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Collins asymmetries in inclusive charged KK and $K\pi$ pairs produced in e^+e^- annihilation

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We present measurements of Collins asymmetries in the inclusive process $e^+e^- \to h_1h_2X$, $h_1h_2 = KK$, $K\pi$, $\pi\pi$, at the center-of-mass energy of 10.6 GeV, using a data sample of 468 fb^{-1} collected by the *BABAR* experiment at the PEP-II B factory at SLAC National Accelerator Center. Considering hadrons in opposite thrust hemispheres of hadronic events, we observe clear azimuthal asymmetries in the ratio of unlike sign to like sign, and unlike sign to all charged h_1h_2 pairs, which increase with hadron energies. The $K\pi$ asymmetries are similar to those measured for the $\pi\pi$ pairs, whereas those measured for high-energy KK pairs are, in general, larger.

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The Collins effect [1] relates the transverse spin component of a fragmenting quark to the azimuthal distribution of final state hadrons about its flight direction. The chiral-odd, transverse momentum-dependent Collins fragmentation function (FF) provides a unique probe of QCD, such as factorization and evolution with the energy scale Q^2 [2–5].

Additional interest has been sparked by the observation of azimuthal asymmetries for pions and kaons in semi-inclusive deep inelastic scattering experiments (SIDIS) [6–10]. These are sensitive to the product of a Collins FF and a chiral-odd transversity parton distribution function (PDF), one of the three fundamental PDFs needed to describe the spin content of the nucleon. Although these observations require nonzero Collins FFs, independent direct measurements of one of these chiral-odd functions are needed to determine each of them.

In e^+e^- annihilation, one can measure the product of two Collins FFs, and detailed measurements have been made for pairs of charged pions [11–13]. No measurements are available for $K\pi$ and KK pairs, which are sensitive to different quark-flavor combinations, in particular the contribution of the strange quark. Such measurements could be combined with SIDIS data to simultaneously determine the Collins FFs and transversity PDF for up, down, and strange quarks [14–19].

In this paper, we report the measurement of the Collins effect (or Collins asymmetry) for inclusive production of hadron pairs in the process $e^+e^- \to q\bar{q} \to h_1h_2X$, where $h_{1,2} = K^\pm$ or $\pi^\pm$, q stands for light quarks u or d or s, and X for any combination of additional hadrons.

The probability that a transversely polarized quark ($q^\uparrow$) with momentum direction $\hat{\mathbf{k}}$ and spin $\mathbf{S}_q$ fragments into a hadron h carrying zero intrinsic spin with momentum $\mathbf{P}_h$ is defined in terms of unpolarized D_1^q and Collins $H_1^{\perp q}$ fragmentation functions [20]:

$$D_h^{q^\uparrow}(z, \mathbf{P}_{hT}) = D_1^q(z, P_{hT}^2) + H_1^{\perp q}(z, P_{hT}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{hT}) \cdot \mathbf{S}_q}{zM_h}, \tag{1}$$

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where M_h, $\mathbf{P}_{hT}$, and $z = 2E_h/\sqrt{s}$ are the hadron mass, momentum transverse to $\hat{\mathbf{k}}$, and fractional energy, respectively, with E_h its total energy and $\sqrt{s}$ the e^+e^- center-of-mass (c.m.) energy. The term including $H_1^\perp$ introduces an azimuthal modulation around the direction of the fragmenting quark, called Collins asymmetry.

In $e^+e^- \to q\bar{q}$ events, the q and $\bar{q}$ must be produced back to back in the e^+e^- c.m. frame with their spin aligned. For unpolarized e^+ and e^- beams at *BABAR* energies, the q and $\bar{q}$ spins are polarized along either the e^+ or e^- beam direction, so there is a large transverse component when the angle between the e^+e^- and the $q\bar{q}$ axis is large. The direction is unknown for a given event, but the correlation can be exploited. Experimentally, the q and $\bar{q}$ directions are difficult to measure, but the event thrust axis $\hat{n}$ [21,22] approximates at leading order the $q\bar{q}$ axis, so an azimuthal correlation between two hadrons in opposite thrust hemispheres reflects the product of the two Collins functions.

