IL NUOVO CIMENTO **40 C** (2017) 88
DOI 10.1393/ncc/i2017-17088-3

Communications: SIF Congress 2016

Highlights from COMPASS SIDIS and Drell-Yan programmes

R. Longo(1)(2) on behalf of the COMPASS Collaboration
(1) *INFN, Sezione di Torino - Torino, Italy*
(2) *Dipartimento di Fisica, Università di Torino - Torino, Italy*

received 12 April 2017

Summary. — One of the main objectives of the COMPASS experiment at CERN is the study of transverse spin structure of the nucleon trough measurement of target spin (in)dependent azimuthal asymmetries in semi-inclusive deep inelastic scattering (SIDIS) and Drell-Yan (DY) processes with transversely polarized targets. Within the QCD parton model these azimuthal asymmetries give access to a set of transverse-momentum-dependent (TMD) parton distribution functions (PDF) which parameterize the spin structure of the nucleon. In the TMD framework of QCD it is predicted that the two naively time-reversal odd TMD PDFs, *i.e.* the quark Sivers functions and Boer-Mulders functions, have opposite sign when measured in SIDIS or DY. The experimental test of this fundamental prediction is a major challenge in hadron physics. COMPASS former SIDIS results and upcoming results from DY measurements give a unique and complementary input to address this and other important open issues in spin physics.

1. – Introduction

Within the "twist-2" approximation of QCD parton model the internal spin-structure of a polarized nucleon is described by eight transverse-momentum-dependent (TMD) parton distribution functions (PDFs) which, in their turn, describe the distributions of longitudinal and transverse momenta of partons and their correlations with nucleon and quark polarizations. A powerful method used to access these TMD PDFs is the study of transverse spin-dependent azimuthal asymmetries (TSAs) arising in Semi-Inclusive Deep Inelastic Scattering (SIDIS) and Drell-Yan (DY) cross-sections.

Using standard notations the leading order part of the cross-section expression for the lepton off transversely(1) polarized nucleon SIDIS processes ($\ell\, N \rightarrow \ell'\, h\, X$) can be

---

(1) W.r.t. the virtual photon direction.

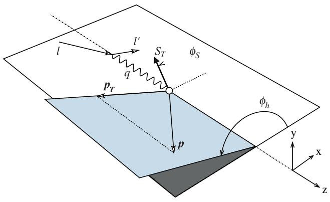

Fig. 1. – The SIDIS reference frame and definition of the azimuthal angles.

written in the following way [1]:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}zp_T^h\mathrm{d}p_T^h\mathrm{d}\phi_h\mathrm{d}\phi_S} \propto F_{UU}\Bigg\{1+\varepsilon A_{UU}^{\cos(2\phi_h)}+S_T\Bigg[A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\Bigg]\Bigg\}, \tag{1}$$

where $\varepsilon = (1-y-\frac{1}{4}\gamma^2y^2)/(1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2)$ is the ratio of longitudinal and transverse photon fluxes, $\gamma = 2Mx/Q$ and ϕ_h and ϕ_S are the azimuthal angles of the produced hadron and of the nucleon spin, respectively (the angles are defines in the γ^*N-system, see fig. 1). Equation (1) contains one unpolarized and three target transverse spin dependent azimuthal modulations.

The amplitude of each modulation appearing in eq. (1) is related to an asymmetry, $A_{BT}^{\omega_i(\phi_h,\phi_S)}$, defined as a ratio of the corresponding structure function $F_{BT}^{\omega_i(\phi_h,\phi_S)}$ to the unpolarized one F_{UU}. Here the superscripts indicate the corresponding modulation, the first subscript the polarization of the beam while the second one the polarization of the target (U - "Unpolarized", T - "Transverse").

Applying similar notations at leading-twist the single-polarized Drell-Yan ($h\,N \rightarrow \ell\,\bar{\ell}\,X$) cross-section can be written as

$$\frac{\mathrm{d}\sigma^{LO}}{\mathrm{d}\Omega} \propto F_U^1\Bigg\{1+\cos^2\theta_{CS}+\sin^2\theta_{CS}A_U^{\cos(2\varphi_{CS})}\cos(2\varphi_{CS}) +S_T\Bigg[(1+\cos^2\theta_{CS})A_T^{\sin\phi_S}\sin\phi_S + \sin^2\theta_{CS}A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) + \sin^2\theta_{CS}A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\phi_S)\Bigg]\Bigg\}. \tag{2}$$

The φ_{CS}, θ_{CS} and Ω, the solid angle of the lepton, are defined in the Collins-Soper frame and ϕ_S is the azimuthal angle of the direction of the nucleon polarization in the target rest frame, see fig. 2.

