PS) models. For this purpose we used the JETSET 7.4 $O(\alpha_s)$ matrix element, $O(\alpha_s^2)$ matrix element, and PS options, and the HERWIG 5.7 PS, and generated events at the parton level. In each case all parameters were left at their default values [23,24], with the exception of the JETSET parton shower parameters listed in Table V. The QCD scale parameter values used were $\Lambda = 1.0$ GeV [$O(\alpha_s)$], 0.25 GeV [$O(\alpha_s^2)$], 0.26 GeV (JETSET PS), and 0.18 GeV (HERWIG PS). The shapes of the x_1 , x_2 , x_3 , and $\cos\theta_{\text{EK}}$ distributions do not depend on Λ at $O(\alpha_s)$ and only weakly so at higher order. The resulting predictions for x_1 , x_2 , x_3 , and $\cos\theta_{\text{EK}}$ are shown in Figs. 4(a), 5(a), 6(a), and 7(a). These results represent Monte Carlo integrations of the respective QCD formulas and are hence equivalent to analytic or numerical QCD results based on the same formulae; in the $O(\alpha_s)$ case, we have checked explicitly that JETSET reproduces the nu-

TABLE IV. Measured Ellis-Karliner angle distribution in three-jet events. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

$\cos\theta_{\text{EK}}$	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{d\cos\theta_{\text{EK}}}$	Stat.	Expt. syst.
0.025	0.689	0.028	0.032
0.075	0.692	0.028	0.032
0.125	0.678	0.027	0.035
0.175	0.669	0.027	0.032
0.225	0.671	0.026	0.030
0.275	0.716	0.027	0.031
0.325	0.718	0.026	0.034
0.375	0.733	0.028	0.043
0.425	0.819	0.028	0.034
0.475	0.803	0.029	0.037
0.525	0.835	0.029	0.035
0.575	0.906	0.030	0.036
0.625	1.055	0.032	0.038
0.675	1.207	0.034	0.047
0.725	1.290	0.034	0.041
0.775	1.420	0.035	0.047
0.825	1.507	0.035	0.056
0.875	1.700	0.035	0.043
0.925	1.696	0.032	0.043
0.975	0.776	0.029	0.039

merical results of the analytic calculation described in Sec. II.

The $O(\alpha_s)$ calculation describes the data reasonably well, although small discrepancies in the details of the shapes of the distributions are apparent and the χ^2 for the comparison between data and the MC calculation is poor (Table VI). The $O(\alpha_s^2)$ calculation describes the x_1 , x_2 , and x_3 data distributions better, but the description of the $\cos\theta_{\text{EK}}$ distribution is slightly worse; this is difficult to see directly in Figs. 4(a), 5(a), 6(a), and 7(a), but is evident from the χ^2 values for the

TABLE V. Parameters in JETSET 7.4 that were changed from default values (see text).

Parameter	Variable name	Default	Optimized
Λ_{QCD}	PARJ (81)	0.29 GeV	0.26 GeV
σ_q	PARJ (21)	0.36 GeV/c	0.39 GeV/c
a	PARJ (41)	0.3	0.18
b	PARJ (42)	0.58 GeV ⁻²	0.34 GeV ⁻²
ϵ_c	PARJ (54)	-0.05	-0.06
ϵ_b	PARJ (55)	-0.005	-0.006
Diquark prob.	PARJ (1)	0.10	0.08
s quark prob.	PARJ (2)	0.30	0.28
s diquark prob.	PARJ (3)	0.40	0.60
V meson prob. (u, d)	PARJ (11)	0.50	0.50
V meson prob. (s)	PARJ (12)	0.60	0.45
V meson prob. (c, b)	PARJ (13)	0.75	0.53
η' prob.	PARJ (26)	0.40	0.20

TABLE VI. Numbers of bins and χ^2 values for comparison between fully corrected data and parton level QCD Monte Carlo calculations. Values in parentheses are for the restricted ranges which exclude the regions where soft and collinear contributions are expected to be large.

