Update on transversity and Collins functions from SIDIS and e^+e^- data

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We present an update of a previous global analysis of the experimental data on azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS), from the HERMES and COMPASS Collaborations, and in $e^+e^- \to h_1h_2X$ processes, from the Belle Collaboration. Compared to the first extraction, a more precise determination of the Collins fragmentation function and the transversity distribution function for u and d quarks is obtained.

1. Introduction

The study of the nucleon spin structure has recently made remarkable progress. Our understanding of the longitudinal degrees of freedom, concerning both the intrinsic motion and the spin content of partons inside unpolarized and longitudinally polarized fast moving nucleons, respectively encoded in the unpolarized quark distribution, $q(x)$, and the helicity distribution, $\Delta q(x)$, is now quite accurate.

A full knowledge of the nucleon quark structure in the collinear, $\boldsymbol{k}_\perp$ integrated, configuration cannot be reached without information on the third twist-two parton distribution function: the transversity distribution, $\Delta_T q(x)$ (also denoted as $h_1(x)$). Despite its fundamental importance [1] and the intense theoretical work of the last decade [2], this function has only very recently been accessed experimentally. The main difficulty in measuring transversity is that, being a chiral-odd quantity, it decouples from inclusive deep inelastic scattering (DIS), since perturbative QED and QCD interactions cannot flip the chirality of quarks.

The only way to access this distribution is by coupling it to another chiral-odd quantity. To such a purpose one can look for a chiral-odd partner either in the initial or the final state. In the first case the most promising approach, and the cleanest one from the theoretical point of view, is the study of the double transverse spin asymmetry, A_{TT}, in Drell-Yan processes. This measurement is in principle feasible at RHIC, but the small x region covered at a c.m. energy $\sqrt{s} = 200$ GeV and the fact that in pp collisions one measures the product of two transversity distributions, one for a quark and one for an antiquark, lead to A_{TT} values of the order of a few percent [3]. A much larger A_{TT}, around 20-40%, could be observed in Drell-Yan processes in $p\bar{p}$ interactions at $s \simeq 200$ GeV^2, as proposed by the PAX Collaboration [4–7]. However, this requires the availability of polarized antiprotons, which is an interesting, but formidable task in itself. Other double transverse spin asymmetries for inclusive production of photons or pions are strongly suppressed by the large gluon contribution in the unpolarized cross sections [8,9].

For the case of a chiral-odd partner in the final state, we mention the spin transfer in $p^\uparrow p \to \Lambda^\uparrow X$

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or $\ell\, p^\uparrow \to \ell' \Lambda^\uparrow X$ processes, where the final hyperon acts as a polarimeter. Here $\Delta_T q$ couples to another unknown quantity: the fragmentation function for a transversely polarized quark into a transversely polarized baryon.

Recently, a promising suggestion has been made and is going to be pursued: the combined study of two-hadron inclusive production in single polarized DIS and in electron-positron annihilation measurements [10]. In this context the new quantity which appears is the so-called dihadron fragmentation function describing the hadronization of a quark in two hadrons [11–15].

Meanwhile, the most accessible and fruitful channel is the azimuthal asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ in SIDIS processes, namely $\ell\, p^\uparrow \to \ell\, h\, X$, involving the convolution of the transversity distribution with the Collins fragmentation function [16]: the spin and transverse momentum dependent (TMD) function parameterizing a left-right asymmetry in the fragmentation of a transversely polarized quark into an unpolarized hadron.

This study has been and still is under active investigation by the HERMES, COMPASS and JLab Collaborations.

A crucial breakthrough has been achieved thanks to the independent measurement of the Collins function (or rather, of the convolution of two Collins functions), in $e^+e^- \to h_1 h_2\, X$ unpolarized processes by the Belle Collaboration at KEK [17]. By combining the SIDIS data from HERMES [18] and COMPASS [19], with the Belle data, a global fit leading to the first extraction of the transversity distribution and the Collins fragmentation functions was performed in Ref. [20].

Recently, much higher statistics data on these spin azimuthal asymmetries have become available: the HERMES Collaboration have presented charged and neutral pion, as well as kaon azimuthal asymmetries [21]; the COMPASS Collaboration have presented their measurements, still on a deuteron target, but now for separate charged pion and kaon production [22]; the Belle Collaboration have issued new high-precision data of the Collins asymmetry in e^+e^- annihilation [23].

Therefore, we reconsider here our previous analysis and study the impact of these new data on the extraction of both the transversity and the Collins functions.

