

A STUDY OF THE ORIENTATION AND ENERGY PARTITION OF THREE-JET EVENTS IN HADRONIC Z^0 DECAYS*

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ABSTRACT

Using hadronic Z^0 decays collected in the SLD experiment at SLAC we have measured the distributions of the jet energies in $e^+e^- \rightarrow Z^0 \rightarrow$ three-jet events and of the three orientation angles of the event plane. We find that these distributions are well described by perturbative QCD incorporating vector gluons. We have also compared our data with models of scalar and tensor gluon production, and discuss limits on the relative contributions of these particles to three-jet production in e^+e^- annihilation.

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1. Introduction

The observation by e^+e^- annihilation experiments 15 years ago [1] of events containing three jets of hadrons, and their interpretation in terms of the process $e^+e^- \rightarrow q\bar{q}g$, provided the first direct evidence for the existence of the gluon, the gauge boson of the theory of strong interactions, Quantum Chromodynamics (QCD) [2]. Following the initial observations a number of more detailed studies were performed at the PETRA storage ring of the partition of energy among the three jets [3]. Comparison of the data with leading-order QCD predictions, and with a model incorporating the radiation of spin-0 (scalar) gluons, provided qualitative evidence for the spin-1 (vector) nature of the gluon, which is a fundamental element of QCD. Similar studies have since been performed at LEP [4][5].

An additional interesting observable in three-jet events is the orientation of the event plane w.r.t. the beam direction, which can be described by three Euler angles. These angular distributions were studied first by TASSO [6], and more recently by L3 [4] and DELPHI [7]. 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 [4].

In this paper we present preliminary 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. In order to maximise jet energy resolution, as well as minimise biases in the sample of selected events, 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 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.

The observables are defined, and the predictions of perturbative QCD and of the

scalar and tensor gluon models are discussed, in Section 2. We describe the detector and the event trigger and selection criteria applied to the data in Section 3. The three-jet analysis is described in Section 4, and a summary and conclusions are presented in Section 5.

2. 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 normalising by the c.m. energy $\sqrt{s}$, we obtain the scaled jet energies:

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

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 [8] to be the angle between jets 1 and 2 in this frame. For massless partons at tree-level:

$$\cos\theta_{EK} = \frac{x_2 - x_3}{x_1}.$$

The inclusive differential cross section can be calculated to $\mathcal{O}(\alpha_s)$ in perturbative QCD incorporating spin-1 (vector) gluons and assuming massless partons [9]:

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

For a model of strong interactions incorporating spin-0 (scalar) gluons one obtains [5]:

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

where

$$R = \frac{\sum_i 10a_i^2}{\sum_i v_i^2 + a_i^2}$$

and a_i and v_i are the axial and vector couplings, respectively, of quark flavor i to the Z^0 . For a model of strong interactions incorporating spin-2 (tensor) gluons one obtains

[10]:

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

Singly-differential cross sections for x_1 , x_2 , x_3 or $\cos\theta_{EK}$ were obtained by numerical integrations of these formulae [11]. These cross sections are shown in Fig. 1; the shapes are different for the vector, scalar and tensor gluon cases.

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 and gluon jet identification is made, θ is the polar angle of the fastest jet w.r.t. the electron beam direction, θ_N is the polar angle of the normal to the event plane w.r.t. the electron beam direction, and χ is the angle between the event plane and the plane containing the electron beam and the fastest jet. In perturbative QCD the distributions of these angles are characterised by [6]:

$$\begin{aligned} \frac{d\sigma}{d\cos\theta} &\propto 1 + \alpha(T)\cos^2\theta \\ \frac{d\sigma}{d\cos\theta_N} &\propto 1 + \alpha_N(T)\cos^2\theta_N \\ \frac{d\sigma}{d\chi} &\propto 1 + \beta(T)\cos 2\chi \end{aligned}$$

where T is the event thrust value. 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 including vector, scalar and tensor gluons [11].

3. Apparatus and Hadronic Event Selection

The e^+e^- annihilation events produced at the Z^0 resonance by the SLC in the 1993 run were recorded using the SLC Large Detector (SLD). A general description of the

SLD can be found elsewhere [12]. Charged tracks are measured in the central drift chamber (CDC) [13] and in the vertex detector (VXD) [14]. Momentum measurement is provided by a uniform axial magnetic field of 0.6 T. Particle energies are measured in the Liquid Argon Calorimeter (LAC) [15], which contains both electromagnetic and hadronic sections, and in the Warm Iron Calorimeter [16].

Three triggers were used for hadronic events. The first required a total LAC electromagnetic energy greater than 12 GeV; the second required at least two well-separated tracks in the CDC; the third required at least 4 GeV in the LAC and one track in the CDC. A selection of hadronic events was then made by two independent methods, one based on the topology of energy depositions in the calorimeters, the other on the number and topology of charged tracks measured in the CDC.

The analysis presented here used particle energy deposits measured in the LAC. After correction for the LAC energy response [17] energy clusters were required to have a non-zero electromagnetic component, a total energy E_d of at least 100 MeV, and to be inconsistent with originating from beam-associated backgrounds produced by SLC. Events whose thrust axis [18] polar angle w.r.t. the beam direction θ_T satisfied $|\cos\theta_T| \leq 0.8$ ($|\cos\theta_T| \geq 0.8$) were then required to contain at least 8 (11) such clusters respectively, to have a total energy in selected clusters $E_{tot} > 15$ GeV, and to have an energy imbalance $\Sigma|\vec{E}_d|/E_{tot} < 0.6$. 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 $0.4 \pm 0.2\%$ [19], dominated by $Z^0 \rightarrow \tau^+\tau^-$ and $Z^0 \rightarrow e^+e^-$ events.

4. Data Analysis

Jets were reconstructed from calorimeter clusters in hadronic events selected according to the criteria defined in Section 3. The JADE jet-finding algorithm [20] was used, with a scaled invariant mass cutoff value $y_c = 0.02$, to identify a sample of 22,114 3-jet final states. This y_c value maximises the rate of events classified as 3-jet final

states; other values of y_c were also considered and found not to affect the conclusions of this study. A non-zero jet momentum sum 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 corrected by rescaling the measured jet energies P_i ($i = 1, 2, 3$) according to the formula:

$$P_i^{j'} = P_i^j - R^j |P_i^j|$$

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

$$R^j = \frac{\sum_{i=1}^3 P_i^j}{\sum_{i=1}^3 |P_i^j|},$$

and the jets were taken to be massless. This procedure significantly improved the experimental resolution on the scaled jet energies x_i [17].

A. Scaled Jet Energy Distributions

The measured distributions of the three scaled jet energies x_1, x_2, 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 [21] 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 simulations describe the data well.

For each observable X , the experimental distributions $D_{SLD}^{data}(X)$ 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 radiation, using bin-by-bin correction factors $C_D(X)$:

$$C_D(X)_m = \frac{D_{hadron}^{MC}(X)_m}{D_{SLD}^{MC}(X)_m}, \quad (1)$$

where m is the bin index; $D_{SLD}^{MC}(X)_m$ is the content of bin m of the distribution obtained from reconstructed clusters in Monte Carlo events after simulation of the detector; and $D_{hadron}^{MC}(X)_i$ 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 [21]. The *hadron level* distributions are then given by

$$D_{hadron}^{data}(X)_m = C_D(X)_m \cdot D_{SLD}^{data}(X)_m. \quad (2)$$

Experimental systematic errors arising from uncertainties in modelling the detector were estimated by varying the event selection criteria over wide ranges, and by varying the cluster response corrections in the detector simulation [17]. In each case the correction factors $C_D(X)$, and hence the corrected data distributions $D_{hadron}^{data}(X)$, were rederived. The correction factors $C_D(X)$ are shown in Figs. 4(b)–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. 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 QCD predictions the data must be corrected for the effects of hadronization. In the absence of a complete theory based on non-perturbative QCD, the phenomenological models implemented in JETSET 7.4 [22] and HERWIG 5.7 represent our best description of the hadronization process. These models have been compared extensively with, and tuned to, $e^+e^- \rightarrow \text{hadrons}$ data at the Z^0 resonance [23], as well as data at $W \sim 35$ GeV from the PETRA/PEP storage rings [24]. We find that these models provide a good description of our data in terms of the observables presented here (Fig. 3) and other hadronic event shape observables [25], and hence employ them to calculate hadronization correction factors. The HERWIG parameters were left at their default values. Several of the JETSET parameters were set to values determined from our own optimisation to hadronic Z^0 data; these are given in Table V.

The correction procedure is similar to that described above for the detector effects.

Bin-by-bin correction factors

$$C_H(X)_m = \frac{D_{parton}^{MC}(X)_m}{D_{hadron}^{MC}(X)_m}, \quad (3)$$

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

$$D_{parton}^{data}(X)_m = C_H(X)_m \cdot D_{hadron}^{data}(X)_m. \quad (4)$$

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 assigned as a symmetric hadronization uncertainty. The correction factors $C_H(X)$ are shown in Figs. 4(c)–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. The fully-corrected data are shown in Figs. 4(a)–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.

We first compare the data with QCD predictions from $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$ perturbation theory, and from parton shower (PS) models. For this purpose we used the JETSET 7.4 $\mathcal{O}(\alpha_s)$ matrix element, $\mathcal{O}(\alpha_s^2)$ 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 [21][22], with the exception of the JETSET parton shower parameters listed in Table V. The resulting predictions for x_1 , x_2 , x_3 and $\cos\theta_{EK}$ are shown in Figs. 4(a) – 7(a). These results represent Monte Carlo integrations of the respective QCD formulae and are hence equivalent to analytic or numerical QCD results based on the same formulae; in the $\mathcal{O}(\alpha_s)$ case we have checked explicitly that the JETSET calculation reproduces the numerical results of the calculation described in Section 2.

The $\mathcal{O}(\alpha_s)$ 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 MC is poor (Table VI). The $\mathcal{O}(\alpha_s^2)$ calculation describes the x_1 , x_2 and x_3 data distributions better, but the description of the $\cos\theta_{EK}$ distribution is slightly worse; this is difficult to see directly in Figs. 4(a)–7(a), but is evident from the χ^2 values for the data–MC comparisons (Table VI). Both parton shower calculations describe the data better than either the $\mathcal{O}(\alpha_s)$ or $\mathcal{O}(\alpha_s^2)$ calculations and yield relatively good χ^2 values (Table VI). This improvement in the quality of description of the data between the $\mathcal{O}(\alpha_s)$ 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 with the data, at the level of at most 10%, arise in the regions $x_1 > 0.98$, $x_2 > 0.93$, $x_3 < 0.09$ and $\cos\theta_{EK} > 0.9$, where soft and collinear divergences are expected to be large and to require resummation in QCD perturbation theory [26]; such resummation has not been performed for the observables considered here. Excluding these regions from comparison yields significantly improved χ^2 values between data and calculations (values in parentheses in Table VI). In this case the $\mathcal{O}(\alpha_s^2)$ calculation has acceptable χ^2 values and those for both parton shower models are typically slightly better. This supports the notion that QCD, incorporating vector gluons, is the correct theory of strong interactions.

We now consider the alternative models of strong interactions, incorporating scalar and tensor gluons, discussed in Section 2. Since these model calculations are at leading order, we also consider first the vector gluon (QCD) case at the same order. We chose the ranges: $0.688 < x_1 < 0.976$, $0.51 < x_2 < 0.93$, $x_3 > 0.09$ and $\cos\theta_{EK} < 0.9$, which exclude the regions requiring resummation, as discussed above, and which also ensure that the correction factors for detector and hadronization effects be close to unity, namely $0.8 < C_D(X), C_H(X) < 1.2$, and be slowly varying (Figs. 4(b)–7(b) and 4(c)–7(c)). The data within these ranges are shown in Fig. 8, together with the leading-order scalar, vector and tensor gluon predictions normalised to the data within the same ranges. The vector calculation clearly provides the best description of the

data; neither the scalar nor tensor cases has the correct shape for any of the observables. This represents the first comparison of a tensor gluon calculation with experimental data. The χ^2 values for the comparisons with data are given in Table VII.

