Feasibility Study for the Measurement of πN Transition Distribution Amplitudes with PANDA

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Abstract.
Transition Distribution Amplitudes (TDA) are parametrizations of the hadronic matrix elements that occur in the perturbative Quantum Chromo Dynamics (QCD) calculations of a certain family of reactions within the framework of collinear factorization. We propose a complete feasibility study of the measurement of one of the reactions covered by the TDA models $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) at PANDA (AntiProton ANnihilation at DArmstadt) experiment currently under construction at the future FAIR (Facility for Antiproton and Ion Research). We show that the PANDA will be ideally suited to access the relevant observables, in particular the pion-to-nucleon TDAs (πN TDAs) which are important for the understanding of the pion cloud contribution in the nucleon wave function.

INTRODUCTION

Collinear factorization has had significant success in the analysis of Deeply Virtual Compton Scatterings where Generalized Parton Distributions are the confinement related hadronic matrix elements. There has been interest within the theoretical community to replicate the success to other families of reactions. These include backward Virtual Compton Scattering and the related $\bar{p}p \to e^+e^-\gamma$ where γN TDAs are the relevant non-perturbative hadronic matrix elements [1], and backward meson electroproduction and the related forward or backward meson production in association with an e^+e^- pair, where πN TDAs are the relevant non-perturbative hadronic matrix elements [2]. More recently, an extension of the idea to J/ψ production with an associated meson in $p\bar{p}$ annihilation was proposed in [3]. The universality of the TDAs for these reactions and the validity of the factorization approach have not been proven yet, but constitute a promising avenue for current and future experiments to extend our understanding of nucleon structure and the reaction mechanisms.

Here, we describe feasibility studies for the measurement of $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) using the currently under construction PANDA detector at the FAIR facility [4]. The $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) process is one of the reactions that is calculable with a TDA based model. The first section describes some of the basic concepts of the TDA model, which we relied on to develop a signal event generator followed by an overview of the proposed PANDA detector. The next section is dedicated to the signal event simulation, selection and an estimation of the global efficiency of detection. After discussion of potential background sources, and their expected impact on this measurement, we conclude by giving a prediction of the precision that can be reached.

π-N TDAs in $\bar{p}p \to \pi^0 J/\psi$

Formally, πN TDAs are Fourier transforms of the non-perturbative hadronic matrix elements representing the non-diagonal three quark operators on the light cone [3]. They capture the dynamics of the transition of a pion to a nucleon, and contain information about the pion cloud contribution to nucleon wave functions. They are parametrized as a function of momentum fractions (x_i), skewness (ξ) and momentum transferred squared (Δ^2). The main interest in TDAs arises from their universality, meaning their independence on reaction type, center-of-mass (CM) energy ($\sqrt{s}$), and virtuality of e^+e^- source (Q^2). This allows to experimentally constrain them in one reaction or at a given CM energy, and use the parametrization to make predictions for different reactions and CM energies.

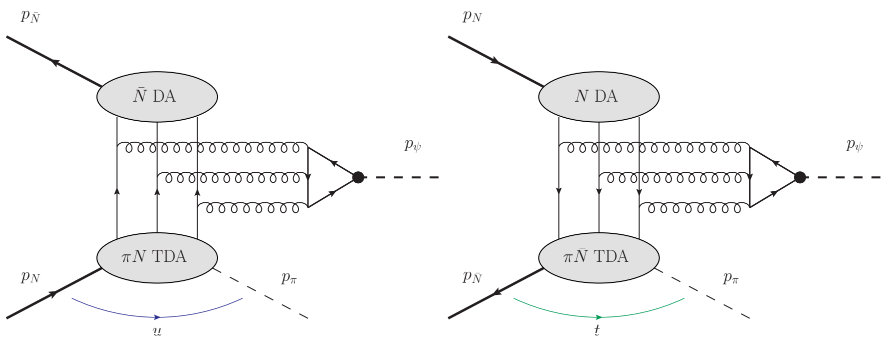

FIGURE 1. Feynman diagrams used in the calculation of the $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) cross section in a πN TDA formalism for the backward kinematics at small $u = (p_\pi - p_N)^2 \approx 0$ (left) and the forward kinematics at small $t = (p_\pi - p_{\bar{N}})^2 \approx 0$ (right) [3].

