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JET HANDEDNESS CORRELATION IN HADRONIC Z^0-DECAYS

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1 Introduction into handedness

The handedness as a new characteristic of the multiparticle parton fragmentation function has firstly been proposed at the end of the seventies [1] and was revived recently [2] in connection with polarized quark production in $e^+e^- \to Z^0 \to$2-jet decay. It can be defined in the following way.

Consider fragmentation of a parton into two hadrons with momenta $\vec{k}_1$ and $\vec{k}_2$ selected and ordered according to some definite criteria. Let the vector $\vec{j}$ is a unit vector in the jet direction defined by the thrust axis or by the total jet momentum. Using this one can build a pseudoscalar variable

$$X = \frac{(\vec{k}_1 \times \vec{k}_2) \cdot \vec{j}}{|\vec{k}_{T1}|\,|\vec{k}_{T2}|} \tag{1}$$

where $\vec{k}_{T1}$ and $\vec{k}_{T2}$ are the momenta projections onto the plane that is perpendicular to the vector $\vec{j}$. The jet with a so selected pair is called right handed if $X > 0$ and left handed if $X < 0$. Then, the longitudinal handedness is defined as asymmetry with respect to the pseudoscalar variable X, i.e. as a relative difference of the right-handed and left-handed jets[1]

$$H = \frac{N_R(X > 0) - N_L(X < 0)}{N}. \tag{2}$$

(Notice, that if a jet contains more than one pair which satisfy the applied criteria the jet could be counted more than once.)

The asymmetry with respect to X is interesting due to the following reason. The dependence on the pseudoscalar X can appear only in a product with another pseudoscalar. The only definitely known one, characterizing the two-particle fragmentation of an object (quark, gluon or resonance), is a longitudinal polarization P. So measurement of the handedness should give information about polarization P.

Indeed, let a probability of a right (left) handed quark (with helicity $h = \pm 1$) to fragment into at least one right handed pair of particles or (assuming the P-invariance of fragmentation) a probability of a left (right) handed quark to fragment into at least one left handed pair with given cuts be

$$w^R_{q\pm} = w^L_{q\mp} = \frac{w_q}{2}(1 \pm \alpha^q) \tag{3}$$

where

$$w_q = \frac{N}{n} = \frac{N_R + N_L}{n^q_+ + n^q_-}. \tag{4}$$

and $n^q_\pm$ and $N_{R,L}$ are numbers of the right and left handed quarks and pairs, respectively.

[1]Similarly, one can define two transverse components of the handedness using two unit transverse vectors instead of $\vec{j}$. So the handedness is in fact a pseudovector similar to polarization.

Instead of the jet axis one can use a unit vector in the direction of total momentum of a triple of particles.

Then, for the jet handedness of a definite quark (antiquark) flavor one can obtain from (3)

$$H^{q,\bar{q}} = \frac{N_R - N_L}{N} = \alpha^{q,\bar{q}} P_{q,\bar{q}} \tag{5}$$

where $P_q = (n_+^q - n_-^q)/n$ is a quark longitudinal polarization. So the knowledge of the *analyzing power* α allows one to measure the quark polarization.

The value of α naturally depends on kinematical cuts implied in selecting the pair of particles (particle rapidity and transverse momenta y and k_T, rapidity difference Δy, pair invariant mass M^{pair} etc.) and on selection of particle "1" in (1). Concerning the selection of particle "1" one can discriminate between a charge independent criterion Y (e.g. the particle "1" is the leading one in a pair, i.e. $|y_1| > |y_2|$) and a charge dependent criterion Q (e.g. the particle "1" is the positive one in a $(+-)$-pair). So the handedness H and the analyzing power α could acquire the label Y or Q depending on a chosen criterion.

Now turn to some features of the analyzing power α. Charge conjugation transforms quarks into antiquarks with the same helicities and the negative particle of the pair into the positive one and *vise versa*. So it does not change the handedness of the jet in the criterion Y but changes it to opposite in the criterion Q. As a consequence, one has [2, 3]

$$\alpha_Y^{\bar{q}} = \alpha_Y^q \quad \text{and} \quad \alpha_Q^{\bar{q}} = -\alpha_Q^q \,. \tag{6}$$

Another relation follows from the $SU(2)$ flavor symmetry which transforms u-quarks into d-quarks and if the $(+-)$-pair is chosen as a pion pair, the handedness of jets does not change under $u \leftrightarrow d$ transformation in the criterion Y but changes to the opposite in the criterion Q, i.e

$$\alpha_Y^u = \alpha_Y^d \quad \text{and} \quad \alpha_Q^u = -\alpha_Q^d \,. \tag{7}$$

Notice, however, that the $SU(2)$ invariance and relation (7) could be broken for heavy flavors.

A few very general statements could give useful indications of the search for the handedness. The handedness just as polarization is an interference phenomenon [2]. So it is most probable when a pair of particles in a resonance region interferes with a non-resonant background. Since in parton fragmentation we have to deal mostly with pions, the most prominent resonances are in a region of 1 GeV in invariant mass of the pair (e.g. in the region of the ρ-resonance). One can also expect that the most leading particles are the most informative about a parton spin state (as well as about its charge or flavor) and that the handedness will be more pronounced for large k_T.

Another possibility could be to use the "formation time" [4] [2]

[2]Recall that according to the uncertainty principle it is a minimal time during which a virtual fluctuation with energy deficit ΔE is undistinguishable from the initial state. So for a zero mass quark with energy E to form a particle with 4-momentum $(\sqrt{m_T^2 + (zE)^2},\ zE,\ \vec{k}_T)$ this is

$$\Delta E = \sqrt{k_T^2 + ((1-z)E)^2} + \sqrt{m_T^2 + (zE)^2} - E \approx \frac{m_T^2}{2Ez(1-z)} \,.$$

$$t_f \approx \frac{2Ez(1-z)}{m_T^2} \,. \tag{8}$$

and to try to select pairs of tracks close in the formation time. Also one could think that an earlier formed pair (i.e. with large k_T and large enough z) is more informative about a spin state of a parent quark.

Concerning the magnitude of the handedness one can state that the commonly used QCD Monte-Carlo models like JETSET or HERWIG deal with probabilities rather than with amplitudes and so do not contain any interference phenomena like the handedness. The lowest order perturbative QCD diagrams give an effect proportional to a squared quark mass while the one loop calculation [5] results in a small value of $\alpha \sim \alpha_s (k_T/M_{\rm jet})^2 z$, where $M_{\rm jet}$ is a jet mass, k_T is a transverse momentum and z is a fraction of longitudinal momentum of the produced $q\bar{q}$-pair. This could mean that partons transmit their helicity to hadrons at a non-perturbative stage of fragmentation. All this makes the problem of theoretical estimation of the handedness rather uncertain.

Simplest estimations of α using an effective Feynmann diagrams of pion interference in the fragmentation $q \to \pi^+ \pi^- q'$ produced via ρ-decay and produced successively give the value of few per cent [6]. A similar estimation was obtained in a classical model proposed by M.Ryskin in Ref. [7]. In that model the handedness arises due to turning of secondary q and $\bar{q}$ produced in breaking of a string in the longitudinal chromo-magnetic field from chromo-magnetic dipole moments of the initial q and $\bar{q}$.

