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Study of Orientation of 3-jet Events in Z^0 Hadronic Decays Using the DELPHI Detector

DELPHI Collaboration

Abstract

The study of the orientation of three-jet events from $e^+e^- \rightarrow Z^o \rightarrow$ *multi-hadrons* is presented, in particular the polar angle distributions of the thrust axis and of the normal to the three-jet plane, and the azimuthal correlations between the hadron plane and the one defined by the beam and thrust axes. The data are compared with results at lower energy and with QCD predictions. Good agreement with QCD predictions is observed. The scalar gluon theory is excluded by the data.

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Introduction

The measurement of the orientation of two-jet events in e^+e^- annihilation relative to the beam axis has been of crucial importance in establishing the spin $-1/2$ nature of quark-partons[1]. The corresponding measurement of the orientation of three-jet events and a comparison with the QCD predictions[2] – [5] is important in establishing the properties of the gluons.

Up to now, such a study in e^+e^- annihilation has only been presented by the TASSO experiment[6]. In this case the data are dominated by photon exchange and cannot distinguish between QCD and scalar gluon theories.

More significant differences between vector and scalar gluon theories are expected in the $q\bar{q}g$ states at higher energy mediated by Z^0 exchange. Furthemore, data on the Z^0 resonance profit from the higher statistics.

The data used in this analysis were taken with the DELPHI detector at LEP at $\sqrt{s}\approx 91$ GeV.

Method

The three-jet events in e^+e^- annihilation

$$e^+e^- \rightarrow \gamma, Z \rightarrow q\bar{q}g \qquad (1)$$

where both electromagnetic and weak production mechanisms contribute (Z^0 resonance decay included) in the helicity frame (three-jet plane) can be characterized by two angles: the polar angle θ between the electron direction and the thrust direction (defined by the momentum of the most energetic jet) and the angle χ between the jet plane and a plane formed by the thrust axis and the lepton beam axis (see Fig.1). The corresponding differential cross section folded around $\cos\theta = 0$ reads[2] – [4]

$$\frac{16\pi}{3}\frac{d^2\sigma}{d\cos\theta\, d\chi} = (1+\cos^2\theta)\sigma_U + 2\sigma_L \sin^2\theta + 2\sigma_T \sin^2\theta \cos 2\chi - 2\sqrt{2}\sigma_I \sin 2\theta \cos\chi, \qquad (2)$$

where $\sigma_U(\sigma_L)$ is the transverse unpolarized (longitudinally polarized) cross section with helicity axis along the thrust axis, while $\sigma_T(\sigma_I)$ is the transverse/longitudinal $(+/-)$ interference terms.

After integration of (2) over χ or $\cos\theta$ one obtains, respectively[2],[4],

$$(1/\sigma)d\sigma/d\cos\theta = (1+\alpha\cos^2\theta)/2(1+\alpha/3), \qquad (3)$$

$$(1/\sigma)d\sigma/d\chi = (1+\beta\cos 2\chi)/2\pi, \qquad (4)$$

where the parameters α and β (depending on the particular thrust value T of the event) can be expressed in terms of the various cross sections as

$$\alpha = (1-2\sigma_L/\sigma_U)/(1+2\sigma_L/\sigma_U), \qquad (5)$$

$$\beta = (\sigma_T/\sigma_U)/(1+\sigma_L/\sigma_U). \qquad (6)$$

One can also measure the distribution of the polar angle ($\bar{\theta}$) of the normal to the three-jet plane also folded around $\cos\bar{\theta} = 0$, which is predicted to be of the form[5]

$$(1/\sigma)d\sigma/d\cos\bar{\theta} = (1+\bar{\alpha}\cos^2\bar{\theta})/2(1+\bar{\alpha}/3) \tag{7}$$

with

$$\bar{\alpha} = -\frac{1}{3}\frac{\sigma_U+\sigma_L-3(\sigma_L-2\sigma_T)}{\sigma_U+\sigma_L-(\sigma_L-2\sigma_T)/3}. \tag{8}$$

If σ_L/σ_U is non-zero for a thrust range below the two-jet limit $T=1$[1] (i.e. when the parameter α extracted from the $d\sigma/d\cos\theta$ distribution becomes significantly smaller than 1) then the parameter $\bar{\alpha}$ extracted from the $d\sigma/d\cos\bar{\theta}$ distribution is expected to be close to $-1/3$ independently of the thrust value chosen and this tests the QCD $O(\alpha_s)$ prediction[2] $\sigma_L = 2\sigma_T$ [2]. This prediction leads also to a relation between α and β

$$\beta = \frac{1}{2}\frac{1-\alpha}{3+\alpha} \tag{9}$$

which is easy to test.