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

$$(1 - a - b) V + a S + b T$$

where a and b are free parameters determined from the fit.

We first used the leading-order calculations; the relative contributions of V, S, and T are shown in the second rows of Tables VIII, IX, X, and XI for fits to x_1 , x_2 , x_3 , and $\cos\theta_{EK}$ respectively. The resulting scalar contribution is below 0.1%, except for the $\cos\theta_{EK}$ distribution, where a value of 4.4% is allowed. Tensor contributions of between 1.7% ($\cos\theta_{EK}$) and 30.5% (x_1) are allowed. The $\chi^2/\text{d.o.f.}$ values for these fits are 2.5 (x_1), 3.1 (x_2), 3.1 (x_3), and 1.0 ($\cos\theta_{EK}$). This exercise was then repeated using in turn for the vector case the JETSET $\mathcal{O}(\alpha_s^2)$, JETSET PS, and HERWIG PS calculations; the results are shown in the third, fourth, and fifth rows, respectively, of Tables VIII–XI. The allowed scalar and tensor contributions can be seen to vary considerably depending on which vector calculation is used and which observable is fitted. The largest scalar contribution (10.8%) occurs for the $\mathcal{O}(\alpha_s^2)$ vector fit to $\cos\theta_{EK}$, and the largest tensor contribution (15.7%) occurs for the JETSET PS vector fit to x_2 . For all four observables the best fits (lowest χ^2) were obtained when either of the vector parton shower calculations was used.

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 identical 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 real data. The simulations describe the data reasonably well. 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 radiation using bin-by-bin correction factors determined from the Monte Carlo simulation. The correction factors C_D are shown in Figs. 10(b)–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 XII–XIV, 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 hadronisation. The hadronisation correction factors are shown in Figs. 10(c)–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)–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)–12(a) are the parton-level predictions of the JETSET 7.4 $\mathcal{O}(\alpha_s)$ matrix element, $\mathcal{O}(\alpha_s^2)$ 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 $\mathcal{O}(\alpha_s)$ 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 to Eqs. (1),(2) and (3) (Section 2), where the parameters α , α_N and β were determined,

respectively, from the fits. The fitted values of these parameters are listed in Table XV, and are shown in Fig. 16, where they are compared with the leading-order QCD predictions [11]. Also shown in Fig. 16 are predictions [11] of the scalar and tensor gluon models; the tensor case has only been calculated for $\alpha_N(T)$. The data are in agreement with the QCD predictions, and the scalar and tensor gluon predictions are disfavoured. 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.

5. Conclusions

We have measured distributions of the jet energies and of the orientation angles of the event plane in $e^+e^- \rightarrow Z^0 \rightarrow \text{three-jet}$ events. Our measurements of these quantities are consistent with those from other experiments [4][5][7] 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 shapes of the jet energy distributions cannot be described by leading-order models incorporating either scalar or tensor gluons alone. A leading-order vector gluon (QCD) calculation describes the basic form of the distributions, and addition of higher-order perturbative contributions modelled by parton showers 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. Outside of these regions one may speculate that residual discrepancies may be resolved by the addition of as yet uncalculated higher-order QCD contributions. It is apparent, however, that the addition of *ad hoc* leading-order contributions from scalar and tensor gluons to the QCD calculations can also improve the description of the data, and that even for the parton shower QCD calculations slightly better fit qualities are obtained with such contributions included. We

conclude that precise limits on the possible relative contributions of scalar and tensor gluons to three-jet production in e^+e^- annihilation cannot be set until $\mathcal{O}(\alpha_s^3)$ QCD contributions to jet energy distributions have been calculated, or parton shower models have been developed that include more completely the phase space for gluon emission.

The event plane orientation angles are well described by $\mathcal{O}(\alpha_s)$ QCD and higher-order corrections appear to be small. These quantities are less sensitive to the gluon spin than the jet energies, but the data disfavor the scalar and tensor hypotheses.

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x_1	$\frac{1}{\sigma_{3-jet}} \frac{d\sigma}{dx_1}$	stat.	exp. 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

Table I. The measured scaled jet energy of the fastest jet in 3-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.

x_2	$\frac{1}{\sigma_{3-jet}} \frac{d\sigma}{dx_2}$	stat.	exp. 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 II. The measured scaled jet energy of the second fastest jet in 3-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.

x_3	$\frac{1}{\sigma_{3\text{-jet}}} \frac{d\sigma}{dx_3}$	stat.	exp. 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

Table III. The measured scaled jet energy of the slowest jet in 3-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.

$\cos\theta_{EK}$	$\frac{1}{\sigma_{3-jet}} \frac{d\sigma}{d\cos\theta_{EK}}$	stat.	exp. 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

Table IV. The measured Ellis-Karliner angle distribution in 3-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.

Parameter	Variable Name	Default	Optimised
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 V. Parameters in JETSET 7.4 changed from default values (see text).

Distribution	# bins	JETSET $\mathcal{O}(\alpha_s)$	JETSET $\mathcal{O}(\alpha_s^2)$	JETSET PS	HERWIG PS
x_1	14 (13)	88.2 (72.9)	38.5 (26.3)	13.5 (6.3)	11.2 (10.7)
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)
$\cos\theta_{EK}$	20 (18)	60.6 (26.3)	86.2 (44.6)	15.8 (9.0)	48.2 (30.2)

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	# 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
$\cos\theta_{EK}$	18	19.5	1684.0	772.1

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.

Vector calc.	Vector	Scalar	Tensor	χ^2
$\mathcal{O}(\alpha_s)$	69.5	< 0.1	30.5	24.7
$\mathcal{O}(\alpha_s^2)$	92.0	1.0	7.0	13.9
JETSET PS	92.0	< 0.1	8.0	5.3
HERWIG PS	100.0	< 0.1	< 0.1	10.3

Table VIII. Relative contributions (%) of vector, scalar, and tensor gluons determined from simultaneous fits to the x_1 distribution (see text); the χ^2 value is shown in the last column.

Vector calc.	Vector	Scalar	Tensor	χ^2
$\mathcal{O}(\alpha_s)$	92.1	< 0.1	7.9	30.8
$\mathcal{O}(\alpha_s^2)$	99.2	0.6	0.2	12.2
JETSET PS	83.6	0.7	15.7	7.3
HERWIG PS	97.0	1.8	1.2	5.7

Table IX. As Table VIII, for the x_2 distribution.

Vector calc.	Vector	Scalar	Tensor	χ^2
$\mathcal{O}(\alpha_s)$	90.1	< 0.1	9.9	34.1
$\mathcal{O}(\alpha_s^2)$	99.7	0.3	< 0.1	27.7
JETSET PS	95.0	3.0	2.0	8.7
HERWIG PS	97.8	2.2	< 0.1	9.9

Table X. As Table VIII, for the x_3 distribution.

Vector calc.	Vector	Scalar	Tensor	χ^2
$\mathcal{O}(\alpha_s)$	93.9	4.4	1.7	16.5
$\mathcal{O}(\alpha_s^2)$	85.7	10.8	3.5	18.3
JETSET PS	95.9	0.1	4.0	7.6
HERWIG PS	90.9	8.7	0.4	9.8

Table XI. As Table VIII, for the $\cos\theta_{EK}$ distribution.

$\cos\theta$	$\frac{1}{\sigma_{3\text{-jet}}} \frac{d\sigma}{d\cos\theta}$	stat.	exp. 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

Table XII. The measured polar angle w.r.t. the electron beam of the fastest jet in 3-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.

$\cos\theta_N$	$\frac{1}{\sigma_{3\text{-jet}}} \frac{d\sigma}{d\cos\theta_N}$	stat.	exp. 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 XIII. The measured polar angle w.r.t. 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.

χ (rad.)	$\frac{1}{\sigma_{3-jet}} \frac{d\sigma}{d\chi}$	stat.	exp. 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

Table XIV. The measured angle between the event plane and the plane containing the fastest 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.

Thrust range	α	χ^2	α_N	χ^2	β	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

Table XV. 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 7 bins.

Figure captions

Figure 1. Leading-order calculations, incorporating vector (solid), scalar (long dashed), and tensor (short dashed) gluons, of distributions of: (a) scaled energy of the fastest jet; (b) scaled energy of the second fastest jet; (c) scaled energy of the slowest jet; (d) the Ellis-Karliner angle.

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

Figure 3. Measured distributions (dots) of: (a) scaled energy of the fastest jet; (b) scaled energy of the second fastest jet; (c) scaled energy of the slowest jet; (d) the Ellis-Karliner angle. The errors are statistical only. The predictions of a Monte Carlo simulation are shown as solid histograms.

Figure 4. (a) The measured distribution (dots) of the scaled energy of the fastest 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 5. (a) The measured distribution (dots) of the scaled energy of the second fastest 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 6. (a) The measured distribution (dots) of the scaled energy of the slowest 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the

statistical component and the outer error bar the total uncertainty.

Figure 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 8. Measured distributions, fully corrected to the parton level (dots), of: (a) scaled energy of the fastest jet; (b) scaled energy of the second fastest jet; (c) scaled energy of the slowest jet; (d) the Ellis-Karliner angle. The errors comprise the total statistical and systematic components added in quadrature. The leading-order predictions described in Section 2 are shown as lines: vector (solid), scalar (long dashed), and tensor (short dashed).

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

Figure 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 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. (b) The correction factor for detector effects and initial-state radiation (see text); (c) the correction factor for hadronisation effects (see text); the inner error bar shows the statistical component and the outer error bar the total uncertainty.

Figure 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) $0.85 < T < 0.90$, (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits to Eq. (1) are shown as solid lines.

Figure 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) $0.85 < T < 0.90$, (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits to Eq. (2) are shown as solid lines.

Figure 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) $0.85 < T < 0.90$, (d) $0.90 < T < 0.95$. The errors comprise the total statistical and systematic components added in quadrature. Fits to Eq. (3) are shown as solid lines.

Figure 16. Coefficients (a) α , (b) α_N , (c) β from the fits shown in Fig. 15, as a function of event thrust. Also shown are the leading-order vector (solid), scalar (long dashed) and tensor ((b) only) (short dashed) gluon predictions.

