Physics Letters B 774 (2017) 635–642

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Collins azimuthal asymmetries of hadron production inside jets

Zhong-Bo Kang [a,b,c,*], Alexei Prokudin [d,e], Felix Ringer [f], Feng Yuan [f]

[a] Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA
[b] Mani L. Bhaumik Institute for Theoretical Physics, University of California, Los Angeles, CA 90095, USA
[c] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[d] Science Division, Penn State University Berks, Reading, PA 19610, USA
[e] Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA
[f] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

ARTICLE INFO

Article history:
Received 12 July 2017
Received in revised form 9 October 2017
Accepted 13 October 2017
Available online 18 October 2017
Editor: A. Ringwald

Keywords:
Collins asymmetry
Jets
Polarized scattering
Perturbative QCD

ABSTRACT

We investigate the Collins azimuthal asymmetry of hadrons produced inside jets in transversely polarized proton–proton collisions. Recently, the quark transversity distributions and the Collins fragmentation functions have been extracted within global analyses from data of the processes semi-inclusive deep inelastic scattering and electron–positron annihilation. We calculate the Collins azimuthal asymmetry for charged pions inside jets using these extractions for RHIC kinematics at center-of-mass energies of 200 and 500 GeV. We compare our results with recent data from the STAR Collaboration at RHIC and find good agreement, which confirms the universality of the Collins fragmentation functions. In addition, we further explore the impact of transverse momentum dependent evolution effects.

1. Introduction

The transverse momentum dependent parton distribution functions and fragmentation functions have recently received an increased interest from both the experimental and theoretical communities [1–3]. Transverse momentum dependent distributions (TMDs) provide new information about the nucleon structure, in particular for the three-dimensional imaging of the nucleon in momentum space. At the same time, TMDs open new windows for a better understanding of the most fundamental and interesting aspects of QCD, such as gauge invariance and universality properties.

One of the widely discussed TMDs is the Collins fragmentation function [4]. It describes a transversely polarized quark fragmenting into an unpolarized hadron. The hadron's transverse momentum with respect to the direction of the fragmenting quark correlates with the transverse polarization vector of the quark. The Collins fragmentation functions generate azimuthal angular asymmetries in the production of hadrons in high energy scattering processes. For example, in semi-inclusive deep inelastic scattering (SIDIS) of leptons on the transversely polarized nucleons, an azimuthal single transverse spin asymmetry has been observed by several collaborations including the HERMES Collaboration [5,6], the COMPASS Collaboration [7], and the JLab HALL A experiment [8]. Such an azimuthal correlation is usually referred to as the Collins asymmetry. The modulation is proportional to $\sin(\phi_s+\phi_h)$, where ϕ_s and ϕ_h are the azimuthal angles of the transverse spin of the nucleon and of the final-state hadron's transverse momentum, respectively. The asymmetry is generated through the quark transversity distributions in the nucleon [9–11] coupled with the Collins fragmentation functions.

The Collins fragmentation functions can also contribute to an azimuthal angular correlation in back-to-back hadron production in electron–positron annihilation [12]. In this case, the correlation has a $\cos(2\phi)$ modulation, where ϕ is the azimuthal angle between the two hadrons. It is generated through the convolution of two Collins fragmentation functions for the observed hadron pair. The resulting $\cos(2\phi)$ azimuthal correlation has now been measured at several facilities. The BELLE and *BABAR* Collaborations published data sets taken at the B-factories at a center-of-mass (CM) energy of $\sqrt{s}\simeq 10.6$ GeV [13–15], and the BESIII Collaboration performed measurements at the BEPC facility at a CM energy of $\sqrt{s}=3.65$ GeV [16]. The combined analyses of the experimental data on SIDIS and electron–positron annihilation have provided important information on both the quark transversity distributions and the Collins fragmentation functions [17,18]. Transversity distri-

* Corresponding author.
E-mail addresses: zkang@physics.ucla.edu (Z.-B. Kang), prokudin@jlab.org (A. Prokudin), fmringer@lbl.gov (F. Ringer), fyuan@lbl.gov (F. Yuan).

https://doi.org/10.1016/j.physletb.2017.10.031

butions give information on the quark contributions to the nucleon tensor charge which is a fundamental property of the nucleon.

Another important process to explore the Collins fragmentation functions is to study the azimuthal asymmetries of hadron production inside highly energetic jets in transversely polarized proton–proton collisions at RHIC [19,20]: $p^\uparrow p \to \text{jet}(\eta, p_T)\, h(z_h, j_\perp) + X$. Here, η and p_T are the rapidity and the transverse momentum of the jet measured in the pp CM frame, respectively. Furthermore, z_h is the momentum fraction of the fragmenting quark jet carried by the hadron, and $j_\perp$ is the hadron transverse momentum with respect to the standard jet axis. The $j_\perp$-distribution of hadrons produced inside jets in unpolarized pp collisions was studied recently in [21,22]. In the transversely polarized $p^\uparrow p$ scatterings, due to the transverse spin transfer in the hard partonic processes [23,24], the final state quark jet inherits the transverse polarization of quarks in the incoming transversely polarized nucleon. Eventually, the transverse spin of the fragmenting quark correlates with the transverse momentum of the hadron with respect to the jet axis, which leads to a nontrivial Collins asymmetry of the azimuthal angular distribution of hadrons inside (quark) jets [19,20]. The detailed study of these azimuthal asymmetries of hadrons produced inside jets is the main focus of this work. We will focus on two main aspects which are the universality and the evolution of the Collins TMD fragmentation functions.