Such a magnitude of α being experimentally confirmed in a process with the known quark polarization allows one to expect the handedness to be applied in other processes for measurement of quark polarization.

The e^+e^--annihilation in the region of the Z^0-peak seems at first sight one of the best places to search for the handedness of quark jets and to measure the analyzing power α. This is due to the fact that the quarks from the Z^0-decay are strongly polarized as a result of the interference of vector and axial couplings. In the Standard Model the quark polarizations are $P_u = -0.67$, $P_d = -0.93$ with the production ratio $\sigma_u/\sigma_d = 0.78$ and opposite sign polarization for the antiquarks. If one does not distinguish between quark and antiquark jets, one can easily find that the total handedness in the no charge criterion cancels to zero due to $H_Y^{\bar{q}} = -H_Y^q$ as it follows from (6). However, for the charge criterion $H_Q^{\bar{q}} = H_Q^q$ and the handedness for q and $\bar{q}$ are added to each other. So one can obtain

$$H_Q^{e^+e^-} = \frac{\sum_q \sigma_q w_q \alpha_Q^q P_q}{\sum_q \sigma_q w_q} \quad \text{and} \quad H_Y^{e^+e^-} = 0 \,, \tag{9}$$

where σ_q is the cross section of flavor q production and w_q is a probability of the flavor to fragment into at least one pair obeying the applied cuts[3].

Now it is clear from (7) that different terms in (9) could be of different signs for up and down quarks and some cancellations are possible. It could be a reason that only a

[3]The latter could be calculated using Monte-Carlo generated events with the same cuts.

rather small value of the handedness was observed experimentally [8] in e^+e^--annihilation via Z^0. The preliminary value

$$H_Q^{e^+e^-} = 1.2 \pm 0.5\% \tag{10}$$

was seen for leading (++−) and (−−+) pion triples with the total longitudinal momentum $k_L = (k_1 + k_2 + k_3)_L \geq 5\ GeV/c$ in the ρ-resonance region of invariant mass of (+−)-pairs $0.62 < m_{13} < m_{12} < 0.92\ GeV/c^2$ while charge independent criterion gives zero value, $H_Y = -0.02 \pm 0.5\%$, as it should be. This agrees with the SLD observation [9] $H_Q < 2.0\%$ obtained with a polarized electron beam. As for the value of the analyzing power α, it should be found using a general expression (9) and determined by probabilities w_q.

The cancellation of different terms in H was a motivation to search for handedness correlation in 2-jet events where no such cancellation is expected. Some preliminary result on the correlation is the main subject of this paper. It is organized as follows. In Sect.2, some theory consideration of the correlation is given. In Sects.3,4 and 5 selection procedures, results of experimental measurements and estimation of systematic errors are presented and Sect.6 is reserved for discussion of a puzzling phenomenon observed.

2 Handedness correlation in 2-jet events

Now let us define the handedness correlation as

$$C = \frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}. \tag{11}$$

Since at the production level $e^+e^- \to q\bar{q}$ the helicities of the quark and antiquark are always correlated (CP-conjugation), i.e. $n_{++}^{q\bar{q}} = n_{--}^{q\bar{q}} = 0$, one can write using (3)

$$N_{RR} = n_{+-}^{q\bar{q}} \cdot \frac{w_q^2}{4}(1+\alpha^q)(1-\alpha^{\bar{q}}) + n_{-+}^{q\bar{q}} \cdot \frac{w_q^2}{4}(1-\alpha^q)(1+\alpha^{\bar{q}})$$

and similar expressions for N_{LL}, N_{RL} and N_{LR}. Substituting this into the correlation (11) and making a sum over the quark flavors one obtains [4]

$$C = \frac{\sum_q \sigma_q w_q^2 \alpha^q \alpha^{\bar{q}}}{\sum_q \sigma_q w_q^2}. \tag{12}$$

An important assumption used here is that each quark in the Z^0 decay fragments independently of its partner. For the Perturbative QCD this independence is guaranteed by the factorization theorem which allows one to present the $e^+e^- \to$2-jet cross section as a product of the $e^+e^- \to q\bar{q}$ cross section sub-process and fragmentation functions of each of the quarks into a pair of hadrons.

[4] In a more general case of quark helicity correlation $c_{q\bar{q}} = (n_{+-} + n_{-+} - n_{++} - n_{--})/n$ each term of the numerator of the r.h.s. of the expression should be multiplied by this correlation number $c_{q\bar{q}}$

Using relation (6), one can find for different criteria

$$C_Q = -\frac{\sum_q \sigma_q w_q^2 (\alpha_Q^q)^2}{\sum_q \sigma_q w_q^2} \quad \text{and} \quad C_Y = \frac{\sum_q \sigma_q w_q^2 (\alpha_Y^q)^2}{\sum_q \sigma_q w_q^2} \tag{13}$$

So, the correlations are sign definite and no cancellation is expected. Moreover, it has to be *negative* in the charge criterion Q and *positive* in the no charge criterion Y.

Similar expression of the type (12) is valid also for two pairs in the same jet if one assumes that these pairs are produced by q (or $\bar{q}$) independently of one another with the same probability w_q. The natural difference is in a common minus sign, since both pairs are originated from the same quark with the same helicity ($c_{qq} < 0$), and in a change of $\alpha^{\bar{q}} \to \alpha^q$. One can expect that this could be true when difference in rapidity (or in the formation time) between two pairs is large enough.

3 Selection of events

An initial statistics of the 91-94 data taking period of the DELPHI collaboration was used to produce miniDST with about 2 MZ^0 hadronic events selected by standard cuts [10].

For the analysis the charged particle tracks measured in the Time Projection Chamber (TPC) were used fulfilling the following criteria (as in ref. [10]) :

1. Impact parameter below 5 cm in the transverse plane and below 10 cm along the beam axis.
2. Particle momentum between 0,1 GeV/c and 50 GeV/c.
3. Measured track length above 50 cm.
4. Polar angle between 25° and 155°.

Hadronic events were then selected by requiring that

1. Each of the forward and backward hemispheres contained a total charge energy larger than 3 GeV (assuming pion mass for the particles).
2. The total charged particle energy seen in both the jets together exceeded 15 GeV.
3. At least 5 charged particles with momentum above 0.4 GeV/c are detected.
4. The polar angle θ of the sphericity axis is between $40° < \theta < 140°$ (so that the events are well contained inside the TPC).

According to the JADE method with jet resolution parameter $Y_{cut} = 0.20$, a number of jets for each event was determined. Only 2-jet events were remained on the miniDST for the following analysis. In addition, acollinearity of two jets $\Delta\Theta_{jj}^{max} \leq 15°$ was implied. After application of the standard cuts, each particle was assigned, in accordance with the sign of its rapidity, to some of two jets.

