Measurement of Collins asymmetry at BESIII

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Abstract. In this talk, I present the recent measurement of the Collins fragmentation function based on a set of 62 pb$^{-1}$ $e^+e^-$ annihilation data at $\sqrt{s} = 3.65$ GeV collected with the BESIII detector at the BEPCII storage rings. In this work, the azimuthal asymmetries of two charged pions in the inclusive process $e^+e^- \rightarrow \pi\pi X$ are explored. These asymmetries can be attributed to the Collins fragmentation function, which describes the behavior of a hadron produced from a transversely polarized quark. The corresponding four-momentum transfer of the virtual photon, $Q^2$, is close to the energy scale of the existing semi-inclusive DIS experimental data. We observe a nonzero asymmetry, which increases with increasing pion momentum and also indicates a larger spin-dependent Collins effect than at higher energy scale. The dependence of the asymmetry on the transverse momentum of hadrons to the reference axis is also investigated. The measured asymmetries are important inputs for the global analysis of extracting the quark transversity distribution inside the nucleon, and are valuable to explore the energy evolution of the spin-dependent fragmentation function.

1. Introduction
The quark-hadron fragmentation process is parameterized with the fragmentation function (FF), which describes the probability that a hadron carrying a fraction of parton energy is found in the hadronization debris of the fragmenting parton. Due to the incorporated non-perturbative physics of the hadronization processes, they are not calculable from the first principle in QCD, but are parameterized with the help of factorization and perturbative calculations, where free parameters can be fixed by fitting to experimental data. The Collins FF, which considers the spin-dependent effects in the fragmentation processes, was firstly discussed by Collins in Ref. [1]. The Collins FF connects transverse quark spin with a measurable azimuthal asymmetry (the so-called Collins effect) in the yields of hadronic fragments along the initial quark’s momentum.

The measurement of the Collins FF provides an important test in understanding strong interaction dynamics, and thus, is of fundamental interest in QCD theory. Because it is chiral-odd, it needs to couple to another chiral-odd function to form accessible observables in experiment. The HERMES experiment [2] presented the first non-zero proof of this function in semi-inclusive deep inelastic scattering (SIDIS) process by probing a chiral-even observable of azimuthal asymmetry, where the Collins FF couples to the chiral-odd transversity [3–5]. Transversity corresponds to the tensor charge of the nucleon and is the least known leading-twist quark distribution function. Subsequently, there were more SIDIS measurements on this asymmetry at HERMES [6], COMPASS [7] and JLab [8]. Further exploration of independent measurement of the Collins FF was implemented in the $e^+e^-$ annihilation process, where two Collins FFs couple to construct a chiral-even azimuthal asymmetry, and their measurements from
Belle [9–11] and BABAR [12] give consistent non-zero asymmetries. Base on the assumption of universality of the Collins FF [13], global analyses [14, 15] have been performed to extract the transversity by combing SIDIS and $e^+e^-$ observables. However, the $e^+e^-$ Collins asymmetries, taken from Belle and BABAR, correspond to considerably higher $Q^2$ ($\sim$100 GeV$^2$) than the typical energy scale of the existing SIDIS data (mostly 2-15 GeV$^2$). Thus, the energy evolution of the FF at different $Q^2$ is a key factor of influencing the uncertainty of the extracted transversity and its theoretical treatment is not well justified [16, 17] due to lack of low-energy $e^+e^-$ data. The BESIII experiment [18] studies the $e^+e^-$ annihilations at a moderate energy scale ($Q^2$: 4-20 GeV$^2$) and its measurement of the Collins asymmetry is timely. Ref. [19] predicts that the Collins asymmetry at BESIII will be larger than at $B$ factories. With comparison with the measurement from the $B$ factories, BESIII data will help to understand the $Q^2$ evolution behavior of the Collins FF. In addition, it holds a unique advantage compared to the $B$ factory that the BESIII data can be connected more reliably to the SIDIS data, as their energy scales are very close.

