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Exclusive ρ^0 production off transversely polarized protons and deuterons

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Abstract. The measurement of the transverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive production of ρ^0 mesons at the COMPASS experiment is discussed. The precise measurement of the asymmetry is done both for the protons and the deuterons. The asymmetry gives an access to the Generalized Parton Distribution function E, which is sensitive on the orbital angular momentum of quarks in the nucleon. The measured asymmetry is compatible with 0 in the kinematic range: $1 < Q^2 < 12$ $(\text{GeV}/c)^2$, $0.003 < x_{Bj} < 0.35$ and $0.05 < p_t^2 < 0.5$ $(\text{GeV}/c)^2$ for protons or $0.01 < p_t^2 < 0.5$ $(\text{GeV}/c)^2$ for deuterons.

1 Introduction

In this analysis the transverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive production of ρ^0 vector mesons is measured. The asymmetry is measured at the COMPASS experiment [1] both for the polarized protons and deuterons. The asymmetry gives an access to the Generalized Parton Distribution function E, which is sensitive on the orbital angular momentum of quarks in the nucleon. The selected samples cover broad kinematic region: $1 < Q^2 < 12$ $(\text{GeV}/c)^2$, $0.003 < x_{Bj} < 0.35$ and $0.05 < p_t^2 < 0.5$ $(\text{GeV}/c)^2$ for protons or $0.01 < p_t^2 < 0.5$ $(\text{GeV}/c)^2$ for deuterons.

Precise study of the spin structure of the nucleon is one of the main aims of the COMPASS experiment. It is now well established, that the spin of quarks accounts only for about 30% of the nucleon spin (*the nucleon spin crisis*). The direct measurements of the gluon polarization and pQCD fits to the spin dependent cross-sections indicate, that the gluon contribution is not large, consistent with 0. It is expected, that missing part of the nucleon spin could be related to the orbital angular momentum of partons.

The angular momentum of partons can be calculated in the Generalized Parton Distribution framework (GPD) [2]. The best reactions to study the GPDs are the exclusive processes, where only one particle is produced. The simplest process is the Deeply Virtual Compton Scattering (DVSC), $\gamma^* N \to \gamma N$, where N is a target nucleon. Description of the Deeply Virtual Mason Production (DVMP), $\gamma^* N \to MN$, is more complicated due to the formation of the meson M. Production of a given meson requires specific contributions of the quark flavors, thus it can be used as a quark flavor filter.

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2 The GPD formalism

The simplest reaction to describe the GPD formalism is the Deeply Virtual Coulomb Scattering (DVCS). In this process one of the partons from the target nucleon interacts with the virtual photon producing the real photon. After interaction the parton is absorbed by the target nucleon. It was proven, that for the high virtuality of the photon Q^2 and the small momentum transfer to the nucleon t the amplitude for this process factories into two terms. Interaction between photons and partons is described by the perturbative Quantum Chromodynamics, while the non-perturbative correlation between the emitted and the absorbed partons is described by the GPDs. For the Deeply Virtual Meson Production (DVMP), the description of the reaction is more complicated. The formation of the meson is described by another non-perturbative part, the Generalized Distribution Amplitude (GDA) [2].

There are four parton helicity-conserving GPDs, $H^{q,g}$, $\widetilde{H}^{q,g}$, $E^{q,g}$, $\widetilde{E}^{q,g}$, defined for the specific quark flavour and for the gluons. The GPDs $H^{q,g}$ and $\widetilde{H}^{q,g}$ are defined in the case where the target nucleon retains its helicity, while the GPDs $E^{q,g}$ and $\widetilde{E}^{q,g}$ are defined if the target nucleon changes its helicity. Each GPD depends on three kinematic variables, x, ξ and t, where x is the average longitudinal momentum fraction of the interacting parton, ξ is the half of the longitudinal momentum transferred to the target nucleon and t is the four-momentum transfer squared.

The production of mesons involves specific combinations of the GPDs. The GPDs $H^{q,g}$ and $E^{q,g}$ are involved in the vector mesons production, while the GPDs $\widetilde{H}^{q,g}$ and $\widetilde{E}^{q,g}$ are involved in the scalar meson production. The contribution of the specific GPDs depends on the type of produced meson. E.g. effective contribution of the GPDs H involved in the ρ^0, ω and ϕ meson production can be expressed in the following way

$$H_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g\right), \tag{1}$$

$$H_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g\right), \tag{2}$$

$$H_{\phi} = -\frac{1}{3}H^s - \frac{1}{8}H^g. \tag{3}$$

The contribution of the gluons enters at the same order of α_s as the contribution from the quarks.