Similarly to the SIDIS case, at leading order the Drell-Yan cross-section contains one unpolarized and three TSA terms. Within the QCD parton model approach the

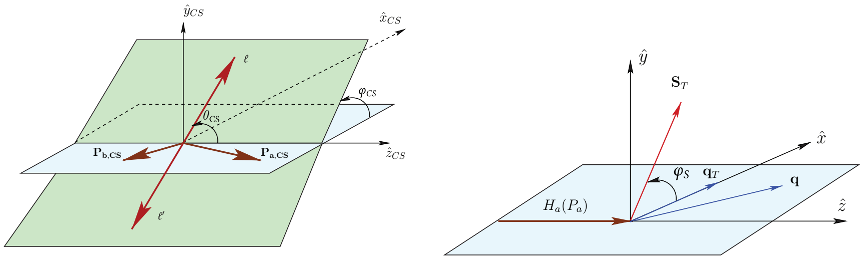

Fig. 2. – Drell-Yan process frameworks. Collins-Soper frame (left panel), where φ_{CS} and θ_{CS} are defined, and target rest frame (right panel), showing φ_S definition.

Table I. – *SIDIS and Drell-Yan leading order TSAs measured at COMPASS and related nucleon TMDs.*

Drell-Yan	Proton TMD PDF	SIDIS
$A_U^{\cos(2\varphi_{CS})} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$	Boer-Mulders	$A_{UU}^{\cos(2\phi_h)} \propto h_{1,p}^{\perp q} \otimes H_{1q}^{\perp h}$
$A_T^{\sin(\varphi_S)} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$	Sivers	$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp q} \otimes D_{1q}^{h}$
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{q}$	Transversity	$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1q}^{\perp h}$
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$	Pretzelosity	$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T,p}^{\perp q} \otimes H_{1q}^{\perp h}$

four LO asymmetries appearing in the SIDIS cross-section are described by the different convolutions of two TMD factorized constituents, *i.e.* the PDFs of the target nucleon and the fragmentation functions (FFs) which describe the quark hadronization process. The so-called "Sivers" asymmetry, $A_{UT}^{\sin(\phi_h-\phi_S)}$, gives access to the Sivers PDF ($f_{1T,p}^{\perp q}$) convoluted with the ordinary FF (D_{1q}^{h}). The other two TSAs, $A_{UT}^{\sin(\phi_h+\phi_S)}$ (referred as Collins asymmetry) and $A_{UT}^{\sin(3\phi_h-\phi_S)}$, are related to convolutions of Collins FF ($H_{1q}^{\perp h}$) with transversity (h_1^q) and pretzelosity ($h_{1T,p}^{\perp q}$) TMD PDFs, respectively. The only unpolarized LO asymmetry, $A_{UU}^{\cos 2\phi_h}$, entering in the SIDIS cross-section gives access to the convolution of Boer-Mulders PDF ($h_{1,p}^{\perp q}$) with Collins FF.

Analogously, also the Drell-Yan LO TSAs from eq. (2) can be related with nucleon TMD PDFs. In this case the asymmetries are given as convolutions of two TMD PDFs, one of the beam (pion) and one of the target nucleon. For instance, the measurement of $A_T^{\sin\varphi_S}$, DY TSA gives access to the convolution of nucleon Sivers TMD PDF with unpolarized pion PDF, while $A_T^{\sin(2\varphi_{CS}-\varphi_S)}$ and $A_T^{\sin(2\varphi_{CS}+\varphi_S)}$ TSAs are related with pion Boer-Mulders TMD PDF convoluted with the transversity and the pretzelosity nucleon TMD PDFs, respectively. The unpolarized $A_U^{\sin\varphi_{CS}}$ asymmetry is given by the convolution of pion and nucleon Boer-Mulders TMD PDFs.