The Detector and Data Selection

The sample of 128290 hadronic events with $n_{ch} \geq 5$ used in this analysis was collected by the DELPHI detector at the LEP e^+e^- collider in 1989 − 1990. The DELPHI detector has been described in detail elsewhere[7]. The present analysis relies on the information provided by charged particle detectors. The similar cuts are applied for event selection as in our earlier study[8] of hadronic decays of the Z^0. The tracks of charged particles were retained only if they were detected in the Time Projection Chamber (TPC), if they extrapolated back to within 5 cm of the beam axis in r and to within 10 cm of the nominal crossing point in z, if their measured momentum p was in the range $0.1 < p < 50$ GeV/c, if their measured track length was above 50 cm and if their polar angle θ was between 25° and 155°. Hadronic events were then selected by requiring that *a*) the total energy of charged particles (assuming π mass) in each of the two hemispheres defined with respect to the beam axis exceeded 3 GeV, *b*) the total energy of charged particles seen in both hemispheres together exceeded 15 GeV, *c*) there were at least 5 charged particles with momenta above 0.2 GeV/c and *d*) the polar angle θ of the thrust axis was in the range $|\cos\theta| < 0.75$. A total of 76046 events satisfied these cuts. The possible contamination from events due to beam-gas scattering, $\gamma\gamma$ interactions and $\tau^+\tau^-$ decays was reduced to a negligible level (< 0.1%, < 0.1% and < 0.15%, respectively) by the imposed cuts.

The angular distributions presented below were obtained after correcting the raw data for the limited geometrical acceptance and resolution of the TPC, limited efficiency of the track finding, particle interactions in the material of the detector, other detector imperfections, applied kinematical cuts, and also for higher order QED initial state radiation[9] and jet fragmentation. The correction procedure

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1 In order to eliminate a trivial case of $q\bar{q}$ pair production, when $\sigma_L = \sigma_T = 0$ and $\bar{\alpha} = -1/3$.

2 The $O(\alpha_s^2)$ corrections to this measure have been found negligible[5].

was based on 54000 Monte Carlo events generated according to the Lund Parton Shower (PS) model (Monte Carlo program JETSET version 6.3) [10],[11]. Correction factors were calculated by comparing the original parton distributions with the observed distributions of the final state particles after reconstruction and selection.

The parton distributions were obtained from the events generated without initial state radiation and without jet fragmentation. The observed distributions of the final state particles were obtained after tracking events, generated with initial state radiation and jet fragmentation, through the DELPHI detector to produce simulated raw data which were then processed through the same reconstruction and analysis programs as the real data. Thus the correction factor for angular distributions reads:

$$C(x) = \frac{(1/N \cdot dn/dx)_{partons}}{(1/N \cdot dn/dx)_{particles}}, \tag{10}$$

with $x = cos\bar{\theta}$, $\cos\theta$ or χ.

The correction factors $C(x)$ are shown for the thrust interval $0.75 < T < 0.80$ in Fig.2. They are close to unity for the $\cos\theta$ distributions in the $\cos\theta$ interval studied, but show more important variations for the $\cos\bar{\theta}$ and χ distributions due to the cuts imposed on the polar angles of the tracks and the thrust axis. The variation of $C(x)$ with T is smallest ($< 10\%$) for $\cos\theta$ distributions, $\leq 15\%$ for $\cos\bar{\theta}$ distributions and is largest ($\leq 25\%$) for χ distributions. These corrections are dominated by the experimental cuts. The corrections from hadron level to parton level, which are included in $C(x)$, are 3%, 1% and 5% for the $\cos\theta$, $\cos\bar{\theta}$ and χ distributions, respectively. The $C(x)$ corrections have been obtained with the Parton Shower option of the Monte Carlo program. It has been checked that similar results are obtained with the exact second order QCD Matrix Element option in this program.

Jets were defined in the data and Monte Carlo events by the LUCLUS algorithm provided with the JETSET Monte Carlo program[11]. In this algorithm two particles (or particle and jet) with momenta p_1, p_2 and opening angle α_{12} are merged together if

$$2\frac{p_1 \cdot p_2}{p_1 + p_2}\sin\frac{\alpha_{12}}{2} \leq d_0 \tag{11}$$

This procedure is repeated in successive steps until a stable configuration is reached. The jet resolution parameter d_0 was set to $6 \cdot \frac{E_{vis}}{\sqrt{s}}$ GeV, where E_{vis} is the sum of energies of the accepted charged particles. This yielded 6308, 3934, 2018 and 756 3-jet events below thrust cut-offs of 0.90, 0.85, 0.80 and 0.75, respectively.

Experimental Results

The $d\sigma/d\cos\bar{\theta}$, $d\sigma/d\cos\theta$ and $d\sigma/d\chi$ distributions, corrected to the parton level and with initial state radiation and detector imperfections taken into account as discussed in the previous section, are presented in Figs. 3, 4 and 5 as a function of the thrust value. The $d\sigma/d\cos\bar{\theta}$ and $d\sigma/d\cos\theta$ distributions have been folded around $\cos\bar{\theta} = \cos\theta = 0$. The $d\sigma/d\chi$ distribution has been folded in the different angular intervals in the following way: $\chi = \chi$ for the $0 \rightarrow \pi/2$ interval, $\chi = \pi - \chi$ for the $\pi/2 \rightarrow \pi$ interval, $\chi = \chi - \pi$ for the $\pi \rightarrow 3\pi/2$ interval and $\chi = 2\pi - \chi$ for the $3\pi/2 \rightarrow 2\pi$ interval.

