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Polarised Drell-Yan at COMPASS-II

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Summary. — The study of Drell-Yan (DY) processes involving the collision of an unpolarised hadron beam on a polarised proton target can result in a fundamental improvement of our knowledge on the transverse-momentum–dependent (TMD) parton distribution functions (PDFs) of hadron. A fundamental test of the factorization theorem in the non-perturbative QCD can be performed as well, by verifying the sign change of T-odd TMDs as they are accessed via Semi-Inclusive Deep Inelastic Scattering (SIDIS) or Drell-Yan process. The future polarised COMPASS Drell-Yan experiment is discussed in this context, the most important features are briefly reviewed, the sensitivity of the measurement is presented.

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1. – Transverse-spin–dependent structure of the nucleon

Spin- and transverse-momentum–dependent semi-inclusive hadronic processes have attracted much interest both, experimentally and theoretically in recent years. These processes provide us more opportunities to study the Quantum Chromodynamics (QCD) and internal structure of the hadrons, as compared to the inclusive hadronic processes or spin-averaged processes. Extensive experimental studies have been made in different reactions. In particular, the single transverse-spin asymmetry (SSA) phenomena observed in various processes [1-6] (such as $H_a + H_b \to H + X$, $l + H \to H' + X$, $H_a + H_b \to l + l' + X$ and $l^+ + l^- \to H_a + H_b + X$,) have stimulated remarkable theoretical developments. Among them, two approaches in the QCD framework have been most explored: the transverse-momentum dependent (TMD) approach see for example [7-11] and the higher twist collinear factorization approach [12-15]. The first one deals with the TMD distributions in the QCD TMD factorization approach which is valid at small transverse momentum $k_T \ll Q^2$. In the second approach the spin-dependent differential cross sections can be calculated in terms of the collinear twist three quark-gluon correlation functions in the collinear factorization formalism. This approach is applicable for large transverse momentum $k_T \gg \Lambda_{QCD}$.

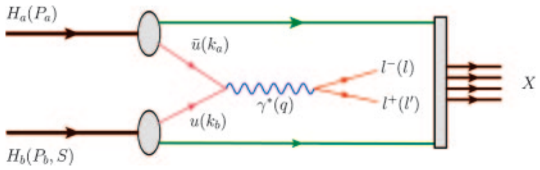

Fig. 1. – Feynman diagram of the Drell-Yan process; annihilation of a quark-antiquark pair with the production of a lepton pair.

Since at COMPASS the Drell-Yan data are expected mainly at small transverse momentum in the following we will discuss only the first, namely QCD TMD factorization based approach. Moreover we limit ourselves by the TMD generated by non-zero transverse momentum $\mathbf{k}_T$.

If we admit a non-zero quark transverse momentum $\mathbf{k}_T$ with respect to the hadron momentum, the nucleon structure is described, at leading twist, by eight PDF([1]): $f_1(x, \mathbf{k}_T^2)$, $g_{1L}(x, \mathbf{k}_T^2)$, $h_1(x, \mathbf{k}_T^2)$, $g_{1T}(x, \mathbf{k}_T^2)$, $h_{1T}^\perp(x, \mathbf{k}_T^2)$, $h_{1L}^\perp(x, \mathbf{k}_T^2)$, $h_1^\perp(x, \mathbf{k}_T^2)$ and $f_{1T}^\perp(x, \mathbf{k}_T^2)$. The first three functions, integrated over $\mathbf{k}_T^2$, give $f_1(x)$, $g_1(x)$ and $h_1(x)$, respectively. The last two ones are T-odd PDFs. The former, known also as Boer-Mulders function, describes the unbalance of number densities of quarks with opposite transverse polarization with respect to the unpolarized hadron momentum. The latter, known as Sivers function describes how the distribution of unpolarized quarks is distorted by the transverse polarization of the parent hadron. The correlation between $\mathbf{k}_T$ and parton/hadron transverse polarization is intuitively possible only for a non-vanishing orbital angular momentum of the quarks themselves.

Extraction of $h_1^\perp$ and $f_{1T}^\perp$, as well as of the poorly known h_1, is of great interest in revealing the partonic (spin) structure of hadrons (see ref. [17] for review).