2. Formalism

We recall here the main steps necessary to calculate the azimuthal asymmetries in SIDIS and in e^+e^- annihilation, addressing to Ref. [20] for details. This approach is based on an extension of the ordinary collinear factorization theorems with inclusion of a new class of spin and TMD distributions [24–27]. For such processes $k_\perp$ factorization has been proven [28–30] in the regime of low observed transverse momenta (compared to the large scale of the processes). Another important result, crucial for this analysis, is the universality of the Collins function entering SIDIS and e^+e^- processes, as discussed in Refs. [31,32]. We will restrict ourselves to tree level expressions, as currently done in phenomenological studies, neglecting the soft factor coming from gluon resummation [28–30] responsible of potential Sudakov suppression [33]. We will briefly comment on this in the sequel.

2.1. SIDIS

Let us consider the single spin asymmetry for the process $\ell\, p^\uparrow \to \ell' h X$:

$$A_{UT} = \frac{d^6\sigma^{\ell p^\uparrow \to \ell' h X} - d^6\sigma^{\ell p^\downarrow \to \ell' h X}}{d^6\sigma^{\ell p^\uparrow \to \ell' h X} + d^6\sigma^{\ell p^\downarrow \to \ell' h X}} \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}\,, \quad (1)$$

where $d^6\sigma^{\ell p^{\uparrow,\downarrow} \to \ell h X} \equiv d\sigma^{\uparrow,\downarrow}$ is a shorthand notation for $(d^6\sigma^{\ell p^{\uparrow,\downarrow} \to \ell h X})/(dx\, dy\, dz\, d^2\boldsymbol{P}_T\, d\phi_S)$ with x, y, z the usual SIDIS variables. The ϕ_S dependence originates from the cross section dependence on the angle between the proton (transverse) polarization vector and the leptonic plane. We adopt here the standard SIDIS kinematics according to the "Trento Conventions" [34], see also [20]. By considering the $\sin(\phi_h + \phi_S)$ moment of A_{UT}, we are able to single out the effect coming from the spin dependent part of the fragmentation function of a transversely polarized quark (embedded in the Collins function, $\Delta^N D_{h/q^\uparrow}(z, p_\perp)$ or $H_1^{\perp q}(z, p_\perp)$ [34]) coupled to the TMD transversity distribution ($\Delta_T q(x, k_\perp)$). More explicitly, we get

$$
\begin{aligned}
A_{UT}^{\sin(\phi_h+\phi_S)} &\\
&= 2\, \frac{\int d\phi_S\, d\phi_h\, [d\sigma^\uparrow - d\sigma^\downarrow]\, \sin(\phi_h+\phi_S)}{\int d\phi_S\, d\phi_h\, [d\sigma^\uparrow + d\sigma^\downarrow]} \\
&\propto \frac{\sum_q e_q^2\, \Delta_T q(x,k_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z,p_\perp)}{\sum_q e_q^2\, f_{q/p}(x,k_\perp) \otimes D_{h/q}(z,p_\perp)}\,, \quad (2)
\end{aligned}
$$

where $\otimes$ stands for a convolution on the transverse momenta (see Eq. (4) of Ref. [20] for full details and related comments).

This analysis can be further simplified by working at $\mathcal{O}(k_\perp/Q)$ and adopting a Gaussian and factorized parameterization of TMDs. In particular for the unpolarized parton distribution (PDF) and fragmentation (FF) functions we use:

$$
\begin{aligned}
f_{q/p}(x,k_\perp) &= f_{q/p}(x)\, \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle} && (3)\\
D_{h/q}(z,p_\perp) &= D_{h/q}(z)\, \frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,, && (4)
\end{aligned}
$$

with $\langle k_\perp^2\rangle$ and $\langle p_\perp^2\rangle$ fixed to the values found in Ref. [35] by analyzing unpolarized SIDIS:

$$
\langle k_\perp^2\rangle = 0.25\ \mathrm{GeV}^2\,, \quad \langle p_\perp^2\rangle = 0.20\ \mathrm{GeV}^2\,. \qquad (5)
$$

Integrated parton distribution and fragmentation functions, $f_{q/p}(x)$ and $D_{h/q}(z)$, are available in the literature; in particular, we use the GRV98LO PDF set [36] and the DSS fragmentation function set [37].

