

# Measurement of Collins asymmetries in inclusive production of pion pairs in $e^+e^-$ collisions at BaBar

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## Abstract

We present a preliminary measurement of the Collins asymmetries in the inclusive process  $e^+e^- \rightarrow q\bar{q} \rightarrow \pi^\pm\pi^\pm X$  at center-of-mass energy near 10.6 GeV. We use a data sample of  $468 \text{ fb}^{-1}$  collected by the BaBar experiment, and we consider pairs of charged pions produced in opposite jets in hadronic events. We confirm a non-zero Collins effect as observed by previous experiments, and we study the Collins asymmetry as a function of pion fractional energies and transverse momenta, and as a function of the polar angle of the analysis axis.

*Proceedings for the 36th International Conference on High Energy Physics,  
July 4-11, 2012  
Melbourne, Australia*

*Published in arXiv:1211.5293*

## Introduction

Transverse spin effects in fragmentation processes were first discussed by Collins [1], who introduced the chiral-odd polarized fragmentation function  $H_1^\perp$ , also called the Collins function, which describes the distribution of the final state hadrons produced by the fragmentation of a transversely polarized quark relative to the momentum direction of their quark.

The first experimental evidence of a non-zero Collins function was obtained in semi-inclusive deep inelastic scattering (SIDIS) [2], where the convolution of the Collins function and the parton transversity distribution function  $h_1$  was measured<sup>1</sup>.

Direct information on the Collins function can be obtained from  $e^+e^-$  annihilation experiments via the study of the semi-inclusive processes  $e^+e^- \rightarrow q\bar{q} \rightarrow \pi\pi X$ , where two charged pions coming from the fragmenting  $q\bar{q}$  pairs ( $q = u, d, s$ ) are detected. In  $e^+e^-$  annihilation, the measurement of the Collins asymmetry can be performed in two reference frames [3], as described in Fig. 1. We refer to them as the thrust reference frame or RF12 (Fig. 1(a)), and the second hadron reference frame or RF0 (Fig. 1(b)).

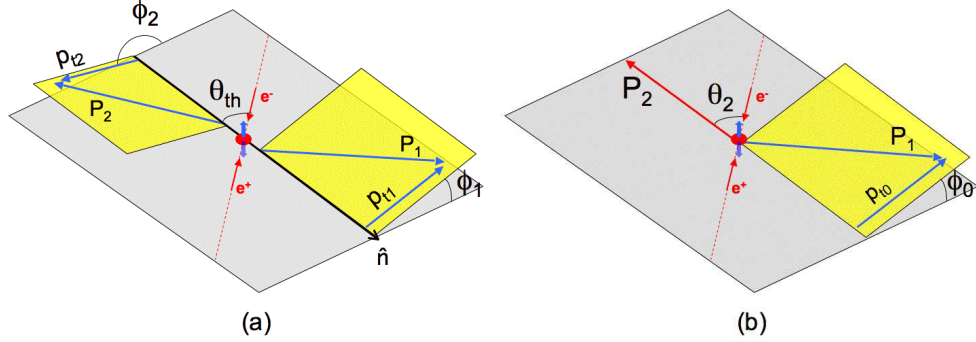


Figure 1: (a) Thrust reference frame or RF12:  $\theta = \theta_{th}$  is the angle between the  $e^+e^-$  collision axis and the thrust axis ( $\hat{n}$ ) [7],  $\phi_{1,2}$  are the azimuthal angles between the scattering plane and the momentum transverse to the thrust axis,  $\mathbf{p}_{t1,t2}$ . Note that the thrust axis provides a good approximation to the  $q\bar{q}$  axis, so that  $\mathbf{p}_{ti} \simeq \mathbf{p}_{\perp i}$  in Eq. (1.1). (b) Second hadron frame or RF0:  $\theta_2$  is the angle between the collision axis and the second hadron momentum;  $\phi_0$  is the azimuthal angle between the plane defined by the beam axis and the second hadron momentum  $\mathbf{P}_2$ , and the first hadron's transverse momentum  $\mathbf{p}_{t0}$ . All tracks are boosted to the  $e^+e^-$  center of mass frame.