The data were fitted to the expressions (7), (3) and (4) suggested by QCD. The fits (solid curves in Figs. 3, 4 and 5) describe the data well. The fitted values of the parameters $\bar{\alpha}$, α and β are given as a function of the thrust value in Table 1 and are also shown in Fig.6.

The values obtained for the anisotropy parameter $\bar{\alpha}$ (Fig.6a) are in very good agreement with the QCD prediction $\bar{\alpha} = -1/3$ [5] independent of the thrust value.

The polar angular distributions of the most energetic jet (Fig.4) are certainly flatter than the $(1 + cos^2\theta)$ distribution for two-jet events. The values obtained for the anisotropy parameter α (Fig.6b) exhibit a strong decrease with decreasing T, again in very good agreement with the QCD prediction (solid curve).

The azimuthal angular distributions (Fig.5) show significant departure from the isotropic behaviour expected for two-jet events. Our values for the parameter β increase with decreasing T (Fig.6c). They follow the trend of the QCD predictions.

We also calculated the parameters $\bar{\alpha}$, α and β in the Lund PS (JETSET 6.3) and Lund Matrix Element (ME) (JETSET 7.2) models [10],[11]. The Lund ME predictions (not shown) completely coincide with QCD predictions, as expected. The Lund PS gives $\bar{\alpha} = -1/3$, while the behaviour of the parameters α and β as a function of T is only slightly different from the QCD predictions (dotted curves in Figs. 6b and 6c).

Finally we compared our measurement of the anisotropy parameter $\bar{\alpha}$ with the theory of coloured scalar gluons[12],[5]. The Born term Feynman diagrams in such a scalar gluon theory include the vector current and axial vector current contributions. The VV part of the hadron tensor[5] leads to a value $\bar{\alpha} = -1/3$ for the anisotropy parameter below the Z^0 peak where the VV contribution dominates. However, for the AA contribution $\bar{\alpha} \neq -1/3$ already at the Born term level. Since the AA contribution is significant on the Z^0 peak this allows the spin property of the gluon to be tested. The deviation from $\bar{\alpha} = -1/3$ is predicted[5] to be highest for u, c, t quarks for thrust values $T < 0.9$, but it is also substantial for a sample of hadron events without identified quarks, as is shown in Fig.6a by the dashed curve. As one can see, our data distinguish unambiguously between vector and scalar gluon theories in $q\bar{q}g$ states mediated by Z^0 exchange.

Summary

Our measurements of the polar angle anisotropy parameters α and $\bar{\alpha}$, which determine the polar angle distribution of the thrust axis and of the normal to the three-jet plane, respectively, in e^+e^- annihilation into three jets around the Z^0 peak show:

- flattening of the $d\sigma/dcos\theta$ distribution with decreasing thrust value, so that the polar angle parameter $\alpha < 1$ and thus $\sigma_L \neq 0$ for $T < 1$.

- constancy of the polar angle parameter $\bar{\alpha} = -1/3$ over the whole range of thrust values. These measurements are in good agreement with the QCD predictions.

The first experimental test of the scalar gluon theory on the Z^0 peak, for which the anisotropy parameter $\bar{\alpha}$ deviates substantially from $\bar{\alpha} = -1/3$, shows that this theory is excluded by the experimental data.

The measurement of the azimuthal correlation between the lepton and hadron planes for the three-jet events shows departure from the isotropic behaviour expected for two-jet events, with the anisotropy parameter β increasing with decreasing thrust value in reasonable agreement with the QCD prediction.

While this paper was prepared, we became aware of similar results obtained by the L3 experiment[13].

Aknowledgement

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Table 1:

Fitted values of the anisotropy parameters $\bar{\alpha}$, α and β for thrust value T with the corresponding confidence level (CL) of the fits.

T	$\bar{\alpha}$	CL(%)	α	CL(%)	β	CL(%)
0.85–0.90	-0.38±0.07	54	0.98±0.18	78	0.06±0.05	97
0.80–0.85	-0.32±0.09	92	0.74±0.18	89	0.03±0.06	98
0.75–0.80	-0.39±0.10	68	0.53±0.21	99	0.08±0.07	99
0.70–0.75	-0.27±0.15	97	0.36±0.25	99	0.12±0.08	93

Figure Captions

Fig.1 The definition of the polar and azimuthal angles θ and χ for three-jet events[4].

Fig.2 The correction factors C for $\cos\theta$, $\cos\bar{\theta}$ and χ distributions for the thrust interval $0.75 < T < 0.80$.

