Probing the hadron structure with polarised Drell-Yan reactions in COMPASS

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Abstract

The study of Drell-Yan (DY) processes involving the collision of an (un)polarised hadron beam on an (un)polarised (proton) target can result in a fundamental improvement of our knowledge on the transverse momentum dependent (TMDs) parton distribution functions (PDFs) of hadrons. The production mechanism of J/ψ and J/ψ - DY duality can also be addressed. The future polarised COMPASS DY experiment is discussed in this context, the most important features briefly reviewed.

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 been made in different reactions. In particular, the single transverse spin asymmetry (SSA) phenomena observed in various processes [1, 2, 3, 4, 5, 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, 8, 9, 11, 10] and the higher twist collinear factorization approach [13, 12, 15, 14]. The first one deals with the TMD distributions in the QCD TMD factorization approach which is valid at small transverse momentum $k_T \ll Q^2$. Such functions generalize the original Feynman parton picture, where the partons only carry longitudinal momentum fraction of the parent hadron. They will certainly provide more information on hadron structure.

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 $k_T \gg \Lambda_{QCD}$. Recently it was shown that the above two approaches are consistent in the intermediate transverse momentum region $\Lambda_{QCD} \ll k_T \ll Q^2$ where both apply [16, 18, 19].

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. More over 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 function 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.

Hence, 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). Here, we concentrate mainly on the leading twist transversity h_1, T-odd Boer-Mulders ($h_1^{\perp}$) and Sivers ($f_{1T}^{\perp}$) functions.

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

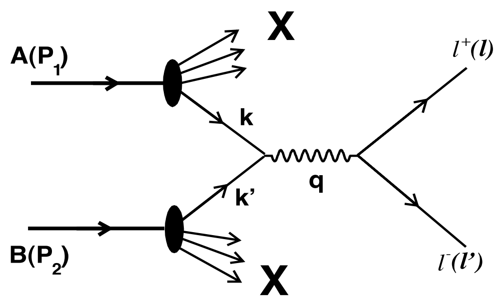

Figure 1: Feynman diagram of the Drell-Yan process; annihilation of a quark-antiquark pair with the production of a lepton pair.

2 Drell–Yan measurements at COMPASS

The proposed measurements of the polarised and unpolarised Drell–Yan process at COMPASS concentrate on the study of transversity (h_1) and of the Boer–Mulders ($h_1^{\perp}$) and Sivers ($f_{1T}^{\perp}$) functions. In the next sections we discuss the angular distributions of the dilepton pair as well as some important aspects of the J/ψ formation mechanism in pion–proton interactions.

The COMPASS DY program focuses on valence quark-antiquark ($x_B > 0.1$) annihilation to access the spin-dependent PDFs in the energy scale $Q^2 >> 1\ (GeV/c)^2$. Valence antiquarks can be provided by using intense pion beams.

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 and the COMPASS Polarised Target which combines a 1.2 m length of the target material with a 90% polarization reached for the ammonia target and a large acceptance of the target superconducting magnet.

[1] We are using the so called Amsterdam notations [20]

The possibility to study the DY process with a pion beam at COMPASS was first discussed at the SPSC Meeting at Villars (September 2004) [31]. Compass is also considering the use of an antiproton beam in a second phase of the DY experiment.

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 reaction of an unpolarised hadron beam (H_a) with a polarized target (H_b) have been considered:

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

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 anti-lepton respectively and S is the four-vector of the target polarization. Among the 12 structure functions which are present in the cross-section for unpolarized, longitudinally or transversely polarized targets, six have a simple interpretation within the LO QCD parton model and 5 of them give rise to azimuthal asymmetries in the dilepton production:

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

where is θ polar lepton angle and ϕ and ϕ_S azimuthal lepton angles. Within the QCD TMD PDFs approach the remaining asymmetries can be interpreted as higher order in q_T/q kinematic corrections and as contribution of non-leading twist PDFs.

4 Unpolarised Drell–Yan processes

The angular distribution for the unpolarised case is known since a long time [22, 21] and it is commonly parametrised as

$$\frac{1}{N}\frac{dN}{d\Omega} \equiv \frac{d\sigma}{d^4q\, d\Omega}\Big/\frac{d\sigma}{d^4q}\frac{3}{4\pi}\frac{1}{(\lambda+3)}[1 + \lambda\cos^2\theta + \mu\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi]\,, \tag{2}$$

where leptons polar and azimuthal angles are defined in the Collins–Soper frame. In the QCD collinear parton model the coefficients λ, μ and ν are not independent and the Lam–Tung sum rule [23] holds

$$1 - \lambda = 2\nu\,, \tag{3}$$

which is trivial in collinear LO approximation:

$$\lambda^{LO} = 1 \,, \qquad \mu^{LO} = 0 \,, \qquad \nu^{LO} = 0 \,. \tag{4}$$

QCD corrections to the Born cross-section allow $\lambda \neq 1$ and $\nu \neq 0$, nevertheless the Lam–Tung sum rule remains valid up to $\mathcal{O}(\alpha_s)$ corrections. However, large azimuthal asymmetries in the distribution of the final leptons observed in high-energetic collisions of pions and anti-protons, with nuclei [24, 25, 26, 27], imply a strong violation of the Lam–Tung sum rule. In particular, an unexpectedly large $\cos 2\phi$ modulation of the cross section was observed. As it was mentioned in the previous subsection this modulation appears at twist-2 level for not vanishing Boer Mulders functions of pions and nucleons.