The calculation of the cross section for $\bar{p}p \to \pi^0 J/\psi$ reaction in this approach involves a hard component that is calculable perturbatively using distribution amplitudes (DA) of nucleons and a soft part including the πN TDAs, as illustrated in Fig. 1. The perturbative part of the calculation is only valid with the existence of a hard scale Q^2 which is taken as the virtuality of the lepton pair emission source. In the case of $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) the large mass of the J/ψ provides a natural hard scale ensuring the validity of the perturbative expansion of the hard subprocess in which the J/ψ is created. In addition the momentum transfer need to be small compared to Q^2. Given the reaction

$$N(p_N) + \bar{N}(p_{\bar{N}}) \to J/\psi(p_{J/\psi}) + \pi(p_\pi) \tag{1}$$

with a squared center-of-mass (CM) energy $s = (p_N + p_{\bar{N}})^2 \equiv W^2$, and charmonium mass squared $Q^2 = M^2_{J/\psi}$, the factorized description admits the following two distinct validity ranges:

- Near-backward kinematics $\Delta^2 \equiv u = (p_\pi - p_N)^2 \ll Q^2$, corresponding to pion emission in the direction of the nucleon in the $N\bar{N}$ CM system, right side of Fig. 1.
- Near-forward kinematics $\Delta^2 \equiv t = (p_\pi - p_{\bar{N}})^2 \ll Q^2$, corresponding to pion emission in the direction of the anti-nucleon in the $N\bar{N}$ CM system, left side of Fig. 1.

A detailed study of the feasibility of accessing πN TDAs in the $\bar{p}p \to \pi^0\gamma^*$ ($\gamma^* \to e^+e^-$) reaction following the cross section predictions of Ref. [5] with PANDA has already been addressed in Ref. [6]. The investigation of the reaction $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) constitutes a natural complement to this work. The universality of TDAs can only be tested by covering different reactions in different kinematic domains.

The resonant $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) reaction presents the noticeable advantage of a larger cross section, and an cleaner signal selection due to the presence of a narrow resonance. While the non-resonant $\bar{p}p \to \pi^0\gamma^*$ ($\gamma^* \to e^+e^-$) has never been measured, some very scarce data [7, 8] exist for the reaction $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) which can be used to constrain the predictions. J/ψ production with an associated π^0 in $\bar{p}p$ annihilation has indeed been investigated in the past since it constitutes a background in the search of charmonium states via their decay to $J/\psi\pi^0\pi^0$ or $J/\psi\gamma$. Part of the PANDA program will also focus on such studies, as described in Ref. [9], which is an additional motivation to study the $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) reaction.

THE PANDA SETUP

The PANDA experiment is one of the four experimental pillars to be built at FAIR [4]. FAIR is an upgrade of the GSI (Gesellschaft fuer Schwerionenforschung) facility, and will use the existing SIS18 synchrotron as injection ring into a new larger synchrotron SIS100. The SIS100 ring will generate an intense pulsed beam of protons of energy reaching up to 29 GeV that can be directed at an antiproton production target. Production rates in the range of 5.6×10^6 to 10^7 $\bar{p}$ s^{-1} are expected. Antiprotons are then transferred to the RESR (Recycled Experimental Storage Ring) accumulator and then injected into the HESR (High Energy Storage Ring) equipped with stochastic and electron cooling where they will be used by the PANDA experiment in a fixed target setup. This *full setup* is designed to provide beams with up to 10^{11} antiprotons, and peak instantaneous luminosities reaching 2×10^{32} cm^{-2}s^{-1}. Such a scenario will allow the accumulation of an integrated luminosity of 2 fb^{-1} in about 5 months. However a likely scenario, for the start of operations is a reduced setup with no RESR. In this scenario, the HESR will be used as an accumulator in addition to its original task of cooling the beam and preparing it for experiments, resulting in a luminosity lower than the design goal. The results shown here correspond to a peak luminosity of 2×10^{32} cm^{-2}s^{-1} that will be achieved with the full FAIR setup.