Distribution	No. bins	JETSET $O(\alpha_s)$	JETSET $O(\alpha_s^2)$	JETSET PS	HERWIG PS
x_1	14 (12)	88.2 (72.6)	38.5 (26.3)	13.5 (6.3)	11.2 (10.6)
x_2	14 (12)	37.8 (20.0)	36.8 (12.2)	34.9 (21.0)	15.2 (6.5)
x_3	15 (13)	92.9 (49.8)	86.5 (29.6)	22.3 (17.5)	25.7 (11.8)
$\cos\theta_{\text{EK}}$	20 (18)	60.6 (26.3)	86.2 (44.6)	15.8 (9.0)	48.2 (30.2)

data-MC comparisons (Table VI). Both parton shower calculations describe the data better than either the $O(\alpha_s)$ or $O(\alpha_s^2)$ calculations and yield relatively good χ^2 values (Table VI). This improvement in the quality of description of the data between the $O(\alpha_s)$ and parton shower calculations can be interpreted as an indication of the contribution of multiple soft gluon emission to the fine details of the shapes of the distributions. In fact, for all calculations the largest discrepancies, at the level of at most 10%, arise in the regions $x_1 > 0.98$, $x_2 > 0.93$, $x_3 < 0.09$, and $\cos\theta_{\text{EK}} > 0.9$, near the boundaries of phase space where soft and collinear divergences are expected to be large and to require resummation in QCD perturbation theory [29]; such a resummation has not been performed for the observables considered here.

For each observable we chose a range such that the detector and hadronization correction factors are close to unity, $0.8 < C_D(X)$, $C_H(X) < 1.2$, have small uncertainty, $\Delta C_D(X)$, $\Delta C_H(X) < 0.2$, and are slowly varying (see Figs. 4–7). The ranges are $0.688 < x_1 < 0.976$, $x_2 < 0.93$, $x_3 > 0.09$, and $\cos\theta_{\text{EK}} < 0.9$; they exclude the phase-space boundary regions. Within these ranges the comparison between data and calculations yields significantly improved χ^2 values (values in parentheses in Table VI); the $O(\alpha_s^2)$ calculation has acceptable

χ^2 values and those for both parton shower models are typically slightly better. These results support the notion that QCD, incorporating vector gluons, is the correct theory of strong interactions.

We now consider alternative models of strong interactions, incorporating scalar and tensor gluons, discussed in Sec. II. Since these model calculations are at leading order in perturbation theory, we also consider first the vector gluon (QCD) case at the same order. It has just been shown that, in the case of QCD, higher-order effects have only a small influence on the shapes of the distributions and that the leading-order calculation provides a reasonable description of the data within the ranges selected; we assume that the leading-order scalar and tensor gluon models can be compared with the data on the same basis. The data within the selected ranges are shown in Fig. 8. The leading-order scalar, vector, and tensor gluon predictions, normalized to the data within the same ranges, are also shown in Fig. 8. The vector calculation clearly provides the best description of the data; neither the scalar nor tensor cases predicts the correct shape for any of the observables. These conclusions also hold if the correction factors for detector and hadronization effects, which are small in the selected ranges, are not applied. The χ^2 values for the comparisons are given in Table VII. This represents the first comparison of a tensor gluon calculation with experimental data.

It is interesting to consider whether the data allow an admixture of contributions from the different gluon spin hypotheses. For this purpose we performed simultaneous fits to a linear combination of the vector (V)+scalar (S)+tensor (T) predictions, allowing the relative normalizations to vary according to

$$(1-a-b)V + aS + bT, \quad (17)$$

where a and b are free parameters determined from the fit. For the vector contribution we used in turn the $O(\alpha_s)$, $O(\alpha_s^2)$, JETSET PS, and HERWIG PS calculations. In all cases

TABLE VII. Numbers of bins and χ^2 values for comparison between fully corrected data and leading-order vector (QCD), scalar, and tensor gluon calculations. The calculations were normalized to the data in the selected ranges (see text).