Figure 1 shows the thrust reference frame (RF12) [23]. If not otherwise specified, all kinematic variables are defined in the e^+e^- c.m. frame. The Collins effect results in a cosine modulation of the azimuthal angle $\phi_{12} = \phi_1 + \phi_2$ of the dihadron yields. Expressing the yield as a function of ϕ_{12} (after the integration over $\mathbf{P}_{hT}$), and dividing by the average bin content, we obtain the normalized rate [11]

$$R_{12}(\phi_{12}) = 1 + \frac{\sin^2\theta_{\mathrm{th}}}{1+\cos^2\theta_{\mathrm{th}}}\cos\phi_{12}\cdot\frac{H_1^{\perp[1]}(z_1)\bar{H}_1^{\perp[1]}(z_2)}{D_1^{[0]}(z_1)\bar{D}_1^{[0]}(z_2)}, \tag{2}$$

where the sum over the involved quark flavors is implied, θ_{th} is defined in Fig. 1, $z_{1(2)}$ is the fractional energy of the first (second) hadron, and the bar denotes the function for the $\bar{q}$. Equation (2) involves only the moments of FF, which are defined as

$$F^{[n]}(z_i) \equiv \int d|\mathbf{k_T}|^2\left[\frac{|\mathbf{k_T}|}{M_i}\right]^n F(z_i, |\mathbf{k_T}|^2), \tag{3}$$

with $n = 0$, 1, and $|\mathbf{k_T}|$ the transverse momentum of the quarks with respect to the hadrons they fragment into, which, in this frame, is related to the measurement of the transverse momenta of the two hadrons with respect to the thrust axis.

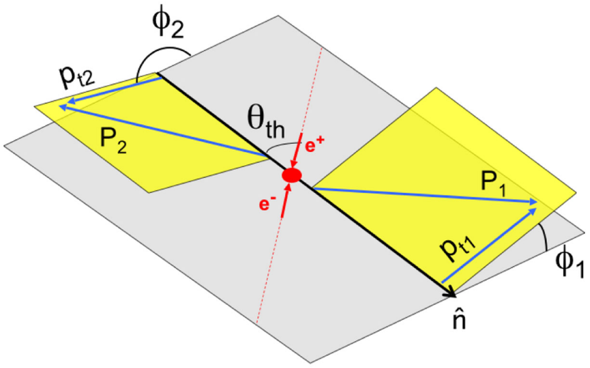

FIG. 1 (color online). Thrust reference frame (RF12). The azimuthal angles ϕ_1 and ϕ_2 are the angles between the scattering plane and the transverse hadron momenta $\mathbf{p}_{t1(t2)}$ around the thrust axis $\hat{\mathbf{n}}$. The polar angle θ_{th} is the angle between $\hat{\mathbf{n}}$ and the beam axis. Note that the difference between $\mathbf{p}_{t1(t2)}$ and $\mathbf{P}_{hT}$ is that the latter is calculated with respect to the $q\bar{q}$ axis.

Despite the simple form of the R_{12} normalized rate, which involves only the product of moments of FFs, the RF12 frame comes with several downsides, among others of having to rely on Monte Carlo (MC) simulations when using the thrust axis as a proxy for the leading-order $q\bar{q}$ axis. An alternative frame is the analogue of the Gottfried-Jackson frame [23,24] which uses the momentum of one hadron as a reference axis, and defines a single angle ϕ_0 between the plane containing the two hadron momenta and the plane defined by the beam and the reference axis. We refer to this frame as RF0 [11,12]. The corresponding normalized yield in the e^+e^- c.m. system is [23]

$$R_0(2\phi_0) = 1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos 2\phi_0 \cdot\frac{\mathcal{F}[(2\hat{\mathbf{h}}\cdot\mathbf{k}_T\hat{\mathbf{h}}\cdot\mathbf{p}_T - \mathbf{k}_T\cdot\mathbf{p}_T)H_1^\perp\bar{H}_1^\perp]}{(M_1M_2)\mathcal{F}[D_1\bar{D}_1]}, \tag{4}$$

