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Recent Results on Light Quark Fragmentation from Belle

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This contribution reviews recent results on fragmentation function related measurements from Belle data. It concentrates on the most recent result of the measurement of azimuthal modulations in the cross-section of di-pion pairs in di-jet production from electron positron annihilation. In particular, Belle recently performed the first measurement of an azimuthal modulation of the cross-section which may arise from the dependence of the di-pion fragmentation function on the helicity of the parent quark. This fragmentation function $G_1^{\perp}$ has not been measured previously and it is of particular interest, because it vanishes if the intrinsic transverse momentum in the fragmentation process is not taken into account. Within uncertainties no significant signal for $G_1^{\perp}$ is observed.

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1. Introduction

Fragmentation functions describe the hadronization of partons into hadrons. The precise knowledge of fragmentation functions is needed to extract information on the nucleon structure from semi-inclusive deep-inelastic scattering (SIDIS) measurements [1, 2]. More recently, the nuclear physics community started to focus on the theory and experimental measurement of fragmentation functions that are sensitive to the polarization of the parent parton [3].

Since fragmentation functions are fundamental, non-perturbative QCD objects, similar to parton distribution functions, they can also be used to study fundamental properties of QCD. They cannot be computed in lattice QCD due to the non-inclusive final-state and therefore they have to be measured. The cleanest way to access fragmentation functions experimentally is in e^+e^- annihilation, $e^+e^- \to q\bar{q}$. In this process, the hadronization of the quarks can be studied without the uncertainty of parton distribution functions that would contribute in semi-inclusive deep-inelastic scattering or hadron-hadron scattering. The disadvantage of using electron-positron annihilation is the limited sensitivity on the flavor dependence and on the gluon fragmentation function. The study of the polarization dependence of the fragmentation process is possible even in unpolarized e^+e^- annihilation by considering the correlation of the produced quark-antiquark pair polarizations [4].

The measurements which access polarized and spin-averaged light quark fragmentation functions are part of the rich physics program of Belle [5]. Recent results include the precision measurement of charged pion and kaon cross-sections [6] and asymmetries from which the transverse polarization dependent Collins fragmentation function for identified pions and kaons can be extracted [7]. For a recent review of Belle results related to fragmentation functions see e.g. Ref. [8].

These contributions will concentrate on the most recent Belle results on hadronization, i.e. on di-pion pair correlations in back-to-back jets measured by the experiment described in detail in Ref. [9]. Di-hadron pair correlations in e^+e^- annihilation are sensitive to di-hadron fragmentation functions [10], in which two distinguishable hadrons in the final state of $q \to h^+h^-X$ are identified. Compared to single-hadron fragmentation functions, they have an additional degree of freedom, due to the relative momentum between the two hadrons in the final state. This allows the existence of di-hadron fragmentation functions that are sensitive to the initial quark polarization without the need for final state polarimetry or the need to measure the relative transverse momentum the hadrons acquire in the fragmentation process, like in the case for the Collins fragmentation function.

A first measurement of the chiral-odd di-hadron fragmentation function $H_1^{\sphericalangle}$ at Belle has already been reported [11] and it can be used by phenomenology to access the transverse spin structure of the nucleon using results on di-pion correlations from SIDIS and p+p scattering experiments [12, 13, 14, 15]. The function $H_1^{\sphericalangle}$ can be considered the counterpart of the transverse polarization dependent Collins fragmentation function in single hadron production. But unlike the single-hadron case, there also exists a chiral-even di-hadron fragmentation function $G_1^{\perp}$ which is sensitive to the fragmenting quark helicity. In addition to using this function as a tool to access the helicity distributions of quarks, the measurement of $G_1^{\perp}$ might also allows the study of fundamental aspects of non-perturbative QCD, since it has been suggested, that the measurement of $G_1^{\perp}$ in di-hadron pair correlations in e^+e^- annihilation is related to jet-handedness correlations, which might receive contributions from CP violating effects [16].

Since theory predicts that $G_1^\perp$ vanishes when integrated over the intrinsic transverse momentum k_T of the hadrons relative to the parent quark axis, similarly to the Collins fragmentation function, a measurement of $G_1^\perp$ can also be a verification of the importance of correlation effects involving k_T in transverse spin observables.
However, when measured in the correlation of two back-to-back hadron pairs in
$e^+e^- \to (h_1h_2)(\bar{h}_1\bar{h}_2)$, a specific weighting factor in the integration leads to the survival of a transverse-momentum moment of the cross-section that is sensitive to the product of the quark and anti-quark fragmentation functions $G_1^{\perp,q}G_1^{\perp,\bar{q}}$, even if the cross-section is integrated over the observed transverse momentum. Accordingly, we will follow a simplified notation for $G_1^\perp(z,M^2)$, without specifying the corresponding k_T moment, adopted from [10]. Here z is the fractional momentum of the parent quark carried by the hadron pair and M is the mass of the pair.

