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DRELL–YAN STUDIES IN $p\bar{p}$ REACTIONS AT FAIR*

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The nucleonic structure is far to be completely understood. A transverse momentum-dependent description of the nucleon structure is a crucial milestone for several forthcoming studies in a wide range of experimental scenarios. By means of antiproton beams, eventually polarized, that will be available at the future FAIR facility with a beam momentum up to 15 GeV/c, the nonperturbative region of the QCD could be accessed. One of the main goals of the forthcoming experiments at FAIR is the investigation of those Drell–Yan lepton pairs produced in proton–antiproton annihilations, taking advantage of the high expected luminosities.

Drell–Yan studies are a unique tool to access the spin-dependent properties of the nucleon, and namely its transverse degrees of freedom. Transverse Momentum-Dependent (TMD) Parton Distribution Functions (PDFs), in particular, the Boer–Mulders, the Sivers, and the transversity distribution functions, could be widely investigated by means of the corresponding experimental azimuthal asymmetries. In later stages of FAIR, single- and double-spin asymmetries could be investigated as well. The Drell–Yan physics program which could be accessed at FAIR will be discussed in detail, with a particular focus on the PANDA experimental scenario.

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INTRODUCTION

The Parton Distribution Functions (PDFs) and the Fragmentation Functions (FFs) are both needed to completely describe the nucleonic structure. At leading twist, three PDFs are needed to describe the cross section of the unpolarized data: $f_1(x)$, $g_1(x)$, and $h_1(x)$. The $f_1(x)$ function describes the probability of finding a quark with a fraction x of the longitudinal momentum of the parent hadron, regardless of the quarks spin orientation. The $g_1(x)$ function is the longitudinal polarization (helicity) distribution of the quarks. The $h_1(x)$, or transversity, describes the quarks transverse spin distribution inside a transversely polarized hadron. While the first two PDFs have a probabilistic interpretation in the helicity base and many experimental data, characterized by a high accuracy, can be found in the literature, the transversity is not diagonal in the helicity base, and it is still

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the subject of deep investigations. Moreover, the $h_1(x)$ could not be extracted from the historical deep inelastic scattering (DIS) data [1] since it is a chirally odd function. The three mentioned distribution functions are connected by the Soffer inequality

$$|h_1(x)| \leqslant \frac{1}{2}|f_1(x) + g_1(x)|, \quad (1)$$

which has some limitations: strictly speaking it holds at leading order and at large Q^2 scales only.

To describe in a consistent way the polarized cross sections in high energy hadron–hadron scattering [2], a Transverse Momentum-Dependent (TMD) approach, which takes into account the transverse momentum of the partons ($\mathbf{k}_T$), has to be introduced. In this scenario, the three PDFs described above are no more enough, and eight independent PDFs, functions of x and $\mathbf{k}_T$, are needed. Figure 1 shows such eight TMD PDFs: f_1, g_{1L}, $f_{1T}^{\perp}$, and g_{1T} are chirally even functions, while $h_1^{\perp}$, $h_{1L}^{\perp}$, h_{1T}, and $h_{1T}^{\perp}$ are chirally odd.

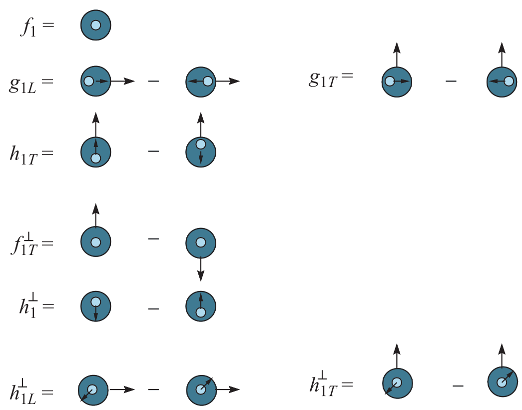

Fig. 1. TMD PDFs distributions. Arrows indicate the polarizations of the quark and of the parent hadron