The cross section in the  $e^+e^-$  center of mass frame is proportional to

$$\sigma \sim 1 + \sin^2 \theta \cos \phi \frac{H_1^\perp(z_1, \mathbf{p}_{\perp 1}) \bar{H}_1^\perp(z_2, \mathbf{p}_{\perp 2})}{D_1^\perp(z_1, \mathbf{p}_{\perp 1}) \bar{D}_1^\perp(z_2, \mathbf{p}_{\perp 2})}, \quad (1)$$

where  $D_1$  is the well-known unpolarized fragmentation function, the bar denotes the  $\bar{q}$  fragmentation,  $z$  is the pion fractional energy,  $\mathbf{p}_\perp$  is the transverse momentum of the pions with respect to

<sup>1</sup>The transversity parton distribution function  $h_1$  is a poorly known chiral-odd function. The first extraction of  $h_1$  [5] was made possible only after the independent measurement of the Collins effect by the Belle Collaboration [4].

the  $q\bar{q}$  direction,  $\theta$  is the polar angle of the analysis axis, and  $\phi$  is a proper combination of the pion azimuthal angles ( $\phi_1 + \phi_2$  in the RF12 frame, or  $2\phi_0$  in the RF0 frame).

The  $\cos \phi$  modulation in Eq. (1), which multiplies the product (convolution) of two  $H_1^\perp$  in the RF12 (RF0) frame, produces an azimuthal asymmetry around the quark momentum, called the Collins effect or Collins asymmetry. The first independent measurement of the Collins effect was performed by the Belle Collaboration [4], while the first simultaneous extraction of  $H_1^\perp$  and  $h_1$  was obtained by the authors of Ref. [5].

We report the measurement of the Collins asymmetry in  $e^+e^-$  annihilation based on a data sample of  $468 \text{ fb}^{-1}$  collected by the BaBar experiment [6] at center-of-mass energy  $\sqrt{s} \sim 10.6 \text{ GeV}$ . We also perform a new measurement of the asymmetry as a function of the transverse momentum  $p_t$  of pions with respect to the analysis axis.

## Analysis strategy

Assuming the thrust axis [7] to define the  $q\bar{q}$  direction and selecting pions in opposite hemispheres with respect to the thrust axis, we measure the azimuthal angles  $\phi_1$ ,  $\phi_2$ , and  $\phi_0$ . In order to select the two-jet topology, an event thrust value larger than 0.8 is required. Only pions coming from the primary vertex with a fractional energy  $z = 2E_\pi/\sqrt{s}$  in the range between 0.15 to 0.9 are selected. The Collins asymmetries can be accessed by measuring the  $\cos \phi$  modulation of the normalized distributions of the selected pions in the two reference frames. The asymmetries resulting from these distributions are significantly affected by detector acceptance effects, making their measurement unreliable. We therefore create suitable ratios of asymmetries in order to eliminate detector effects and first order radiative effects [3]. We construct different ratios by selecting different combinations of charged pions: pions with same charge (L), opposite charge (U), and the sum of the two samples (C). In this way we also access information on the favored and disfavored fragmentation functions [5], where a favored process describes the fragmentation of a quark of flavor  $q$  into a hadron containing a valence quark of the same flavor. These ratios are fitted with a function linear in  $\cos \phi$ ,

$$\frac{N^U(\phi_i)/\langle N^U \rangle}{N^{L(C)}(\phi_i)/\langle N^{L(C)} \rangle} = B_i + A_i \cdot \cos \phi_i, \quad (2)$$

where  $i = 12$  or  $i = 0$  identifies the reference frame (RF12 or RF0),  $\phi_i = \phi_1 + \phi_2$  or  $\phi_i = 2\phi_0$ ,  $N(\phi_i)$  is the di-pion yield,  $\langle N \rangle$  is the average bin content, and  $A_i$  is the parameter sensitive to the Collins effect. Thanks to the large amount of data, corresponding to about  $10^9$  events, we are able to choose a  $6 \times 6$  ( $z_1, z_2$ ) matrix of intervals, with boundaries  $z_i = 0.15, 0.2, 0.3, 0.4, 0.5, 0.7, \text{ and } 0.9$ , and the following  $p_t$  intervals:  $p_t < 0.25 \text{ GeV}/c$ ,  $0.25 < p_t < 0.5 \text{ GeV}/c$ ,  $0.5 < p_t < 0.75 \text{ GeV}/c$ , and  $p_t > 0.75 \text{ GeV}/c$ .

