PROCEEDINGS OF SCIENCE

Polarized Drell-Yan measurement at COMPASS-II

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The COMPASS experiment at CERN prepares a new measurement on the nucleon structure via Drell-Yan reactions using a transversely polarized ammonia target and a π^- beam. This first-ever polarized Drell-Yan measurement will provide the insight into the transverse momentum dependent parton distribution functions such as the Sivers and Boer-Mulders functions, complementary to what is measured in the semi-inclusive deep-inelastic scattering process. The important features and status of this project are introduced.

XV International Conference on Hadron Spectroscopy-Hadron 2013
4-8 November 2013
Nara, Japan

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 http://pos.sissa.it/

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1. Transverse spin-dependent structure of the nucleon

The partonic structure of the hadron in collinear case is described by three kinds of parton distribution functions (PDFs) at leading order (LO): the unpolarized distribution function $f_1(x)$, the helicity distribution $g_1(x)$ and the transversity $h_1(x)$, where x is a fraction of the momentum carried by the parton of parent hadron. If one admit non-zero transverse momentum of quark in the nucleon, five more PDFs appear at LO, known as transverse momentum dependent (TMD) PDFs. Among them, two are naïve T-odd objects: the Sivers function $f_{1T}^{\perp}(x,\mathbf{k}_T^2)$ describes the influence of the transverse spin of the nucleon onto the quark transverse momentum distribution and the Boer-Mulders function $h_1^{\perp}(x,\mathbf{k}_T^2)$ describes the correlation between the transverse spin and transverse momentum of quarks in an unpolarized nucleon. In case of single-polarized Drell-Yan (COMPASS case: an unpolarized pion beam and a transversely polarized target), the Sivers and the Boer-Mulders functions could be extracted from the angular distributions of the Drell-Yan cross section represented at LO as [1, 2]

$$\begin{aligned}
\frac{d\sigma}{d^4q\,d\Omega} &\overset{\text{LO}}{=} \frac{\alpha_{em}^2}{Fq^2}\,\hat{\sigma}_U \left\{ \left(1 + D_{[\sin^2\theta]} A_U^{\cos 2\phi} \cos 2\phi\right) \right. \\
&+ |\mathbf{S_T}| \left[A_T^{\sin\phi_S} \sin\phi_S + D_{[\sin^2\theta]} \left(A_T^{\sin(2\phi+\phi_S)} \sin(2\phi+\phi_S) \right.\right. \\
&+ \left.\left.\left. A_T^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) \right)\right] \right\}
\end{aligned} \tag{1.1}$$

where q is the 4-momentum of the virtual photon, α_{em} is the fine structure constant, $\mathbf{S_T}$ and ϕ_S are the transverse target spin and its azimuthal angle in the target rest frame, θ and ϕ are polar and azimuthal angle of the lepton in the Collins-Soper frame. $\hat{\sigma}_U$ is the part of cross section surviving integration over ϕ and ϕ_S, $D_{[\sin^2\theta]}$ is the depolarization factor and F is the flux of incoming hadrons. The observables of the asymmetries are $A_U^{\cos 2\phi}$ gives access to the Boer-Mulders functions of the beam hadron and the target nucleon, $A_T^{\sin\phi_S}$ 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 the pretzelosity function of the target nucleon, and $A_T^{\sin(2\phi-\phi_S)}$ to the Boer-Mulders function of the beam hadron and the transversity function of the target nucleon.

The Sivers and the Boer-Mulders functions, formerly considered to be zero by the requirement of time-reversal property of QCD, was found to survive because of the presence of a gauge line (Wilson line) which ensures the gauge invariance in the definition of TMD parton distribution. Nevertheless, this Wilson line introduces process dependence, and these two TMD PDFs extracted from the Drell-Yan (DY) processes and those from semi-inclusive deep-inelastic scattering (SIDIS) are predicted to be of the opposite sign [3–5]. Therefore the comparison of these TMD PDFs from the SIDIS and DY processes will provide an essential test/verification of perturbative QCD and TMD physics. It is rather unique to perform both types of measurements with the same apparatus in COMPASS experiment as introduced below.

2. Transversely polarised Drell-Yan experiment at COMPASS

The COMPASS [6] collaboration is preparing a new series of measurements using a π^- beam at 190 GeV/c impinging on a transversely polarized ammonia (NH_3) target. COMPASS has a two-stages spectrometer: the large angle spectrometer (LAS) covering a large angular acceptance, and the small angle spectrometer (SAS) for particles emitted at small angles. The set-up includes two dipole magnets and approximately 350 tracking planes [7]. The target is segmented into two cylindrical cells transversely polarized in opposite directions in order to minimize the systematic errors in the asymmetries. A hadron absorber will be installed downstream of the polarized target in order to suppress the flux of secondary hadrons produced in the interactions of the π^- beam with the target. The configuration and material of this absorber was optimized to maximize the hadron stopping power and minimize the multiple scattering of muon. As a consequence, this absorber shall be made of aluminum oxide (Al_2O_3) and stainless steel, containing a conical beam stopper of tungsten in the center along the beam direction.