The TMD PDFs can be investigated in different experimental scenarios. In Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments those functions are convoluted with the FFs, posing hence theoretical and experimental challenges to their extraction. The Drell–Yan (DY) process should offer a direct access to those functions, since it is possible to define experimental azimuthal asymmetries depending on the TMD PDFs only. The DY production of lepton pairs is an electromagnetic process in which a virtual photon, produced in a quark–antiquark annihilation, decays into a lepton pair final state: $h_1 h_2 \to \gamma^* \to l^+ l X$. DY processes are usually investigated in the so-called Collins–Soper frame [3], the rest frame of the virtual photon. In this frame, shown in Fig. 2, a hadron plane and a lepton plane can be defined. If one defines the angle between the two planes as φ, then $\varphi_{S1,2}$ is the angle between the nucleon spin ($S_{1,2}$) with respect to the lepton plane.

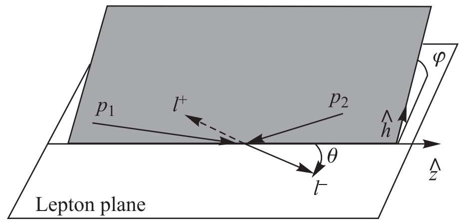

Fig. 2. The Collins–Soper frame [3]

A unique kinematic region for those investigations should be granted by the centre-of-mass energy foreseen at FAIR. A low centre-of-mass energy range and the availability of antiproton beams should characterize the FAIR scenario. In DY processes, each valence quark can contribute to the diagram. At much higher energies, those measurements are affected by a big contribution coming from the sea quarks. In the golden case, with proton and antiproton both transversely polarized, in the handbag diagram the quark lines are not correlated with each other, hence we have no FF involved in the reaction. Chirally odd distribution functions can hence be investigated without the suppression typical of the DIS experiments.

One more argument to extend the experimental investigation to low centre-of-mass energies comes from the literature [4], where the calculations of the k factors to the leading order cross section and double spin asymmetry are reported, for the two experimental scenarios corresponding to the centre-of-mass energies of the fixed target and of the asymmetric collider layouts proposed at FAIR. The higher order contributions to the cross section are expected to decrease at higher energies, while they are still sizeable at lower s; the double spin asymmetry is marginally affected even at lower energies. As suggested by the GSI PAC Committee, the perturbative corrections at $s = 200$ GeV^2 were investigated as well. At such centre-of-mass energies, the influence of the higher orders' perturbative contributions should be strongly reduced, as reported for the DY dilepton production k factors in the completely unpolarized scenario.

In the FAIR scenario, the distribution functions of the quarks inside the proton and of the antiquark in the antiproton should be the same. The Soffer inequality is significantly larger, and the limitations due to the high centre-of-mass energy described above here vanish. Large expectations for the double spin asymmetry in a wide Q^2 range are foreseen in different theoretical predictions [4, 5]. Hence, in order to access the valence quark transversity the DY production at FAIR is a golden channel.

The double spin asymmetries are the final goal, but many indications on the nucleon structure can be obtained from the single polarized reactions, and even from the completely unpolarized ones. In the latter scenario, where the differential cross section depends on the parameters λ, μ, and ν [6], the fractional spin nature of the quarks is reflected by the Lam–Tung sum rule

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

where the values λ, μ, and ν are predicted by leading order and next-to-leading order QCD to be ~ 1, ~ 0, and ~ 0, respectively; such values lead to the usual dipole distribution for the polar angle. In a peculiar system along the z direction, where the quarks are considered massless, this sum rule should be valid. However, many experimental data show an important role of the azimuthal effects, characterized by large ν values up to $\sim 30\%$: the E615 Collaboration [6] at Fermilab confirmed the early observation of the dipole shape for the polar angle distributions, and determined the large azimuthal asymmetries leading to the ν values quoted above. This was not an effect due to the composition of the nuclear target, since further studies performed at CERN with different target configurations demonstrated that a target effect is not the dominant contribution [7]. The violation of the Lam–Tung sum rule leads to relevant azimuthal asymmetries; such sizeable transverse effects cannot be explained by higher-order contributions. Such a violation stresses the role of the transverse dynamics of partons inside hadrons, even in the unpolarized case.