The unit vector $\vec{t}$ along the thrust axis was taken as a jet axis vector. The jet axis $\vec{j}$ was chosen as $\pm\vec{t}$ depending on the sign of rapidity of the pair. In each event nonintersecting pairs of hadrons were selected which satisfy sets of one- and two-particle cuts. The following sets of cuts were applied:

Variant # 0.

i. The rapidity with respect to the thrust axis $|y| > Y_{min} > 1$ to be in the leading (presumably the most informative) group of particles.

ii. The transverse momentum $k_T > k_T^{min} > 0.5\ GeV/c$ – an average k_T in a jet – to get rid of low k_T hadrons created by hadronization of soft gluons.

iii. The difference in rapidity of hadrons in the pair $|\Delta y| < \Delta Y_{max}$ to select correlated pions created mostly from the same breaking of the $q\bar{q}$-string.

iv. The invariant mass of the pair $M^{pair} \leq M^{pair}_{max} \leq 1\ GeV/c^2$ to be in the resonance region.

v. The absolute value of X defined by (1) (but normalized to the total momenta instead of transverse projections) is greater than 0.01. This cut is due to the limited momenta resolution of the DELPHI apparatus and off-line analysis procedure [11]. For each given track among different pairs, which satisfy the above cuts, only the pair with the largest value of $|X|$ was selected.

The set of cuts which is presented above is rather severe and only a few hundred events survived giving an indication of correlation under study. It would be desirable to reduce a number of cuts in order to find such cuts that are more adequate to this phenomenon. It was supposed that the formation time (8) – a proper combination of the longitudinal and transverse particle momentum connected with such a basic law as the uncertainty principle – could be such a variable.

At the beginning, all tracks in an event were ordered with respect to their formation time t_f. For tracks with a negative value of rapidity with respect to the thrust axis the negative sign for t_f was prescribed. The event was scanned then along the formation time axis by an interval Δ to select pairs of tracks close in the formation time t_{f1} and t_{f2}, i.e. those which satisfy the condition

$$\left|\frac{t_{f1} - t_{f2}}{t_{f1} + t_{f2}}\right| \leq \Delta. \qquad (14)$$

For such selected pairs the other cuts where applied. It was possible to add cuts for the minimal and maximal transverse momentum of particle k_T^{min} and k_T^{max}, the minimal and maximal invariant mass of the pair M^{pair}_{min} and M^{pair}_{max}, the minimal and the maximal azimuthal angle between the two selected particles $\Delta\phi_{min}$ and $\Delta\phi_{max}$. In this procedure, the following variants were used:

Variant # 1. $\Delta = 0.25$ and $\Delta\Theta^{max}_{jj} \leq 5°$. In this case, one can gain a larger ratio of the effect to error and use it to investigate the dependence on other cut parameters mentioned above.

Variant # 2. $\Delta = 0.20$ and $\Delta\Theta^{max}_{jj} \leq 15°$. This set of cuts was used to study systematic errors.

Variant # 3. Additional one- and two-particle cuts were applied which where motivated by:

i. Uncertainty in the thrust direction which may result in a wrong sign of X. For this reason the polar angle θ_k between $\vec{k}_i$ and $\vec{t}$ was restricted to $\theta_k > 0.1\ rad.$

ii. To avoid a possibility of a wrong sign of a particle rapidity a lower boundary $|y_i| > 0.1$ was put.

iii. Pairs with nearly collinear or anti-collinear tracks in the transverse plane to the thrust axis were rejected to $0.1 < \Delta\phi < \pi - 0.1\ rad.$

iv. Pairs of tracks nearly coplanar with the trust axes were also excluded, since a small variation of the thrust direction could change the sign of X. The corresponding cut was chosen $\Delta\phi < \pi - 0.1\ rad.$

v. The interval (14) was chosen $\Delta = 0.14$.

vi. The same track can be included in a few different pairs. It is not allowed however to be present in both correlated pairs simultaneously.

For the sake of control, approximately the same number of about 2 MZ^0 of simulated JETSET7.3 PS events were used with the same cuts for selection of hadronic 2-jet events and pairs.

4 Experimental observation of correlation

The first observation of the handedness correlation by using the DELPHI data was reported at the Moriond-94 workshop [12] with the cuts described above as the variant # 0.

The handedness correlation (11) of two pairs in events both in the same and in the opposite jets was investigated for the charge dependent Q and for the charge independent Y criteria for the particle "1". For the former case both neutral $(+-)$ and double charged $(++)$ or $(--)$-pairs were taken into account.

The Y_{min} dependence of the xx (C_Q or C_Y)-correlation for two selected pairs in jets, after reprocessing of the experimental material is shown in Fig. 1 for the following cuts: $M^{pair}_{max} = 0.75\ GeV/c^2$, $\Delta y \leq 1$, $k_t^{max} = 0.65\ GeV/c$. For the opposite jets, an increasing with Y_{min} positive C_Q correlation was observed in the region of $1 < Y_{min} < 2$. It shows that a left handed pair in one jet prefers a right handed pair in the opposite jet. Maximal value of the effect to error ratio is obtained at $Y_{min} = 1.75$ with the correlation value about $11 \pm 5\%$. Some indication of a negative correlation can be seen for pairs in the same jet. No such correlation was found for the JETSET7.3 PS Monte Carlo events in the whole domain of the given cuts variation.

Figs. 2a and b present inclusive dependence of the xx-correlations for the DELPHI 91-93 data and for DELPHI simulated data in the opposite and in the same jets on the maximal value of formation time t_f^{max} of selected pairs with variant # 1 cuts. No additional cuts except $M^{pair}_{max} = 0.75\ GeV/c^2$ and neutrality of pairs were applied. There is no correlation seen for $(+-)$ pairs with small formation times ($t_f^{max} \leq 20\ GeV^{-1}$) either in the opposite or in the same jets. Above $t_f^{max} = 30\ GeV^{-1}$ the correlation has reached

Table 1: C_Q-correlation (‰) for pairs from opposite jets in different intervals of angles between the thrust and beam axes

$\cos\Theta_{min}$	$\cos\Theta_{max}$	$91-93$ *data*	94 *data*	*JETSET7.3 PS*
0.00	0.25	12.3 ± 3.7	11.3 ± 4.4	-2.3 ± 2.7
0.25	0.50	8.8 ± 2.9	-1.8 ± 3.3	-1.1 ± 2.0
0.50	0.75	5.8 ± 3.1	2.1 ± 3.6	-1.6 ± 2.1
0.75	1.00	7.0 ± 4.8	13.8 ± 5.5	-6.2 ± 3.2
average		8.5 ± 1.7	4.0 ± 2.0	-2.2 ± 1.2

its constant value that is about 8.5 ± 1.7‰ for opposite jets. No such correlation is found for the MC-simulated events. The correlations in the same jet are similar for data and JETSET7.3 PS and reach -4.0 ± 1.5‰.

In Figs. 3a,b DELPHI 91-93 data and 94 data are separately presented together with the corresponding JETSET7.3 PS simulated data for dependence of the xx-correlations on the variation of maximal value of formation time difference Δ (see (14)). There is no distinction between data and Monte-Carlo for pairs from the same jet. For pairs from the opposite jets the xx-correlations are seen at the level of $6.0\div9.0$‰ for 91-93 data, twice smaller for 94 data and practically no correlations for Monte-Carlo events.

