

## Search for Jet Handedness Correlations in Hadronic Z decays

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### Abstract

The study of longitudinal jet handedness correlations in  $e^+e^-$ -annihilation into two jets at the  $Z^0$  resonance region is presented using DELPHI statistics of about 1 MZ events. Noticeable effect of the order of  $20 \pm 5\%$  was observed for selected pion pairs in opposite jets. No such correlation was found for Monte Carlo events or for two back-to-back jets from different events. The theoretical significance of the effect is discussed.

### 1. Introduction.

Recently a new property of the multiparticle parton fragmentation function was proposed [1] for experimental measurement of partons polarization – its asymmetry with respect to pseudoscalar variable

$$X = \frac{(\vec{k}_1 \times \vec{k}_2) \cdot \vec{j}}{|\vec{k}_1| |\vec{k}_2|} \quad (1)$$

in Lab frame of reference. (It was named the longitudinal *handedness*.) Here  $\vec{k}_1, \vec{k}_2$  are momenta of two particles of jet, selected according to some criteria. The vector  $\vec{j}$  is a unit vector in jet direction defined by thrust axis or by total jet momenta. Concerning the particle "1" one can discriminate between a charge independent criteria Z (e.g. the particle "1" is the leading one in pair) and a charge dependent criteria Q (e.g. the particle "1" is positive one in (+-) -pair). In this paper some results of experimental search of the longitudinal handedness correlation in 2-jet events in  $e^+e^-$  annihilation in the region of  $Z^0$ -peak are presented.

The asymmetry with respect to  $X$  is interesting due to the following reason. The dependence on the pseudoscalar  $X$  can appear only in pair with another pseudoscalar. The only one characterizing the two particle fragmentation of an object (quark, gluon or resonance) is a longitudinal polarization  $P$ . Really, let a probability of a right (left) handed quark (with helicity  $h = \pm 1$ ) to fragment into a right handed jet ( $X > 0$ ) or (assuming the P-invariance of fragmentation) a probability of left (right) handed quark to fragment into left handed jet ( $X < 0$ ) be

$$\frac{N_R}{n_{\pm}^q} = \frac{N_L}{n_{\mp}^q} = \frac{1}{2}(1 \pm \alpha^q) \quad (2)$$

where  $n_{\pm}^q$  and  $N_{R,L}$  are numbers of right and left handed quarks and jets correspondingly. (The latter one and  $\alpha$  could acquire also the label Z or Q depending on chosen criteria on particle "1"). Then for jet handedness of definite flavor quark (antiquark) one can obtain from (2)

$$H^{q,\bar{q}} = \frac{N_R - N_L}{N} = \alpha^{q,\bar{q}} P_{q,\bar{q}} \quad (3)$$

where  $P_q = (n_+^q - n_-^q)/N$  is a quark polarization and  $N = N_R + N_L = n_+^q + n_-^q$ . So the knowledge of the *analyzing power*  $\alpha$  allows to measure the quark polarization. The value of  $\alpha$  naturally depends on the chosen criteria and on cuts implied.

Charge conjugation transforms quarks into antiquarks with the same helicities and negative particle of the pair into positive one. So it does not change the handedness of jet in the criteria Z but change it for opposite in the criteria Q. As a consequence one have

$$\alpha_{\bar{p}}^{\bar{q}} = \alpha_p^q \quad \text{and} \quad \alpha_{\bar{Z}}^{\bar{q}} = -\alpha_Z^q. \quad (4)$$

Another relation follows from  $SU(2)$  flavor symmetry which transforms  $u$ -quarks into  $d$ -quarks and if the  $(+-)$ -pair are chosen as pion pair the handedness of jets does not change in the criteria Z but changes for the opposite in the criteria Q, i.e

$$\alpha_Z^u = \alpha_Z^d \quad \text{and} \quad \alpha_Q^u = -\alpha_Q^d. \quad (5)$$

Notice however that  $SU(2)$  invariance and the relation (5) could be broken for heavy flavors.

The theoretical estimates for the value of jet handedness are rather uncertain. A few very general statements however could give useful indications for the search. The handedness just as a polarization is an interference phenomena [1]. So it is most probable when a pair of particles in the resonance region interferes with a nonresonant background. Since in parton fragmentation we have to deal mostly with pions, the most prominent resonances are in a region of 1 GeV/c in invariant mass of a pair (e.g. in the region of the  $\rho$ -resonance). One can expect also that the most leading particles are the most informative about parton spin state (just as about its charge or flavor) and that the handedness will be more pronounced for large  $k_T$  where the variable  $X$  is large due to the fragmentation function have to be linear in  $P$  and thus in  $PX$ .

