Spectator model for TMDs

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Within the framework of a spectator diquark model of the nucleon, involving both scalar and axial vector diquarks, all the leading-twist T-even and T-odd transverse-momentum-dependent (TMD) parton distribution functions are calculated. The final analytic results, combined with a proper fitting of the model free parameters, allow fruitful comparisons with experimental parametrizations, when available. Particular attention is devoted to the phenomenology of single- and double-spin-asymmetries, in SIDIS and Drell-Yan processes, for which model predictions are presented and confronted with HERMES@DESY and NA10@CERN experimental results.

1 Introduction

Despite our fair knowledge of the longitudinal low-energy structure of the nucleon, encoded in the well known non-perturbative unpolarized and helicity collinear parton densities, as explored in deep-inelastic-scattering (DIS) processes by employing high energy leptonic probes, its transverse momentum/spin structure is still poorly understood: on the one hand, the transverse spin distribution, though appearing at leading twist in an expansion of the parton model quark-quark correlator, decouples from inclusive DIS, due to its chiral odd nature; on the other hand, transverse-momentum-distributions (TMDs), describing the probability to find, in a hadron, a parton with light-cone longitudinal momentum fraction x and transverse momentum $\boldsymbol{p}_T$ with respect to the direction of the parent hadron momentum, are still poorly constrained by experiments. Nevertheless, these functions deserve particular attention: requiring to go beyond the usual collinear approximation, they in fact do potentially encode information on the orbital angular momentum (OAM) content of the corresponding partons, and can thus shed new light on still not fully understood issues such as the proton spin crisis, possible spin-orbit correlations and the theoretical origin of single-spin-asymmetries (SSA), this latter topic being strictly connected with the existence of non-zero Time-odd TMDs.

2 TMDs in a spectator diquark model

Nowadays, we still have poor phenomenological information on TMDs, especially concerning their $\boldsymbol{p}_T$ dependence, even though the analysis of azimuthal spin asymmetries both in hadron-hadron collisions and in semi-inclusive-deep-inelastic-scattering (SIDIS) allowed a first extraction of the Sivers function [2], a T-odd TMD describing how the parton distribution is distorted by the transverse polarization of the parent hadron, and an analogous attempt to extract the T-odd Boer-Mulders function, i.e. the distribution of transversely polarized partons in an unpolarized hadron [3]. All of the above studies assume an x-$\boldsymbol{p}_T$ factorized form for all TMDs, with flavor-independent Gaussian $\boldsymbol{p}_T$-shapes, although there is no compelling physical reason for such a choice: e.g. an x-dependence of the $\boldsymbol{p}_T$-distribution was already introduced to describe data at low x [5], and strong indications of x-$\boldsymbol{p}_T$ factorization breaking have been recently obtained in a chiral-quark-soliton-model [6]; furthermore, lattice simulations clearly call for the inclusion of a quark flavour-dependence of transverse-momentum-disptributions [7], while the gaussian ansatz is useful in allowing to analytically performed the involved deconvolutions, but it is known to be inadequate for high transverse momenta, and in general it does not rely upon strong physical grounds, since there is no compelling physical reason to choose it even at low $\boldsymbol{p}_T$ [8]; moreover, contributions from partons with non-zero OAM have to vanish at $\boldsymbol{p}_T = 0$ an thus cannot be described by a simple gaussian shape. Model studies of TMDs are then not only useful but highly recommended.

The spectator diquark model [9, 10] consists in inserting a completeness relation into the quark-quark correlator hadronic matrix element and truncate, at tree-level, the sum over final states to a single on-shell spectator state with mass M_X and diquark quantum numbers, which also automatically provides an off-shellness condition for the corresponding active quark. It is s a simple but powerful testbench to investigate matters of principle (e.g. it was employed in [4] to prove the existence of non-zero T-odd functions), but if properly refined it also allows phenomenological studies. At this purpose, we included both scalar and axial-vector diquarks, these latter needed in order to describe the down quark distributions, and we further distinguish between isoscalar (ud-like) and isovector (uu-like) spectators. The relative phases necessary to produce T-odd structures are generated by approximating (at $\mathcal{O}(\alpha_s)$) the gauge link operator, ensuring color gauge invariance for the QCD correlators, with a one gluon-exchange mechanism. We concentrate on a particular choice of the vector diquark polarization states and on a dipolar form-factor at the nucleon-quark-diquark vertex, and we particularly focus on a possible interpretation of the model results in terms of light-cone wave functions, which in turn gives a more general and physical dress to the results and opens the way to a wider range of applications. The free parameters of the model are fixed by reproducing the phenomenological parametrization of unpolarized and longitudinally polarized parton distributions at the lowest available scale.