Within the concept of generalized universality of TMD PDFs, nucleon parton distributions functions accessed via TSAs in SIDIS and Drell-Yan (see table I for the full list) are expected to be process-independent. The two T-odd TMD PDFs (Sivers and Boer-Mulders functions) are predicted to have opposite sign when measured in SIDIS or DY and thus are only conditionally universal.

All aforementioned SIDIS TSAs were studied at HERMES and COMPASS experiments using transversely polarised targets [2-11]. yielding, in particular, significant nonzero results for Sivers and Collins TSAs. Comparing COMPASS and HERMES results in the commonly accessible range of the Bjorken-x variable, the Sivers TSA at HERMES was found to be somewhat larger compared to that measured at COMPASS. Taking into account that in this range the hard scale at COMPASS is ~ 2 times larger, this observation may be a manifestation of possible TMD evolution effects. In order to test this conjecture, measuring TSAs at COMPASS in various Q^2 regions may yield very useful input for testing the effect of TMD evolution. Recently, COMPASS published the first multi-differential results of the SIDIS TSAs, which were extracted from SIDIS data at four different hard scales [7]. Details on this measurement and results themselves will be discussed in the next sections.

As for the DY TSAs, the COMPASS experiment is presently the only place to explore the transverse spin structure of the nucleon in Drell-Yan. In addition, the experiment possess unique capability to measure TSAs both in SIDIS and DY at a similar hard scale using essentially the same experimental setup. Thus, COMPASS has the unprecedented possibility to test, in a unique experimental environment, the universality and other key-features of TMDs, such as the sign change of the Sivers PDF [12].

By the time of this review COMPASS has already collected first polarized DY data in 2015 and will perform another series of measurements in 2018. So far only $\sim 30\%$ of the 2015 data-sample has been analysed. Corresponding kinematic distributions and projected uncertainties for DY TSAs will be shown in the next sections.

2. – COMPASS SIDIS and DY measurements

The COMPASS spectrometer [13] is situated at the M2 beam line in the north area of the CERN Super Proton Synchrotron. The experiment is in operation since 2002 taking data with muon and pion beams. During phase-I (2002-2010) COMPASS has performed a series of SIDIS TSAs measurements using a longitudinally polarized ($\sim 80\%$) high intensity ($4 \times 10^7\,\mathrm{s}^{-1}$) $160\,\mathrm{GeV}/c$ μ^+ beam impinging on a transversely polarized ^{6}LiD (2002-2003) and NH_3 (2007, 2010) targets. The polarized target (PT) used for proton measurements consisted of three cylindrical cells (30 cm, 60 cm, 30 cm) of 2 cm radius, each separated by 5 cm gaps. The target material was polarised along the vertical direction. Polarization is maintained in a magnetic field (0.5 T) generated by the PT dipole magnet. Neighbouring cells were polarized in opposite directions, so that data for both spin directions were recorded simultaneously. The polarization was reversed every ~ 5 days, to minimize the acceptance effects.

The large-acceptance (polar angle acceptance is of 180 mrad) high-precision COMPASS spectrometer is well suited for investigating high-energy reactions. Outgoing charged particles are detected by the tracking system and their momenta are determined using two large-aperture analysing magnets. Calorimetric measurements are performed by means of hadron and electromagnetic calorimeters, while the PID of outgoing hadrons is provided by the RICH-detector. For more details on the spectrometer and SIDIS data-taking see [4, 8, 10, 13, 14] and references therein.

The polarized Drell-Yan measurements are an important part of the COMPASS phase-II (2012–2018) physics programme. First DY data were collected in 2015 using a high-intensity ($6 \times 10^7\,\mathrm{s}^{-1}$) $190\,\mathrm{GeV}/c$ π^- beam impinging on a transversely polarized NH_3 target. Another year (~ 140 days/year) of polarized DY run is scheduled for 2018. During 2015 DY data-taking the polarized target consisted of two longitudinally aligned

