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Exclusive meson production at COMPASS

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In this paper we summarize recent measurements of exclusive meson production performed by the COMPASS Collaboration. In particular, recent results on the transverse target spin asymmetries for exclusive ρ^0 production are presented. Some of these asymmetries are sensitive to the GPDs E, which are related to the orbital angular momentum of quarks. Other asymmetries are sensitive to the chiral-odd, transverse GPDs H_T. Measurements of exclusive processes, which are a part of the COMPASS-II proposal, are also discussed.

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1. Introduction

Hard exclusive electro- and muoproduction of mesons on nucleons has played an important role in studies of the hadron structure and recently gained renewed interest as it allows access to generalised parton distributions (GPDs). GPDs provide a novel and comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. For instance GPDs give a description of the nucleon as an extended object, referred to as 3-dimensional nucleon tomography, and give access to the orbital angular momentum of quarks.

At leading twist, the chiral-even GPDs H and E are sufficient to describe exclusive vector meson production on a spin ½ target. These GPDs are of special interest as they are related to the total angular momentum carried by partons in the nucleon [1]. GPDs H are well constrained in accessible x_{Bj} range by HERA, HERMES and JLAB data. Constraints on GPDs E are weak and come mainly from measurements of nucleon Pauli form factors. There exist also chiral-odd, "transverse" GPDs, in particular H_T and $\bar{E}_T$. It was shown in Ref. [2] that they are required to describe exclusive π^+ production on transversely polarized protons.

In this paper we summarize recent measurement of the transverse target spin asymmetries for exclusive ρ^0 production. These observables are sensitive both to chiral-even and chiral-odd GPDs. The interpretation of results is done in the framework of the GPD model proposed by Goloskokov and Kroll [3]. Planned measurements of exclusive meson production, which are a part of the approved COMPASS-II proposal, are also discussed.

2. Formalism

For exclusive meson production off a transversely polarized target five single (UT) and three double (LT) spin asymmetries can be defined. These are

$$
\begin{aligned}
A_{\rm UT}^{\sin(\phi-\phi_s)} &= -\frac{\mathrm{Im}\left(\sigma_{++}^{+-}+\varepsilon\sigma_{00}^{+-}\right)}{\sigma_0}, &
A_{\rm LT}^{\cos(\phi-\phi_s)} &= \frac{\mathrm{Re}\sigma_{++}^{+-}}{\sigma_0}, &
A_{\rm UT}^{\sin(\phi+\phi_s)} &= -\frac{\mathrm{Im}\sigma_{+-}^{+-}}{\sigma_0}, \\
A_{\rm UT}^{\sin(2\phi-\phi_s)} &= -\frac{\mathrm{Im}\sigma_{+0}^{-+}}{\sigma_0}, &
A_{\rm LT}^{\cos(2\phi-\phi_s)} &= -\frac{\mathrm{Re}\sigma_{+0}^{-+}}{\sigma_0}, &
A_{\rm UT}^{\sin(3\phi-\phi_s)} &= -\frac{\mathrm{Im}\sigma_{+-}^{-+}}{\sigma_0}, \\
A_{\rm UT}^{\sin\phi_s} &= -\frac{\mathrm{Im}\sigma_{+0}^{+-}}{\sigma_0}, &
A_{\rm LT}^{\cos\phi_s} &= -\frac{\mathrm{Re}\sigma_{+0}^{+-}}{\sigma_0}.
\end{aligned} \tag{2.1}
$$

The photoabsorption cross sections or the interference terms σ_{mn}^{ij} are proportional to the bilinear combinations of the helicity amplitudes $\mathscr{M}$ for the photoproduction subprocess $\gamma^* p \to \rho^0 p$,

$$\sigma_{mn}^{ij} \propto \sum \mathscr{M}^*_{m'i',mi}\mathscr{M}_{m'i',nj}, \tag{2.2}$$

where the helicity of the virtual photon is denoted by $m,n=-1,0,+1$ and the helicity of the initial-state proton is given by $i,j=-1/2,+1/2$. The sum runs over all spin combinations for the final state, given by the spin of the meson $m'=-1,0,+1$ and the spin of the final-state proton $i'=-1/2,+1/2$. For brevity a dependence on the kinematic variables is omitted here.

