IL NUOVO CIMENTO Vol. 35 C, N. 2 Marzo-Aprile 2012
DOI 10.1393/ncc/i2012-11210-1

Colloquia: Transversity 2011

Study of Collins asymmetries at BaBar

I. Garzia for the BaBar Collaboration
INFN and University of Ferrara - Italy

ricevuto il 24 Ottobre 2011; approvato l' 11 Gennaio 2012
pubblicato online il 26 Marzo 2012

Summary. — Transversity distribution describes the quark transverse polarization inside a transversely polarized nucleon. It is the less known leading-twist piece of the QCD description of the partonic structure of the nucleon. Transversity can be extracted from semi-inclusive deep inelastic scattering (SIDIS) where, however, it couples to a new, unknown fragmentation function, called `Collins function`. We present the preliminary results of the measurement of the azimuthal asymmetries in the process $e^+e^- \to q\bar{q} \to \pi\pi X$, where the two pions are produced in opposite hemispheres. These preliminary results are based on a data sample of about 45 fb^{-1}, collected by the *BABAR* experiment at a center-of-mass energy of 10.54 GeV, and are compared with the Belle measurements.

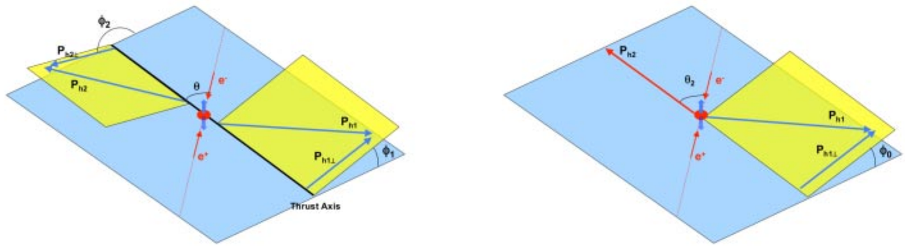
PACS 13.66.Bc – Hadron production in e^-e^+ interactions.
PACS 13.87.Fh – Fragmentation into hadrons.

1. – Motivation for extraction of Collins function in e^+e^- annihilation

Transversity (h_1) is the less known function [1] among the three parton distribution functions needed for a complete description of the momentum and spin distribution of the quarks inside the nucleon. We can measure h_1 in semi-inclusive lepton-nucleon scattering (Semi Inclusive Deep Inelastic Scattering or SIDIS), in which the proton target is transversely polarized. Using the factorization theorem, the SIDIS cross-section is

$$\sigma^{ep\to ehX} = \sum_q DF \times \sigma(eq \to eq) \times FF, \tag{1}$$

with DF the parton Distribution Function, and FF the Fragmentation Function. For transversely polarized target, DF is the transversity distribution (h_1), and FF is the Collins fragmentation function ($H_1^\perp$). Therefore, to extract h_1 we need to know $H_1^\perp$. The measurement of the Collins function can be done in e^+e^- annihilation taking into account the process $e^+e^- \to q\bar{q} \to h_1h_2X$, in which the two hadrons are detected in opposite jets. A non-zero value of the Collins FF produces an asymmetry in the azimuthal distribution



(a) RF12 (b) RF0

Fig. 1. – (Color online) RF12 (a): $\theta = \theta_T$ is the angle between the beam and thrust axis; $\phi_{1,2}$ are the azimuthal angles between the scattering plane and the transverse momentum $P_{h\perp}$ around the thrust axis. RF0 (b): θ_2 is the angle between the beam axis and the second hadron momentum; ϕ_0 is the azimuthal angle between the plane spanned by the beam axis and the second hadron momentum P_2, and by the first hadron's transverse momentum $P_{1\perp}$. All tracks are boosted in the e^+e^- center-of-mass frame.