The xx-correlation dependence on a maximal value of transverse momentum k_t^{max} for selected hadrons is presented on Fig.4 for DELPHI 91-93 data and for simulated JETSET7.3 PS data. It seems that the effect decreases with increasing transverse momentum down to a constant value beyond $k_T^{max} > 0.4\ GeV/c$.

The result of measurement of the xx-correlation as a function of M_{max}^{pair} is plotted in Figs. 5a,b. for variant # 3 cuts. One can see that the effect decreases with increasing M_{max}^{pair} and practically does not change outside the ρ-resonance region. Besides, the correlations are essentially smaller for Monte-Carlo events comparing 91-93 or 94 data. Qualitatively, the same behavior with a larger correlation value is seen for the variants # 1 and # 2 cuts.

In Table 1 the results are presented for the C_Q-correlation of pairs from the opposite jets in different intervals of angles between the thrust and the beam axes ($e^+e^-\to q\bar{q}$ scattering angle). The effect has a positive sign in all 4 intervals but the errors are too big for a definite conclusion about the Θ_{thrust} dependence.

The C_Y handedness correlations with ordering in rapidity Y, the formation time t_f, transverse momentum k_T and energy fraction z were also investigated. Both neutral and double charge pairs were taken into account with the same cuts. The results are presented in Table 2. The correlation in the opposite jet is also positive but essentially smaller in values.

Table 2: C_Y-correlation (‰) for neutral and double charged pairs from opposite jets, 91-93 data

Charge of pairs	$Y-$ *order.*	t_f- *order.*	k_T- *order.*	$z-$ *order.*
$0-2$	-2.3 ± 2.2	0.7 ± 2.2	1.8 ± 2.2	0.6 ± 2.2
$0+2$	0.7 ± 2.2	1.4 ± 2.2	-1.6 ± 2.2	-0.8 ± 2.2
$-2-2$	2.7 ± 5.1	-0.8 ± 5.1	2.8 ± 5.1	5.5 ± 5.1
$-2+2$	6.3 ± 3.4	-1.4 ± 3.4	1.3 ± 3.4	6.9 ± 3.4
$+2+2$	10.9 ± 4.9	8.1 ± 4.9	5.3 ± 4.9	7.5 ± 4.9
$0-0$	2.4 ± 2.0	-1.6 ± 2.0	0.0 ± 2.0	0.0 ± 2.0
average	1.7 ± 1.1	0.3 ± 1.1	0.6 ± 1.1	1.3 ± 1.1

5 Systematic errors

Different checks were done by comparing the distributions before and after cuts for the total momentum of all charged particles, energy, charged multiplicity, lepton multiplicity, azimuthal angle, thrust axis, etc. All the distributions well correspond to each other except the visible energy of charged particles where the variant # 1 cuts result in a shift about 5 GeV between these two distributions. The shift is well reproduced by the Monte-Carlo distributions as well.

For the variants # 1 and 2 in Table 3 the results of selection with different "visible volumes", i.e. with different cuts for polar angles of tracks and thrust axes are given. It was noticed that the Θ_{thrust} distribution of selected events after cuts was more pronounced in the region of inefficient zones between barrel and end cup detectors of the DELPHI than the corresponding distributions before cuts. To investigate an effect of these zones the analysis of the correlations was repeated but the "visible volume" was shrunk by 10° from each side, which results in decrease in statistics but not in elimination of the effect, as it is seen from Table 3.

A special study was made of the limited momentum resolution effect of the DELPHI apparatus and of the off-line analysis procedure which can be approximately described by the formula $\Delta k\approx0.002k^2$. As it is seen from Table 3, a variation of all track momenta leaves the C_Q-correlation at the same value in the error bars.

There was a suspicion that a reason for the correlation could be tracks from secondary interactions in detector elements or a loss of some tracks in the detector dead zones. A role of these effects was considered by evaluation of the C_Q correlations with additional rejection of 5% or 10% of tracks from each event. The results are presented in Table 3 for the variants # 0 and 2. It is seen that the correlation does not change inside the error bars. An additional cut for tracks to get at least 2 hits in the Vertex Detector results in removing 20% of tracks. As seen from Table 3, the removing of such a number of tracks from each Monte-Carlo event does not lead to any C_Q correlation.

Another natural suspicion was an effect of DELPHI magnetic field on produced (+−)-

Table 3: Systematic errors of C_Q-correlation (‰) for variation of selection criteria.

Data selection	$\Delta N_{xx}^{opp}/N_{xx}^{tot}$	$\Delta N_{xx}^{same}/N_{xx}^{tot}$	*Comments*
Variation of "visible" volume			
variant #1 cuts : $\Delta = 0.25$, $\Delta\Theta_{jj}^{max} = 5°$	8.5 ± 1.7	-2.1 ± 1.6	$91-93$
variant #1 cuts and			data
$35° < \Theta_{tr} < 145°$			
$50° < \Theta_{th} < 130°$	4.5 ± 2.0	-2.9 ± 1.9	"
variant #2 cuts : $\Delta = 0.20$, $\Delta\Theta_{jj}^{max} = 15°$	3.5 ± 1.1	-4.7 ± 1.0	$91-94$
variant #2 cuts and			data
$35° < \Theta_{tr} < 145°$			
$50° < \Theta_{th} < 130°$	2.1 ± 1.2	-4.9 ± 1.2	"
Variation of momentum due to $\Delta k \approx 0.002k^2$ *resolution*			
variant #2 cuts, resolution	2.6 ± 1.1	-3.5 ± 1.0	"
Effect of a rejection of tracks			
variant #0 cuts	$103. \pm 56.$	$-35. \pm 46.$	$91-93$
var. #0 cuts, rejection of 10% tracks	$40. \pm 76.$	$-70. \pm 59.$	*data*
variant #2 cuts	4.8 ± 1.4	-5.0 ± 1.3	$91-93$
var. #2 cuts,rejection of 5% tracks	4.3 ± 1.6	-2.8 ± 1.5	*data*
var. #2 cuts,rejection of 10% tracks	4.5 ± 1.7	-2.8 ± 1.6	"
Vertex Detector cut : $N_{hits} \geq 2$			
variant #1 cuts	-3.8 ± 1.7	-1.4 ± 1.6	*JETSET*
var #1 cuts, VD − cut	-1.4 ± 2.7	1.8 ± 2.6	*7.3 PS*
DELPHI magnetic field influence			
variant #2 cuts	-1.0 ± 1.4	-3.5 ± 1.3	*JETSET*
var. #2 cuts, shift of reference point	-1.5 ± 1.4	-3.1 ± 1.3	*7.3 PS*
Jets from different events variant #2 cuts			
$\Theta_{thrust} = 30° - 45°$	0.3 ± 0.8	-	$91-93$
$\Theta_{thrust} = 45° - 60°$	-0.5 ± 0.8	-	*data*
$\Theta_{thrust} = 60° - 75°$	0.2 ± 0.8	-	"

pairs. This effect could be possible because reference points of different tracks do not coincide exactly with a primary vertex point of an event. The difference is smaller or about 1 cm. For every track its momentum was recalculated with 1 cm shift of this reference point along its trajectory and then the analysis of correlation was repeated. No such correlation was found for Monte-Carlo events, and these results are presented in Table 3 as well.

