JET HANDEDNESS CORRELATION IN HADRONIC Z^0-DECAYS*

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A short introduction into the jet handedness and the handedness correlation is given. Its experimental status in $Z^0 \to q\bar{q} \to 2\ jets$ decay using the DELPHI 91-95 data is considered. For the longitudinal jet handedness correlation a puzzling effect was confirmed. The sign of the correlation is opposite to that predicted by the Standard Model, assuming factorization of q and $\bar{q}$ fragmentation process. The hypothesis on the influence to the effect of a vacuum chromo-magnetic field was tried to check experimentally.

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1. Handedness and the handedness correlation

The *longitudinal jet handedness* for jets initiated by quarks of a definite flavor is defined as [1]:

$$H^{q,\bar{q}} \equiv \frac{N(X>0)-N(X<0)}{N(X>0)+N(X<0)} = \alpha^{q,\bar{q}} P_{q,\bar{q}}\,, \tag{1}$$

where the pseudoscalar variable X in the laboratory reference frame is

$$X = \frac{(\vec{k}^{+} \times \vec{k}^{-}) \cdot \vec{j}}{|\vec{k}^{+}_{T}|\ |\vec{k}^{-}_{T}|}\,, \tag{2}$$

$\vec{k}^{\pm}$ and $\vec{k}^{\pm}_{T}$ are the momenta of two charged (positive and negative) particles in the jet selected according to some criteria and its projections onto

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the plane perpendicular to $\vec{j}$ – a unit vector in the jet direction[1]. The second equality in (1) is due to the pseudoscalar X can appear only in a product with another pseudoscalar. The only one known, characterizing the quark fragmentation, is the longitudinal quark polarization P_q. Therefore the asymmetry with respect to X should be proportional to the polarization P with a proportionality coefficient (*analyzing power*) α.

Charge conjugation transforms quarks into antiquarks with the same helicities and changes particle charges of the pair into opposite ones. So it gives

$$\alpha^{\bar{q}} = -\alpha^q \ . \tag{3}$$

A few words on the pair selection. The handedness, just like the polarization, is an interference phenomena [1]. That is why the commonly used QCD Monte-Carlo models, like JETSET or HERWIG, dealing with probabilities rather than with amplitudes do not contain any interference phenomena like the handedness. The interference is most probable when a pair of particles in a resonance region interferes with a non-resonant background. Since in partons fragmentation mostly pions are produced, the most probable resonances are in a region of 1 GeV in invariant mass of the pair (*e.g.* the $\rho-$resonance). One can expect also that the leading particles are the most informative about parton spin state (just as they are 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' [2] [2]

$$t \approx \frac{2Ez(1-z)}{m_T^2} \ , \tag{4}$$

where z is a fraction of longitudinal momentum, and try to select particles in a pair close in the formation time. One can think that the new variable connected with such a basic law as the uncertainty principle is more adequate to hadronization.

The best way to know the analyzing power is to measure it in a process with known quark polarization, *e.g.* in $Z^o \to q\bar{q}$ decay. With opposite polarization of q and $\bar{q}$ one obtains a non-zero result:

$$H^{e^+e^-} = \frac{\sum_q \sigma_q w_q \alpha^q P_q}{\sum_q \sigma_q w_q} \, , \tag{5}$$

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

[2] According to the uncertainty principle, it is a minimal time during which a massless quark is undistinguishable from a final state hadron and a residual quark with energy deficit $\Delta E \simeq 1/t = \sqrt{k_T^2 + ((1-z)E)^2} + \sqrt{m_T^2 + (zE)^2} - E \approx m_T^2/2Ez(1-z)$.

where σ_q is the production cross section of flavor q and w_q is the probability of the flavor to fragment into a pair selected by applied cuts.