The PANDA experiment has a very rich physics program. These include spectroscopy of QCD bound states including exotics, study of hypernuclei (nuclei with a hyperon in place of one or more nucleons), and the electromagnetic structure of nucleons. In order to achieve the physics goals, the PANDA experiment has a very versatile detector setup. A detailed discussion of the proposed setup and physics program can be found in [4].

Here, we will only give a brief description of those PANDA detector subsystems that are most relevant for the feasibility of $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$). The PANDA detector design consists of a target spectrometer and forward spectrometer. The central part of the PANDA detector is occupied by the charged particle tracking detectors surrounded by a solenoid magnet that generates a nearly uniform 2 T field pointing in the direction of the beam line throughout the tracking detectors. The inner most layers of tracking are provided by the Micro Vertex Detector (MVD) [10], a silicon pixel based detector and the Straw Tube Tracker (STT) [11]. In the forward direction, tracking is provided by a set of four disc shaped MVD layers followed by three layers of Gas Electron Multiplier (GEM) trackers. Charged particles traversing the forward spectrometers are subject to a field integral of 2 Tm generated by a dipole magnet. Particles identification (PID) is preformed using information from an Electromagnetic Calorimeter (EMC) [12] and a DIRC (Detection of Internally Reflected Cerenkov light) subsystem. In addition, energy loss information from the MVD and STT detectors is used to augment the identification capability offered by the EMC and DIRC.

FEASIBILITY OF $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$)

The feasibility studies of $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) were carried out using PANDAroot, a GEANT [13] simulation and reconstruction package implementing the proposed PANDA setup in detail. The study was performed at three incident antiproton momenta, 5.513 GeV/c, 8 GeV/c and 12 GeV/c, assuming the collection of data corresponding to an integrated luminosity 2 fb^{-1} at each momentum. The first energy was chosen to correspond to the existing measurement of $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) cross section at the E835 experiment of Fermilab [14]. The two other energies are chosen to investigate the CM energy dependence of reconstruction efficiencies and background suppression. Below we describe the main points about how the event generation, cross section determination and analysis were preformed.

Signal Event Generation and Reconstruction

A Monte Carlo event generator was implemented based on cross section formulas provided in [15]. The procedure is as follows: First $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) events are generated according to phase-space. The t and u values are then calculated and an event is accepted with a probability proportional to the value of the cross section at that Δ^2, where Δ^2 stands for u in the backward approximation regime, and t in the forward approximation regime. This method enforces that the t and u distributions of the accepted events are the same as those predicted by the TDA model. Figure 2 shows a comparison of the t distribution output from this event generator with the analytic formula provided by the TDA model, as a cross check that the model has been correctly implemented by the Monte Carlo event generator. We considered that the model is valid for $|\Delta^2| < 1$ GeV^2 to ensure the applicability of factorization. In addition, at incident antiproton momentum of 5.513 GeV/c, the validity range is restricted further to $|\Delta^2| < 0.092$ GeV^2 due to numerical approximations made in [15]. The validity ranges are depicted in Fig. 2 as the blue and red shaded regions at the backward and forward approximation regimes.