where θ_2 is the angle between the hadron used as reference and the beam axis $\hat{\mathbf{h}}$ is the unit vector in the direction of the transverse momentum of the first hadron relative to the axis defined by the second hadron, and $\mathcal{F}$ is used to denote the convolution integral

$$\mathcal{F}[X\bar{X}] \equiv \sum_q e_q^2\int d^2\mathbf{k}_T d^2\mathbf{p}_T\delta^2(\mathbf{p}_T + \mathbf{k}_T - \mathbf{q}_T) \times X^q(z_1, z_1^2\mathbf{k}_T^2)\bar{X}^q(z_2, z_2^2\mathbf{p}_T^2), \tag{5}$$

with $\mathbf{k}_T$, $\mathbf{p}_T$, and $\mathbf{q}_T$ the transverse momentum of the fragmenting quark, antiquark, and virtual photon from e^+e^- annihilation, respectively, in the frame where the two hadrons are collinear, and $X(\bar{X}) \equiv D_1(\bar{D}_1)$ or $H_1^\perp(\bar{H}_1^\perp)$. In this frame, specific assumptions on the $\mathbf{k}_T$ dependence of the involved functions are necessary to explicitly evaluate the convolution integrals.

For this analysis we use a data sample of 468 fb^{-1} [25] collected at the c.m. energy $\sqrt{s} \approx 10.6$ GeV with the *BABAR* detector [26,27] at the SLAC National Accelerator Laboratory. We use tracks reconstructed in the silicon vertex detector and in the drift chamber (DCH) and identified as pions or kaons in the DCH and in the Cherenkov ring imaging detector (DIRC). Detailed MC simulation is used to study detector effects and to estimate contribution from various background sources. Hadronic events are generated using the Jetset[28] package and undergo a full detector simulation based on GEANT4 [29].

We make a tight selection of hadronic events in order to minimize biases due to detector acceptance and hard initial-state photon radiation (ISR), as they can introduce fake azimuthal modulations. Furthermore, final-state gluon ($q\bar{q}g$) radiation also leads to angular asymmetries to be taken into account [23]. Requiring at least three charged tracks consistent with the e^+e^- primary vertex and a total visible energy of the event in the laboratory frame $E_{\mathrm{tot}} > 11$ GeV, we reject $e^+e^- \to \tau^+\tau^-$ and two-photon backgrounds, as well as ISR ($q\bar{q}g$) events with the photon (one jet) along the beam line. About 10% of ISR photons are within our detector acceptance, and we reject events with a photon candidate with energy above 2 GeV. We require an event thrust value $T > 0.8$ to suppress $q\bar{q}g$ and $B\bar{B}$ events, and $|\cos\theta_{\mathrm{th}}| < 0.6$ so that most tracks are within the detector acceptance.

We assign randomly the positive direction of the thrust axis, and divide each event into two hemispheres by the plane perpendicular to it. To ensure tracks are assigned to the correct hemispheres, we require them to be within a 45° angle of the thrust axis and to have $z > 0.15$. A "tight" identification algorithm is used to identify kaons (pions), which is about 80% (90%) efficient and has misidentification rates below 10% (5%). We select those pions and kaons that lie within the DIRC acceptance region with a polar angle in laboratory frame $0.45\ \mathrm{rad} < \theta_{\mathrm{lab}} < 2.46$ rad. To minimize backgrounds, such as $e^+e^- \to \mu^+\mu^-\gamma$ followed by photon conversion, we require $z < 0.9$.

We construct all the possible pairs of selected tracks reconstructed in opposite thrust hemispheres, and we calculate the corresponding azimuthal angles ϕ_1, ϕ_2, and ϕ_0 in the respective reference frames. In this way, we identify three different samples of hadron pairs: KK, $K\pi$, and $\pi\pi$. To reduce low-energy gluon radiation and the contribution due to wrong hemispheres assignment, we require $Q_t < 3.5\ \mathrm{GeV}/c$, where Q_t is the transverse momentum of the virtual photon from e^+e^- annihilation in the frame where the two hadrons are collinear [23].

