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Measurement of Collins asymmetry in inclusive production of pion pairs at BaBar

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Abstract. We present a measurement of the azimuthal asymmetries induced by the Collins effect in inclusive production of pion pairs in the $e^+e^- \to \pi\pi X$ annihilation process, where two charged pion pairs are produced in opposite hemispheres. The data collected by the BABAR detector at the SLAC Linear Accelerator Laboratory allows the determination of the Collins fragmentation function as a function of the pion fractional energies and transverse momenta, as well as the determination of its behavior in a 4-dimensional space. These results can be combined with semi-inclusive deep inelastic scattering data to extract the transversity parton distribution function, which is the least known leading-twist component of the QCD description of the nucleon.

1 Introduction

Transverse spin effects in fragmentation processes were first discussed by Collins in Ref. [1], who introduced the chiral-odd polarized fragmentation function $H_1^\perp$, also called Collins function, used to describe the distribution of the final state hadrons around the momentum direction of the fragmenting quark. Direct evidence of Collins function can be obtained from e^+e^- annihilation experiments by studying the process of semi-inclusive pions production $e^+e^- \to q\bar{q} \to \pi\pi X$, where the two charged pions, coming from the fragmentation of a q and a $\bar{q}$ ($q = u,\ d,\ s$) with opposite transverse spin component, are detected simultaneously. In e^+e^- annihilation, the measurement of the Collins effect can be performed in two different reference frames [2], shown 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)).

The normalized cross section in the e^+e^- center-of-mass (CM) frame is proportional to

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

where D_1 is the well known unpolarized fragmentation function, the bar denotes the $\bar{q}$ fragmentation, $z = 2E_h/\sqrt{s}$ is the pion fractional energy with $\sqrt{s}$ the energy in the CM frame, $\mathbf{p}_\perp$ is the transverse momentum of the pion with respect to the $q\bar{q}$ direction, θ is the polar angle of the analysis axis with respect to the beam axis, and ϕ is a proper combination of the pion azimuthal angles ($\phi_1 + \phi_2$ in RF12, or $2\phi_0$ in RF0).

The $\cos\phi$ term in Eq. (1) produces an azimuthal modulation around the $q\bar{q}$ axis, called Collins effect or Collins asymmetry. The first measurement of the Collins effect in e^+e^- annihilation experiments was performed by the Belle Collaboration [4, 5], which studied in detail the dependence of the asymmetry as a function of the pion fractional energies z and polar angles θ. In this proceedings, we summarize the results of the Collins effect obtained by using the BaBar data [6]. In addition, we also report the behavior of the asymmetry as a function of the transverse momentum p_t of pions calculated with respect to the analysis axis.

2 Analysis strategy

We measure the Collins effect using a sample of data collected with the BaBar detector [7] at the PEP-II asymmetryc-energy e^+e^- collider at the SLAC National Accelerator Laboratory. In this analysis we use a total integrated luminosity of 468 fb^{-1} collected at the CM energy of about 10.6 GeV. In e^+e^- annihilation experiments, the $q\bar{q}$ axis is not accessible, but can be approximated by the thrust axis [3], which is defined as that axis that maximize the longitudinal momentum of the particles in an event. We use the thrust axis to select charged pions in opposite hemispheres, and then we calculate the azimuthal angles ϕ_1 and ϕ_2 in the RF12 frame, and ϕ_0 in the RF0 frame (see Fig. 1).

In order to select the two-jet topology, we select those events with a thrust value $T > 0.8$. The event thrust value ranges between 0.5 to 1; spherical events are characterized by lower value of the thrust, while for jet-like events the thrust value is close to 1. We select only pions coming from the primary vertex with a fractional energy z in the range between 0.15 to 0.9.