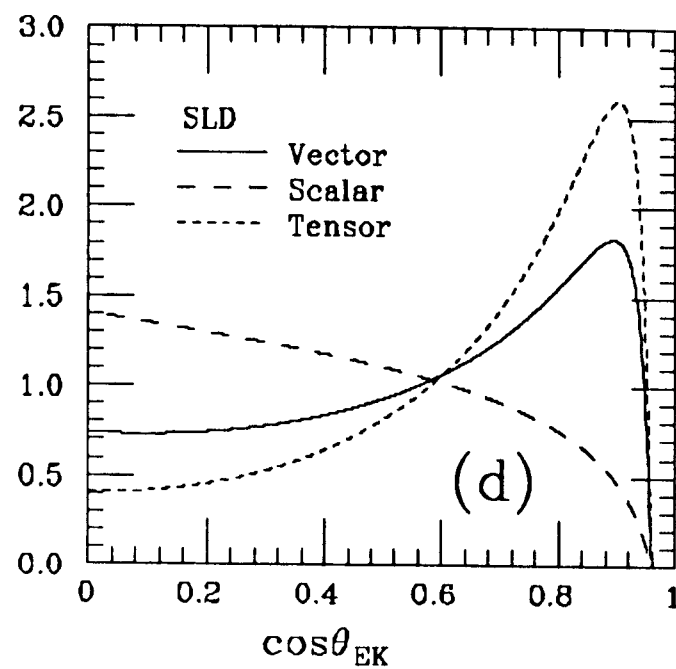
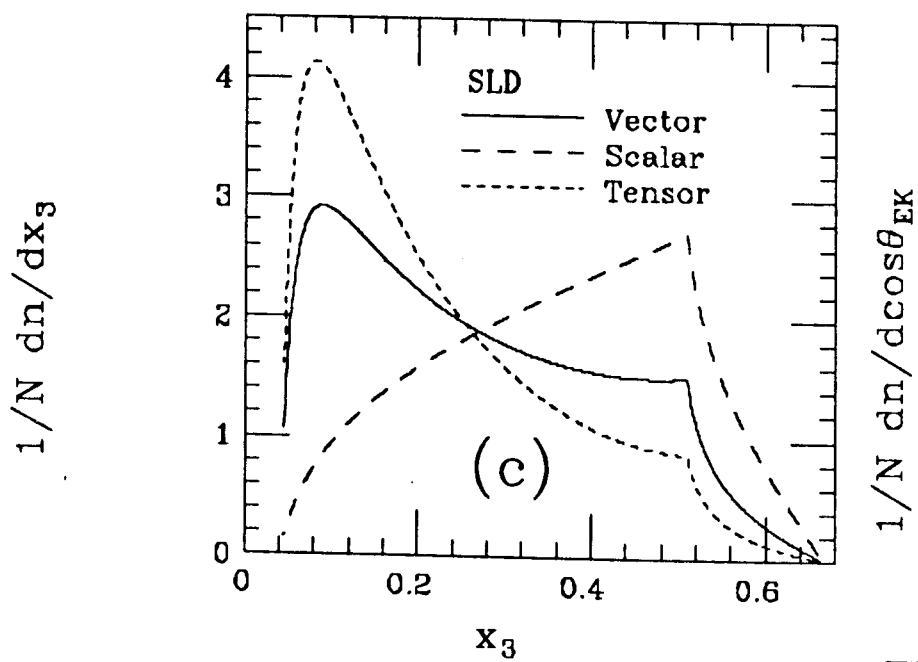
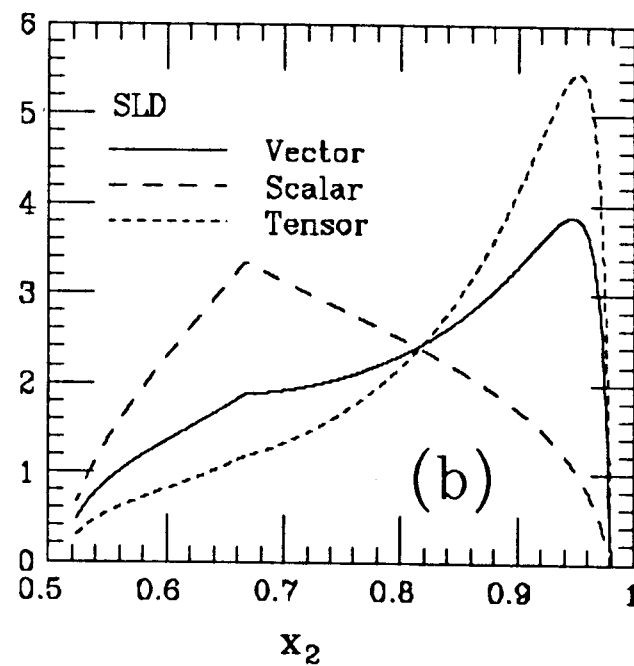
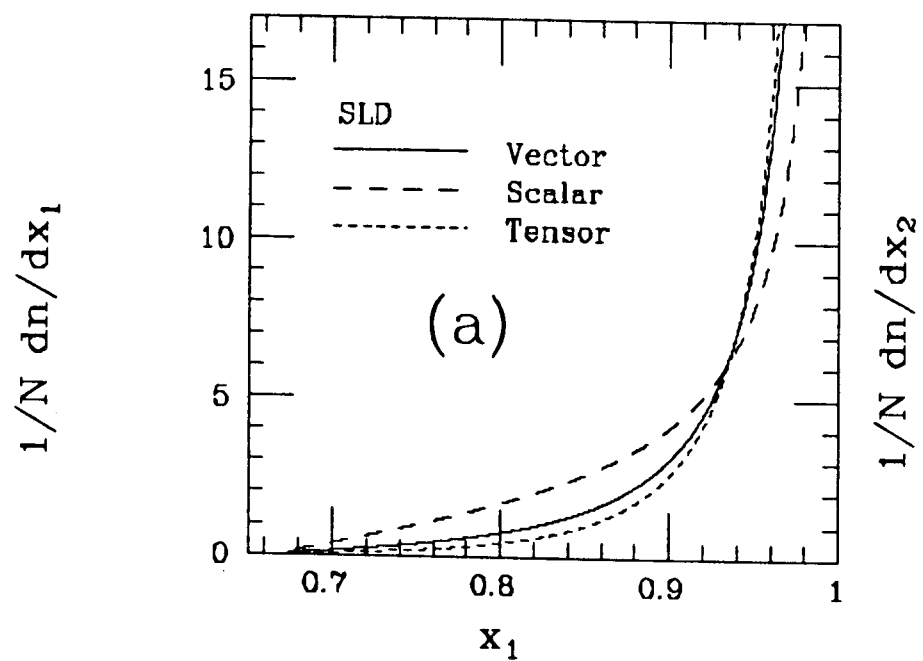