The jet handedness correlation is defined as

$$C_{LL} = \frac{N(XX' < 0) - N(XX' > 0)}{N(XX' < 0) + N(XX' > 0)} \ , \tag{6}$$

where N is a number of couples of pairs with X and X' defined by (2) for the same or opposite jets *of the same event.* Since for $e^+e^- \rightarrow q\bar{q}$ the helicities of q and $\bar{q}$ are always opposite (CP-conjugation), one can write using (3) for opposite jet pairs

$$C_{LL} = \frac{\sum_q \sigma_q w_q^2 \alpha^q \alpha^{\bar{q}}}{\sum_q \sigma_q w_q^2} = -\frac{\sum_q \sigma_q w_q^2 (\alpha_q)^2}{\sum_q \sigma_q w_q^2} \ . \tag{7}$$

An important assumption made here is the so-called factorization theorem which allows to write the $e^+e^- \rightarrow$ 2-jet cross section as product of $e^+e^- \rightarrow q\bar{q}$ cross section sub-process and two 2-particle fragmentation functions for each of the quark into a pair of hadrons. So, the correlation is signed and, moreover, has to be *negative.*

2. The experimental results

The result of the DELPHI handedness measurement [3] was $H^{e^+e^-} = (1.2 \pm 0.5)\%$ seen for leading $(++-)$ and $(--+)$ pion triples in the ρ-resonance region of invariant mass of $(+-)$-pairs. The SLD result [4] obtained with a polarized electron beam is $H < 2\%$.

The first observation of the handedness correlation using cuts in rapidity y, transverse momenta k_T, rapidity interval Δy and invariant mass $M^{\rm pair}$ was reported at the Moriond-94 workshop [5]. It was found that the opposite jet correlation is rather big ($C_{LL} = 11 \pm 5\%$ after reprocessing of data) and *positive.* After that set of cuts only a few hundred events from a million survived. It would be desirable to reduce the number of cuts using a combined variable which are better suited to this phenomena. It was supposed that the formation time (4) could be such a variable. Results of the handedness correlations (6) using the formation time for DELPHI 91-93 data was presented at the Brussels EPS conference [6] and Amsterdam SPIN96 Symposium [10]. Here we present the result for DELPHI 91-95 data after a new reprocessing of the data.

Jets were reconstructed in each event according to the JADE algorithm with the jet resolution parameter $Y_{\rm cut} = 0.08$. Only 2-jet events were retained for the analysis and the acollinearity of the two jets $\Delta\theta_{jj}^{\rm max}$ was required to be $\leq 5°$. The jet axis $\vec{j}$ was chosen as $\pm\vec{\tau}$ (the unit vector $\vec{\tau}$ along the thrust axis), depending on the sign of the rapidity of the pair. All tracks in the event were ordered with respect to their formation time t. For tracks with negative rapidity, a negative sign was assigned to t. The event was scanned then along the formation time axis by an interval Δ to select *all neighboring* pairs of tracks close in their relative formation time, *i.e.*

$$\left|\frac{t_1 - t_2}{t_1 + t_2}\right| \leq \Delta = 0.2 \; . \tag{8}$$

In each event, independent pairs (*i.e.* pairs not sharing any particles) were selected satisfying sets of one- and two-particle cuts on the maximal formation time $t^{\max}$ and invariant mass of pair $M^{\mathrm{pair}}_{\max}$.

It was found earlier [6] that the maximal effect to error ratio reaches for $M^{\mathrm{pair}}_{\max} = 0.75$ GeV$/c^2$ with $C^{\mathrm{opp}}_{LL} = 8.5 \pm 1.7$ ppm. The new data show some smaller value

$$\begin{aligned} C^{\mathrm{opp}}_{LL} &= \;\; 2.6 \pm 1.0 \text{ ppm for the pairs from opposite jets} \;, \\ C^{\mathrm{same}}_{LL} &= -1.9 \pm 1.0 \text{ ppm for the pairs from the same jet} \;. \end{aligned} \tag{9}$$

No such correlation is seen in the MC-simulated events ($C^{MC\,\mathrm{opp}}_{LL} = -1.9 \pm 1.1$ ppm). The correlations in the same jet are similar for the data and the MC-data. It is found also that the correlations increase up to $C^{\mathrm{opp}}_{LL} = 5.4 \pm 1.3$ with increase of the disbalance in momenta of the two jets $|\vec{P}_{\mathrm{jet}\,1} + \vec{P}_{\mathrm{jet}\,2}| > 5\,\mathrm{GeV}/c$ and when the number of selected pairs is more then 2. The reason for this is not clear yet. The handedness itself with new selection criteria is equal $H_{\mathrm{exp}} \approx 1 \pm 1$ ppm.

To estimate the systematic errors, it seems crucially important to investigate the background, *i.e.* the correlation in 'artificial' events constructed from jets of different events taken from real data with the same acollinearity. For the same selection of pairs, no C_{LL} correlation at a level of less than 1.1 ppm was found for the opposite jets pairs. This convincing that the C_{LL} correlation is not an apparatus effect.

