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Interplay among transversity induced asymmetries in hadron leptoproduction

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ABSTRACT

In the fragmentation of a transversely polarized quark several left–right asymmetries are possible for the hadrons in the jet. When only one unpolarized hadron is selected, it exhibits an azimuthal modulation known as the Collins effect. When a pair of oppositely charged hadrons is observed, three asymmetries can be considered, a di-hadron asymmetry and two single hadron asymmetries. In lepton deep inelastic scattering on transversely polarized nucleons all these asymmetries are coupled with the transversity distribution. From the high statistics COMPASS data on oppositely charged hadron-pair production we have investigated for the first time the dependence of these three asymmetries on the difference of the azimuthal angles of the two hadrons. The similarity of transversity induced single and di-hadron asymmetries is discussed. A new analysis of the data allows quantitative relationships to be established among them, providing for the first time strong experimental indication that the underlying fragmentation mechanisms are all driven by a common physical process.

1. Introduction

The description of the partonic structure of the nucleon at leading twist in the collinear case requires the knowledge of three parton distribution functions (PDFs), the number, helicity and transversity functions. Very much like the helicity distribution, which gives the longitudinal polarization of a quark in a longitudinally polarized nucleon, the transversity distribution gives the transverse polarization of a quark in a transversely polarized nucleon. Its first moment, the tensor charge, is a fundamental property of the nucleon. While the number and the helicity PDFs can be obtained from cross-sectional measurements of unpolarized or doubly polarized lepton–nucleon deeply inelastic scattering (DIS), respectively, the transversity distribution is chiral-odd and as such can be measured only if folded with another chiral-odd quantity. As suggested more than 20 years ago [1,2], it can be accessed in semi-inclusive DIS (SIDIS) off transversely polarized nucleons from a left–right asymmetry of the hadrons produced in the struck quark fragmentation with respect to the plane defined by the quark momentum and spin directions. Recently, both the HERMES and the COMPASS experiments have provided unambiguous evidence that transversity is different from zero by measuring SIDIS off transversely polarized protons [3]. Two different processes have been addressed. In the first process, a target spin azimuthal asymmetry in single-hadron production is measured, referred to as Collins asymmetry [2]. It depends on the convolution of transversity and a hadron transverse-momentum dependent chiral-odd fragmentation function (FF), the Collins function, which describes the correlation between the hadron transverse momentum and the transverse polarization of the fragmenting quark. The second process is the production of two oppositely charged hadrons [1,4–6]. In this case the so-called di-hadron target spin azimuthal asymmetry originates from the coupling of transversity to a di-hadron FF, also referred to as interference FF, in principle independent from the Collins function. In both cases, measurements of the corresponding azimuthal asymmetries of the hadrons produced in e^+e^- annihilation [7–9] provided independent information on the two types of FFs, allowing for first extractions of transversity from the SIDIS and e^+e^- data [10–13].

The high precision COMPASS measurements on transversely polarized protons [14,15] showed that in the x-Bjorken region, where the Collins asymmetry is different from zero and sizable, the positive and negative hadron asymmetries exhibit a mirror symmetry and the di-hadron asymmetry is very close to and somewhat larger than the Collins asymmetry for positive hadrons. These facts have been interpreted as experimental evidence of a close relationship between the Collins and the di-hadron asymmetries, hinting at a common physics origin of the two FFs [15–18], as suggested in the $^3P_0$ recursive string fragmentation model [19,20] and, for large invariant mass of the hadron pair, in Ref. [21]. The interpretation is also supported by calculations with a specific Monte Carlo model [22].

In order to better investigate the relationship between the Collins asymmetry and the di-hadron asymmetry the correlations between the azimuthal angles of the final state hadrons produced in the SIDIS process $\mu p \to \mu' h^+ h^- X$ have been studied using the COMPASS data. These correlations play an important role in the understanding of the hadronization mechanism and in so far have been studied only in unpolarized SIDIS [23]. In this article for the first time the results for SIDIS off transversely polarized protons are presented. The investigation has proceeded through three major steps:

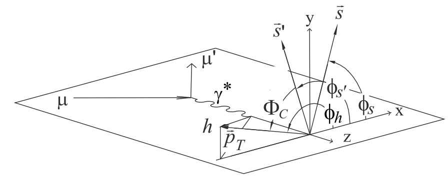

Fig. 1. Definition of the Collins angle Φ_C of a hadron h. The vectors $\vec{p}_T$, $\vec{s}$ and $\vec{s}\,'$ are the hadron transverse momentum and the spin of the initial and struck quarks respectively.

i) the Collins asymmetries for positive and negative hadrons have been compared with the corresponding asymmetries measured in the SIDIS process $\mu p \to \mu' h^+ h^- X$, i.e. when in the final state at least two oppositely charged hadrons are detected (2h sample);
ii) using the 2h sample the asymmetries of h^+ and h^- have been measured and their relation has been investigated as function of $\Delta\phi$, the difference of the azimuthal angles of the two hadrons;
iii) the dihadron asymmetry has been measured as function of $\Delta\phi$ and, using a new general expression, compared with the h^+ and h^- asymmetries. The integrated values of the three asymmetries have also been compared.

2. The COMPASS experiment and data selection

COMPASS is a fixed-target experiment at the CERN SPS taking data since 2002 [24]. The present results have been extracted from the data collected in 2010 with a 160 GeV/c μ^+ beam and a transversely polarized proton (NH_3) target, already used to measure the transverse spin asymmetries [14,25,15]. They refer to the 2h sample, i.e. SIDIS events in which at least one positive and one negative hadron have been detected.

The selection of the DIS events and of the hadrons is described in detail in Ref. [15]. Standard cuts are applied on the photon virtuality ($Q^2 > 1$ GeV$^2/c^2$), on the fractional energy transfer to the virtual photon ($0.1 < y < 0.9$), and on the invariant mass of the final hadronic state ($W > 5$ GeV/c^2). Specific to this analysis is the requirement that each hadron must have a fraction of the virtual photon energy $z_{1,2} > 0.1$, where the subscript 1 refers to the positive hadron and subscript 2 to the negative hadron. A minimum value of 0.1 GeV/c for the hadron transverse momenta $p_{T\,1,2}$ ensures good resolution in the azimuthal angles. As shown in Fig. 1 the virtual photon direction is the z axis of the coordinate system while the x axis is directed along the lepton transverse momentum. The direction of the y axis is chosen to have a right-handed coordinate system. Transverse components of vectors are defined with respect to z axis.

The 2h sample consists of 33 million h^+h^- pairs, to be compared with the 85 million h^+ or 71 million h^- of the standard event sample (1h sample) of the previous analysis [15], where at least one hadron (either positive or negative) per event was required.

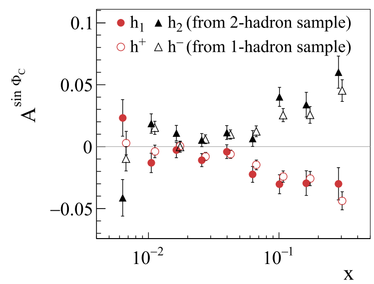

Fig. 2. (Color online.) Comparison of the CL asymmetries for h_1 (full red circles) and h_2 (full black triangles) in $lp \to l'h^+h^-X$ with the standard Collins asymmetries in $lp \to l'h^\pm X$ for $z > 0.1$ (open circles and triangles) measured as function of x.

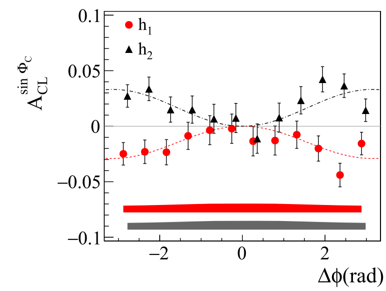

Fig. 3. (Color online.) The $A_{CL1}^{\sin\Phi_{C1}}$ (red circles) and the $A_{CL2}^{\sin\Phi_{C2}}$ (black triangles) vs. $\Delta\phi$. Superimposed are the fitting functions described in the text.

Table 1
Integrated values of the Collins and CL asymmetries for positive and negative hadrons in the region $x > 0.032$.