## Study of systematic effects

A crucial point for the measurement of the Collins asymmetry is the identification of all systematic effects that can influence the azimuthal distributions of the pion pairs. We test the double ratio

method on a Monte Carlo (MC) sample. In addition, we study the influence of particle identification and the uncertainties due to the fit procedure, the possible dependence of detector response on pion charge, the presence of residual polarization of the beams, and other minor effects. When the effects are sizable we correct the measured asymmetries for them and assign appropriate systematic errors. All systematic uncertainties and/or corrections are evaluated for each interval of fractional energy  $z$  and transverse momentum  $p_t$ .

### Dilution of the asymmetries due to the thrust axis

In this analysis we approximate the  $q\bar{q}$  axis by the thrust axis. The distribution of the opening angle between the two axes peaks at about 100 mrad, and this deviation leads a dilution of the measured asymmetry. This effect can be evaluated using a MC sample. However, spin effects, and so the Collins fragmentation function, are not implemented in our JETSET generator [8]. Therefore, we re-weight the angular distributions of the generated tracks (that is before the detector simulation is applied), in order to reproduce the expected asymmetry<sup>2</sup>. The reconstructed azimuthal distributions of the re-weighted sample are then fitted, and the resulting asymmetries are compared to the applied weights. We find that the asymmetries are significantly underestimated in the RF12 frame, and we evaluate the correction factors for each range of  $z$  and  $p_t$  according to the measured value.

### Contribution of background events to the asymmetries

The presence of background processes can introduce azimuthal modulations not related to the Collins effect. The background sources giving a significant contribution after the selection procedure are:  $e^+e^- \rightarrow \tau^+\tau^-$ ,  $e^+e^- \rightarrow c\bar{c}$ , and  $e^+e^- \rightarrow B\bar{B}$ , and we refer to them as  $\tau$ , charm, and bottom backgrounds, respectively. The asymmetry measured ( $A^{meas}$ ) by fitting the double ratio of Eq. (2) includes

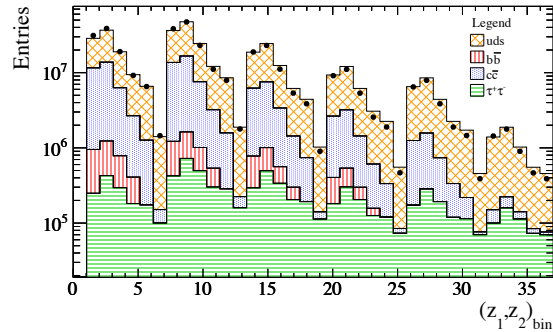


Figure 2: Fraction  $F_i$  of pion pairs due to  $\tau^+\tau^-$ ,  $B\bar{B}$ ,  $c\bar{c}$ , and  $uds$  components estimated using MC simulation as a function of  $6 \times 6$   $(z_1, z_2)$  matrix intervals. The black dots represent the fraction  $F$  in the data sample. The same distribution is obtained for  $f_i$  in the  $D^*$ -enhanced data sample.

also the azimuthal dependence of every physics process contributing to the final sample, and can be

<sup>2</sup> Note that for the generated sample the analysis axis is the true  $q\bar{q}$  axis in the RF12 frame, and is the generated momentum of the second pion in the RF0 frame.