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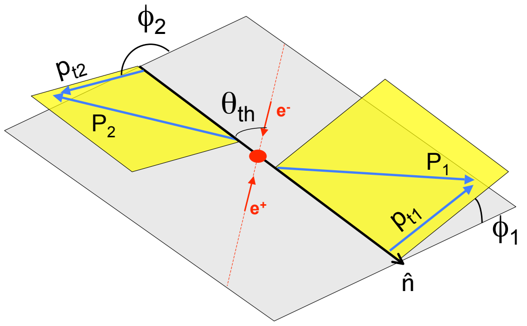


Figure 1. (a) Thrust reference frame or RF12: $\theta = \theta_{th}$ is the angle between the e^+e^- collision axis and the thrust axis ($\hat{n}$) [3], $\phi_{1,2}$ are the azimuthal angles between the scattering plane and the momentum transverse to the thrust axis, $\mathbf{p}_{t1,t2}$. Note that the 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). (b) Second hadron frame or RF0: θ_2 is the angle between the beam axis and the second hadron momentum P_2; ϕ_0 is the azimuthal angle between the plane defined by the beam axis and 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 Collins asymmetry can be accessed by measuring the cos(ϕ) modulation of the normalized distributions of the selected pion pairs, as shown in Eq. (1). However, the resulting asymmetry is largely affected by the detector acceptance effects, making this measure unreliable. To reduce the detector induced azimuthal modulations, we construct suitable ratios of normalized distributions by selecting combinations of pions with same charge (L=like), opposite charge (U=unlike), and the sum of the two samples (C=charged). These double ratios are then fitted with a linear cosine function:

$$\frac{N^U(\phi_i)/\langle N^U\rangle}{N^{L(C)}(\phi_i)/\langle N^{L(C)}\rangle} = B_{i,UL(UC)} + A_{i,UL(UC)} \cdot \cos\phi_i. \quad (2)$$

The A_i parameter in Eq. (2) is sensitive to the Collins effect, $i = 12$ or $i = 0$ identifies the reference frame, $\phi_i = \phi_1 + \phi_2$ or $\phi_1 = 2\phi_0$, $N(\phi_i)$ is the di-pion yield, and $\langle N\rangle$ is the average bin content. The ratios thus constructed can be written as a combination of favored and disfavored fragmentation functions. For example, considering the production of U pion pair ($\pi^\pm\pi^\mp$) form a $u\bar{u}$ pair, the following fragmentation processes can occur: $u \to \pi^+$ and $\bar{u} \to \pi^-$, or $u \to \pi^-$ and $\bar{u} \to \pi^+$. The first two are described by favored fragmentation functions, since the u ($\bar{u}$) is a valence quark of the π^+ (π^-), while the last two are described by disfavored fragmentation functions. Following the same procedure for L and C pion pairs, it is easy to verify that the ratios in Eq. (2) contain different combination of favored and disfavored functions [8].

Thanks to the large amount of data, we are able to choose a 6×6 (z_1, z_2) intervals, with boundaries z_i =0.15, 0.2, 0.3, 0.4, 0.5, 0.7, 0.9, and the following p_t bins: $p_t < 0.25$ GeV/c, $0.25 < p_t < 0.5$ GeV/c, $0.5 < p_t < 0.75$ GeV/c, and $p_t > 0.75$ GeV/c. In addition, we also report the asymmetry measured in the RF12 frame in a four-dimensional space, as a function of $(z_1, z_2, p_{t1}, p_{t2})$.

3 Study of systematic effects and asymmetry corrections

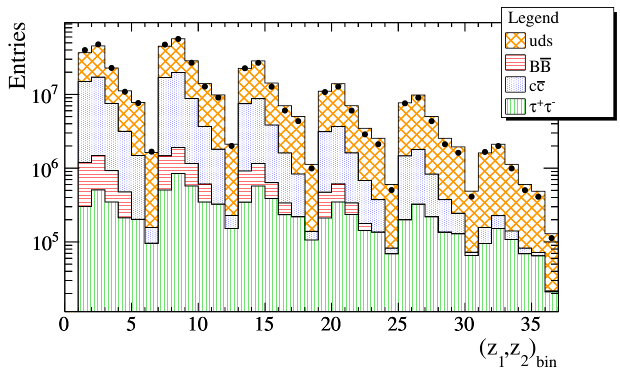


Figure 2. Number of pion pairs measured in the data sample (black points) for each (z_1, z_2) intervals compared with the sum of the contributions due to the charm, bottom, τ, and uds events estimated using MC simulation.

A crucial point for the measurement of the Collins asymmetry is the identification of all the systematic effects that can influence the azimuthal distribution of hadron pairs. We test the double ratio method on a Monte Carlo (MC) sample, we study the influence of the particle identification, the uncertainties due to the fit procedure, and other minor effects.