For the transversity distribution, $\Delta_T q(x, k_\perp)$, and the Collins FF, $\Delta^N D_{h/q^\uparrow}(z, p_\perp)$, we adopt the following parameterizations [20]:

$$
\begin{aligned}
\Delta_T q(x,k_\perp) &= \frac{1}{2}\mathcal{N}_q^T(x)\,[f_{q/p}(x) + \Delta q(x)] \\
&\quad \times \frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T} && (6)\\
\Delta^N D_{h/q^\uparrow}(z,p_\perp) &= 2\mathcal{N}_q^C(z)\, D_{h/q}(z) \\
&\quad \times h(p_\perp)\, \frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,, && (7)
\end{aligned}
$$

with

$$
\mathcal{N}_q^T(x) = N_q^T\, x^\alpha (1-x)^\beta\, \frac{(\alpha+\beta)^{(\alpha+\beta)}}{\alpha^\alpha \beta^\beta} \qquad (8)
$$

$$
\mathcal{N}_q^C(z) = N_q^C\, z^\gamma (1-z)^\delta\, \frac{(\gamma+\delta)^{(\gamma+\delta)}}{\gamma^\gamma \delta^\delta} \qquad (9)
$$

$$
h(p_\perp) = \sqrt{2e}\, \frac{p_\perp}{M_h}\, e^{-p_\perp^2/M_h^2}\,, \qquad (10)
$$

and $-1 \le N_q^T \le 1$, $-1 \le N_q^C \le 1$. We assume $\langle k_\perp^2\rangle_T = \langle k_\perp^2\rangle$. The helicity distributions $\Delta q(x)$ are taken from Ref. [38]. Notice that with these choices both the transversity and the Collins function automatically obey their proper positivity bounds.

Using these parameterizations we obtain the following expression for $A_{UT}^{\sin(\phi_h+\phi_S)}$:

$$
\begin{aligned}
A_{UT}^{\sin(\phi_h+\phi_S)} &= \frac{P_T}{M_h}\, \frac{1-y}{1+(1-y)^2}\, C(P_T) \\
&\times \frac{\sum_q e_q^2\, \mathcal{N}_q^T(x)\, \big[f_{q/p}(x) + \Delta q(x)\big]\, \mathcal{N}_q^C(z) D_{h/q}(z)}{\sum_q e_q^2\, f_{q/p}(x) D_{h/q}(z)}\,,
\end{aligned}
\qquad (11)
$$

where $C(P_T)$ is given by [20]

$$
C(P_T) = \sqrt{2e}\, \frac{\langle p_\perp^2\rangle_C^2}{\langle p_\perp^2\rangle}\, \frac{e^{-P_T^2/\langle P_T^2\rangle_C}}{\langle P_T^2\rangle_C^2}\, \frac{\langle P_T^2\rangle}{e^{-P_T^2/\langle P_T^2\rangle}}\,, \qquad (12)
$$

with

$$
\langle p_\perp^2\rangle_C = \frac{M_h^2 \langle p_\perp^2\rangle}{M_h^2 + \langle p_\perp^2\rangle}\,, \quad \langle P_T^2\rangle_{(C)} = \langle p_\perp^2\rangle_{(C)} + z^2\langle k_\perp^2\rangle\,. \qquad (13)
$$

When data or phenomenological information at different Q^2 values are considered, we take into account, at leading order (LO), the QCD evolution of the transversity distribution. For the Collins FF, $\Delta^N D_{h/q^\uparrow}$, as its scale dependence is unknown, we tentatively assume the same Q^2 evolution as for the unpolarized FF, $D_{h/q}$.

By performing a best fit of the measurements of HERMES, COMPASS and Belle Collaborations we then fix the free parameters, $\alpha, \beta, \gamma, \delta, N_q^T, N_q^C$ and M_h appearing in $A_{UT}^{\sin(\phi_h+\phi_S)}$ ($q = u, d$).

2.2. $e^+e^- \to h_1 h_2\, X$ processes

One might think that hadron production in e^+e^- collisions is the cleanest process for the study of TMD polarized fragmentation functions, like the Collins function, thanks to the lack of corresponding TMD effects in the initial state. However, in the process $e^+e^- \to q\,\bar{q}$ there is no transverse polarization transfer to a single, on-shell final quark. Therefore, the single Collins effect, i.e. the asymmetry in the distribution around the jet thrust axis (given by the fragmenting quark direction) of hadrons produced in the quark fragmentation, cannot be measured. Instead, in hadron production from $e^+e^- \to q\,\bar{q} \to 2\,\text{jets}$ events, the Collins effect can be observed when the quark and the antiquark are considered *simultaneously*. The Belle Collaboration at the KEK-B asymmetric-energy e^+e^- storage rings have in fact performed a measurement of azimuthal hadron-hadron correlations for inclusive charged dihadron production, $e^+e^- \to \pi^+\pi^- X$ [17,23]. This asymmetry has been interpreted as a direct measure of the Collins effect, involving the convolution of two Collins functions.

