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Measurements of the Collins asymmetries for kaons and pions in e^+e^- annihilations at BABAR

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Abstract. New measurements of the Collins asymmetries were performed by BABAR exploiting inclusive $e^+e^- \rightarrow h_1h_2X$ annihilations (with $h_{1,2} = \pi$ and/or K) mainly at the energy of the $\Upsilon(4S)$, which corresponds to a squared transferred momentum $Q^2 \sim 110$ GeV$^2/c^4$. For the first time asymmetries following strange quarks fragmentation could be derived as a function of the fractional energy carried out by inclusively emitted hadron pairs.

1 Introduction

The inclusive cross section of e^+e^- annihilation in hadrons, produced following the hadronization of a $q\overline{q}$ pair, may be parameterized via phenomenologial fragmentation functions (FF's), which are universal, non-perturbative and have to be determined from experimental data. According to the factorization theorem this cross section may be written as:

$$\frac{d\sigma}{dz}(e^+e^- \rightarrow hX) = \sum_q \sigma(e^+e^- \rightarrow q\overline{q}) \cdot [D_q^h(z, Q^2) + D_{\overline{q}}^h(z, Q^2)] \qquad (1)$$

where $z = 2E_h/\sqrt{s}$ is the fractional energy carried by the emitted hadron h, $D_{q(\overline{q})}$ is the FF for q ($\overline{q}$), Q is the transferred momentum, σ is the cross section for the $e^+e^- \rightarrow q\overline{q}$ elementary process and the sum runs over the quark flavors allowed by the center-of-mass energy of the reaction.

The description of the hadronization stage can largely benefit from the information related to the parton spins and transverse degrees of freedom of the parton motion. The Collins FF's were introduced [1] to describe this contribution, and are related to the probability that a transverse polarized quark will fragment into a spinless hadron. The fragmentation function of a polarized quark $q^\uparrow$ hadronizing into spinless hadron, $D_1^{q\uparrow}$, reported in eq. (2), is given by the sum of the D_1^q unpolarized contribution, and a polarized term. The latter is proportional to a spin-orbit coupling, expressed through a mixed product of the quark spin $\mathbf{s}_q$, its direction $\mathbf{k}_q$ and the transverse momentum $\mathbf{P}_\perp$ of the emitted hadron, times the polarized fragmentation function $H_1^{\perp q}$:

$$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, \mathbf{P}_\perp; s_q) + \frac{P_\perp}{zM_h} H_1^{\perp q} \mathbf{s_q} \cdot (\mathbf{k_q} \times \mathbf{P}_\perp). \qquad (2)$$

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This function is known as Collins FF and basically describes the strength of the cosine dependence of the polarized part of $D_1^{q\uparrow}$. The so-called *Collins effect* stands in the azimuthal modulation of the production cross section of spinless hadrons in a e^+e^- annihilation process, and can be measured experimentally from the azimuthal distribution of hadron pairs emitted in opposite hemispheres in the reaction center of mass. Differences in the amplitude of this modulation for hadron pairs of different charges and flavors determine the presence of measurable asymmetries.

First measurements of the Collins effect were performed in Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments, like HERMES [2] and COMPASS [3], with unpolarized lepton beams off polarized targets. In this case the direction of the quark spin is known, but the cross section of the hadron production depends on the convolution of the Collins FF and another chiral-odd probability distribution function, known as transversity. Therefore, one of the two needs to be determined independently. This can be done resorting to e^+e^- annihilations in $q\bar{q}$, with the inclusive production of hadron pairs (h_1, h_2): $e^+e^- \to q\bar{q} \to h_1^{\pm} h_2^{\mp(\pm)} X$. In this case, the reaction cross section is proportional, through a cosine term expressing an azimuthal modulation with respect to the quark spins, to the product of the Collins FF's for the fragmenting q and $\bar{q}$. The e^+e^- annihilation reaction is a golden channel for the derivation of Collins FF's since no hadron is present in the initial state; moreover, even if the directions of the q and $\bar{q}$ spins are unknown, they have to be parallel and this introduces a correlation in the emission of hadron pairs. The first measurements of the Collins asymmetries, as a function of z of each inclusively produced hadron, were performed by Belle [4] for pion pairs, at $Q^2 \sim 110$ GeV$^2/c^4$. Later, BABAR confirmed these results, at the same energy, with additional information on the dependence of the Collins asymmetries also on fractional pion momenta [6]. New results on inclusive pion pairs production have been recently obtained also by BESIII [5], and are in agreement with the previous findings (even though data were taken at a lower Q^2, ~ 13 GeV$^2/c^4$).