Concerning the universality aspect, it has been shown in [19] that the Collins fragmentation functions are universal in the sense that they are the same for hadrons inside jets as for SIDIS and electron–positron annihilation. This assessment is expected to be true even when the soft factor is included in order to obtain the full TMD factorization formalism [22]. Therefore, it is possible to predict the Collins azimuthal asymmetries for hadron production inside jets at RHIC by using the quark transversity distributions and Collins fragmentation functions determined from SIDIS and electron–positron annihilation. The comparison of our results with the experimental data from RHIC [25–28] then provides an important test of the universality of the Collins fragmentation functions for these different processes.

The second important aspect of the Collins fragmentation function is its TMD evolution, i.e. the appropriate QCD evolution of TMD sensitive observables [29]. It is crucial to take into account TMD evolution of the Collins fragmentation functions for phenomenological studies since the experimental measurements are usually performed at different scales. The hard momentum scale Q^2 ranges between a couple of GeV^2 up to several hundred GeV^2. In a recent study, the evolution effects have been implemented in a global analysis of the Collins azimuthal asymmetries in SIDIS and electron–positron annihilation [17]. It has been demonstrated in [22] that the same TMD evolution applies to the relevant TMD fragmentation functions encountered in the transverse momentum distribution of hadrons inside jets. In this work, we assess the impact of TMD evolution for the azimuthal asymmetries for hadrons inside jets by comparing to the available data from RHIC.

The hadron distribution inside fully reconstructed jets has received broad interest from the high energy nuclear and the particle physics communities in the past years [30–33]. In particular, the transverse momentum distribution of hadrons relative to a predetermined jet axis may provide important new information about the hadronization of particles at current collider experiments. In [21,22] the standard jet axis was discussed, whereas in [34] a recoil-free axis, e.g. the winner-take-all axis, was considered. Interestingly, the choice of the axis probes different physics of the hadronization process. In this work, we consider the standard jet axis which allows for a direct relation to standard TMDs extracted from other processes. Needless to say that many studies have been carried out where the longitudinal momentum distribution of different hadrons and even photons inside jets were considered [35–43]. Studying the correlations of hadrons inside jets constitutes a new opportunity to study TMDs besides the traditional observables. In addition, it may shed new light on other interesting topics such as the effect of non-global logarithms as advocated in [44,45].

The azimuthal distributions of hadrons inside a jet were also considered in the framework of the so-called Generalized Parton Model (GPM) in Refs. [20,46]. In the GPM, one naively uses TMDs for both parton distribution functions and fragmentation functions, and at the same time assumes that all functions are universal. Both statements lack full justification in QCD, and therefore, the GPM cannot include QCD evolution for these functions properly. On the other hand, the factorization formula used in the current paper involves a mixture of collinear and TMD factorization, following [19,22]. In this formula, the production of the jet involves only a collinear factorization, in which collinear parton distribution functions are used. At the same time, the internal structure of the jet, i.e., the hadron $j_\perp$ distribution inside the jet is given by the TMD factorization, where the proper evolution of the Collins fragmentation function can be studied. This approach is applicable in the narrow jet approximation, i.e. up to corrections that are power suppressed by $\mathcal{O}(R^2)$. See the next section for a more detailed discussion.

The remainder of this paper is organized as follows. In Sec. 2, we review the leading order calculation of the Collins azimuthal asymmetry for hadron production inside jets in pp collisions. In addition, we outline how the TMD evolution effects are implemented. We also present the parton model results where no TMD evolution is taken into account. Numerical results are presented in Sec. 3, by making use of the recent global extractions of the quark transversity distributions and the Collins fragmentation functions. We calculate the Collins azimuthal asymmetry for charged pion production inside jets in proton–proton collisions for both CM energies 200 and 500 GeV. We compare our results with the experimental data from the STAR Collaboration at RHIC and we conclude our paper in Sec. 4.

2. Theoretical framework

We consider the hadron azimuthal distribution inside jets in transversely polarized $p^\uparrow p$ collisions,

$$p^\uparrow(P_A, S_T, \phi_S) + p(P_B) \to \text{jet}(\eta, p_T)\, h(z_h, j_\perp, \phi_H) + X\,.$$

The momentum of the incoming transversely polarized proton is denoted by P_A (moving in the "$+z$" direction) and its transverse polarization vector is S_T. The reaction plane is defined by the two incoming protons and the axis of the observed jet in the final state. We denote the azimuthal angle of the transverse polarization vector S_T with respect to the reaction plane by ϕ_S. The unpolarized proton (moving in the "$-z$" direction) has momentum P_B. Moreover, η and p_T are the rapidity and transverse momentum of the final state jet. The observed hadron inside that jet is characterized by the following variables: the longitudinal momentum fraction of the jet carried by the hadron is denoted by z_h and its transverse momentum with respect to the (standard) jet axis is given by $j_\perp$. The hadron transverse momentum vector $j_\perp$ forms an angle ϕ_H with the reaction plane. See Fig. 1 for an illustration of the setup of this process and the definition of all the relevant kinematic variables.

2.1. QCD formalism

The differential cross section of the hadron azimuthal distribution inside jets can be written as [19]