Two methods have been adopted in the experimental analysis performed by Belle. These can be schematically described as (for details and definitions see, e.g., Refs. [39,20,23]):
i) the "$\cos(\varphi_1+\varphi_2)$ method" in the Collins-Soper frame where the jet thrust axis is used as the $\hat{z}$ direction and the $e^+e^- \to q\,\bar{q}$ scattering defines the $\widehat{xz}$ plane;
ii) the "$\cos(2\varphi_0)$ method", using the Gottfried-Jackson c.m. frame where one of the produced hadrons (h_2) identifies the $\hat{z}$ direction and the $\widehat{xz}$ plane is determined by the lepton and the h_2 directions. There will then be another relevant plane, determined by $\hat{z}$ and the direction of the other observed hadron h_1, at an angle φ_0 with respect to the $\widehat{xz}$ plane.

In both cases one integrates over the magnitude of the intrinsic transverse momenta of the hadrons with respect to the fragmenting quarks. For the $\cos(\varphi_1+\varphi_2)$ method the cross section for the process $e^+e^- \to h_1 h_2\, X$ reads:

$$\frac{d\sigma^{e^+e^-\to h_1h_2X}}{dz_1\,dz_2\,d\cos\theta\,d(\varphi_1+\varphi_2)} = \frac{3\alpha^2}{4s}\sum_q e_q^2\Big\{(1+\cos^2\theta)\,D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2) + \frac{\sin^2\theta}{4}\cos(\varphi_1+\varphi_2)\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)\Big\}, \tag{14}$$

where θ is the angle between the lepton direction and the thrust axis and

$$\Delta^N D_{h/q^\uparrow}(z) \equiv \int d^2\boldsymbol{p}_\perp \Delta^N D_{h/q^\uparrow}(z,p_\perp)\,. \tag{15}$$

Normalizing to the azimuthal averaged unpolarized cross section one has:

$$\begin{aligned} &A_{12}(z_1,z_2,\theta,\varphi_1+\varphi_2) \\ &\equiv \frac{1}{\langle d\sigma\rangle}\,\frac{d\sigma^{e^+e^-\to h_1h_2X}}{dz_1\,dz_2\,d\cos\theta\,d(\varphi_1+\varphi_2)} \\ &= 1+\frac{1}{4}\,\frac{\sin^2\theta}{1+\cos^2\theta}\,\cos(\varphi_1+\varphi_2) \\ &\times\frac{\sum_q e_q^2\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2)}\,\cdot \end{aligned} \tag{16}$$

For the $\cos(2\varphi_0)$ method, where the Gaussian ansatz (7) becomes extremely helpful, the analogue of Eq. (16) reads

$$\begin{aligned} &A_0(z_1,z_2,\theta_2,\varphi_0) \\ &= 1+\frac{1}{\pi}\,\frac{z_1\,z_2}{z_1^2+z_2^2}\,\frac{\sin^2\theta_2}{1+\cos^2\theta_2}\,\cos(2\varphi_0) \\ &\times\frac{\sum_q e_q^2\,\Delta^N D_{h_1/q^\uparrow}(z_1)\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2)}{\sum_q e_q^2 D_{h_1/q}(z_1)\,D_{h_2/\bar{q}}(z_2)}\,, \end{aligned} \tag{17}$$

where θ_2 is now the angle between the lepton and the h_2 hadron directions.

To eliminate false asymmetries, the Belle Collaboration [23] consider the ratio of unlike-sign to like-sign pion pair production, A_U and A_L.

For fitting purposes, it is usually convenient to express these relations in terms of favoured and unfavoured fragmentation functions,

$$D_{\pi^+/u,\bar{d}} = D_{\pi^-/d,\bar{u}} \equiv D_{\text{fav}}\,, \tag{18}$$
$$D_{\pi^+/d,\bar{u}} = D_{\pi^-/u,\bar{d}} = D_{\pi^\pm/s,\bar{s}} \equiv D_{\text{unf}}\,, \tag{19}$$

and similarly for the $\Delta^N D$'s.

3. Results

A combined fit of SIDIS asymmetries together with $e^+e^- \to h_1h_2X$ data, Eqs. (11,16,17), allows the simultaneous extraction of the transversity distribution and the Collins fragmentation functions. We assume flavour independent values of α and β (neglecting transversity distributions of sea quarks) and, similarly, we assume that γ and δ

are the same for favoured and unfavoured Collins fragmentation functions; we then remain with a total number of 9 parameters.

The first study along this line was presented in Ref. [20]. Here we repeat the analysis, exploiting the new high-precision data recently released by the HERMES [21] and COMPASS [22] Collaborations for SIDIS, and by the Belle Collaboration [23] for e^+e^- annihilation processes, in order to refine and reduce the uncertainty of the previous extraction.