Fig.1 demonstrates the dependence of the C_{LL} correlations on XX' for DELPHI 91-95 data, background, JETSET7.3 PS events and MC simulation of DELPHI setup for this events.

The cumulative momenta variables in jets proposed in [8]

$$\vec{k}^{+} = \sum_{\mathrm{jet}} \vec{k}^{+}_{i} \;, \qquad \vec{k}^{-} = \sum_{\mathrm{jet}} \vec{k}^{-}_{i} \;, \tag{10}$$

were also tried instead of the pair selection. With some additional cuts for tracks: $Y_{\min} \leq |Y_i| \leq Y_{\max}$ and $|\vec{k}_T| \geq k^{\min}_T$ one gets

$$C^{\mathrm{opp}}_{\mathrm{cumul}} = 2.4 \pm 1.0 \text{ ppm}. \tag{11}$$

Generally speaking this two statistics are independent of each other, nevertheless the sign of the correlation $C^{\rm opp}_{\rm cumul}$ is also *positive.*

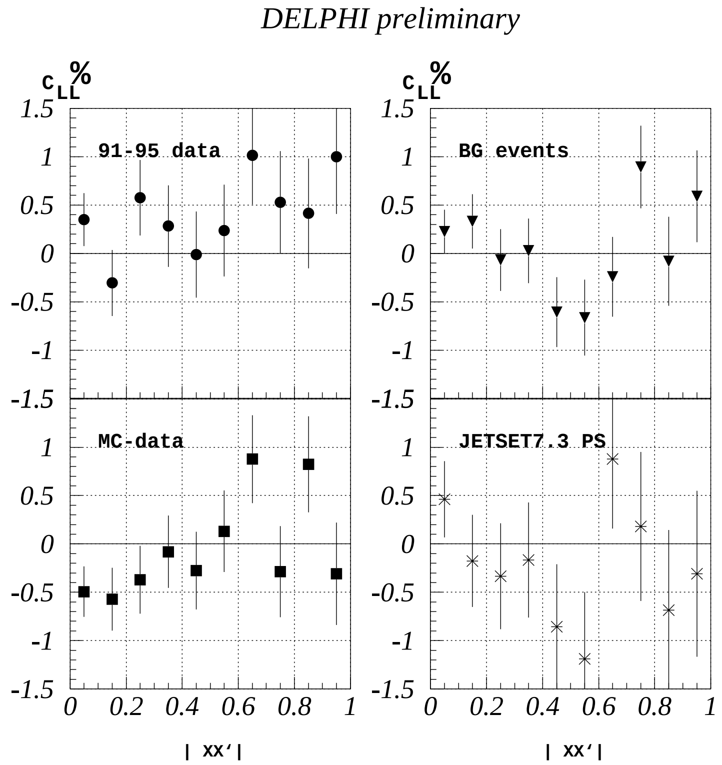

Fig. 1. The dependence of $C^{\rm opp}_{LL}$ on the value $|XX'|$.

3. Discussion

The most puzzling thing is that the correlation measured in opposite jets has a sign *opposite* to those predicted by (7) based on the standard parton picture. This picture includes the helicity correlation of $q\bar{q}$ in 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 two latter of the statements were checked independently [6] with no significant deflection from Monte-Carlo events. So, it seems that the observed positive correlation has nothing to do with the spin correlation of quarks. Also it is much larger than the squared handedness limit with the same pair selection.

The natural question arises of what could be the reason for it. One has hypothesized [5–7] that the positive sign could be a consequence of a nonzero vacuum chromo-magnetic field in some space-time domain which influence the fragmentation function of both q and $\bar{q}$ in the same event of Z^0-decay. Being C-odd, it breaks C-conjugation of the two jets and leads to a positive C_{LL}-correlation. The covariant form of the two-particle fragmentation function in the field contains a term proportional to $G^a_{\mu\nu}k^+_\mu k^-_\nu = [(\vec{B}^a\vec{n})-(\vec{E}^a d\vec{v})]\varepsilon_+\varepsilon_-$, where $\vec{n}=\vec{v}^+\times\vec{v}^-$, $d\vec{v}=\vec{v}^+-\vec{v}^-$ and $\vec{v}=\vec{k}/\varepsilon$. From this one can show (see Appendix) that correlation of longitudinal components of normals n_L should be accompanied by the *opposite sign* correlation of transversal velocity difference $d\vec{v}_T$, and that of the transversal normals by the longitudinal velocity difference. Moreover the correlation of definite combination of this variables, $(n_L n'_L - d\vec{v}_T d\vec{v}_T{}')$ and $(\vec{n}_T\vec{n}'_T - dv_L v'_L)$, should correspond to different components of vacuum chromo-magnetic field (longitudinal and transversal). The results of the measurement of this correlations for the same selection of pairs are presented in Table I, where C's are defined by Eq. (6) with the change of X and X' by corresponding components of $\vec{n}$ or $d\vec{v}$ [3]. The last column in the Table shows the corrected values since $C_{\rm corr} = C_{\rm data} - C_{MC} + C_{\rm jetset}$ with a good accuracy.

