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Study of the nucleon structure with the PANDA experiment at FAIR

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The PANDA experiment is a core project of the future Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt. It will measure annihilation reactions induced by a high intensity antiproton beam of momentum in the range between 1.5 GeV/c and 15 GeV/c. An important part of the PANDA physics program will be dedicated to the investigation of the nucleon structure using electromagnetic processes. Measurements of the proton electromagnetic form factors in the time-like region, nucleon-to-meson transition distribution amplitudes, generalised distribution amplitudes, and transverse momentum dependent parton distribution functions, are foreseen at PANDA. In the framework of the PANDARoot software, which encompasses PANDA detector simulation and event reconstruction, feasibility studies for the measurement of various electromagnetic processes have been performed. It has been shown that unique studies of the nucleon structure can be experimentally performed at PANDA. In this report, the physics program of PANDA related to the study of the electromagnetic form factors and the transition distribution amplitudes is described with the results of the Monte Carlo feasibility studies.

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The future PANDA experiment [1] at FAIR will exploit the annihilation of antiprotons with protons and nuclei to study the strong interaction and carry out precision measurements in the field of particle, hadron and nuclear physic. The PANDA detector will be installed at the High Energy Storage Ring (HESR) of FAIR. It is versatile detector designed to provide large angular acceptance, high resolution and tracking capability and efficient neutral and charged particle identification in a high production rate environment. The setup is designed to provide a beam of up to 10^{11} antiprotons per filling and peak instantaneous luminosities up to 2×10^{32} cm^{-1}s^{-1} (PANDA-Phase3). However, in the initial start-up phase of the FAIR operation, a luminosity about a factor of 20 lower than the nominal design value will be available (PANDA-Phase1 and Phase2). The physics program [1, 2] includes hadron spectroscopy in the charmonium, hyperon and light quark sectors, hypernuclear physics, and studies of hadron properties in a nuclear medium. An important part of the PANDA physics program will be dedicated to the investigation of the nucleon structure. In the following, we focus on the feasibility studies for the measurements of the proton electromagnetic form factors (FFs) in the time-like region and the nucleon-to-meson transition distribution amplitudes (TDAs) at PANDA.

1. Measurements of the proton electromagnetic form factors at PANDA

Electromagnetic FFs are fundamental quantities that describe the internal structure of hadrons as a function of the four momentum transfer squared q^2. In the space-like region ($q^2 < 0$), the proton FFs are studied in elastic electron proton scattering assuming the one photon exchange. In the time-like region ($q^2 > 0$), they are accessed in annihilation processes of the type $e^+e^- \leftrightarrow \bar{p}p$ and $\rightarrow e^+e^- \rightarrow \bar{p}p\gamma$, where γ is a hard photon emitted by initial state radiation. In contrast to the measurements in the space-like region, the precision of the measurements of the proton FFs $|G_E|$ and $|G_M|$ in the time-like region has been limited over the past decades by low statistics [3]. Recently, precise measurements of the time-like proton FFs have been provided by the BESIII collaboration [4]. Uncertainties on the FF ratio $|G_E|/|G_M|$ better than 10% have been achieved in the q^2 range between 4 (GeV/c)^2 and 5 (GeV/c)^2.

The modulus of the time-like proton FFs will be measured at PANDA in the annihilation processes $\bar{p}p \rightarrow e^+e^-$ and $\bar{p}p \rightarrow \mu^+\mu^-$. Feasibility studies for the measurement of these two processes at PANDA have been performed based on Monte Carlo simulations within the PANDARoot framework at different q^2 values between 5 (GeV/c)^2 and 14 (GeV/c)^2 [2, 5, 6]. The difficulty of these measurements is related to the hadronic background, mainly from the annihilation process $\bar{p}p \rightarrow \pi^+\pi^-$. This background has a cross section about five to six orders of magnitude larger than that of the lepton pair production. In the study of the reaction $\bar{p}p \rightarrow e^+e^-$, a sufficient suppression factor of the main background process in the order of 10^8 is achieved in this q^2 range, keeping the signal efficiencies larger than 40 %. For the muon case, signal to background ratios up to 1:5 to 1:13 can be achieved, and a subtraction of the residual background is applied in the analysis. The main contributions of the systematic uncertainties, e.g. background and luminosity determination, are also studied. The results of the simulations for $|G_E|$ and $|G_M|$ are shown in Figure 1 together with the existing data. They correspond to an integrated luminosity of 0.1 and 2 fb^{-1} per beam momentum setting for PANDA Phase-1 and Phase-3, respectively. Using the designed luminosity of PANDA (Phase-3), a total relative uncertainty on the measurement of the proton FF ratio between 3% at 5 (GeV/c)^2 and $\sim$ 57% at 14 (GeV/c)^2 is expected for the electron channel. The muon channel will also provide precise measurements of the ratio with a precision between 5% at 5 (GeV/c)^2 and $\sim$ 37% at 8.2 (GeV/c)^2. It is shown that PANDA will extend the precise BESIII measurements up to higher q^2 values. These high precision and unique measurements can be already started during PANDA Phase-1 in the low q^2 region.