In the DY process, as shown in fig. 1, quark and antiquark annihilate with the production of a lepton pair. Contrary to SIDIS, the fragmentation process is absent in DY, but here we have to deal with the convolution of quark and antiquark PDFs.

2. – Drell-Yan measurements at COMPASS

The COMPASS DY program focuses on valence quark-antiquark ($x_B > 0.1$) annihilation in the process $\pi^- p^\uparrow \to \mu^+\mu^- X$ to access the spin-dependent PDFs in the energy scale $Q^2 \gg 1$ (GeV/c)^2. Valence antiquarks can be provided by using intense pion beam and valence quark by transversely polarised proton target.

Because of the low cross section of the Drell-Yan process (fractions of nanobarn) high-luminosity and a large-acceptance set-ups are required, as well as large value of the polarisation in order to access spin structure information.

All these features are provided by the multi-purpose large-acceptance COMPASS spectrometer in combination with the SPS M2 secondary beams. High-performance COMPASS Polarised Target provides us a possibility to have 1.2 meters long solid-state proton target (target material is ammonia NH_3) with a 90% polarization.

The possibility to study the DY process with a pion beam at COMPASS was first discussed at the SPSC Meeting at Villars (September 2004) [18]. After a six-year-long

([1]) We are using the so-called Amsterdam notations [16].

effort on the feasibility study the new COMPASS-II Proposal [19] including the Deep Virtual Compton Scattering (DVCS) and polarised Drell-Yan experiments, was submitted to the SPS Committee at CERN. The Proposal was recommended for approval by the SPSC on September 30th, 2010 and approved by the CERN Research Board on December 1st, 2010. According to the preliminary running plan of COMPASS-II the start of the Drell-Yan program is scheduled for the beginning of 2014.

3. – Description of Drell-Yan processes

In the following we have adopted the formalism of Schlegel [11]. Since COMPASS will not have the possibility to use a polarized hadron beam, only reactions of an unpolarised hadron (pion) beam (H_a) with a polarized target (H_b) have been considered:

$$H_a(P_a) + H_b(P_b, S) \rightarrow \gamma^*(q) + X \rightarrow l^-(l) + l^+(l') + X, \tag{1}$$

where $P_{a(b)}$ is the momentum of the beam (target) hadron, $q = (l + l')$, l and l' are the momenta of the virtual photon, lepton and antilepton, respectively, and S is the four-vector of the target polarization.

If we stick to the Leading-Order (LO) approximation, the general formula for the Drell-Yan cross section [11] simplifies to [19]:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\mathrm{d}\Omega} = {} & \frac{\alpha_{em}^2}{Fq^2}\hat{\sigma}_U\Big\{\Big(1 + D_{[\sin^2\theta]}A_U^{\cos 2\phi}\cos 2\phi\Big) \\ & +|\mathbf{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) \\ & +A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},\end{aligned} \tag{2}$$

where $D_{[f(\theta)]}$ are the depolarisation factors, $\mathbf{S}_T$ is the target polarisation vector, F is the flux of incoming hadrons and the A's are the azimuthal asymmetries, $\hat{\sigma}_U$ is the part of the cross section which survives the integration over ϕ and ϕ_S, ϕ and θ are the azimuthal and polar angles of the lepton in the Collins-Soper frame [20] and ϕ_S is the angle of the spin in the proton rest frame. As is described in details in [19] the measurement of the asymmetry

- $A_U^{\cos 2\phi}$ gives access to the Boer-Mulders functions of the incoming hadrons,
- $A_T^{\sin\phi_S}$ to the Sivers function of the target nucleon,
- $A_T^{\sin(2\phi+\phi_S)}$ to the Boer-Mulders function of the beam hadron and to $h_{1T}^{\perp}$, the pretzelosity function of the target nucleon,
- $A_T^{\sin(2\phi-\phi_S)}$ to the Boer-Mulders function of the beam hadron and h_1, the transversity function of the target nucleon.

4. – T-odd TMDs in the transversely polarised Drell-Yan

The spin-dependent part of the single transversely polarised Drell-Yan process in general contains 5 asymmetries that do not vanish over azimuthal angle integration. Within the QCD parton model with TMD PDFs at twist-2 level only 3 of them survive and give access to the Boer-Mulders function of the pion and to the Sivers ($f_{1T}^{\perp}$), pretzelosity ($h_{1T}^{\perp}$) and transversity (h_1) PDFs of the nucleon, see the previous subsection.