Distribution	No. bins	Vector	Scalar	Tensor
x_1	12	45.2	1116.4	141.9
x_2	12	33.5	1321.7	490.6
x_3	13	39.9	2011.4	546.9
$\cos\theta_{\text{EK}}$	18	19.5	1684.0	772.1

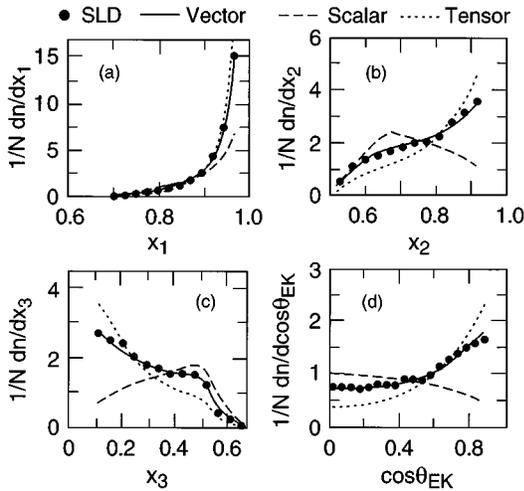


FIG. 8. Measured distributions, fully corrected to the parton level (dots), of (a) scaled energy of the highest-energy jet, (b) scaled energy of the second-highest-energy jet, (c) scaled energy of the lowest-energy jet, and (d) the Ellis-Karliner angle. The errors comprise the total statistical and systematic components added in quadrature. The leading-order predictions described in Sec. II are shown as lines: vector (solid lines), scalar (long dashed lines), and tensor (short dashed lines).

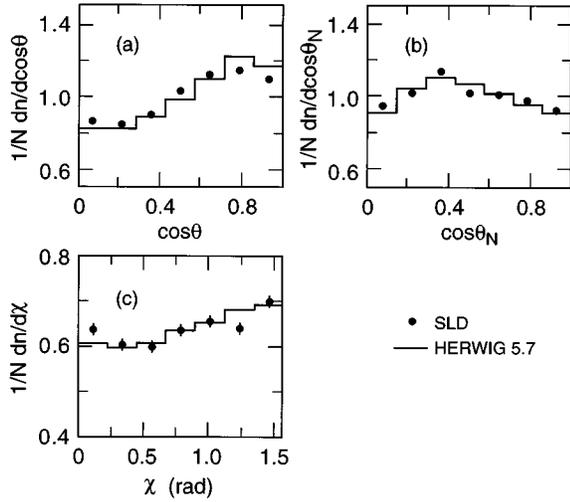


FIG. 9. Measured distributions (dots) of the event plane orientation angles: (a) $\cos\theta$, (b) $\cos\theta_N$, and (c) χ . The errors are statistical only. The predictions of a Monte Carlo simulation are shown as solid histograms.

a fit to the distribution of each observable of quality comparable with the vector-only fit was obtained. We found that, though they are not required to describe the data, contributions of scalar and tensor gluons can be accommodated to a degree that depends upon the order of the vector calculation used, as well as on the observable. The largest scalar contribution was $a=0.11$ from the fit to $\cos\theta_{EK}$ using the $O(\alpha_s^2)$ calculation. The largest tensor contribution was $b=0.31$

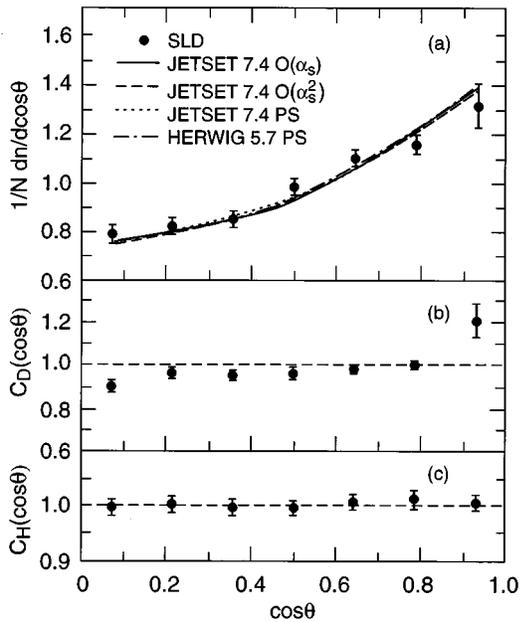


FIG. 10. (a) The measured distribution (dots) of $\cos\theta$, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

