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Azimuthal distributions of pions inside jets at RHIC

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Summary. — We evaluate the azimuthal asymmetries for the distributions of leading pions inside a jet, produced in high-energy proton-proton collisions, in kinematic configurations currently under active investigation at RHIC. Adopting a transverse momentum dependent approach, which assumes the validity of a perturbative QCD factorization scheme and takes into account all the spin and intrinsic parton motion effects, we show how the main mechanisms underlying these asymmetries, namely the Sivers and the Collins effects, can be disentangled. Furthermore, we consider the impact of color-gauge invariant initial and final state interactions and suggest a method for testing the universality properties of the Sivers function for quarks.

PACS 13.85.Ni – Inclusive production with identified hadrons.
PACS 13.88.+e – Polarization in interactions and scattering.

1. – Introduction

We study the process $p^\uparrow p \to \text{jet}\,\pi + X$, where one of the protons is transversely polarized and the jet has a large transverse momentum. Specifically, we calculate the azimuthal asymmetries in the distribution of leading pions around the jet axis within the so-called transverse momentum dependent framework, which takes into account all the possible spin and intrinsic parton motion effects, assuming the validity of perturbative QCD factorization. Within this approach, the leading-twist azimuthal asymmetries are expressed in terms of convolutions of different transverse momentum dependent distribution and fragmentation functions (TMDs) [1]. We focus on the ones which are the most relevant from a phenomenological point of view, namely the Sivers distribution function and the Collins fragmentation function. By defining appropriate moments of the asymmetries, it is possible to separate the effects due to these two different TMDs, in strong analogy with the case of semi-inclusive deep inelastic scattering (SIDIS). This will also help in clarifying the role played by the Sivers and the Collins mechanisms in the sizable single-spin asymmetries observed at RHIC for inclusive pion production, where these two effects cannot be isolated.

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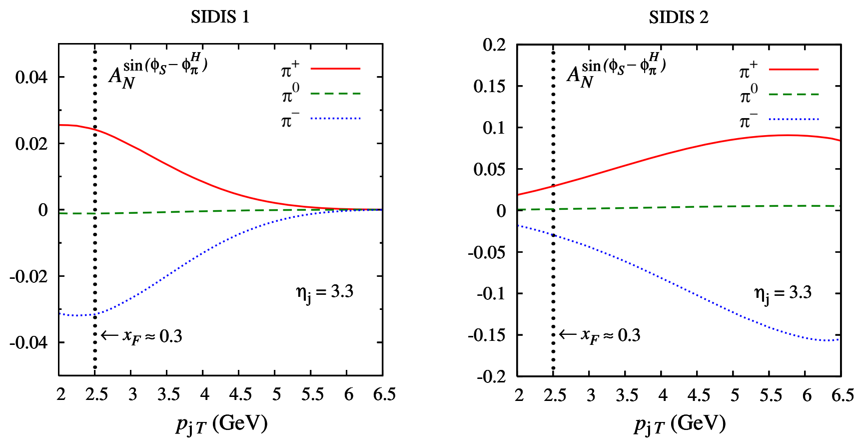

Fig. 1. – Estimate of the Collins asymmetry $A_N^{\sin(\phi_S-\phi_\pi^H)}$ in the GPM approach adopting the two sets of parameterizations SIDIS 1 (left panel) and SIDIS 2 (right panel), at $\sqrt{s} = 200\,\text{GeV}$ and fixed jet rapidity $\eta_{\text{j}} = 3.3$, as a function of the transverse momentum of the jet $p_{\text{j}T}$.

2. – Theoretical framework

In the hadronic center-of-mass, or in any other frame connected to it by a boost along the direction of the two colliding protons, the single-transverse polarized cross section for the process $p^\uparrow p \to \text{jet}\,\pi + X$, at leading order in pQCD, can be written as [1]

$$(1)\qquad \begin{aligned} 2\text{d}\sigma(\phi_S, \phi_\pi^H) \sim\ & \text{d}\sigma_0 + \text{d}\Delta\sigma_0 \sin\phi_S + \text{d}\sigma_1 \cos\phi_\pi^H + \text{d}\sigma_2 \cos 2\phi_\pi^H \\ & + \text{d}\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + \text{d}\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H) \\ & + \text{d}\Delta\sigma_2^- \sin(\phi_S - 2\phi_\pi^H) + \text{d}\Delta\sigma_2^+ \sin(\phi_S + 2\phi_\pi^H), \end{aligned}$$

with ϕ_S being the azimuthal angle of the proton spin vector S relative to the jet production plane and ϕ_π^H being the azimuthal angle of the three-momentum of the pion around the jet axis, as measured in the helicity frame of the fragmenting quark or gluon [1].