The total unpolarized cross section, σ_0, is given by the sum of cross sections for longitudinally, σ_L, and transversely, σ_T, polarized virtual photons,

$$\sigma_0 = \frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\sigma_{00}^{++} = \sigma_L+\varepsilon\sigma_T \ , \tag{2.3}$$

and the virtual photon polarization parameter can be approximated by $\varepsilon \simeq (1-y)/(1-y+y^2/2)$.

Each asymmetry is related with specific modulation of the cross section in ϕ and ϕ_s angles indicated by the superscript. The angle ϕ is the azimuthal angle between the lepton plane, given by the momenta of the incoming and the scattered leptons, and the hadron plane, given by the momenta of the virtual photon and the meson. The angle ϕ_s is the azimuthal angle between the lepton plane and the spin direction of the target nucleon. Full formula for the cross section can be found in Ref. [4].

The asymmetries are extracted from data selected as described in the following.

3. COMPASS experiment

The COMPASS experiment (Common Muon Proton Apparatus for Structure and Spectroscopy) is situated at the high-intensity M2 muon beam of the CERN SPS. A detailed description can be found in Ref. [8].

The μ^+ beam had a nominal momentum of 160 GeV$/c$ with a spread of 5% and a longitudinal polarisation of 80%. The data were taken at a mean intensity of $3.5 \cdot 10^8$ μ^+/spill, for a spill length of about 10 s every 40 s. A measurement of the trajectory and the momentum of each incoming muon is performed upstream of the target.

The muon beam was scattered 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, which is the cross-section-weighted fraction of polarisable material, is about 38% for ^{6}LiD and about 14% 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 spectrometer is a 50 m long two stage spectrometer with excellent capability for the tracking and the particle identification. Each stage of spectrometer has a dipole magnet with tracking detectors before and after the magnet, hadron and electromagnetic calorimeters and muon identification. Identification of charged tracks is possible with a RICH detector in the first stage. The spectrometer is equipped with about 300 tracking detectors planes, which provide a high redundancy for the reconstruction.

4. Event selection

To determine the transverse target spin asymmetries for exclusive production of ρ^0 meson the data taken in 2007 and 2010 with polarized protons were analysed. Each selected event contains a primary vertex with only one incoming and one outgoing muon track and with only two outgoing hadron tracks of opposite charges. It is assumed, that the outgoing hadrons are pions. The ρ^0 resonance is selected by the cut on the reconstructed invariant mass $0.5\ \mathrm{GeV}/c^2 < M_{\pi\pi} < 1.1\ \mathrm{GeV}/c^2$. Because recoiled target particle in undetected, the exclusivity is checked by the missing energy, $E_{miss} = ((p+q-v)^2 - p^2)/2M_p$, where M_p is the mass of the proton and p, q and v are the four-momenta of proton, photon and meson, respectively. For exclusive events the reconstructed values of E_{miss} are close to zero. To select these events the cut -2.5 GeV $< E_{miss} < 2.5$ GeV is used. The cut $0.05\ (\mathrm{GeV}/c)^2 < p_T^2 < 0.5\ (\mathrm{GeV}/c)^2$ is also applied, where p_T^2 is the squared transverse momentum of ρ^0 with respect to the virtual photon direction. The lower cut on p_T^2 suppresses a contribution from the coherent production on the target nuclei, while the upper cut provides a further reduction of non-exclusive background.

The kinematic region is defined by the following cuts: $1\ (\mathrm{GeV}/c)^2 < Q^2 < 10\ (\mathrm{GeV}/c)^2$, $0.1 < y < 0.9$, $0.003 < x_{Bj} < 0.35$, $W > 5\ \mathrm{GeV}/c^2$ (invariant mass of the virtual photon - nucleon system) and p_T^2 cuts as indicated above. The asymmetries were extracted using the 2D binned likelihood method after subtraction of remaining semi-inclusive background. Details of the analysis can be found in Ref. [5].

