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Collins asymmetries in inclusive charged KK and $K\pi$ pairs at BABAR

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Inclusive hadron production cross sections and angular distributions in e^+e^- collisions shed light on fundamental questions of hadronization and fragmentation processes. We present measurements of the so called Collins azimuthal asymmetries in inclusive production of hadron pairs in $e^+e^- \to h_1 h_2 X$ annihilation process, where the two hadrons (either kaons or 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 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 hadrons production $e^+e^- \to q\bar{q} \to h_1h_2X$, where the two charged hadrons, 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)).

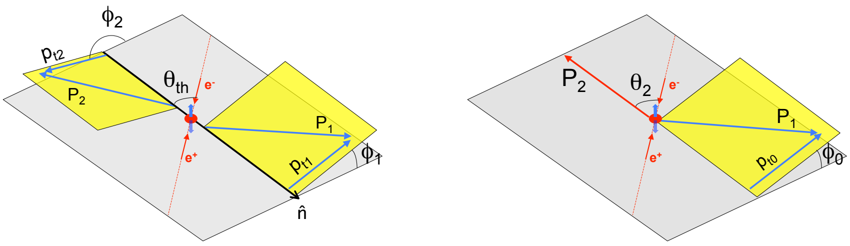

Figure 1: (a) Thrust reference frame or RF12: $\theta = \theta_{th}$ is the angle between the e^+e^- collision axis and the thrust axis ($\hat{n}$) [3], $\phi_{1,2}$ are the azimuthal angles between the plane defined by the beam axis and $\hat{n}$, and the momentum transverse to the thrust axis, $\mathbf{p}_{t1,t2}$. (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 normalized cross section in the e^+e^- center-of-mass (CM) frame for inclusive production of spinless hadrons, like pions and kaons, is proportional to

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

In this equation, D_1 is the well known unpolarized fragmentation function (FF), the bar denotes the anti-quark fragmentation, $z_{1(2)}$ is the hadron fractional energy defined as the ratio of hadron energy over the beam energy, $\mathbf{p}_{\perp 1(2)}$ is the transverse momentum of the hadron with respect to the $q\bar{q}$ direction, $\theta = \theta_{th,2}$ is the polar angle, and $\phi = \phi_1 + \phi_2$, $2\phi_0$ is a proper combination of azimuthal angles, which are defined in Fig. 1. The azimuthal modulation in Eq. (1.1), which corresponds to the $\cos\phi$ term, is called Collins effect or Collins asymmetry.

The first observation of the Collins effect for charged pion pairs in e^+e^- annihilation experiments was performed by Belle Collaboration [4, 5], and confirmed by *BABAR* in Ref [6]. In addition to the studies of the asymmetry dependence as a function of z and polar angle θ, *BABAR* investigated the asymmetry behavior as a function of the pion transverse momenta p_t. More recently, BESIII

Collaboration has shown preliminary results of Collins effect for pion pairs [7], which are obtained using data collected at lower CM energy with respect to the B factory.

We present the first study of the Collins effect for kaons in e^+e^- annihilation. In particular, using the BABAR data, we measure the azimuthal modulation for charged KK and $K\pi$ pairs as a function of the hadron fractional energies [8], which are sensitive to the contribution of the strange quark. In addition, we simultaneously extract the asymmetries for $\pi\pi$ pairs, which are found to be in good agreement with the previous measurements [6].

2. Event and track selection

The preliminary measurement of Collins asymmetries is performed using a sample of data collected with the BaBar detector [9] at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory. In this analysis, a total integrated luminosity of 468 fb^{-1} collected at the CM 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 event thrust axis, which is defined as the axises that maximize the longitudinal momentum of the particles in an event [3]. We select charged hadrons in opposite hemispheres with respect to the thrust axis, and we measure the azimuthal angles ϕ_1, ϕ_2, and ϕ_0. For each event, we require at least charged tracks consistent with the interaction point and with a total visible energy in the laboratory frame $E_{tot} > 11$ GeV, needed to reject $e^+e^- \to \tau^+\tau^-$ and two-photon background, as well as initial state radiation (ISR) events. In order to select the two-jet topology, an event thrust value larger than 0.8 is required [1]. The additional requirement of $|\cos\theta_{th}| < 0.6$ allows to reduce the detector effects by selecting those events with most of the tracks within the detector acceptance region. Only charged tracks with a fractional energy z in the range between 0.15 to 0.9 are selected. To ensure tracks are assigned to the correct hemispheres, we require them to be within a cone of 45° around the thrust axis. A 'tight' identification algorithm is used to identify kaons (pions), which is about 80% (90%) efficient and has misidentification rates below 10% (5%).

The Collins asymmetry can be accessed by measuring the $\cos\phi$ modulation of the normalized distributions of the selected hadron pairs (Eq. (1.1)). However, the resulting asymmetry is largely affected by detector acceptance effects, making this measurement unreliable. To reduce these fake azimuthal modulations, we construct suitable double ratios (DRs) of normalized distributions by selecting combinations of hadrons 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 contain different combination of favored and disfavored

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

FFs[2]. In particular, they contain the strange-favored Collins FF, which cannot be determined if we consider only pion pairs.