Fig.3 The polar angle distributions of the normal to the three-jet plane for different thrust values. The solid curves represent the results of a fit to the form (7).

Fig.4 The polar angle distributions of the thrust axis for three-jet events for different thrust values. The solid curves represent the results of a fit to the form (3).

Fig.5 The azimuthal correlation between the lepton and hadron planes for three-jet events for different thrust values. The solid curves represent the results of a fit to the form (4).

Fig.6 Values of the anisotropy parameters $\bar{\alpha}$, α and β as a function of the thrust value. The solid, dashed and dotted curves represent the predictions of QCD, scalar gluon theory and the Lund PS model, respectively. Note that for the TASSO data, the scalar gluon theory would give the same predictions as QCD.

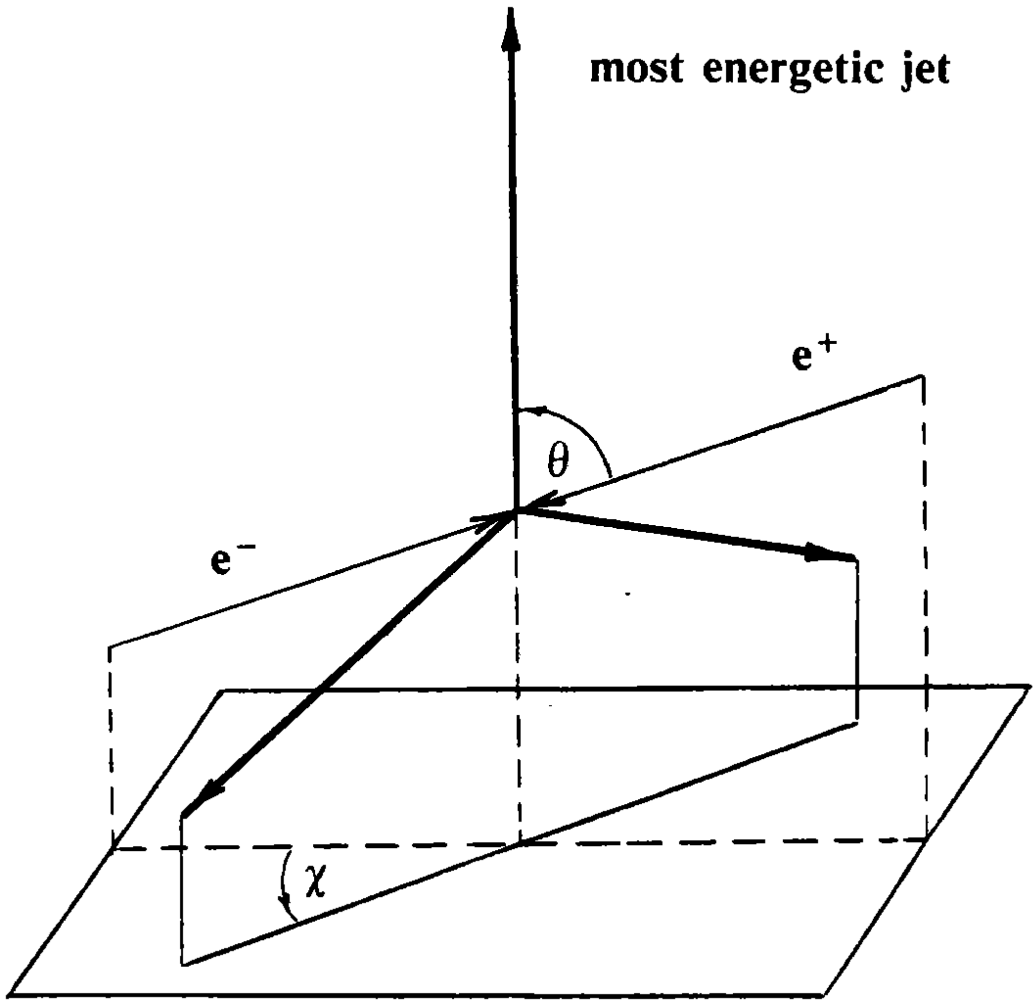