Concerning the value of the handedness one can state that the commonly used QCD Monte-Carlo models like JETSET or HERWIG deal with probabilities rather than with amplitude and so does not contain any interference phenomena like the handedness. The lowest order perturbative QCD diagrams give an effect proportional to squared quark mass. This should mean that partons transmit their helicity to hadrons at a very late nonperturbative stage of fragmentation. All this makes the problem of estimation of the handedness rather uncertain. Simplest estimations of  $\alpha$  due to  $\rho$ -background interference give the value of few percent [2]. That allows to hope for applications of the handedness in measuring the quark polarization if the analyzing power is obtained from a process with known quark polarization.

The  $e^+e^-$ -annihilation in the region of the  $Z^0$ -peak seems at the first sight as one of the best places for searching the handedness of quark jets and measuring the analyzing power  $\alpha$ . This is due to the fact that the quarks from  $Z^0$ -decay are strongly polarized as a result of the interference of vector and axial couplings. In the Standard Model the quark polarization and production ratio are  $P_u = -0.67, P_d = -0.93$  and  $\sigma_u/\sigma_d = 0.78$  and opposite sign polarization for the antiquarks. If one do not distinguish between quark and antiquark jet one can easily find from (4) that  $H_Z^q = -H_Z^{\bar{q}}$  and the total handedness cancels to zero. However  $H_Q^q = H_Q^{\bar{q}}$  and the handedness for  $q$  and  $\bar{q}$  add to each other. With no distinction between quark flavor also one has

$$H_Q^{e^+e^-} = \sum_q w_q \alpha_Q^q P_q \quad \text{and} \quad H_Z^{e^+e^-} = 0, \quad (6)$$

where the probabilities  $w$ 's consist of a flavor rate production and of probability of the flavor to fragment into a pair obeying the applied cuts,  $w_q = \sigma_q w_{cut}^q / (\sum_q \sigma_q w_{cut}^q)$ .

Now it is clear from (5) that different terms in (6) could be of different signs and some cancellation are possible. It could be a reason that only a rather small value of the handedness

was observed experimentally [2] in  $e^+e^-$ -annihilation via  $Z^0$ . The best value  $H_Q^{e^+e^-} = 1.19 \pm 0.48\%$  was seen for leading  $(+-)$  and  $(--)$  pion triples in the  $\rho$ -resonance region of  $m_{+-}$ -pairs. This agrees with SLD observation  $H_Q < 2.4\%$  reported here by D.Muller [3].

It was the reason of turning to the search for handedness correlation in 2-jet events

$$C = \frac{\Delta N_{xx}}{N_{xx}} = \frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}. \quad (7)$$

Since at the production level  $e^+e^- \rightarrow q\bar{q}$  the helicities of quark and antiquark are always correlated (CP-conjugation), i.e.  $n_{++}^{q\bar{q}} = n_{--}^{q\bar{q}} = 0$ , one can write using (2)

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

and similar expressions for  $N_{LL}$ ,  $N_{RL}$  and  $N_{LR}$ . An important assumption used here is that each quark in  $Z^0$  decay fragments independently of its partner. Substituting this into the correlation (7) and making a sum over the quark flavors one obtains  $C = \sum_q \bar{w}_q \alpha^q \alpha^{\bar{q}}$ . The probabilities  $\bar{w}$ 's here have to contain probabilities of both quark and antiquark to fragment into desired pairs in addition to the flavor production rate  $\bar{w}^q = (w_{cut}^q)^2 \sigma_q / [\sum_q (w_{cut}^q)^2 \sigma_q]$ . Using the relation (4) one can obtain for different criteria (numbering)

$$C_Q = - \sum_q \bar{w}_q (\alpha_Q^q)^2 \quad \text{and} \quad C_Z = \sum_q \bar{w}_q (\alpha_Z^q)^2. \quad (8)$$

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

## 2. Event selection

The search for handedness began using part of data collected by the DELPHI detector [4] during 1991 - 1993 at the center of mass energies around  $\sqrt{s} = 91.2 \text{ GeV}$  ( $86.2 \leq \sqrt{s} \leq 94.2 \text{ GeV}$ ). Only charged tracks were used in this analysis. The trigger conditions and features of the tracking apparatus for the registration of charged multihadronic events can be found in ref. [4].

For the analysis of the  $Z^0$  hadronic decays the charged particle tracks measured in the tracking detectors were used fulfilling the following standard criteria [4]:

1. Impact parameter below 5 cm in 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 standard requirements:

1. Each of the forward and backward hemispheres contained total charged particles energy larger than 3 GeV ( assuming  $\pi$  mass for the particles).
2. The total charged particles energy seen in both hemispheres together exceeded 15 GeV.
3. At least 5 charged particles were detected with momentum above 0.4 GeV/c.
4. The polar angle  $\theta$  of the sphericity axis was between  $40^\circ < \theta < 140^\circ$  (so that the events were well contained inside the tracking detectors)

An initial statistics of about 1 MZ<sup>0</sup> hadronic events with three types of selection cuts were used. According to JADE method with jet resolution parameter  $Y_{cut} = 0.08$  a number of jets for each event was determined. Only 2-jet events were remained for the following analysis. In addition, acollinearity of two jets less than 15° was implied.