A new analysis performed by BABAR extends also to strange quarks the investigation of spin related effects in the hadronization process [7], thanks to the inclusion of kaons in the set of identified pairs. This is the first attempt to infer Collins FF's for the fragmentation of strange quarks both to strange and non-strange mesons, known respectively as "favored" and "disfavored" FF's, depending on the preservation of the parent quark flavor in the hadronization process. According to the flavor of the measured particles and their charge, different combinations of Collins favored and disfavored FF's can occur and therefore be measured.

In the following a summary of the results obtained in the latest BABAR analysis will be reported. In this analysis, 468 fb^{-1} of e^+e^- annihilations, taken at the $\Upsilon(4S)$ resonance mass and 40 MeV below, were used. More details are available in Ref. [7].

2 Method and analysis overview

The extraction of Collins asymmetries is based on the determination of the yields of particle pairs as a function of the azimuthal angles of their emission. These angles, and consequently the cross section for the particles production, can be defined in different reference systems. The fundamental step is to identify an axis that, together with the e^+e^- direction in the reaction rest frame, forms the plane with respect to which the directions of the emitted hadrons and azimuthal angles can be defined. A natural choice for this axis is the $q\bar{q}$ emission direction, but since this is unknown, approximations have to be applied. The most used reference systems are the "Thrust Reference Frame" (RF12), in which this preferential direction is taken by the thrust axis, and the transverse momenta of both the hadrons are being measured, and the "Second Hadron Reference Frame" (RF0), in which the axis used to define the reaction plane coincides with the direction of one of the two emitted hadrons [6]. In both the cases the cross sections exhibit an azimuthal cosine modulation; however, the dependence on Collins FF's of the parent q and $\overline{q}$ is different. Even if from the experimental point of view in RF0 the particle distributions can be obtained in a more direct way, the theoretical interpretation of the results is much more difficult as compared to RF12 due to the more complicated entanglement of the involved FF's.

The analysis strategy for the extraction of the Collins effect is based on the simultaneous measurements of hadron pair yields ($\pi\pi$, πK and KK in whichever charge combination) and their fit through $(b + a\cos\phi)$ functions. Care must be taken as the modulation due to a genuine Collins effect is to be distinguished by similar effects due to apparatus acceptance and other asymmetry sources. The evaluation of asymmetries is performed in both the mentioned reference systems, which deliver complementary results (even if strongly correlated, as obtained from the same experimental sample).

Events are selected with a minimum of three hadrons, belonging to two jets emitted in opposite hemispheres in the reaction center of mass and well contained within the apparatus acceptance. The requirement of a total measured energy larger than 11 GeV allows to reject most of the 2τ and 2γ background, and photon/gluon radiation events with the γ or the jets emitted almost collinear to the beam line. *Ah hoc* cuts are moreover applied on the total energy and the event thrust in order to remove most of the leptonic events (Bhabha, $\mu^+\mu^-$, $\mu^+\mu^-\gamma$).