The GPD E is of a special interest, as it is related to the orbital angular momentum of quarks. Due to the angular momentum conservation, if the proton helicity is changed, i.e. when $E \neq 0$, the orbital angular momentum must be involved.

One of the most interesting properties of the GPDs is the Ji's sum rule

$$\int_{-1}^{1} dx x \left[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\right] = 2J^q, \tag{4}$$

where the total angular momentum $J^q = L^q + S^q$ is the sum of the orbital angular momentum L^q and the spin S^q. These relation can be used to estimate unknown contribution of the quark orbital angular momentum in the nucleon spin puzzle.

3 Access to the GPDs through the exclusive ρ^0 production

The cross-section of the exclusive meson production was obtained by M. Diehl and S. Sapeta in [3]. For the COMPASS kinematics the leading twist terms of the cross section for transversely polarized target can be expressed in the following way

$$\left[\frac{\alpha_{em}}{8\pi^3}\frac{y^2}{1-\epsilon}\frac{1-x_{Bj}}{x_{Bj}}\frac{1}{Q^2}\right]^{-1}\frac{d\sigma}{dx_{Bj}dQ^2d\phi d\phi_s}\simeq$$
$$\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\epsilon\sigma_{00}^{++}-S_T\sin\left(\phi-\phi_s\right)\Im\left(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-}\right), \quad (5)$$

where S_T is the target polarization and ϵ is a kinematic-dependent virtual photon polarization parameter. The angle ϕ is between the lepton plane, defined by momenta of incoming and scattered leptons, and the hadron plane, defined by momenta of virtual photon and produced meson. The angle ϕ_s is the angle between the lepton plane and the direction of the target spin. The spin-dependent photoabsorption cross sections and the interference terms σ_{mn}^{ij} are proportional to the bilinear combinations of amplitudes for subprocess $\gamma^*p\to Vp$ with the photon helicity m and the target nucleon helicity i

$$\sigma_{mn}^{ij}\propto\sum_{\text{spins}}\left(A_m^i\right)^*A_n^j. \quad (6)$$

For vector mesons, the two terms in Eq. 5 give the access to the GPDs $H^{q,g}$ and $E^{q,g}$

$$\frac{1}{\Gamma'}\frac{\sigma_{00}^{++}}{dt}=\left(1-\xi^2\right)\left|\mathcal{H}_V\right|^2-\left(\xi^2+\frac{t}{4M_p^2}\right)\left|\mathcal{E}_V\right|^2-2\xi^2\Re\left(\mathcal{E}_V^*\mathcal{H}_V\right), \quad (7)$$

$$\frac{1}{\Gamma'}\Im\frac{\sigma_{00}^{+-}}{dt}=-\sqrt{1-\xi^2}\frac{\sqrt{t_0-t}}{M_p}\Im\left(\mathcal{E}_V^*\mathcal{H}_V\right), \quad (8)$$

where $\mathcal{H}_V$, $\mathcal{E}_V$ are weighted sums of the convolutions of the GPDs $H^{q,g}$ and $E^{q,g}$ with the GDA of the meson V and with the hard scattering kernel, t_0 is a minimal value of t depending on an event kinematics and $\Gamma'=(\alpha_{\rm em}x_{Bj})/(Q^6(1-x_{Bj}))$.

At COMPASS kinematics, the two last terms in Eq. 7 are suppressed due to the small values of ξ. The cross section σ_{00}^{++} is equivalent to the cross section for longitudinally polarized virtual photons σ_L, which can be calculated using the unpolarized cross section σ_0 and measured angular distributions of the vector meson decay. Eq. 8 is suppressed at low values of t by the kinematic factor $\sqrt{t_0-t}$. The interference term σ_{00}^{+-} can be calculated using the transverse target spin asymmetry

$$A_{UT}^{\sin(\phi-\phi_s)}=-\frac{\Im\left(\sigma_{++}^{+-}+\epsilon\sigma_{00}^{+-}\right)}{\sigma_0}. \quad (9)$$

4 COMPASS experiment

The COMPASS (Common Muon Proton Apparatus for Structure and Spectroscopy) is the experiment ongoing at the CERN laboratory. The main task of the experiment is to study the hadron structure and the hadron spectroscopy. The hadron structure is studied using polarized muon beam with the average energy 160 GeV/c and the polarized targets, while to study the hadron spectroscopy, a hadron beam with the average energy 190 GeV/c and the liquid hydrogen or nuclear targets are used.