In the process $e^+e^- \to (h_1h_2)(\bar{h}_1\bar{h}_2)$, the correlation sensitive to $G_1^{\perp,q}(z,M^2)G_1^{\perp,\bar{q}}(\bar{z},\bar{M}^2)$ can be expressed as a moment of the azimuthal modulation in the angle $\Phi_{R'_1} - \Phi_{R'_2}$,

$$\left\langle \cos(2(\Phi_{R'_1} - \Phi_{R'_2})) \right\rangle \propto \sum_{q,\bar{q}} e_q^2 G_1^{\perp,q}(z,M^2) G_1^{\perp,\bar{q}}(\bar{z},\bar{M}^2), \tag{1.1}$$

where the angles $\Phi_{R'_{1,2}}$ are defined in Ref. [10], in the center-of-mass system, as the azimuthal angles of the difference vector $\vec{R}_{1,2}$ of the hadron pairs around the sum of the momentum vectors $\vec{P}_h = \vec{h}_1 + \vec{h}_2$ of one of the hadrons pairs with respect to the event plane spanned by the beam axis and $\vec{P}_h$.

Here, $\bar{z}$ and $\bar{M}$ are the kinematics relating to the hadron pair originating from the fragmentation of the anti-quark and e_q the charge of the fragmenting quark. It should be noted that the coordinate system defined in this way is asymmetric.

2. The Belle Experiment

The Belle experiment [17] at the KEKB storage ring [18] recorded about 1 ab^{-1} of e^+e^- annihilation data. The data was taken mainly at the $\Upsilon(4S)$ resonance at $\sqrt{s} = 10.58$ GeV, but also at $\Upsilon(1S)$ to $\Upsilon(5S)$ resonances and at $\sqrt{s} = 10.52$ GeV. Of importance to the fragmentation function analysis are the central drift chamber and silicon vertex detector, which provide precision tracking for tracks between 17.0° and 150.0° in the polar angle of the laboratory system, as well as the electromagnetic calorimeters (ECL) covering the same region. Particle identification is performed using information on dE/dx in the CDC, a time-of-flight system in the barrel, aerogel Cherenkov counters in the barrel and the forward endcap, as well as a muon and K_L identification system outside the superconducting solenoid, which provides a 1.5 T magnetic field.

3. Analysis and Results

Instead of using the asymmetric frame used in eq. 1.1, the Belle measurement uses a symmetric reference frame in back-to-back dijet event where the angles $\Phi_{R_{1,2}}$ are measured around the reconstructed jets in the respective hemisphere. With the jet axis $\vec{j}_i$, the e^- beam axis $\vec{e}$ and the momentum difference $\vec{R} = \vec{h}_1 - \vec{h}_2$, the azimuthal angles Φ_{R_i} can be expressed as

$$\Phi_{R_i} = \mathrm{sgn}\left(\vec{j}_i \cdot \left((\vec{e}\times\vec{j}_i)\times(\vec{j}_i\times\vec{R}_i)\right)\right) \arccos\left(\frac{\vec{e}\times\vec{j}_i}{|\vec{e}\times\vec{j}_i|}\cdot\frac{\vec{j}_i\times\vec{R}_i}{|\vec{j}_i\times\vec{R}_i|}\right). \tag{3.1}$$

These quantities are depicted in figure 1.

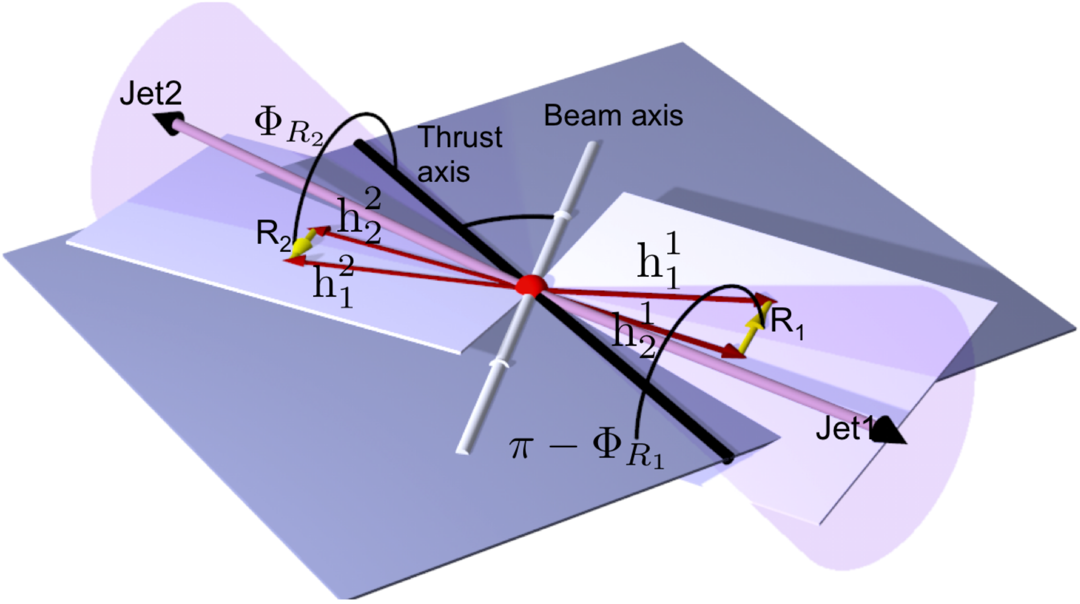

Figure 1: The coordinate system used for this measurement. For convenience, the jets are depicted to lie in the event plane which in turn is spanned by the beam axis and the jets.

