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 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 to the orbital angular momentum of quarks in the nucleon. The measured asymmetry is compatible with zero in the kinematic range: $1 < Q^2 < 12$ $(\mathrm{GeV}/c)^2$, $0.003 < x_{Bj} < 0.35$ and $0.05 < p_t^2 < 0.5$ $(\mathrm{GeV}/c)^2$ for protons or $0.01 < p_t^2 < 0.5$ $(\mathrm{GeV}/c)^2$ for deuterons.

1 Introduction

In this analysis the transverse target spin asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ for exclusive production of ρ^0 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 to the orbital angular momentum of quarks in the nucleon. The selected samples cover a broad kinematic region: $1 < Q^2 < 12$ $(\mathrm{GeV}/c)^2$, $0.003 < x_{Bj} < 0.35$ and $0.05 < p_t^2 < 0.5$ $(\mathrm{GeV}/c)^2$ for protons or $0.01 < p_t^2 < 0.5$ $(\mathrm{GeV}/c)^2$ for deuterons.

The 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 and spin asymmetries indicate, that the gluon contribution is not large, consistent with zero. It is expected, that the missing part of the nucleon spin could be related to the orbital angular momentum of partons. The angular momentum of partons can be evaluated in the Generalized Parton Distribution formalism (GPD) [2].

2 The GPD formalism

The simplest reaction described by the GPD formalism is the Deeply Virtual Coulomb Scattering (DVCS). In this process a parton from the target nucleon interacts with the virtual photon and a real photon is produced. After interaction the parton is absorbed by the target nucleon. It was proven, that for longitudinal virtual photons with high virtuality Q^2 and the small momentum transfer to the nucleon t the amplitude for this process factories into two terms. The interaction between photons and partons is described by the perturbative theory, 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 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.

Depending on the type of the meson, its quark content and quantum numbers, there exists sensitivity to various types of GPDs and different quark flavours. The vector meson production is sensitive only to GPDs $H^{q,g}$ and $E^{q,g}$, while the scalar meson production is sensitive only to the GPDs $\widetilde{H}^{q,g}$ and $\widetilde{E}^{q,g}$. The GPD E is of a special interest, as it is related to the orbital angular momentum of quarks. Due to angular momentum conservation, orbital angular momentum must be involved if the proton helicity is changed, i.e. when $E \neq 0$.

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

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

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 a role 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 exclusive meson production was obtained by M. Diehl and S. Sapeta in Ref. [3]. For a transversely polarized target the cross section in the COMPASS kinematics can be expressed in the following way

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

where only terms relevant for this analysis are shown explicitly. Here S_T is the target polarization and ε is a kinematic-dependent virtual photon polarization parameter. The angle ϕ is the angle between the lepton plane, defined by the momenta of incoming and scattered leptons, and the hadron plane, defined by the 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 bilinear combinations of amplitudes for subprocess $\gamma^* p \to V p$ with the photon helicity m and the target nucleon helicity i

$$\sigma_{mn}^{ij} \propto \sum_{\text{spins}}\left(A_m^i\right)^* A_n^j. \tag{3}$$

For vector mesons, the two terms in Eq. 2 give the access to the GPDs $H^{q,g}$ and $E^{q,g}$

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

$$\frac{1}{\Gamma'}\,\mathrm{Im}\,\frac{\sigma_{00}^{+-}}{dt} = -\sqrt{1-\xi^2}\,\frac{\sqrt{t_0-t}}{M_p}\,\mathrm{Im}\left(\mathcal{E}_V^*\mathcal{H}_V\right), \tag{5}$$

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 the event kinematics and $\Gamma' = (\alpha_{em}x_{Bj})/(Q^6(1-x_{Bj}))$.