Keeping the DY cross section differential on the transverse momentum of the lepton pairs ($\mathbf{q}_T$) [8], a $\cos 2\varphi$ contribution to the cross section provides asymmetries which could lead to the product $\bar{h}_1^\perp h_1^\perp$, where $h_1^\perp$ is the so-called Boer–Mulders function (a T-odd chirally odd TMD), the distribution of the transversely polarized quarks inside an unpolarized nucleon. Predictions for protons and for pions could be extracted from the experimental data collected at different energies. The sign of ν is expected to be the same as $h_1^\perp$, and the contribution coming from the sea quarks is predicted to be small.

When considering the single polarized case, more terms with respect to the unpolarized cross section appear, terms depending on φ_S and leading to single-spin asymmetries weighted by $\sin(\varphi - \varphi_{S_2})$ and $\sin(\varphi + \varphi_{S_2})$ and proportional to two of the TMD PDFs discussed above: $h_1^\perp$ and transversity [8].

1. EXPERIMENTAL SCENARIOS

The present FAIR facility layout foresees different storage rings: among the others, the HESR (High-Energy Storage Ring) will be devoted to the accumulation of the antiprotons. In order to achieve the required luminosity, the HESR will be equipped with stochastic and electron cooling systems. Two spectrometers to be hosted on the HESR ring have been proposed: PANDA and PAX. The main aim of the PANDA Collaboration [1, 9] is a deep investigation of the QCD properties and limits via a systematic exploration of the hadronic matter; its gluon

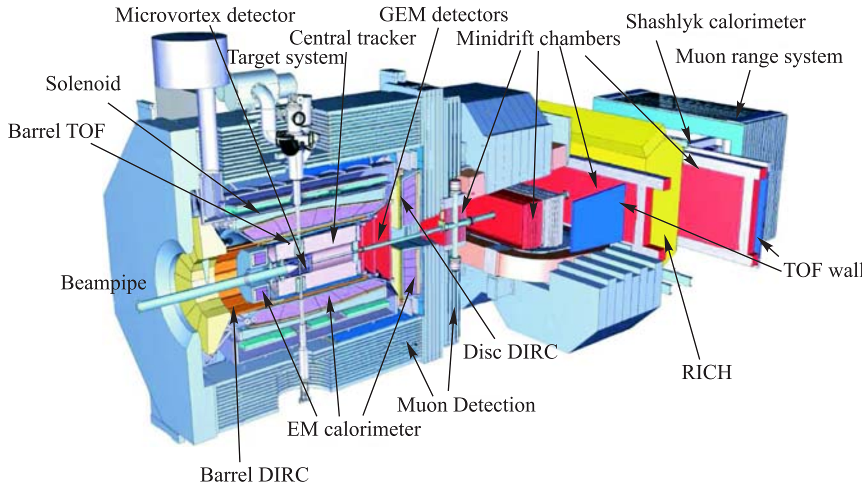

Fig. 3. 3D view of the PANDA spectrometer

rich environment will lead to access a wide range of final states, and to perform hadron spectroscopy studies in the interaction dynamics as well as in the nuclear medium. A possible connection between perturbative and lattice QCD will be also investigated. The PANDA detector, shown in Fig. 3, is designed to achieve an almost 4π acceptance, and it is composed of two magnetic spectrometers: the Target Spectrometer (TS), based on a superconducting solenoid magnet which surrounds the interaction point, and the Forward Spectrometer (FS), based on a dipole magnet to detect the most forward emitted particles.

For a later FAIR stage, two further rings have been proposed: the Antiproton Polarizer Ring (APR) and the Cooler Synchrotron Ring (CSR). The APR could be used to polarize $\bar{p}$ that would hence be accelerated in the CSR. These two rings would allow the PAX Collaboration [10] to investigate processes involving polarized antiprotons. Nowadays, the PAX Collaboration has focused in finding the experimental technique most suitable to polarize antiprotons. The proposed PAX spectrometer is optimized to detect electromagnetic final states making use of an HESR asymmetric collider mode and taking advantage of a toroidal magnetic field. More details on the PAX experiment can be found in this volume in the reports of A. Nass, G. Ciullo, and E. Steffens.

