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Azimuthal distributions of pions inside a jet in hadronic collisions

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Summary. — Using a generalized parton model approach including spin and intrinsic parton motion effects, and assuming the validity of factorization for large- p_T jet production in hadronic collisions, we study the azimuthal distribution around the jet axis of leading pions, produced in the jet fragmentation process. We identify the observable leading-twist azimuthal asymmetries, which are generated by all the physically allowed combinations of transverse-momentum dependent (TMD) parton distribution and fragmentation functions. In particular, we show how one can isolate the Collins and Sivers contributions, and suggest a test of the process dependence of the Sivers function by considering the effect of color-gauge invariant initial and final state interactions.

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1. – Introduction

Transverse single-spin and azimuthal asymmetries in high-energy hadronic reactions have raised a lot of interest in the last years (see, *e.g.*, ref. [1] and references therein). In particular, the huge spin asymmetries measured in the inclusive forward production of pions in high-energy proton-proton collisions, at moderately large transverse momentum, cannot be explained in the realm of leading-twist (LT) perturbative QCD (pQCD), based on the usual collinear factorization theorems. Out of the theoretical approaches proposed in order to account for these measurements, in the following we will adopt the so-called transverse-momentum dependent (TMD) formalism, which takes into account spin and intrinsic parton motion effects assuming a pQCD factorization scheme. In this framework, single-spin and azimuthal asymmetries are generated by TMD polarized partonic distribution and fragmentation functions, among which the most relevant from a phenomenological point of view are the Sivers distribution [2] and, for transversely polarized quarks, the Boer-Mulders distribution [3] and the Collins fragmentation function [4] (similar functions can be defined for linearly polarized gluons, see, *e.g.*, ref. [5]).

Azimuthal asymmetries in the distribution of pions inside a large transverse-momentum jet are quite interesting observables [6] and are presently under active investigation at the Relativistic Heavy Ion Collider (RHIC). In contrast to inclusive pion production, where several underlying competing mechanisms (mainly the Sivers and Collins ones) cannot be separated, and in close analogy with the semi-inclusive deep inelastic scattering (SIDIS) case, one could discriminate among different effects by taking suitable moments of these asymmetries. In principle, quark and gluon originating jets can also be distinguished, at least in some kinematic regimes. Furthermore, information on the size of TMD distributions and fragmentation functions can be gained, in a kinematic region in which they are still poorly known. This would be very helpful in clarifying the role played by the quark(gluon) Sivers distribution and by the Collins(-like) fragmentation function in the sizable single spin asymmetries observed at RHIC for single inclusive pion production. A similar analysis where transverse partonic motion was considered only in the fragmentation process, aimed at a study of the universality of the Collins function for quarks, was presented in ref. [7]. Our approach, named generalized parton model (GPM), has in principle a richer structure in the observable azimuthal asymmetries, because intrinsic motion is taken into account in the initial hadrons as well. Preliminary data from the STAR collaboration at RHIC seem to support our model, since they report on a Sivers asymmetry for neutral pions larger than zero [8, 9] and compatible with our predictions. However, since factorization has not been proven in this case, but is rather taken as a reasonable phenomenological assumption, the validity of the scheme and the universality of the TMD distributions involved require a severe scrutiny by further comparison with experiments.

2. – Theoretical framework

We consider the process $p^\uparrow p \rightarrow \text{jet} + \pi + X$, with one of the protons in a transverse-spin state described by the four-vector S . We work in the pp c.m. frame, where the polarized proton moves along the $+\hat{Z}_{\text{cm}}$ direction, and define $(XZ)_{\text{cm}}$ as the production plane containing the colliding beams and the observed jet, with $(\mathbf{p}_j)_{X_{\text{cm}}} > 0$. In this frame $S = (0, \cos \phi_S, \sin \phi_S, 0)$ and $p_j = p_{jT}(\cosh \eta_j, 1, 0, \sinh \eta_j)$, where $\eta_j = -\log[\tan(\theta_j/2)]$ is the jet (pseudo)rapidity. We denote by z and $\mathbf{k}_{\perp\pi}$ respectively the light-cone momentum fraction and the transverse momentum of the observed pion inside the jet w.r.t. the jet (fragmenting parton) direction of motion. Calculations have been performed within the GPM framework at leading-order (LO) in pQCD utilizing the helicity formalism. More details can be found in ref. [6].