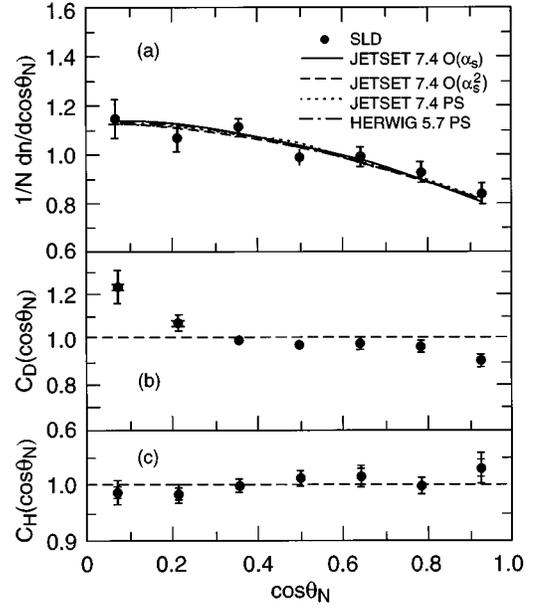


FIG. 11. (a) The measured distribution (dots) of $\cos\theta_N$, fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

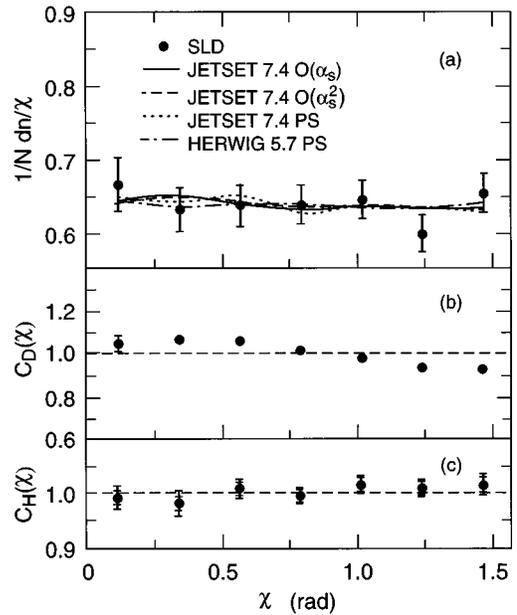


FIG. 12. (a) The measured distribution (dots) of χ , fully corrected to the parton level, compared with QCD Monte Carlo calculations. The errors comprise the total statistical and systematic components added in quadrature. The correction factors for detector effects and initial state radiation (b) and for hadronization effects (c); the inner error bars show the statistical component and the outer error bars the total uncertainty; in some cases the error bars are smaller than the size of the dot representing the central value.

TABLE VIII. Measured polar angle with respect to the electron beam of the highest-energy jet in three-jet events. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

$\cos\theta$	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{d\cos\theta}$	Stat.	Expt. syst.
0.071	0.792	0.021	0.031
0.214	0.822	0.023	0.031
0.357	0.853	0.023	0.030
0.500	0.982	0.024	0.033
0.643	1.088	0.026	0.031
0.786	1.135	0.028	0.035
0.929	1.306	0.035	0.090

from the fit to x_1 using the $O(\alpha_s)$ calculation. The smallest contributions were a and $b < 0.001$ from the fit to x_1 using the HERWIG PS.

Any pair of the observables x_1 , x_2 , x_3 , and $\cos\theta_{\text{EK}}$ may be taken to be independent variables, subject to the overall constraint $x_1 + x_2 + x_3 = 2$. Therefore, in order to utilize more information, we also performed fits of Eq. (17) simultaneously to the x_2 and x_3 distributions. We found the relative S , V , and T contributions and χ^2/N DOF values to be comparable with those from the fits to x_2 alone.