2. DRELL–YAN EVENTS IN PANDA

Part of the PANDA Collaboration physics program will focus on the investigation of electromagnetic processes. The large foreseen luminosity (up to $2 \cdot 10^{32}$ cm$^{-2} \cdot$ s^{-1}) should allow one to investigate the Drell–Yan production of muon pairs in annihilations as $p\bar{p} \to \gamma^* X \to \mu^+\mu^- X$. At the maximum centre-of-mass energy available ($s = 30$ GeV^2), the DY cross section is expected to be of the order of 1 nb [1]. Being the main background source, the production of events of the type $p\bar{p} \to n(\pi^+\pi^-)X$, where n indicates the number of pion pairs, has been investigated in the PANDA scenario. The background cross section is estimated to be around 20–30 mb [1], leading to a required rejection factor $\sim 10^7$.

The kinematic region that can be accessed in the DY phase space is described by the τ variable, defined as the product between the momentum fractions (x_1 and x_2) of the incident nucleon momenta carried away by the two partons taking part to the annihilation vertex. A limited centre-of-mass energy affects the possible momentum transfer and hence which τ values and which kinematic regions could be accessed. The top-right corner of Fig. 4 ($\tau \geqslant 0.5$) corresponds to the DY safe region defined by $4 \leqslant M_{\gamma^*} \leqslant 9$ GeV/c^2, so called because of free-from-resonant contributions. Since we expect a higher DY cross section (by almost three orders of magnitude) at lower τ values ($0.05 < \tau < 0.2$), PANDA will investigate also the kinematic region defined by $1.5 \leqslant M_{\gamma^*} \leqslant 2.5$ GeV/c^2, free from resonances as well.

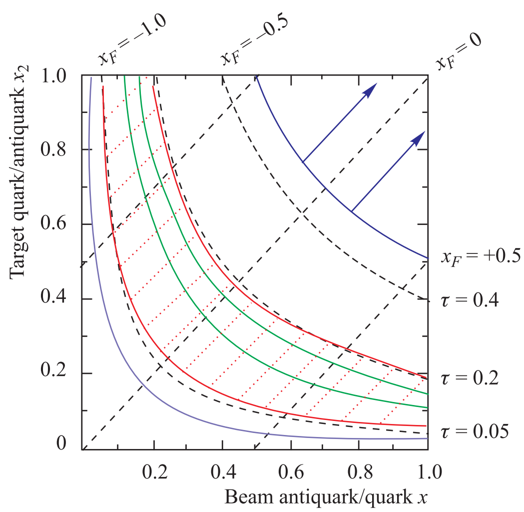

Fig. 4. Phase space regions accessible in the PANDA scenario: $\tau \geqslant 0.5$ corresponds to $4 \leqslant M_{\gamma^*} \leqslant 9$ GeV/c^2, and $0.05 < \tau \leqslant 0.2$ to $1.5 \leqslant M_{\gamma^*} \leqslant 2.5$ GeV/c^2

The corresponding feasibilities studies have been performed with the generator described in [11]. Based on the experimental data available in the literature, it can provide final states containing muon pairs produced in $\bar{p}$ interactions with polarized or with unpolarized nuclear targets. The above-described asymmetries, reconstructed from $5{\cdot}10^5$ simulated events, are shown in Figs. 5, *a–c* as functions