For understanding the systematic errors, it seems crucially important to investigate correlation in artificial events that are constructed from jets of different events taken from real data. Artificial events consist of 2 jets with the same cut for acollinearity as for the real events. Distributions for tracks and for thrust axes automatically reproduce the corresponding distributions in the real events. This study was done and the results are presented in Table 3 for three intervals of angles between the thrust axis and beam direction. No C_Q correlation was found for the pairs from the opposite jets of these artificial events. This carries convinction that C_Q correlation is not an apparatus effect. Joining all these three intervals gives an overall systematic error smaller than 0.5‰ which is much smaller than the statistical error.

6 Discussion

Some evidence for the jet handedness correlations were found. The value of the correlation C_Q depends on the method of selecting pairs (rapidity or formation time ordering) and on cuts applied. The puzzling thing however is that the C_Q correlation of selected pairs from the opposite jets has a sign which *contradicts* the one predicted according to (13) based on the standard parton picture. This picture includes the helicity correlation of $q\bar{q}$ in the Z^0-decay, $c_{q\bar{q}} = 1$, independent fragmentation of q and $\bar{q}$ into a pair and charge conjugation of the two jets. The question is now which of the statements is broken and why?

The same sign quark helicity contribution (negative $c_{q\bar{q}}$) seems suppressed by a factor m_q/M_{Z^0}. Also it would give a negative correlation C_Y with rapidity ordering (e.g. $|y_1| > |y_2|$) of the particles 1 and 2 in (1), which contradicts the observation ($C_Y = 1.7 \pm 1.1$‰). The same sign helicity correlation in the leading twist could arise in the $Z^0 \to$2-gluon decay via the triangle anomaly diagram. However, the total contribution of the process to C_Q remains negative since $\alpha^q\alpha^{\bar{q}}$ in (12) changes by $(\alpha^g)^2$ and except that it would give a negative charge independent correlation C_Y in contradiction with observation.

Break of factorization due to a high twist contribution seems unreliable since the opposite jet correlation should decrease with increasing rapidity interval between pairs because of the decrease on overlapping region of the wave functions. Indeed, from a simple minded dimensional argument one can see that

$$C_Q^{high\ tw.} \propto \frac{\epsilon_{tk_1k_2}\epsilon_{tk'_1k'_2}}{(k_1k'_1)\,(k_2k'_2) + (k_1k'_2)\,(k_2k'_1)} \approx \frac{\sin\Delta\phi \sin\Delta\phi'}{\cosh^2(y-y')} < e^{-4Y_{min}} \tag{15}$$

where $\Delta\phi$ and $\Delta\phi'$ are the azimuthal angles between transverse momenta of particles in pairs. In contrast with this, the observed correlation *increases* with Y_{min}. This can be

Table 4: C_Q-correlation (‰) for pairs the from opposite jets for different rapidity gaps of selected pairs

Rapidity gap	91 − 93 *data*	94 *data*	*JETSET7.3 PS*
$\Delta Y \leq 3.5$	5.9 ± 2.8	3.5 ± 3.3	-8.3 ± 3.0
$\Delta Y \geq 3.5$	9.9 ± 2.1	4.3 ± 2.5	-1.8 ± 2.0

seen from Fig. 1 for the variant # 0 cuts and from Table 4 for the variant # 1 cuts. Moreover, the factorization could be checked in a more direct way comparing squared production probability of one pair and production probability of two pairs in the opposite jets obtained for the same collection of data (variant # 1). The difference of $< w >^2$ and $< w^2 >$ averaged with flavor production rate is of an order of 2.5% and is the same as in the MC generated events where the factorization property is built in.

Concerning the charge conjugation, it is hardly seen directly in the selected pairs. E.g. charge correlation of leading particles in the pairs was only $C_{ch} = (N_{+-} - N_{++/--})/N \approx 0.49 \pm 0.23\%$ (91-94 data). However, it is the same as seen in the MC-generated events, $C_{ch}^{MC} = 0.63 \pm 0.22\%$, where with no doubt one has to deal with $q\,\bar{q}$ jets.

So it seems that the observed positive correlation has nothing to do with the spin correlation of quarks. The natural question arises of what could be the reason for it.

The model [7] predicts the negative sign correlation for pairs in *the same* jet which seems supported by observation. For the *opposite* jet handedness correlation the model also gives a normal (negative) sign since the chromo-magnetic moments q and $\bar{q}$ are opposite to each other. To produce the observed positive sign, one needs a *universal* longitudinal chromo-magnetic field in a color tube between q and $\bar{q}$. It is clear that there is none in QED or Perturbative QCD. It could only arise as a non-perturbative (topological? vacuum?) effect. Moreover, in the QCD Sum Rule method it is even suggested that $< 0| : G^a_{\mu\nu} G^a_{\mu\nu} : |0 >$ is non zero beyond the perturbation theory [13]. This inevitably implies that at least for some short space-time scale $G^a_{\mu\nu}$ itself is non zero. Such a self-dual field was used by many authors [14] to provide, in particular, color confinement and linearly rising Regge trajectories. Being C-odd and the same for the quark and antiquark it breaks the CP-invariance of the fragmentation.

Indeed, the two-particle fragmentation function of a polarized quark into a (+−)-pair in a chromo-magnetic field $\vec{B}^a$ could be written in the Lab system as

$$D_q^B = w_q[1 + \alpha_q(\vec{s}\vec{X}) + \beta_q(\vec{B}^a\vec{X})] \tag{16}$$

where w, α, and β depends on fraction of longitudinal and transverse particle momenta with respect to the trust axis, $z^{\pm}$, $k_T^{\pm}$, on invariant mass M^{pair} and on the field strength B^2. Here $\vec{s}$ is for the spin of the quark and $\vec{X}$ is a unit vector in the direction of $(\vec{k}_+ \times \vec{k}_-)$ (see Eq. (1)). Under charge conjugation $\vec{X}$ and $\vec{B}$ change sign, $\vec{s}$ does not and due to C-conservation of fragmentation $D_q^B = D_{\bar{q}}^{-B}$. This results in

$$\alpha_{\bar{q}} = -\alpha_q \quad \text{and} \quad \beta_{\bar{q}} = \beta_q\,. \tag{17}$$

