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Kaon Collins Fragmentation Function Access at Belle

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Fragmentation functions (FFs) describe the formation of final state particles from a partonic initial state and are directly related to the intriguing QCD phenomenon of confinement. Precise knowledge of these functions is a key ingredient in accessing quantities such as the nucleon spin structure in semi-inclusive deep inelastic scattering and proton-proton collisions. However, fragmentation functions can currently not be determined from Quantum Chromodynamics first principles and have to be extracted from experimental data. The Belle experiment at KEK, Japan, provides a large data sample for high precision measurements of unpolarized and polarized fragmentation functions. Here, the preliminary results involving kaons for the Collins FF, that describes the correlation between the transverse polarization of the fragmenting quark and the outgoing direction of the produced hadron, are presented.

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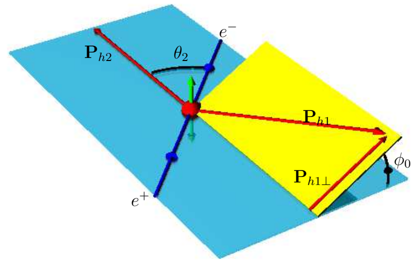

Figure 1: Definition of the azimuthal ϕ_0 angle between the plane defined by the e^+e^- direction and hadron 2 momentum (in blue) and the hadron 1 production plane (in yellow).

1. Introduction

Fragmentation is the QCD process for which partons hadronize to colorless hadrons. Being a non-perturbative process, it is not possible to define it from first QCD principles, and it is generally parametrized in a number of fragmentation functions. Fragmentation functions are not only interesting as they shed light on parton hadronization and confinment, but are also needed for a complete description of the internal structure of the proton, QCD fundamental state. Indeed, proton structure is mainly accessed in semi-inclusive deep inelastic scattering or in proton-proton reactions. In both cases, the parton distribution functions, describing the non-perturbative distribution of partons in the proton, come in combination with fragmentation functions. Thus, the knowledge of fragmentation functions is a necessary input for a clean extraction of parton distributions. The cleanest way to access fragmentation functions is via e^+e^- annihilation into $q\bar{q}$ that fragment into hadrons, as for this reaction fragmentation is the only non-perturbative object in the cross section. A special set of fragmentation functions, the Collins functions ($H_1^\perp(z)$, with z the fractional energy of the hadron with respect to the fragmenting parton energy), are used to described the hadronization mechanism by which the final state hadron is generated with a transverse momentum (with respect to the $q\bar{q}$ axis) correlated with the transverse spin of the fragmenting quark. In semi-inclusive deep inelastic scattering and proton-proton reactions the Collins fragmentation function can be exploited to access the transverse spin structure of the proton, as it comes in combination with the transversity parton distribution function. If we consider the reaction

$$e^+e^- \to q\bar{q} \to h_1 h_2 X, \tag{1.1}$$

where h_1 is the hadron produced by the quark in one hemisphere and the h_2 the hadron produced by the anti-quark in the other hemisphere, then the cross-section is proportional to convolutions of two Collins fragmentation functions (one for h_1, one for h_2) [1]:

$$\sigma \propto \left(1 + \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\cos(2\phi_0)\frac{\mathscr{F}\left[(2\hat{\mathbf{h}}\cdot\mathbf{k_{T1}}\hat{\mathbf{h}}\cdot\mathbf{k_{T2}} - \mathbf{k_{T1}}\cdot\mathbf{k_{T2}})H_1^\perp(z_1)\bar{H}_1^\perp(z_2)\right]}{\mathscr{F}\left[D_1^\perp(z_1)\bar{D}_1^\perp(z_2)\right]}\right), \tag{1.2}$$

where the $D_1^\perp(z_i)$ represent the standard spin-averaged fragmentation functions, and ϕ_0 is the azimuthal angle of the first hadron with respect to the second hadron, as shown in figure 1. Here θ_2 is the polar angle of the second hadron with respect to the e^+e^- axis, and $\mathscr{F}$ represents a convolution integral over the partons transverse momenta k_{T1}, k_{T2} with respect to the $q\bar{q}$ axis of two generic functions $X\bar{X}$:

$$\mathscr{F}[X\bar{X}] \equiv \sum_{q,\bar{q}} \int d^2\mathbf{k_{T1}} d^2\mathbf{k_{T2}}\, \delta^2(\mathbf{k_{T1}} + \mathbf{k_{T2}} - \mathbf{q_T}) X^q(z_1, \mathbf{k_{T1}}) \bar{X}^{\bar{q}}(z_2, \mathbf{k_{T2}}), \tag{1.3}$$

where $X\bar{X}$ can be $H_1^\perp \bar{H}_1^\perp$ or $D_1^\perp \bar{D}_1^\perp$ of equation 1.2. Above, $\hat{\mathbf{h}}$ is the normalized vector $P_{h_1\perp}/|P_{h_1\perp}|$, with $P_{h_1\perp}$ the first hadron transverse momentum with respect to the second hadron (see figure 1), and q_T is transverse momentum of the virtual photon with respect to one of the hadron in the frame in which the two hadrons are back to back