of the two hadrons around the fragmenting $q\overline{q}$ direction. The Collins asymmetry can be measured in two different reference frames. In the first frame, called *thrust reference frame* or RF12, the azimuthal angles ϕ_1 and ϕ_2 shown in fig. 1(a) are calculated with respect to the thrust axis, that is the axis that maximizes the longitudinal momentum of the event. In this frame the cross-section is [2]

$$\begin{aligned}(2)\qquad \frac{\mathrm{d}\sigma(e^+e^- \to h_1h_2X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}\cos\theta\,\mathrm{d}\phi_1\mathrm{d}\phi_2} = \sum_{q,\overline{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 [(1+\cos^2\theta) D_1^{(0)}(z_1)\overline{D}_1^{(0)}(z_2) \\ + \sin^2(\theta)\cos(\phi_1+\phi_2) H_1^{\perp,(1)}(z_1)\overline{H}_1^{\perp,(1)}(z_2)].\end{aligned}$$

In the second reference frame, *second hadron momentum frame* or RF0, the azimuthal angle ϕ_0 is calculated with respect to the second hadron momentum, as shown in fig. 1(b), and the differential cross-section is [2]

$$\begin{aligned}(3)\qquad & \frac{\mathrm{d}\sigma(e^+e^+ \to h_1h_2X)}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}^2\mathbf{q}_T\mathrm{d}\cos\theta_2\,\mathrm{d}\phi_0} = \\ & \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \Bigg\{ A(y)\mathcal{F}(D_1(z_1)\overline{D}_1(z_2)) \\ & \quad + B(y)\cos(2\phi_0)\mathcal{F}\left[(2\hat{\mathbf{h}}\cdot\hat{\mathbf{k}}_T\,\hat{\mathbf{h}}\cdot\hat{\mathbf{p}}_T - \hat{\mathbf{k}}_T\cdot\hat{\mathbf{p}}_T)\frac{H_1^{\perp}(z_1)\overline{H}_1^{\perp}(z_2)}{M_1M_2}\right]\Bigg\},\end{aligned}$$

where $A(y) = 1/4(1+\cos^2\theta_2)$ and $B(y) = 1/4(\sin^2\theta_2)$ in the e^+e^- center of mass frame.

In eqs. (2) and (3), D_1 is the unpolarized FF, $H_1^{\perp}$ is the Collins FF, $z_{1,2}$ are the fractional energy of the hadrons ($z = 2E/Q$), Q^2 is the center-of-mass energy, and the angles are defined in fig. 1. In conclusion, the Collins asymmetry in e^+e^- annihilation is proportional to $H_1^{\perp}(z_1)\times\overline{H}_1^{\perp}(z_2)$ and, therefore, we can obtain a independent measurement of this FF.

2. – Analysis strategy

The preliminary measurement of Collins asymmetries is performed using a sample of data collected by the *BaBar* experiment at the energy of 10.54 GeV, that is 40 MeV below the nominal energy of the collider, which corresponds to the peak of $\Upsilon(4S)$ resonance. For this reason, we refer to this data sample as off-peak sample.

Assuming the thrust axis as the $q\overline{q}$ direction and selecting pions in opposite hemispheres with respect to the thrust axis, we measure the azimuthal angles ϕ_1, ϕ_2, and ϕ_0. In order to select the two jets topology, we require a thrust higher than 0.8. In addition, we select pions coming from the primary vertex with a fractional energy higher than 0.2. The total visible energy of the event (sum of the energies of reconstructed charged and neutral particles) is required to be higher than 7 GeV. The Collins asymmetries are obtained by measuring the $\cos(\phi)$ modulation of the normalized azimuthal distributions of the selected pion pairs, where $\phi = \phi_1 + \phi_2$ or $\phi = 2\phi_0$ for the two reference frames. The asymmetries resulting by these distributions are largely affected by detector acceptance effects, making their measurement unreliable. We therefore perform suitable double ratios of the asymmetries in order to eliminate the detector effects and the first order of radiative corrections [2]. In particular we use the ratio of the normalized distributions of unlike sign (R_{UL}) over those of like sign (R_L) pion pairs. In addition, the possibility to select pion pairs with same charge or opposite charge allows to be sensitive to favored and disfavored fragmentation functions. Favored FFs describe the fragmentation of a quark of flavor q into a hadron with a valence quark of the same flavor: *i.e.* $u \to \pi^+$ and $d \to \pi^-$. Instead, we refer to $u \to \pi^-$ and $d \to \pi^+$ as disfavored fragmentation processes. Consider, for example, the production of unlike-sign charged pions from a $u\overline{u}$ pair: $e^+e^- \to u\overline{u} \to \pi^\pm\pi^\mp X$. The pion pair can be either created through two favored fragmentation processes or through two disfavored fragmentation processes. Taking into account what said above, the double ratio can be written as