Let us stress that the Sivers and the Boer-Mulders TMD PDFs are T-odd objects. Their field theoretical definition involves a non-local quark-quark correlator which contains the so-called gauge-link operator. While ensuring the colour-gauge invariance of the correlator, this gauge-link operator makes the Sivers and the Boer-Mulders functions process dependent. In fact, on general grounds it is possible to show that the $f_{1T}^{\perp}$ and the $h_1^{\perp}$ functions extracted from Drell-Yan processes and those obtained from semi-inclusive DIS should have opposite signs [21], *i.e.*

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \qquad \text{and} \qquad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS}. \tag{3}$$

An experimental verification of the sign-reversal property of the Sivers and Boer-Mulders functions would be a crucial test of QCD in the non-perturbative regime.

5. – COMPASS DY apparatus acceptance

The acceptance of the COMPASS spectrometer for Drell-Yan process $\pi^- p^\uparrow \to \mu^+\mu^- X$ was evaluated using a Monte Carlo chain starting from PYTHIA 6.2 [22] as event generator following with Comgeant, based on Geant 3.21 [23] program which simulates the particles interaction with the COMPASS apparatus. Three main criteria were used to optimize the energy of the incoming pion beam: the total DY event rate, the acceptance of the DY events by the COMPASS apparatus, and the covered range in x_1 and x_2. Also studies of the combinatorial background and open-charm decays was performed. As a result a pion beam momentum of 190 GeV/c was chosen.

As one can see from fig. 2, the COMPASS is sensitive (has a high acceptance in x_p) exactly in the range where the maximal asymmetry is expected. Also visible is that the COMPASS kinematics acceptance is large in the valence region of both q and $\bar{q}$ that corresponds in practice to the pure u-dominance in the quark annihilation and simplifies all analysis.

6. – Expected statistical errors and theory predictions on asymmetries

In our estimates we assume two years of running with the pion beam intensity of $6 \times 10^7\,\mathrm{p\,s^{-1}}$ and a 120 cm long NH_3 polarized target, resulting in expected luminosity of $\mathcal{L} \approx 1.18 \times 10^{32}\,\mathrm{s^{-1}\,cm^{-2}}$.

In our calculations of the statistical error projections of asymmetries we use 90% for the polarisation of the target material and $f = 0.22$ for the dilution factor. Table I presents the expected statistical errors for the unpolarised and the three transverse-spin–dependent asymmetries that we can access, using only one bin in x_F and a beam momentum of 190 GeV/c. The statistical errors of the asymmetries are calculated independently for the three mass ranges considered. For the J/Ψ mass region, the fraction of $q\bar{q}$-produced J/Ψ's was assumed to be 60% and the tail of the open-charm contamination was neglected except in the lowest mass region.

For a measurement in the DY high-mass region of the four asymmetries discussed above, the statistical error projections are shown in fig. 3 together with some theoretical predictions. In the case of the Sivers asymmetry, all data are combined in one bin in order to allow the best possible conclusion on its sign. Two error bars are shown with the smaller one being the systematic error, together with the theoretical prediction [24] (the only existing prediction that is given together with its uncertainties, which are derived

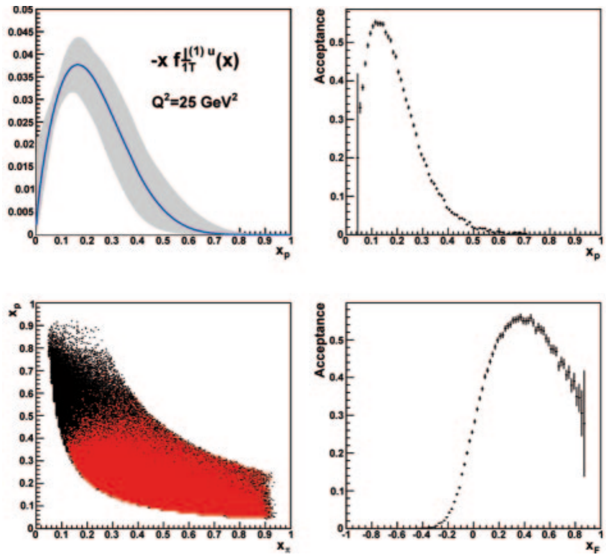

Fig. 2. – (Colour on-line) Dimuon mass range 4–9 GeV/c^2. The left upper panel shows the first $\mathbf{k}_T$-moment of the u-quark Sivers PDF calculated at $Q^2 = 25\,\text{GeV}^2$ from ref. [25]. The left lower panel shows the covered kinematic region in x_p *versus* x_π (simulated events are shown in black, reconstructed in red). In the right upper and lower panels the COMPASS acceptance is shown as a function of x_p and x_F, respectively.