Jets are reconstructed using the anti-k_T algorithm, implemented in the FastJet 3.05 package [19, 20]. A jet radius of $R = 1.0$ is used and jets are required to have a minimum energy of 3.75 GeV. From dijet events, where both jets are reconstructed in the barrel region of the detector, charge ordered pairs of identified di-pion pairs are selected where all involved hadrons fulfill a cut of $z > 0.1$. Then a two-dimensional χ^2 fit is performed to the normalized di-pion pair yields $\frac{N(\Phi_{R_1},\Phi_{R_2})}{\langle N\rangle}$ using the truncated Fourier expansion

$$1 + A^{\cos\left(\Phi_{R_1}+\Phi_{R_2}\right)}\cos\left(\Phi_{R_1}+\Phi_{R_2}\right) + A^{\cos\left(2(\Phi_{R_1}-\Phi_{R_2})\right)}\cos\left(2(\Phi_{R_1}-\Phi_{R_2})\right). \tag{3.2}$$

The amplitude $A^{\cos\left(2(\Phi_{R_1}-\Phi_{R_2})\right)}$ corresponds then to the quantities in Eq. (1.1), whereas the amplitude $A^{\cos\left(\Phi_{R_1}+\Phi_{R_2}\right)}$ corresponds to the previously published measurement of $H_1^{\sphericalangle}$ [11]. Results binned in M and z of one hadron pair are shown in Fig. 2 integrated over z and M of the other pair.

Within the experimental uncertainties, no signal for the $A^{\cos\left(2(\Phi_{R_1}-\Phi_{R_2})\right)}$, which is thought to be sensitive to $G_1^{\perp,q}G_1^{\perp,\bar{q}}$, is observed.

4. Summary and Outlook

The large dataset of e^-e^+ annihilation data collected by the Belle experiment enables the precision measurement of quantities from which polarized and spin averaged fragmentation functions can be extracted. Most recently, azimuthal modulation of di-pion pairs in di-jet events where

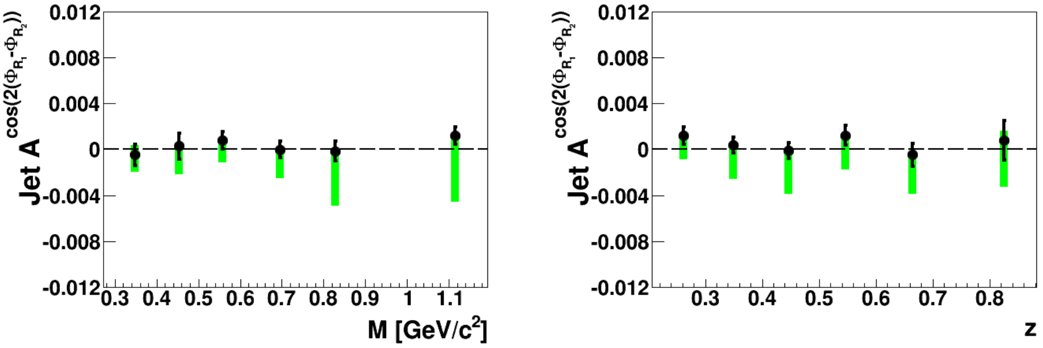

Figure 2: Results for $A^{\cos\left(2(\Phi_{R_1}-\Phi_{R_2})\right)}$ binned in M and z. The black error bars are statistical and the green bands show the systematic uncertainty.

measured which are thought to be sensitive to the helicity dependent fragmentation function $G_1^\perp$. This function is supposed to vanish in the absence of helicity dependent correlations of the intrinsic transverse momentum in the fragmentation process with momentum difference of hadrons in the pair. Therefore, the existence of this function might be interpreted as a validation of the so-called TMD framework which forms the base for the theoretical interpretation of a large class of transverse spin phenomena [21]. However, within the experimental uncertainties no signal is observed at Belle. In addition to ongoing analysis on the Belle dataset, an upgraded experiment, Belle-II is currently under construction with the plan to use an upgraded KEKB storage ring, then called Super-KEKB, to sample about 40 times the luminosity compared to Belle [22]. For the fragmentation function program in particular the upgraded particle identification capabilities and the improved vertex resolution are of importance to select multi-kaon final states and effectively isolate contributions from charm production. In addition, the hermiticity of the detector as well as energy and momentum resolution will be improved. Together with the improved capability to reconstruct low momentum tracks, this will help increase the precision of future measurements of observables related to the extraction of fragmentation functions.

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