Using a MC sample, we evaluate the dilution of the asymmetry due to the approximation of the thrust axis as the $q\bar{q}$ direction and due to the tracking reconstruction efficiency. We also evaluate the systematic uncertainty associated to the p_t resolution in the determination of the asymmetry as a function of the pion transverse momenta in the RF12 frame, where p_t is calculated with respect to the thrust axis.

When the systematic effects are sizable we correct the measured asymmetries for them and assign appropriate systematic uncertainties. Unless otherwise stated, all systematic uncertainties and/or corrections are evaluated for each interval of fractional energies z and transverse momenta p_t.

3.1 Background contributions

Background processes, like $e^+e^- \to \tau^+\tau^-$, $e^+e^- \to c\bar{c}$, and $e^+e^- \to \Upsilon(4S) \to B\bar{B}$, can introduce azimuthal modulations not related to the Collins effect, and we refer to them as τ, charm, and bottom backgrounds, respectively. The asymmetry A^{meas} measured by fitting the double ratios of Eq. (2) can also include the azimuthal dependences of the above processes, and can be written as:

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

where F_i and A_i are respectively the fraction of pion pairs and the asymmetry due to the i^{th} background component, and $i = \tau$, charm, or bottom. The asymmetries and the fractions of the background processes are determined using both MC and data samples specific to each process. In particular, the fraction F_{bottom} is very low (less than 2%), while F_τ is relevant only for very energetic tracks. The fractions F_i, evaluated for each interval of fractional energy, are shown in Fig. 2.
In addition, the asymmetries measured in a τ-enhanced data and MC samples are consistent with zero. For these reasons, in Eq. (3), we set $A_\tau = 0$ and $A_{bottom} = 0$. The charm contribution, instead, is the dominant background, since the fraction of pion pairs coming from $e^+e^- \to c\bar{c}$ processes is about 30% on average and both fragmentation and weak decay can introduce azimuthal modulations. To estimate this contribution we select a charm-enhanced data and MC samples requiring at least one D^* candidate from the decay $D^{*\pm} \to D^0\pi^\pm$. Given A^{meas} in the full data sample and A^{D^*} in the charm-enhanced sample, we extract the real contribution from light quarks to the Collins asymmetry (A^{uds}).

4 Results

We report the results of the Collins effect in the RF12 and RF0 frames as a function of pion fractional energy z, pion transverse momentum p_t, and a function of $\sin^2\theta_{th(2)}/(1 + \cos^2\theta_{th(2)})$. Figure 3 shows the corrected asymmetries in the RF12 and RF0 frame, respectively. We observe a strong increase of the asymmetry as a function of z, which is in overall good agreement with previous Belle results [5].

Figure 4 shows the asymmetry behavior as a function of (p_{t1}, p_{t2}) and p_{t0}, respectively. No previous data from e^+e^- annihilation were still published for the asymmetries as a function of p_t, but only preliminary results from Belle Collaboration are available [9]. This dependence was studied only in the space-like region at low $|Q^2|$ (~ 2.4 (GeV/c)^2) [10], and thus can be used to investigate the evolution of the Collins function.