The analysis is performed in intervals of hadron fractional energies with the following boundaries: 0.15, 0.2, 0.3, 0.5, 0.9, for a total of 16 two-dimensional (z_1, z_2) intervals.

For each of the three samples, we evaluate the normalized yield distributions R_{12} and R_0 for unlike (U), like (L), and any charge combination (C) of hadron pairs as a function of $\phi_1 + \phi_2$ and $2\phi_0$, as shown in the left plot of Fig. 2 for KK pairs, for example. These combinations of charged hadrons contain different contributions of favored and disfavored FFs, where a favored (disfavored) process refers to the production of a hadron for which one (none) of the valence quarks is of the same kind as the fragmenting quark. In particular, by selecting KK pairs, we are able to study the favored contribution $H_s^{\perp\mathrm{fav}}$ of the strange quark, not accessible when considering $\pi\pi$ pairs only.

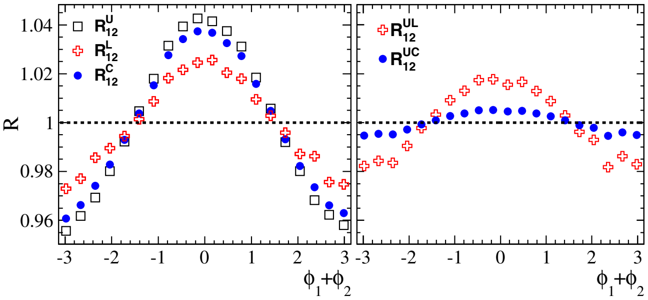

FIG. 2 (color online). Distributions of normalized yields (left plot) for unlike (U), like (L), and any charge combination (C) of KK pairs, and their double ratios (right plot) in RF12.

The normalized distributions can be parametrized with a cosine function: $R_\alpha^i = b_\alpha + a_\alpha^i \cos\beta_\alpha$, where $\alpha = 0,\ 12$ indicates the reference frames, $i = U,\ L,\ C$ the charge combination of hadron pairs, and $\beta_{12(0)} = \phi_{12}(2\phi_0)$.

The R_α^i distributions are strongly affected by instrumental effects. In order to reduce the impact of the detector acceptance, as well as any remaining effect from gluon bremsstrahlung [23], we construct two double ratios (DRs) of normalized distributions, R_α^U/R_α^L and R_α^U/R_α^C. The two ratios give access to the same physical quantities as the independent R_α^i, that is the favored and disfavored FFs, but in different combinations. We report the results for both kinds of DRs, which are strongly correlated since they are obtained by using the same data set. These are shown in the right plot of Fig. 2 for KK pairs in RF12. At first order, the double ratios are still parametrized by a function that is linear in the cosine of the corresponding combination of azimuthal angles:

$$R_\alpha^{ij} = \frac{R_\alpha^i}{R_\alpha^j} \simeq B_\alpha^{ij} + A_\alpha^{ij} \cdot \cos\beta_\alpha, \tag{6}$$

with B and A free parameters, and $i,\ j = U,\ L,\ C$. The constant term B must be consistent with unity, while A contains the information about the favored and disfavored Collins FFs.

We fit the binned R_α^{ij} distributions independently for KK, $K\pi$, and $\pi\pi$ hadron pairs. Using the MC sample, we evaluate the K/π (mis)identification probabilities for the 16 (z_1, z_2) intervals in each of the three samples. For example, the probability f_{KK}^{KK} that a true KK pair is reconstructed as KK pair is about 90% on average, slightly decreasing at higher momenta, while the probability $f_{K\pi}^{KK}$ that a true $K\pi$ pair is identified as KK is about 10%, and $f_{\pi\pi}^{KK}$ is negligible.