The cross section σ_{00}^{++} is equivalent to the cross section for longitudinal virtual photons σ_L, which can be calculated from the unpolarized cross section σ_0. The interference term σ_{00}^{+-} is related to the transverse target spin asymmetry

$$A_{UT}^{\sin(\phi-\phi_s)} = -\frac{\mathrm{Im}\left(\sigma_{++}^{+-} + \varepsilon\sigma_{00}^{+-}\right)}{\sigma_0}. \tag{6}$$

Both leading twist terms σ_{00}^{++} and σ_{00}^{+-} can be extracted using measured decay angular distributions of the meson.

4 COMPASS experiment

In the COMPASS experiment the muon beam scatters off the lithium deuteride (^{6}LiD) or the ammonia target (NH_3), with polarized deuterons or protons, respectively. The target can be polarized transversely or longitudinally. The polarization is obtained by the Dynamic Nuclear Polarization method and is about 50% for ^{6}LiD and about 90% for NH_3. The dilution factor, i.e. the fraction of events originating from polarized deuterons or protons, for incoherent exclusive ρ^0 production is about 45% for ^{6}LiD and about 25% for NH_3. To minimise systematic effects due to a possible spectrometer instability and the 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.

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 particles produced with small momenta. It 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. This stage is equipped with the second set of calorimeters and the second muon filter.

5 Event selection

The data used in this analysis were taken in 2002-2004 and in 2007, for the transversely polarized deuteron and proton target, respectively. Each selected event contains a primary vertex with only one incoming and one outgoing muon track and with only two outgoing hadron tracks

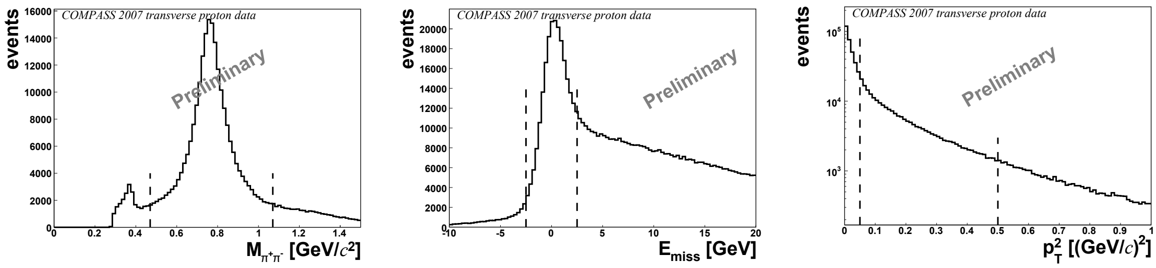

Figure 1: Distributions of $M_{\pi\pi}$, E_{miss} and p_t^2 for the NH_3 target with indicated cuts.

with opposite charges. It is assumed, that the outgoing hadron tracks come from the ρ^0 decay and they are 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. Because recoiled target particle in unmeasured, 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 event. For exclusive events the reconstructed values of E_{miss} are close to zero. 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 a 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 applied 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.

For the selected sample 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 is used.

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

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

$$N(\phi-\phi_s) \simeq Fna(\phi-\phi_s)\sigma_0\left(1 \pm fP_T A_{UT}^{\sin(\phi-\phi_s)}\sin(\phi-\phi_s)\right), \tag{7}$$

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. 6.

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

$$\text{DR}(\phi-\phi_s) = \frac{N_{u/d}^{\uparrow}(\phi-\phi_s)}{N_c^{\downarrow}(\phi-\phi_s)}\frac{N_c^{\uparrow}(\phi-\phi_s)}{N_{u/d}^{\downarrow}(\phi-\phi_s)}, \tag{8}$$