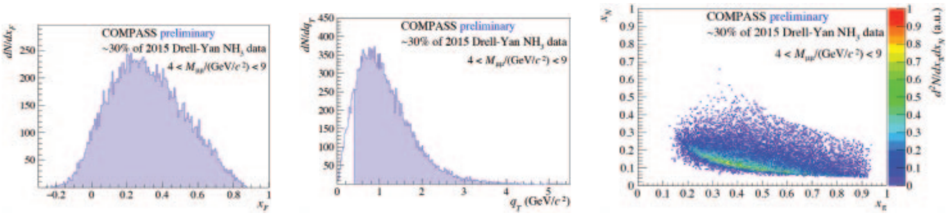

Fig. 3. – The x_F distribution (left), q_T distribution (center) and the two-dimensional (x_π, x_N) distribution (right) of the selected high-mass dimuons. The latter distribution is normalized to have a maximum value equal to one.

cylindrical cells of 55 cm length and 2 cm in radius, divided by a 20 cm gap and placed in a magnetic field of 0.6 T generated by the PT magnet. Similarly to the SIDIS case the cells were polarized vertically in opposite directions. In case of DY measurements the polarization reversal took place every two weeks. A 240 cm long structure made mostly of alumina with a tungsten core, placed downstream of the target, acted as hadron absorber and beam dump. In spite of several upgrades and modifications the COMPASS spectrometer as it was used for DY measurements is very similar to the configuration used for proton SIDIS data takings.

For various Drell-Yan studies being carried out at COMPASS it is convenient to disentangle the following four dimuon mass, $M_{\mu\mu}$, ranges:

i) $1 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2$: *low mass range*,

ii) $2 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 2.5$: *intermediate mass range*,

iii) $2.5 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 4$: J/ψ *mass range*,

iv) $4 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 9$: *high-mass range*.

Among the four aforementioned $M_{\mu\mu}$ regions, range iv) is particularly suited for studies of the predicted sign change of the Sivers TMD PDF when comparing SIDIS and DY results. First, this range best fulfils the requirement of TMD factorisation that the transverse momentum of the hadron in SIDIS or of the dimuon in DY has to be much smaller than the hard scale $M_{\mu\mu}$. Secondly, in this range, both SIDIS and DY cross sections for a proton target are dominated by the contribution of u-quark nucleon TMD PDFs in the valence region, where the extracted Sivers TMD PDF reaches its maximum [15, 16]. Third, in this region the background contaminations are estimated to be negligible. The distributions of the dimuon Feynman variable $x_F = x_\pi - x_N$, the dimuon transverse momentum q_T and two-dimensional distribution of the Bjorken scaling variables of pion and nucleon, x_π and x_N for the dimuon high-mass range(²) are shown in fig. 3. The shaded regions identify the kinematic ranges currently selected for the analysis. Since the average q_T is of the order of 1 GeV/c, the relation $q_T << M_{\mu\mu}$ holds for high-mass Drell-Yan events and thus ensures the applicability of the TMD approach. Presented in fig. 3 two-dimensional (x_π, x_N) distribution demonstrates that indeed the high-mass range favors the valence-quark region.

(²) The presented distributions correspond to $\sim 30\%$ of the 2015 data-sample analyzed so far.

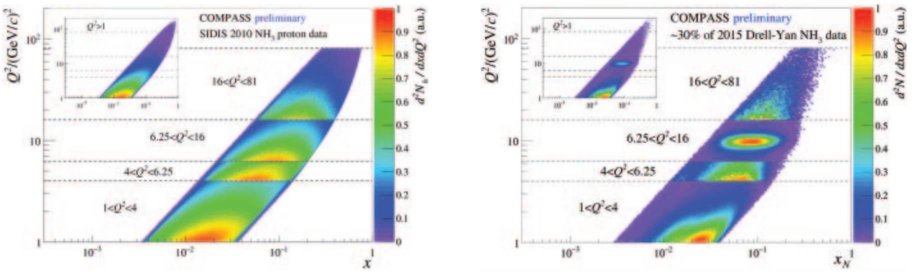

Fig. 4. – Left panel: The two-dimensional (x, Q^2) distributions for charged-hadron production at $z > 0.1$ (SIDIS 2010 data). Right panel. The two-dimensional (x_N, Q^2) distributions for dimuons ($\sim$ 30% of DY 2015 data). The distributions are normalised to have a maximum value equal to one. In both figures the upper left inserts show overall distributions, while main figures are showing the same distributions for four DY Q^2 ranges.