The final expression for the single-transverse polarized cross section has the following general structure:

$$(1) \quad 2d\sigma(\phi_S, \phi_\pi^H) \sim d\sigma_0 + d\Delta\sigma_0 \sin \phi_S + d\sigma_1 \cos \phi_\pi^H + d\sigma_2 \cos 2\phi_\pi^H \\ + d\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H) \\ + d\Delta\sigma_2^- \sin(\phi_S - 2\phi_\pi^H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_\pi^H),$$

where ϕ_π^H is the azimuthal angle of the pion three-momentum around the jet axis, as measured in the fragmenting parton helicity frame [6]. In close analogy with the SIDIS case, in order to single out the different contributions of interest, we can define appropriate

azimuthal moments,

$$(2) \quad A_N^{W(\phi_S, \phi_\pi^H)}(\mathbf{p}_j, z, k_{\perp\pi}) = 2 \frac{\int d\phi_S d\phi_\pi^H W(\phi_S, \phi_\pi^H) [d\sigma(\phi_S, \phi_\pi^H) - d\sigma(\phi_S + \pi, \phi_\pi^H)]}{\int d\phi_S d\phi_\pi^H [d\sigma(\phi_S, \phi_\pi^H) + d\sigma(\phi_S + \pi, \phi_\pi^H)]},$$

where $W(\phi_S, \phi_\pi^H)$ is some appropriate circular function of ϕ_S and ϕ_π^H .

3. – Phenomenology

In this section we present and discuss some phenomenological implications of our approach in kinematic configurations accessible at RHIC by the STAR and PHENIX experiments. We consider both central ($\eta_j = 0$) and forward ($\eta_j = 3.3$) (pseudo)rapidity configurations at a c.m. energy $\sqrt{s} = 200$ GeV (different c.m. energies, namely $\sqrt{s} = 62.4$ and 500 GeV, are also studied in [6]).

For numerical calculations all TMD distribution and fragmentation functions are taken in the simplified form where the functional dependence on the parton light-cone momentum fraction and on transverse motion are completely factorized, assuming a Gaussian-like flavour-independent shape for the transverse-momentum component. Concerning the parameterizations of the transversity and quark Sivers distributions, and of the Collins functions, we consider two sets: SIDIS 1 [10,11] and SIDIS 2 [12,13]. Furthermore, for the usual collinear distributions, we adopt the LO unpolarized set GRV98 [14]. For fragmentation functions, we adopt two well-known LO sets among those available in the literature, the set by Kretzer [15] and the DSS one [16]. Our choice is dictated by the subsequent use of the two available parametrization sets for the Sivers and Collins functions in our scheme, that have been extracted in the past years by adopting these sets of fragmentation functions. Since the range of the jet transverse-momentum (the hard scale) covered is significant, we take into account proper evolution with scale. On the other hand, the transverse-momentum component of all TMD functions is kept fixed with no evolution with scale. In all cases considered, $\mathbf{k}_{\perp\pi}$ is integrated over and, since we are interested in leading particles inside the jet, we present results obtained integrating the light-cone momentum fraction of the observed hadron, z , in the range $z \geq 0.3$.

We have considered first, for π^+ production only, a scenario in which the effects of all TMD functions are over-maximized. By this we mean that all TMD functions are maximized in size by imposing natural positivity bounds. The transversity distribution has been fixed at the initial scale by saturating the Soffer bound and then we let it evolve. Moreover, the relative signs of all active partonic contributions are chosen so that they sum up additively. In this way we set an upper bound on the absolute value of any of the effects playing a potential role in the azimuthal asymmetries. Therefore, all effects that are negligible or even marginal in this scenario may be directly discarded in subsequent refined phenomenological analyses. See ref. [6] for a more detailed discussion.

As a second step in our study we consider, for both neutral and charged pions, only the surviving effects, involving TMD functions for which parameterizations are available from independent fits to other spin and azimuthal asymmetries data in SIDIS, Drell-Yan (DY), and e^+e^- processes. In fig. 1 we present, in the forward rapidity region, the quark-generated asymmetry $A_N^{\sin(\phi_S - \phi_\pi^H)}$, which comes mainly from the convolution between the transversity distribution and the Collins fragmentation function. The plots are obtained adopting the parameterizations SIDIS 1 and SIDIS 2. The Collins asymmetry for neutral pions results to be almost vanishing, in agreement with preliminary RHIC data [8,9].