FIG. 1

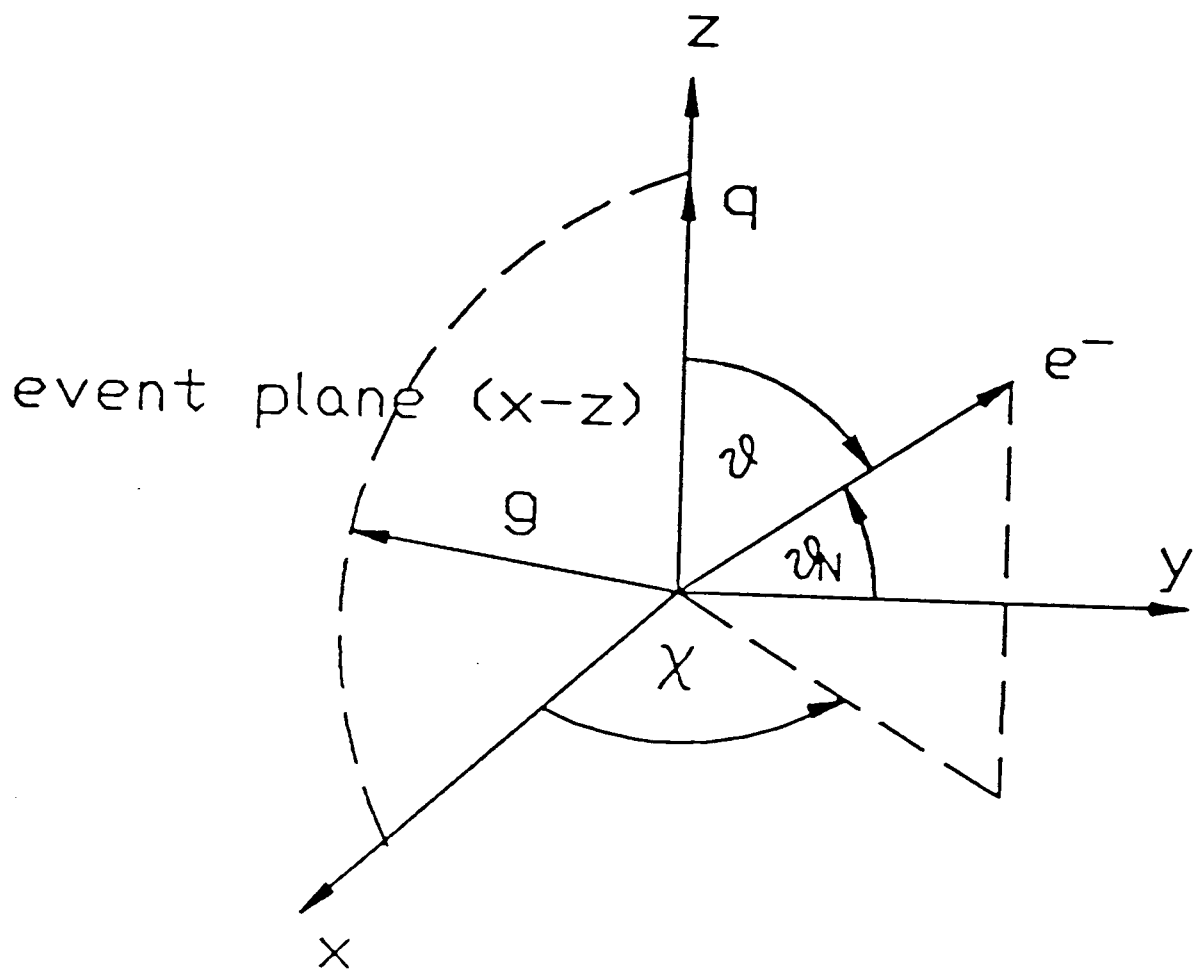


FIG. 2

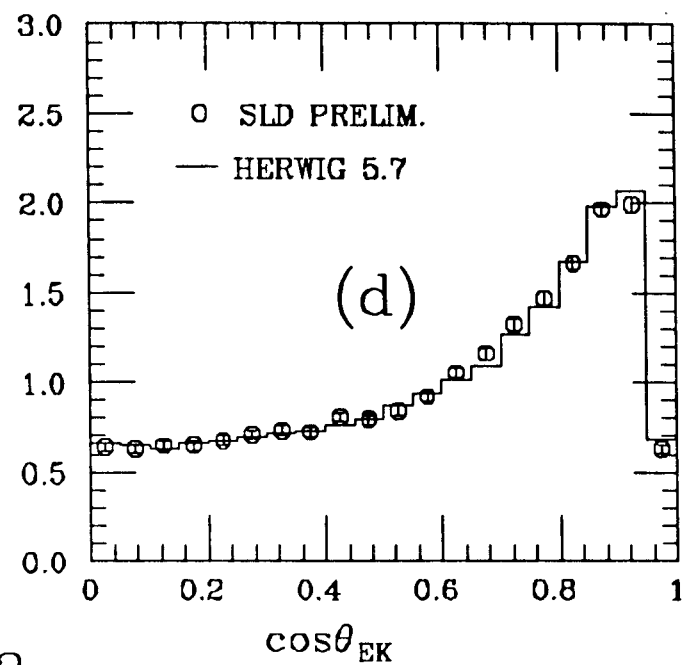
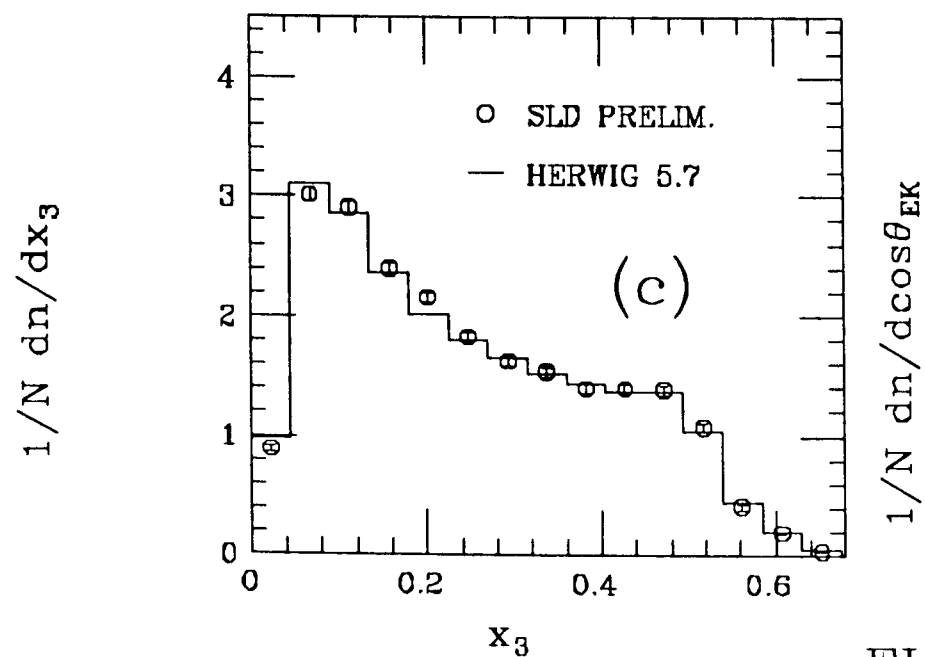
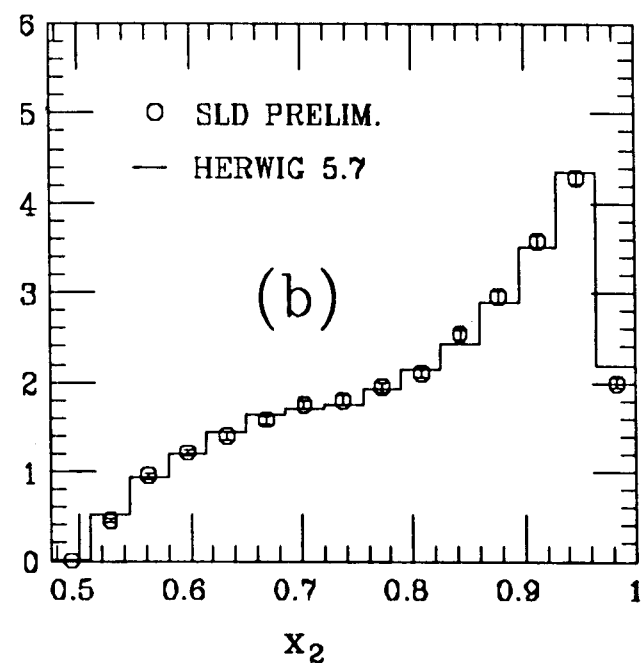
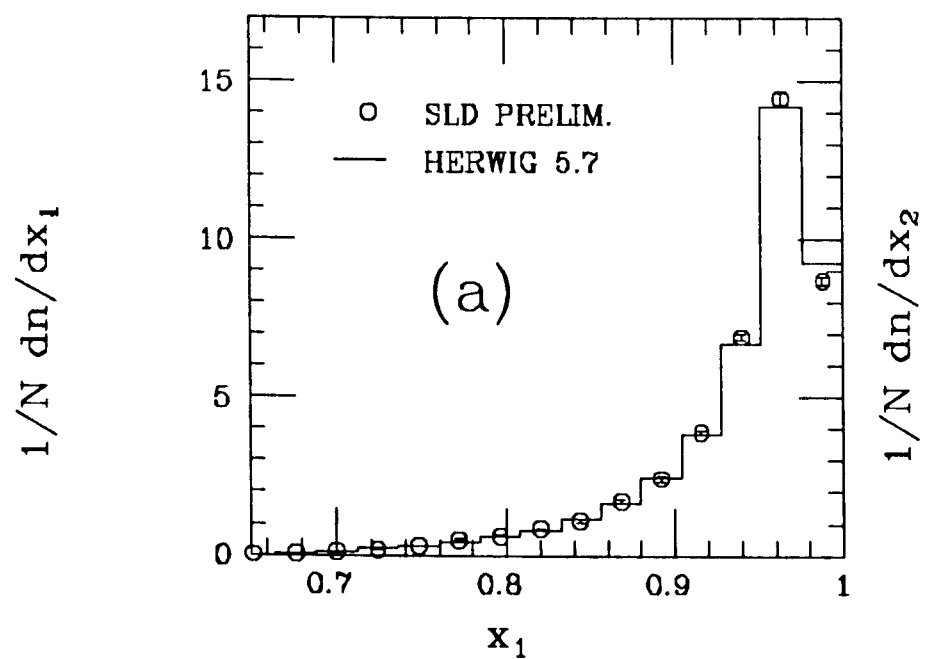