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

- i. The rapidity with respect to the thrust axis  $|Y_i| > Y_{min} > 1$  to be in a leading (most informative) group of particles.
- ii. The transversal momenta  $k_t > k_t^{min} > 0.5 \text{ GeV}/c$  – an average  $k_t$  in jet – to get rid of low  $k_t$  hadrons created by hadronization of soft gluons.
- iii. The difference in rapidity of pions in pair  $|\Delta Y_i| < \Delta Y_{max}$  to select correlated pions created from the same breaking of the  $q\bar{q}$  string.
- iv. The invariant mass of the pair  $M^{pair} \leq M_{max}^{pair} \leq 1 \text{ GeV}/c^2$  to be in resonance region.
- v. The absolute value of  $X$  defined by (1) is greater than 0.01. For each given track among different pairs which satisfy the above cuts only the pair with largest value of  $|X|$  was selected.

The last cut is due to limited momentum resolution of the DELPHI apparatus and off-line analysis procedure [5]. Since  $\Delta k/k \approx 0.002k$  a confusion is possible of the left ( $X < 0$ ) and right ( $X > 0$ ) pairs at small values of  $X$  and this region must be excluded from the handedness study. Monte-Carlo events were used to investigate the  $X$  resolution. The identical cuts were applied on the Lund generator ( $G$ ) and on the off-line reconstruction ( $R$ ) levels to select the triples of charged tracks and to find value  $\Delta X = X(R) - X(G)$ . Its distribution gives an estimate of the  $X$  resolution which was found to be  $X_{res} = 0.007$ .

### 3. Results and discussion.

The handedness correlation (7) of two pairs in the same events both in the same and in opposite jets was investigated for the charge and for the rapidity criteria for particle "1". For the former case only (+-)pairs were taken into account.

For the sake of control approximately the same number (about 1 MZ) of Monte Carlo events produced by JETSET7.3 PS and by HERWIG5.7 generators were used with the same cuts for hadronic 2-jet events and pair selection.

In the Fig. 1-2  $Y_{min}$  dependence of  $\Delta N_{cc}/N_{cc}^{tot}$  and  $\Delta N_{xx}/N_{xx}^{tot}$  is presented where  $\Delta N_{cc}$  is number of neutral and double charged pairs difference. The Fig. 1 shows correlation of the charges in the same pair known as local charge conservation. It demonstrates a dominance of neutral pairs over charged ones as a result of local string breaking. The JETSET and HERWIG Monte-Carlo programs reproduce this behavior. This serves as an internal check of analysis procedure. The other checks were done comparing the distributions before and after cuts for the total momenta of all charged particles, energy, charged multiplicity, lepton multiplicity etc. All the distributions well correspond to each other except of the energy where the cuts result in a shift about 5GeV. The shift is well reproduced by the Monte-Carlo distributions also.

The  $Y_{min}$  dependence of the  $C_Q$  correlation for two selected pairs in the same jet is shown on (Fig. 2a) and same for opposite jets on (Fig. 2b) at the following cuts:  $M_{max}^{pair} = 0.75 \text{ GeV}/c^2$ ,  $\Delta Y \leq 1$ ,  $P_t^{max} = 0.65 \text{ GeV}$ ,  $|X| \geq 0.01$ . An increasing of positive  $C_Q$  correlation for the opposite jets is clearly seen in the region of high  $Y_{min}$  values. It demonstrates that left handed pair in one jet prefers a right handed pair in opposite jet. Maximal value of the correlation about  $20 \pm 5\%$  is obtained at  $Y_{min} = 1.75$ . Some indication to a negative correlation can be seen for pairs in the same jet. Neither JETSET7.3 PS nor HERWIG 5.7 Monte Carlo programs show this effect at the whole domain of the given cuts variation. No correlation is seen for the pairs from different events with the same cuts including the back-to-back acollinearity cut of

the two jets. This should convince that it is not an apparatus effect.

The mass cut dependence  $M_{mass}^{pair}$  of  $C_Q$  correlation for opposite jets is shown in Fig. 3. It is difficult to say something about the effect in the region below 0.5 GeV because of decrease of statistics. The most definitely the correlation is seen at the  $\rho$ -meson mass region and clearly decreases for the higher masses. Such behavior confirms the above mentioned theoretical expectation that for handedness phenomena manifestation one needs an interference of the different amplitude.