By means of the azimuthal moments

$$(2)\qquad A_N^{W(\phi_S,\phi_\pi^H)} = 2\,\frac{\int \text{d}\phi_S \text{d}\phi_\pi^H\, W(\phi_S, \phi_\pi^H)\,[\text{d}\sigma(\phi_S, \phi_\pi^H) - \text{d}\sigma(\phi_S + \pi, \phi_\pi^H)]}{\int \text{d}\phi_S \text{d}\phi_\pi^H\, [\text{d}\sigma(\phi_S, \phi_\pi^H) + \text{d}\sigma(\phi_S + \pi, \phi_\pi^H)]}\,,$$

where $W(\phi_S, \phi_\pi^H)$ is one of the circular functions in (1), it is possible to single out the different angular modulations of the cross section. An estimate of the upper bounds of all the azimuthal moments has been given in [1] for the ongoing experiments at RHIC. In the following we will focus only on those (sizable) asymmetries that receive contributions from the Sivers and the Collins functions. These TMDs are known and their parameterizations have been determined from independent fits to e^+e^- and SIDIS data.

3. – Collins and Sivers asymmetries in the generalized parton model

In this section the Collins and Sivers asymmetries are evaluated at the RHIC energy $\sqrt{s} = 200\,\text{GeV}$ and at forward jet rapidity, within the generalized parton model (GPM) approach, according to which TMDs are considered to be process independent [1]. In our analysis, two different sets of parameterizations for the TMDs have been used, named SIDIS 1 and SIDIS 2 [1].

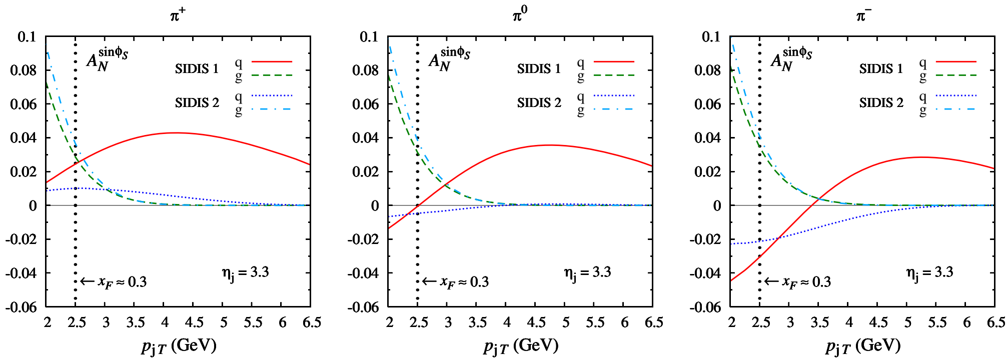

Fig. 2. – The quark and gluon contributions to the Sivers asymmetry $A_N^{\sin\phi_S}$ obtained in the GPM approach adopting the two sets of parameterizations SIDIS 1 and SIDIS 2, at $\sqrt{s} = 200\,\text{GeV}$ and fixed jet rapidity $\eta_{\text{j}} = 3.3$, as a function of the transverse momentum of the jet $p_{\text{j}T}$.

The Collins asymmetry $A_N^{\sin(\phi_S-\phi_\pi^H)}$, presented in fig. 1, is mainly given by a convolution of the Collins fragmentation function and the transversity distribution. We note that our prediction of a negligible value of $A_N^{\sin(\phi_S-\phi_\pi^H)}$ for neutral pions has been confirmed by preliminary RHIC data [2]. The Sivers asymmetry $A_N^{\sin\phi_S}$ is shown in fig. 2. Its quark and gluon contributions are depicted separately, but cannot be disentangled experimentally. In order to provide an estimate of the unknown gluon Sivers function, we have taken it positive, saturating an upper bound derived from the analysis of PHENIX data for central production of neutral pions [5]. Recently the STAR Collaboration at RHIC reported preliminary data on the Sivers asymmetry for neutral pions, which turns out to be larger than zero [2] and compatible with our results obtained within the GPM framework.