FIG. 3

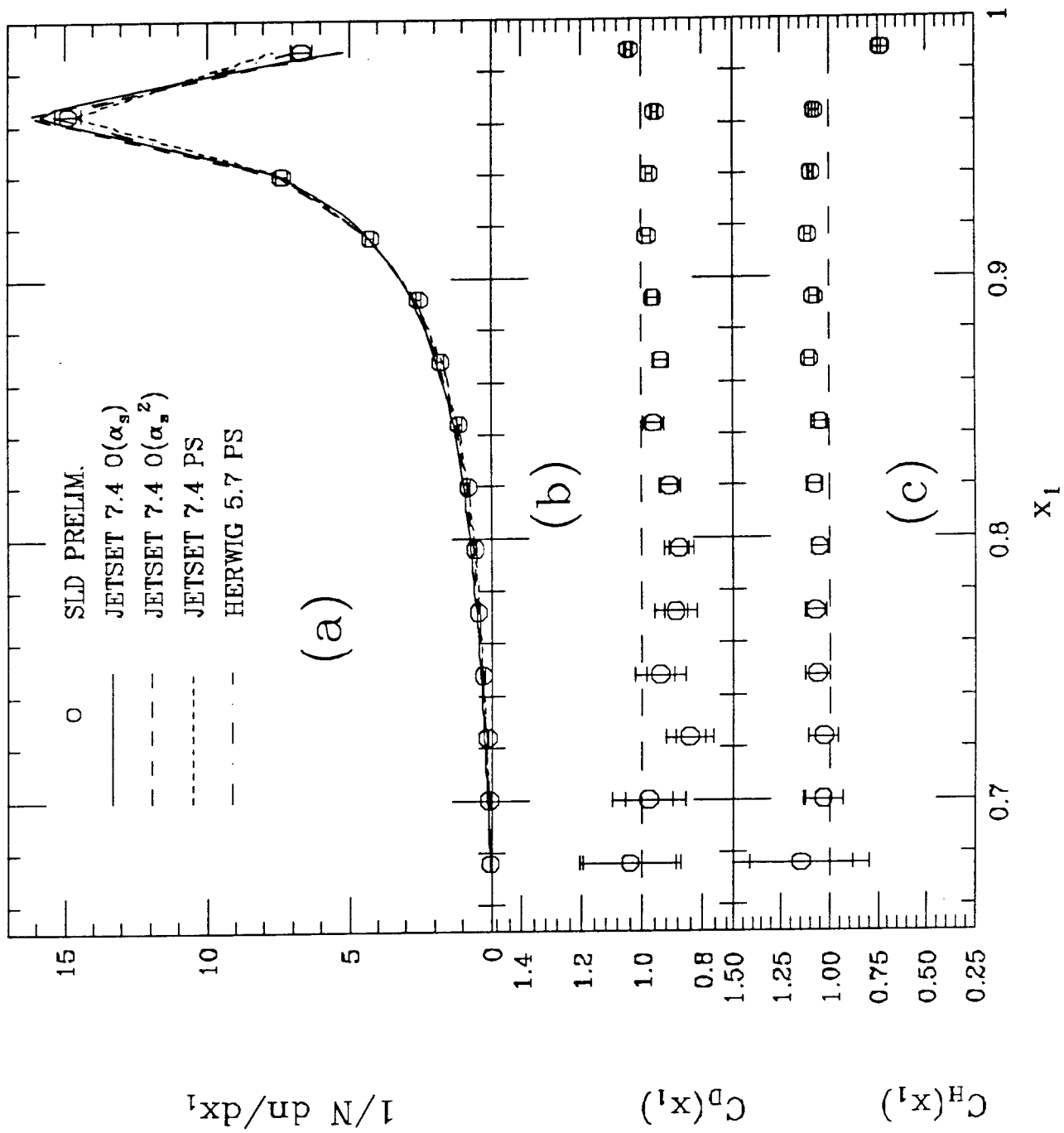


FIG. 4

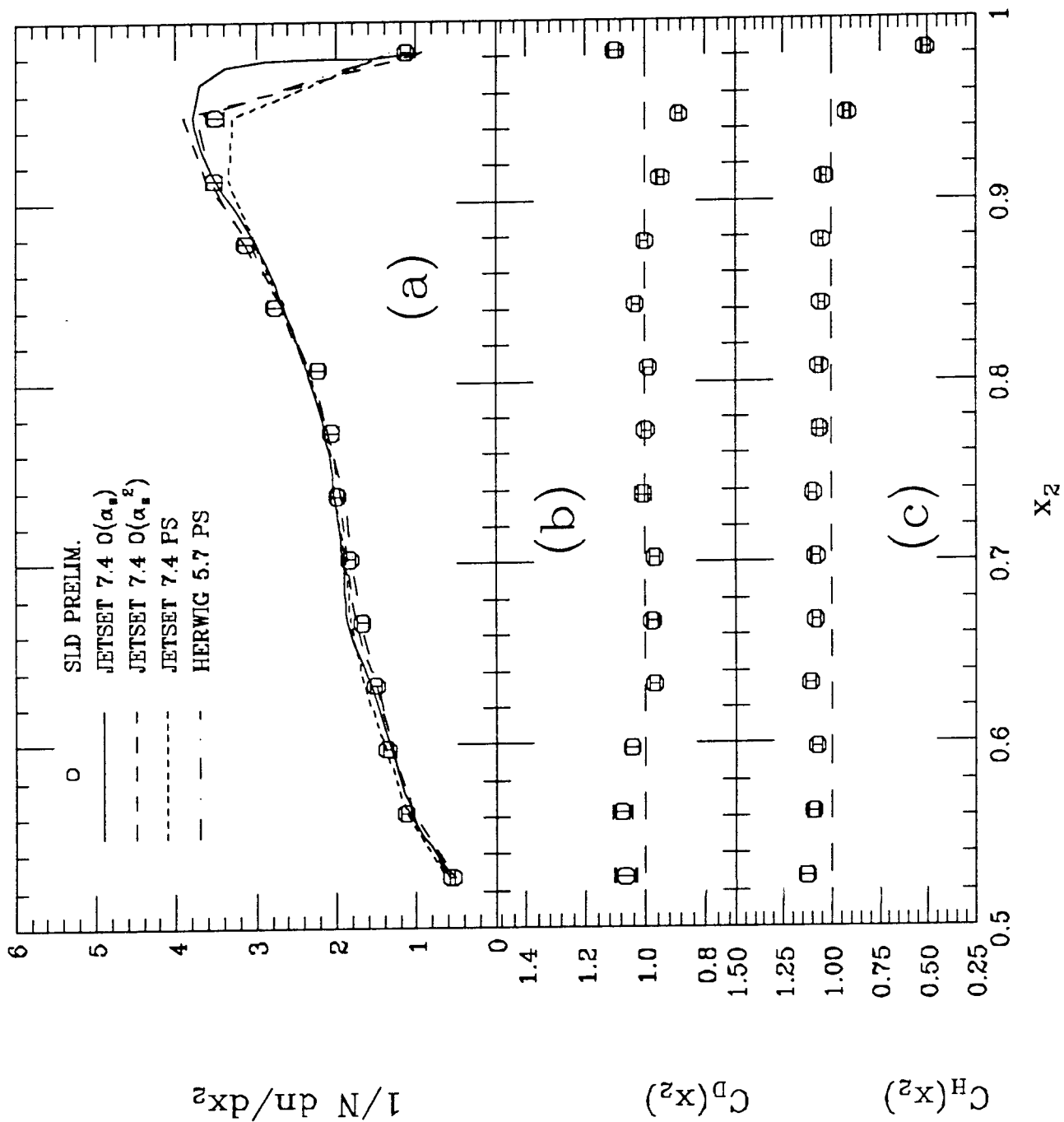


FIG. 5

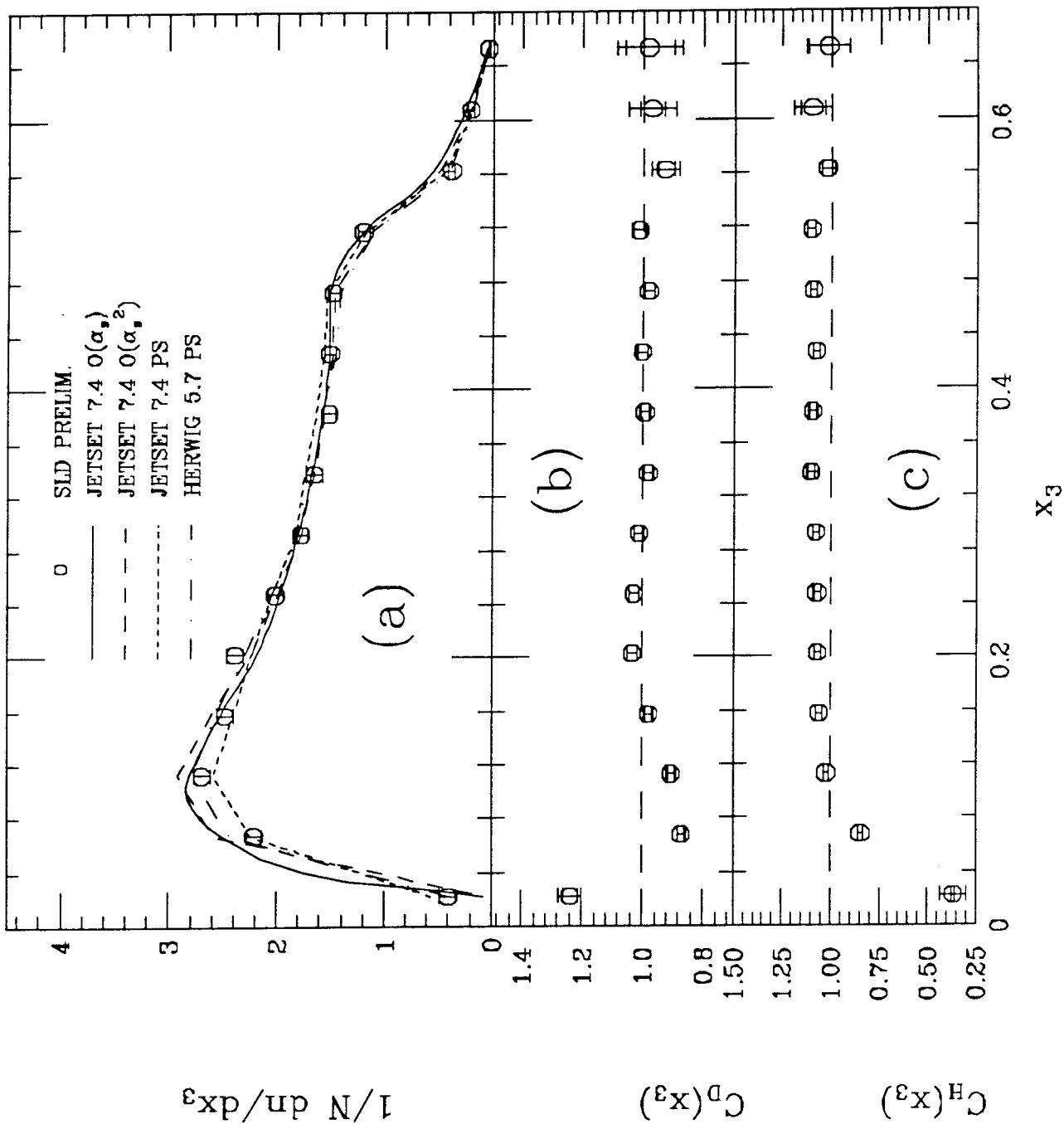


FIG. 6

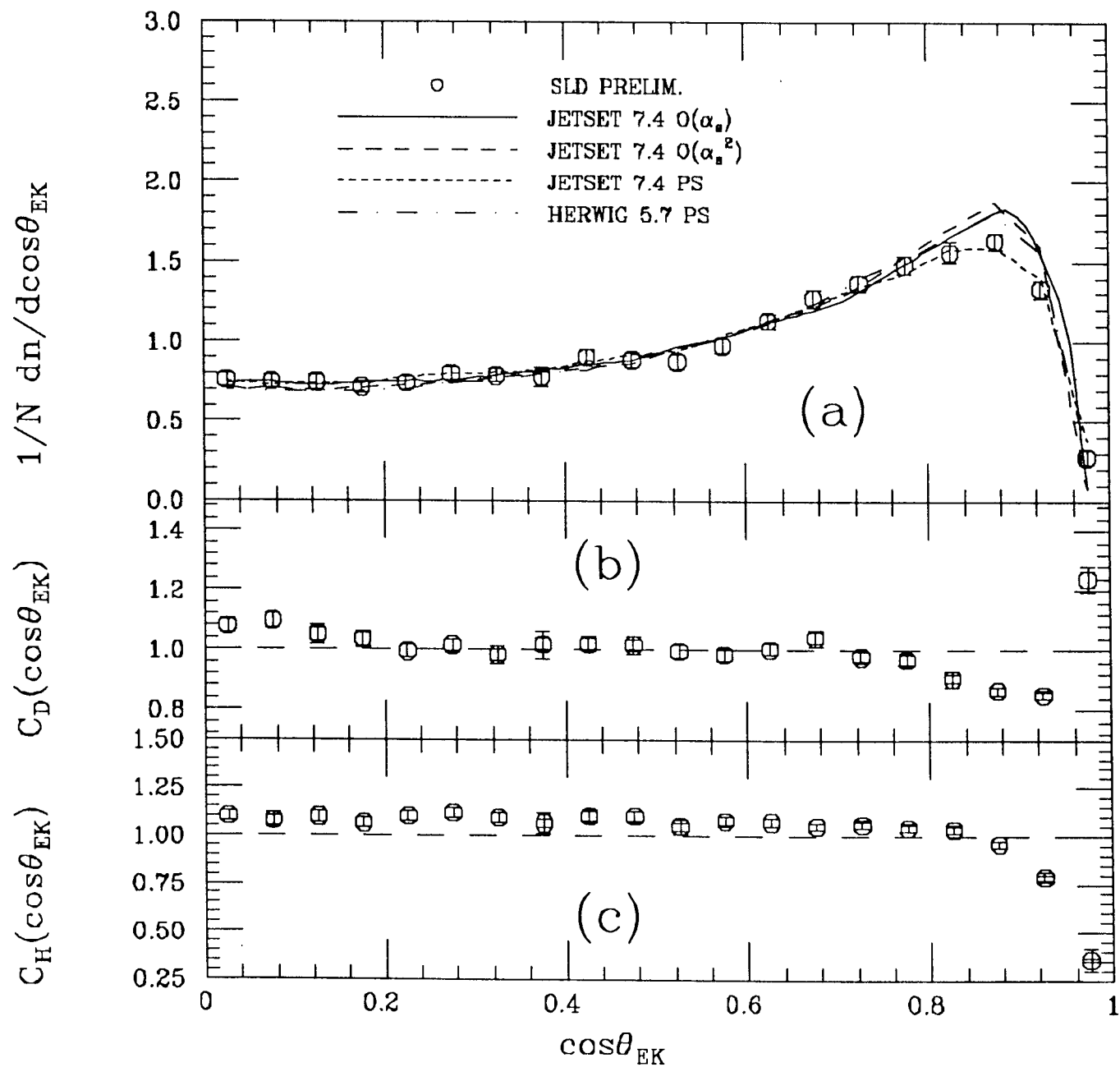


FIG. 7

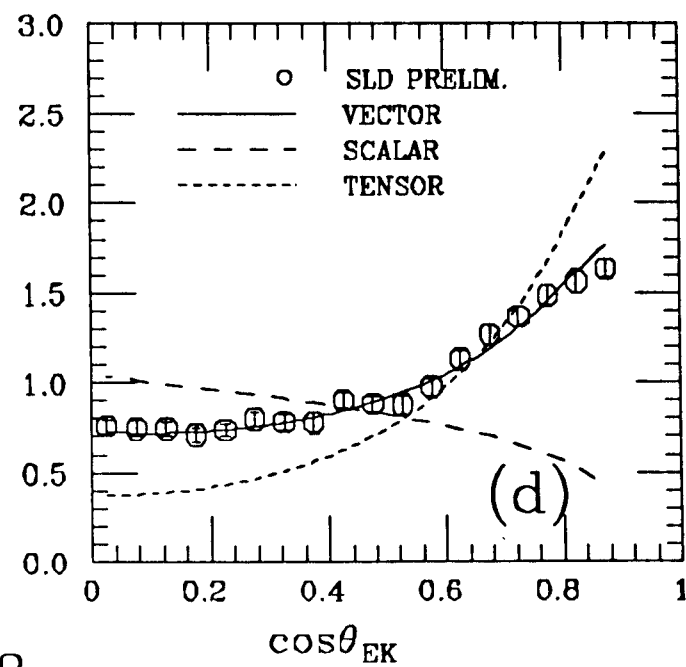
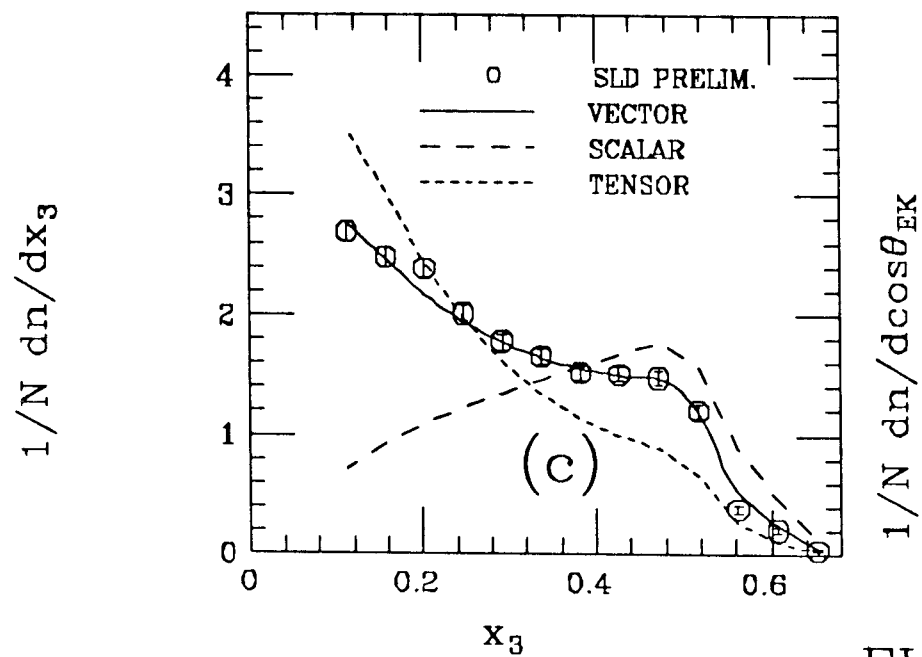
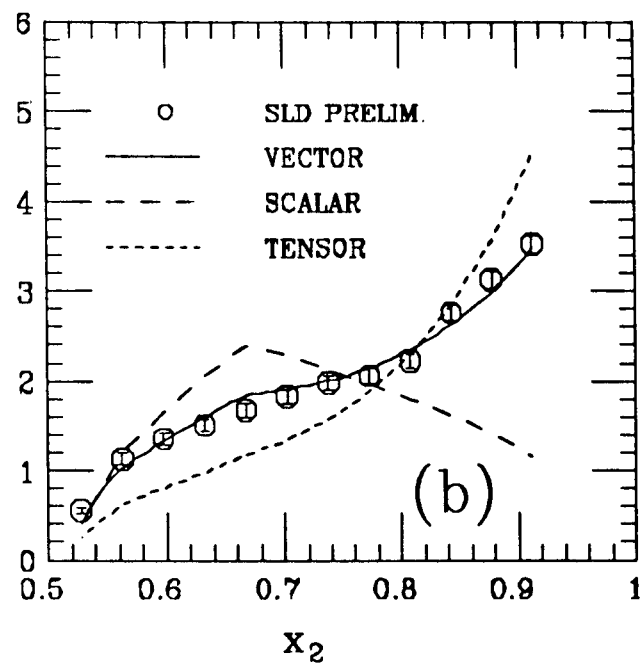
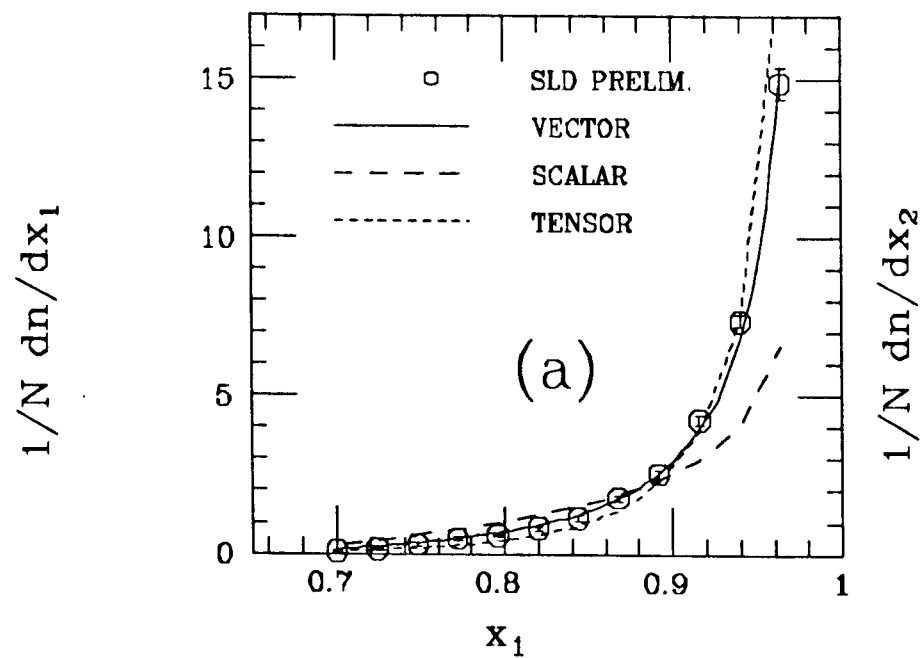