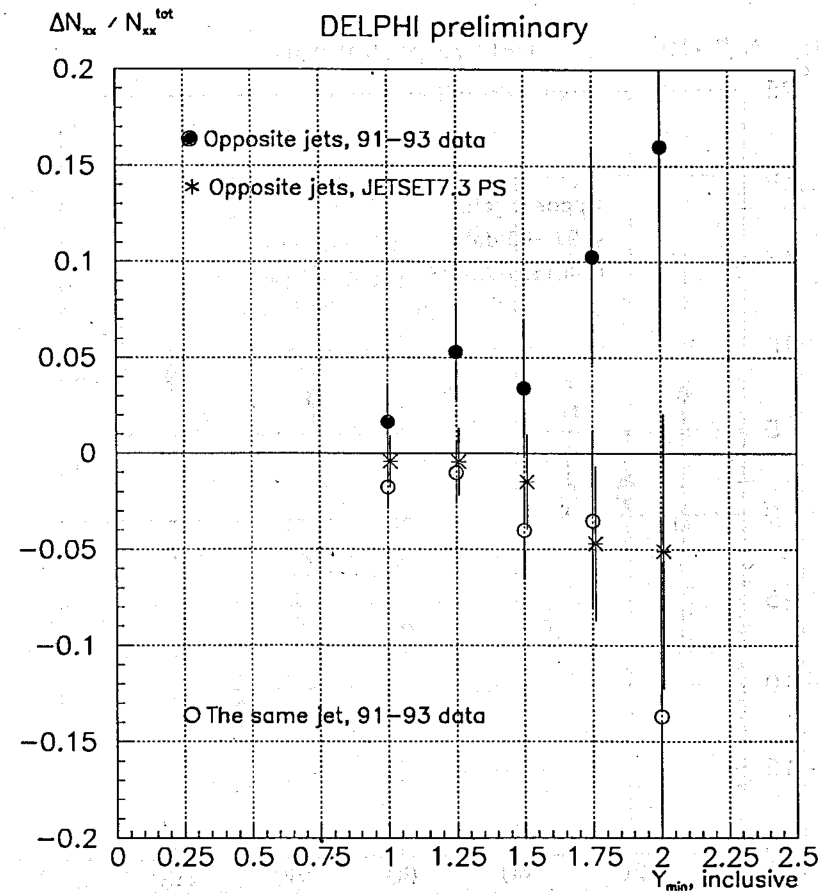

Fig. 1. Y_{min} - dependence of xx-correlation

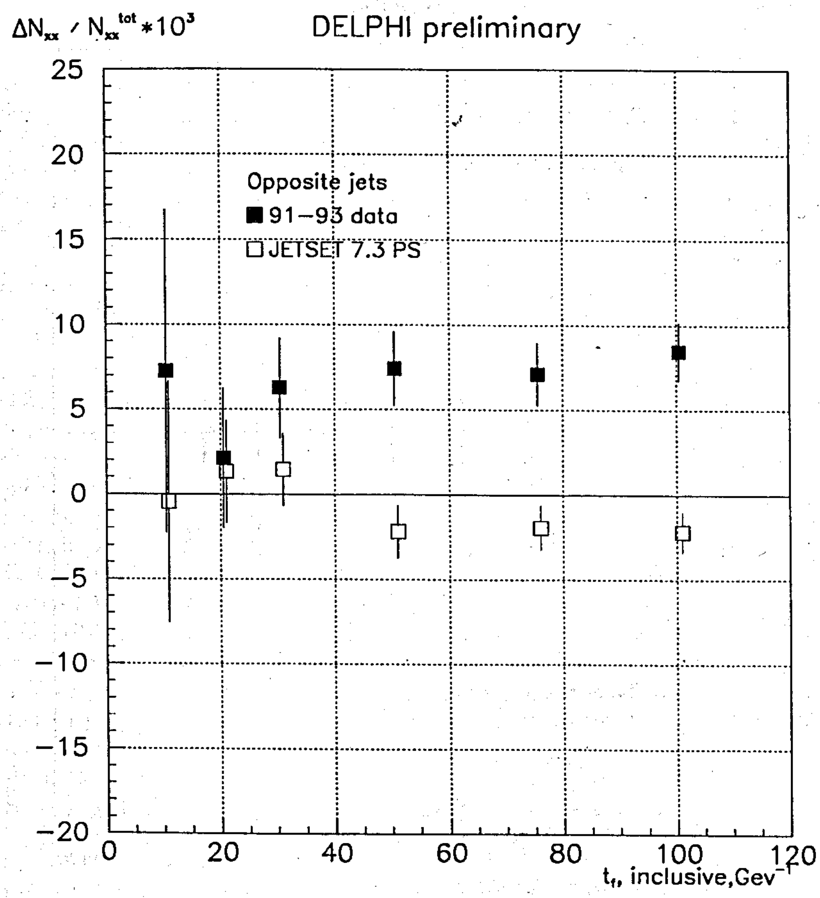

Fig. 2a. t_f – dependence of xx–correlation

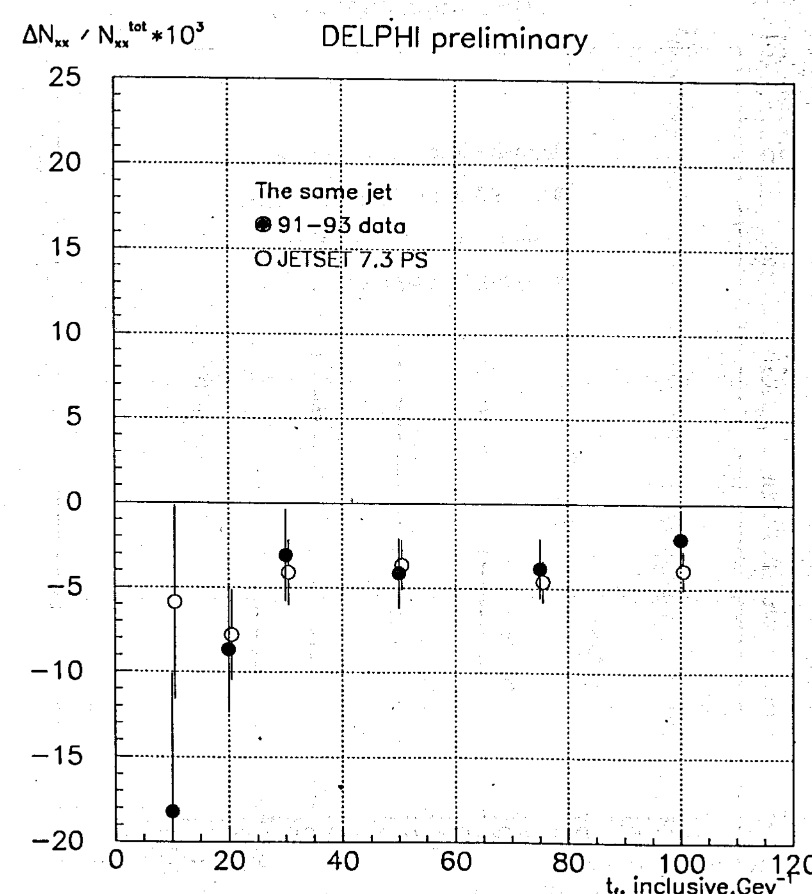

Fig. 2b. t_f – dependence of xx–correlation

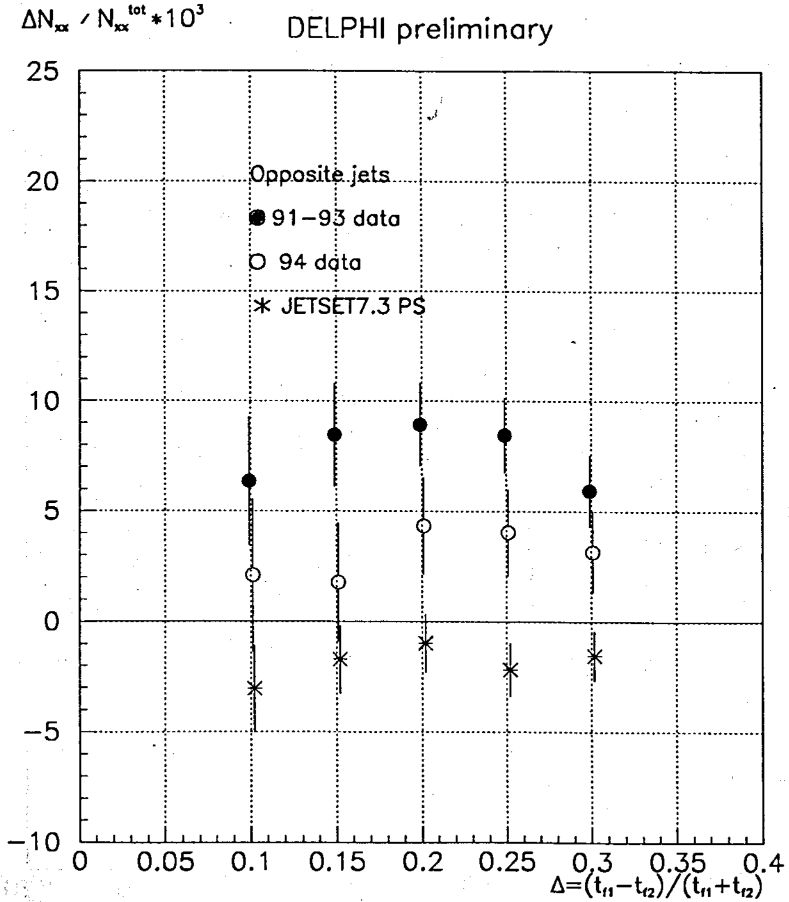

Fig. 3a. Δ - dependence of xx-correlation

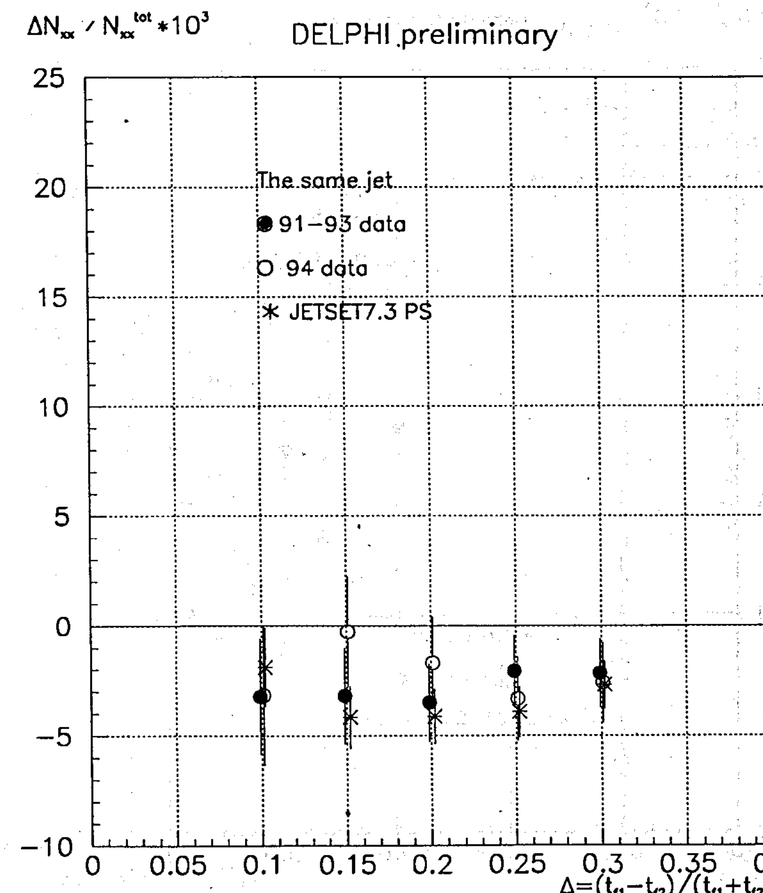

Fig.3b. Δ - dependence of xx-correlation in the same jet

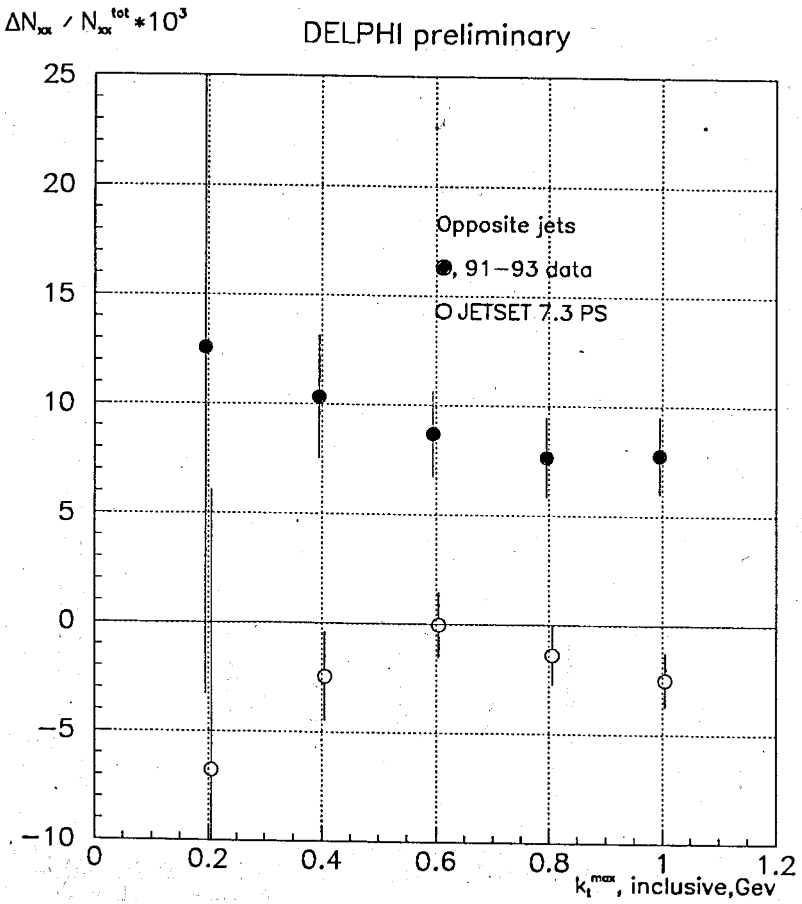

Fig. 4. k_t^{max} - dependence of xx-correlation

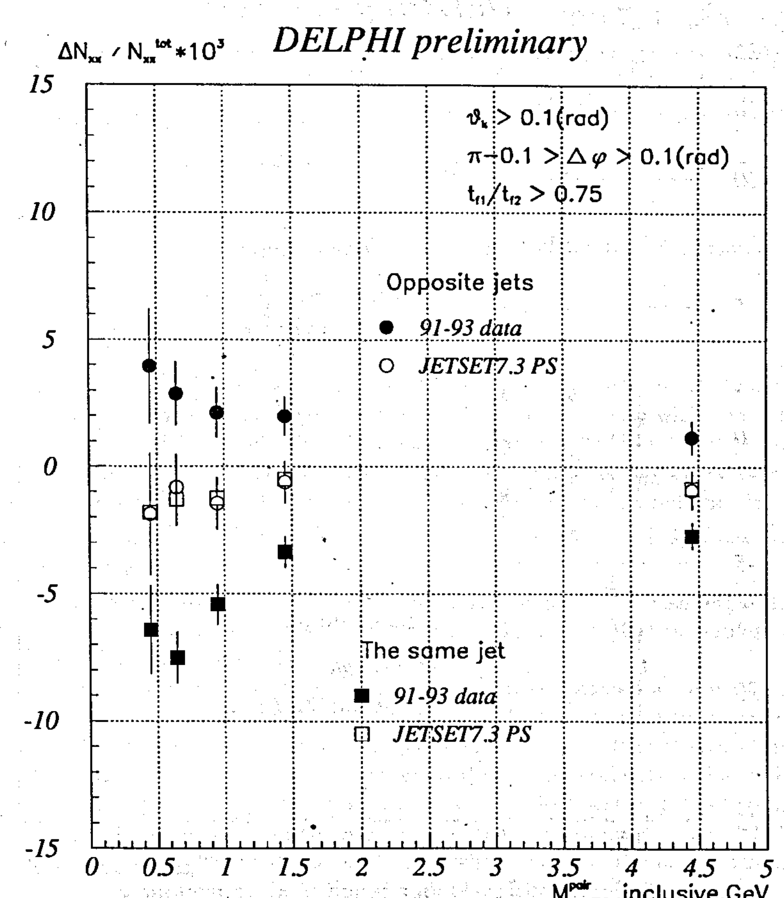

Fig.5a. M^{pair}_{max}−dependence of xx−correlation

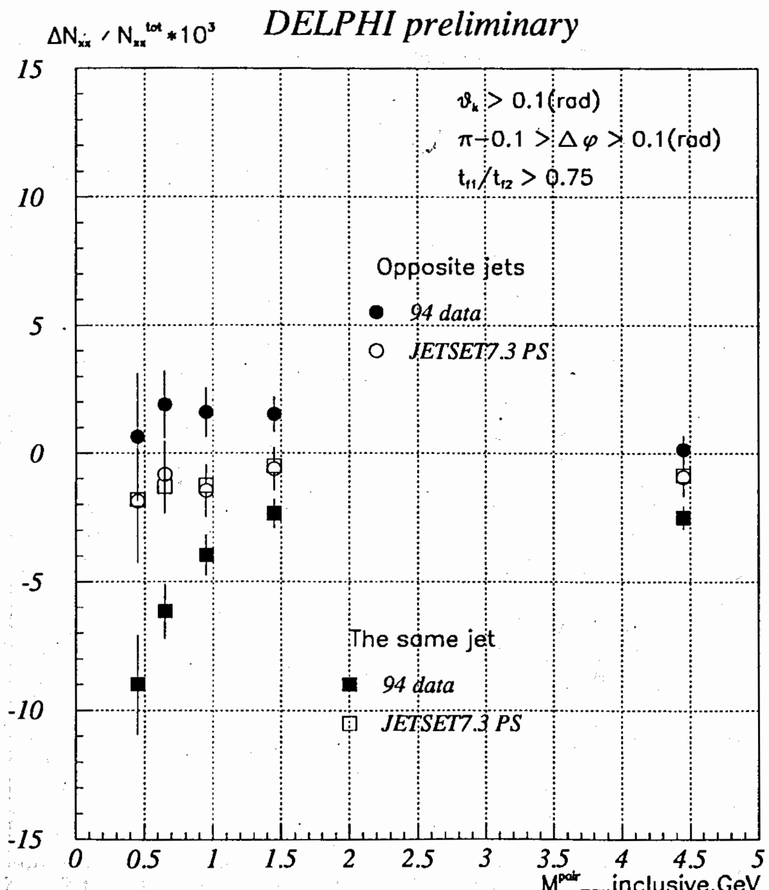

Fig.5b. M^{pair}_{max}–dependence of xx–correlation

Averaging over different events with presumably different direction of $\vec{B}$ and over azimuthal angle of $\vec{X}$ gives the old expression (5) for the longitudinal handedness, due to $<\vec{B}>=0$, and restores the CP-invariance. For the handedness correlation, however, one has

$$C = \frac{\sum_q \sigma_q w_q^2(-\alpha_q^2 c_{q\bar{q}} + \beta_q^2 < B^2 >)}{\sum_q \sigma_q w_q^2} \tag{18}$$

So one can see that a stochastic chromo-magnetic field could result in a positive sign correlation observed experimentally if the second term is dominant. Its dominance well agrees with a small magnitude of handedness observed with the same cuts (the variant # 1)

