Reweighting the quark Sivers function with STAR jet data

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Abstract

The Bayesian reweighting procedure is applied for the first time to a TMD distribution, the quark Sivers function extracted from SIDIS data. By exploiting the recent published single spin asymmetry data for the inclusive jet production in $p^{\uparrow}p$ collisions from the STAR collaboration at RHIC, we show how such a procedure allows to incorporate the information contained in the new data set, without the need of re-fitting, and to explore a much wider x region compared to SIDIS measurements. The reweighting method is also extended to the case of asymmetric errors, and the results show a significant improvement on the knowledge of the quark Sivers function.

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1 Introduction

The three-dimensional structure of nucleons can be described in terms of Transverse Momentum Dependent (TMD) quark and gluon distributions. At leading twist, among the eight independent quark TMDs, the Sivers function $f_{1T}^{\perp}$ [1, 2] is one of the most studied and plays a seminal role. It is a genuine TMD distribution that encodes the correlation between the transverse polarization of the nucleon and the intrinsic transverse momentum of the quarks inside the nucleon. At variance with unpolarized TMD PDFs, it is also expected to be process dependent, changing sign when probed in Semi-Inclusive DIS (SIDIS) and Drell-Yan (DY) processes [3,4]. A non-zero Sivers function is also an indirect signal of nonvanishing parton orbital angular momentum.

Here, we report on the findings of Ref. [5], where we applied, for the first time, a reweighting procedure to a TMD density.

2 Formalism

The quark Sivers function is usually extracted from the SIDIS azimuthal asymmetries $A_{UT}^{\sin(\phi_h-\phi_S)} \equiv F_{UT}^{\sin(\phi_h-\phi_S)}/F_{UU} = \mathcal{C}\left[f_{1T}^{\perp q} D_1^q\right]/\mathcal{C}\left[f_1^q D_1^q\right]$. At the same time, its corresponding effect could be responsible for the transverse single-spin asymmetries (SSAs) measured in $p^\uparrow p \to \text{jet}\, X$ processes. At variance with SIDIS processes, for which we detect two separate energy scales ($Q_2 \gg Q_1 \sim \Lambda_{\text{QCD}}$), in this latter class of reactions only a single, hard scale is measured. Although in principle such single-scale processes are described within the collinear twist-3 approach [6], one can also use some alternative, phenomenological approaches such as the generalized parton model (GPM) [7–9] and its color gauge invariant version (CGI-GPM) [10–13]. Within these effective models, a factorized formulation in terms of TMDs is assumed as a starting point. In the GPM, the Sivers function is considered to be the same as extracted in SIDIS measurements, and no sign-change effect is taken into account. The sign change is recovered in the CGI-GPM, by including initial and final state interactions within a one-gluon exchange approximation. In the spirit of testing the compatibility of the extraction of the Sivers function from SIDIS data, we analyzed the recent SSA data for inclusive jet production in pp collisions from the STAR Collaboration at RHIC [14], within the GPM and CGI-GPM approaches.

The SSA for inclusive jet production in polarized pp collisions is defined as

$$A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \equiv \frac{d\Delta\sigma}{2d\sigma}. \tag{1}$$

In the CGI-GPM approach, numerator and denominator of the asymmetry are given by [10]:

$$d\Delta\sigma^{\text{CGI}-\text{GPM}} = \frac{2\alpha_s^2}{s} \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{x_a\, x_b}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b} \left(-\frac{k_{\perp a}}{M_p}\right) f_{1T}^{\perp a}(x_a, k_{\perp a}) \cos\varphi_a \\ \times f_{b/p}(x_b, k_{\perp b}) H_{ab\to cd}^{\text{Inc}}\, \delta(\hat{s}+\hat{t}+\hat{u}), \tag{2}$$

$$d\sigma = \frac{\alpha_s^2}{s} \sum_{a,b,c,d} \int \frac{dx_a\, dx_b}{x_a\, x_b}\, d^2\boldsymbol{k}_{\perp a}\, d^2\boldsymbol{k}_{\perp b} f_{a/p}(x_a, k_{\perp a}) f_{b/p}(x_b, k_{\perp b}) H_{ab\to cd}^{U}\, \delta(\hat{s}+\hat{t}+\hat{u}), \tag{3}$$

where α_s is the strong coupling constant, s is the pp center-of-mass energy, and $\hat{s}$, $\hat{t}$, $\hat{u}$ are the usual Mandelstam variables for the partonic subprocess $ab \to cd$. Moreover, $f_{b/p}(x_b, k_{\perp b})$ is the unpolarized TMD distribution for parton b. Notice that in a leading-order approach the jet is identified with the final parton c. Finally, $H_{ab\to cd}^{\text{Inc}}$'s are the perturbatively calculable hard scattering functions, that can be found in Ref. [10] for the case when $a = q, \bar{q}$. The GPM expressions are obtained from Eq. (2) by simply replacing $H_{ab\to cd}^{\text{Inc}}$ with the standard unpolarized partonic cross sections, $H_{ab\to cd}^{U}$.