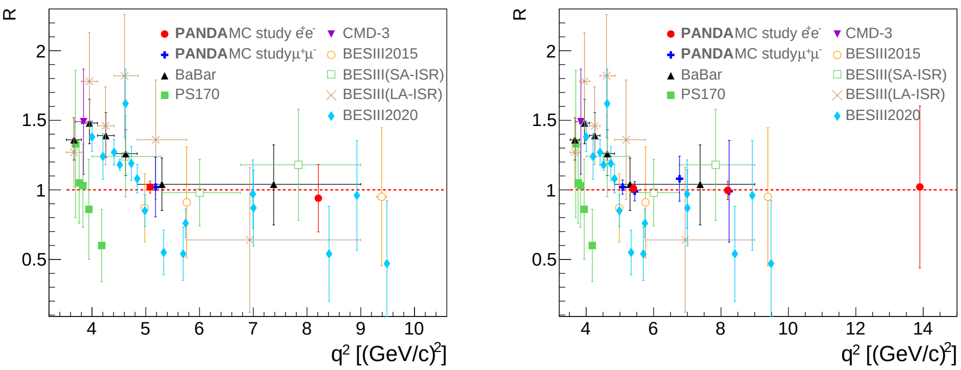

Figure 1: Expected total precisions on the determination of the proton FF ratio ($|G_E|/|G_M|$), from the simulations for PANDA Phase-1 (left) and PANDA Phase-3 (right) as a function of q^2 [2, 5, 6], together with the existing data.

2. Nucleon-to-pion Transition distribution amplitudes

Baryon-to-meson TDAs [7, 8] are non-perturbative objects encoding valuable information on the hadron structure and appear in the collinear factorized description for several types of hard exclusive reactions. They probe partonic correlations between states of different baryonic charge and may be used as a tool for spatial imaging of the structure of the pion cloud inside the nucleon. The factorization property allows to describe the amplitudes of hard exclusive and inclusive reactions as convolutions of hard parts, computable in perturbation theory, and universal non-perturbative hadronic matrix elements such as TDAs. Therefore, the same baryon-to-meson TDAs can be studied in different processes, in space-like and time-like regimes. Nucleon to pion TDAs can be studied in the space-like regime in backward electroproduction of pions off nucleons (e.g. at Jlab, COMPASS) [8]. The PANDA experiment offers possibilities to access the same non perturbative functions in the time-like regime in the processes $\bar{p}p \to \gamma^*\pi^0 \to e^+e^-\pi^0$ and $\bar{p}p \to J/\Psi\pi^0 \to e^+e^-\pi^0$ [8]. The collinear factorization theorem for the TDA has not yet been proven experimentally. At PANDA, this can be performed by verifying the characteristic scaling behavior of the cross section in $1/q^2$ and by checking the angular dependence of the produced leptons specific for the dominant mechanism of the reaction.

The feasibility of measuring the two processes $\bar{p}p \to \gamma^*\pi^0 \to e^+e^-\pi^0$ and $\bar{p}p \to J/\Psi\pi^0 \to e^+e^-\pi^0$ at PANDA have been investigated [9, 10]. At high center of mass energy (s) and four-momentum transfer squared ($q^2 = (p_{e^+} + p_{e^-})^2$), the collinear factorization is supposed to be valid in two distinct kinematic regimes, the near forward regime (small momentum transfer $|t| = |p_{\bar{p}} - p_{\pi^0}| << s,\ q^2$) and the near backward regime (small momentum transfer $|u| = |p_p - p_{\pi^0}| << s,\ q^2$). The process $\bar{p}p \to \gamma^*\pi^0 \to e^+e^-\pi^0$ has been studied at $s = 5$ GeV^2 and $s = 10$ GeV^2, in the q^2 ranges of $3.0 < q^2 < 4.3$ (GeV/c)^2 and $5 < q^2 < 9$ (GeV/c)^2, respectively. Assuming an integrated luminosity of 2 fb^{-1}, the results show that the differential cross section can be measured at PANDA in bins of q^2 with an averaged statistical uncertainty of 12% at $s = 5$ GeV^2, and 24% at $s = 10$ GeV^2. The distributions of $d\sigma/dq^2 \sim (1/q^2)^5$ and of the lepton angular distribution in the photon center of mass system $d\sigma/d\cos\theta^* \sim (1 + \cos^2\theta^*)$ obtained from the simulations are fitted with the theoretical form of the cross section used in the simulation (figure 2). The parameters describing these distributions can be determined in most of the kinematic regions with good precisions, and therefore the test of the collinear factorization in this process can be done at PANDA. The process $\bar{p}p \to J/\Psi\pi^0 \to e^+e^-\pi^0$ has been investigated at $s = 12.3$ GeV^2, $s = 16.9$ GeV^2 and $s = 24.3$ GeV^2 with q^2 equal to the J/Ψ mass squared. The resulting uncertainties to measure the differential cross section as a function of t and u is expected to be in the order of 5–10%. Figure 3 shows that the angular distribution of the leptons in the J/Ψ center of mass frame can be also used to test the TDA models and the factorization description.