New data from COMPASS operating on a transversely polarized hydrogen target have recently been released [40]: these are not included in the fit but compared with our predictions.

The two sets of Belle data, coming from two analyses of the same experimental events, are not independent. Therefore we include only one set of data in the fit, either A_0 or A_{12} data. In this analysis we report the results obtained by using A_{12} data, the $\cos(\varphi_1 + \varphi_2)$ method. The consequences of fitting A_0 instead of A_{12} are presently under investigation.

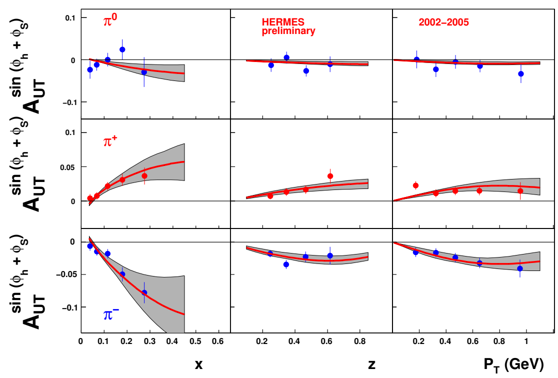

Figure 1. Fit of HERMES [21] data. The shaded area corresponds to the statistical uncertainty in the parameter values, see text.

In Figs. 1 and 2 we show the best fit to the HERMES [21] and COMPASS [22] data, respectively. Notice that the π^0 data (HERMES) have not been used in the fit; in Fig. 1 we show our estimates, based on the extracted transversity and Collins functions, and compare them to data. Fig. 3 shows the fit to the Belle A_{12} asymmetry, whereas in Fig. 4 our predictions for the A_0 asymmetry are compared with data [23].

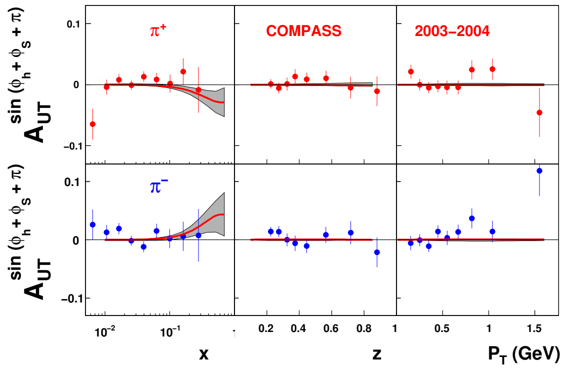

Figure 2. Fit of COMPASS [22] data. The shaded area corresponds to the statistical uncertainty in the parameter values, see text. The extra π phase in addition to $\phi_h + \phi_S$ comes from the different convention adopted by COMPASS.

The curves shown are evaluated using the central values of the parameters in Table 1, while the shaded areas correspond to a two-sigma deviation at 95.45% Confidence Level (for details see Appendix A of Ref. [41]).

Table 1 collects the results of our best fit to the new data sets [21–23], while in Figs. 5 and 6 we show our updated transversity distribution and Collins fragmentation functions together with the uncertainty bands of our previous extraction [20]. We can definitely say that the two extractions are compatible with each other, with the new error bands strongly reduced. The transversity for up quarks results now larger (compared to our previous extraction), while that for down quarks is better constrained in sign and not compatible with zero. In this respect the new data from SIDIS have been crucial. It is worth noticing that while the transversity for up quarks is strongly constrained by HERMES data, in particular through

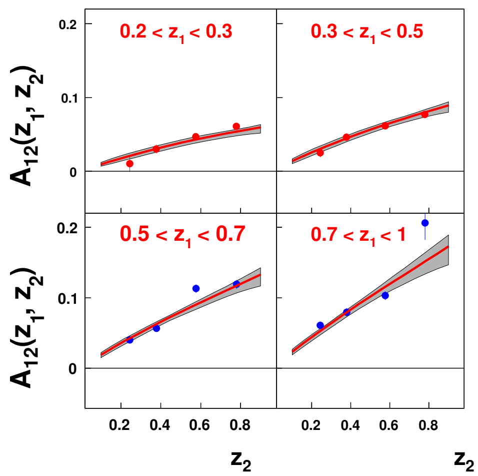

Figure 3. Fit of the Belle [23] data on the A_{12} asymmetry (the $\cos(\varphi_1 + \varphi_2)$ method).