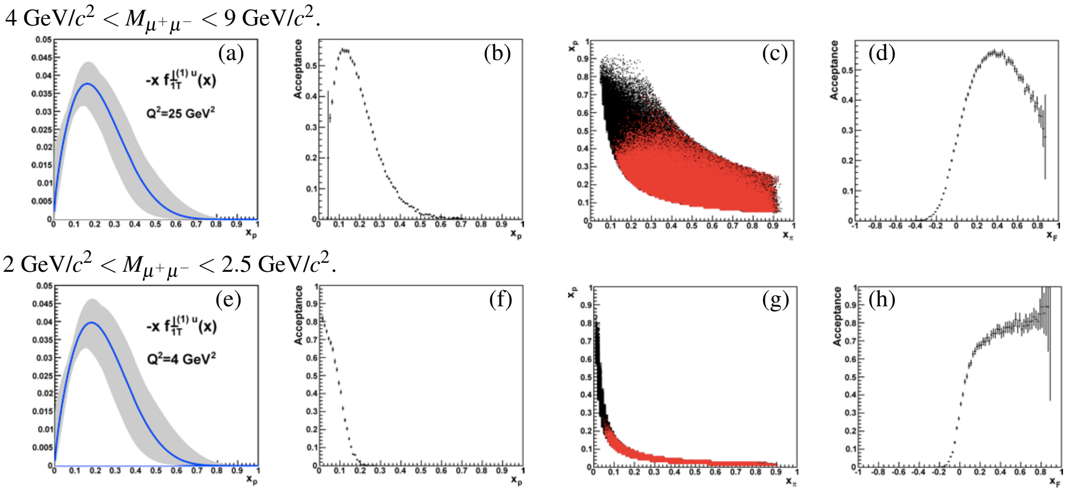

Figure 1: In the dimuon mass region 4 GeV/$c^2 < M_{\mu^+\mu^-} < 9$ GeV/c^2, (a) the first k_T-moment of the u-quark Sivers PDF calculated at $Q^2 = 25$ GeV^2 from Ref. [10]. (c) shows the covered kinematic region in x_p versus x_π (in red). (b) and (d) the COMPASS acceptances are shown as a function of x_p and x_F, respectively. The figures (e)-(h) are for 2 GeV/$c^2 < M_{\mu^+\mu^-} < 2.5$ GeV/c^2.

Short beam tests were performed in 2007, 2008, 2009 and 2012 in order to establish the feasibility of the proposed polarized DY program at COMPASS. The open spectrometer configuration (no hadron absorber after the target) was used in 2007 and 2008 beam tests. It was confirmed that in this spectrometer configuration high flux of secondary particles hitting the tracking detectors do not allow reasonable beam intensity (luminosity). In 2009 DY beam test, the prototype hadron absorber was installed just behind the target. A π^- beam with momentum 190 GeV/c and the targets consist of two cylinders of polyethylene (CH_2) were used. The upstream part of the absorber consisted of concrete, while the downstream part was made of stainless steel. In the center of the absorber, along the beam axis, a beam plug made of tungsten was installed. The results of 2009 beam test were found to be very close to the expectations. The desired luminositiy was achieved and the detector configuration with the hadron absorber was validated.

The acceptance of the COMPASS spectrometer for DY events with $\mu^+\mu^-$ pairs in the final state was evaluated using a Monte Carlo simulation based on the PYTHIA 6.2 [8] and the COMPASS Monte Carlo simulation program based on GEANT 3.21 [9] (COMGEANT). The average

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geometrical acceptance of dimuon is 42% in the high dimuon-mass region 4 GeV/c^2 < $M_{\mu^+\mu^-}$ < 9 GeV/c^2 and 46% in the intermediate dimuon-mass region 2 GeV/c^2 < $M_{\mu^+\mu^-}$ < 2.5 GeV/c^2. In Fig. 1(a)-(d), the acceptance is shown as a function of x_p, x_p versus x_π, and x_F, where $x_F = x_\pi - x_p$, for 4 GeV/c^2 < $M_{\mu^+\mu^-}$ < 9 GeV/c^2. The COMPASS kinematics is in the valence region of both the u quark from the proton and the $\overline{u}$ antiquark from the pion. In the same figure, the x_p-dependence of the first k_T-moment of the u-quark Sivers function is also shown for comparison. Its value is expected to be largest where the acceptance is largest. In Fig. 1(e)-(f), the same distributions are shown for 2 GeV/c^2 < $M_{\mu^+\mu^-}$ < 2.5 GeV/c^2. In the proposed DY experiment, a beam intensity of 6×10^7 particles/s can achieve a luminosity of 1.2×10^{32} cm^{-2}s^{-1}. Assuming two years of DY data-taking (280 days), 2.5×10^5 DY events are expected in 4 GeV/c^2 < $M_{\mu^+\mu^-}$ < 9 GeV/c^2, and 1.4×10^6 are in 2 GeV/c^2 < $M_{\mu^+\mu^-}$ < 2.5 GeV/c^2. The projected statistical errors are shown in Fig. 2 together with some theoretical predictions [10–14].