written as:

$$A^{meas} = (1 - \sum_i F_i) \cdot A^{uds} + \sum_i F_i \cdot A^i, \quad (3)$$

where  $F_i$  and  $A^i$  are respectively the asymmetry and the fraction of pion pairs due to the  $i^{th}$  background component, with  $i = \tau$ , charm or bottom. The fraction  $F_{bottom}$  is very low (less than 2%), while  $F_\tau$  is relevant only for very energetic tracks. In addition, we measured  $A_\tau$  in a  $\tau$ -enhanced data sample, and found that the asymmetry is consistent with zero. For these reasons, in Eq. (3), we set  $A_\tau$  and  $A_{bottom}$  equal to zero. The charm contribution is the dominant background, with  $F_{charm} \sim 30\%$  on average; both fragmentation processes and weak decays can introduce an azimuthal modulation. To estimate this contribution we select a charm-enhanced data sample requiring at least one  $D^*$  candidate from the decay  $D^{*\pm} \rightarrow D^0 \pi^\pm$ , with the  $D^0$  candidate reconstructed in one of the following four decay channels:  $D^0 \rightarrow K^- \pi^+$ ,  $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ ,  $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ , and  $D^0 \rightarrow K^- \pi^+ \pi^0$ . Given  $A^{meas}$  in the full data sample and  $A^{D^*}$  in the  $D^*$ -enhanced sample, we can write the following equations:

$$A^{meas} = (1 - F_{charm} - F_\tau - F_{bottom}) \cdot A^{uds} + F_{charm} \cdot A^{charm} \quad (4)$$

$$A^{D^*} = f_{charm} \cdot A^{charm} + (1 - f_{charm} - f_{bottom}) \cdot A^{uds}. \quad (5)$$

Inverting these equations, we extract the real contribution from light quarks ( $A^{uds}$ ) to the Collins asymmetry.

A significant source of systematic error in this procedure can arise from the fractions  $F_i$  ( $f_i$ ) shown in Fig. 2, which are estimated using MC samples. We conservatively assign as errors the observed data-MC differences to the most significant contributions ( $F_{charm}$ ,  $F_\tau$ , and  $f_{charm}$ ), and we propagate them together with the statistical errors through Eqs. (4), (5).

## Preliminary results and conclusion

We study the behavior of the Collins asymmetries in the RF12 and RF0 frames as a function of pion fractional energy  $z$ , pion transverse momentum  $p_t$ , and as a function of the polar angle of the analysis axis. Figure 3 shows the corrected asymmetries in the RF12 frame after subtraction of the background contributions, as an example. The systematic errors are represented by error bands superimposed on the data points. We observe a strong increase of the asymmetry as a function of pion fractional energy  $z$  (Fig. 3(a)), which is in overall good agreement with previous Belle results [4], and theoretical expectations [9]. No previous data from  $e^+e^-$  annihilation are available for the asymmetries as a function of  $p_t$ . This dependence was studied only in the space-like region at low  $|Q^2|$  ( $\sim 2.4$  (GeV/c) $^2$ ) in SIDIS experiments [2], and so can be used to investigate the evolution of the Collins function. Finally, the Collins asymmetries are shown in Fig. 4 as a function of the polar angle of the thrust axis  $\theta_{th}$  in the RF12 frame, or the polar angle of the momentum of the second pion  $\theta_2$  in the RF0 frame. The dotted lines represent the results of the fit of a linear function,  $(p_0 + p_1 \cdot x)$ , to the data points. In the case of RF12 the fitted lines extrapolate rather close to the origin, which is consistent with the expectation. In contrast, the fits clearly favor a non-zero constant parameter for the asymmetries in RF0; this behavior may be explained by the fact that  $\theta_2$  is more weakly correlated to the original  $q\bar{q}$  direction than is the thrust axis. These results are also in good agreement with Belle data.

