PROCEEDINGS OF SCIENCE

Investigation of the proton structure at $\overline{\text{P}}$ANDA-FAIR

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An important goal of the future $\overline{\text{P}}$ANDA Experiment at FAIR (Darmstadt, Germany) is the investigation of the proton structure. Electromagnetic form factors parameterize the electric and magnetic structure of protons. In the time-like region electromagnetic proton form factors can be accessed experimentally through the annihilation processes $\bar{p}p \to \ell^+\ell^-$ $(\ell = e, \mu)$, assuming that the interaction takes place through the exchange of one virtual photon. In frame of the PANDA-Root software, which encompasses detector simulation and event reconstruction, the statistical precision at which the proton form factors will be determined at $\overline{\text{P}}$ANDA is estimated for both signal processes $\bar{p}p \to \ell^+\ell^-$ $(\ell = e, \mu)$. The signal identification and the suppression of the main background process $(\bar{p}p \to \pi^+\pi^-)$ is studied. Different methods have been used to generate and analyse the processes of interest. The results show that time-like electromagnetic proton form factors can be measured at $\overline{\text{P}}$ANDA with high statistical accuracy over a large kinematical region.

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1. Introduction

The understanding of the hadron structure is one of the challenging issues of the strong interaction in the non perturbative regime. Structure observables, such as the electromagnetic form factors, can provide essential information on the internal structure and the static properties of the hadrons. Electromagnetic form factors are fundamental quantities, which describe the distribution of the electric charges and magnetization within the hadrons. The number of electromagnetic form factors is determined by the spin of the hadron taking into account the symmetry properties of the electromagnetic interaction. The proton which is a spin 1/2 particle is characterized by the electric G_E and the magnetic G_M form factor. The cross section of the unpolarized elastic electron proton scattering has been studied since the 1960s with increasing accuracy to determine the electromagnetic form factors of the proton in the region of negative 4-momentum transfer squared ($q^2 < 0$, space-like region) [1]. However, the polarization transfer method [3] that was used for the first time in 1998 gave rise to new questions in the field. The ratio of the electric and the magnetic form factor measured by the JLab-GEp collaboration (see [2] and references therein), based on the polarization transfer method, decreases almost linearly from unity as the momentum transfer squared increases. This result is in contrast to the previous measurements. In addition to the elastic electron proton scattering, the annihilation reactions allow to extend the determination of the proton form factors to the region of positive 4-momentum transfer squared ($q^2 > 0$, time-like region). In the time-like region, electromagnetic form factors can be associated with the time evolution of the distributions of the electric charges and magnetization within the proton [4]. In this region, proton electromagnetic form factors are accessible through measurements of differential and total cross sections of $e^+e^- \leftrightarrow \bar{p}p$, assuming that the interaction takes place through the exchange of one virtual photon which carries the momentum transfer squared q^2. Due to the low statistics achieved up to now, the precision on the time-like proton form factors measurements has been limited. In this contribution, we report on the feasibility studies for future measurements of the proton electromagnetic form factors in the time-like region with the $\overline{\text{P}}$ANDA (antiProton ANnihilations at DArmstadt) experiment [5] at FAIR (Facility for Antiproton and Ion Research). The future $\overline{\text{P}}$ANDA experiment offers unique possibilities for new investigations of the nucleon structure complementing the results obtained from the studies of lepton beam induced reactions. The proton form factors can be accessed at the $\overline{\text{P}}$ANDA experiment via annihilation processes of the type $\bar{p}p \to l^+l^-$ with l=e,μ. The differential cross section for the $\bar{p}p \to l^+l^-$ channel, for the case of unpolarized particles [6] can be written as:

$$\frac{d\sigma}{d\cos\theta} = \frac{\alpha^2\pi(\hbar c)^2}{2s}\frac{\beta_l}{\beta_{\bar{p}}}\left[\frac{s}{4M_p{}^2}\left(1-\beta_l{}^2cos^2\theta\right)|G_E|^2+\left(1+\frac{s}{4M_l{}^2}+\beta_l{}^2cos^2\theta\right)|G_M|^2\right], \quad (1.1)$$

where θ is the angle of the outgoing lepton with negative charge in the $\bar{p}p$ center of mass frame, $\alpha \approx 1/137$ is the fine structure constant and $\beta_{l,p} = \sqrt{1-4M_{l,p}^2/s}$ is the velocity of the lepton or the proton. In proton-antiproton annihilation, the selection of a pair of leptons accompanied by a neutral pion in the final state allows the measurements of the proton form factors in the unphysical region, below the kinematical threshold of the proton antiproton production of $(2M_p)^2$ [7, 8]. The time-like unphysical region has never been experimentally explored. The antiproton-proton annihilation into lepton pair and a neutral pion can be also investigated at the $\overline{\text{P}}$ANDA experiment [9].