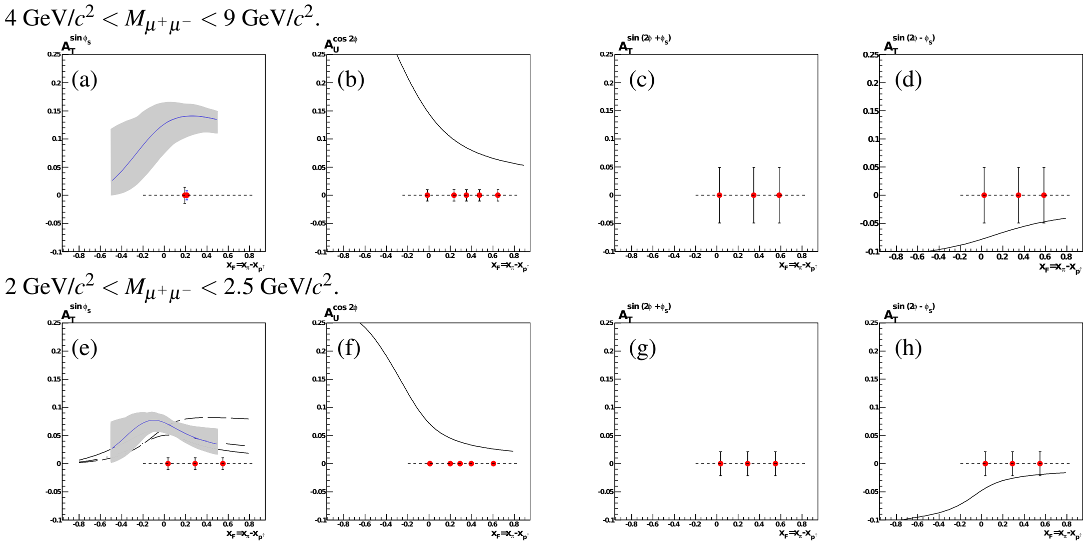

Figure 2: (a)-(d) Theoretical predictions and expected statistical errors on the asymmetries for 4 GeV/c^2 < $M_{\mu^+\mu^-}$ < 9 GeV/c^2, and (e)-(h) for 2 GeV/c^2 < $M_{\mu^+\mu^-}$ < 2.5 GeV/c^2.

Unique additional opportunity might be provided with the usage of the CErenkov Differential counter with Achromatic Ring focus (CEDAR) detectors [15] in front of the COMPASS polarized target. The negative hadron beam available at COMPASS, consists of 96.8% π^-, 2.4% K^-, and 0.8% $\overline{p}$, whereas the positive beam consists of 74.6% p, 24.0% π^+ and 1.4% K^+, all with momenta of 190 GeV/c. The beam particles could be identified by CEDAR which is located upstream the target. The use of CEDAR not only increase the purity of the π^- beam, but also provides a unique opportunity to take the data with π^--, K^-- and $\overline{p}$-induced DY at the same time. The K^--induced DY would enable the determination of the kaon structure and the strange sea inside the nucleons. Especially the $\overline{p}$-induced DY give a proton TMD PDFs and transversity function with model-independent approach.

It was recently shown that it is feasible to install additional (unpolarized) nuclear targets between the polarized NH_3 target and the hadron absorber along the beam axis. This would allow us to further enrich COMPASS DY physics program by studying, for example, longitudinally polarized virtual photons at large x_p and violation of Lam-Tung relation at large p_T [16]. The pion-induced DY process with nuclei targets in COMPASS will help further investigate these interesting phenomena and also explore the newly predicted the flavor dependence of the EMC effect.

3. Summary

The polarized DY process is an important tool to study TMD PDFs and improve our understanding of the nucleon spin structure. The comparison of TMD PDFs from SIDIS and DY processes will be an essential test/verification of the theoretical framework of TMD physics and pursuing both types of measurements with the same apparatus at COMPASS will be unique. The DY experiment at COMPASS is expected to be the first-ever polarized DY experiment in the world. The beginning of the data taking is scheduled for mid-October 2014.

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