As shown in equation 1.2, to access the term related to the Collins functions we can measure the amplitudes of a $\cos 2\phi_0$ azimuthal modulation of the two-hadrons production cross-section. Previously Belle has published non-zero asymmetries of this modulations for pairs of pions [2], confirming the existence of a non-zero Collins mechanism for pions.

In this report we present the first preliminary Collins amplitudes involving charged kaons, where h_1 and h_2 are πK or KK, and they are compared to the $\pi\pi$ pairs.

2. Belle experiment

The high statistics collected by the Belle experiment [3] at the KEKB e^+e^- asymmetric collider [4] provides an optimal data sample for precise fragmentation measurements.

Belle is a large solid-angle magnetic spectrometer consisting of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel Cherenkov counters (ACC), a time of flight detector (TOF), and an electromagnetic calorimeter (ECL), all located in a superconducting solenoid magnet (1.5 T). A K^0-Muon detector (KLM) consisting of a sandwich of resistive plate chambers is located around the solenoid.

Belle collected both data on the Y(4S) resonance energy ($\sqrt{s} = 10.58$ GeV) and in the continuum region ($\sqrt{s} = 10.52$ GeV). After assuring the two data sample yielded compatible results, both data samples have been included in this analysis, providing a total luminosity of about 790 fb^{-1}.

3. Accessing the Collins amplitudes for $\pi\pi$, πK and KK

To correct for the fake azimuthal modulations generated by acceptance effects and for gluon radiation modulation, which are charge-independent, the Collins amplitudes are measured from the ratio between unlike-sign and like-sign hadron pairs.

In the limit of small $\cos 2\phi_0$ amplitudes for both the unlike-sign and like-sign pairs, the double ratio of unlike-sign over like-sign pairs is proportional to $B_0(1 + A_0 \cos(2\phi_0))$, where the amplitudes A_0 are to first order linear combinations involving different hadron pairs h_1h_2 of the second term in equation 1.2 (without the cosine).

The cross-sections for like- and unlike-sign hadron pairs are proportional to different combination of Collins functions; for instance, in case the two hadrons are both pions, like-sign pion cross-section is related to the sum of convolutions of a favored and an unfavored Collins FF, where favored and unfavored refers to the fact that the fragmenting quark is or is not a valence quark in

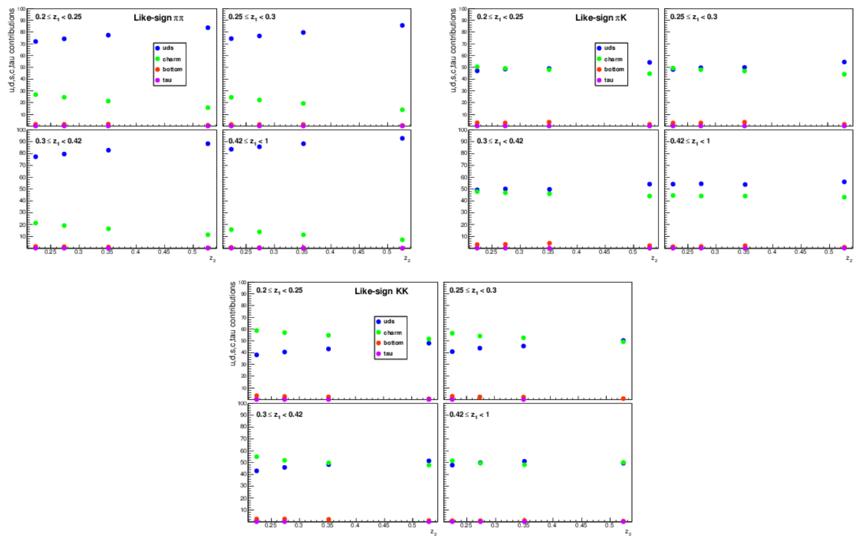

Figure 2: Relative contributions for the uds, charm, bottom and tau reaction-type to the event sample for every bin in z_1, z_2 bins for like-sign $\pi\pi$ (top left), πK (top right) and KK (bottom). Each panel represents a bin in z_1, the z value for the first hadron (from top left to bottom right), and each point in a panel represents a z_2 bin, the z value for the second hadron. Unlike-sign pairs show only slightly different contributions.

the final hadron. This combinations of Collins functions is reflected finally in the amplitudes of the double ratios.