$$\frac{R^{UL}}{R^L} = \frac{1 + \frac{\sin^2\theta}{1+\cos^2\theta}\cos(\phi)G^{UL}}{1 + \frac{\sin^2\theta}{1+\cos^2\theta}\cos(\phi)G^{L}} \simeq 1 + \frac{\sin^2\theta}{1+\cos^2\theta}\cos(\phi)\left\{G^{UL} - G^L\right\}, \tag{4}$$

$$G^{UL} = \frac{\sum_q e_q^2 \mathcal{F}(H_1^{fav}H_2^{fav} + H_1^{dis}H_2^{dis})}{\sum_q e_q^2 (D_1^{fav}D_2^{fav} + D_1^{dis}D_2^{dis})}, \quad G^L = \frac{\sum_q e_q^2 \mathcal{F}(H_1^{fav}H_2^{dis} + H_1^{dis}H_2^{fav})}{\sum_q e_q^2 (D_1^{fav}D_2^{dis} + D_1^{dis}D_2^{fav})};$$

where θ is the polar angle of the thrust axis in the RF12 frame ($\theta = \theta_T$) or the polar angle of the second hadron momentum in the RF0 frame ($\theta = \theta_2$), as shown in fig. 1.

Fitting the double ratio with a cosine function

$$\frac{R_{UL}}{R_L} = \frac{N^{UL}(\phi)/\langle N^{UL}\rangle}{N^L(\phi)/\langle N^L\rangle} = P_0 + P_1 \cdot \cos(\phi), \tag{5}$$

the P_1 parameter contains only the Collins effect and higher order of radiative effects, since acceptance and radiative contributions do not depend on the charge combination of the pion pairs.

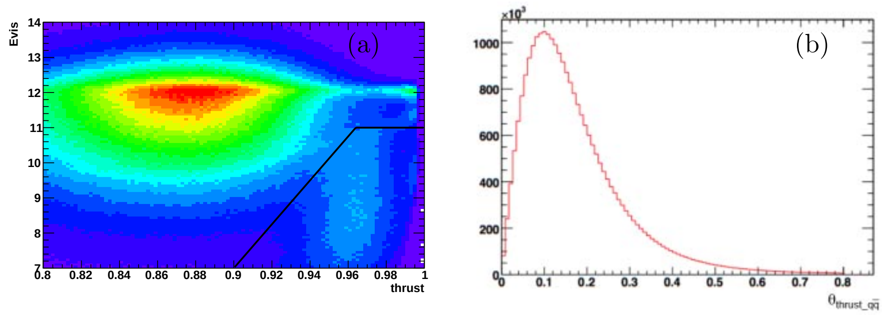


Fig. 2. – (a) Total visible energy of the events *versus* the thrust value. The peak at about 12 GeV of energy and very high thrust values is due to BhaBha and $\mu^+\mu^-(\gamma)$ events, while the small accumulation visible at lower energies and thrust higher than 0.94 is due to $\tau^+\tau^-$ events. (b) Opening angle between the thrust axis and the $q\bar{q}$ axis.