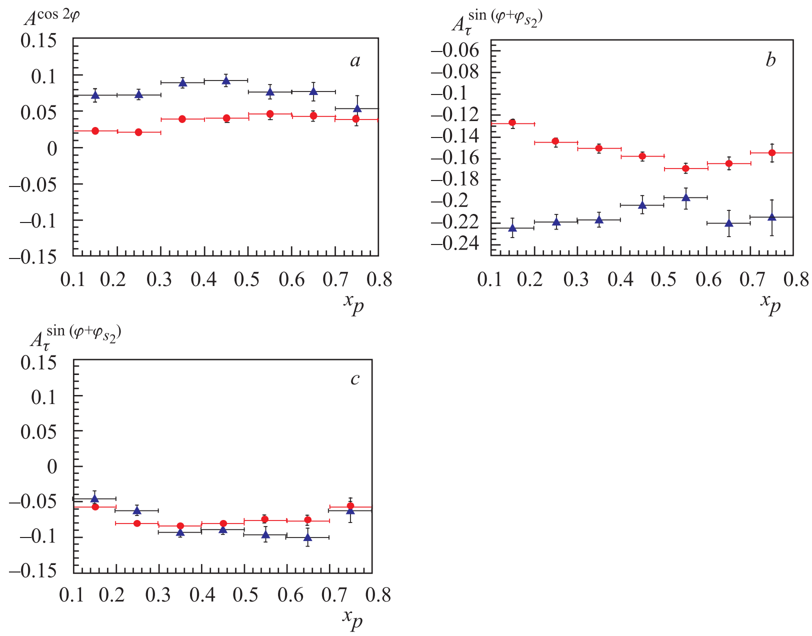

Fig. 5. Simulated experimental asymmetries corresponding to the terms of the differential DY cross section [8] weighted by $\cos 2\varphi$ (*a*), $\sin(\varphi+\varphi_{S_2})$ term (*b*), and $\sin(\varphi-\varphi_{S_2})$ (*c*), plotted as a function of x_p, the longitudinal momentum fraction of the hadronic probe

of the longitudinal momentum of the hadronic probe (x_p) for the unpolarized and the single-polarized cases. The x dependence of the asymmetries included in these simulations is not relevant, and it has been introduced only in order to probe which kinematic region can be accessed. The asymmetries are reported for two different selected kinematic regions of the transverse momentum of the muon pair (q_T): $1 \leqslant q_T \leqslant 2$ GeV/c (squares), and $2 \leqslant q_T \leqslant 3$ GeV/c (triangles). The acceptance and the efficiency corrections, still under investigation, are crucial for such a kind of measurement. As is indicated by the small error bars of Fig. 5, a scan of the asymmetries in different transverse momentum regions could be performed; the investigation of the dependence of the azimuthal asymmetries on the lepton pair transverse momentum allows one to probe the limits of the perturbative approach and to balance soft and hard contributions to the DY processes in the PANDA energy range. The distributions obtained for the single-polarized case depict a more complex scenario: the dependence of the considered TMD PDFs could be probably only partially determined.

Taking into account the geometrical acceptance, the material budget, and the preliminary estimated reconstruction efficiency ($\epsilon = 0.33$) at the highest foreseen luminosity ($2 \cdot 10^{32}$ cm$^{-2} \cdot$ s^{-1}), 130K DY events are expected per month. In such an experimental scenario, a one year data taking could already allow one to determine the azimuthal asymmetries with uncertainties of the order of those quoted in Fig. 5. The optimization of the background rejection is still in progress.

REFERENCES

1. *Erni W. et al.* arXiv:0903.3905v1[hep-ex].
2. *Bourrely C., Soffer J.* // Eur. Phys. J. C. 2004. V. 36. P. 371.
3. *Collins J. C., Soper D. E.* // Phys. Rev. D. 1977. V. 16. P. 2219.
4. *Shimizu H. et al.* // Phys. Rev. D. 2005. V. 71. P. 114007.
5. *Anselmino M. et al.* // Phys. Lett. B. 2004. V. 594. P. 97;
   Efremov A. et al. // Eur. Phys. J. C. 2004. V. 35. P. 207.
6. *Conway J. S. et al.* // Phys. Rev. D. 1989. V. 39. P. 92.
7. *NA10 Collab.* // Z. Phys. C. 1988. V. 37. P. 545.
8. *Burkardt M., Hwang D. S.* // Phys. Rev. D. 2004. V. 69. P. 074032.
9. *PANDA Collab.* // PANDA Technical Progress Report. 2005.
10. *Barone V. et al.* Technical Proposal for PAX. 2005.
11. *Bianconi A.* // Nucl. Instr. Meth. A. 2008. V. 593. P. 562–571.