The yields for $\pi\pi$, πK and KK pairs are binned in z and $P_{h\perp}$, according to the table 1. In addition, to check if the amplitudes behave according to equation 1.2 with respect to θ_2, a binning in $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$ is also considered in table 1. To reduce fake asymmetries related to acceptance and

z	0.2	0.25	0.3	0.42	1			
$P_{h\perp}$	0	0.13	0.3	0.5	3			
$\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$	0.45	0.5	0.6	0.7	0.8	0.9	0.97	1

Table 1: Binning ranges used for the asymmetries extraction.

gluon radiation the following cuts were applied:
- To limit gluon radiation: $q_T < 2.5$ GeV;
- To avoid detector edge effects $|T_z| < 0.6$
- To avoid spherically-shaped events, where the definition of the hamispheres belonging to the partons would be difficult: |T>0.8|.

Above, T_z is the z-component of the Thrust axis, a proxy for the $q\bar{q}$ axis, evaluated as the axis $\hat{t}$ that maximize the value of $T = \max|\frac{\sum_{i,N}\hat{t}\cdot P_i}{\sum_{i,N} P_i}|$, where the sum includes all the particles N with momentum P_i generated in the event.

The Collins mechanism strength is expected to have inverse proportionality with respect to the fragmenting-quark mass, therefore we would like to focus on the light-mass quarks u, d and s. Other contributions possibly present in the data sample are evaluated with a Monte Carlo simulation and shown in figure 2, which reports the relative contributions for the uds, charm, bottom and tau reaction-type to the event sample for every z_1, z_2 bins.

As expected, uds and charm provide the major contributions to the event sample, while bottom and tau contributions are generally $< 1\%$ and barely visible in the plots. For the pion-pion case the charm is only about 20%, but for pion-kaon and kaon-kaon though, the charm contribution reaches 50%. In the published pion-pion asymmetries, where charm contribution is small, a dedicated study with a charm-enhanced sample showed that the charm contribution could be considered just as a dilution and was corrected out. Here though, where the data samples including kaons have contributions from charm sometimes higher than 50%, this type of correction might bias the results. Therefore, at this preliminary stage of this analysis we have decided not to correct for charm dilution and to present the results together with the charm relative contribution.

Before evaluating the double ratios, the hadron yields have been corrected for possible particle misidentification with a 2-dimensional (momentum, polar angle) unfolding procedure. The Belle particle identification detectors and algorithm (pid) does an incredible job in identifying pions and kaons: for identified tracks we know the pid with an efficiency $\gtrsim 90\%$ for pions and $\gtrsim 85\%$ for kaons. Nonetheless, this means that we still possibly misidentify pions (kaons) 10% (15%) of the time. To correct for such pid inefficiencies and misidentifications PID probability matrices have been defined, that provide the probability for a track to be correctly identified/misidentified from the Belle PID algorithm [5]. Such matrices have been extracted by studying the decay of particles whose decay product species can be determined just from kinematic considerations: $D^*, J/\Psi, \Lambda$. For example in the decay of the D^*: $D^* \to \pi + D^0 \to \pi + (K\pi)$ the 2 pions have same sign, so it is straightforward to infer which tracks are pions and which is the kaon, and to study how the Belle PID identify those tracks, and consequently extract a correction factor.

4. Collins asymmetries for $\pi\pi$, πK and KK

Figure 3 shows the preliminary asymmetries versus the z_1, z_2 binning extracted from the double ratios for unlike- over like-sign hadron pairs: each panel represents a bin in z_1, the z value for the first hadron (from top left to bottom right), and each point in a panel is the asymmetry binned in the z_2, the z value for the second hadron. As shown in the mentioned figure $\pi\pi$ and KK present similar non-zero positive A_0 amplitudes, which increase with z, while πK are consistent with zero. On the left of figure 4 are shown the same amplitudes but versus p_{T0}, the p_T of hadron 1 with respect to hadron 2, where we can see that, as expected for the Collins mechanism, the non-zero asymmetries increase versus the transverse momentum, and also the πK asymmetries seem to gain a non-zero value at high p_{T0}.