The  $k_t^{min}$  dependence of the  $C_Q$  correlation shown in Fig. 4. As expected the correlation disappeared for small  $k_t$  and seems saturated at  $k_t = 0.65$  GeV.

The  $C_Z$  handedness correlation with rapidity ordering was also investigated. Both neutral and double charge pairs were taken into account with the same cuts. The correlation in opposite jet is also positive and has the same behavior on the cut parameters but about two times smaller in magnitude. The maximal value obtained is about  $10 \pm 4\%$  at approximately the same cut parameters.

So, one can conclude that clear indication to jet handedness correlations was found. As it follows from Figs. 1-4 the  $C_Q$  correlation of selected pairs from opposite jets has a sign which is opposite to predicted one according to (8). Now one can only guess what is a true physical reason for this. It is clear that this contradict to the standard parton picture based on the factorization property of perturbative QCD claiming that  $q$  and  $\bar{q}$  fragments independently of each other and thus the fragmentation functions are CP-conjugated. The sign of the correlation would be natural if some longitudinal chromo magnetic field in the color tube between  $q\bar{q}$  would exist as proposed recently by M.Ryskin in [6]. However aside of the nature of the field is rather obscure it is not obvious how such a field is connected with spins of quarks. Also the model

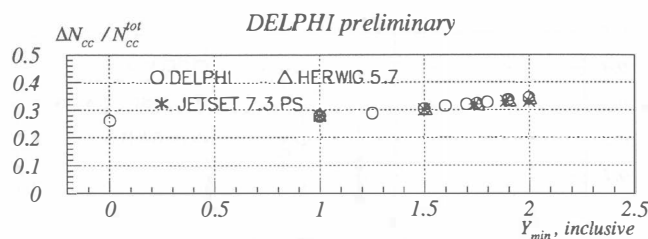


Fig 1. Local charge conservation

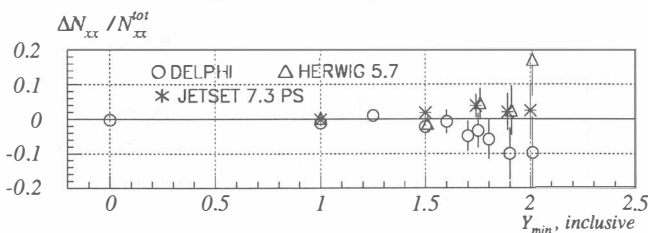


Fig 2a. xx-correlation in the same jet

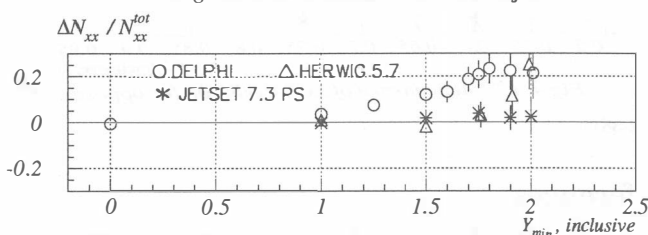


Fig 2b. xx-correlation in opposite jets

predict opposite sign but the same value of correlation for pairs in the same jet. It is questionable if the data on Fig. 2a supports the statements.

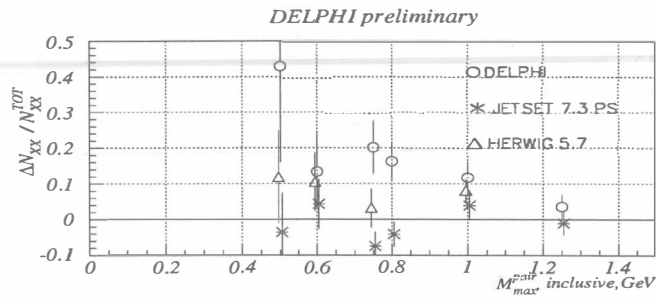


Fig 3. Mass dependence of  $xx$ -correlation for opposite jets

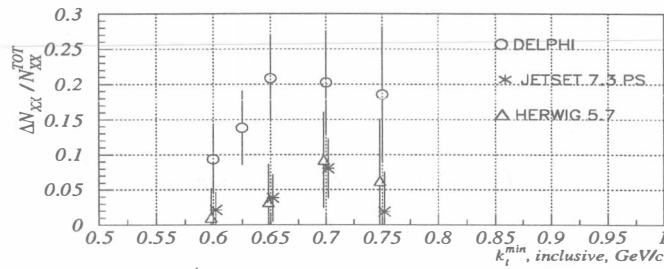


Fig 4.  $k_t^{\min}$ -dependence of  $xx$ -correlation for opposite jets

Having in mind the importance of the handedness phenomena for the jet physics itself as well as for its application to the whole spin physics, one needs to continue the hunting for the handedness in future. It is of special interest to study jet handedness correlations at the other LEP experimental data.

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