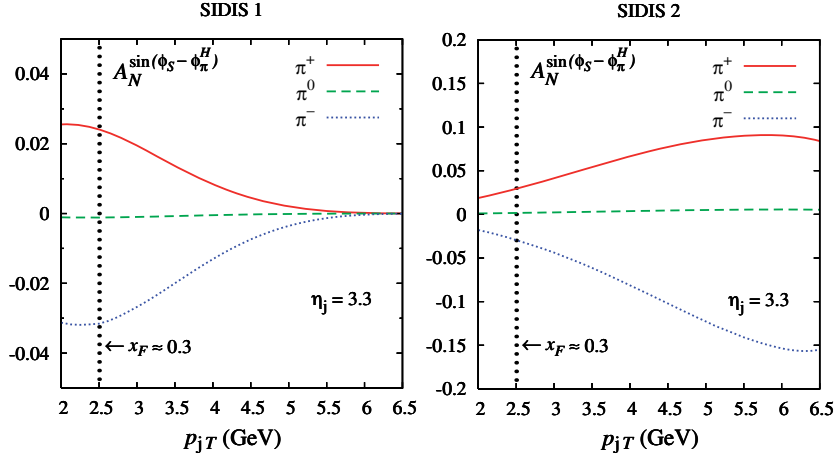


Fig. 1. – The estimated quark Collins asymmetry for the $p^\uparrow p \rightarrow \text{jet} + \pi + X$ process, obtained adopting the parameterizations SIDIS 1 and SIDIS 2 respectively, at $\sqrt{s} = 200$ GeV in the forward rapidity region. The dotted black vertical line delimits the region $x_F \approx 0.3$.

The dotted black vertical line delimits the region $x_F \approx 0.3$, with $x_F = 2p_{jL}/\sqrt{s}$, beyond which the SIDIS parameterizations for transversity are extrapolated outside the Bjorken x region covered by SIDIS data and are therefore plagued by large uncertainties. For this reason, the two parameterizations for charged pions give comparable results only below this limit (notice the difference in scale between the two panels). A measurement of such asymmetries would be then very important and helpful in clarifying the large x behaviour of the quark transversity distribution. Furthermore, it turns out that in the central rapidity region the quark Collins asymmetries are practically negligible.

In fig. 2 we show, for both neutral and charged pions, the quark and gluon contributions to the Sivers asymmetry $A_N^{\sin\phi_S}$, which cannot be disentangled, in the forward rapidity region as a function of p_{jT} . The quark term is obtained adopting the SIDIS 1 and SIDIS 2 parameterizations. The almost unknown gluon Sivers function is tentatively

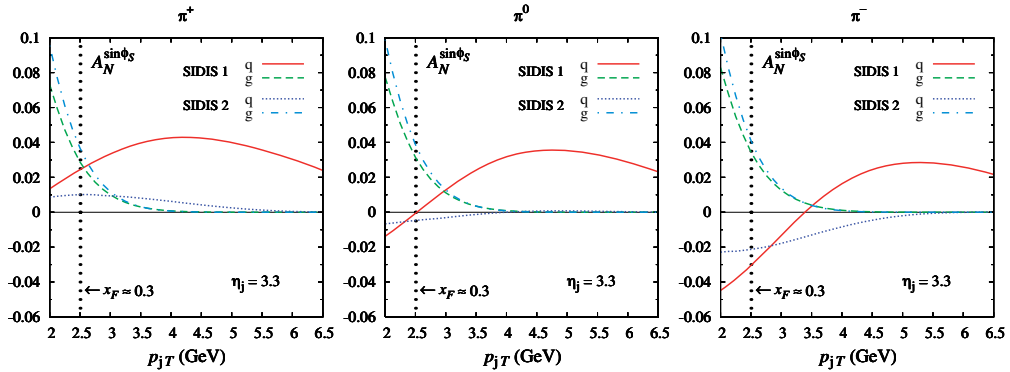


Fig. 2. – The estimated quark and gluon contributions to the Sivers asymmetry for the $p^\uparrow p \rightarrow \text{jet} + \pi + X$ process, obtained adopting the parametrization sets SIDIS 1 and SIDIS 2, at forward rapidity and $\sqrt{s} = 200$ GeV. The dotted black vertical line delimits the region $x_F \approx 0.3$.