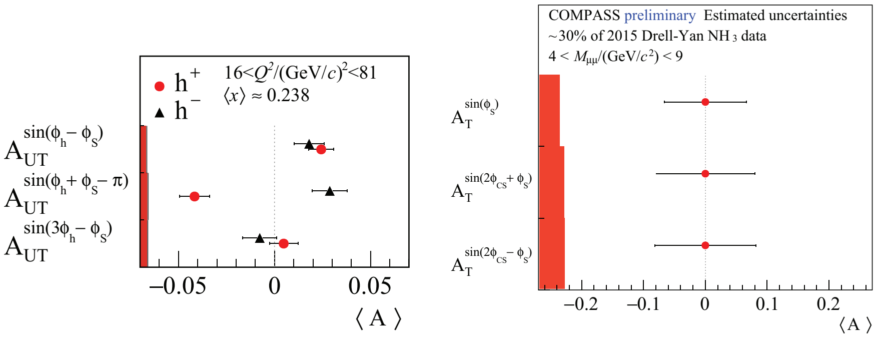

Fig. 5. – Mean SIDIS TSAs (left) and current estimates for uncertainties for DY TSAs (right) in the high-mass range. Systematic uncertainties are shown as error bands next to the vertical axes.

In order to minimize possible effects due to differences in Q^2 coverage between SIDIS and DY measurements and provide a useful input for future global analyses that will compare TMD PDFs obtained from SIDIS data with those obtained from DY data, COMPASS performed a dedicated analysis of the SIDIS 2010 data, extracting the Sivers and other TSAs in the aforementioned four Q^2 regions of the dimuon mass ($M_{\mu\mu} \sim \sqrt{Q^2}$) used in the ongoing analysis of the Drell-Yan measurements [7]. A comparison of two-dimensional (Q^2, x) distribution from SIDIS 2010 data with the (Q^2, x_N) phase-space covered in Drell-Yan measurements in 2015 is presented in fig. 4.

In fig. 5 (left panel) the results for LO SIDIS TSAs for the high-mass range are shown after averaging over all other kinematic dependences. The Sivers TSA is determined with good statistical accuracy. The asymmetry is clearly positive in the high-mass range, both for positive and negative hadrons. Also the Collins TSA, which gives access to the transversity TMD PDF, is significant both for positive and negative hadrons (negative for h^+ and positive for h^-). The last presented SIDIS LO TSA, $A_{UT}^{\sin(3\phi_h-\phi_S)}$, is related to the pretzelosity TMD PDF. This asymmetry appears to be compatible with zero.

The projected uncertainties for LO Drell-Yan TSAs corresponding to the 30% of 2015 data analyzed so far, are shown in fig. 5 (right panel). Given the statistical error obtained

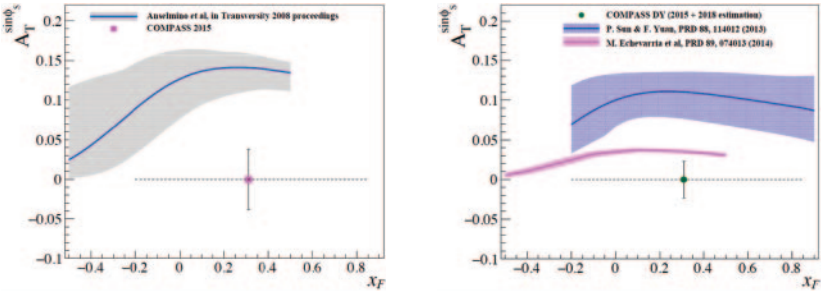

Fig. 6. – Left: projected uncertainty for Sivers TSA in the high-mass range for overall 2015 statistics. Right: projected uncertainty for Sivers TSA in the high-mass range for two years of data taking (2015+2018).

from the analysis of this 30% fraction of 2015 data, an uncertainty of about 4% for the Sivers asymmetry is expected from the analysis of the whole 2015 data sample. At the end of the DY run scheduled for 2018 a precision of $\sim$ 2–3% is expected to be achieved. These values are shown in fig. 6 together with the phenomenological predictions from [17], [18] and [19]. Current estimate for the expected systematic point-to-point uncertainties are about 0.5 times the statistical uncertainties.

3. – Conclusions

In 2015 COMPASS became the first fixed target experiment to collect polarized DY data. As from the SIDIS cross-studies, COMPASS has recently extracted TSAs in those four Q^2-regions, which correspond to the four regions of the di-muon mass used in the ongoing analyses of the COMPASS Drell-Yan measurements.