3. – Study of systematic effects

A crucial point for the measurement of Collins asymmetry is the identification of all the effects that can influence the azimuthal distribution of the pion pairs. We study the influence of the particle identification, the possible dependence of the detector response on the pion charge, the presence of residual polarization of the beams, and other minor effects.

Asymmetry dilution due to the charm and τ decays. – Measured asymmetries are diluted by the presence of background sources like charm and τ decays. For this reason we study and evaluate the correction to the asymmetries in order to obtain the true Collins effect.

- $e^+e^- \to \tau^+\tau^-$ contribution. Since weak decays are well described in Monte Carlo, any azimuthal asymmetries should be visible in simulated events. The study of simulated $e^+e^- \to \tau^+\tau^-$ gives an asymmetry consistent with zero. In addition we consider a τ-enhanced data sample, sitting in the lower-right side of the E_{tot} *vs.* T distribution of fig. 2(a). Taking into account the contamination of 25% from $e^+e^- \to q\bar{q}$ in this enhanced sample, the fitted asymmetries are consistent with zero in both reference frames. The measured asymmetry is then corrected following the equation $A_\alpha = A_\alpha^{measured}/(1-D_\tau)$, with the fraction of pion pairs (D_τ) from $\tau^+\tau^-$ events estimated using MC to vary from about 1 to 18% in the individual bins of fractional energy.

- $e^+e^- \to c\bar{c}$ contribution. The fraction of pion pairs due to the $c\bar{c}$ events is much larger than the τ component. Furthermore, both fragmentation processes and weak decays can introduce azimuthal asymmetries. For this reason, in addition to the $c\bar{c}$ MC sample, we select a charm-enhanced data sample requiring at least one D^* candidate from the decay $D^{*\pm} \to D^0\pi^\pm$, with the D^0 candidate reconstructed only in the decay channel $D^0 \to K^-\pi^+$. We estimate the $c\bar{c}$ contribution in this enhanced sample (d) and in the main data sample (D_{charm}), and we measure the asymmetry in both samples. In this way, we are able to extract the Collins asymmetry (A_α) and the charm asymmetry (A^{charm}) solving the following system

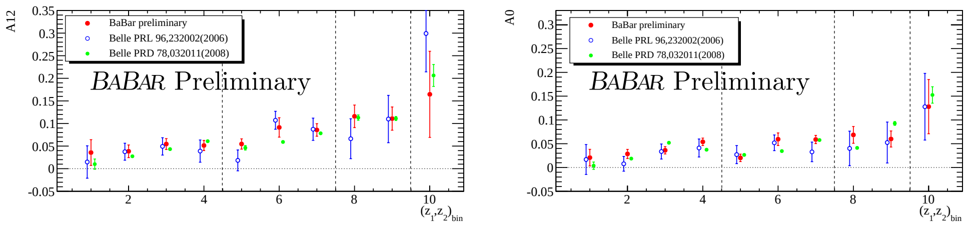


Fig. 3. – (Colour on-line) Preliminary *BABAR* measurement of Collins asymmetries (full circle in red). By comparison the superseded Belle off-peak results (open circle in blue), and Belle results on the full data sample (full green circles) are shown. Systematic and statistical errors are added in quadrature.

of equations:

$$A_\alpha^{meas} = (1 - D_{charm}) \cdot A_\alpha + D_{charm} \cdot A_\alpha^{charm},$$
$$A_\alpha^{D*} = d \cdot A_\alpha^{charm} + (1 - d) \cdot A_\alpha.$$

Asymmetry dilution due to reconstruction of the thrust axis. – The deviation of the thrust axis from the real $q\bar{q}$ direction as shown in fig. 2(b) can lead to a dilution of the measured asymmetries. This effect could be evaluated using a MC sample. However, the Collins fragmentation functions are not defined in our MC generator. Therefore, we simulate the asymmetries applying different weights to the angular distribution of generated tracks. We finally fit the reconstructed azimuthal distributions and we compare the resulting asymmetries with the weights introduced in the simulation. We find that, in RF12, the asymmetry is significantly underestimated, and we apply a correction factor according to the measured value.