5 Transversely polarised Drell–Yan processes

The spin dependent part of the single transversely polarised Drell–Yan process in general contains 5 non vanishing over azimuthal angle integration asymmetries (Sec. 3). Within the QCD parton model with TMD DFs 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) DFs of the nucleon, see 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 [30], i.e.

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{DIS} \qquad \text{and} \qquad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{DIS} \,. \tag{5}$$

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

5.1 COMPASS DY apparatus acceptance

The acceptance of the COMPASS spectrometer for Drell-Yan events with $\mu^+\mu^-$ pairs in the final state was evaluated using a Monte-Carlo chain starting from PYTHIA 6.2 [32] as event generator following with Comgeant, based on Geant 3.21 [33] program which simulates the particles interaction with the COMPASS apparatus. Three main creation 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 un 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 the Figure 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 $\bar{q}$ what corresponds in practice to the pure u-dominance in the quark annihilation and simplify all analysis.

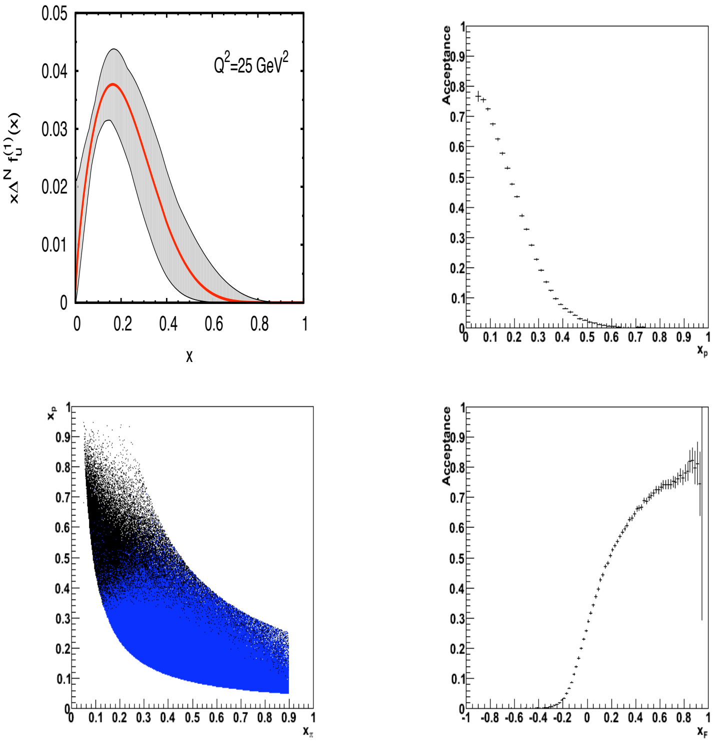

Figure 2: The left upper panel shows the first moment of the Sivers function for the u quark calculated at $Q^2 = 25$ GeV^2 from [37]. The left lower panel shows the COMPASS covered kinematic region in x_p versus x_π (in blue). In the right upper and lower panels the COMPASS acceptance as a function of x_p and x_F respectively are shown.

5.2 Expected statistical errors and theory predictions on asymmetries

In our estimates we assume two years of running with the luminosity of $\approx 1.18 \times 10^{32}\ s^{-1}cm^{-2}$ and a 120 cm long NH_3 polarized target. Table 1 presents the expected statistical errors for the Sivers asymmetry $\delta\, A_T^{\sin\phi_S}(x_F)$, taking into account single bin, as a function of the beam energy. In the first column the simulated pion beam momentum is presented as it was used in Monte-Carlo, second column corresponds to the $\mu\bar{\mu}$ mass range $2. - 2.5\ GeV$, where some contribution from the combinatorial background is expected, and third one – to the most favourable (background free) $\mu\bar{\mu}$ mass range $4. - 9.\ GeV$.

$\delta\, A_T^{\sin\phi_S}$	$2 < M_{\mu\mu} < 2.5$	$4 < M_{\mu\mu} < 9.$
$p_{\pi^-} = 106$ GeV/c	x*0.0087	0.0236
$p_{\pi^-} = 160$ GeV/c	x*0.0081	0.0188
$p_{\pi^-} = 190$ GeV/c	x*0.0079	0.0174
$p_{\pi^-} = 213$ GeV/c	x*0.0078	0.0166

Table 1: Expected statistical errors in the Sivers asymmetry, assuming 2 years of data-taking for pion beam momentuma used in the Monte-Carlo and two $\mu\bar{\mu}$ invariant mass ranges.

In figure 3 the expected errors on the Sivers asymmetry are presented, as an example, with different number of x_F bins, for the DY high mass region; together with different theory predictions. As can be seen, depending on the number of bins, a statistical error of 0.01 to 0.02 is reachable.