B. Event-plane orientation

We now consider the three Euler angles that describe the orientation of the event plane: θ , θ_N , and χ (Fig. 2). The analysis procedure is similar to that described in the previous section. The measured distributions of these angles are shown in Fig. 9, together with the predictions of HERWIG 5.7, combined with a simulation of the SLD and the same selection and analysis cuts as applied to the data. The simulations describe the data reasonably well. The small discrepancies between the data and simulations are within the experimental systematic uncertainties. The data distributions were then corrected for the effects of selection cuts, detector acceptance, efficiency, and resolution, particle decays, and interactions within the detector, and for initial state photon radi-

TABLE IX. The measured polar angle with respect to the electron beam of the normal to the three-jet plane. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

$\cos\theta_N$	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{d\cos\theta_N}$	Stat.	Expt. syst.
0.071	1.159	0.034	0.076
0.214	1.079	0.029	0.046
0.357	1.110	0.026	0.029
0.500	0.969	0.025	0.028
0.643	0.967	0.025	0.035
0.786	0.917	0.023	0.036
0.929	0.804	0.020	0.030

TABLE X. Measured angle between the event plane and the plane containing the highest-energy jet and the electron beam. The data were corrected for detector effects and for initial state photon radiation. The first error is statistical, and the second represents the experimental systematic uncertainty, which is strongly correlated between bins.

χ (rad)	$\frac{1}{\sigma_{3 \text{ jet}}} \frac{d\sigma}{d\chi}$	Stat.	Expt. syst.
0.112	0.671	0.025	0.034
0.336	0.644	0.025	0.027
0.561	0.633	0.025	0.026
0.785	0.642	0.024	0.025
1.009	0.635	0.023	0.025
1.234	0.592	0.021	0.023
1.458	0.645	0.021	0.023

ation using bin-by-bin correction factors determined from the Monte Carlo simulation. The correction factors C_D are shown in Figs. 10(b), 11(b), and 12(b); the errors comprise the sum in quadrature of the statistical component from the finite size of the Monte Carlo event sample and the systematic uncertainty derived as described in the previous section. The hadron level data are listed in Tables VIII–X, together with statistical and systematic errors; the central values represent the data corrected by the central values of the correction factors.

The data were further corrected bin by bin for the effects of hadronization. The hadronization correction factors are shown in Figs. 10(c), 11(c), and 12(c); the errors comprise the sum in quadrature of the statistical component from the finite size of the Monte Carlo event sample and the systematic uncertainty. The fully corrected data are shown in Figs. 10(a), 11(a), and 12(a); the data points correspond to the central values of the correction factors, and the errors shown comprise the statistical and total systematic components added in quadrature. Also shown in Figs. 10(a), 11(a), and

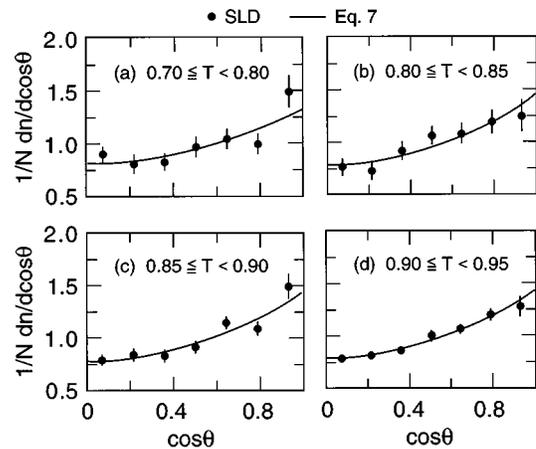


FIG. 13. The measured distributions (dots) of $\cos\theta$, fully corrected to the parton level, in the event thrust ranges (a) $0.70 < T < 0.80$, (b) $0.80 < T < 0.85$, (c) $0.85 < T < 0.90$, and (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits of Eq. (7) are shown as solid lines.