On the right panel of figure 4 the asymmetries are shown versus $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$. As seen in equation 1.2 , the A_0 asymmetries are expected to have a linear trend versus $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$ and they are also expected to go to zero when θ_2 is going to zero. The results of a fit of the asymmetries with a

Hadron pair	p_0	p_1	χ^2
$\pi\pi$	0.008 ± 0.006	0.008 ± 0.007	$0.25/5$
πK	0.007 ± 0.007	-0.005 ± 0.009	$1.22/5$
KK	-0.015 ± 0.005	0.035 ± 0.008	$6.04/5$

Table 2: Parameters obtained from the fit of the asymmetries with the functional form $p_0 + p_1 \frac{\sin^2\theta_2}{1+\cos^2\theta_2}$.

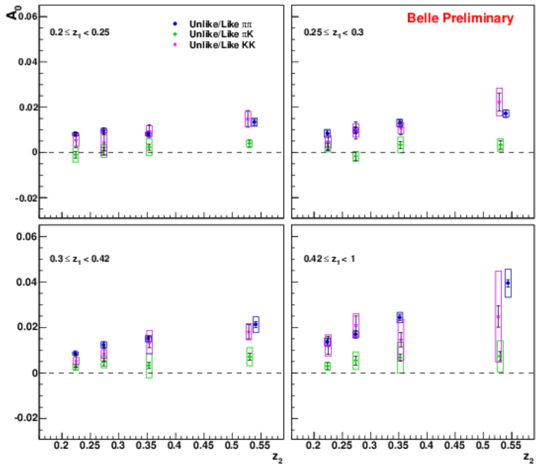

Figure 3: A_0 asymmetries extracted from the unlike-over-like-sign double ratios for $\pi\pi$ (blue circles), πK (green crosses) and KK (violet stars) versus the z_1, z_2 binning: each panel represents a bin in z_1 the z value for the first hadron (from top left to bottom right), and each point in a panel is the asymmetry binned in the z_2, the z value for the second hadron.

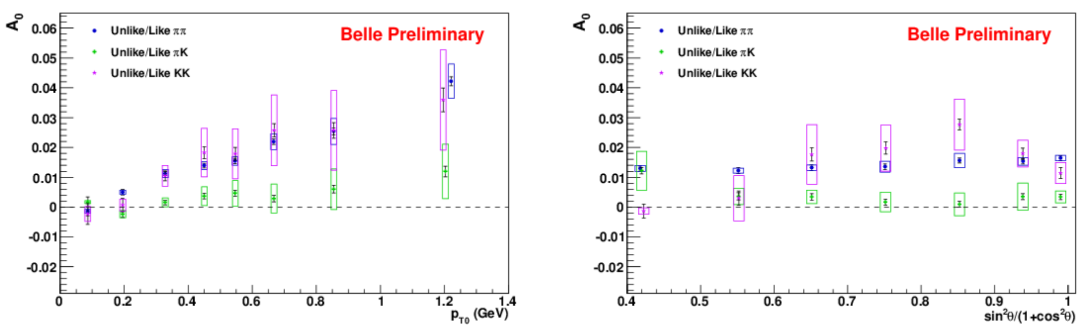

Figure 4: Left: A_0 asymmetries extracted from the unlike-over-like-sign double ratios for $\pi\pi$ (blue circles), πK (green crosses) and KK (violet stars) versus p_{T0}, the p_T of hadron 1 with respect to hadron 2. Right: A_0 asymmetries extracted from the unlike-over-like-sign double ratios versus the $\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$ binning

functional form $p_0 + p_1\frac{\sin^2\theta_2}{1+\cos^2\theta_2}$ are shown in table 2; here the fit is done including the total uncertainties (systematics plus statistics), to account in the fit for known acceptance effect at low It is clear already from figure 4 that at least for the KK pairs there seems not be a linear trend.

The extraction of the Collins functions from the amplitudes presented here is not trivial, as one has to consider all possible combinations of Collins functions from all possible sources. If we limit ourselves to u, d, s and charm we have a total of 16 possible Collins fragmentation functions for pions and 16 possible Collins fragmentation functions for kaons. Even if, for simplicity, we assume that the charm contributes only as a dilution factor (Collins mechanism is expected to be suppressed at the charm mass), there remain 12 possible Collins FF for pions and 12 for kaons. Therefore, for a meaningful extraction of the Collins fragmentation functions, a complete phenomenological study is needed.

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