The asymmetries are evaluated at $\langle M \rangle \simeq 5\,GeV$ (estimated using PYTHIA). The three lower curves (solid, dashed and dot-dashed lines) represent the estimate of the Sivers single spin asymmetry for COMPASS for 3 different parametrization of the Sivers functions.

Solid and dashed lines correspond respectively to fits I (Eq.6) and II (Eq.7) for Sivers function from Ref.[34] and dot-dashed line corresponds to fit from Ref.[35] (fit III – Eq.8).

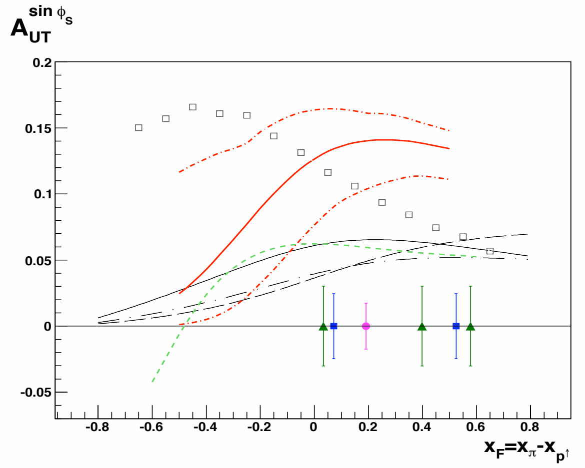

Figure 3: Theoretical predictions and expected statistical errors on Sivers asymmetry in the DY process $\pi^- p \to \mu^+\mu^- X$ in the high dimuon mass region $4. < M_{\mu\mu} < 9.$ GeV/c ^{2}. The three lower curves (black solid, dashed and dot-dashed lines) Ref.[34] and [35], the solid red line Ref.[36] and the predictions obtained in Ref.[29] and Ref.[38] are shown by squares and short-dashed line correspondingly.

$$x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = 0.4x(1-x)^5, \tag{6}$$

$$x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = 0.1x^{0.3}(1-x)^5, \tag{7}$$

$$x f_{1T}^{\perp(1)u} = -x f_{1T}^{\perp(1)d} = (0.17...0.18)x^{0.66}(1-x)^5 \tag{8}$$

$$\tag{9}$$

The solid red line shows the Sivers asymmetry for the same mass range, integrated in q_T up to 1 GeV/c Ref.[36], while the dashed lines shows the 1 sigma error band of the prediction. The predictions obtained in Ref.[29] and Ref.[38] are shown by squares and short-dashed line correspondingly.

6 Competition and complementarity

There are plans for future polarised Drell-Yan experiments at BNL, CERN, Fermilab, GSI, J-PARC and JINR. Some of them are presented in table 2.

Only PAX at FAIR (GSI-Darmstadt) and NICA at JINR (Dubna) plan to measure transverse double polarised Drell-Yan processes. In Dubna it is proposed to study Drell-Yan in proton–proton or deuteron–deuteron polarised beams collisions (access only to interactions between valence quarks and sea anti-quarks). The PAX collaboration plans to polarise anti-protons to study the interactions between valence quarks and valence antiquarks. However the possibility to get a beam of polarised anti-protons still has to be demonstrated. Both these collaborations plan to study e^+e^- final states.

The Drell-Yan programs at RHIC and J-PARC both foresee, like COMPASS, to measure single-spin asymmetries in the Drell-Yan process, but unlike COMPASS, they have only access to valence-sea quarks interactions in $p - -p$ collisions. The E906 project is

Facility		Type		s (GeV^2)	Timeline
RHIC (STAR)	[39]	collider,	$p^{\Uparrow}p$	200^2	> 2013
E906 (Fermilab)	[40]	fixed target,	pp,	250	> 2011
J-PARC	[41]	fixed target,	$pp^{\Uparrow}$, $\pi p^{\Uparrow}$	$60 \div 100$	> 2015
GSI (PAX)	[42]	collider,	$\overline{p}^{\Uparrow}p^{\Uparrow}$	200	> 2017
GSI (Panda)	[43]	fixed target,	$\overline{p}p$	30	> 2016
NICA	[44]	collider,	$p^{\Uparrow}p^{\Uparrow}$, $d^{\Uparrow}d^{\Uparrow}$	676	> 2014
COMPASS	(this letter)	fixed target,	$\pi^{\mp}p^{\Uparrow}$	$300 \div 400$	> 2010

Table 2: Future Drell–Yan experiments.

oriented to the study of the sea quark distribution in the proton and can be considered as a good complementary measurement with respect to COMPASS DY.

The Panda experiment is rather designed for the J/ψ formation mechanism study than for the Drell-Yan physics, because of the very small anti-proton beam energy (15 GeV).

7 Conclusion

Single polarised Drell-Yan is a powerful tool to study hadron spin structure. Because of its nature it can provides us with new and complementary information with respect to what we can learn from polarised SIDIS.

If the COMPASS DY program will be approved, COMPASS will have the chance to be the first ever experiment to perform SSA measurements in Drell–Yan processes to access the spin-dependent PDFs in the valence quark region and the statistical significance of the result will be high.

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