The generated events are then processed through a GEANT implementation of the PANDA detector geometry as well digitization of hits and reconstruction. The resulting reconstructed events are then searched for pairs of photons that satisfy π^0 selection cuts. If at least one π^0 is found in the event, we proceed to search J/ψ candidates. All e^+e^- pairs are considered as potential J/ψ candidates. If there are more than one $\pi^0 J/\psi$ candidates per event at this stage, we select pair with an opening angle in the CM frame that is closest to being back-to-back. The efficiency of this procedure is shown in Fig. 3 as a function of momentum transfer t for the three incident antiproton momenta simulated for this study.

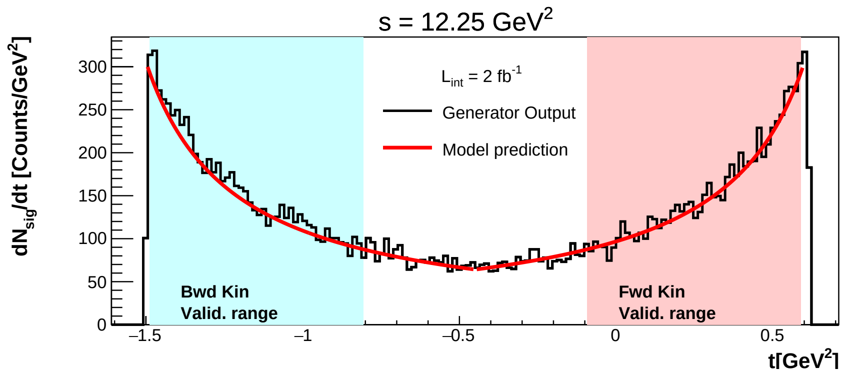

FIGURE 2. Comparison between event generator output and analytic formula from the TDA model prediction [15] at incident antiproton momentum of 5.513 GeV/c. An integrated luminosity of 2 fb^{-1} was assumed. The blue and red shaded regions represent the validity ranges of the TDA model.

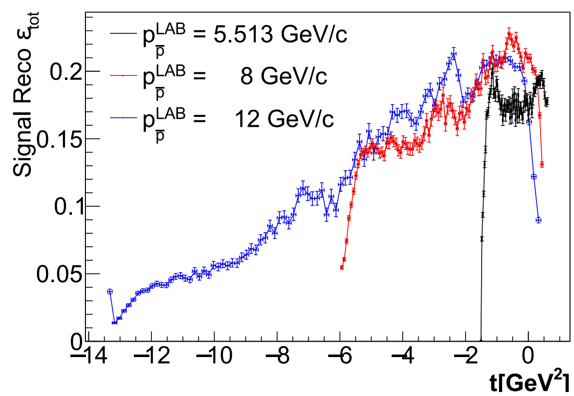

FIGURE 3. The overall signal reconstruction efficiency as a function of t for the three incident antiproton momenta considered in this study, after application of all selection criteria described above.

Background Sources

The $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) channel has multiple background sources, with varying degree of importance. In this section the potential background sources are discussed. After event generation, full GEANT simulation and reconstruction, the exact same analysis procedure as the one applied to select signal events is used to estimate the background contamination to be expected, assuming the same integrated luminosity of 2 fb^{-1}. The background cross sections were fixed based on existing data when available, and on hadronic event generator predictions when not available. The details of how these background sources were simulated are described in this section.

We first consider three pion production reaction $\bar{p}p \to \pi^0\pi^+\pi^-$, which can be selected as signal if the two charged pions are misidentified as electron-positron pair, and have an invariant mass near the J/ψ mass. The cross section for this reaction has been studied in the past at various incident antiproton momenta [16]. Despite the limited statistics that were collected, the results from these early measurements provide a valuable benchmark for this study.

The total cross section measurements by the various experiments, which are tabulated in Ref. [16] are used to fix the number of background events to expect. We used conservatively larger values than the interpolation between the nearest existing data points as the basis for calculating the rate of background events to expect: 2 mb, 0.5 mb and 0.2 mb respectively at incident antiproton momenta of 5.513 GeV/c, 8 GeV/c and 12 GeV/c respectively. They are more than six orders of magnitude larger than the signal cross sections. For the detailed angular distributions, we rely on a hadronic event generator DPM (Dual Parton Model) [17] to generate the background events.