The COMPASS setup is a 50 m long two stage spectrometer with excellent capability for tracking and particle identification. It is equipped with about 300 tracking detectors planes, which provide high redundancy for the reconstruction. The first stage, grouped around the first magnet, is dedicated to provide reconstruction of the particles produced with small momenta and large polar angles. The first stage is equipped with the electromagnetic and hadron calorimeters, the muon filter, providing reconstruction of scattered muons, and the large ring imaging Cerenkov detector. The second stage, grouped around the second magnet, is able to reconstruct particles produced with high momenta and small polar angles. This stage is equipped with the second set of calorimeters and the second muon filter.

In the COMPASS experiment the muon beam is scattered at the deuterated lithium (^{6}LiD) or the ammonia target (NH_3), with polarizable deuterons or protons, respectively. The target can be polarized transversely or longitudinally. The polarization is obtained by the Dynamic Nuclear Polarization effect and is about 50% for ^{6}LiD and about 90% for NH_3. The dilution factor, i.e. the fraction of the polarizable material in the target region, is about 35% for ^{6}LiD and about 14% for NH_3. To minimise systematic effects due to a possible spectrometer instability and an acceptance variation, the target was divided into two cells in 2002-2004 and into three cells since 2006. The consecutive cells have opposite polarization. The polarization in each cell is reversed periodically.

5 Data sample

The data used in this analysis were taken in 2002-2004 and in 2007, for the transversely polarized deuteron and proton target, respectively. The data were selected by various cuts and selections. Each selected event contains a primary vertex with only one incoming and one outgoing muon track and with only two outgoing hadron tracks with opposite charges. It is assumed, that the outgoing hadron tracks come from the ρ^0 decay and they are the pions. The ρ^0 resonance is selected by the cut on the reconstructed invariant mass $-0.3 < M_{\pi\pi} - M_{\rho^0} < 0.3$ GeV/c^2, where M_{ρ^0} is the nominal (PDG) mass of the ρ^0 resonance. Due to an unmeasured recoiled target particle, the exclusivity is checked by the missing energy $E_{\text{miss}} = (M_x^2 - M_p^2)/2M_p$, where M_p is the mass of the proton and M_x is the missing mass in the reaction. For exclusive events the reconstructed values of E_{miss} are close to 0. To select these events the cut $-2.5 < E_{\text{miss}} < 2.5$ GeV is used. The cuts $0.05 < p_t^2 < 0.5$ (GeV/c)^2 for the proton target and $0.01 < p_t^2 < 0.5$ (GeV/c)^2 for the deuteron target are also used. The upper cuts on p_t^2 provide further reduction of non-exclusive background. The lower cut on p_t^2 for the proton target suppresses a contribution from the coherent production on the target nuclei, while for the deuteron target it is just to remove events with a large smearing of the azimuthal angle. Distributions of $M_{\pi\pi}$, E_{miss} and p_t^2 for the NH_3 target, with indicated cuts, are shown in Fig. 1.

The selected sample is defined in the kinematic region $1 < Q^2 < 12$ (GeV/c)^2, $0.1 < y < 0.9$ (the fraction of incoming muon energy lost in the laboratory system), $0.003 < x_{Bj} < 0.35$, $W > 5$ GeV (the total energy in the virtual photon - nucleon center of mass system) and p_t^2 ranges indicated above.

6 Extraction of $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry

Number of observed events as a function of the $\phi - \phi_s$ angle can be expressed in the following way

$$N(\phi - \phi_s) \simeq Fna(\phi - \phi_s)\,\sigma_0 \left(1 \pm fP_T A_{UT}^{\sin(\phi-\phi_s)} \sin(\phi - \phi_s)\right), \tag{10}$$

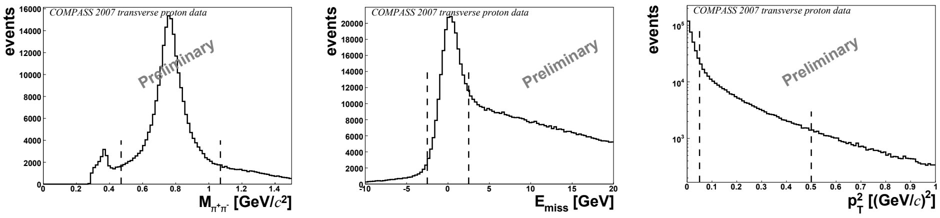

Fig. 1. Distributions of $M_{\pi\pi}$, E_{miss} and p_t^2 with indicated cuts for the NH_3 target.

where F is the muon flux, n the number of target nucleons, a the acceptance, f the dilution factor, P_T the target polarization and the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry is defined by Eq. 9.