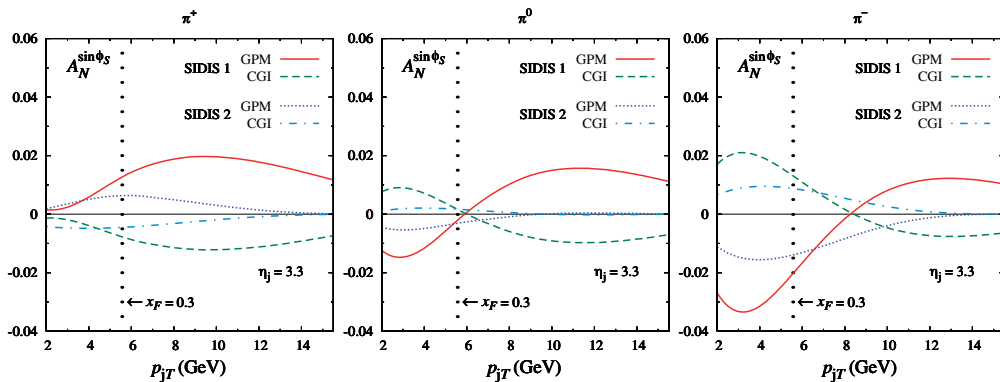


Fig. 3. – The Siverson asymmetry $A_N^{\sin \phi_S}$ for the $p^\uparrow p \rightarrow \text{jet} + \pi + X$ process as a function of p_{jT} , at fixed jet rapidity $\eta_j = 3.3$, for the RHIC energy $\sqrt{s} = 500$ GeV.

taken positive and saturated to an updated version of the bound obtained in ref. [17] by considering PHENIX data for the π^0 transverse-single-spin asymmetry at mid-rapidity. Similarly to the case of the Collins asymmetry, the two parameterizations give comparable results only in the p_{jT} region where the behaviour of the quark Siverson distribution is reasonably well constrained by SIDIS data (see again the dotted black vertical line).

4. – Test of the process dependence of the Siverson function

In the GPM approach one applies the TMD distribution and fragmentation functions extracted from SIDIS, considering them to be universal. Very recently [18] the azimuthal distribution of leading pions inside jets has been studied allowing for process dependence of the (quark) Siverson function. This is referred to as the colour gauge invariant (CGI) GPM [19]. Namely, we have taken into account the effects of initial (ISIs) and final state interactions (FSIs) between the active parton and spectator remnants in the different scattering sub-processes. Since the details of such interactions depend on the particular partonic reaction considered, they render the Siverson function non-universal (see [19] and references therein). The oft-discussed case is the difference between the FSIs in SIDIS and the ISIs in DY scattering which leads to the prediction of an opposite relative sign of the Siverson functions in the two processes. This is considered to be a crucial test of our understanding of single spin asymmetries in QCD and still has to be confirmed by experiments.

When applying similar reasoning to hadron production in pp collisions, typically the Siverson function has a more complicated colour factor structure since both ISIs and FSIs contribute. However, in the forward rapidity region the process under study is dominated by only one channel, $qg \rightarrow qg$, with the final quark identified with the observed jet. As a consequence, one finds that the predictions for the Siverson asymmetries obtained with and without inclusion of color gauge factors are comparable in size but with *opposite signs* [18], similarly to the DY case. Therefore the experimental observation of a sizable asymmetry could easily discriminate among the two approaches and test the universality properties of the Siverson function in hadronic reactions. Our results are shown in fig. 3, where we plot $A_N^{\sin \phi_S}$ as a function of the jet transverse momentum p_{jT} at $\eta_j = 3.3$, for the RHIC energy $\sqrt{s} = 500$ GeV, integrated over $\mathbf{k}_{\perp\pi}$ and z ($z \geq 0.3$). The predictions labeled SIDIS 1 and SIDIS 2 are similar in the intermediate $p_{jT} \leq 5.5$ GeV region

(corresponding to $x_F < 0.3$). This region is then optimal to test directly the process dependence of the Sivers function. Note that for $\sqrt{s} = 200$ GeV the behavior of our estimates would be similar to that shown in fig. 3, gaining almost a factor of 2 in size. However the range of p_{jT} covered would be narrower ($p_{jT} \leq 6.5$ GeV) and with $x_F \leq 0.3$ now corresponding to $p_{jT} \leq 2.5$ GeV.

Finally, as a natural extension of this analysis, one can consider single inclusive jet asymmetry in pp scattering, which is described solely by the Sivers function. The results obtained for $A_N^{\sin\phi_S}$ (not shown) look almost indistinguishable from the case of neutral pion-jet production (central panel of fig. 3).

5. – Conclusions

We have presented a study of the azimuthal asymmetries measurable in the distribution of leading pions inside a large- p_T jet produced in single-transverse polarized proton proton collisions for kinematic configurations accessible at RHIC. To this end, we have adopted a generalized TMD parton model approach with inclusion of spin and intrinsic parton motion effects both in the distribution and in the fragmentation sectors. In contrast to inclusive pion production, where the Sivers and Collins mechanisms cannot be separated, the leading-twist azimuthal asymmetries discussed above would allow one to single out the different effects by taking suitable moments of the asymmetries. This will give us the opportunity of testing the factorization and universality assumptions, and of gaining information on the size and *sign* of the various TMD functions in a kinematic region not covered by SIDIS data.

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