The vertical dotted lines in figs. 1 and 2 delimit the range $x_F \leq 0.3$ in which TMDs are presently constrained by SIDIS data. Their extrapolation beyond this region leads to results plagued by large uncertainties. Hence a measurement of the proposed observables would shed light on the large x behavior of the Sivers and the transversity distribution functions.

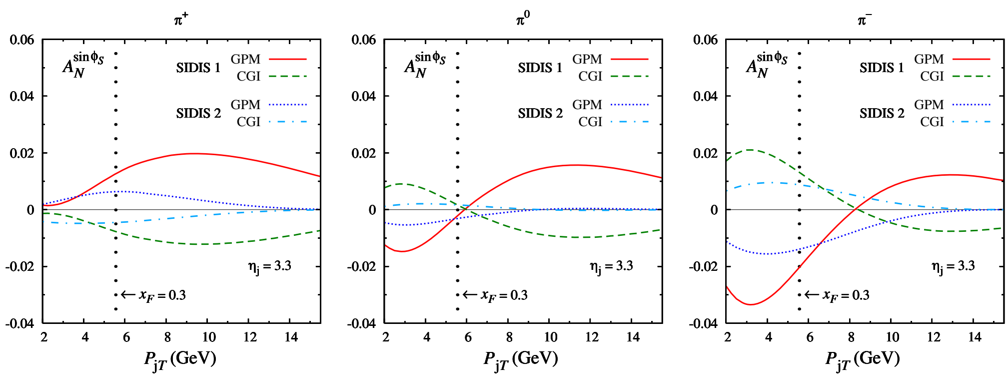

Fig. 3. – The quark contribution to the Sivers asymmetry $A_N^{\sin\phi_S}$ calculated in the GPM and in the CGI GPM approaches adopting two sets of parameterizations, SIDIS 1 and SIDIS 2, at $\sqrt{s} = 500\,\text{GeV}$ and jet rapidity $\eta_{\text{j}} = 3.3$, as a function of the jet transverse momentum $p_{\text{j}T}$.

4. – The Sivers asymmetry in the color-gauge invariant parton model

In contrast to the GPM approach adopted in the previous section, in the color-gauge invariant (CGI) GPM [3, 4] TMDs can be process dependent, due to the effects of initial (ISI) and final (FSI) state interactions. A fundamental example (still to be confirmed by experiments) is provided by the ISI in SIDIS and the FSI in the DY processes, which lead to two quark Sivers functions with an opposite relative sign. For the reaction under study the quark Sivers function has in general a more involved color structure, since both ISI and FSI contribute [4]. However, at forward rapidities only the $qg \to qg$ channel gives a dominant contribution. As a consequence, our predictions for the Sivers asymmetries obtained with and without ISI and FSI are comparable in size but have opposite signs, as depicted in fig. 3 at the RHIC energy $\sqrt{s} = 500\,\text{GeV}$. Therefore the measurement of a sizable asymmetry would verify one of the two approaches and test the process dependence of the Sivers function.

Finally, we have also studied single-spin asymmetries for inclusive jet production, which are described solely by the Sivers function [1, 4]. Our predictions for $A_N^{\sin\phi_S}$ turn out to be very similar to the ones for jet-neutral pion production, shown in the central panel of fig. 3. According to preliminary data reported by the AnDY Collaboration at RHIC, which have been analyzed very recently in the different framework of the twist-3 collinear formalism [6], the Sivers asymmetry for $p^\uparrow p \to \text{jet} + X$ is small and positive [7]. These results seem to agree with the GPM predictions only for $x_F \geq 0.3$ and suggest the need for further studies along these lines, aiming to confirm or disprove the validity of our factorization hypotesis and to test the universality properties of the different TMDs. Currently, a further comparison with experiments is ongoing [8], in which the imposed kinematic cuts are as close as possible to the ones used at RHIC in the analysis of the azimuthal asymmetries for the processes $p^\uparrow p \to \text{jet}\,\pi + X$ and $p^\uparrow p \to \text{jet} + X$.

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