The particle identification efficiency, performed through the energy loss and Cherenkov radiation information from, respectively, the BABAR drift chamber and DIRC [8], is required to be as large as ~80% for kaons and ~90% for pions, with a minimal misidentification of electrons and muons (smaller than 2 and 4%, respectively). Pion/kaon pairs misidentification probabilities must also be known with good accuracy, as they must be used to weight the function fitting the modulated yield distributions.

2.1 Raw asymmetries

All the distributions of the normalized yields of $\pi\pi$, πK, KK pairs of the same (L), opposite (U) or all charge combinations (C) exhibit a cosine dependence as a function of the azimuthal angle, in both the considered reference frames. The difference in the amplitude of the distributions for particles of different charge is the signal of the Collins effect. As an example, the normalized yield distributions for KK pairs of the same (L, open crosses), opposite (U, open squares) and all charges (C, full points) are reported, for RF12, in Fig. 1 (left).

Asymmetries not dependent on the charge are generated by other sources, which have to be identified and isolated to extract the information on the pure Collins effect. The use of (uds) simulated data samples helps identifying these sources: visible modulations in simulated data where no Collins effect has been injected are mainly due to the apparatus acceptance, and to the emission of gluon radiation from the final state (FSR) and/or photon radiation from the initial state (ISR). In order to eliminate these contributions, which occur for all charge combinations, a common procedure consists on performing the ratios of the normalized raw yields, known as *double ratios* method.

2.2 Double ratios

The ratio of unlike-to-like (A^{UL}) and unlike-to-all sign hadron pairs (A^{UC}) carry the same information of raw yield distributions and still present a cosine modulation, also after the factorization of acceptance effects. Residual modulations not due to the Collins effect and mainly related to ISR emission can still be observed in the double ratios of simulated distributions, and they can be retained as systematic errors. The double ratio (DR) distribution for KK pairs in RF12, is reported in Fig. 1 (right): the UL ratio is represented by open crosses, the UC ratio by full points.

The DR distributions for each of the three particle combinations ($j = \pi\pi$, πK, KK), may again be fitted by a $(B + A\cos\phi)$ function, in which the A coefficients contain the Collins and residual radiative

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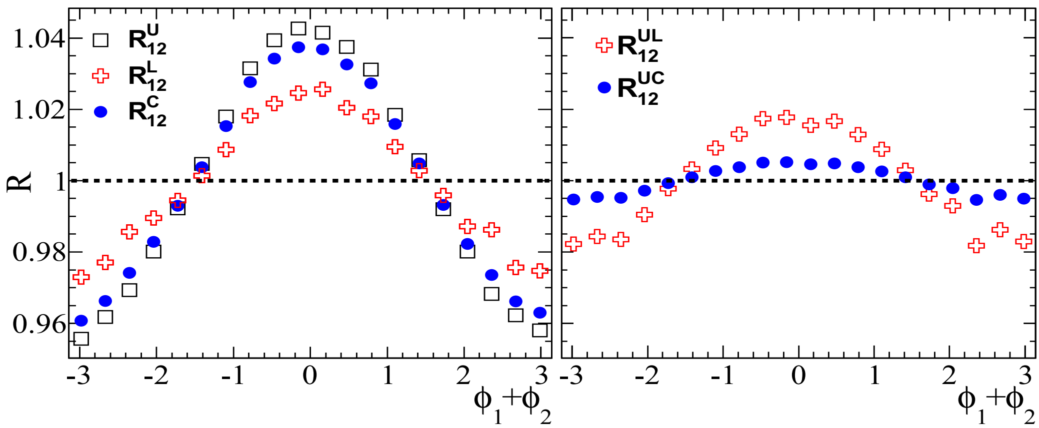

Figure 1. Distribution of normalized yields (left) of KK pairs for unlike (U), like (L) and all charge combinations (C), and their double ratios in RF12 (right).

effects. On the other hand, they may also be expressed as a sum of a pure (uds) Collins-related part, and a non-Collins contribution carried by background channels:

$$A_j^{meas} = F_{uds}^j A_j^{Collins} + \sum_i F_i^j A_j^i. \tag{3}$$

In this equation, the F^j coefficients express the fraction of j-type pairs coming from (uds) (signal) or from the i-th background channel, constrained by the requirement $F_{uds} + \sum_i F_i = 1$, and may be determined by means of proper Monte Carlo simulations. Eq. (3) is a system of linear equations whose unknowns are the three Collins asymmetries $A_j^{Collins}$ (corrected by the proper pair misidentification efficiency mentioned above) and the A_j^i contributions to the DR asymmetry given by the background channels.