from a fit to the experimental data). For the other three asymmetries, equipopulated bins in x_F are chosen. In the case of the Boer-Mulders (BM) asymmetry $A_U^{\cos 2\phi}$, the theoretical predictions were obtained using the Boer-Mulders function of the pion extracted from NA10 data [10] and a parametrisation of the Boer-Mulders function of the proton from ref. [26]. In the case of the Boer-Mulders-transversity asymmetry $A_T^{\sin(2\phi-\phi_S)}$, the theoretical predictions were obtained using the Boer-Mulders model for the pion BM function [17] and the evolution model for the transversity function [27].

In fig. 4 the statistical precision of the COMPASS DY experiment (Sivers Asymmetry) in case of 3 and 5 bins in x_F is shown, assuming 2 years of data taking (280 days).

Table I. – *Expected statistical errors for various asymmetries assuming two years of data taking and a beam momentum of* 190 GeV/c.

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/Ψ region	$4 < M_{\mu\mu} < 9$
$\delta\, A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta\, A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta\, A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta\, A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

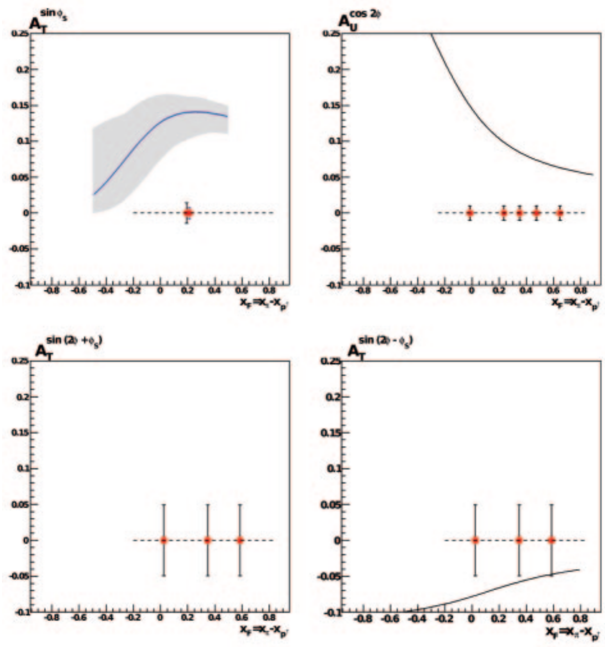

Fig. 3. – Theoretical predictions and expected statistical errors on the Sivers (top-left), Boer-Mulders (top-right), $\sin(2\phi + \phi_S)$ (bottom-left) and $\sin(2\phi - \phi_S)$ (bottom-right) asymmetries for a DY measurement $\pi^- p \to \mu^+\mu^- X$ with a $190\,\mathrm{GeV}/c$ π^- beam in the high-mass region $4\,\mathrm{GeV}/c^2 < M_{\mu\mu} < 9\,\mathrm{GeV}/c^2$. In the case of the Sivers asymmetry also the systematic error is shown (smaller error bar).

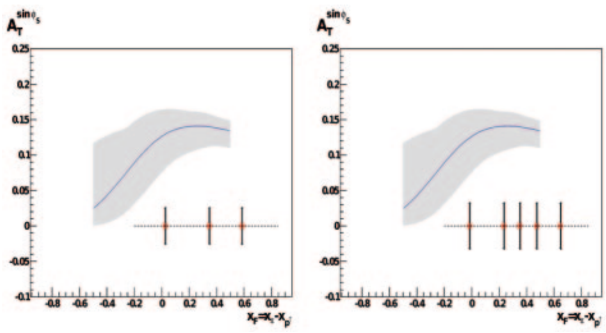

Fig. 4. – Expected statistical error of the Sivers asymmetry, for a measurement in 3 (left) and 5 (right) bins in x_F, and assuming 2 years of data taking (280 days). The theoretical prediction of the asymmetry from Anselmino *et al.* is also shown.

