Study of T-odd Quark Fragmentation Function in $Z^0 \to 2$-jet Decay

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The first probe of the correlation of the T-odd one-particle fragmentation function responsible for the left–right asymmetry of fragmentation of a transversely polarized quark and an antiquark is done by using the 1991-95 DELPHI data for $Z \to 2$ jet decay. Integrated over the fraction of longitudinal and transversal momenta, this correlation is of 2.5 ppm order, which means order of 7% for the analyzing power. This makes us hope to use certain effects in polarized DIS experiments for transversity measurement.

1 Introduction

The study of spin effects in high-energy interactions provide a sensitive test for models of strong-interaction dynamics and have produced a number of surprises. The transfer of nucleon polarization to quarks is investigated in deep-inelastic polarized lepton – polarized nucleon scattering experiments [1]. The corresponding nucleon spin structure functions for the longitudinal spin distribution g_1 and transversal spin distribution h_1 for proton are well known. The *opposite* process, the spin transfer from partons to a final hadron, is also of fundamental interest. Analogies of f_1, g_1 and h_1 are functions D_1, G_1 and H_1, which describe the fragmentation of a non-polarized quark into a non-polarized hadron and a longitudinally or transversely polarized quark into a longitudinally or transversely polarized hadron, respectively [b].

These fragmentation functions are integrated over the transverse momentum $\vec{k}_T$ of a quark with respect to a hadron. With $\vec{k}_T$ taken into account, new possibilities arise. Using the Lorentz- and P-invariance one can write in the leading twist approximation write 8 independent spin structures[2,3]. Most spectacularly it is seen in the helicity basis where one can build 8 twist-2 combinations, linear in spin matrices of the quark and hadron $\vec{\sigma}$, $\vec{S}$ with momenta $\vec{k}$, $\vec{P}$. Especially interesting is a new structure that describes a left–right asymmetry in the fragmentation of a transversely polarized quark: $H_1^{\perp}\vec{\sigma}(\vec{P}\times\vec{k}_T)/P\langle k_T\rangle$, where the coefficient $H_1^{\perp}$ is a functions of the longitudinal momentum fraction z, quark transversal momentum k_T^2 and $\langle k_T\rangle$ is an average of the transverse momentum.

In the case of fragmentation to a non-polarized or a zero spin hadron, not only D_1 but also the $H_1^{\perp}$ term will survive. Together with its analogies in

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[b] We use the notation of the work [2].

distribution functions f_1 and $h_1^{\perp}$, this opens a unique chance of doing spin physics with non-polarized or zero spin hadrons! In particular, since the $H_1^{\perp}$ term is helicity-odd, it makes possibile to measure the proton transversity distribution h_1 in semi-inclusive DIS from a transversely polarized target by measuring the left-right asymmetry of forward produced pions (see [4,5] and references therein).

The problem is that, first, this function is completely unknown both theoretically and experimentally and should be measured independently. Second, one should keep in mind that the function $H_1^{\perp}$ is the so-called T-odd fragmentation function: under the naive time reversal $\vec{P}$, $\vec{k}_T$, $\vec{S}$ and $\vec{\sigma}$ change sign, which demands a purely imaginary (or zero) $H_1^{\perp}$ in the contradiction with hermiticity. This, however, does not mean the breaking of T-invariance but rather the presence of an interference term of different channels in forming the final state with different phase shifts, like in the case of the single spin asymmetry phenomena [6]. A simple model for this function could be found in [7]. It was also conjectured [8] that the final state phase shift can average to zero for a single hadron fragmentation upon summing over unobserved states X. Thus, the situation here is far from being clear.

Meanwhile, the data collected by DELPHI (and other LEP experiments) give a unique possibility to measure the function $H_1^{\perp}$. The point is that despite the fact that the transverse polarization of a quark (an antiquark) in Z^0 decay is very small ($O(m_q/M_Z)$), there is a non-trivial correlation between transverse polarizations of a quark and an antiquark in the Standard Model: $C_{TT}^{q\bar{q}} = (v_q^2 - a_q^2)/(v_q^2 + a_q^2)$, which reaches rather high values at Z^0 peak: $C_{TT}^{u,c} \approx -0.74$ and $C_{TT}^{d,s,b} \approx -0.35$. With the production cross section ratio $\sigma_u/\sigma_d = 0.78$ this gives the value $\overline{C_{TT}} \approx -0.5$ for the average over flavors.

