Exclusive meson production at HERMES

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Abstract. Hard exclusive production of mesons provides access to the unknown generalized parton distributions (GPDs), which give a unified description of the structure of the nucleon. Exclusive electroproduction of π^+ and ρ^0 mesons has been measured on an internal hydrogen gas target at HERMES by using the 27.6 GeV polarized electron or positron beam of HERA. The cross section for exclusive π^+ production is presented and compared with calculations based on GPD models. For ρ^0 production, the azimuthal single spin asymmetry for a transversely polarized target is sensitive to J^q , the quark total angular momentum contribution to the proton spin. Preliminary results are compared to GPD based calculations. In addition, new measurements are reported for the Spin-Density Matrix Elements (SDMEs) for ρ^0 production on an unpolarized target.

Keywords: generalized parton distributions, exclusive meson production, cross sections, transverse target spin asymmetries, quark angular momentum, spin-density matrix elements

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INTRODUCTION

It has been proven that a QCD factorization theorem applies to hard exclusive electroproduction of mesons in case the exchanged virtual photon has longitudinal polarization [1]. The factorization theorem expresses the corresponding amplitude in terms of Generalized Parton Distributions (GPDs), which describe the correlations between partons in the nucleon with different momenta. GPDs provide a unified description of exclusive and inclusive reactions. They are related to the usual parton distribution functions and nucleon form factors and can provide new information about nucleon structure, such as the total angular momentum contribution of partons to the nucleon spin. For each quark flavour q there are four leading twist GPDs: H^q , E^q , $\tilde{H}^q$ and $\tilde{E}^q$. The quantum numbers of the produced meson determine the sensitivity to different GPDs. While exclusive production of vector mesons is sensitive only to the GPDs H^q and E^q , pseudoscalar meson production is sensitive to the GPDs $\tilde{H}^q$ and $\tilde{E}^q$.

In this paper measurements are reported for the cross section of exclusive π^+ production, and the transverse target spin asymmetry and Spin-Density Matrix Elements (SDMEs) for exclusive ρ^0 production. The results for the cross section and the asymmetry are compared with calculations based on GPD models. Using the results of the SDME analysis the ratio $R = \sigma_L/\sigma_T$ of longitudinal to transverse production cross sections is determined.

DATA SELECTION

Exclusive production of π^+ and ρ^0 mesons has been measured on an internal hydrogen target using the HERMES spectrometer [2] and the 27.6 GeV polarized electron or positron beam of HERA.

For pion production both the scattered lepton and the produced meson have been detected by the spectrometer, which offers excellent lepton-hadron separation and good pion identification for momenta between 1 and 15 GeV. The missing mass squared (M_X^2) of the reaction $ep \rightarrow e\pi^+X$ has been used to select exclusive events by requiring that M_X^2 corresponds to the nucleon mass squared M^2 . Data for the process $ep \rightarrow e\pi^-X$ have been used to estimate the contribution of non-exclusive events as the process $ep \rightarrow e\pi^-n$ is forbidden due to charge conservation.

Exclusive ρ^0 production can be identified by detecting the scattered lepton and the decay products of the produced meson ($\rho^0 \rightarrow \pi^+\pi^-$). The pion pairs resulting from ρ^0 decay have been selected by requiring that the invariant mass $M_{2\pi}$ of the two-pion system satisfies $0.6 < M_{2\pi} < 1.0$ GeV. The missing energy $\Delta E = (M_X^2 - M^2)/2M$ has been used to select exclusive ρ^0 events, where M_X^2 is the missing mass squared of the reaction $ep \rightarrow e\rho^0X$. For the exclusive data set the value of ΔE is centered around zero. The missing energy is required to be less than 0.6 GeV. The non-exclusive background contribution coming from semi-inclusive deep inelastic scattering has been estimated using Monte Carlo simulations.

CROSS SECTION FOR EXCLUSIVE PION PRODUCTION

The cross section for exclusive π^+ production has been determined in different ranges of the Bjorken variable x and Q^2 , the negative squared four-momentum of the virtual photon. This has been done using:

$$\sigma^{\gamma^*p \rightarrow n\pi^+}(x, Q^2) = \frac{N_{\pi^+}^{excl}(x, Q^2)}{L\Delta x\Delta Q^2\Gamma_V(\langle x \rangle, \langle Q^2 \rangle)\kappa(x, Q^2)}, \quad (1)$$

where $N_{\pi^+}^{excl}$ is the obtained number of π^+ mesons corrected for background, L is the integrated luminosity, Γ_V is the virtual photon flux factor, κ is the probability to detect the scattered positron and the produced π^+ in the HERMES spectrometer. The size of the x, Q^2 bin is represented by Δx and ΔQ^2 . The detection probability has been determined using two exclusive Monte Carlo simulations with calculations based on different GPD parametrizations [3, 4]. The difference between the results has been used to estimate the systematic error of the detection probability. The systematic error on the cross section is dominated by the uncertainty on the background subtraction and the uncertainty on the efficiency correction due to different detection probabilities in different years.