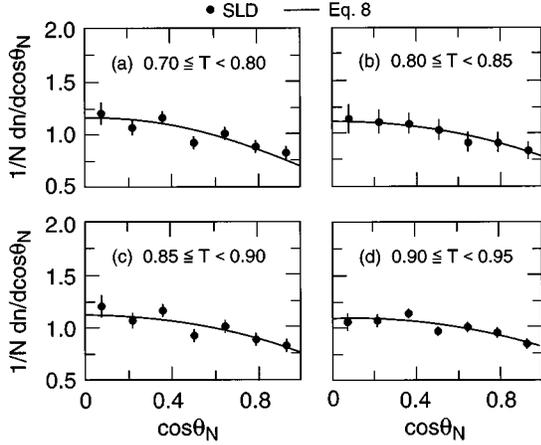


FIG. 14. The measured distributions (dots) of $\cos\theta_N$, fully corrected to the parton level, in the event thrust ranges (a) $0.70 < T < 0.80$, (b) $0.80 < T < 0.85$, (c) $0.85 < T < 0.90$, and (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits of Eq. (8) are shown as solid lines.

12(a) are the parton level predictions of the JETSET 7.4 $O(\alpha_s)$ matrix element, $O(\alpha_s^2)$ matrix element, and parton shower options, and the HERWIG 5.7 parton shower. All calculations describe the data well, and higher-order corrections to the $O(\alpha_s)$ predictions are seen to be small.

The data were divided into four samples according to the thrust values of the events: (i) $0.70 < T < 0.80$, (ii) $0.80 < T < 0.85$, (iii) $0.85 < T < 0.90$, and (iv) $0.90 < T < 0.95$. The distributions of $\cos\theta$, $\cos\theta_N$, and χ are shown for these four ranges in Figs. 13, 14, and 15, respectively. Also shown in these figures are fits of Eqs. (7), (8), and (9) (Sec. II), where the parameters $\alpha(T)$, $\alpha_N(T)$, and $\beta(T)$ were determined, respectively, from the fits. The fitted values of these parameters are listed in Table XI and are shown in Fig. 16, where they are compared with the leading-order QCD predictions and with the predictions of the scalar and tensor gluon models. Values of χ^2 for these comparisons are given in Table XII. The data are in agreement with the QCD predictions, and the scalar and tensor gluon predictions are disfavored. It should be noted, however, that the event-plane orientation angle distributions are less sensitive to the different gluon spin cases than are the jet energy distributions discussed in the previous section.

V. CONCLUSIONS

We have measured distributions of the jet energies and of the orientation angles of the event plane in

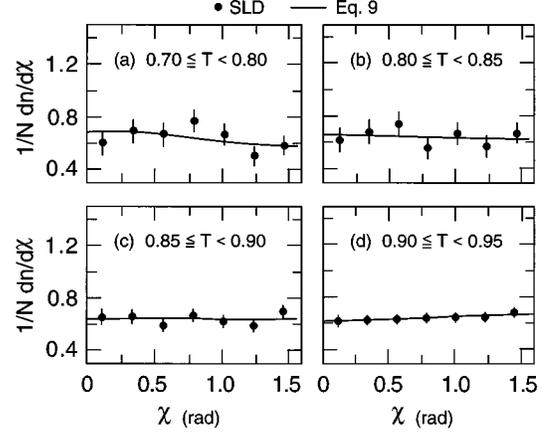


FIG. 15. The measured distributions (dots) of χ , fully corrected to the parton level, in the event thrust ranges (a) $0.70 < T < 0.80$, (b) $0.80 < T < 0.85$, (c) $0.85 < T < 0.90$, and (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits of Eq. (9) are shown as solid lines.

$e^+e^- \rightarrow Z^0 \rightarrow$ three-jet events recorded in the SLD experiment at SLAC. Our measurements of these quantities are consistent with those from other experiments [5,6,8] at the Z^0 resonance. We have compared our measurements with QCD predictions and with models of strong interactions incorporating scalar or tensor gluons; this represents the first comparison with a tensor gluon calculation.