In the following, we briefly summarize the main results of our analysis [10]:

- analytic results have been obtained for all leading twist TMDs, by using a dipolar form factor and the light-cone choice for the axial-vector diquark polarization sum, physically representing the propagation of just transverse degrees of freedom; the theoretical motivation behind this last preference is that it guarantees, unlike other more common choices, that in DIS processes the (charged) axial-vector diquark only contributes to the longitudinal structure function F_L (the same situation which naturally occurs for the scalar case): this surely implies a violation of the Callan-Gross relation, but leaves unchanged the leading-order interpretation of the transverse structure function F_T as a charge-weighted sum of quark distributions, thus limiting the phenomenological impact represented by the presence of the diquarks;

- the connection with the formalism of light-cone wave-functions (LCWF), which naturally encode angular momentum conservation, grants the possibility to explore the OAM content of the model: the presence of non-zero p-wave ($L_{q,Dq} = 1$) components drives us to the conclusion that the ground state of a quark inside a Nucleon is not $J^P = (1/2)^+$, hence the nucleon wave-function could exhibit a violation of the simple SU(4) spin-isospin symmetry: this in turn modifies the model flavour decomposition, which is described in terms of three free parameters, fixed by the fitting procedure; LCWF overlap representations have been devised for T-even and T-odd TMDs, in this latter case requiring the inclusion of a final-state-interaction (FSI) kernel, with universal character, to mimic the one-gluon-exchange T-odd phases;

- the model results clearly shows an explicit x-$\boldsymbol{p}_T$ factorization breaking, with dipolar, rather than gaussian, x-dependent $\boldsymbol{p}_T$ shapes (due not only to the form-factor choice, but also to the quark propagator structure), and also produce quite different results for u and d quarks, thus encoding a strong flavour-dependence; the presence of p-wave LCWFs brings about a non-monotonic $\boldsymbol{p}_T$ profile, due to the their vanishing behaviour at zero transverse-momentum;

- a quite good general agreement is found between model results and the available parametrizations for the transversity distribution and the Sivers function, though the u quark distributions are usually better reproduced than the d quark ones; the model predicts the correct signs and magnitudes of the u and d Sivers and Boer-Mulders functions, and also displays a change of sign (at $x \approx 0.5$) for $h_1^u(x)$, a possibility non taken into account by present parametrizations [11].

3 Predictions for spin asymmetries

Our version of the spectator diquark model has been also employed to make predictions for a wide range of spin asymmetries for the SIDIS and Drell-Yan processes, at the purpose to arrange a comparison between model curves and experimental points, when available, as well as to yield useful indications for future facilities. Concerning the SIDIS process, a SSA is generally defined as

$$A_{UT}^{w} \equiv \frac{\int \mathrm{d}\phi_S \, \mathrm{d}\boldsymbol{P}_{h\perp} \, w(\phi_S, \phi_h, |\boldsymbol{P}_{h\perp}|) \left(\mathrm{d}^6\sigma_{UT}^{\uparrow} - \mathrm{d}^6\sigma_{UT}^{\downarrow} \right)}{\int \mathrm{d}\phi_S \, \mathrm{d}\boldsymbol{P}_{h\perp} \left(\mathrm{d}^6\sigma_{UT}^{\uparrow} + \mathrm{d}^6\sigma_{UT}^{\downarrow} \right)} \,, \tag{1}$$