	Collins asymmetry	Collins-like asymmetry
h_1	-0.017 ± 0.002	-0.018 ± 0.003
h_2	0.018 ± 0.002	0.020 ± 0.003

3. Comparison of 1h and 2h sample asymmetries

For each hadron the Collins angle Φ_{Ci}, $i = 1, 2$, is defined as usual as $\Phi_{Ci} = \phi_i + \phi_S - \pi$, where ϕ_i is the azimuthal angle of the hadron transverse momentum, ϕ_S is the azimuthal angle of the transverse nucleon spin, and $\pi - \phi_S$ is the azimuthal angle of the spin $\vec{s}\,'$ of the struck quark [26], as shown in Fig. 1. All the azimuthal angles are measured around the z axis. For the positive and negative hadrons in the 2h sample, the amplitudes $A_{CL1}^{\sin\Phi_{C1}}$ and $A_{CL2}^{\sin\Phi_{C2}}$ of the $\sin\Phi_{C1,2}$ modulations in the cross-section have been extracted with the same method as of Ref. [15] and labeled "CL" (Collins-like) to distinguish them from the standard Collins asymmetries, which are defined in the 1h sample.

Within the accuracy of the measurements the CL asymmetries turn out to be the same as the standard Collins asymmetries, as can be seen in Fig. 2. The integrated values of the Collins and CL asymmetries are given in Table 1 for $x > 0.032$ that is in the x-region where they are sizable. Taking into account statistical correlation the difference between the Collins and the CL asymmetries is less than a standard deviation for both h_1 and h_2. This observation implies that the Collins asymmetry does not depend on additional observed hadrons in the event. As an important result of the first step of this investigation the 2h sample can be used to study the mirror symmetry and to investigate the interplay between the Collins single-hadron asymmetry and the di-hadron asymmetry, as described in the following. All the results of the following work are obtained in the kinematical region $x > 0.032$, which is the one where the Collins and the di-hadron asymmetries are largest.

4. $\Delta\phi$ dependence of the CL asymmetries of positive and negative hadrons

The azimuthal correlations between ϕ_1 and ϕ_2 in transversely polarized SIDIS had been investigated by measuring the asymmetries as a function of $|\Delta\phi|$ [17], where $\Delta\phi = \phi_1 - \phi_2$. The final results as function of $\Delta\phi$ are shown in Fig. 3. The two asymmetries look like even functions of $\Delta\phi$, are compatible with zero when $\Delta\phi$ tends to zero, and increase in magnitude as $\Delta\phi$ increases. Very much as in Fig. 2 the mirror symmetry between positive and negative hadrons is a striking feature of the data. The overall picture agrees with the expectation from the $^3P_0$ recursive string fragmentation model of Refs. [19,20], which predicts a maximum value for $\Delta\phi \simeq \pi$.

The framework to access the $\Delta\phi$ dependence of CL asymmetries was proposed in Ref. [27]. After integration over x, Q^2, z_1, z_2, p_{T1}^2 and p_{T2}^2 the cross-section for the SIDIS process $lN \to l'h^+h^-X$ can be written as

$$\frac{d\sigma^{h_1h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U + S_T\left[\sigma_{C1}\frac{(\vec{p}_{T1}\times\vec{q})\cdot\vec{s}\,'}{|\vec{p}_{T1}\times\vec{q}|\,|\vec{s}\,'|} + \sigma_{C2}\frac{(\vec{p}_{T2}\times\vec{q})\cdot\vec{s}\,'}{|\vec{p}_{T2}\times\vec{q}|\,|\vec{s}\,'|}\right]$$
$$= \sigma_U + S_T\left[\sigma_{C1}\sin\Phi_{C1} + \sigma_{C2}\sin\Phi_{C2}\right], \quad (1)$$

where the unpolarized σ_U and the polarized σ_{C1} and σ_{C2} structure functions (SFs) might depend on $\cos\Delta\phi$. To access the azimuthal correlations of the polarized SFs Eq. (1) is rewritten in terms of ϕ_1 and $\Delta\phi$, or alternatively in terms of ϕ_2 and $\Delta\phi$:

$$\frac{d\sigma^{h_1h_2}}{d\phi_1 d\Delta\phi d\phi_S} = \sigma_U + S_T\Big[\Big(\sigma_{C1} + \sigma_{C2}\cos\Delta\phi\Big)\sin\Phi_{C1} - \sigma_{C2}\sin\Delta\phi\cos\Phi_{C1}\Big],$$
$$\frac{d\sigma^{h_1h_2}}{d\phi_2 d\Delta\phi d\phi_S} = \sigma_U + S_T\Big[\Big(\sigma_{C2} + \sigma_{C1}\cos\Delta\phi\Big)\sin\Phi_{C2} + \sigma_{C1}\sin\Delta\phi\cos\Phi_{C2}\Big]. \quad (2)$$