The leading-order vector gluon (QCD) calculation describes the basic shape of the scaled jet energy distributions, and addition of higher-order perturbative contributions leads to a reasonable description of the finer details of these distributions, provided the regions of phase space are avoided where soft and collinear singularities need to be resummed. One may speculate that the addition of as-yet uncalculated higher-order QCD contributions may yield further improvement. The shapes of the jet energy distributions cannot be described by leading-order models incorporating either scalar or tensor gluons alone. However, the *ad hoc* addition of leading-order contributions from scalar and tensor gluons, each with arbitrary relative weight, to the QCD predictions also leads to a reasonable description of the data. Though they are not required to describe the data, contributions of scalar and tensor gluons can be accommodated to a degree depending upon the order of the vector calculation, as well as the observable; the smallest contribution of 0.1% for both scalar and tensor gluons is obtained with the HERWIG parton shower fit to the scaled energy of the most energetic jet.

The event-plane orientation angles are well described by $O(\alpha_s)$ QCD, and higher-order corrections are small. These

TABLE XI. Thrust ranges, values, and errors of the fit parameters α , α_N , and β , and χ^2 values for the fits. For each fitted observable there are seven bins.

Thrust range	$\alpha(T)$	χ^2	$\alpha_N(T)$	χ^2	$\beta(T)$	χ^2
$0.7 < T < 0.8$	0.61 ± 0.18	6.1	-0.42 ± 0.10	1.9	0.090 ± 0.069	5.4
$0.8 < T < 0.85$	0.83 ± 0.19	3.6	-0.31 ± 0.11	0.6	0.034 ± 0.071	3.3
$0.85 < T < 0.9$	0.82 ± 0.12	8.3	-0.33 ± 0.07	7.8	0.004 ± 0.041	4.4
$0.9 < T < 0.95$	0.81 ± 0.09	2.6	-0.26 ± 0.06	6.8	-0.033 ± 0.030	0.5

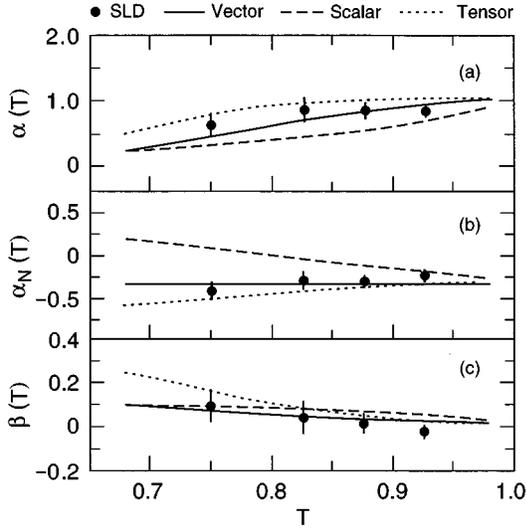


FIG. 16. Coefficients (a) $\alpha(T)$, (b) $\alpha_N(T)$, and (c) $\beta(T)$ from the fits shown in Figs. 13, 14, and 15, respectively. Also shown are the leading-order vector (solid lines), scalar (long dashed lines), and tensor (short dashed lines) gluon predictions.

quantities are less sensitive to the gluon spin than the jet energies, but the data disfavor the scalar and tensor hypotheses.

ACKNOWLEDGMENTS

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APPENDIX: TENSOR GLUON MODEL

Since the tensor gluon toy model is new, whereas the vector and scalar cases have been studied in detail in the literature, we discuss briefly how Eq. (6) was obtained.

The only well-known theory involving the exchange of massless, spin-2 gauge fields is the quantized version of general relativity, which is both highly nonlinear and nonrenormalizable. To obtain a simple parallel model for tensor gluons, which couple only to color nonsinglet sources, we begin by linearizing the theory of quantum gravity based on general relativity by keeping only the lowest-order terms in the coupling and by ignoring the tensor field self-interactions [30]. Although now linear, the theory remains nonrenormalizable, as will the tensor gluon model, which should be

TABLE XII. Values of χ^2 for comparisons between the predictions including vector, scalar, or tensor gluons for the coefficients $\alpha(T)$, $\alpha_N(T)$, and $\beta(T)$ and the measured values (Fig. 16).