FIG. 8

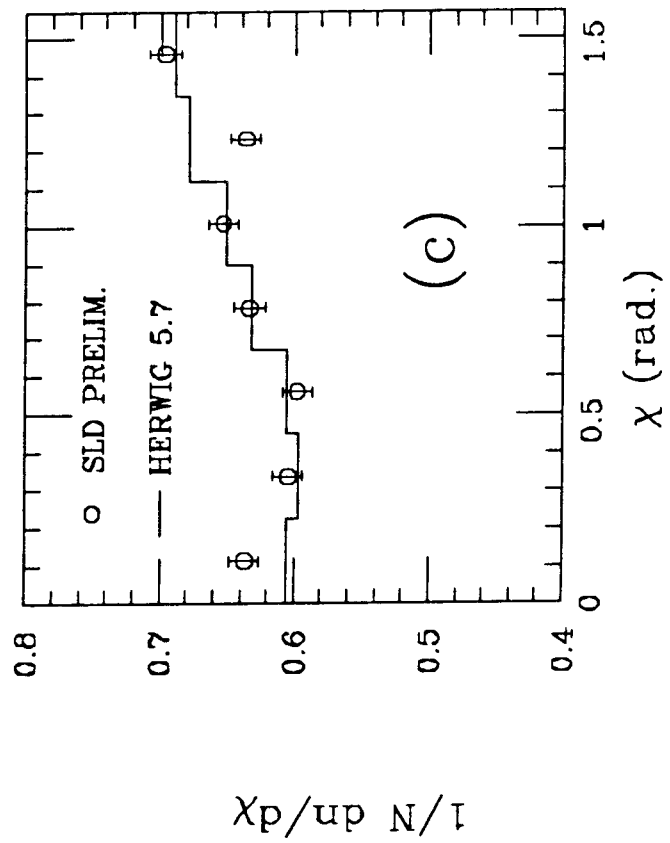
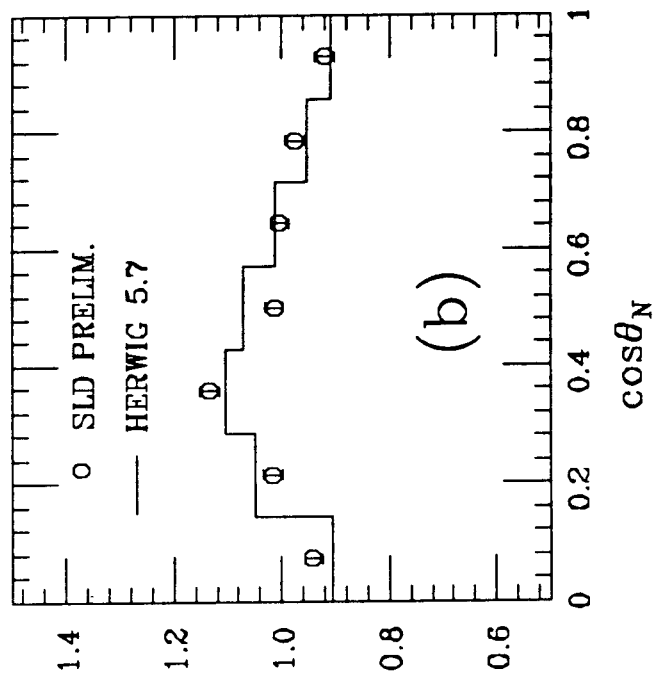
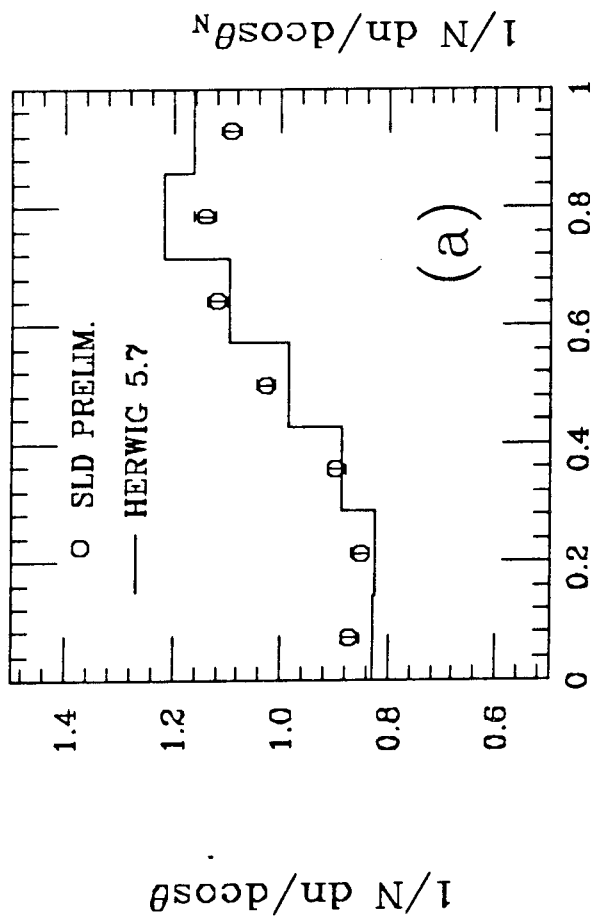