7. – Conclusion

The data from the future polarised Drell-Yan experiment at COMPASS will give a new input on the spin of the nucleon, probing the TMD PDFs. An important test of the TMD factorization approach in QCD will be performed: the sign and the amplitude of the Sivers asymmetry will be measured in order to verify the fundamental QCD prediction $f_{1T}^{\perp}(\mathrm{DY}) = -f_{1T}^{\perp}(\mathrm{SIDIS})$. The preliminary schedule of the COMPASS-II program foresees the start of the Drell-Yan experiment in 2014.

REFERENCES

[1] Bunce G. *et al.*, *Phys. Rev. Lett.*, **36** (1976) 1113 and references therein.
[2] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Rev. Lett.*, **84** (2000) 4047; **94** (2005) 012002.
[3] Alexakhin V. Y. *et al.* (COMPASS Collaboration), *Phys. Rev. Lett.*, **94** (2005) 202002.
[4] Adler S. S. *et al.* (PHENIX Collaboration), *Phys. Rev. Lett.*, **95** (2005) 202001.
[5] Adams J. *et al.* (STAR Collaboration), *Phys. Rev. Lett.*, **92** (2004) 171801 and references therein.
[6] Abe K. *et al.*, *Phys. Rev. Lett.*, **96** (2006) 232002; Seidl R. *et al.* (Belle Collaboration), *Phys. Rev. D*, **78** (2008) 032011.
[7] Sivers D. W., *Phys. Rev. D*, **43** (1991) 261.
[8] Collins J. C., *Nucl. Phys. B*, **396** (1993) 161.
[9] Anselmino M., Boglione M. and Murgia F., *Phys. Lett. B*, **362** (1995) 164 and references therein.
[10] Boer D., *Phys. Rev. D*, **60** (1999) 014012.
[11] Arnold S., Metz A. and Schlegel M., *Phys. Rev. D*, **79** (2009) 034005.
[12] Efremov A. V. and Teryaev O. V., *Sov. J. Nucl. Phys.*, **36** (1982) 140; *Yad. Fiz.*, **36** (1982) 242; Efremov A. V. and Teryaev O. V., *Phys. Lett. B*, **150** (1985) 383.
[13] Qiu J. W. and Sterman G., *Phys. Rev. Lett.*, **67** (1991) 2264 and references therein.
[14] Kouvaris C., Qiu J. W., Vogelsang W. and Yuan F., *Phys. Rev. D*, **74** (2006) 114013.
[15] Eguchi H., Koike Y. and Tanaka K., *Nucl. Phys. B*, **752** (2006) 1; **763** (2007) 198.
[16] Boer D. and Mulders P. J., *Phys. Rev. D*, **57** (1998) 5780.
[17] Barone V., Drago A. and Ratcliffe P. G., *Phys. Rep.*, **359** (2002) 1.
[18] CERN SPSC meeting, September 22–28, 2004, Villars, Switzerland.
[19] The COMPASS Collaboration, COMPASS-II Proposal, 2010, CERN-SPSC-2010-014; SPSC-P-340.
[20] Collins J. C. and Soper D. E., *Phys. Rev. D*, **16** (1977) 2219.
[21] Collins J. C., *Phys. Lett. B*, **536** (2002) 43.
[22] Sjöstrand T., Lönnblad L. and Mrenna S., PYTHIA 6.2 Physics and Manual, hep-ph/0108264; LU TP 01-21.
[23] Brun R. *et al.*, GEANT 3 Manual, CERN Program Library Long Writeup W5013 (1994).
[24] Anselmino M., Melis S. *et al.*, *Proceedings II International Workshop on Transverse Polarization Phenomena in Hard Scattering Processes, Transversity 2008, 27-31 May 2008, Ferrara, Italy*, arXiv:0809.3743 [hep-ph] (2008).
[25] Anselmino M. *et al.*, arXiv:0805.2677v1 [hep-ph] (2008).
[26] Zhang B. *et al.*, *Phys. Rev. D*, **77** (2008) 054011.
[27] Barone V. *et al.*, *Phys. Rev. D*, **56** (1997) 527.