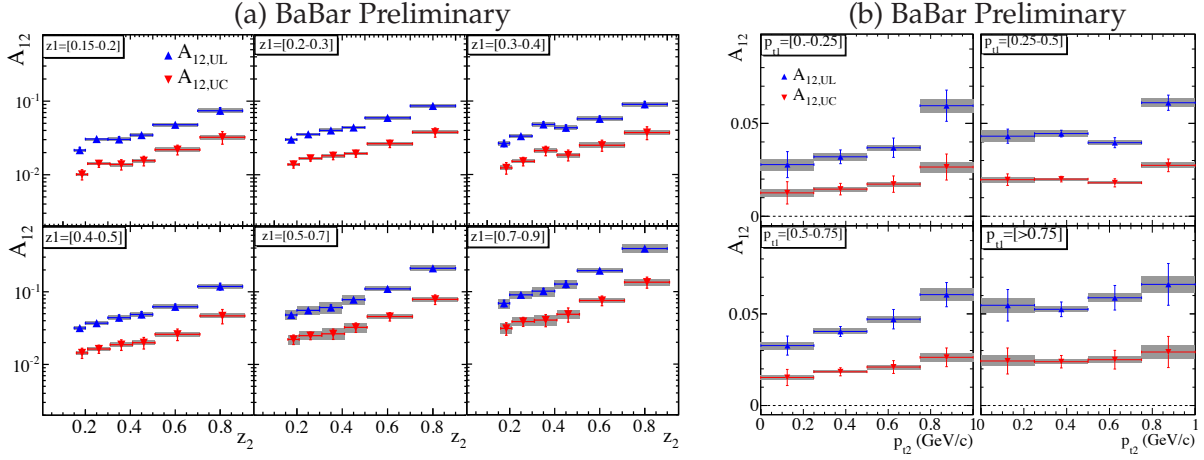


Figure 3: RF12 frame: (a) Collins asymmetries for light quark as a function of  $(z_1, z_2)$ , and (b) as a function of  $(p_{t1}, p_{t2})$  intervals. Blue triangles refer to the ratio U over L (UL), while red triangles to the UC ratio. Statistical and systematic errors are shown as error bars and bands around the points, respectively.

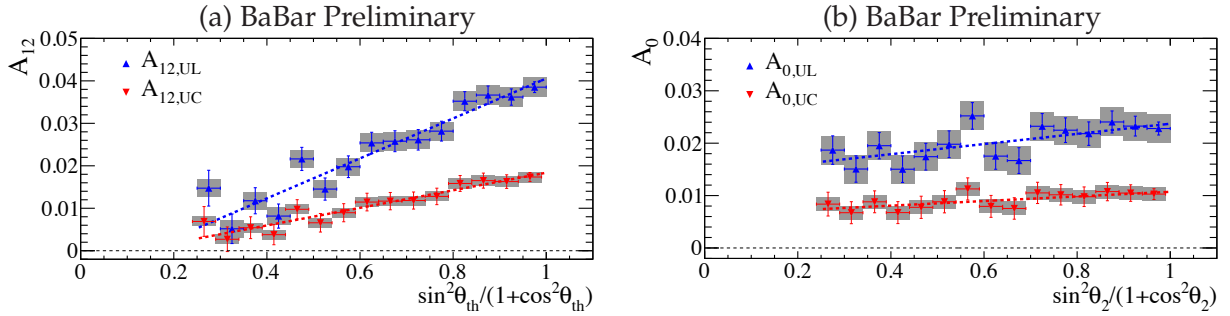


Figure 4: Collins asymmetries *vs.* polar angle  $\theta_{th}$  (a), and  $\theta_2$  (b). Blue and red triangles indicate the UL and UC double ratio, respectively, while systematic uncertainties are shown by the gray bands. The linear fit to  $p_0 + p_1 \cdot x$  is represented by a dotted line for each double ratio.

In summary, we have reported preliminary BaBar results on the Collins asymmetries in the pion system, obtained from a data sample corresponding to an integrated luminosity of  $468 \text{ fb}^{-1}$  collected at a center-of-mass energy near 10.6 GeV. The results shown are in good agreement with the Belle measurements, and with theoretical expectations. In addition, we have extended the analysis by studying the asymmetry for different  $p_t$  intervals. This may help to shed light on the evolution of the Collins fragmentation function. These data, combined with SIDIS and Belle data, can also be valuable for improving global analyses, such as that of Ref. [5].

We thank Ralf Seidl of the Belle Collaboration for useful discussions about the analysis method.

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