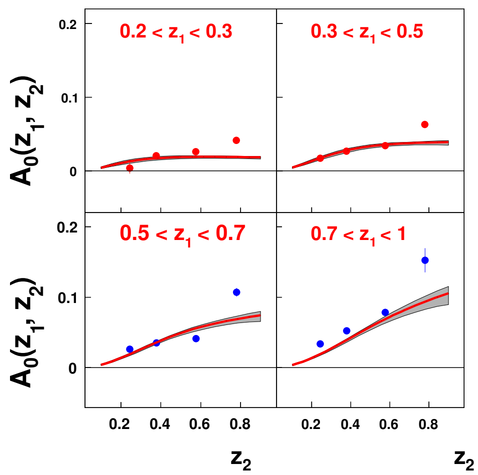

Figure 4. Comparison of our predictions with Belle [23] data for the A_0 Belle asymmetry (the $\cos(2\,\varphi_0)$ method).

the positive pion azimuthal asymmetry, the addition of COMPASS deuteron data to the fit allows a better determination of $\Delta_T d$. We recall here

Table 1
Best values of the free parameters for the u and d transversity distribution functions and for the favoured and unfavoured Collins fragmentation functions. We obtain χ^2/d.o.f. = 1.3. Notice that the errors generated by MINUIT are strongly correlated, and should not be taken at face value. The significant fluctuations in our results are shown by the shaded areas in the plots.

$N_u^T = 0.64 \pm 0.34$	$N_d^T = -1.00 \pm 0.02$
$\alpha = 0.73 \pm 0.51$	$\beta = 0.84 \pm 2.30$
$N_{fav}^C = 0.44 \pm 0.07$	$N_{unf}^C = -1.00 \pm 0.06$
$\gamma = 0.96 \pm 0.08$	$\delta = 0.01 \pm 0.05$
$M_h^2 = 0.91 \pm 0.52$ GeV^2	

that, in analyzing SIDIS data, we have assumed the transversity distributions for sea quarks and antiquarks to vanish. The extracted Collins FFs are well constrained and much smaller than their positivity bounds, with the unfavoured Collins function large in size and negative, consistently with other extractions [42,43,20].

A word of caution has to be added here since SIDIS data (HERMES and COMPASS) are collected at a much smaller scale ($Q^2 \simeq 2.5$ GeV^2) compared to the Belle data ($Q^2 = 110$ GeV^2).

Both azimuthal asymmetries in SIDIS and in e^+e^- collisions involve spin and TMD functions whose behaviour upon scale variation should be described in the context of Collins-Soper factorization [28,30]. Beyond tree level this would result in a soft factor entering TMD convolutions, with the corresponding Sudakov suppression. This, as discussed in Refs. [44,45], might imply an underestimation of the Collins function as extracted at tree level from the azimuthal asymmetry at Belle. Hence the combined extraction of the transversity from SIDIS at a lower Q^2 (less Sudakov suppression), might lead to an overestimation of $\Delta_T q$. This issue is currently under study. Here, as in Ref. [20], the Q^2 dependence of the Collins FF *is* included assuming it to be the same as that of the unpolarized fragmentation function, $D_{h/q}$: although this might not be the proper evolution, it should mitigate the above-mentioned effect.

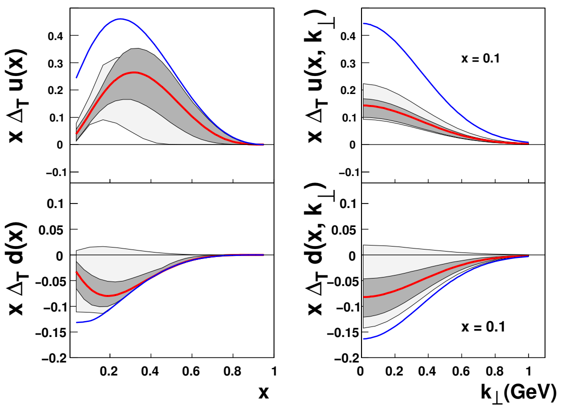

Figure 5. The transversity distribution functions for u and d flavours as determined by our global fit, at $Q^2 = 2.4$ GeV^2; we also show the Soffer bound [46] (highest or lowest lines) and the (wider) uncertainty bands of our previous extraction [20].

