Measurement of Collins asymmetries in e^+e^- annihilation at BaBar

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We present a measurement of the azimuthal asymmetries induced by the Collins effect in inclusive production of charged pion pairs, in the $e^+e^- \to \pi\pi X$ annihilation process, where the two pions are produced in opposite hemispheres. The data collected by the BaBar detector allows the determination of the Collins fragmentation function as a function of hadron fractional energies and transverse momenta, and can be combined with semi-inclusive deep inelastic scattering data to extract the transversity distribution function, which is the least known leading-twist component of the QCD description of the partonic structure of the nucleon.

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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, which describes 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], 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)).

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

$$\sigma \propto 1 + \sin^2(\theta)\cos(\phi)\frac{H_1^\perp(z_1, \mathbf{p}_{\perp 1})\overline{H}_1^\perp(z_2, \mathbf{p}_{\perp 2})}{D_1^\perp(z_1, \mathbf{p}_{\perp 1})\overline{D}_1^\perp(z_2, \mathbf{p}_{\perp 2})}, \tag{1.1}$$

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 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).

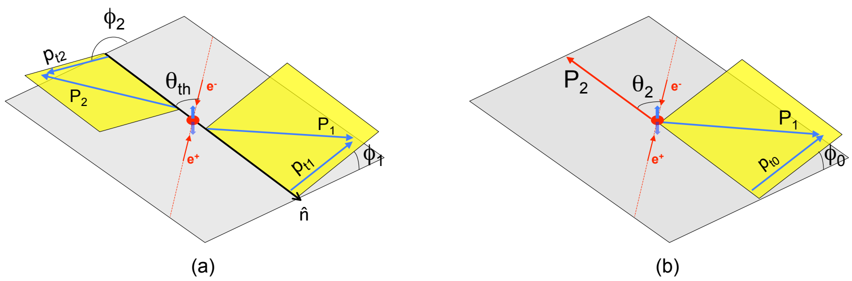

Figure 1: (a) Thrust reference frame or RF12: $\theta = \theta_{th}$ is the angle between the e^+e^- collision axis and the thrust axis ($\hat{n}$) [3], $\phi_{1,2}$ are the azimuthal angles between the scattering plane and the momentum transverse to the thrust axis, $\mathbf{p}_{t1,t2}$. Note that the thrust axis provides a good approximation to the $q\bar{q}$ axis, so that $\mathbf{p}_{ti} \simeq \mathbf{p}_{\perp i}$ in Eq. (1.1). (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 $\cos\phi$ term in Eq. (1.1) 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], which studied in detail the dependence of the asymmetry as a function of the pion fractional energies z and polar angles θ. In this analysis, we measure this effect using the BaBar data. In addition, we study the behavior of the asymmetry as a function of the transverse momentum p_t of pions with respect to the analysis axis.

2. Analysis strategy

The preliminary measurement of Collins asymmetries is performed using a sample of data collected with the BaBar detector [5] at the PEP-II asymmetric-energy e^+e^- collider at SLAC National Accelerator Laboratory. In this analysis, a total integrated luminosity of 468 fb^{-1} collected at the center-of-mass energy of about 10.6 GeV is used. The $q\bar{q}$ axis is not accessible in e^+e^- annihilation experiments, but can be approximated well by the thrust axis, which is defined as that axis that maximize the longitudinal momentum of the particles in an event [3]. We select charged pions in opposite hemispheres with respect to the thrust axis, and we measure the azimuthal angles ϕ_1, ϕ_2, and ϕ_0, as defined in Fig. 1. In order to select the two-jet topology, an event thrust value larger than 0.8 is required [1]. Only pions coming from the primary vertex with a fractional energy z in the range between 0.15 to 0.9 are selected. The Collins asymmetry can be accessed by measuring the $\cos\phi$ modulation of the normalized distributions of the selected pion pairs (Eq. (1.1)). However, the resulting asymmetry is largely affected by detector acceptance effects, making this measure unreliable. To reduce these fake 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), which are fitted with a function linear in $\cos\phi$:

$$\frac{N^U(\phi_i)/<N^U>}{N^{L(C)}(\phi_i)/<N^{L(C)}>} = B_{i,UL(UC)} + A_{i,UL(UC)} \cdot \cos(\phi_i). \tag{2.1}$$

The A_i parameter in Eq. (2.1) is sensitive to the Collins effect, $i = 12$ 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, and $<N>$ is the average bin content. The ratios thus constructed allow to be sensitive to the favored and disfavored fragmentation functions. For example, considering the production of U pion pair ($\pi^\pm\pi^\mp$) from a $u\bar{u}$ pair, the following fragmentation processes can accour: $u \to \pi^+$ and $\bar{u} \to \pi^-$, or $u \to \pi^-$ and $\bar{u} \to \pi^+$. The first two are described by a favored fragmentation function, since the u ($\bar{u}$) is a valence quark of the π^+ (π^-), while $u \to \pi^-$ ($\bar{u} \to \pi^+$) is described by a disfavored function. Following the same procedure for L and C pion pairs, we can easily verify that the ratios in Eq. 2.1 contain different combination of favored and disfavored fragmentation functions [6].

Thanks to the large amount of data, corresponding to about 10^9 events, we are able to choose a 6×6 (z_1, z_2) matrix of intervals, with boundaries $z_i = 0.15, 0.2, 0.3, 0.4, 0.5, 0.7, 0.9$, and the following p_t intervals: $p_t < 0.25$ 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.