Fig. 1

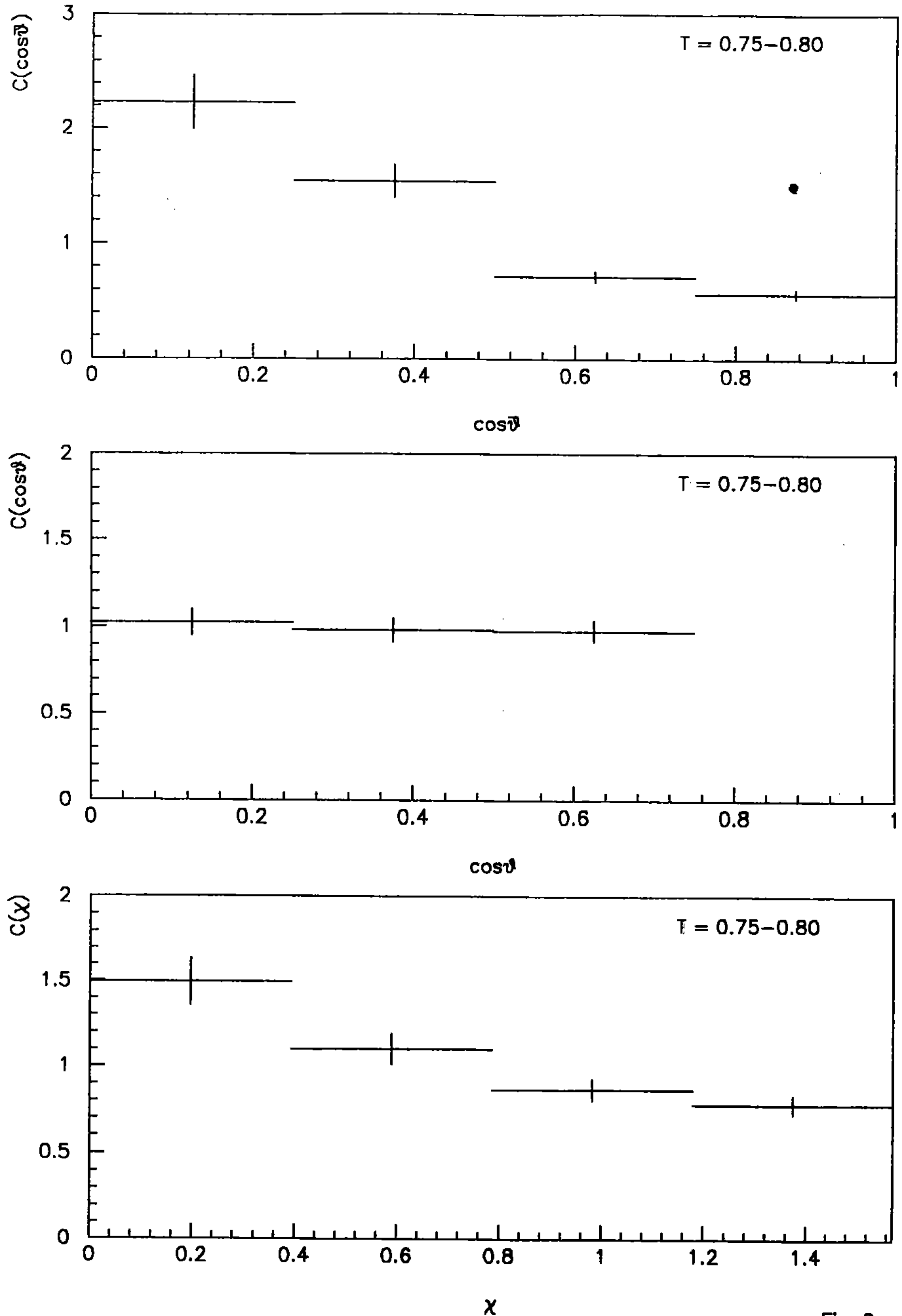

Fig. 2

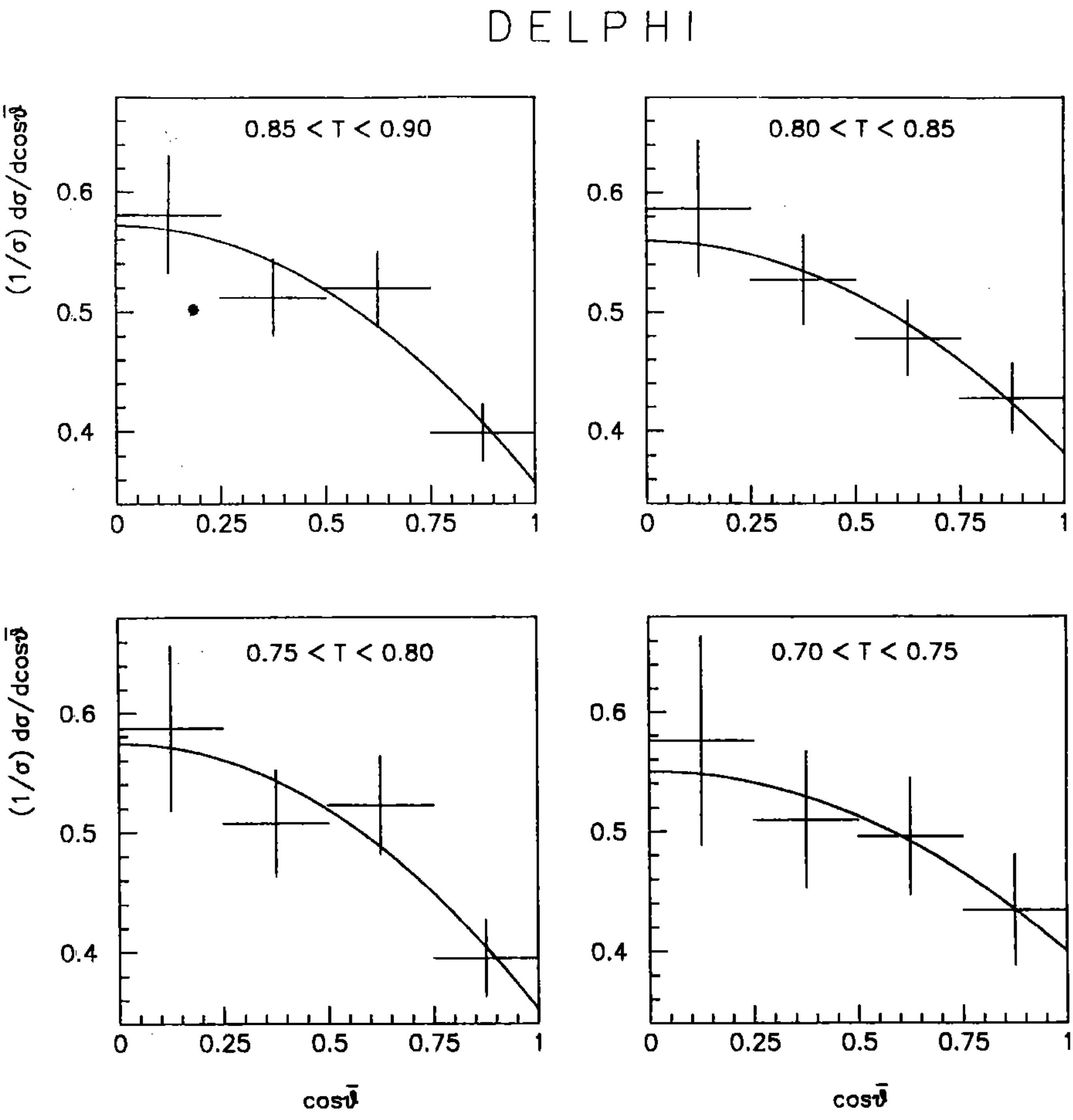
DELPHI
0.85 < T < 0.90
0.80 < T < 0.85
0.75 < T < 0.80
0.70 < T < 0.75
(1/σ) dσ/dcos$\bar{\vartheta}$
cos$\bar{\vartheta}$
0.4
0.5
0.6
0
0.25
0.5
0.75
1

Fig. 3

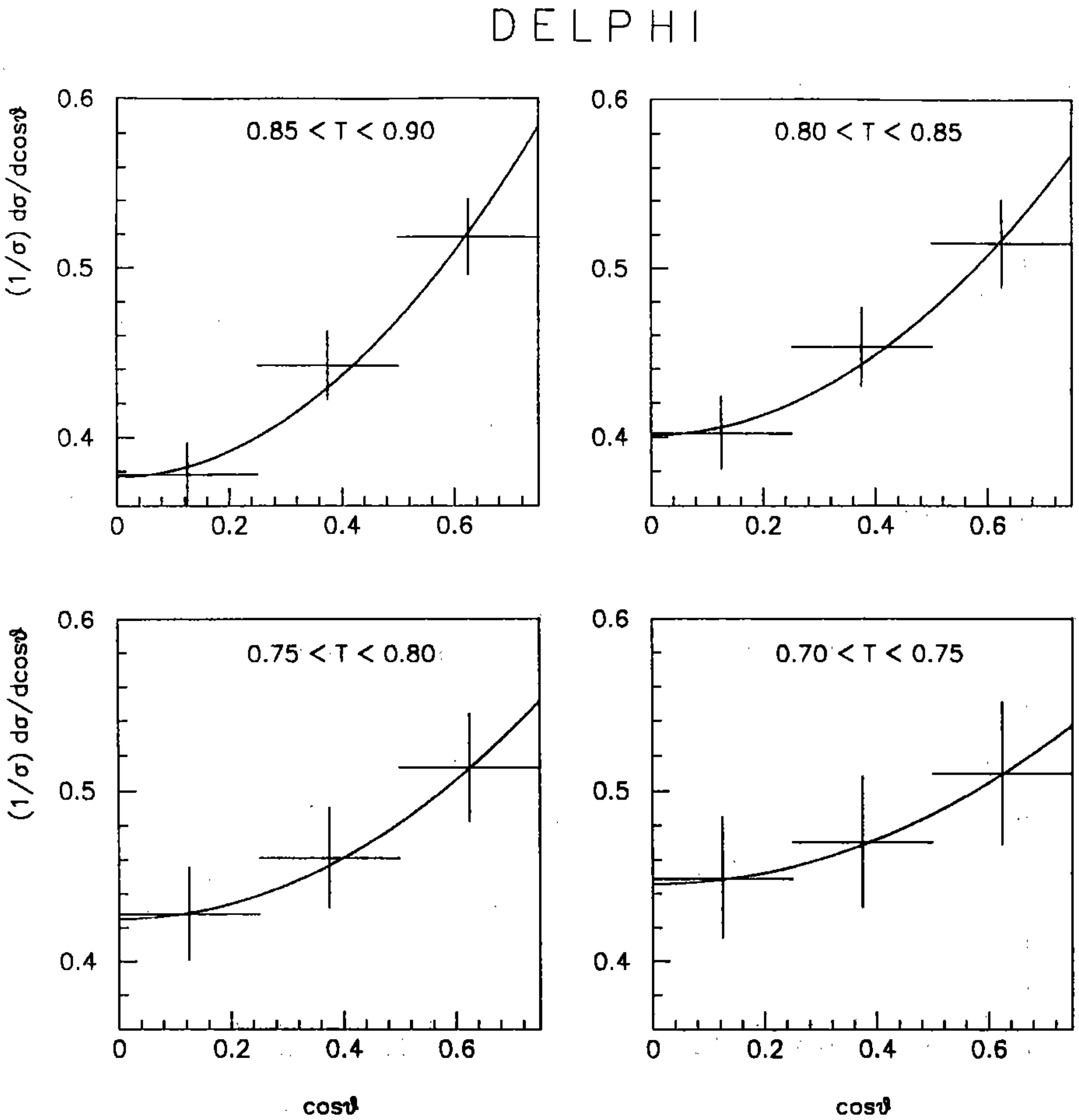
DELPHI
0.85 < T < 0.90
0.80 < T < 0.85
0.75 < T < 0.80
0.70 < T < 0.75
(1/σ) dσ/dcosϑ
(1/σ) dσ/dcosϑ
cosϑ
cosϑ