5. Results and discussion

The mean values of measured asymmetries are shown in Fig. 1. They are given for the mean values of kinematic variables, $\langle Q^2\rangle = 2.2\ (\mathrm{GeV}/c)^2$, $\langle x_{Bj}\rangle = 0.039$, $\langle p_T^2\rangle = 0.2\ (\mathrm{GeV}/c)^2$, $\langle W\rangle = 8.1\ \mathrm{GeV}/c^2$ and $\langle y\rangle = 0.24$, of the selected data set. The asymmetry $A_{UT}^{\sin\phi_s}$ was found to be $-0.019 \pm 0.008\ (stat) \pm 0.003\ (sys)$. All other asymmetries were found to be small, consistent with zero within experimental uncertainty. The asymmetries measured as a function of Q^2, x_{Bj} or p_T^2 can be found in Ref. [5], together with a comparison with predictions of the GPD model proposed by Goloskokov and Kroll [4]. The model agrees well with our data.

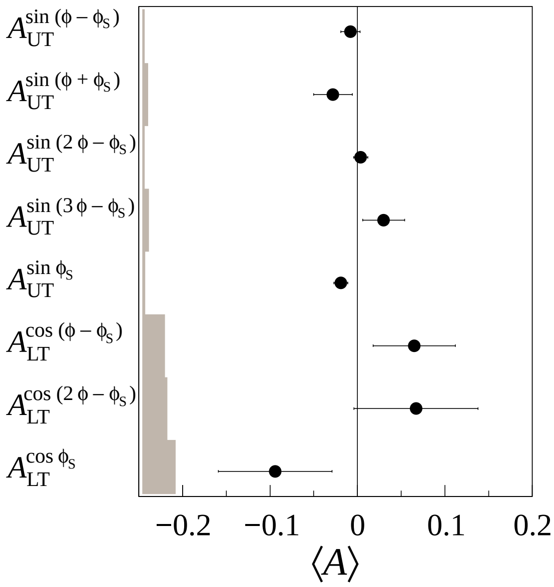

Figure 1: Mean values of azimuthal asymmetries for a transversely polarized proton target. The error bars (left bands) represent the statistical (systematic) uncertainties. Mean values of kinematic variables are indicated in the text.

For an interpretation of results in the framework of the model of particular interest are the following asymmetries, for which the dependence on the helicity amplitudes reads

$$\begin{aligned}
\sigma_0 A_{UT}^{\sin(\phi-\phi_s)} &= -2\mathrm{Im}\left[\varepsilon \mathscr{M}^*_{0-,0+}\mathscr{M}_{0+,0+} + \mathscr{M}^*_{+-,++}\mathscr{M}_{++,++} + \tfrac{1}{2}\mathscr{M}^*_{0-,++}\mathscr{M}_{0+,++}\right] , \\
\sigma_0 A_{UT}^{\sin(2\phi-\phi_s)} &= -\ \mathrm{Im}\left[\mathscr{M}^*_{0+,++}\mathscr{M}_{0-,0+}\right] , \\
\sigma_0 A_{UT}^{\sin\phi_s} &= -\ \mathrm{Im}\left[\mathscr{M}^*_{0-,++}\mathscr{M}_{0+,0+} - \mathscr{M}^*_{0+,++}\mathscr{M}_{0-,0+}\right] . \qquad (5.1)
\end{aligned}$$

The dominant contribution from the $\gamma^*_L \to \rho^0_L$ transition is given by $\mathscr{M}_{0+,0+}$ and $\mathscr{M}_{0-,0+}$ helicity amplitudes, which are related to chiral-even GPDs H and E, respectively. The suppressed contribution from the $\gamma^*_T \to \rho^0_T$ transition is given by $\mathscr{M}_{++,++}$ and $\mathscr{M}_{+-,++}$ helicity amplitudes, which are also related to chiral-even GPDs. Description of the $\gamma^*_T \to \rho^0_L$ transition is possible by inclusion of chiral-odd GPDs H_T and $\bar{E}_T$, which are related to $\mathscr{M}_{0-,++}$ and $\mathscr{M}_{0+,++}$ helicity amplitudes, respectively. The $\gamma^*_L \to \rho^0_T$ and $\gamma^*_T \to \rho^0_{-T}$ transitions are known to be suppressed and are neglected in this formalism.