2.1 The reweighting procedure

In order to assess the impact of the new STAR data on the extraction of the Sivers function, we adopt a reweighting procedure. Such a technique has been already used in the context of usual collinear PDFs [15–18], but so far it has never been applied to a TMD density.

In brief, the reweighting procedure works as follows. Let us consider a model for a TMD depending on a set of parameters $\boldsymbol{a} = \{a_1, \cdots, a_n\}$ with prior probability distribution $\pi(\boldsymbol{a})$. Defining the χ^2 for a specific set of data $\boldsymbol{y}$ as:

$$\chi^2[\boldsymbol{a},\boldsymbol{y}] = \sum_{i,j=1}^{N_{\rm dat}} (y_i[\boldsymbol{a}] - y_i)\, C_{ij}^{-1} (y_j[\boldsymbol{a}] - y_j)\,, \tag{4}$$

one finds the best fit $\boldsymbol{a}_0$, by usual χ^2 minimization, that renders a minimum value χ_0^2. The uncertainty on the extracted TMD is then calculated by generating $k = 1, \cdots, N_{\rm set}$ Monte Carlo (MC) sets $\boldsymbol{a}_k$[1]. Each of these sets have a corresponding $\chi_k^2[\boldsymbol{a}_k, \boldsymbol{y}]$ (calculable using Eq. (4)) within a certain tolerance: $\chi_k^2 \in [\chi_0^2 : \chi_0^2 + \Delta\chi^2]$. By using Bayes theorem, one calculates the posterior density given the data:

$$\mathcal{P}(\boldsymbol{a}|\boldsymbol{y}) = \frac{\mathcal{L}(\boldsymbol{y}|\boldsymbol{a})\,\pi(\boldsymbol{a})}{Z}\,, \tag{5}$$

where $\mathcal{L}(\boldsymbol{y}|\boldsymbol{a})$ is the likelihood and $Z \equiv \mathcal{P}(\boldsymbol{y})$ is the evidence. Following Refs. [15, 17, 18], we adopt an exponential form of the likelihood, with weights:

$$w_k(\chi_k^2) = \frac{\exp\left\{-\frac{1}{2}\,\chi_k^2[\boldsymbol{a}_k, \boldsymbol{y}]\right\}}{\sum_i w_i} \tag{6}$$

that can be used to calculate expectation values and variances of an observable $\mathcal{O}[\boldsymbol{a}_k]$ as $\mathrm{E}[\mathcal{O}] \simeq \sum_k w_k\, \mathcal{O}(\boldsymbol{a}_k)$, $\mathrm{V}[\mathcal{O}] \simeq \sum_k w_k\, (\mathcal{O}(\boldsymbol{a}_k) - \mathrm{E}[\mathcal{O}])^2$ respectively. Such quadratic forms render only symmetric uncertainties, and to properly take into account non Gaussian distributions, we extend this method calculating asymmetric uncertainties. In what follows, the median is used at central value, and the asymmetric errors are given at 2σ confidence level (CL).

New data $\boldsymbol{y}_{\rm new}$ will change the weights $w_k \to w_k^{\rm new}\left(\chi_k^2 + \chi_{{\rm new},k}^2\right)$ and so the posterior densities will vary, indicating the impact of such new data on the extracted TMD.