TABLE I

C-correlation of normals and velocity difference (in ppm) for pairs from opposite jets for DELPHI 91-95 data (preliminary), JETSET, Monte-Carlo events and corrected data.

Correlation	Data91-95	JETSET	MC-data	Corr. Data
$C(n_L n'_L)$	-2.5 ± 1.0	1.2 ± 2.0	1.9 ± 1.2	-3.2 ± 2.5
$C(d\vec{v}_T d\vec{v}_T{}')$	-2.8 ± 1.1	2.7 ± 2.0	-3.2 ± 1.2	3.1 ± 2.6
$C(\vec{n}_T\vec{n}'_T)$	2.8 ± 1.1	-0.9 ± 2.0	3.6 ± 1.2	-1.7 ± 2.6
$C(dv_L v'_L)$	-0.7 ± 1.1	-6.0 ± 2.0	-2.5 ± 1.2	-4.2 ± 2.6
$C(n_L n'_L - d\vec{v}_T d\vec{v}_T{}')$	2.7 ± 1.1	-2.6 ± 2.0	3.8 ± 1.2	-3.7 ± 2.6
$C(\vec{n}_T\vec{n}'_T - dv_L v'_L)$	1.9 ± 1.1	0.5 ± 2.0	3.4 ± 1.2	-1.0 ± 2.6

One can see that the numbers in the last column of the Table give some indication to the presence of longitudinal chromo-magnetic field since *(i)* the correlation $C(n_L n'_L)$ and $C(d\vec{v}_T d\vec{v}_T{}')$ are of *opposite* sign and approximately the same value, *(ii)* the correlation $C(n_L n'_L - d\vec{v}_T d\vec{v}_T{}')$ is respectively large. One should have in mind however that the bulk part of the corrected values comes from the correction itself which is yet known with a large error.

Concerning the correlations due to transverse component of the field one should notice that they could be masked by a more strong effect of leading charge correlation which is well seen in the fourth row of JETSET events. One should also pay attention to the $C(d\vec{v}_T d\vec{v}_T{}')$ since it is close to the 'Collins asymmetry' correlation [9].

[3] Notice, that for opposite jet pairs $C(n_L n'_L) = -C_{LL}$.

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Appendix

The relativistic invariant form of a two-particle fragmentation function of a quark q with 4-momentum k into a $(+-)$-pair of 4-momentum k^+, k^- in a background chromo-electro-magnetic (CEM) field $G^a_{\mu\nu}$ should contain a term with odd power $G^a_{\mu\nu}$

$$D_q^G = w_q[1 + \cdots + \beta_q G^a_{\mu\nu} k^+_\mu k^-_\nu], \tag{A.1}$$

where w and β depend on the longitudinal and transverse (with respect to the thrust axis) momenta $k^\pm_{L,T}$ of the particles.

Due to C-invariance of fragmentation $D_q^G = D_{\bar{q}}^{-G}$ and $\beta_{\bar{q}} = \beta_q$in contrast with (3), since G changes sign under the charge conjugation.

Averaging over different events with presumably random orientation of G kills this term in (A.1) (assuming naturally that $\langle G \rangle = 0$ for to restore the Lorentz and C-invariance) and one obtains for longitudinal handedness in $e^+e^- \rightarrow$2-jet annihilation the old expressions (5).