Extraction of the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry is based on the double ratio method. For instance, for the three-cell target used in 2007, the double ratio method is defined as

$$DR\,(\phi-\phi_s) = \frac{N_{u/d}^{\uparrow}(\phi-\phi_s)}{N_c^{\downarrow}(\phi-\phi_s)}\frac{N_c^{\uparrow}(\phi-\phi_s)}{N_{u/d}^{\downarrow}(\phi-\phi_s)}, \tag{11}$$

where the number of observed events N_c corresponds to the central cell and $N_{u/d}$ corresponds to the sum of events from the upstream and downstream cells. The polarization of cells is indicated by the arrows. With Eq. 10, formula for the double ratio can be expressed as

$$DR\,(\phi-\phi_s) = \left(\frac{1+fP_T A_{UT}^{\sin(\phi-\phi_s)}\sin(\phi-\phi_s)}{1-fP_T A_{UT}^{\sin(\phi-\phi_s)}\sin(\phi-\phi_s)}\right)^2, \tag{12}$$

where the flux, the number of target nucleons and the unpolarized cross section cancel. The acceptance also cancels provided the ratio of acceptances in different cells is constant before and after reversal of the target polarization, i.e. $a_{u/d}^{\uparrow}/a_c^{\downarrow} = a_{u/d}^{\downarrow}/a_c^{\uparrow}$. Values of the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry are extracted from fits to the measured $DR(\phi-\phi_s)$ distributions.

7 Results of $A_{UT}^{\sin(\phi-\phi_s)}$ extraction

The extracted $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry for the protons as a function of Q^2, x_{Bj} and p_t^2 is shown in Fig. 2. In the covered kinematic range the asymmetry is compatible with 0. The results are in good agreement with the results obtained at the HERMES experiment [4], [5] and with the GPD model of S. V. Goloskokov and P. Kroll [6], which predicts the asymmetry to be ≈ -0.02.

The results for the deuterons are shown in Fig. 3. In this case, however, the cut on p_t^2 does not eliminate the coherent production. In the covered kinematic range the asymmetry is also compatible with 0.

8 Summary and outlook

The transverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive production of ρ^0 mesons was measured for the protons and the deuterons. The results for both targets are

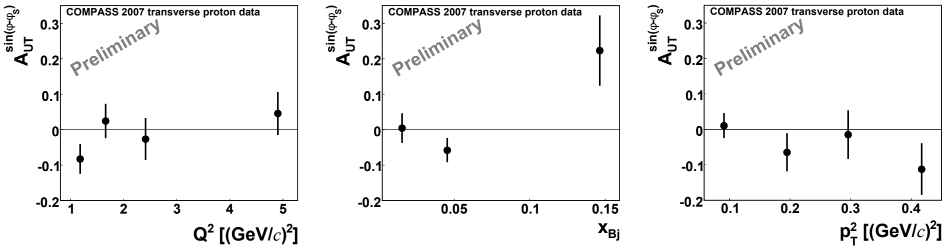

Fig. 2. The $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry for protons as a function of Q^2, x_{Bj} and p_t^2.

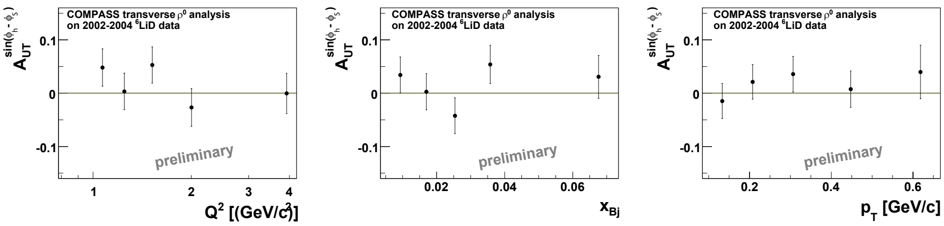

Fig. 3. The $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry for deuterons as a function of Q^2, x_{Bj} and p_t^2.

compatible with 0 in the broad kinematic range. The results are in good agreement with the results obtained at the HERMES experiment and are compatible with the predictions of the GPD model of S. V. Goloskokov and P. Kroll.

The work on the estimation of an influence of the background on the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry extraction and on the separation of contributions of longitudinally and transversely polarized virtual photons is in progress.

Data taken in 2010 at the COMPASS experiment will allow to increase about three times the present statistics of ρ^0 sample for transversely polarized protons. These data will be used to study exclusive channels with small cross-sections, e.g. the production of ϕ or ω mesons. The ω channel seems particularly interesting, as the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry is expected to be large, about -0.1 [6].

A new proposal for the COMPASS experiment has been submitted [7]. Future GPD studies are a substantial part of this proposal. The use of a new detector, a large Recoil Proton Detector, will allow a clean selection of the sample of exclusive events for the studies of the DVCS and DVMP processes. The measurements with the unpolarized liquid hydrogen target are foreseen first, while the measurements with transversely polarized NH_3 target are considered for the future.

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