Fig. 4

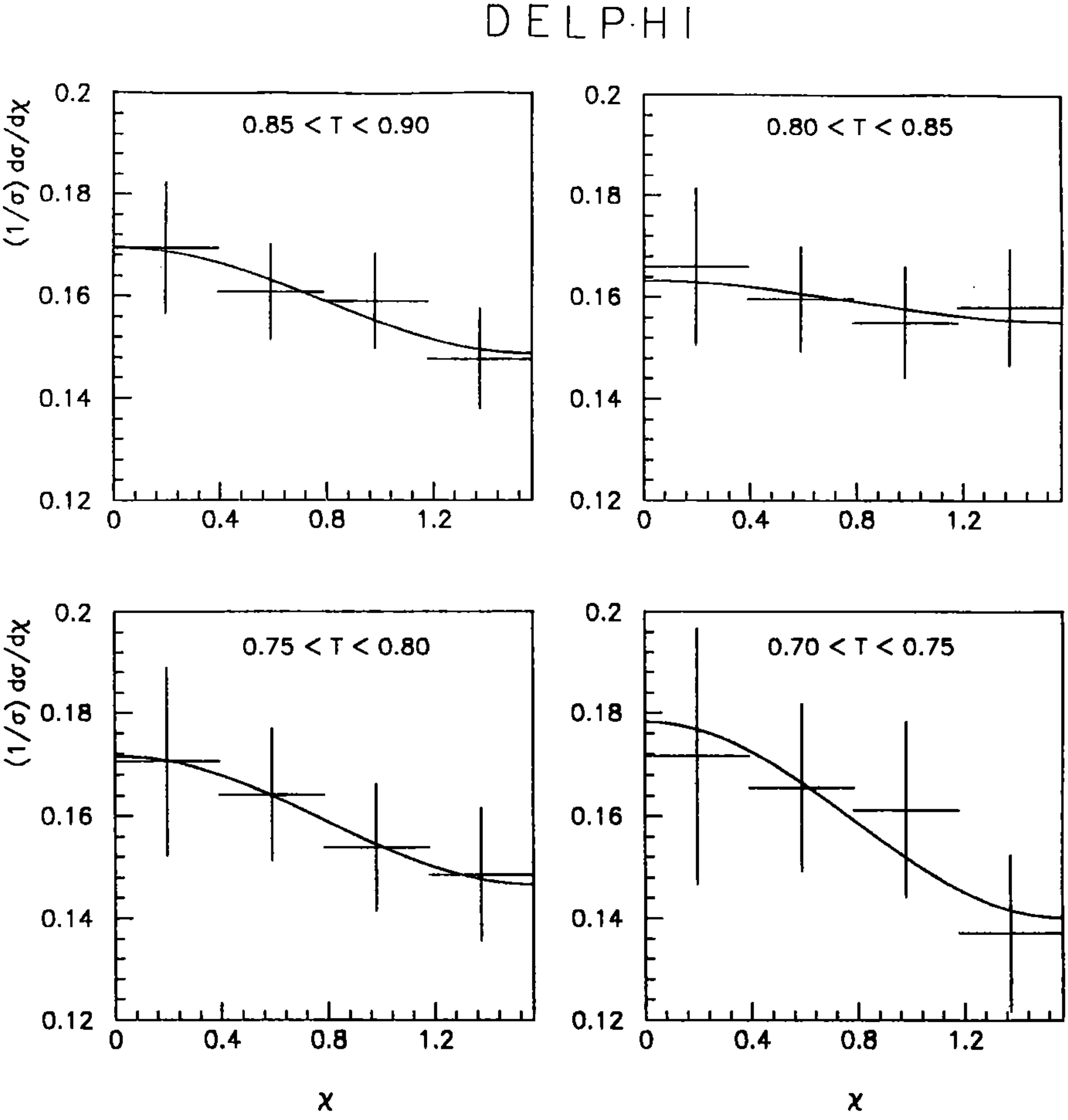
DELPHI
(1/σ) dσ/dχ
0.85 < T < 0.90
0.80 < T < 0.85
0.75 < T < 0.80
0.70 < T < 0.75
0.2
0.18
0.16
0.14
0.12
0
0.4
0.8
1.2
χ