With the change of variables above a new modulation, of the type $\cos\Phi_{C1,2}$, appears in the cross section, which can then be rewritten in terms of the sine and cosine modulations of the Collins angle of either the positive or the negative hadron. The explicit expressions for the four asymmetries are:

$$A_{CL1}^{\sin\Phi_{C1}} = \frac{1}{D_{NN}}\frac{\sigma_{C1} + \sigma_{C2}\cos\Delta\phi}{\sigma_U},$$
$$A_{CL1}^{\cos\Phi_{C1}} = -\frac{1}{D_{NN}}\frac{\sigma_{C2}\sin\Delta\phi}{\sigma_U},$$
$$A_{CL2}^{\sin\Phi_{C2}} = \frac{1}{D_{NN}}\frac{\sigma_{C2} + \sigma_{C1}\cos\Delta\phi}{\sigma_U},$$
$$A_{CL2}^{\cos\Phi_{C2}} = \frac{1}{D_{NN}}\frac{\sigma_{C1}\sin\Delta\phi}{\sigma_U}, \quad (3)$$

where D_{NN} is the mean transverse-spin-transfer coefficient, equal to 0.87 for these data. Fig. 4 shows the measured values of the new asymmetries $A_{CL1,2}^{\cos\Phi_{C1,2}}$. It is the first time that they are measured. They have almost equal values for positive and negative hadrons, seem to be odd functions of $\Delta\phi$, and average to zero when integrating over $\Delta\phi$. Note that the data are in very good agreement with Eq. (3) if $(\sigma_{C1}/\sigma_U) = -(\sigma_{C2}/\sigma_U) = \mathrm{const.}$

The quantities σ_{C1}/σ_U and σ_{C2}/σ_U, which in principle can still be functions of $\Delta\phi$, can be obtained from the measured asymmetries using

$$\frac{\sigma_{C1}}{\sigma_U} = D_{NN}\left[A_{CL1}^{\sin\Phi_{C1}} + A_{CL1}^{\cos\Phi_{C1}}\cot\Delta\phi\right],$$

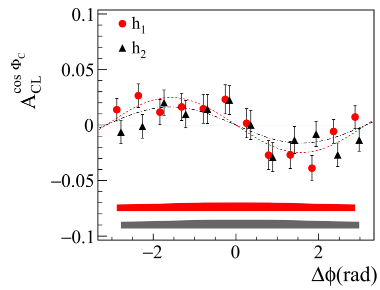

Fig. 4. (Color online.) The $A_{CL1}^{\cos\Phi_{C1}}$ (red circles) and the $A_{CL2}^{\cos\Phi_{C2}}$ (black triangles) vs. $\Delta\phi$. Superimposed are the fitting functions described in the text.

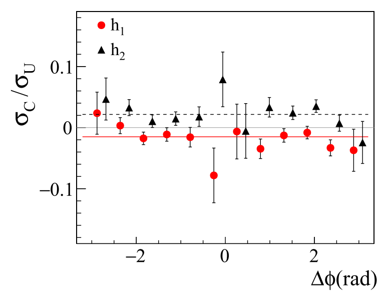

Fig. 5. (Color online.) The measured values of the ratios σ_{C1}/σ_U and σ_{C2}/σ_U. The lines give the fitted mean values, -0.015 ± 0.004 for h_1 and 0.022 ± 0.004 for h_2.

Table 2
Fitted values of the a parameter for the two CL asymmetries for positive and negative hadrons.