The spin correlation results in a peculiar azimuthal angle dependence of produced hadrons (the so-called "one-particle Collins asymmetry"), if the T-odd fragmentation function $H_1^{\perp}$ does exist [7,9,10]. The first probe of it was done three years ago [11] by using a limited DELPHI statistics with the result $\left|\overline{H_1^{\perp}/D_1}\right| \leq 0.3$,, as averaged over quark flavors.

A simpler method has been proposed recently by an Amsterdam group [3]. They predict a specific azimuthal asymmetry of a hadron in a jet around the axis in direction of the second hadron in the opposite jet [c]:

$$\frac{d\sigma}{d\cos\theta_2 d\phi_1} \propto (1+\cos^2\theta_2)\cdot\left(1+\frac{6}{\pi}\left[\frac{H_1^{q\perp}}{D_1^q}\right]^2 C_{TT}^{q\bar{q}}\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_1)\right) \quad (1)$$

[c] We assume the factorized Gaussian form of k_T dependence for $H_1^{q\perp}$ and D_1^q integrated over $|k_T|$.

where θ_2 is the polar angle of the electron and the second hadron momenta $\vec{P}_2$, and ϕ_1 is the azimuthal angle counted-off the $(\vec{P}_2, \vec{e}^-)$-plane. This looks simpler since there is no need to determine the $q\bar{q}$ direction.

2 Event Selection and Measurements

This analysis covered the DELPHI data collected from 1991 through 1995. All particles were generically assumed to be pions. Only charged particles were analyzed. About 3.5 millions of Z° hadronic decays were selected by using the standard selection criteria [12].

Jets were reconstructed by the JADE algorithm with varying the parameter $Y_{cut} = 0.08,\ 0.05,\ 0.03$ or 0.01. Only 2-jet events were retained for the analysis with additional thrust value selection requirement either $T \geq 0$ or $T \geq 0.95$. To get rid of low efficiency of the end-caps of the detector, events with the polar angle of the sphericity axis $|\cos\theta_{\rm sp}| \geq 0.90$ were cut off and tracks with $|\cos\theta_{\rm tr}| \geq 0.98$ were rejected, too. In addition, the acollinearity of the two jets $\Delta\theta_{jj}^{max}$ was required to be $\leq 5^\circ$. A leading particle in each jet was selected both positive and negative.

To study the detector response, a sample of Monte-Carlo events, generated with JETSET and passed through the same analysis chain as the data, was used. With these events, the correction factor

$$f_{\rm corr} = \frac{N_{\rm generated}(\theta_2, \phi_1)}{N_{\rm simulated}(\theta_2, \phi_1)} \tag{2}$$

was built for each bin in the azimuthal angle of the first leading particle ϕ_1 and in the polar angle of the leading particle from the opposite jet θ_2 (see Expr. (1)).

The true distribution was defined as $N_{\rm true} = f_{\rm corr} N_{\rm raw}$ and histograms in ϕ_1 for each bin of θ_2 were fitted by the expression [d]

$$P_0(1 + P_2\cos 2\phi_1 + P_3\cos\phi_1). \tag{3}$$

3 Results and Discussion

For raw data $P_2^{\rm raw}$ is positive (≈ 0.02) for θ_2 close to 90° but it becomes negative (up to -0.09) for θ_2 close to 0° and 180°. The same property but with a larger value of $P_2^{\rm sim}$ (≈ 0.03 in the vicinity of 90°) is shown by MC-simulated events too. This feature is clearly interpreted as a consequence of

[d] The term with $\cos\phi_1$ is due to the twist-3 contribution of usual one-particle fragmentation, proportional to the k_T/E.

low efficiency of the DELPHI detector in the end-cups region and of the polar angle cut-offs.

Indeed, track 1 is more close to the cone of the "dead zone" when the angle ϕ_1 is close to 180° (for $\theta_2 < 90°$) or to 0° (for $\theta_2 > 90°$), which decreases the number of events at the ends of ϕ_1-histogram and produces a negative value of P_2. In contrast to this, the low efficiency between TPC-segments of the detector decreases in the number of events in the center of the ϕ_1-histogram (near 90°) and produces a positive values of P_2.

The positivity area increases for stronger jet selection criteria (smaller $y_{\rm cut}$ and larger T-cut) with more narrow jets, but the value of P_2 decreases.