Dedicated Monte Carlo simulations show that just a few background reactions really bring an important contribution to the yields. While the selection cuts are effective enough to reduce the contribution by $B\overline{B}$ and $\tau^+\tau^-$ events, which are, respectively, mainly important at low and high z (therefore $A^{B\overline{B}} = 0$ and $A^{\tau^+\tau^-} = 0$ may be set), the contribution from the charm source is sizeable and larger than 30%, so it cannot be neglected. A charm-enhanced control data sample, in which the presence of at least one D^* per event is required, is used to perform an analogous evaluation of the asymmetry, and provides additional equations to the linear system. In this way eq. (3) can be solved to extract the relevant (uds) Collins asymmetries for the $\pi\pi$, $K\pi$ and KK channels.

2.3 Corrections and systematic effects

The obtained results need to be corrected for a number of effects, and an accurate estimation of systematic errors is needed as well. One of the most important corrections mainly affects the evaluations performed in RF12, and is related to the approximation of taking the thrust axis in place of the unknown $q\overline{q}$ direction. By means of Monte Carlo simulations one sees that the opening angle between the two axes has a distribution with the maximum around 100 mrad. By means of the same simula-

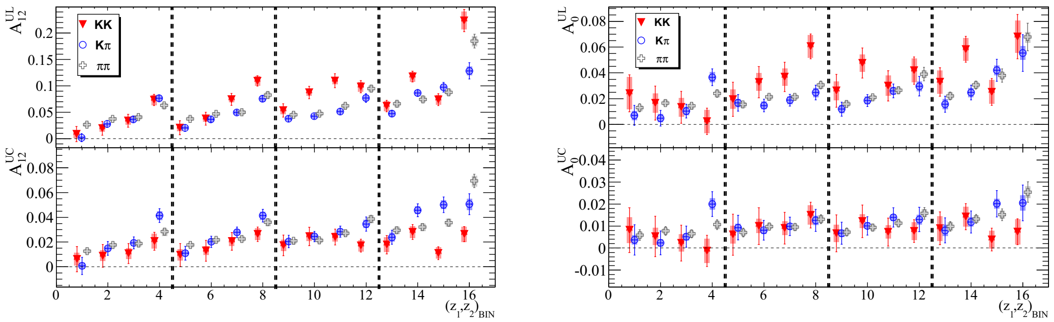

Figure 2. Collins asymmetries measured by *BABAR* [7] for KK (triangles), πK (circles) and $\pi\pi$ (crosses) pairs, in RF12 (left) and RF0 (right). Vertical dashed lines defines subplots for ranges of z_1: [0.15,0.2], [0.2,0.3], [0.3,0.5], [0.5,0.9]. In each subplot z_2 varies in the same ranges. The bars and bands report the statistical and systematic uncertainty, respectively.

tions a dilution factor can determined, to be applied to the measured asymmetries; it depends on the fractional energy and increases with it.

Several sources of systematic uncertainties have to be taken into account; they act differently in the two considered reference systems and depend sizeably on the fractional energies of both the emitted hadrons. The larger effects are played by uncertainties in the Monte Carlo simulations of background channels, in the particle identification efficiencies and in the fit procedures, and by fluctuations due to different choices for the selection cuts. Minor effects are added by beam polarization, fluctuations of asymmetries in different data taking periods, second order couplings between the Collins asymmetries and detector acceptance effects, and higher order harmonics neglected in the fits.