FIG. 9

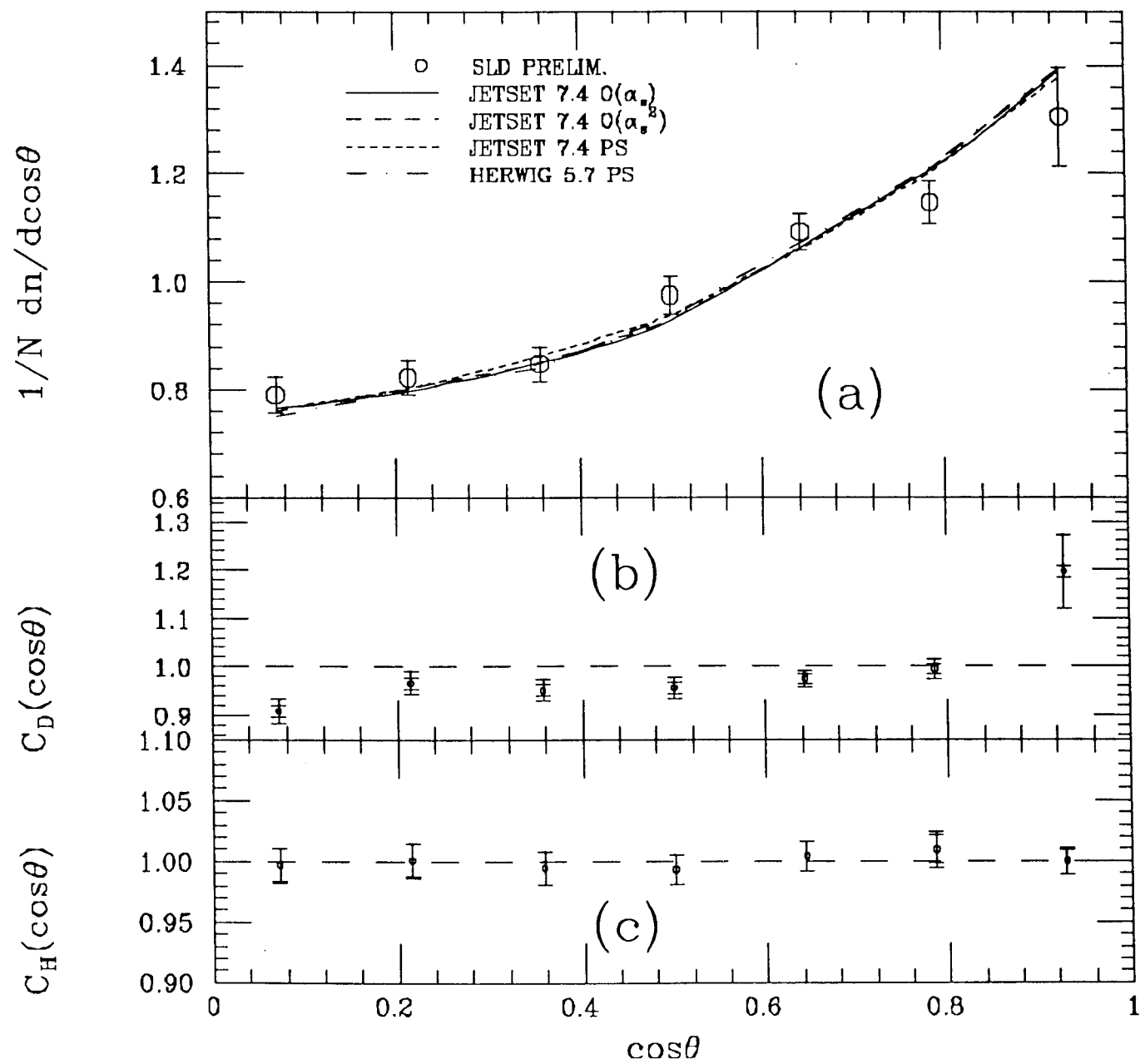


FIG. 10

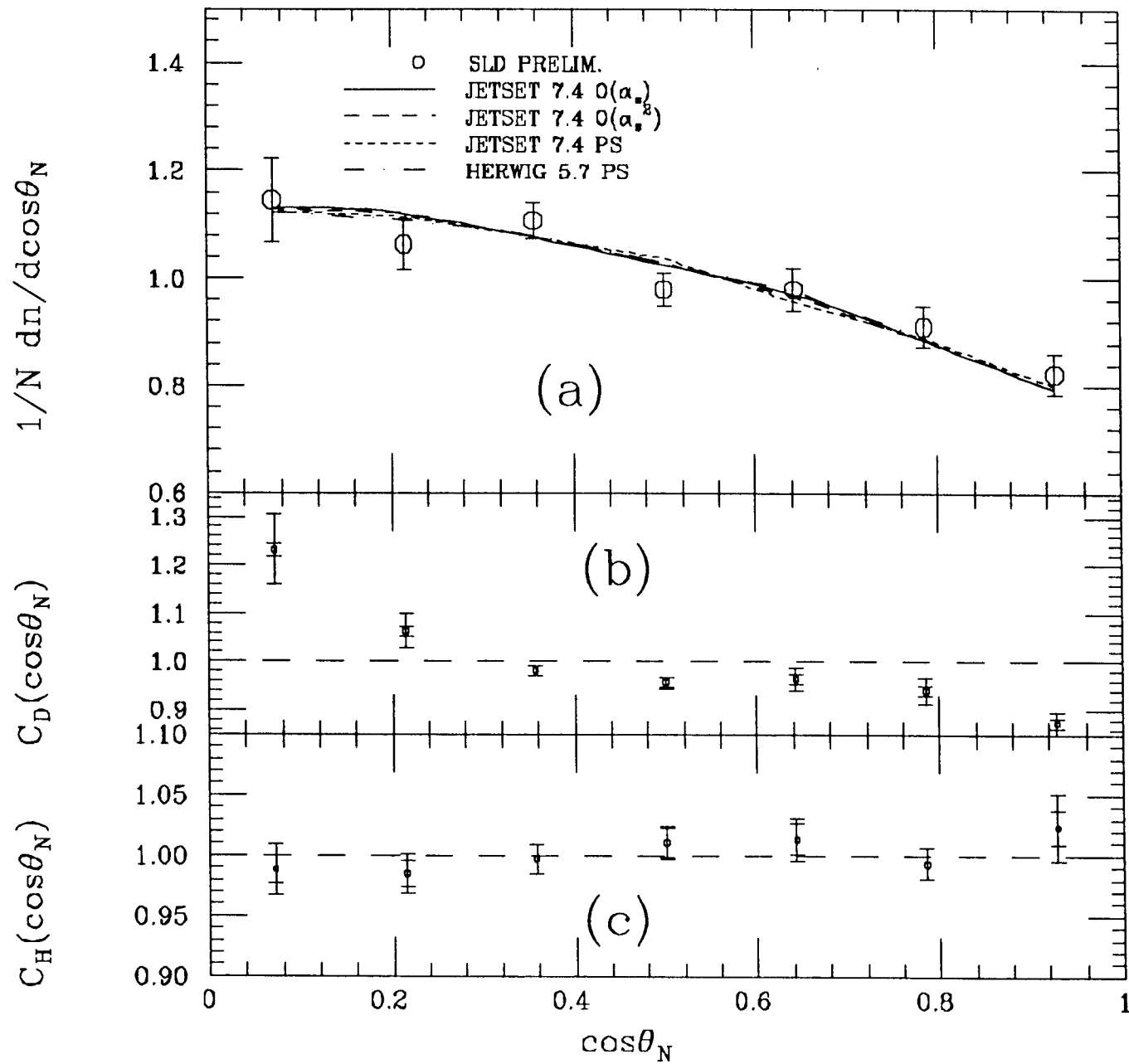


FIG. 11

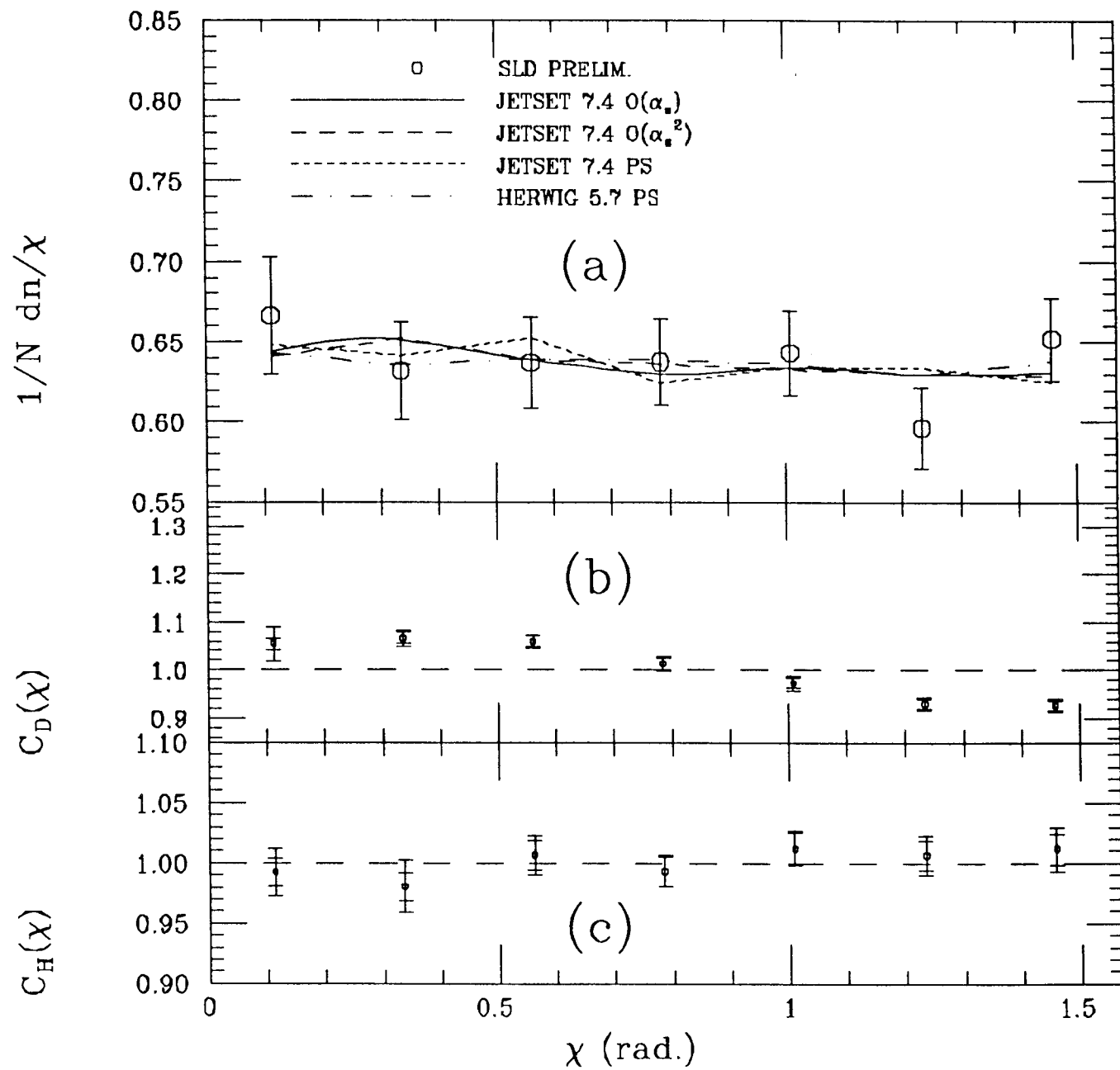


FIG. 12