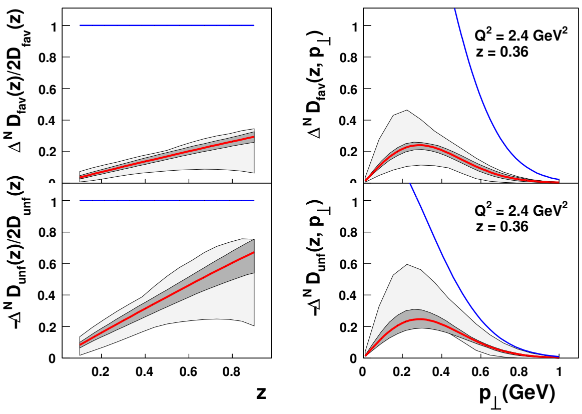

Figure 6. Favoured and unfavoured Collins fragmentation functions as determined by our global fit, at $Q^2 = 2.4$ GeV^2; we also show the positivity bound and the (wider) uncertainty bands as obtained in Ref. [20].

As it is well known, in a non relativistic theory the helicity and the transversity distributions should be equal. We then show in Fig. 7 the extracted transversity distribution together with the helicity distribution of Ref. [38] at $Q^2 = 2.4$ GeV^2. It results that, both for u and d quarks, we have $|\Delta_T q| < |\Delta q|$.

Another interesting quantity, related to the first x-moment of the transversity distribution, is the tensor charge:

$$\delta q = \int_0^1 dx\, (\Delta_T q - \Delta_T \bar{q}) = \int_0^1 dx\, \Delta_T q \tag{20}$$

where the last equality is valid for zero antiquark transversity, as assumed in our approach. From our analysis we get, at $Q^2 = 0.8$ GeV^2,

$$\delta u = 0.54^{+0.09}_{-0.22} \qquad\qquad \delta d = -0.23^{+0.09}_{-0.16}\,. \tag{21}$$

Such values are quite close to various model predictions [47–50] for tensor charges which span the ranges $0.5 \le \delta u \le 1.5$ and $-0.5 \le \delta d \le 0.5$ (see Fig. 8). In this context it is worth mentioning a subtle point concerning the strong scale dependence of the tensor charge, recently addressed in

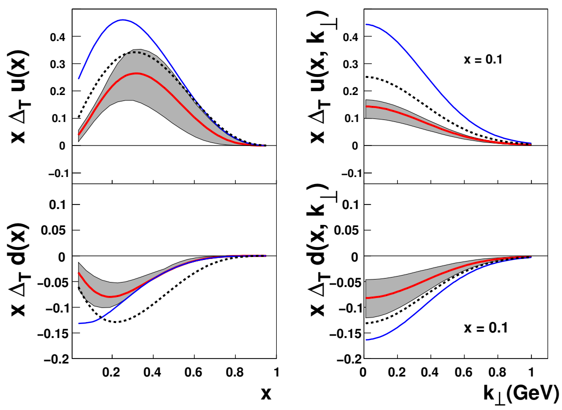

Figure 7. Comparison of the extracted transversity (solid line) with the helicity distribution (dashed line) at $Q^2 = 2.4$ GeV^2. The Soffer bound [46] (blue solid line) is also shown.

Ref. [51]. For the effective models of baryons, as those referred to above, the choice of their starting energy scale and their Q^2 evolution could play a significant role and, eventually, mask the true nature of the model. Consequently, the results shown in Fig. 8, where our LO phenomenological extraction seems in better agreement with the quark-diquark model of Ref. [47] than with other models, should be taken with some care. A safer quantity, totally scale independent, and therefore easy to compare with, would be the ratio of two tensor charges. From our fit, for instance, we obtain $\delta d/\delta u = -0.42^{+0.0003}_{-0.20}$, and all model predictions considered above would fall within our uncertainty band, as shown in Fig. 7 of Ref. [51].

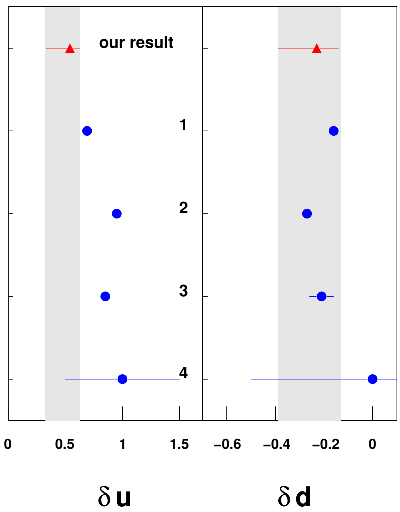

Figure 8. Tensor charge from different models compared to our result. 1: Quark-diquark model of Ref. [47], 2: Chiral quark soliton model of Ref. [48], 3: Lattice QCD [49], 4: QCD sum rules [50].

4. Predictions

We now use the extracted transversity and Collins functions to give predictions for new measurements performed or planned at COMPASS and JLab. The transverse single spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ has been recently measured by the COMPASS experiment operating with a polarized hydrogen target (rather than a deuterium one). In Fig. 9 we show our predictions compared with these preliminary data. The agreement is excellent.