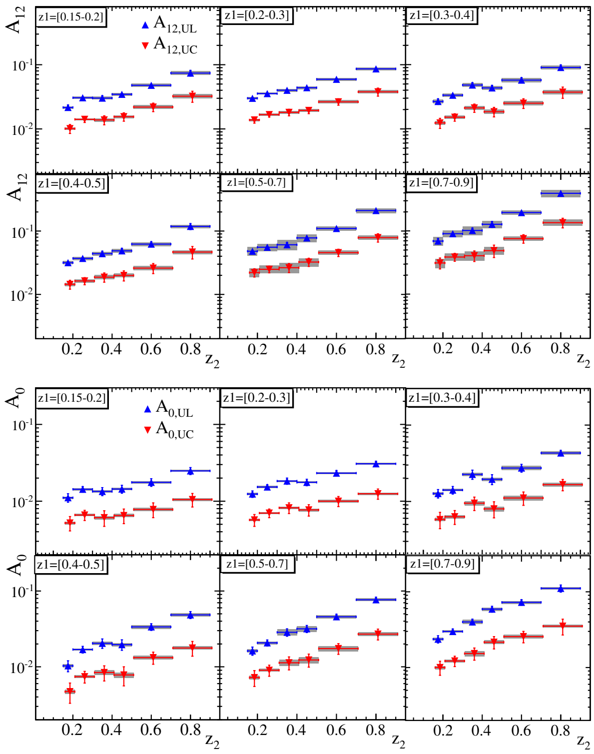
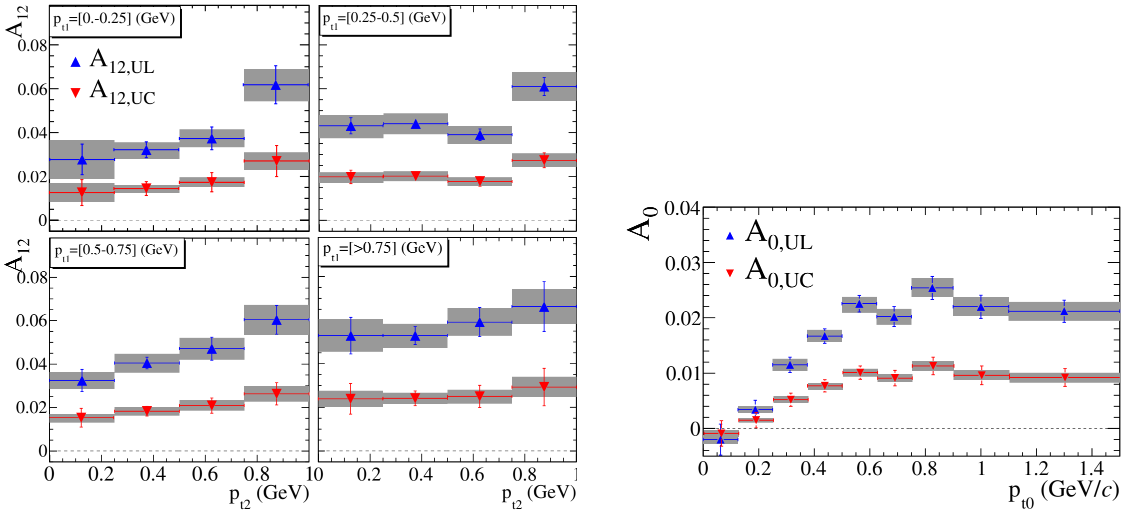


Figure 3. Collins asymmetries for light quarks as a function of (z_1, z_2) in RF12 (a) , and RF0 (b). Blue triangles refer to the ratio U over L (UL), while red triangles to the UC ratio. Statistical and systematic errors are shown as error bars and bands around the points, respectively.

The study of the asymmetry as a function of both z and p_t is an important test to probe the factorization of the Collins fragmentation function and, in general, it provides a powerful tool to access the $z - p_t$ correlations in the Collins effect. The results for the UL double ratio are summarized in Fig. 5.

Finally, Fig. 6 reports the Collins asymmetries as a function of the polar angle of the thrust axis θ_{th} in the RF12 frame, or the polar angle of the momentum of the second pion θ_2 in the RF0 frame. The dotted lines represent the results of the fit with a linear function 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 favor a non-zero constant parameter for the asymmetries in RF0; this behavior may be explained by the fact that θ_2 is more weakly correlated to the original $q\bar{q}$ direction than is the thrust axis.

In summary, we have reported preliminary results on the pion Collins asymmetries [6], extending our analysis to the study of the asymmetry behavior as a function of p_t. This may help to shed light on the evolution of the Collins fragmentation function. These data can also be valuable for improving global analyses, such as of Ref. [11].