2. $\overline{\text{P}}$ANDA experiment

The $\overline{\text{P}}$ANDA experiment at FAIR will detect the products of the annihilation reactions induced by a high-intensity antiproton beam with momenta from 1.5 to 15 GeV/c. The different components of the detector have been designed following the experience gained in high energy experiments. The $\overline{\text{P}}$ANDA detector will be installed at the High Energy Storage Ring (HESR) of FAIR. The physics program of the $\overline{\text{P}}$ANDA experiment [5] includes charmonium spectroscopy, search for hybrids and glueballs, search for charm and strangeness in nuclei, baryon spectroscopy and hyperon physics, as well as nucleon structure studies. The $\overline{\text{P}}$ANDA experiment will offer this broad physics program thanks to the large acceptance, high resolution and tracking capability and excellent neutral and charged particle identification in a high rate environment.

3. Feasibility study of $\bar{p}p \to e^+e^-$ for the measurements of electromagnetic proton form factors at $\overline{\text{P}}$ANDA

Feasibility studies for the measurement of the process $\bar{p}p \to e^+e^-$ at $\overline{\text{P}}$ANDA [10] have been performed with the $\overline{\text{P}}$ANDARoot software [11]. $\overline{\text{P}}$ANDARoot is the offline software for the $\overline{\text{P}}$ANDA detector simulation and event reconstruction. Full simulations for the processes $\bar{p}p \to e^+e^-$ have been carried out at different center of mass energies between 5.4 and 13.9 GeV^2. A total of 300 million events of the main background process $\bar{p}p \to \pi^+\pi^-$ have been generated and reconstructed at three energy points, s =5.4, 8.2 and 13.9 GeV^2. In order to separate the signal from the background the raw output and the PID probability algorithms for different sub-detectors as the ElectroMagnetic Calorimeter, the Straw Tube Tracker, the Micro Vertex Detector and Cherenkov detectors have been used. A background suppression factor of the order of $\sim 10^8$ has been achieved, keeping a large and sufficient signal efficiency for the proton form factor measurements at $\overline{\text{P}}$ANDA. Taking into account the ratio of cross sections $\sigma(\bar{p}p \to \pi^+\pi^-)/\sigma(\bar{p}p \to e^+e^-) \simeq 10^6$ [12, 13], in order to make a reliable measurement of the proton form factors at $\overline{\text{P}}$ANDA, a background rejection factor on the order of 10^8 is needed. Two independent simulations have been performed for the signal (Method I and Method II) using i) two different models in the event generator, ii) a different number of generated events iii) two sets of event selection criteria and iv) two fit functions to extract the proton electromagnetic form factors from the angular distribution of the produced lepton.

The results from the two simulations, assuming $R = |G_E|/|G_M| = 1$, are shown in Fig. 1, together with the existing experimental data. They correspond to an integrated luminosity of 2 fb^{-1} per beam momentum setting. The determination of the statistical uncertainties on R has been extended with Method II to different theoretical models of the proton form factor ratio.

The study of the systematic uncertainties shows that the background misidentification and luminosity uncertainty dominate the total uncertainty at lower q^2, while in the high energy domain the total uncertainty is dominated by the statistical fluctuations due to the smaller $\bar{p}p \to e^+e^-$ cross section. The total (statistical and systematic) relative uncertainty is expected to be in the

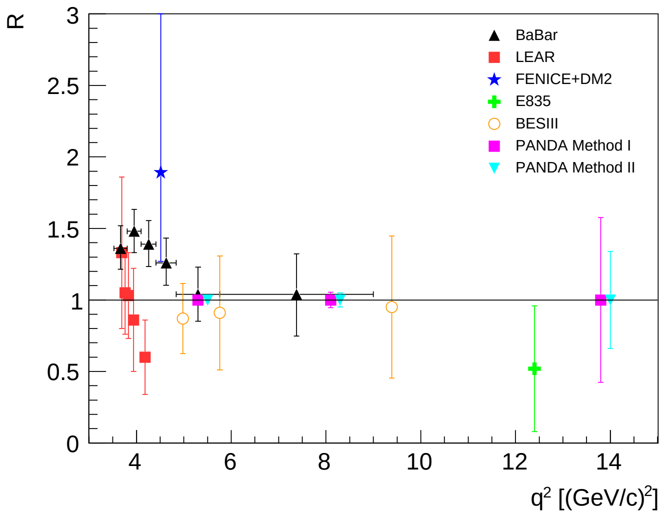

Figure 1: Expected statistical precision on the determination of the proton form factor ratio $R = |G_E|/|G_M|$ at $\overline{\text{P}}$ANDA as a function of q^2, compared with the existing data ((see [10] and references therein)).

range $3.3-57.0\%$ for the proton form factor ratio R. In addition, the extraction of individual values of $|G_E|$ and $|G_M|$ is also possible in the momentum range below 13.9 $(\text{GeV}/c)^2$ with a total precision of $2.2\%-48.0\%$ and $3.5\%-9.7\%$, respectively. The absolute cross section measurement depends essentially on the precision achieved in the luminosity measurement, which is expected to be around 4%. The measurement of the total cross section of $\bar{p}p \to e^+e^-$ can be extended to higher values of q^2 depending on the signal efficiency.