where $\mathrm{d}^6\sigma_{UT}^{\uparrow,\downarrow}$ is the fully differential cross section for a target proton with polarization parallel or anti-parallel to a certain transverse (with respect to the reaction plane) direction, and $w(\phi_S, \phi_h, |\boldsymbol{P}_{h\perp}|)$ is a possible weight factor (for notations and conventions, see Ref. [12]). Although unweighted SSA can be evaluated by a suitable numerical treatment, we choose to focus on a particular class of weighted asymmetries, thus exploiting the corresponding possibility to analytically perform the required convolution integrals over the partons transverse momenta. Results have been obtained, among others, for two particularly interesting SSA, namely the Collins and Sivers one, $A_{UT}^{(|\boldsymbol{P}_{h\perp}|/M)\,\sin(\phi_h+\phi_S)}$ and $A_{UT}^{(|\boldsymbol{P}_{h\perp}|/M)\,\sin(\phi_h-\phi_S)}$, the former being proportional to the product of transversity parton density, $h_1(x)$, and the first transverse moment of the Collins fragmentation function (FF), $H_1^{\perp\,(1)}(z)$, and the latter to the product of the first moment of the Sivers function, $f_{1T}^{\perp\,(1)}(x)$, and the unpolarized fragmentation function, $D_1(z)$. We limit ourselves to the valence sector and explicitly use our model results for the distribution functions involved, while the D_1 FF is taken from a recent parametrization [13] and for $H_1^{\perp}$ we adopt the diquark model results of Ref. [14]. In figures 1 and 2 we show a comparison of our model results for the Sivers and Collins SIDIS weighted SSA with the corresponding experimental data collected by the HERMES@DESY experiment [15], focusing on the x-dependence of the asymmetries: a good qualitative agreement is obtained, though the large experimental error bars still do not provide strong constraints.

We also present model predictions for the Lam-Tung sum rule violation in unpolarized Drell-Yan process, namely the results for the $\nu/2$ coefficient of the $\cos 2\phi$ part (in the Collins-Soper frame) entering the final lepton pair angular distribution. While pQCD predicts a vanishing value for this ν function, the TMD parton model (non-perturbative) picture can yield a non-zero result, in terms of the convolution, over transverse-momenta, of two Boer-Mulders $h_1^\perp$ functions ($\mathcal{F}[\ldots] \equiv \int \mathrm{d}^2\boldsymbol{p}_{T1}\, \mathrm{d}^2\boldsymbol{p}_{T2}\; \delta^{(2)}(\boldsymbol{p}_{T1}+\boldsymbol{p}_{T2}-\boldsymbol{q}_T)\ \ldots$):

$$\frac{\nu}{2} = \frac{\sum_q e_q^2\, \mathcal{F}\left\{\left[\dfrac{2\,(\hat{\boldsymbol{q}}_T\cdot\boldsymbol{p}_{T1})(\hat{\boldsymbol{q}}_T\cdot\boldsymbol{p}_{T2}) - \boldsymbol{p}_{T1}\cdot\boldsymbol{p}_{T2}}{M_1\, M_2}\right] h_1^{\perp\, q}(x_1,\boldsymbol{p}_{T1}^2)\, h_1^{\perp\, \bar{q}}(x_2,\boldsymbol{p}_{T2}^2)\right\}}{\sum_q e_q^2\, \mathcal{F}\Big\{f_1^q(x_1,\boldsymbol{p}_{T1}^2)\, f_1^{\bar{q}}(x_2,\boldsymbol{p}_{T2}^2)\Big\}}\,. \qquad (2)$$

By considering the $\pi^- W \to \mu^+\mu^- X$ process, studied in the NA10@CERN experiment [16], and limiting as usual to the valence sector, one focus on the $\bar{u}(\pi^-)u(p)$ annihilation channel, where the $\bar{u}(\pi^-)$ distribution is identified with the $\bar{u}(\bar{p}) \approx u(p)$ one. In figure 3, we confront our model prediction for the $2\nu - (1-\lambda)$ coefficients combinations, as a function of the virtual photon transverse momentum $\boldsymbol{q}_T$, with the NA10 data: a general agreement is found, both concerning the trend and the magnitude of the asymmetry. In the same figure, we also present some predictions concerning the Sivers weighted asymmetry for the $\pi^\pm p^\uparrow \to \mu^+\mu^- X$ Drell-Yan process on transversely polarized protons, which is of interest for the COMPASS@CERN collaboration.