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

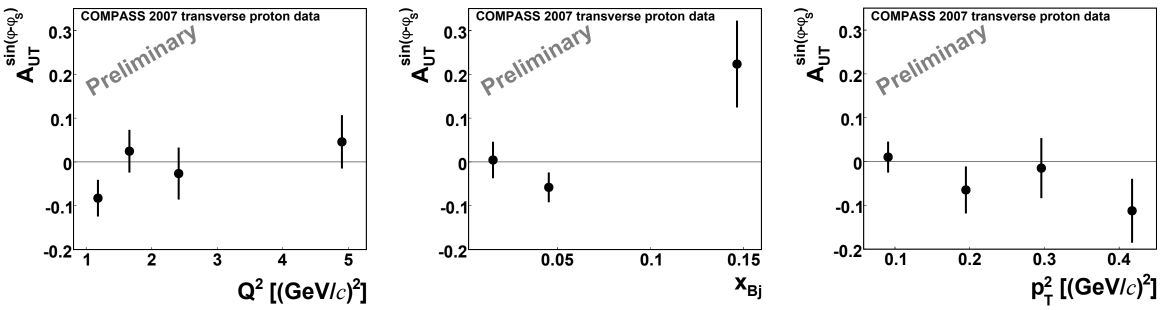

Figure 2: The $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry for protons as a function of Q^2, x_{Bj} and p_t^2.

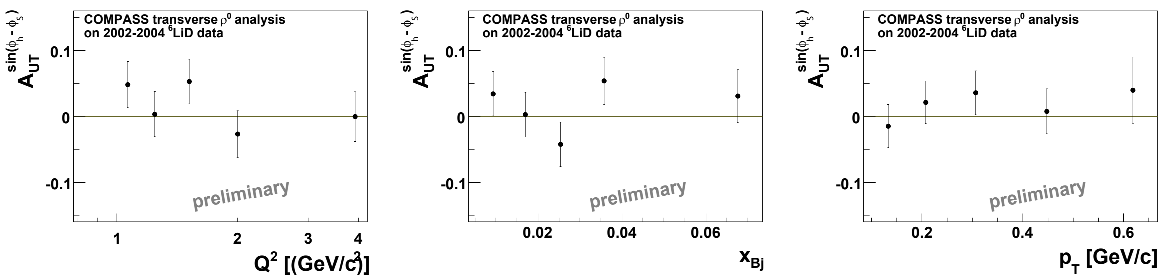

Figure 3: The $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry for deuterons as a function of Q^2, x_{Bj} and p_t.

by the arrows. With Eq. 7, the formula for the double ratio can be expressed as

$$\mathrm{DR}\,(\phi-\phi_s) = \left(\frac{1 + fP_T A_{UT}^{\sin(\phi-\phi_s)} \sin(\phi-\phi_s)}{1 - fP_T A_{UT}^{\sin(\phi-\phi_s)} \sin(\phi-\phi_s)} \right)^2, \tag{9}$$

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 $\mathrm{DR}(\phi-\phi_s)$ distributions.

7 Results

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 small and compatible with zero. The results are in good agreement with the results obtained at the HERMES experiment [4] and with the GPD model of S. V. Goloskokov and P. Kroll [5], 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 completely. In the covered kinematic range the asymmetry is also compatible with zero.

8 Recent developments of the analysis

The work on the estimation of an influence of the background on the $A_{UT}^{\sin(\phi-\phi_S)}$ asymmetry extraction as well as detailed systematic studies are in progress. Release of new results and dedicated paper are expected soon.

In the new analysis background asymmetry is calculated analysing fraction of background events as a function of $\phi - \phi_s$ angle. The fraction in a given $\phi - \phi_s$ bin is estimated analysing missing energy distribution, E_{miss}, for this bin. Shape of E_{miss} distribution for semi-inclusive events is parametrized from MC studies and normalized to the data in large E_{miss} region (cf. Fig. 1).

The most important sources of possible systematic uncertainties checked in the new analysis are false asymmetries, data stability, method of background subtraction and sensitivity to the MC. To suppress uncertainty of asymmetry extraction double ratio method is replaced by the binned likelihood method.

9 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 compatible with zero in the broad kinematic range. The results are in good agreement with the results obtained at the HERMES experiment and with the predictions of the GPD model [5].

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 [5]. Moreover separation of contributions of longitudinally and transversely polarized virtual photons and extraction of non-leading asymmetries are considered.

A new proposal for the COMPASS-II experiment has been approved [6]. 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 the transversely polarized NH_3 target are considered for the future.

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