The vanishing $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry is interpreted as a cancellation of GPDs E^u and E^d due to their different sign but similar magnitude. A contribution of chiral-odd GPDs is negligible here, as one can see from comparison of calculations of Refs. [3] and [6]. The $A_{UT}^{\sin\phi_s}$ asymmetry represents an imaginary part of two bilinear products of helicity amplitudes. The first product is related with GPDs H and H_T, while the second one is related with GPDs E and $\bar{E}_T$. The latter product appears also in the $A_{UT}^{\sin(2\phi-\phi_s)}$ asymmetry. The $A_{UT}^{\sin\phi_s}$ asymmetry is found to be different from zero, while the $A_{UT}^{\sin(2\phi-\phi_s)}$ asymmetry vanishes. It implies non-negligible contribution of GPDs H_T. It is the first experimental evidence from hard exclusive ρ^0 production for the observation of these chiral-odd GPDs.

In preparation is a measurement of azimuthal asymmetries for exclusive ω production. The comparison between ρ^0 and ω is of special interest, since they probe different combinations of GPDs for u and d quarks. In particular, for ω the $A_{UT}^{\sin(\phi-\phi_s)}$ asymmetry is expected to be ≈ -0.1 [6].

6. Future measurements at COMPASS-II

The GPD program at COMPASS will be continued. The COMPASS-II proposal [7] of the new measurements has been already approved by CERN. Measurement of exclusive meson production on unpolarized target is one of the main goals of this proposal, together with the measurement of DVCS. The data for the GPD program at COMPASS-II were successfully taken during 2012 pilot run and will be taken in 2016-2017.

For purpose of the GPD program at COMPASS-II the apparatus has been optimized for measurements of exclusive reactions. In particular, new equipment has been build, like a new large angle electromagnetic calorimeter to cover high x_{Bj} region for the DVCS measurement (ECAL0, 1/3 ready in 2012) and a 2.5 m long liquid hydrogen target surrounded by a 4 m long recoil proton detector (CAMERA).

For the COMPASS-II proposal projections of expected results were made. One of the projections was made to evaluate expected precision of the measurement of slope b of Mandelstam variable t distribution as a function of x_{Bj} for exclusive ρ^0 meson production. The slope is related to the transverse size of the nucleon and thus it can be used for the nucleon tomography. The projection of measurement of slope in four bins of Q^2 for 2016-2017, together with existing data points from ZEUS in a similar Q^2 range, is shown in Fig. 2. In 2012 pilot run 1/10 expected statistics from 2016-2017 was collected.

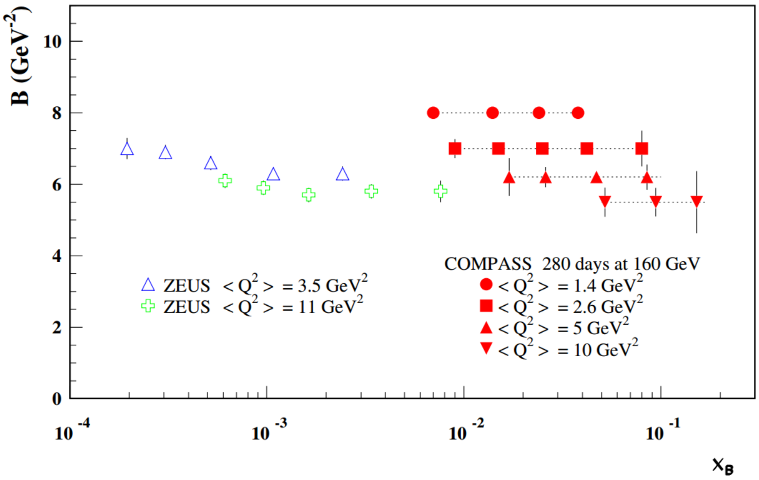

Figure 2: The projection of measurement of slope b for 2016-2017. Also existing data points from ZEUS in a similar Q^2 range are shown.

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