The $P_2^{\rm gen}$ for pure JETSET shows a weaker dependence on θ_2 and is much smaller in magnitude. In the region $45° < \theta_2 < 135°$ this parameter is zero within the error bars. Therefore this region was considered as the most reliable for the determination of $P_2^{\rm true}$.

The best result for corrected data was obtained for $y_{\rm cut} = 0.03$ and $T \geq 0.95$ selections. The value of $P_2^{\rm true}$ averaged over the region $45° < \theta_2 < 135°$ and over quarks flavors with $\overline{C_{TT}} \approx -0.5$ was found to be

$$P_2^{\rm true} = -0.0026 \pm 0.0018 \ . \quad (4)$$

The corresponding analyzing power according to Exp.(1) is

$$\left| \frac{\overline{H_1^\perp}}{D_1} \right| = 6.3 \pm 1.7\% \ . \quad (5)$$

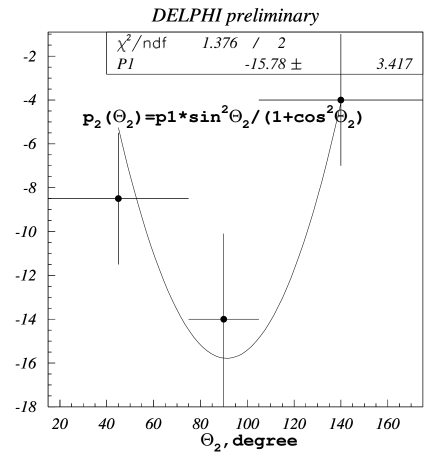

Fig.1. The θ_2-dependence of the $P_2^{\rm true}$ (in ppm).

Regretfully, a rather small value of $P_2^{\rm true}$ and, especially, the fact that it was obtained effectively as a result of subtraction of much larger values of $P_2^{\rm raw}$ and $P_2^{\rm sim}$ do not allow us to consider the θ_2-dependence of $P_2^{\rm true}$ seriously. Nevertheless, we risk to present this dependence in the whole interval of θ_2 in Fig.1 with corresponding fit

$$P_2^{\rm true}(\theta_2) = -(15.8 \pm 3.4) \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \ ppm$$

which increases the value of analyzing power (5) up to $12.9 \pm 1.4\%$. The distinction with (5) demonstrates, however, that systematic errors are by all means larger than the statistical ones and need further investigation.

To study this dependence in more detail, one has to increase the statistics. It could be gained by inclusion not only the leading but also next-to-leading particles into study. Also, the classical "Collins effect" should be investigated and confronted with the effect obtained.

In conclusion, we present some arguments in favor of a non-zero T-odd transversely polarized quark fragmentation function. The corresponding analyzing power could reach an order of 10 per cent, which makes us hope to use this effect for measiring of the transverse quark polarization in other hard processes. In particular, it can be done in the deep inelastic scattering for measurement of nucleon transversety distribution. Further increase of the accuracy and the investigation of systematic errors are required.

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1. M.Anselmino, A.Efremov and E. Leader, Phys. Rep. **265** (1995) 1.
2. D.Boer and P.J.Mulders, Phys. Rev. **D57** (1998) 5780.
3. D.Boer, R.Jakob and P.J.Mulders, Phys. Lett. **B424** (1998) 143.
4. P.J.Mulders and R.Tangerman, Nucl. Phys. **B461** (1995) 234; D.Boer and R.Tangerman, Phys. Lett. **B381** (1996) 305.
5. A. Kotzinian, Nucl. Phys. **B441** (1995) 236.
6. S.Gasiorowich, Elementary particle physics (Wiley, New-York,1966) p.515.
7. J.Collins, Nucl. Phys. **B396** (1993) 161.
8. R.L.Jaffe, X.Jin and J.Tang, Phys. Rev. **D57** (1998) 5920; Phys. Rev. Lett. **80** (1998) 1166.
9. J.Collins et al., Nucl.Phys. **B420** (1994) 565.
10. X.Artru and J.Collins, Z. Phys. **C69** (1996) 277.
11. DELPHI-Collab., W.Bonivento *et al.* Int. Note DELPHI-95-81. Contr. eps0549 to EPS-HEP conf., Brussels (1995).
12. DELPHI Collab., Aarnio P. *et al.*, Phys. Lett. **B240** (1990) 271.