The absolute value of the systematic uncertainty is at most at the 2% level, mostly relevant in higher z bins; the maximum relative total systematic uncertainty is about 10%.

3 Results

The experimental results are expressed in terms of double ratio asymmetries for unlike-to-like (A^{UL}) and unlike-to-all sign particles (A^{UC}), in four bins of fractional energy z for both the hadrons, and in both RF12 and RF0. The measured asymmetries for KK, $K\pi$ and $\pi\pi$ pairs, corrected for the above mentioned effects, are reported in Fig. 2, for RF12 (left) and RF0 (right). The total systematic uncertainties are depicted in the figure as bands.

Some traits may be singled out in the trends of the measured asymmetries, common to both reference systems:

- most of the asymmetries are significantly different from zero;
- the asymmetries show a similar magnitude for all channels;
- all A^{UL} asymmetries increase with z; the same is approximately valid for A^{UC} except for the KK channel, for which the rising trend is less remarkable;
- A^{UC} is always smaller than A^{UL};
- the asymmetries for the KK pairs are almost consistent with zero at low z;
- A^{UL} for KK and $K\pi$ pairs is larger than A^{UL} for $\pi\pi$ pairs especially at large z values; this observation is important as directly related to the magnitude of the favored Collins FF for the strange quark.

The results obtained in the two reference systems, even if correlated, are complementary as referring to different combinations of the Collins FF's. Global fits based on each of them are expected to deliver consistent outcomes.

4 Conclusions

The new results for $\pi\pi$ pairs have been checked for consistency with the previous $\pi\pi$ results published by *BABAR* [6]. After a proper rescaling through a factor depending on the polar angle, needed since the two sets of results are referred to two different kinematic regions, such consistency emerges clearly, which fosters more confidence on the reliability of the novel results involving strangeness.

The new measurements deliver important information to the present knowledge of strange quark fragmentation, since this is the first time they are provided for KK and $K\pi$ pairs. Therefore, they are valuable inputs for global fits, which include SIDIS data and are aimed to the simultaneous extraction of both the Collins FF and the transversity PDF. First global fits were performed on the results from pion pairs [9] and are currently being updated using the new experimental findings. The trend found for asymmetries of strange hadron pairs are in agreement with the existing theoretical expectations [10]. New results on this subject are awaited from Belle and the coming Belle-II experiment.

References

[1] J.C. Collins, Nucl. Phys. **B396**, 161 (1993);
J.C. Collins and D.E. Soper, Nucl. Phys. **B193**, 381 (1981)
[2] HERMES Collaboration, A. Airapetian *et al.*, Phys. Lett. **B693** (2010), 11
[3] COMPASS Collaboration, M. Alekseev *et al.*, Phys. Rev. Lett. **B692**, 240 (2010)
[4] Belle Collaboration, R. Seidl *et al.*, Phys. Rev. **D78**, 032011 (2008)
[5] BESIII Collaboration, M. Ablikin *et al.*, ArXiv:1507.06824 (2015) [hep-ex]
[6] *BABAR* Collaboration, J.P. Lees *et al.*, Phys. Rev. **D90**, 052003 (2014)
[7] *BABAR* Collaboration, B. Aubert *et al.*, ArXiv:1506.05864 (2015) [hep-ex], accepted for publication in Phys. Rev. **D**
[8] *BABAR* Collaboration, B. Aubert *et al.*, Nucl. Instr. Meth. **A729**, 615 (2013)
[9] A. Bacchetta *et al.*, Phys. Lett. **B659**, 234 (2007);
M. Anselmino *et al.*, Phys. Rev. **D75**, 054032 (2007);
M. Anselmino *et al.*, Phys. Rev. **D87**, 094019 (2013)
[10] D. Boer, Nucl. Phys. **B306**, 23 (2009)