Gluon spin	$\alpha(T)$	$\alpha_N(T)$	$\beta(T)$
Vector	3.0	2.8	2.4
Scalar	17.4	38.0	8.8
Tensor	7.3	5.7	4.4

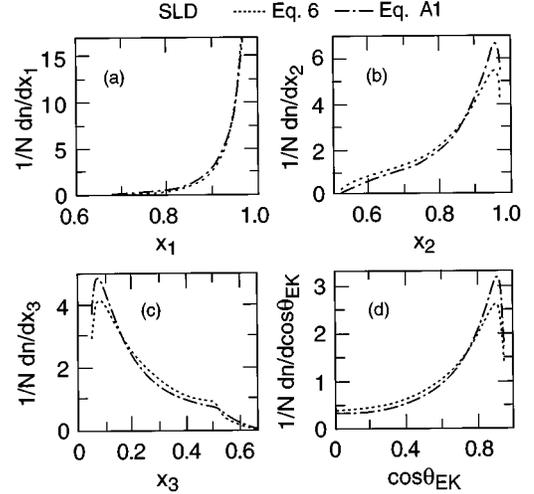


FIG. 17. Leading-order tensor gluon model calculations, based on Eq. (6) (short dashed lines) and Eq. (18) (dash-dotted lines), of distributions of (a) scaled energy of the highest-energy jet, (b) scaled energy of the second-highest-energy jet, (c) scaled energy of the lowest-energy jet, and (d) the Ellis-Karliner angle.

viewed only as a toy model against which to test the predictions of QCD.

If tensor gluons behaved in the same way as gravitons, one could write down the complete gauge-invariant amplitude for the three-level process $Z^0 \rightarrow q\bar{q}g$. The various contributions arise from a set of four Feynman diagrams: the usual two which involve gluon bremsstrahlung from the q or \bar{q} in the final state, the bremsstrahlung of a tensor gluon from the Z^0 in the initial state, producing an off-shell Z^0 which “decays” to $q\bar{q}$, and finally a new $Z^0 q\bar{q}g$ contact interaction. We need to remove or modify the $Z^0 Z^0 g$ piece of the amplitude as the Z^0 is known phenomenologically not to carry a color charge.

We consider two possible approaches to this problem. In the first instance we surrender the possibility of a gauge symmetry for the tensor gluon theory and omit the diagram involving the $Z^0 Z^0 g$ vertex. (We note that the scalar gluon model is also not a gauge theory.) In this case, using the Feynman gauge for the tensor gluon, we arrive at the distribution given in Eq. (6). A second possibility is to mimic the quantum gravity theory as far as possible and include the $Z^0 Z^0 g$ diagram in a modified form. To do this we extend the particle spectrum of the standard model by introducing a color octet partner to the Z^0 , Z^0_8 , which is degenerate with the Z^0 and couples to quarks in exactly the same way as does the Z^0 , except for the presence of color generators. The problematic $Z^0 Z^0 g$ vertex is now replaced by the $Z^0 Z^0_8 g$ coupling. In this case we arrive at a form for the tensor distribution given by [31]:

$$\frac{1}{\sigma} \frac{d^2\sigma^T}{dx_1 dx_2} \propto \frac{(x_1 + x_2 - 1)(x_1^2 + x_2^2)}{(2 - x_1 - x_2)^2} + \frac{(1 - x_2)[x_1^2 + (2 - x_1 - x_2)^2]}{x_2^2} + \frac{(1 - x_1)[x_2^2 + (2 - x_1 - x_2)^2]}{x_1^2}, \quad (\text{A1})$$

which, apart from the overall normalization, is the same as that for graviton radiation in Z^0 decays. Although algebraically different, this form yields numerically similar results to Eq. (6) (Fig. 17).

In the analysis presented in the text, the comparison of the tensor model with the data is based on Eq. (6). It is clear from Fig. 17, however, that our conclusions would not differ if Eq. (A1) had been chosen instead.

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