$$H_Q = -0.122 \pm 0.067\% \, . \tag{19}$$

which surely reflects the polarization of quarks.

A simple estimation for the C_Q-correlation in the spirit of the model [7] results in the expression [15]

$$C_Q \simeq \frac{64}{3\pi} < G^2(0) > \exp\left(-2\frac{\sqrt{t_f t'_f}}{l}\right) \frac{t_f t'_f}{k_T k'_T \gamma^2} \, . \tag{20}$$

were $\gamma = E_{jet}/M_{jet} \simeq 9$ is the Lorentz-factor for transformation from the Lab system to the jet center of mass system and l is a dimension of "domain" with the field. It correctly reproduces qualitatively the observed behavior in t_f^{max} and k_T^{max}. Using the value [13] $< G^2 >= 0.04\ GeV^4$ for the gluon condensate and assuming an average value $\langle k_T \rangle \simeq 0.4\ GeV/c$ for the k_T we find for the maximal value of the handedness correlation parameter at $\sqrt{t_f t'_f} \simeq l \simeq 0.3\ fm$ (obtained from lattice simulation [16]) from (20) the value of the order of 0.6%.

It is interesting to note also that till now the gluon condensation manifested itself as a high twist correction to a perturbative contribution like in the QCD sum rules. In the correlation (18) it enters as a leading twist term.

In conclusion, a very nontrivial effect in the handedness correlation seems to be observed which has no simple explanation in the present theory. It could be considered as an evidence in favor of a random chromo-magnetic vacuum field. It is of special interest to study jet handedness correlations in the other LEP experimental data and as well as in data for smaller energy e^+e^--colliders since the observed effect seems to have nothing to do with polarization of quarks from the Z^0-decay. It would be interesting also to observe the spin correlation of $\Lambda\bar{\Lambda}$ from the opposite jets where one could expect a wrong sign (singlet) correlation, at least in the region $z < 0.4$ because of the influence of the same chromo-magnetic field. This is due to the fact that an $s\bar{s}$ pair, produced in the field, should have the same direction of its chromo-magnetic moments and opposite direction of spins. Also, if it is really an effect of a vacuum chromo-magnetic field, it should be accompanied by asymmetry corresponding to a vacuum *chromo-electric* field approximately of the same strength. It is not difficult to show that it has to be asymmetry with respect to difference of velocities of particles in pairs. The difference for a pair in one jet is prefered to be in the opposite hemisphere to the difference in the opposite jet. It is interesting to observe this effect experimentally.

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