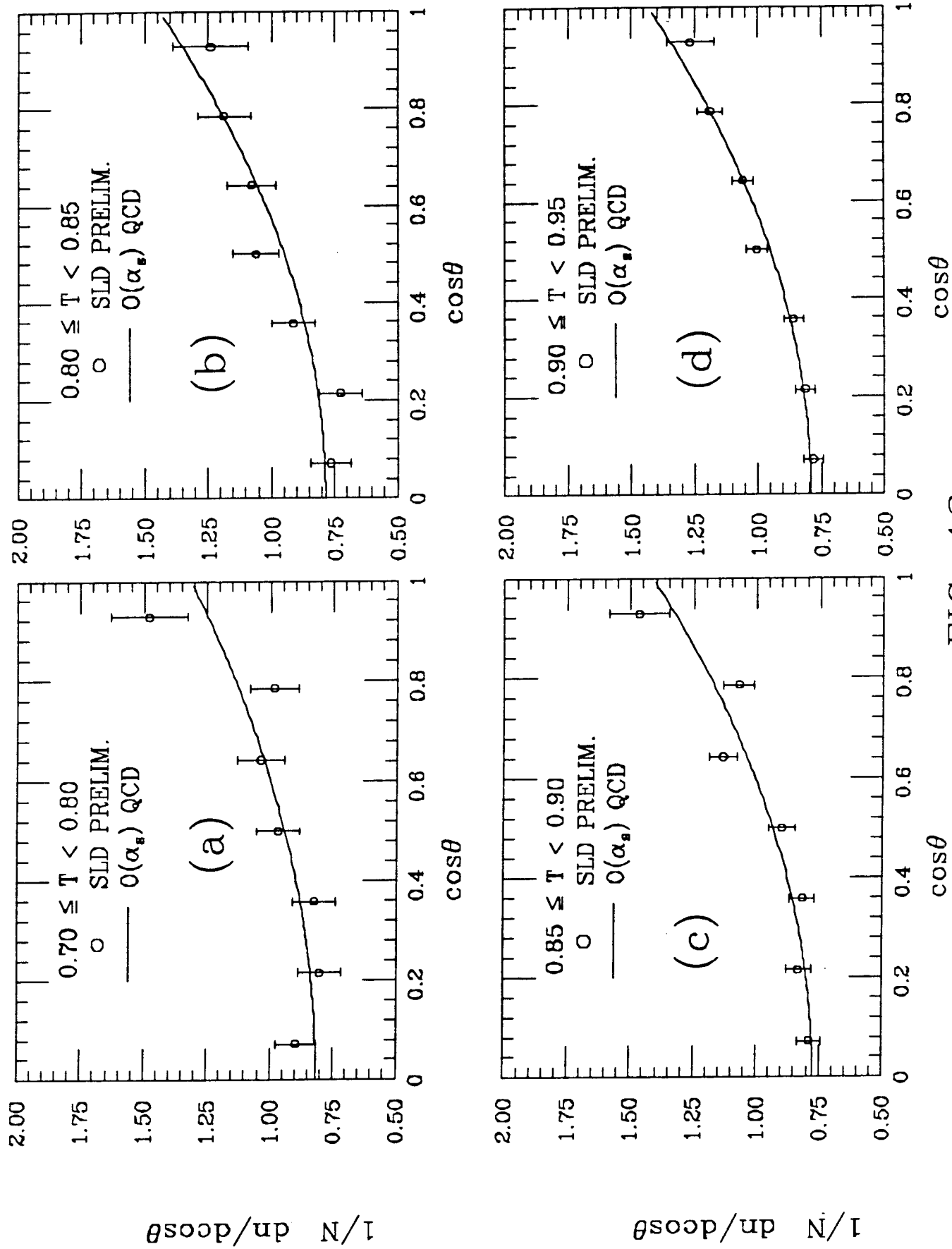


FIG. 13

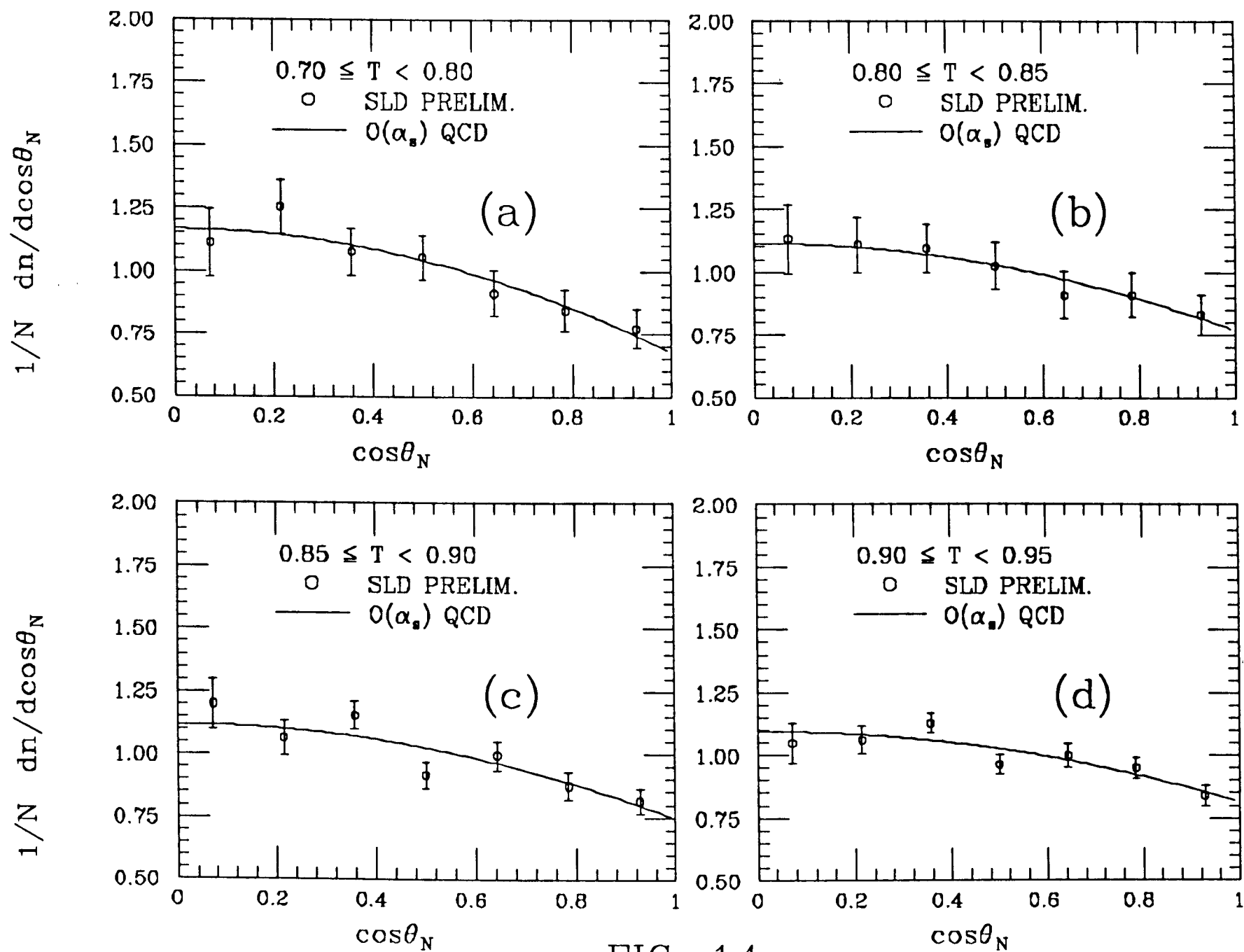


FIG. 14

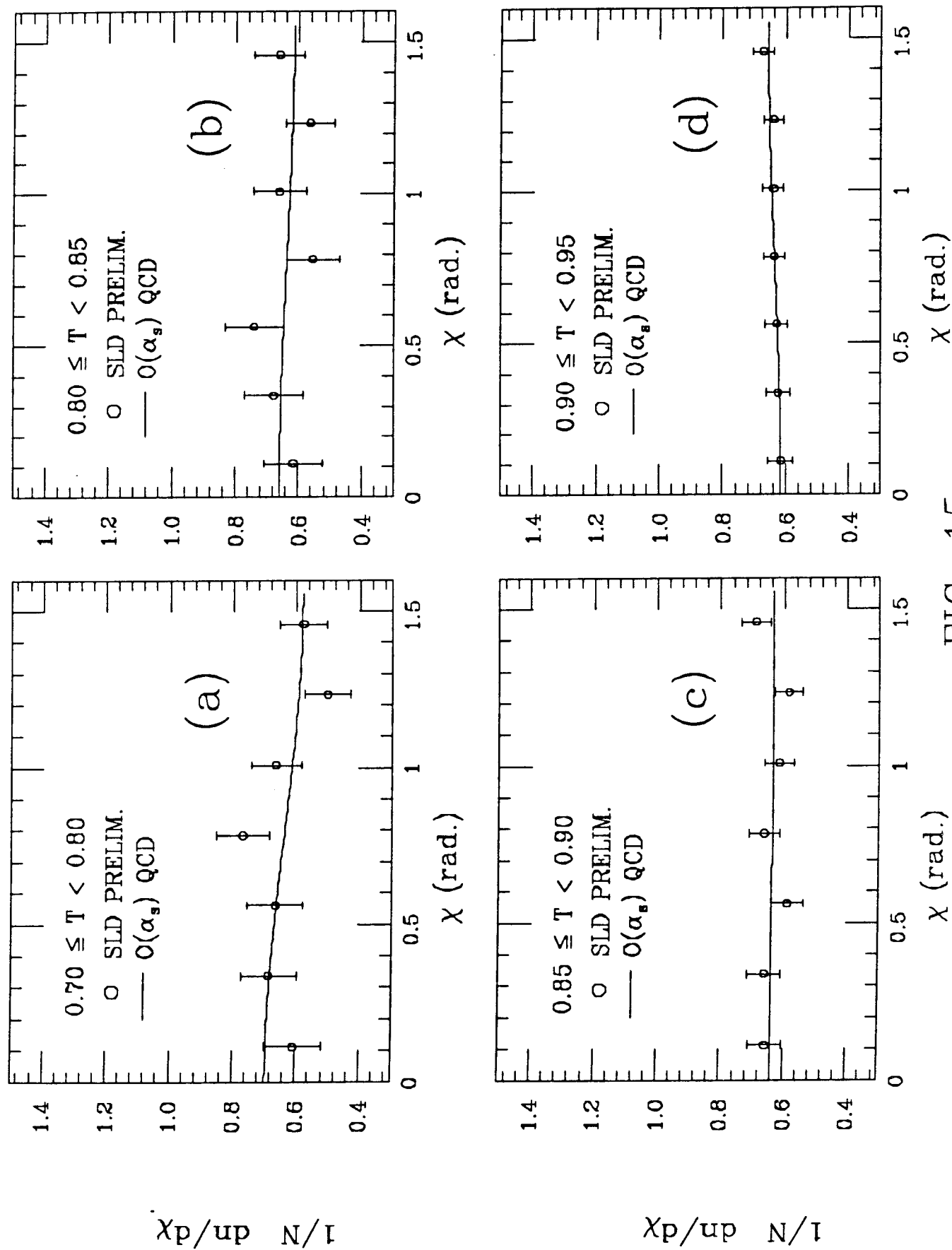


FIG. 15

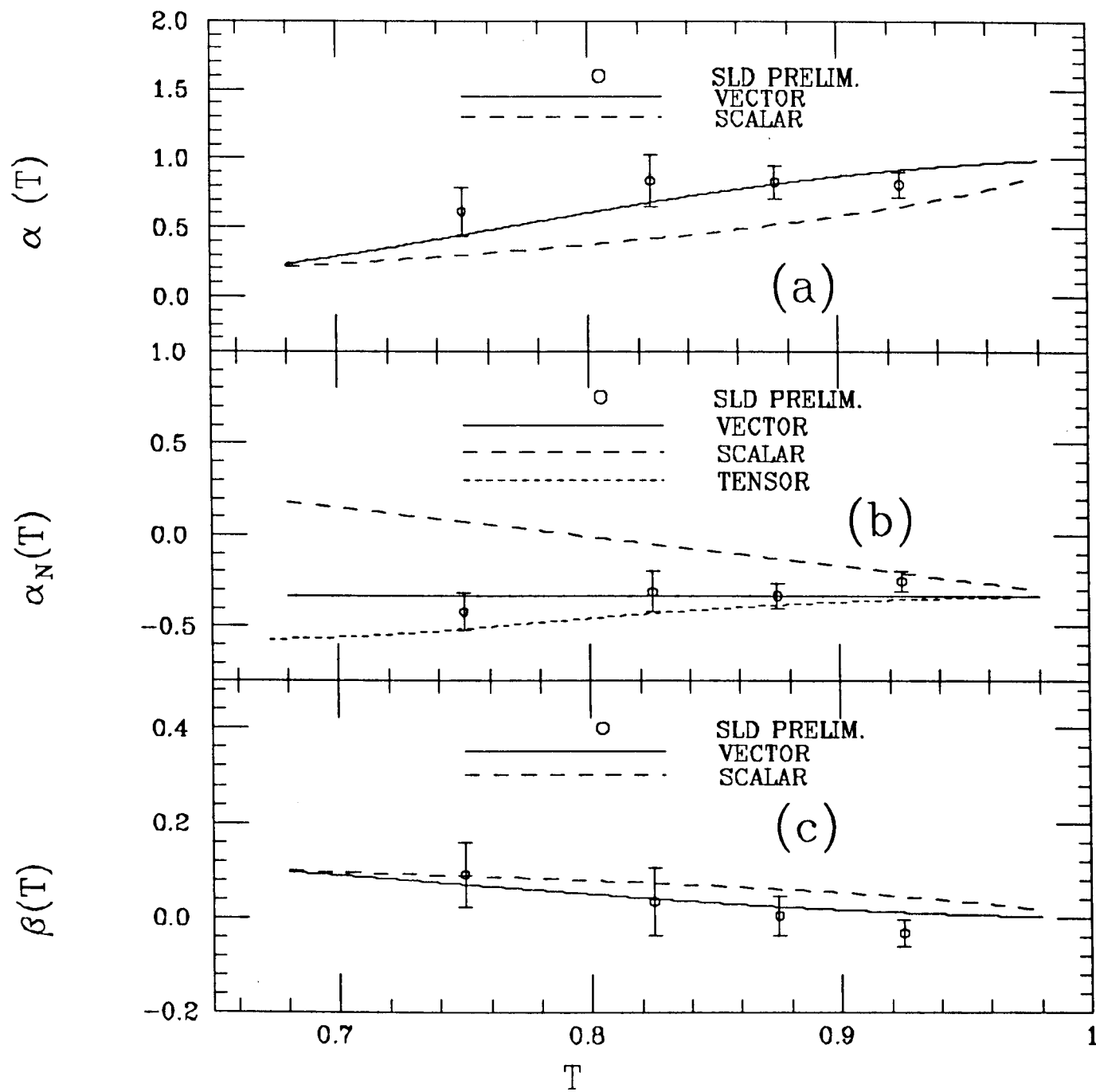


FIG. 16