3. Study of systematic effects

A crucial point for the measurement of the Collins asymmetries is the identification of all the systematic effects that can influence the azimuthal distributions for pion 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 MC a sample, we evaluate the dilution of the asymmetry due to the approximation of the thrust

[1]The event thrust value ranges between 0.5 to 1. The lower the thrust is, the more spherical is the event. The higher the thrust is, the more jet-like is the event.

axis as the $q\bar{q}$ direction and due to the tracking reconstruction efficiency. When the systematic effects are sizable we correct the measured asymmetries for them and assign appropriate systematic uncertainties. All systematic uncertainties and/or corrections are evaluated for each interval of fractional energies z and transverse momentum 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 modulation 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 ratio of Eq. (2.1) can also include the azimuthal dependence of the above processes, and can be written as:

$$A^{meas} = (1 - \sum_i F_i) \cdot A^{uds} + \sum_i F_i \cdot A^i, \tag{3.1}$$

where F_i and A_i are respectively the fraction of pion pairs and the asymmetry due to the i^{th} background component, with $i = \tau$, charm, or bottom, which are determined using both MC and data samples specific to each process. The fraction F_{bottom} is very low (less than 2%), while F_τ is relevant only for very energetic tracks. In addition, the asymmetries measured in a τ-enhanced data sample is consistent with zero. For these reasons, in Eq. (3.1), we set $A_\tau = A_{bottom} = 0$. The charm contribution, instead, is the dominant background ($F_{charm} \sim 30\%$ on average); both fragmentation and weak decay can introduce azimuthal modulations. To estimate this contribution we select a charm-enhanced data sample 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. Preliminary results and conclusions

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 polar angle of the analysis axis. Figure 2 shows the corrected asymmetries in the RF12 frame, as an example. We observe a strong increase of the asymmetry as a function of z (Fig. 2(a)), which is in overall good agreement with previous Belle results [4].
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 $|Q^2|$ (~ 2.4 (GeV/c)^2) [7], and thus can be used to investigate the evolution of the Collins function.

Finally, the Collins asymmetries are shown in Fig. 3 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 of 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, extending our analysis to the study of the asymmetry behavior as a function of p_t. This may help to shed

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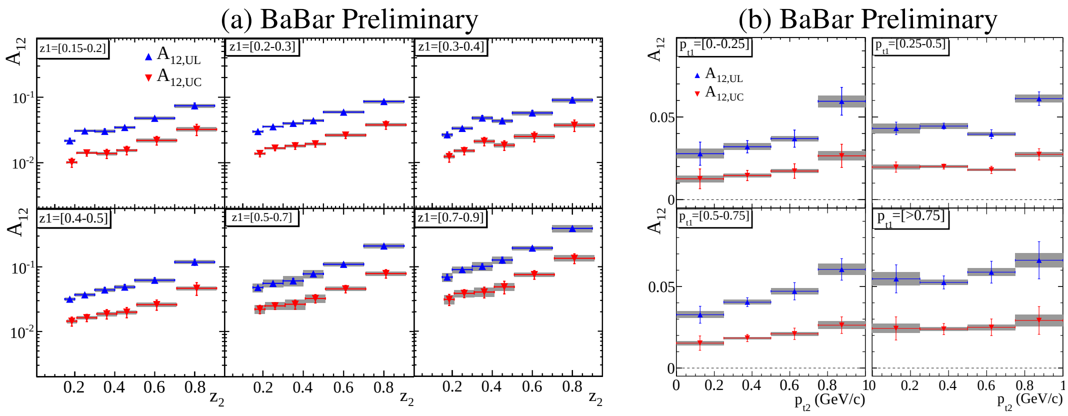

Figure 2: RF12 frame: (a) Collins asymmetries for light quarks as a function of (z_1, z_2) , and (b) as a function of (p_{t1}, p_{t2}) intervals. Blue triangles refer to the ratio U over L (UL), while red triangles to the UC ratio. Statistical and systematic errors are shown as error bars and bands around the points, respectively.

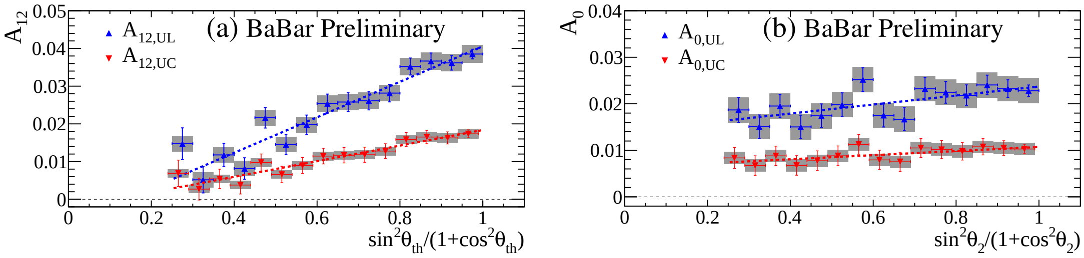

Figure 3: Collins asymmetries *vs.* polar angle θ_{th} (a), and θ_2 (b). Blue and red triangles indicate the UL and UC double ratio, respectively, while systematic uncertainties are shown by the gray bands. The linear fit to $p_0 + p_1 \cdot x$ is represented by a dotted line for each double ratio.

light on the evolution of the Collins fragmentation function. These data can also be valuable for improving global analyses, such as of Ref. [8].

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