After a full MC simulation and analysis, the signal to background ratio (S/B) for $\bar{p}p \to \pi^0\pi^+\pi^-$ is shown in

Fig. 4. It has to be stressed here that, owing to the good S/B and the smooth behavior of the invariant mass spectra of misidentified $\pi^+\pi^-$ pairs near the J/ψ mass, the contribution of $\bar{p}p \to \pi^0\pi^+\pi^-$ can be subtracted precisely. We find that the background contamination from $\bar{p}p \to \pi^0\pi^+\pi^-$ decreases with increasing CM energy. This is mostly due to the much faster decay as a function of CM energy of the background cross section as compared to the TDA model cross section prediction for the signal reaction.

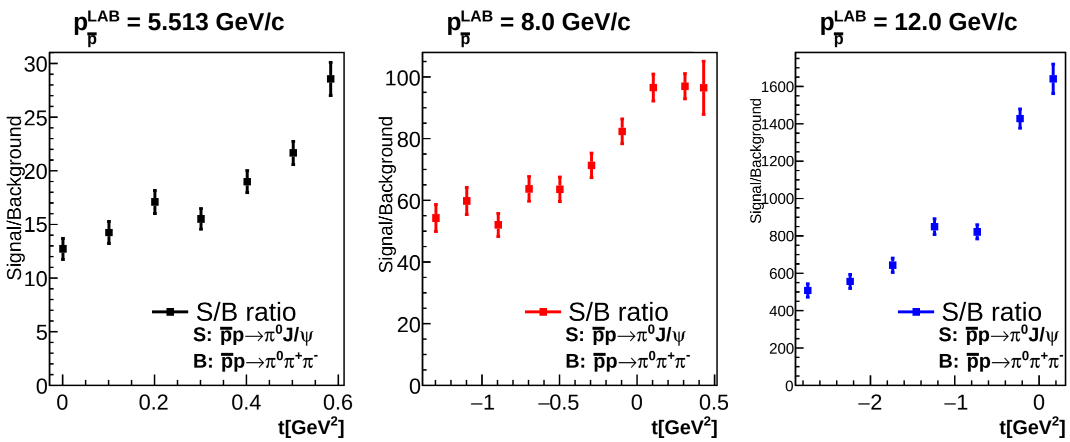

FIGURE 4. Signal to $\bar{p}p \to \pi^0\pi^+\pi^-$ background ratio as a function of t for the near-forward approximation. The statistical uncertainties correspond to the an integrated luminosity of 2 fb^{-1}, after application of all selection criteria described in section "Signal Event Generation and Reconstruction". The TDA model is valid down to -0.092 GeV^2 at 5.513 GeV/c and -1.0 GeV^2 at the two higher incident antiproton momenta.

In addition to $\bar{p}p \to \pi^0\pi^+\pi^-$, we also considered partially reconstructed multi-pion events with more than four pions in the final states. These events can be potential background sources if for example, in a $\pi^0\pi^0\pi^+\pi^-$ event, one of the π^0 fails to be reconstructed and the $\pi^+\pi^-$ pair is misidentified as an e^+e^- pair, or a $\pi^0\pi^+\pi^-\pi^+\pi^-$ event where one of the $\pi^+\pi^-$ pairs is not reconstructed. Even though the cross section of these reactions is larger than that of $\pi^0\pi^+\pi^-$ background, such backgrounds can be further rejected by using kinematic cuts.

The reaction $\bar{p}p \to \pi^0\pi^0 J/\psi$ ($J/\psi \to e^+e^-$) can be misidentified as signal if at least one $\gamma\gamma$ pair in the final states is reconstructed within the π^0 selection windows used for the signal identification. The contribution from this source can be suppressed using kinematic cuts.