The presence of background processes could introduce azimuthal modulations not related to the Collins effect, and modifies the measured asymmetry as follows:

$$
\begin{aligned}
A_{KK}^{\mathrm{meas}} = F_{uds}^{KK} \cdot \left(\sum_{nm} f_{nm}^{KK} \cdot A_{nm} \right) \\
+ \sum_{i} F_{i}^{KK} \left(\sum_{nm} f_{nm}^{(KK)i} \cdot A_{nm}^{i} \right), \qquad (7)
\end{aligned}
$$

with $nm = KK$, $K\pi$, $\pi\pi$, and $i = c\bar{c}$, $B\bar{B}$, $\tau^+\tau^-$. In Eq. (7), A_{nm} are the true Collins asymmetries produced from the fragmentation of light quarks in the three samples, A_{nm}^{i} is the ith background asymmetry contribution, and $F_{uds(i)}^{KK}$ are the fractions of reconstructed kaon pairs coming from uds and background events, calculated from the respective MC samples. By construction, $\sum_i F_i + F_{uds} = 1$. A similar expression holds for $K\pi$ and $\pi\pi$ samples.

Previous studies [11] show that $e^+e^- \to B\bar{B}$ and $\tau^+\tau^-$ events have negligible A_{nm}^{i}, $F_{B\bar{B}} < 2\%$, and $F_{\tau^+\tau^-}$ significantly different from zero only for the $\pi\pi$ sample at high z values. Since $F_{c\bar{c}}$ can be as large as 30%, and $A^{c\bar{c}}$ are unknown, we determine $A_{nm}^{c\bar{c}}$ in Eq. (7) from samples enhanced in $c\bar{c}$ 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 candidate reconstructed in the following four Cabibbo-favored decay modes: $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$, $K_s^0\pi^+\pi^-$, and $K^-\pi^+\pi^0$. These modes are assumed to provide a representative sample of $\pi\pi$, $K\pi$, and KK pairs to be used in the correction, an assumption that is strengthened by the observation that the background asymmetries for those modes were found to be consistent. We solve the system of equations for A_{KK}^{meas}, $A_{K\pi}^{\mathrm{meas}}$, $A_{\pi\pi}^{\mathrm{meas}}$, for the standard and charm-enhanced samples, and we extract simultaneously the Collins asymmetries A_{KK}, $A_{K\pi}$, and $A_{\pi\pi}$, corrected for the contributions of the background and K/π (mis) identification. The dominant uncertainties related to this procedure come from the limited statistics of the D^*-enhanced sample and from the fractions F_i. The uncertainties on the fractions are evaluated by data-MC comparison and amount to a few percent. All these uncertainties are therefore included in the statistical error of the asymmetries extracted from the system of Eq. (7).

We test the DR method on the MC sample. Spin effects are not simulated in MC, and so the DR distributions should be uniform. However, when fitting the distributions for reconstructed KK pairs with Eq. (6), we measure a cosine term in the full sample of 0.004 ± 0.001 and 0.007 ± 0.001 in the RF12 and RF0 frames, respectively, indicating a bias. Smaller values are obtained for $K\pi$ and $\pi\pi$ pairs [30]. Studies performed on the MC samples, both at generation level and after full simulation, demonstrate that the main source of this bias is due to the emission of ISR, which boosts the hadronic system and distorts the angular distribution of the final state particles, resulting in azimuthal modulations not related to the Collins effect. This effect is more pronounced for KK pairs due to the lower multiplicity with respect to the other two combinations of hadrons. Assuming the bias, which is everywhere smaller than the asymmetries measured in the data sample in each bin, is additive, we subtract it from the background-corrected asymmetry.

Using the uds MC sample, or light quark $e^+e^- \to q\bar{q}$ MC events, we study the difference between measured and true azimuthal asymmetries. The asymmetry is introduced into the simulation by reweighting the events according to the distribution $1 \pm a \cdot \cos\phi_{\alpha}^{\mathrm{gen}}$, where we use different values of a ranging from 0 to 8% with positive (negative) sign for U (L and C) hadron pairs, and $\phi_{\alpha}^{\mathrm{gen}}$ are the azimuthal angles combinations calculated with respect to the true $q\bar{q}$ axis in RF12, or the generated hadron momentum in RF0. The reconstructed asymmetries in RF12 are systematically underestimated for the three samples of hadron pairs, as expected since we use the thrust axis instead of the $q\bar{q}$ axis, while they are consistent with the simulated ones in RF0, where only particle identification and tracking reconstruction effects could introduce possible dilution. Since we measure the same dilution for KK, $K\pi$, and $\pi\pi$ samples, the asymmetry is corrected by rescaling A_{KK}, $A_{K\pi}$, and $A_{\pi\pi}$ using the same correction factor, which ranges from 1.3 to 2.3 increasing with z, as shown in Fig. 3. No corrections are needed for the asymmetries measured in RF0. The uncertainties on the correction factors are assigned as systematic contributions.