2. The BESIII experiment

The analysis is based on a data sample with an integrated luminosity of 62 pb$^{-1}$ collected with the BESIII [18] detector at the center-of-mass energy $\sqrt{s} = 3.65$ GeV. The BESIII detector is a general-purpose solenoidal detector at the BEPCII [20] $e^+e^-$ storage rings. The detector has a geometrical acceptance of 93% of the full solid angle. The apparatus relevant to this work includes, from inside to outside, a small-cell main drift chamber (MDC), using a helium-based gas to measure momenta and specific ionizations of charged particles, a time-of-flight (TOF) system based on plastic scintillators that determines the flight times of charged particles, a CsI(Tl) electromagnetic calorimeter (EMC) detects electromagnetic showers. These components are all situated inside a superconducting solenoid magnet, that provides a 1.0 T magnetic field parallel to the beam direction. The momentum resolution for charged tracks in the MDC is 0.5% for a transverse momentum of 1 GeV/c. The energy resolution for showers in the EMC is 2.5% (5.0%) for 1 GeV photons in the barrel (end cap) region. More details on the features and capabilities of the BESIII detector can be found elsewhere [18].

3. Data analysis

Taking into account the spin of the quark, the number density for finding a spinless hadron $h$ with transverse momentum $P_{h\perp}$ produced from a transversely polarized quark $q$ with spin $S_q$ can be described in terms of the unpolarized FF, $D_1^q$, and the Collins FF, $H_1^{1q}$, at the leading twist [21],

$$D_1^{q\perp}(z, P_{h\perp}) = D_1^q(z, P_{h\perp}\perp) + H_1^{1q}(z, P_{h\perp}\perp)\frac{\langle \hat{k} \times P_{h\perp}\perp \rangle \cdot S_q}{z M_h},$$

where $\hat{k}$ denotes the motion direction of the initial quark $q$, $z = 2E_h/Q$ denotes the fractional energy of the hadron relative to half of $Q = \sqrt{s}$, and $M_h$ is the hadron mass. The second term contains the Collins function and depends on the spin orientation of the quark $q$, which leads to a $\sin(\phi)$ modulation, where $\phi$ is defined as the angle spanned by the transverse momentum of hadron and the plane normal to the quark spin.

In inclusive hadron production process, $e^+e^- \rightarrow q\bar{q} \rightarrow hX$, with unpolarized beams, studying on the azimuthal asymmetries of single (anti-)quark fragmentation is impossible due to the absence of the specific (anti-)quark spin. However, the Collins effect can be observed when the fragments of the quark and anti-quark are considered simultaneously. The correlation of quark and anti-quark Collins functions gives a cosine modulation of the distribution of azimuthal angles of the two hadrons, with the azimuthal angle $\phi_0$ defined as in Fig. 1.
Figure 1. The angle $\phi_0$ is defined as the angle between the plane spanned by the beam axis and the momentum of the second hadron ($P_2$), and the plane spanned by the transverse momentum $p_t$ of the first hadron relative to the second hadron. The $\theta_2$ is the polar angle of the the second hadron.

The normalized dihadron yields is recorded as a function of $\phi_0$ and can be parameterized as $a \cos (2\phi_0) + b$ with $b$ referring to the term which is independent on $\phi_0$, and [22, 23]

$$a(\theta_2, z_1, z_2) = \frac{\sin^2 \theta_2}{1 + \cos^2 \theta_2} \frac{F (H_1^+(z_1)H_1^+(z_2)/M_1M_2)}{D_1(z_1)D_1(z_2)}, \quad (1)$$

where $F$ denotes a convolution over the transverse hadron momenta. $M_1$ and $M_2$ are the masses of the two hadrons, $z_1$ and $z_2$ are their fraction energies, and $\theta_2$ is the polar angle of the second hadron with respect to the beam axis, $D_1$ and $H_1^+$ denote FFs for anti-quarks.

In this analysis, for each charged $\pi$-pair candidate, basic track qualification and particle identification requirements are imposed [24]. The angle between two pions must be larger than $120^\circ$. We label the two pions randomly as $h_1$ and $h_2$, and we use the momentum direction of $h_2$ as reference axis. To select the inclusive $e^+e^- \rightarrow \pi\pi X$ events of interest, at least three charged tracks are required. To suppress backgrounds from the processes of QED, two photon fusions and ISR returned hadron productions, the visible energy in the detector, which is defined as the total energy of all reconstructed charged and neutral tracks, is required to exceed 1.5 GeV and no electron is present.