Finally, the production of a virtual photon γ^* with an associated π^0 is another process which can be considered as a background source for $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) when the invariant mass of the e^+e^- pair is near the J/ψ mass. Using the prediction of the $\bar{p}p \to \pi^0\gamma^*$ ($\gamma^* \to e^+e^-$) cross section estimate given in [5, 18], and subsequently used in [6] as a basis for a feasibility study of its measurement in PANDA, we were able to estimate the rate of $\bar{p}p \to \pi^0\gamma^*$ ($\gamma^* \to e^+e^-$) that falls within the kinematic range of our signal $\bar{p}p \to \pi^0 J/\psi$ ($J/\psi \to e^+e^-$) and thus can be considered as a background. We obtain cross sections of 13.6 fb, 21.6 fb and 24.8 fb at incident antiproton momenta of 5.513 GeV/c, 8 GeV/c and 12 GeV/c respectively, resulting in negligible background contributions with S/B ratios of ≈ 900, 850, and 750.

PRECISION ON OBSERVABLES

After full efficiency correction, the differential cross section distribution as a function of t corresponding to an integrated luminosity of 2 fb^{-1} at each collision energy is shown in Fig. 5. As a consistency check of the analysis procedure, the cross section prediction curves from [3] are plotted with the simulation results. We see that with the integrated luminosity assumption made, a precision of the order of 5 to 10% can be achieved in the differential cross section measurement, which is more than enough to validate and provide constraints to the TDA model.

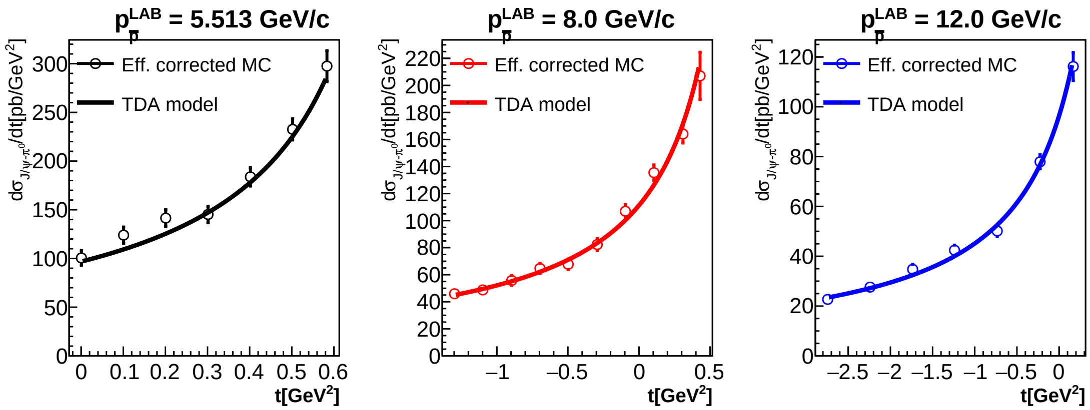

FIGURE 5. Comparison between the fully efficiency corrected differential cross section as a function of t in the near-forward approximation regime expected from a data sample corresponding to an integrated luminosity of 2 fb^{-1} together with the analytic curves from the TDA model prediction. The TDA model is valid down to -0.092 GeV^2 at 5.513 GeV/c and -1.0 GeV^2 at the two higher incident antiproton momenta.

SUMMARY

The feasibility of measuring $\pi^0 J/\psi$ production in $\bar{p}p$ annihilation at the PANDA experiment at the future FAIR facility is investigated. The study is based on a TDA model for the description of the signal, and hadronic event generators for the background. A full GEANT simulation was performed to study in detail the feasibility of the measurement with an assumed integrated luminosity of 2 fb^{-1}. We show that with this assumption, very high quality measurement of the differential cross section is possible with a well controlled background contamination. Such a measurement is expected to provide valuable constraints to TDA models, and further our understanding of nucleon structure.

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