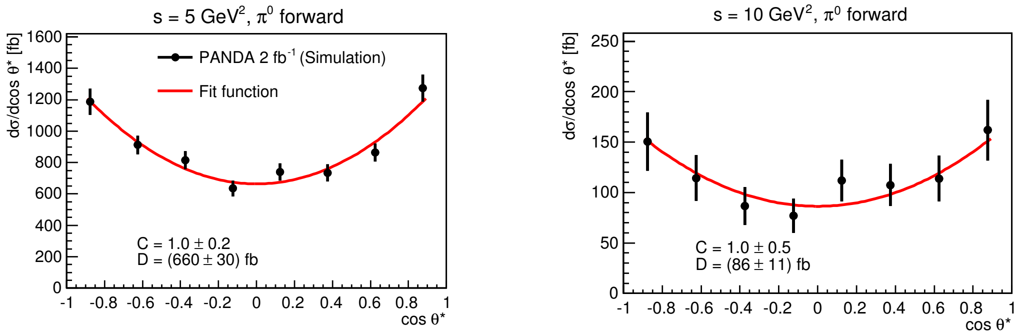

Figure 2: The $\bar{p}p \to \gamma^*\pi^0 \to e^+e^-\pi^0$ differential cross section as a function of the lepton angular distrbution in the photon center of mass obtained from the simulations ($L = 2$ fb^{-1}) for $s = 5$ GeV^2 and $s = 10$ GeV^2 (t-channel kinematic regime) is fitted with the theoretical leading twist predictions ($d\sigma/d\cos\theta^* \sim D(1 + C\cos^2\theta^*)$).

3. Summary

The simulation studies presented in this report show that PANDA will improve the current situation of the time-like FFs of the proton by providing data in a large kinematic region between 5.08 (GeV/c)^2 and $\sim$ 30 (GeV/c)^2. Precisions at least a factor 3 better than the current data can be achieved. The reaction $\bar{p}p \to \mu^+\mu^-$ can be studied for the first time. In addition, hadron structure functions that appear in hard processes can be also addressed at PANDA and used as tests of the QCD and phenomenological approaches of the strong interaction in the confinement domain. In particular, the onset of the collinear factorization regime for hard exclusive reactions in terms of the nucleon-to-meson TDAs can be studied using channels with different intermediate/final states.

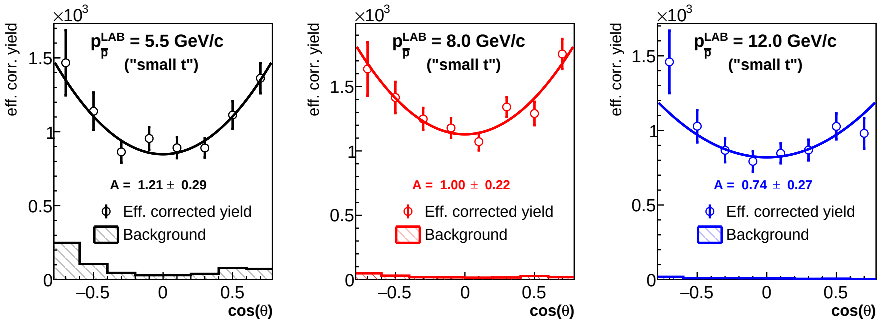

Figure 3: The efficiency corrected yield of $\bar{p}p \to J/\Psi\pi^0 \to e^+e^-\pi^0$ (open markers) and background yield (shaded histogram) as a function of the lepton angular distrbution $\cos\theta$ in the J/Ψ center of mass (t-channel kinematic regime). The signal yields are fitted with the function $B(1 + A\cos^2\theta)$ (solid line).

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