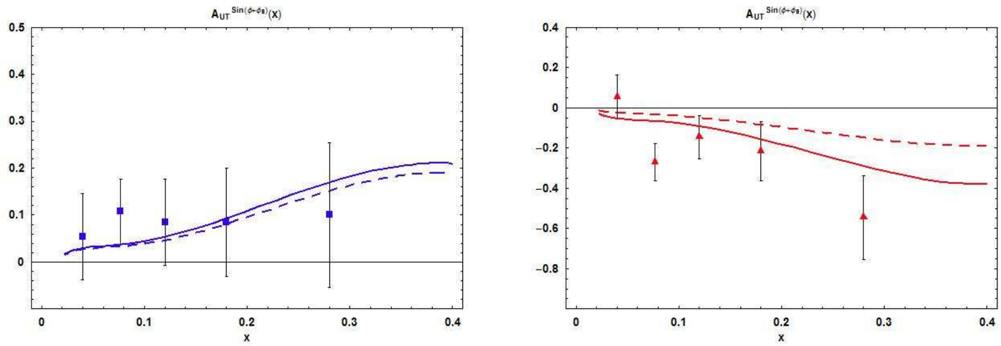

Figure 1: Diquark model vs experiment for the Collins SSA $A_{UT}^{(|\boldsymbol{P}_{h\perp}|/M)\,\sin(\phi_h+\phi_S)}(x)$ in SIDIS: $ep^\uparrow \to e'\pi X$. Solid lines: no Collins FF evolution; dashed lines: Collins FF evolved mimicking the D_1 scale evolution, from Ref. [13] (D_1 FF always properly evolved at the experimental scale). Data from HERMES@DESY ($Q^2 = 2.5$ GeV^2) [15]. Left: π^+ production; right: π^- production.

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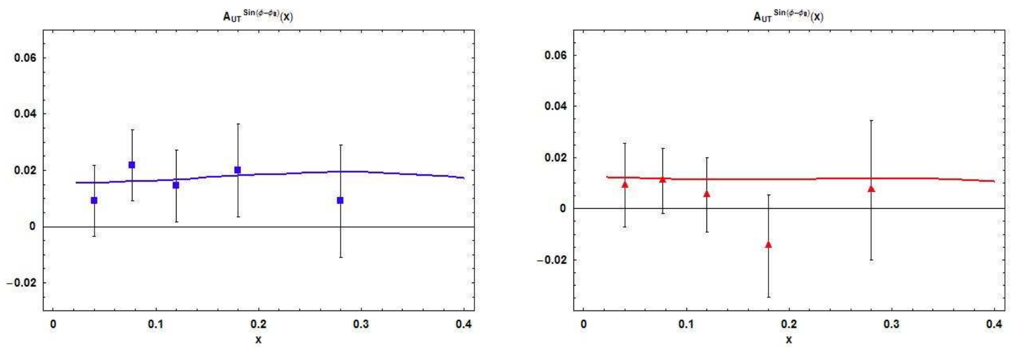

Figure 2: Same as in figure 1, but for the Sivers asymmetry $A_{UT}^{(|\boldsymbol{P}_{h\perp}|/M)\ \sin(\phi_h+\phi_S)}(x)$. D_1 FF always properly evolved at the experimental scale, $Q^2 = 2.5\ \mathrm{GeV}^2$ [13].

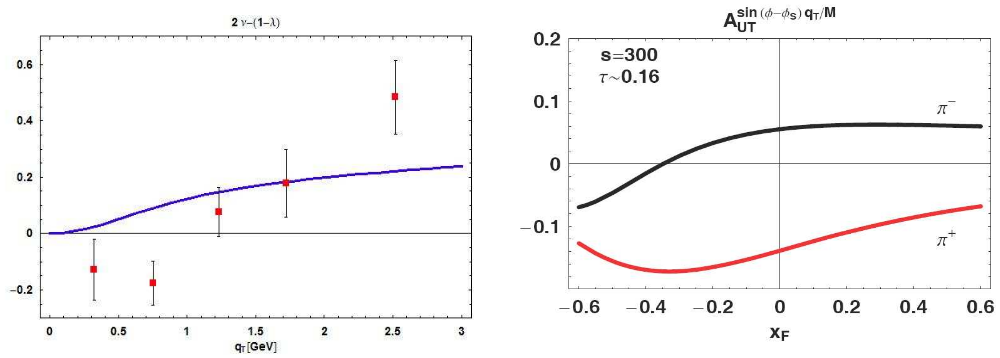

Figure 3: Left: model vs experiment for the $2\nu-(1-\lambda)$ coefficients combination, concerning the lepton pair angular distribution in unpolarized Drell-Yan; data from [16]. Right: diquark model predictions for the Sivers effect in Drell-Yan process, e.g. for COMPASS@CERN.

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