3. Simultaneous extraction of KK, $K\pi$, and $\pi\pi$ Collins asymmetries

We simultaneously measure the Collins effect for KK, $K\pi$, and $\pi\pi$ pairs in 4×4 intervals of (z_1,z_2) with the boundaries at $z_{1,2} = 0.15, 0.2, 0.3, 0.5$, and 0.9. We use the MC sample to evaluate the K/π (mis)identification probabilities in each bin of (z_1,z_2) and for the tree samples. We refer to them using the symbol $\zeta(z_1,z_2)^{nm}_{jk}$, where the subscript and apex indicate the generated and reconstructed hadron pair, respectively. For example, the probability, on average, that a true KK pairs is reconstructed as KK pair is $\zeta^{KK}_{KK}\sim 90\%$, while $\zeta^{KK}_{K\pi}\sim 10\%$, and $\zeta^{KK}_{\pi\pi}$ is negligible. Taking into account the contribution of possible background sources, which could introduce fake azimuthal modulation, the measured modulation for KK pairs can be written as:

$$A^{\text{meas}}_{KK} = F^{KK}_{uds}\cdot\left(\sum_{nm}\zeta^{KK}_{nm}\cdot A_{nm}\right)+\sum_i F^{KK}_i\cdot\left(\sum_{nm}\zeta^{(KK)i}_{nm}\cdot A^i_{nm}\right), \tag{3.1}$$

with $nm = KK, K\pi, \pi\pi$, and $i = c\bar{c}, B\overline{B}, \tau^+\tau^-$. Similar expressions hold for $K\pi$ and $\pi\pi$ pairs. From Eq. (3.1) is clear that to extract the Collins asymmetries A_{nm}, we need to know the i-th background asymmetry contributions A^i_{nm} and the fractions $F^{KK(K\pi,\pi\pi)}_{uds,i}$ of KK ($K\pi$, $\pi\pi$) pairs coming from uds and background events. Each fractions F is calculated from the corresponding MC sample; previous studies [6] show that the $B\overline{B}$, and $\tau^+\tau^-$ asymmetries have negligible effects. However, charm contribution cannot be neglected since $F_{c\bar{c}}$ can be as large as 30%. To evaluate the charm asymmetries $A^{c\bar{c}}_{nm}$, we construct representative $c\bar{c}$ data and MC samples by requiring the reconstruction of at least one $D^{*\pm}$ meson from the decay $D^{*\pm}\to D^0\pi^\pm$, with the D^0 reconstructed in four differente decay modes: $K\pi$, $K\pi\pi\pi$, $K^0_s\pi\pi$ and $K\pi\pi^0$. Then, we measure the asymmetries in the charm-enhanced data samples, which can be expressed following the same form as in Eq. (3.1), but using quantities calculated from the corresponding samples. We solve the system of six equations, three for the standard and three for the charm-enhanced ones, and we extract simultaneously the Collins asymmetries $A_{KK}, A_{K\pi}$, and $A_{\pi\pi}$, corrected for the background contributions and K/π (mis)identification.

4. Asymmetry corrections and systematic contributions

The DR method allows to eliminate detector effects, as well as any effect that are independent of the charge of the hadron pairs. Since azimuthal modulations related to the Collins effect are not included in the simulation, we use the MC sample to test the DR method: the $A_{UL(UC)}$ parameters should be consistent with zero. However, the MC distribution for KK pairs shows a small modulation in the full sample of 0.4% and 0.7% in the RF12 and RF0 frames, respectively. Smaller values are obtained for $K\pi$ and $\pi\pi$ pairs. These residual asymmetries result from several effects, in particular emission of ISR and detector effects, and they are subtracted bin by bin. The

[2]A favored process describes the fragmentation, for example, of a u quark into a π^+ since the u is a valence quark for the π^+, while we refer to the $u\to\pi^-$ fragmentation as a disfavored process.

differences between the nominal MC asymmetries and those calculated by changing the detector acceptance region are combined in quadrature with the statistical errors and assigned as systematic uncertainties.

A non perfect reconstruction of the thrust axis could produce strong asymmetry dilutions, which are particularly important in the RF12 frame where ϕ_1 and ϕ_2 are calculated with respect to the thrust axis. We evaluate this effect using the MC sample: we introduce different asymmetries a by reweighting MC event according to the distribution $1+a\cdot\cos\phi_{gen}$, where ϕ_{gen} is the azimuthal angles combinations calculated with respect to the true $q\bar{q}$ axis in RF12, or the generated P_2 in RF0. The asymmetries reconstructed in RF12 are systematically underestimated, while we found a very good agreement between simulated and reconstructed asymmetries in RF0. The correction factors are evaluated for each bin of (z_1, z_2) and are summarized in Fig. 2.