The range $Q^2 > 16\,(\mathrm{GeV}/c)^2$ is particularly well suited for the future comparison of COMPASS results between SIDIS and DY measurements. In this range the mean Sivers asymmetry measured in SIDIS was found to be positive with an accuracy that appears to be sufficient to test the predicted sign change of the Sivers function when comparing it to the upcoming results of the analysis of the COMPASS DY measurement in the corresponding range of dimuon mass.

Even if the Sivers effect in Drell-Yan is a flagship measurement for COMPASS also the results of 2015 DY analysis for the other TSAs, together with their SIDIS “analogues” presented in this letter, will represent a very important input for general TMD QCD studies.

* * *

The author gratefully acknowledge Dr. Bakur Parsamyan for fruitful discussions.

REFERENCES

[1] Kotzinian A., *Nucl. Phys. B*, **441** (1995) 234, arXiv:ph/9412283.
[2] HERMES Collaboration (Airapetian A. *et al.*), *Phys. Rev. Lett.*, **103** (2009) 152002, arXiv:0906.3918 [hep-ex].
[3] COMPASS Collaboration (Alekseev M. *et al.*), *Phys. Lett. B*, **673** (2009) 127, arXiv:0802.2160 [hep-ex].

[4] COMPASS Collaboration (Adolph C. *et al.*), *Phys. Lett. B*, **717** (2012) 383, arXiv:1205.5122 [hep-ex].

[5] COMPASS Collaboration (Adolph C. *et al.*), *Phys. Lett. B*, **744** (2015) 250, arXiv:1408.4405 [hep-ex].

[6] COMPASS Collaboration (Adolph C. *et al.*), *Phys. Lett. B*, **736** (2014) 124, arXiv:1401.7873 [hep-ex].

[7] COMPASS Collaboration (Adolph C. *et al.*), arXiv:1609.07374 [hep-ex].

[8] COMPASS Collaboration (Adolph C. *et al.*), *Phys. Lett. B*, **717** (2012) 376, arXiv:1205.5121 [hep-ex].

[9] COMPASS Collaboration (Adolph C. *et al.*), *Phys. Lett. B*, **713** (2012) 10, arXiv:1202.6150 [hep-ex].

[10] COMPASS Collaboration (Parsamyan B.), *Phys. Part. Nucl.*, **45** (2014) 158, arXiv:1301.6615 [hep-ex].

[11] HERMES Collaboration (Pappalardo L. L.), *Studies of TMDs at HERMES*, in *Proceedings of the IV Workshop on Exclusive Reactions, JLAB, Newport News, VA, USA, 18–21 May 2010* (World Scientific) 2011, pp. 312–320, DOI: 10.1142/9789814329569_0033.

[12] Collins J. C., *Phys. Lett. B*, **536** (2002) 43, arXiv:hep-ph/0204004.

[13] COMPASS Collaboration (Abbon P. *et al.*), *Nucl. Instrum. Methods A*, **577** (2007) 455, arXiv:hep-ex/0703049.

[14] Parsamyan B., *EPJ Web of Conference*, **85** (2015) 02019, arXiv:1411.1568 [hep-ex].

[15] Anselmino M., Boglione M., D'Alesio U., Kotzinian A., Murgia F. and Prokudin A., *Phys. Rev. D*, **72** (2005) 094007; *Phys. Rev. D*, **72** (2005) 099903 (Erratum) arXiv:hep-ph/0507181.

[16] Anselmino M., Boglione M., D'Alesio U., Kotzinian A., Melis S., Murgia F., Prokudin A. and Turk C., *Eur. Phys. J. A*, **39** (2009) 89, arXiv:0805.2677 [hep-ph].

[17] Anselmino M., Boglione M., D'Alesio U., Melis S., Murgia F. and Prokudin A., *Phys. Rev. D*, **79** (2009) 054010, arXiv:0901.3078 [hep-ph].

[18] Sun P. and Yuan F., *Phys. Rev. D*, **88** (2013) 034016, arXiv:1304.5037 [hep-ph].

[19] Echevarria M. G., Idilbi A., Kang Z. B. and Vitev I., *Phys. Rev. D*, **89** (2014) 074013, arXiv:1401.5078 [hep-ph].