Turn now to correlation of two $(+-)$-pairs from opposite jets. It could be obtained from the product of D_q^G and $D_{\bar{q}}^G$ averaged over all possible configuration of the vacuum field G

$$\langle D_q^G D_{\bar{q}}^G \rangle_G = w_q^2 \left[1 + \cdots + \beta_q^2 \langle G^a_{\mu\nu} G^{a'}_{\mu'\nu'} \rangle_G k^+_\mu k^-_\nu k'^+_{\mu'} k'^-_{\nu'} \right] \ . \tag{A.2}$$

Consider now the momenta correlation due to CEM in more detail. The strength tensors $G^a_{\mu\nu}$ and $G^{a'}_{\mu'\nu'}$ are in different space-time points $(t, \vec{r})$ and $(t', \vec{r}')$ due to different space-time points of fragmentation[4] of q and $\bar{q}$. For to respect the translation invariance of the vacuum the average $\langle G^a_{\mu\nu} G^{a'}_{\mu'\nu'} \rangle_G$ should depend only on the difference $\Delta_\mu = (x' - x)_\mu$ and for to respect Lorentz covariance, P-invariance and colorless one can build only two rank-4 tensors antisymmetric in two pairs of indices

$$\langle G^a_{\mu\nu} G^{a'}_{\mu'\nu'} \rangle_G = \delta^{aa'} \left[(g_{\mu[\mu'} g_{\nu']\nu}) A + (\Delta_{[\mu} g_{\nu][\nu'} \Delta_{\mu']}) C \right] \tag{A.3}$$

where A and C are scalar functions of the spacelike interval Δ^2 and $[\cdots]$ around indices indicate anti-symmetrization.

[4] As a time of fragmentation one may accept the "formation time" of the pair the formation time of one of the particles since the particles in the pairs are selected close in the formation time.

It is easy to find that

$$2A+\Delta^2C=\frac{1}{6}\langle G^2\rangle_G=\frac{1}{3}(B^2-E^2)$$

and

$$A+\Delta^2C=\frac{1}{3\Delta^2}\langle(\Delta\cdot G)^2\rangle_G=\frac{1}{3}(B_T^2-E_L^2)\,. \tag{A.4}$$

Convolution of (A.3) with momenta of (A.2) gives for the coefficients of A and C

$$\left(\prod\varepsilon\right)\left[(\vec{n}\vec{n}')-d\vec{v}d\vec{v}'\right]\quad\text{and}\quad\left(\prod\varepsilon\right)\Delta^2\left[(\vec{n}_T\vec{n}_T')-dv_Ldv_L'\right]\,, \tag{A.5}$$

where $\vec{n}=\vec{v}^+\times\vec{v}^-$, $d\vec{v}=\vec{v}^+-\vec{v}^-$, ε and $\vec{v}=\vec{k}/\varepsilon$ are energy and velocity of particles, $v_L=-(\Delta\cdot v)/\sqrt{-\Delta^2}$, $\vec{n}_T=v_L^+\vec{v}^--v_L^-\vec{v}^+$ and $\prod\varepsilon=\varepsilon^+\varepsilon^-\varepsilon'^+\varepsilon'^-$.

Now consider the situation when the selected pairs in opposite jet are in the same formation time interval. In this case one can accept $\Delta_0=t'-t\approx 0$ and, assuming the velocities of particles are close to the light velocity ($c=1$), $\vec{\Delta}\approx\vec{\tau}(t+t')\approx 2t\vec{\tau}$, where $\vec{\tau}$ is an unit thrust vector in the Lab r.f. In this case $dv_{L,T}$ and $n_{L,T}$ obtain the real sense of longitudinal and transversal components the velocity difference and normals with respect to the thrust axes and the invariants (A.4) could be expressed via longitudinal and transversal components of chromo-magnetic and -electric fields strength.

Substituting all this into CEM term of (A.2) one obtains for it

$$\begin{aligned}\langle D_q^G D_{\bar q}^G\rangle_G \;=\; w_q^2\Bigg\{1+\cdots+\frac{\beta_q^2}{3}\left(\prod\varepsilon\right)\Big[&\langle B_L^2-E_T^2\rangle_G(n_Ln_L'-d\vec{v}_Td\vec{v}_T')\\ &+\langle B_T^2-E_L^2\rangle_G(\vec{n}_T\vec{n}_T'-dv_Ldv_L')\Big]\Bigg\}\,.\end{aligned} \tag{A.6}$$

The usual idea of a nonzero vacuum field is a self-dual in Euclidian space-time ($\vec{E}^a=\pm\vec{B}^a$) [11]. For the pseudo-Euclidian space-time this means $E^2=-B^2$ and both field factors in (A.6) are positive this case.

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