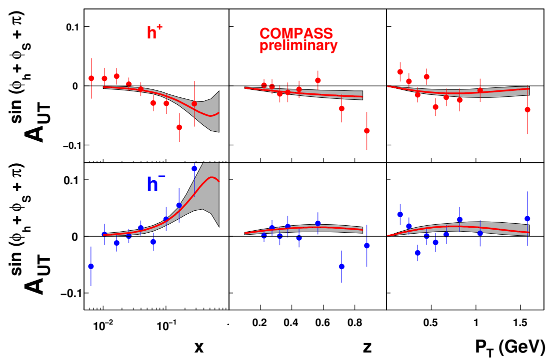

Figure 9. Predictions for the single spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S+\pi)}$ compared to preliminary data by the COMPASS experiment operating with a transversely polarized hydrogen target [40].

In Fig. 10 we present our estimates for JLab operating with a proton target at 12 GeV. Notice that JLab results will give important information on the large x region, which is left basically unconstrained by the present SIDIS data from HERMES and COMPASS. In this region our estimates must be taken with some care. We recall that the large x behaviour of our parameterization is controlled by the same β parameter for $\Delta_T u$ and $\Delta_T d$ (since present data do not cover the large x region). The same is true for the Collins fragmentation functions, whose large z behaviour is driven by the same parameter δ for favoured and unfavoured Collins FFs. On the other hand for the small to medium x region, well constrained by SIDIS measurements, data support the choice of a universal behaviour x^α for $\Delta_T u$ and $\Delta_T d$. The future JLab measurements, which will extend to larger x values, will test the validity of this approximations.

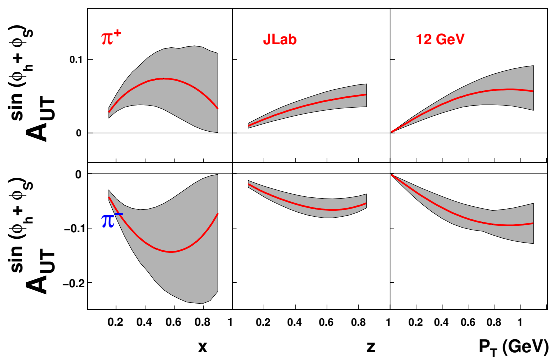

Figure 10. Estimates of the single spin asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ for JLab operating with proton target.

5. Conclusions

We have performed a re-analysis of recent high-precision experimental data on spin azimuthal asymmetries which involve the transversity distributions of u and d quarks and the Collins fragmentation functions. The values of the 9 free parameters are fixed by simultaneously best fitting the HERMES, COMPASS and Belle data.

All data can be accurately described, leading to the extraction of the favoured and unfavoured Collins functions, in agreement with similar results previously obtained in the literature [43,42,20]. In addition, we have improved the extraction of the so far poorly known transversity distributions for u and d quarks, $\Delta_T u(x)$ and $\Delta_T d(x)$. They turn out to be opposite in sign, with $|\Delta_T d(x)|$ smaller than $|\Delta_T u(x)|$, and both smaller than their Soffer bound [46]. The previous uncertainty bands are strongly reduced by the present analysis. The new distributions are compatible with our previous extraction [20] and close to some model predictions for the transversity distribution.

The extracted transversity distributions and the Collins fragmentation functions allow to compute the azimuthal asymmetry $A_{UT}^{\sin(\phi_h+\phi_S)}$ for any SIDIS process. In particular, our predictions for the COMPASS measurements with a proton target are in very good agreement with preliminary data, while the large x behaviour of $\Delta_T q$, yet unknown, could be explored by JLab experiments. These will provide further important tests of our complete understanding of the partonic properties which are at the origin of SSAs.

Further expected data from Belle will allow to study in detail not only the z dependence of the Collins functions, but also their $p_\perp$ dependence.

The TMD approach to azimuthal asymmetries in SIDIS and $e^+e^- \to h_1 h_2 X$ processes has definitely opened a new powerful way of studying the nucleon structure and fundamental QCD properties.

Acknowledgments

U.D. would like to thank the organizers of this very interesting workshop for their kind hospitality. We acknowledge the support of the European Community - Research Infrastructure Activity under the FP6 "Structuring the European Research Area" program (HadronPhysics, RII3-CT-2004-506078). M.A., M.B., and A.P. acknowledge partial support by MIUR under PRIN 2006 and by the Helmholtz Association through funds provided to the virtual institute "Spin and strong QCD"(VH-VI-231).

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