Fig. 5

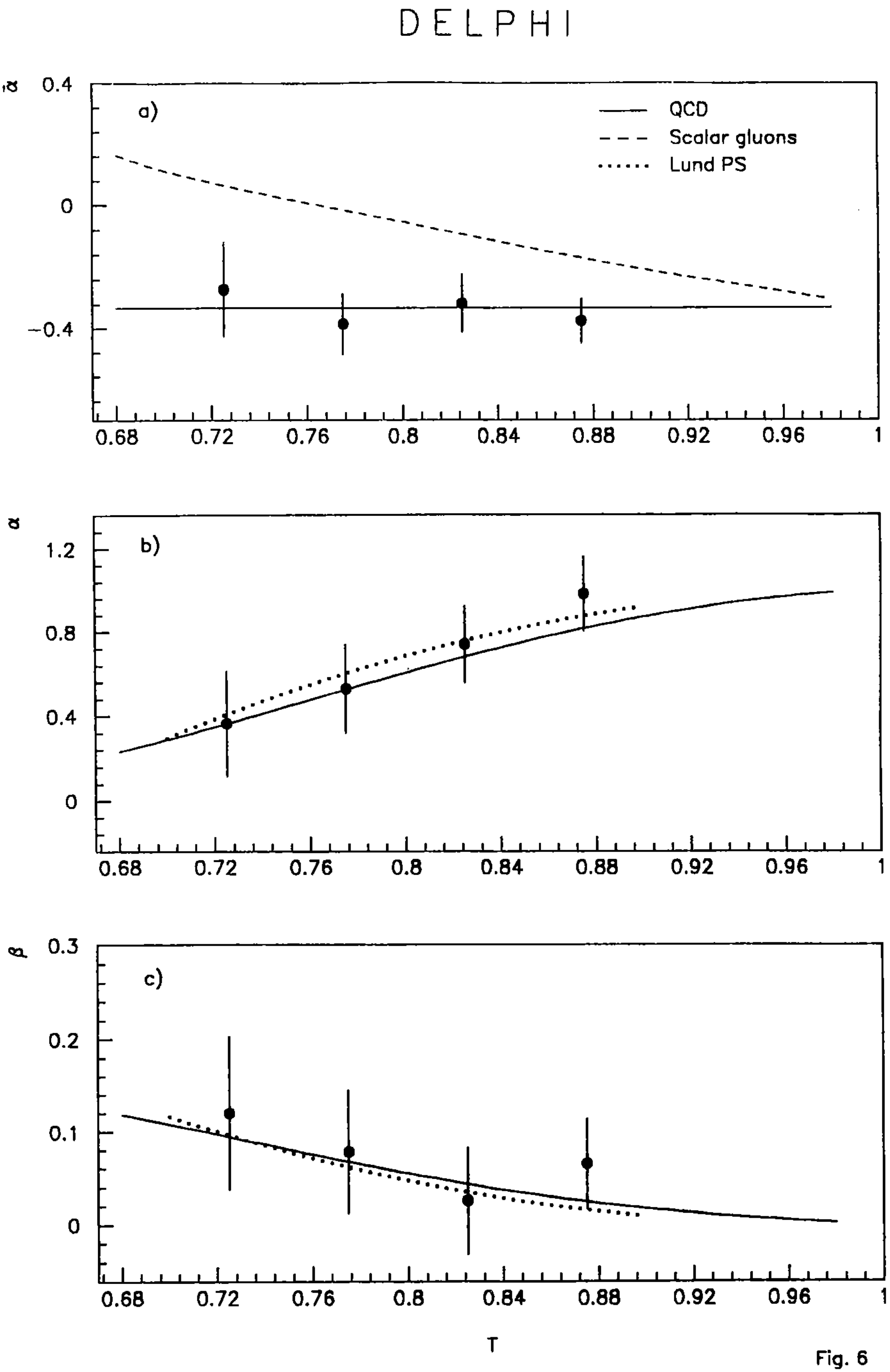

Fig. 6

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