	$A_{CL}^{\sin\Phi_C}$	$A_{CL}^{\cos\Phi_C}$
h_1	0.014 ± 0.003	0.025 ± 0.005
h_2	0.016 ± 0.003	0.017 ± 0.005

$$\frac{\sigma_{C2}}{\sigma_U} = D_{NN}\left[A_{CL2}^{\sin\Phi_{C2}} - A_{CL2}^{\cos\Phi_{C2}} \cot\Delta\phi\right]. \tag{4}$$

The values of the ratios σ_{C1}/σ_U and σ_{C2}/σ_U extracted from the measured asymmetries are given in Fig. 5. Within the statistical uncertainty they are constant, hinting at similar azimuthal correlations in polarized and unpolarized SFs. Moreover, they are almost equal in absolute value and of opposite sign. Assuming $(\sigma_{C1}/\sigma_U) = -(\sigma_{C2}/\sigma_U) = \text{const.}$, the measured asymmetries can be fitted with the simple functions $\pm a(1-\cos\Delta\phi)$ in the case of the sine asymmetries, and $a\sin\Delta\phi$ for the cosine asymmetries. The results of the fits for positive (negative) hadrons are the dashed red (dot-dashed black) curves shown in Figs. 3 and 4. The agreement with the measurements is very good and the four values for the constants a are compatible, as can be seen in Table 2.

As a conclusion of this second step of the investigation, the h_1 and h_2 CL asymmetries as functions of $\Delta\phi$ agree with the expectation from the $^3P_0$ recursive string fragmentation model and with the calculations of the $\Delta\phi$ dependence obtained in Ref. [27]. As in the one-hadron sample a mirror symmetry for the positive and negative hadron sine asymmetries is observed in the 2h sample, which is a consequence of the experimentally established relation $\sigma_{C1} = -\sigma_{C2}$.

These results allow a quantitative relation between the h_1 and h_2 CL asymmetries and the di-hadron asymmetry to be derived, as described in the following.

5. Comparison of CL and di-hadron asymmetries

The third and last step of this investigation has been the formal derivation of a connection between the CL and the di-hadron

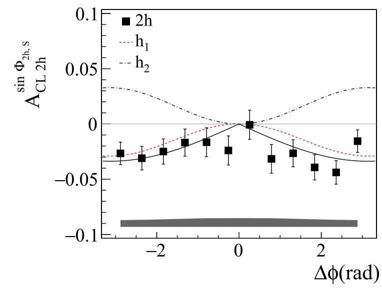

Fig. 6. (Color online.) $A_{CL2h}^{\sin\Phi_{2h,S}}$ vs. $\Delta\phi$ and the corresponding fit (black full curve). The dashed red and dot-dashed black curves are the fits to $A_{CL1}^{\sin\Phi_{C1}}$ and $A_{CL2}^{\sin\Phi_{C2}}$ from Fig. 3.

asymmetries and the comparison with the experimental data. In the standard analysis, the $\Delta\phi$ integrated di-hadron asymmetry is measured from the amplitude of the sine modulation of the angle $\Phi_{RS} = \phi_R + \phi_S - \pi$, where ϕ_R is the azimuthal angle of the relative hadron momentum $\vec{R} = \left[z_2\vec{p}_1 - z_1\vec{p}_2\right]/[z_1+z_2] =: \xi_2\vec{p}_1 - \xi_1\vec{p}_2$. In the present analysis, the azimuthal angle ϕ_{2h} of the vector $\vec{R}_N = \hat{p}_{T1} - \hat{p}_{T2}$ is evaluated for each pair of oppositely charged hadrons, with the hat indicating unit vectors. As discussed in Ref. [15], the azimuthal angle ϕ_R is strongly correlated with $\phi_{2h} = [\phi_1 + \phi_2 + \pi\,\mathrm{sgn}(\Delta\phi)]/2$, where sgn is the signum function. Also, introducing the angle $\Phi_{2h,S} = \phi_{2h} + \phi_S - \pi$, which is a kind of mean of the Collins angle of the positive and negative hadrons after correcting for a π phase difference, it was shown [15] that the di-hadron asymmetry measured from the amplitude of $\sin\Phi_{2h,S}$ is essentially identical to the standard di-hadron asymmetry. In order to establish a connection between the di-hadron asymmetry and the CL asymmetries $\Phi_{2h,S}$ will be used rather than Φ_{RS} in the following. Starting from the general expression for the cross section given in Eq. (1), changing variables from ϕ_1 and ϕ_2 to $\Delta\phi$ and ϕ_{2h}, and using the relations $\sin\Phi_{2h,S} = (\hat{R}_N \times \hat{q})\cdot\hat{s}'$ and $\cos\Phi_{2h,S} = -\,\mathrm{sgn}(\Delta\phi)(\hat{P}_N \times \hat{q})\cdot\hat{s}'$, where $\vec{P}_N = \hat{p}_{T1} + \hat{p}_{T2}$, Eq. (1) can be rewritten as:

$$\begin{aligned}\frac{d\sigma^{h_1h_2}}{d\Delta\phi\, d\phi_{2h}\, d\phi_S} = \sigma_U + S_T\frac{1}{2}\Big[&(\sigma_{C1}-\sigma_{C2}) \\ &\times\sqrt{2(1-\cos\Delta\phi)}\sin\Phi_{2h,S} \\ &-\mathrm{sgn}(\Delta\phi)(\sigma_{C1}+\sigma_{C2}) \\ &\times\sqrt{2(1+\cos\Delta\phi)}\cos\Phi_{2h,S}\Big],\end{aligned} \tag{5}$$

which simplifies to

$$\frac{d\sigma^{h_1h_2}}{d\phi_{2h}d\Delta\phi d\phi_S} = \sigma_U + S_T\cdot\sigma_{C1}\cdot\sqrt{2(1-\cos\Delta\phi)}\cdot\sin\Phi_{2h,S} \tag{6}$$

using the experimental result $\sigma_{C2} = -\sigma_{C1}$. This last cross-section implies a sine modulation with amplitude

$$A_{CL2h}^{\sin\Phi_{2h,S}} = \frac{1}{D_{NN}}\frac{\sigma_{C1}}{\sigma_U}\cdot\sqrt{2(1-\cos\Delta\phi)}. \tag{7}$$

At variance with the single hadron case, no $A_{CL2h}^{\cos\Phi_{2h,S}}$ asymmetry is present in Eq. (6) and the measured values are indeed compatible with zero. In Fig. 6 the $A_{CL2h}^{\sin\Phi_{2h,S}}$ asymmetry is shown together with the curve $-c\sqrt{2(1-\cos\Delta\phi)}$ with $c = 0.017 \pm 0.002$ (black solid line) as obtained by the fit. The dashed red and dot-dashed black curves are the fitted curves $a(1-\cos\Delta\phi)$ of Fig. 3. As can be seen the fit is good, and the value of c is compatible with the corresponding values of Table 2, in agreement with the fact that σ_{Ci}/σ_U is the same for the three asymmetries. Evaluating the ratio of the integrals of the di-hadron amplitudes over the one-hadron amplitudes one gets a value of 1.4 ± 0.2 which agrees with the value $4/\pi$ evaluated from Eqs. (7) and (3) and with our original observation that the di-hadron asymmetry is somewhat larger than the Collins asymmetry for positive hadrons.

6. Conclusions

We have shown that in SIDIS hadron-pair production the x-dependent Collins-like single hadron asymmetries of the positive and negative hadrons are compatible with the standard Collins asymmetries and are mirror symmetric. Also, the Collins-like asymmetries exhibit a $\pm a(1 - \cos\Delta\phi)$ dependence on $\Delta\phi$, which we have derived from the general expression for the two-hadron cross-section and is a consequence of the experimentally verified similar $\Delta\phi$ dependence of the unpolarized and polarized structure functions and the mirror symmetry of the polarized structure functions.

Most important, for the first time it has been shown that the amplitude of the di-hadron asymmetry as a function of $\Delta\phi$ has a very simple relation to that of the single hadron asymmetries in the 2h sample, namely it can be written as $-a\sqrt{2(1-\cos\Delta\phi)}$, where the constant a is the same as that which appears in the expressions for the Collins-like asymmetries. After integration on $\Delta\phi$, the di-hadron asymmetry is larger than the single hadron asymmetries by a factor $4/\pi$, in good agreement with the measured values.

In conclusion, we have shown that the integrated values of Collins asymmetries in the 1h sample are the same as the Collins-like asymmetries of 2h sample which in turn are related with the integrated values of di-hadron asymmetry. This gives an indication that both the single hadron and di-hadron transverse-spin dependent fragmentation functions are driven by the same elementary mechanism. As a consequence of this important conclusion we can add that the extraction of transversity distribution using the di-hadron asymmetry in SIDIS does not represent an independent measurement with respect to the extractions which are based on the Collins asymmetry.

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