3 Results

We apply the Bayesian reweighting procedure of Section 2.1 to the following quark Sivers function parametrization, extracted in Ref. [20] from $N_{\rm dat}^{\rm SIDIS} = 220$ datapoints[2]:

$$\Delta^N f_{q/p^\uparrow}(x, k_\perp) = \frac{4 M_p k_\perp}{\langle k_\perp^2 \rangle_S}\, \Delta^N f_{q/p^\uparrow}^{(1)}(x)\, \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_S}}{\pi \langle k_\perp^2 \rangle_S}\,. \tag{7}$$

Here, $q = u,\, d$, and $\Delta^N f_{q/p^\uparrow}^{(1)}(x)$ is the Sivers first $k_\perp$-moment:

$$\Delta^N f_{q/p^\uparrow}^{(1)}(x) = \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{4M_p} \Delta^N f_{q/p^\uparrow}(x, k_\perp) \equiv -f_{1T}^{\perp(1)q}(x) = N_q\,(1-x)^{\beta_q}\,. \tag{8}$$

As new evidence, we consider the recent STAR data [14], that have a wide coverage in $x_F = 2P_L/\sqrt{s} \in [0.1 : 0.6]$. We stress that such a region is complementary to SIDIS measurements, and can give important information on the poorly constrained large-x behavior of the Sivers function. Notice also that, as these data are referred to electromagnetic jets, we select the

[1] In Ref. [5], we generated $N_{\rm set} = 2 \cdot 10^5$ MC sets adopting a Markov-Chain MC procedure with Metropolis-Hastings algorithm [19].

[2] The corresponding $\Delta\chi^2$ for $N = 5$ parameters at 2σ CL is $\Delta\chi^2 = 11.31$.

subset of data with photon multiplicity $n_\gamma > 2$, as it is not contaminated by single photon or π^0 production contributions.

In Fig. 1 we show the results of the reweighting procedure for the A_N predictions at STAR kinematics in the GPM (left, red) and the CGI-GPM (right, green) approaches. The grey hatched curves and bands are relative to the predictions based on SIDIS data only, while the solid colorful ones are the reweighted curves, dubbed as "SIDIS+jet". Although the predictions from SIDIS already describe the data within large uncertainties, the reweighted curves show a good improvement and reduced errors.

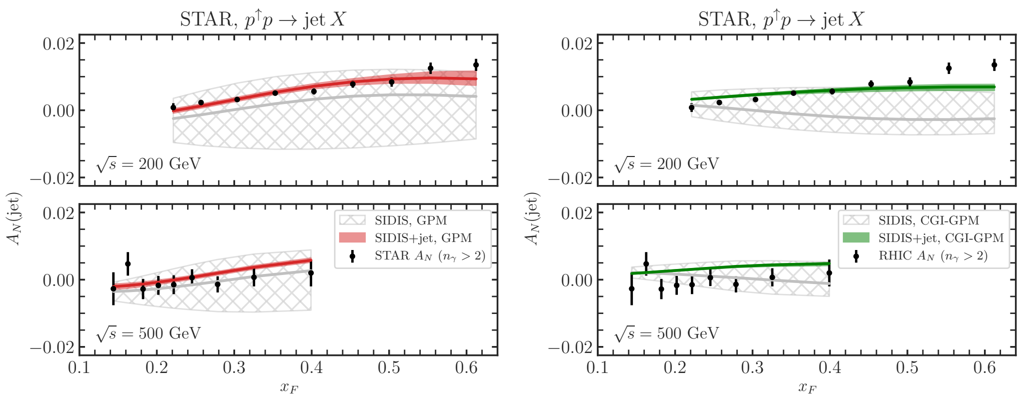

Figure 1: Results for the reweighting procedure from SIDIS and A_N jet data in the GPM (left) and CGI (right) formalisms, compared with STAR measurements [14] at $\sqrt{s} = 200$ GeV (upper panels) and $\sqrt{s} = 500$ GeV (lower panels). Uncertainty bands are at 2σ CL. The results before (hatched grey bands) and after (solid red/green bands) reweighting are shown.

To check the impact on the parameter and χ^2 distributions, we show in Fig. 2 the comparison between the priors from SIDIS and the posteriors after the reweighting. Some comments are in order: 1. the Gaussian width $\langle k_\perp^2 \rangle_S$ does not vary much; 2. the β_q parameters, governing the large-x behavior of the Sivers function, change, but in a different way when applying the GPM or CGI-GPM formalisms; 3. while the normalization for the u-quark Sivers function N_u changes slightly, N_d is smaller in size in the CGI-GPM, but $f_{1T}^{\perp,d}$ is less suppressed at large x; 4. the χ^2_{dof} after the reweighting for $N_{\text{dat}}^{\text{SIDIS+jet}} = 238$ slightly favors the GPM approach. For reference, we address the reader to Table I of Ref. [5].