All systematic effects, if not otherwise specified, are evaluated for each bin of z. The main contribution comes from the MC bias. We compare the bias results from the nominal selection, with those obtained by requiring different cuts on E_{tot}, and/or by changing the detector acceptance region for the hadrons. The largest variation of the bias is combined in quadrature with the MC statistical error and

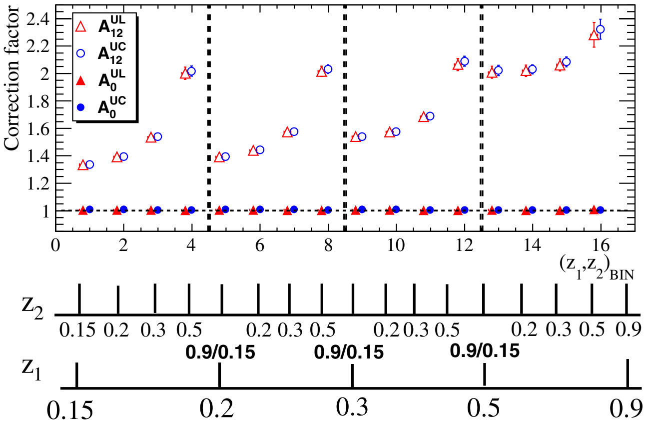

FIG. 3 (color online). Correction factors for the dilution of the asymmetry due to the difference between the thrust and the $q\bar{q}$ axis. The open (full) markers, triangles and circles, refer to the U/L and U/C double ratios in the RF12 (RF0) frame, respectively. The 16 (z_1, z_2) bins are shown 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.

taken as systematic uncertainty. The effects due to the particle identification are evaluated using tighter and looser selection criteria. The largest deviations with respect to the nominal selection are taken as systematic uncertainties: the average relative uncertainties are around 10%, 7%, and 5% for the KK, $K\pi$, and $\pi\pi$ pairs. Fitting the azimuthal distributions using different bin sizes, we determine relative systematic uncertainties, which are not larger than 5%, 1.9%, and 1% for the three samples. The systematic uncertainty due to the E_{tot} cut is obtained by comparing the measured asymmetries with those obtained with the looser selection $E_{\mathrm{tot}} > 10$ GeV. The average systematic contribution is around 10% for the three samples in both reference frames. We use different fitting functions with additional higher harmonic terms. No significant changes in the value of the cosine moments with respect to the standard fits are found. As a cross-check of the double ratio method we fit the difference of R^i distributions, and we compare the two results. The difference between the two procedures is negligible for $K\pi$ and $\pi\pi$ pairs, while it reaches 1% and 3% for kaon pairs in RF12 and RF0, respectively. All the other systematic contributions are negligible [11].

The Collins asymmetries measured for the 16 two-dimensional (z_1, z_2) bins, for reconstructed KK, $K\pi$, and $\pi\pi$ hadron pairs, are shown in Fig. 4 for RF12 and RF0, and are summarized in tables reported in the Supplemental Material [30]. The asymmetries are corrected for the background contributions and K/π contamination following Eq. (7), the MC bias is subtracted, and the corrections due to the dilution effects are applied. The total systematic uncertainties are obtained by adding in quadrature the individual contributions, and are represented by the bands around the data points.