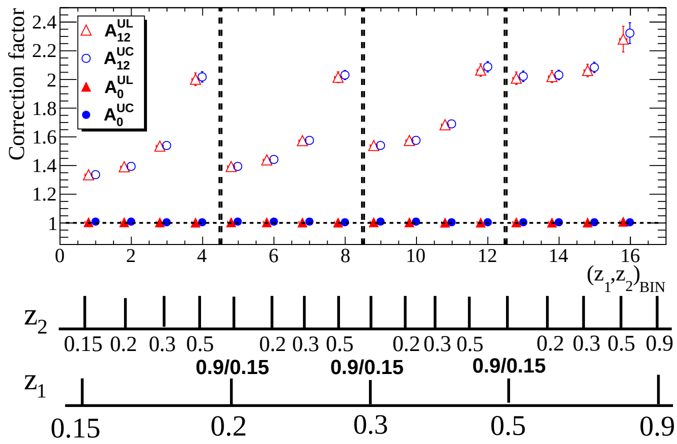

Figure 2: Correction factors for the dilution of the asymmetry due to the difference between the thrust and the $q\bar{q}$ axis. The open markers, triangles and circles, show the corrections applied to the U/L and U/C double ratios in the RF12 frame, respectively. The correction factors for in RF0, full markers, are consistent with unity for both double ratios, and so no corrections are applied. Since we find the same dilutions for KK, $K\pi$, and $\pi\pi$, we apply the same correction factors to the three samples.

Systematic contribution due to particle identification are evaluated using looser and tighter selection criteria. We calculate the (mis)identification probabilities ζ under the new conditions and the corresponding asymmetries. The relative differences for the asymmetries with respect to the standard selection are around 10%, 7%, and 5% for KK, $K\pi$, and $\pi\pi$ pairs, respectively. Systematic effects originated from the E_{tot} cut, the fitting procedure, the analysis method, and others are added in quadrature if their contributions are not negligible.

5. Results

The Collins asymmetries for KK, $K\pi$, and $\pi\pi$ pairs, measured as a function of (z_1, z_2), are shown in Fig. 3. The systematic uncertainties are obtained by adding in quadrature the individual contributions, and are represented by the bands around the data points. We observe a clear increasing of the asymmetries as a function of the hadron energies in both reference frames. The largest effects is observed for KK pairs, even if less precise. At low (z_1, z_2) bins, A^{UL} for KK is consistent

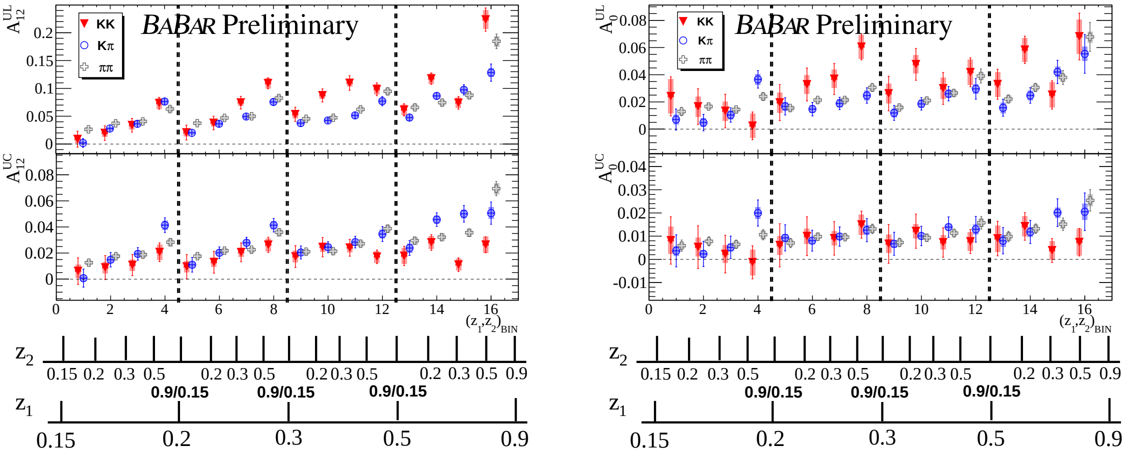

Figure 3: Comparison of U/L (top) and U/C (bottom) Collins asymmetries in RF12 (left) and RF0 (right) for KK, $K\pi$, and $\pi\pi$ pairs. The statistical and systematic uncertainties are represented by the bars and the bands around the points, respectively. The 16 (z_1, z_2) bins are shown on the x-axis: in each interval between the dashed lines, z_1 is chosen in the following ranges: $[0.15, 0.2]$, $[0.2, 0.3]$, $[0.3, 0.5]$, and $[0.5, 0.9]$, while within each interval the points correspond to the four bins in z_2.

with zero, while it is nonzero for $\pi\pi$ pairs; at higher values the KK asymmetries are higher than $K\pi$ and $\pi\pi$ asymmetries. The A^{UC} asymmetry is smaller than A^{UL} in all cases, and the rising behavior as a function of z for KK pairs is less pronounced.

In summary, for the first time in e^+e^- annihilation, we have measured the Collins asymmetries for KK and $K\pi$ pairs as a function of the hadron fractional energies [8]. We simultaneously determine also the Collins effect for $\pi\pi$ pairs, which are consistent with those obtained in previous studies [5, 6]. These results can be combined with SIDIS measurements and can be used in a global analysis to extract information related to the strange quark and to improve the knowledge of the fragmentation process.

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