Looking now at Fig. 3, one can see the impact of the reweighting procedure on the extracted functions. On the left panel, we compare the fitted first $k_\perp$-moments before and after the reweighting in the GPM and CGI-GPM approaches. The uncertainties are reduced in both cases, especially at large x. This appears more evident by looking at the right panel of Fig. 3, where the first moments, normalized to their central values, are plotted. It is then clear that these new STAR data allows to constrain the quark Sivers function at large values of x, a region left unconstrained by current SIDIS measurements.

4 Conclusion

We have presented the first application of the Bayesian reweighting method to a TMD density, the quark Sivers function extracted from SIDIS data. Such a procedure has also been extended to the case of asymmetric uncertainties. The new STAR data allows to improve and extend the knowledge on the Sivers function at large x. Our findings also point to a compatibility between

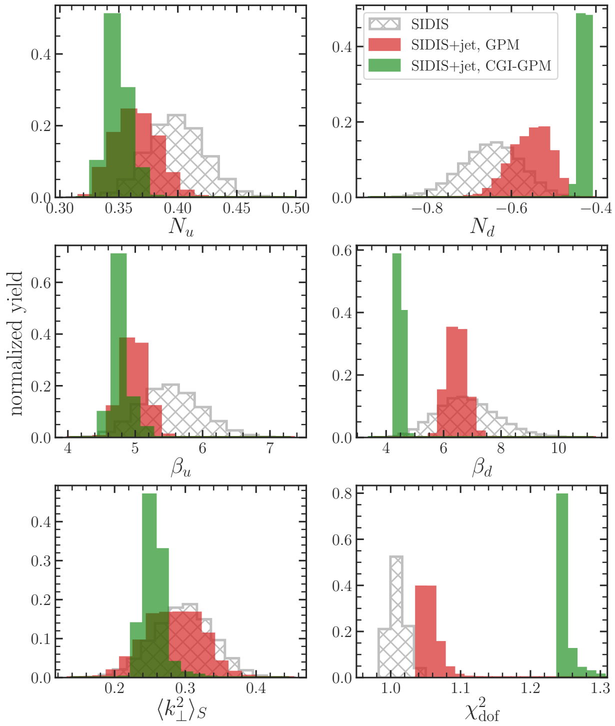

Figure 2: Parameters and $\chi^2_{\rm dof}$ probability densities. Hatched histograms refer to the priors coming from SIDIS data only. Color code is the same as in Fig. 1.

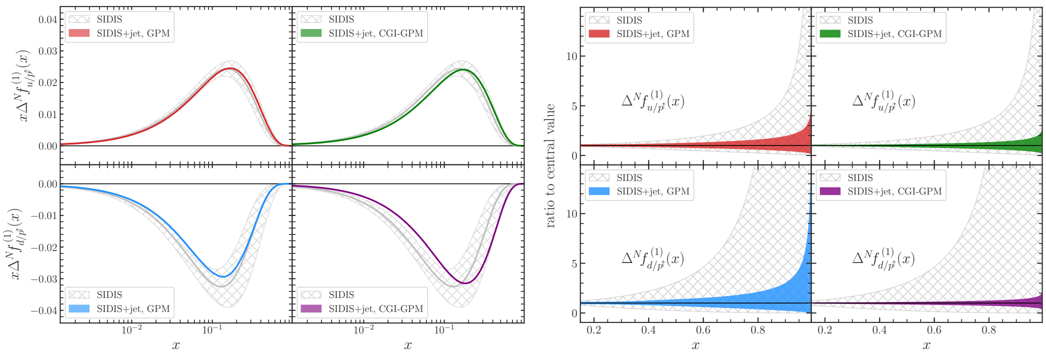

Figure 3: Comparison between the Sivers first $k_\perp$-moments (left) and their values normalized to the corresponding central value (right) from SIDIS data and their reweighted SIDIS+jet counterparts in the GPM (left panels) and CGI-GPM (right panels) framework. In both plots, results for u- (upper panels) and d-quarks (lower panels) are shown. Bands correspond to a 2σ CL.

SIDIS and inclusive jet data.

A natural extension of this exploratory study will be a global analysis including also A_N data for inclusive pion production. This would allow for a simultaneous reweighting of the Sivers, transversity and Collins functions. We expect as well that forthcoming measurements at COMPASS [21], JLab [22] and the future Electron Ion Collider [23, 24] will play a crucial role in unraveling the nucleon structure in its full complexity.

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