We introduce the $2\phi_0$ normalized distribution, $R = \frac{N(2\phi_0)}{\langle N_0 \rangle}$, where $N(2\phi_0)$ is the dipion yields in each $(2\phi_0)$ subdivision, and $\langle N_0 \rangle$ is the averaged bin content. The normalized ratios are built for unlike-sign ($\pi^\pm\pi^\mp$), like-sign ($\pi^\pm\pi^\pm$) and charged pion-pairs ($\pi\pi$), as $R^U$, $R^L$ and $R^C$, respectively, in which different combinations of favored FFs and disfavored FFs are involved. A favored fragmentation process refers to the fragmentation of a quark into a hadron containing a valence quark of the same flavor, for example $u(\bar{d}) \rightarrow \pi^+$, while the corresponding $u(\bar{d}) \rightarrow \pi^-$ is a disfavored process. Since the normalized ratio $R$ is strongly affected by detector acceptance effects, to extract the physical asymmetries, double ratios $R^U/R^L(C)$ (UL and UC ratios) are constructed [9, 10]. In the double ratios, instrumental effects, which are charge-independent cancel out, and the QCD radiative effects are negligible to the first order, while the Collins asymmetries which are charge-dependent are kept. The double ratio $R^U/R^L(C)$ follows the expression

$$\frac{R^U}{R^L(C)} = A \cos(2\phi_0) + B, \quad (2)$$

where $A$ and $B$ are free parameters, while $B$ should be consistent with unity, and $A$ mainly contain the Collins effect.
The analysis is performed in \((z_1, z_2)\) bins with boundaries at \(z_i = 0.2, 0.3, 0.5, 0.9\) \((i = 1, 2)\), where complementary off-diagonal bins \((z_1, z_2)\) and \((z_2, z_1)\) are combined. In each \((z_1, z_2)\) bin, normalized rates \(R^{U,L,C}\) and double ratios \(R^U/R^{L,C}\) are evaluated in 15 bins of constant width in the angles \(2\phi_0\). The fits using Eq. (2) for the two highest \((z_1, z_2)\) bins are shown in Fig. 2, while in Fig. 3 and Table 1 are summarized the fit results as a function of six symmetric \((z_1, z_2)\) bins. We see significant nonzero asymmetries [24]. The Collins asymmetries are investigated also in bins of \(p_t\), and in bins of \(\sin^2\theta_2/(1 + \cos^2\theta_2)\), where definition of \(p_t\) and \(\theta_2\) are illustrated in Fig. 1. The results are shown in Fig. 4 and Fig. 5, and are summarized in Table 1.

As illustrated in Fig. 3, the measured Collins asymmetries rise with fractional energies as expected from theoretical predictions [22]. The moments of Collins asymmetries at the BEPCII energy scale is larger than at \(B\) factories, in agreement with the theoretical prediction from Ref. [19]. We observe an increase of the asymmetries with increasing \(p_t\). The expected behavior of Collins asymmetries as a function of \(\sin^2\theta_2/(1 + \cos^2\theta_2)\) is linear and vanish at \(\theta = 0\), as
formulated in Eq. (1). Thus, we perform a linear fit \((c_0+c_1 x)\) to the points in Fig. 5, with the constant term \(c_0\) set to be zero or float, which gives the goodness of fit to be 1.82 or 1.26 for \(A_{UL}\) and 1.70 or 1.09 for \(A_{UC}\), respectively, which indicates the results may favor a nonzero constant term. But current data statistics can not provide a conclusive test on whether the constant term is nonzero.

4. Summary and outlook
In summary, we perform a measurement of the azimuthal asymmetry in the inclusive production of charged pion pairs, which can be attributed the product of a quark and an anti-quark Collins functions. Our results exhibit nonzero asymmetries in the region of large fraction energy \(z\) and also indicate larger spin-dependent Collins effect than those at higher energy scale [9–12]. This is the first time the Collins asymmetries are measured at moderate energy scale in \(e^+e^−\) collider experiment. The results are of great importance to explore the \(Q^2\) evolution of Collins function, and thus, also to extract the transversity distribution in nucleon.

In 2016, BESIII will take about 0.36 fb\(^{-1}\) data at \(\sqrt{s} = 3.51\) GeV for studying the Collins fragmentation functions. It will improve the precision of this measurement at least by a factor of two. With larger statistics, we can extend this work to the Collins asymmetries of the charged \(\pi K\) and \(\pi K\) pairs. We also can provide data for the inclusive dipion productions involving natural \(\pi^0\).

As for higher \(Q^2\) region above charm threshold, BESIII has accumulated more than 5 fb\(^{-1}\) data [25]. However, the charmed hadron decay backgrounds need to be well understood before to extract the Collins effect. More efforts will be spent on investigating this issue.

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