4. Feasibility study of $\bar{p}p \to \mu^+\mu^-$ for the measurements of electromagnetic proton form factors at $\overline{\text{P}}$ANDA

An independent Monte Carlo simulation study in order to test the feasibility of using signal reaction $\bar{p}p \to \mu^+\mu^-$ is performed at antiproton momentum $p = 1.7$ GeV/c (s=5.4 GeV^2). This channel contains the same information on the proton form factors as the electron pair production and therefore also serves as a consistency check. One advantage of measuring $\bar{p}p \to \mu^+\mu^-$ is that radiative corrections due to final state photon emission are suppressed by the muon mass and are neglected in this study. In contrast to the studies using $\bar{p}p \to e^+e^-$, the suppression of the strong hadronic background is more challenging. The muon identification is mainly based on detector information from the Muon System, other sub-detectors show less separation power, which complicates the signal background separation considerably. For both the signal and the main background channel, $\bar{p}p \to \pi^+\pi^-$, two statistically independent data samples have been generated. After the Monte Carlo event generation, the simulated events undergo the same standard chain of simulation and analysis as in the studies on $\bar{p}p \to e^+e^-$. To optimize the signal background separation, a method (Boosted Decision Trees) based on multivariate data classification is used. A signal to background ratio of 1:4 (background rejection factor of $\sim 10^{-6}$) is achieved. At this level of background rejection, a background subtraction can be applied in the experiment to extract the signal channel $\bar{p}p \to \mu^+\mu^-$. In order to study the effect of the background statistical fluctuations on the precision of the form factor measurements, the two statistically independent Monte Carlo samples of 10^8 events each for $\bar{p}p \to \pi^+\pi^-$, have been used. After full analysis, one of the samples was added to the signal in order to perform a background subtraction by using the second reconstructed background sample. An efficiency correction follows the background subtraction using the reconstruction efficiency distribution of the signal. The form factor ratio R, $|G_E|$ and $|G_M|$ are extracted from the fit to the angular distribution of $\bar{p}p \to \mu^+\mu^-$, after efficiency correction. At a beam momentum of 1.7 GeV/c, statistical precisions on R of $\sim 5.1\%$ (Fig. 2) as well as for $|G_E|$ of $\sim 8.6\%$ respectively $|G_M| \sim 4.1\%$ are obtained. The feasibility studies of $\bar{p}p \to \mu^+\mu^-$ will be extended to the other beam momenta 1.5, 2.5 and 3.3 GeV/c.

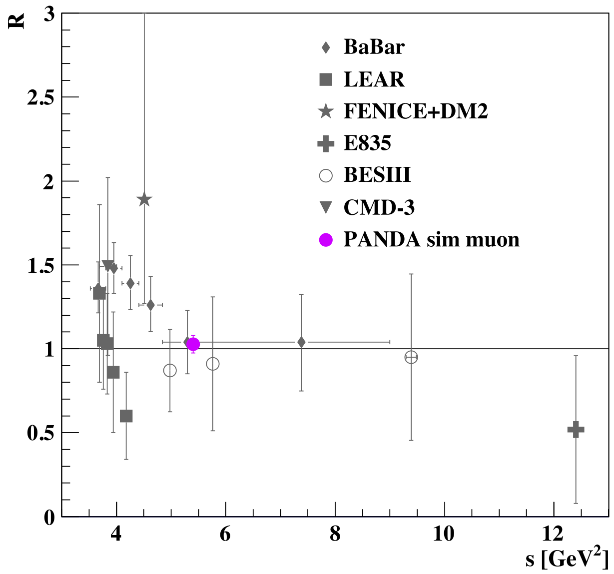

Figure 2: Expected statistical precision on the determination of the proton form factor ratio $R = |G_E|/|G_M|$ at $\overline{\text{P}}$ANDA from the study of $\bar{p}p \to \mu^+\mu^-$ in comparison to existing world data.

5. Conclusion

The $\overline{\text{P}}$ANDA experiment at FAIR will extend the knowledge of the time-like electromagnetic proton form factors in a large kinematic range. Feasibility studies for the measurement of the processes $\bar{p}p \to \ell^+\ell^-$ $(\ell = e, \mu)$ have been performed. The results of the simulations show that the the proton form factors $|G_E|$, $|G_M|$ and their ratio can be measured at $\overline{\text{P}}$ANDA up to $q^2 = 13.9$ (GeV/c)^2 with a high precision. It will be the first time that muons in the final state will be used to measure the time-like form factors of the proton. The possibility to access the relative phase of the proton time-like form factors using a transversally polarized proton target at $\overline{\text{P}}$ANDA will be investigated. The $\overline{\text{P}}$ANDA experiment will provide a complementary study of the nucleon structure with the annihilation processes. The future data from the $\overline{\text{P}}$ANDA experiment are expected to set a stringent test of nucleon models.

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