An increasing asymmetry with increasing hadron energies is visible for the U/L double ratio in both reference frames. The largest effects, but with less precision, are observed for KK pairs, for which A_{12}^{UL} is consistent with zero at low z, and reaches 22% in the last z bin, while somewhat smaller values are seen for $\pi\pi$ and $K\pi$ pairs. In particular, at low (z_1, z_2) bins A^{UL} for $\pi\pi$ pairs is nonzero, in agreement with the behavior observed in [11]. The small differences between the two data sets are due to the different kinematic region selected after the cut on $\cos\theta_{th}$. The A^{UC} asymmetry is smaller than A^{UL} in all cases, and, for the KK pairs, the rise of the asymmetry with the hadron energies is not evident. We also note that the asymmetries for the KK pairs are larger than the others when the U/L ratio is considered, while they are at the same level, or lower, when they are extracted from the U/C ratio.

In summary, we have studied for the first time in e^+e^- annihilation the Collins asymmetry for inclusive production of KK and $K\pi$ pairs as a function of (z_1, z_2) in two distinct reference frames. We measure the azimuthal modulation of the double ratios U/L and U/C, which are sensitive to the favored and disfavored Collins FFs for light quarks. We simultaneously extract also the Collins asymmetries for $\pi\pi$ pairs, which are found to be in agreement with those obtained in previous studies [11,13]. The results reported in this paper and those obtained from SIDIS experiments can be used in a global analysis to extract the favored contribution of the strange quark, and to improve the knowledge on the u and d fragmentation processes [14–16].

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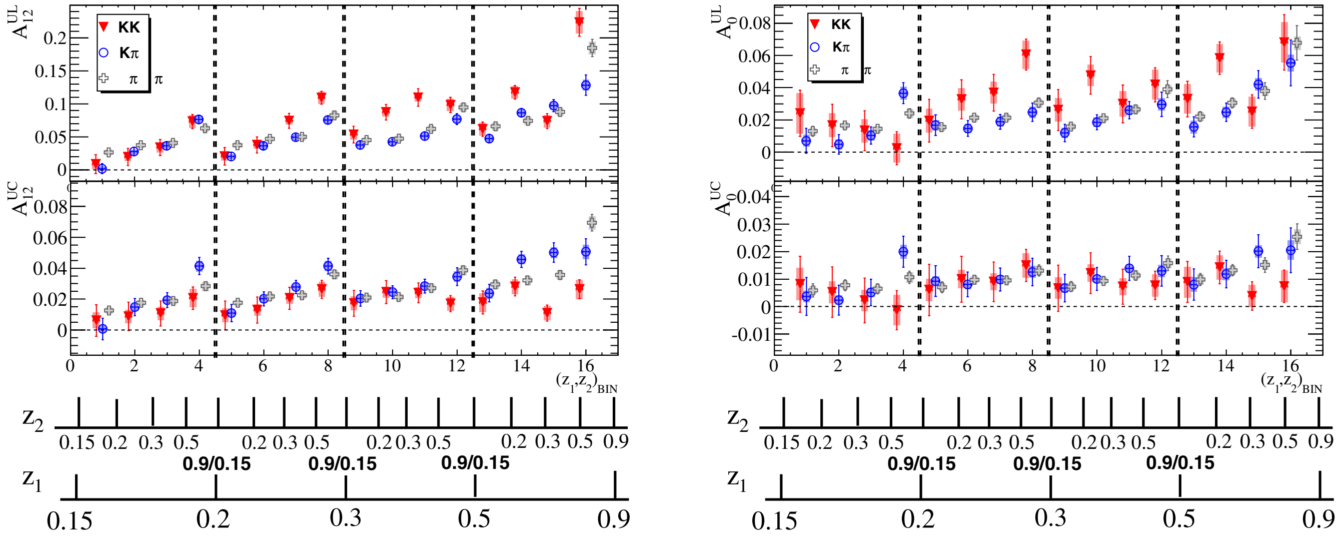

FIG. 4 (color online). Comparison of U/L (top) and U/C (bottom) Collins asymmetries in RF12 (left) and RF0 (right) for KK, $K\pi$, and $\pi\pi$ pairs. The statistical and systematic uncertainties are represented by the bars and the bands around the points, respectively. The 16 (z_1, z_2) bins are shown 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.

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