4. – Preliminary results

The preliminary results are presented in 10 symmetric combinations of (z_1, z_2) intervals, as described in table I. All significant systematic errors are evaluated and added in quadrature for each bins. In fig. 3 the *BABAR* preliminary results are compared with

Table I. – *Symmetrised z-bin subdivision: we divided the asymmetry results in 10 "bins" of z_1 and z_2 as summarized above.*

z_2					
1					
	4	7	9	10	
0.7					
	3	6	8	9	
0.5					
	2	5	6	7	
0.3					
	1	2	3	4	
0.2					
0.2	0.3	0.5	0.7	1	z_1

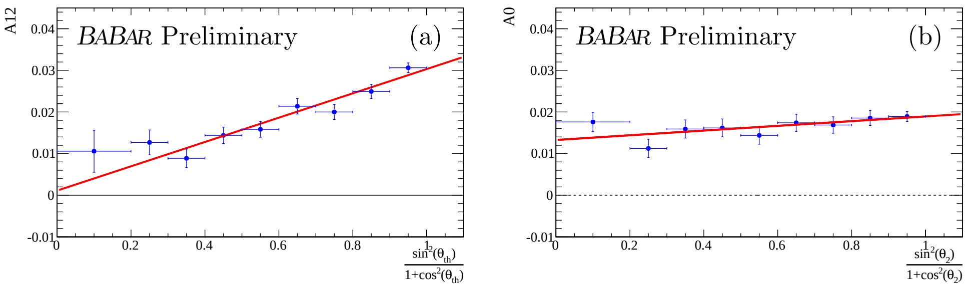


Fig. 4. – Collins asymmetry A_{12} (a), and A_0 (b), as a function of $(\sin^2\theta)/(1+\cos^2\theta)$, where $\theta=\theta_T$ and $\theta=\theta_2$ have been used in plot (a) and (b), respectively.

the superseded off-peak Belle data and the off- and on-peak combined Belle data [3, 4]. We should note that in the newer Belle publication [4], they estimated a new correction factor due to the approximation of the $q\bar{q}$ axis with the thrust axis, so that we correct the first Belle results by the factor 1.66/1.21.

Following eq. (4), we studied also the $\sin^2\theta/(1+\cos^2\theta)$ dependence of the Collins asymmetries in both reference frames, as reported in fig. 4. The expected $\sin^2\theta_T/(1+\cos^2\theta_T)$ linear dependence of asymmetry is observed in the thrust reference frame, but it seems not to hold in the second hadron momentum frame, where $\theta=\theta_2$ is taken. The same dependences are observed by Belle in ref. [4], and explained by the fact that the thrust axis describes the original $q\bar{q}$ direction better than the second hadron momentum.

5. – Conclusions

We reported the preliminary *BABAR* results of Collins asymmetries in the pion system, performed using a data sample of about 45 fb^{-1} collected at the energy of 10.54 GeV. The asymmetries are studied as a function of symmetric bins (z_1, z_2) of the pion fractional energies and as a function of $\sin^2\theta/(1+\cos^2\theta)$, and are compared with the Belle analysis. The results are in overall good agreement each other. However, the off-peak data sample is statistically limited, and the update of the measurement with the full *BABAR* data sample is ongoing.

REFERENCES

[1] Anselmino M. *et al.*, *Phys. Rev. D*, **75** (2007) 054032.
[2] Boer D., *Nucl. Phys. B*, **806** (2009) 23; arXiv:0804.2408v2 (2008).
[3] Seidl R. *et al.* (Belle Collaboration), *Phys. Rev. Lett.*, **96** (2006) 232002.
[4] Seidl R. *et al.* (Belle Collaboration), *Phys. Rev. D*, **78** (2008) 032011.