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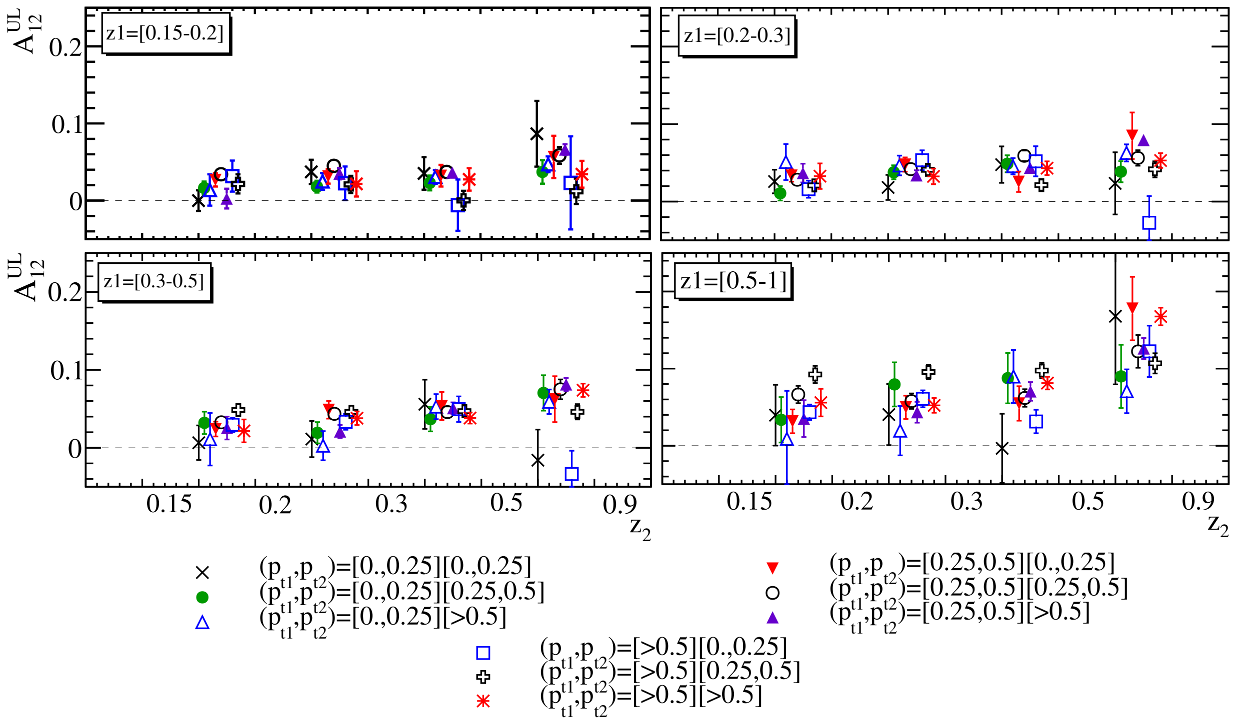

Figure 5. UL double ratio results calculated in the RF12 frame as a suction of $(z_1, z_2, p_{t1}, p_{t2})$. The plot shows the (z_1, z_2) dependence for each (p_{t1}, p_{t2}) intervals, identified by the different markers and colors as reported in the legend. Similar results are also obtained for the UC double ratio.

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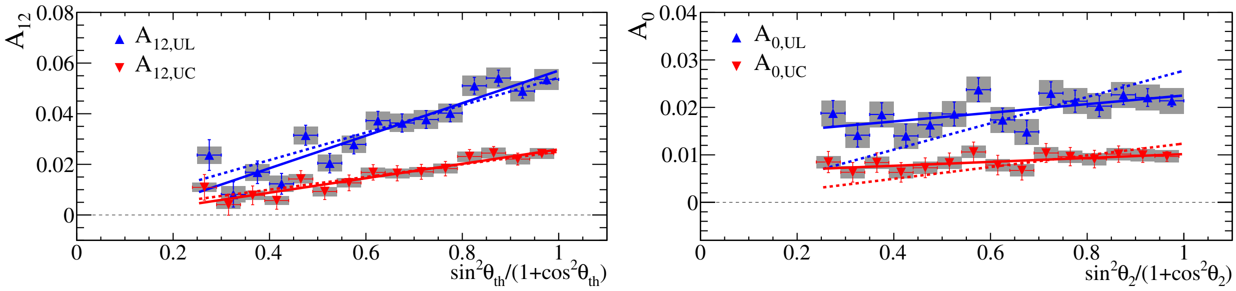

Figure 6. Collins asymmetries *vs*. polar angle θ_{th} (a), and θ_2 (b). Blue and red triangles indicate the UL and UC double ratio, respectively, while systematic uncertainties are shown by the gray bands. The linear fit to $p_0 + p_1 \cdot x$ is represented by a dotted line for each double ratio.

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