Fig. 1 shows the Q^2 dependence of the cross section for three x ranges. These preliminary results have not been corrected for radiative effects, which are roughly estimated to be about 20% and are expected to show little dependence on x or Q^2 . The measured cross section has been compared with the results of calculations based on GPD models

FIGURE 1. The cross section for $\gamma^* p \rightarrow \pi^+ n$ versus Q^2 for three different x ranges. The inner and outer error bars represent, respectively, the statistical uncertainty and the combined statistical and systematic uncertainty. The curves represent calculations based on the GPD model of ref. [4]. The solid lines represent a leading order calculation of the longitudinal cross section, while the dashed lines represent a similar calculation also including power corrections.

[4] for the x and Q^2 ranges of the data, integrated over t , the squared four-momentum transfer to the nucleon.

The solid lines in Fig. 1 represent the leading-order calculations. The dashed lines represent the leading-order calculations with in addition the power corrections due to intrinsic transverse momenta of the partons in the nucleon and due to soft overlap type contributions. While the leading-order calculations underestimate the data, the evaluation of the power corrections appears to be too large.

The measured cross section can be written as $\sigma = \sigma_T + \varepsilon \sigma_L$, where σ_T and σ_L are, respectively, the transverse and the longitudinal virtual photon contribution and ε is the virtual photon polarization parameter. The GPD based calculations apply only to the longitudinal part of the cross section. A separation of the longitudinal and the transverse contribution of the cross section is not feasible for exclusive pion production at HERMES. However, since the transverse contribution is predicted to be suppressed by a factor of the order of $1/Q^2$ with respect to the longitudinal contribution [1], and since ε ranges from 0.8 to 0.95, the data at larger Q^2 are expected to be dominated by the longitudinal part. Calculations based on a Regge model [5] predict that in the Q^2 range of the data the transverse contribution of the cross section is at least a factor four smaller than the longitudinal contribution. Furthermore, it has been checked that the Q^2 dependence of the measured cross section [6] is in agreement with a $1/Q^6$ dependence at fixed x predicted by the factorization theorem [1] for the longitudinal cross section.

TRANSVERSE TARGET SPIN ASYMMETRY IN EXCLUSIVE ρ^0 PRODUCTION

The transverse target spin asymmetry in exclusive ρ^0 production is sensitive to the interference between the GPDs E and H [7]. Whereas the cross section depends on a quadratic sum of these GPDs, with E kinematically suppressed compared to H , the asymmetry depends linearly on the GPD E . The transverse spin asymmetry is therefore considered to be a key observable for obtaining more information about the GPD E . It has been shown that $A_{UT}^{\sin(\phi-\phi_s)}$, the $\sin(\phi-\phi_s)$ moment of the single spin asymmetry $A_{UT}(\phi, \phi_s)$, is sensitive to the quark total angular momentum contribution J^q to the proton spin [7, 8]. The asymmetry $A_{UT}(\phi, \phi_s)$, where the subscript UT denotes the use of an unpolarized beam and a transversely polarized target, is calculated as:

$$A_{UT}(\phi, \phi_s) = \frac{1}{|P_t|} \frac{N^\uparrow(\phi, \phi_s) - N^\downarrow(\phi, \phi_s)}{N^\uparrow(\phi, \phi_s) + N^\downarrow(\phi, \phi_s)}. \quad (2)$$

Here $|P_t| = 0.76 \pm 0.05$ is the average target polarization and $N^\uparrow$ and $N^\downarrow$ are the luminosity normalized yields for a positively and negatively polarized target, respectively. The angles ϕ and ϕ_s are the azimuthal angles of, respectively, the ρ^0 production plane and the transverse component $\vec{S}_\perp$ of the target spin with respect to the lepton scattering plane (see Fig. 2). The data used for this analysis were taken in 2002-2004 with a positron beam impinging on a transversely polarized hydrogen target.

Preliminary results for the asymmetry are shown in Fig. 3. The $\phi - \phi_s$ dependence of A_{UT} is shown in the left panel. The asymmetry has been fitted by the function $\sin(\phi - \phi_s)$. The resulting moment $A_{UT}^{\sin(\phi-\phi_s)}$ has been corrected for non-exclusive and non-resonant background contributions. The x dependence of $A_{UT}^{\sin(\phi-\phi_s)}$ is shown in the right panel of Fig. 3. Note that a longitudinal/transverse separation has not yet

FIGURE 2. The azimuthal angles ϕ and ϕ_s of, respectively, the ρ^0 production plane (grey plane) and the transverse component $\vec{S}_\perp$ of the target spin, with respect to the lepton scattering plane (white plane).

been carried out for the asymmetry. The measured values of $A_{UT}^{\sin(\phi-\phi_s)}$ are compared with GPD based calculations for different values of the quark total angular momentum contribution ($J^u = 0, 0.2, 0.4, J^d = 0$) [8]. Although the measurements are consistent with the calculations, the statistical uncertainties are too large to distinguish between different values of J^u . It is expected that the data taken in the year 2005 will double the amount of data available for this analysis.

FIGURE 3. Left: Measured values of the asymmetry A_{UT} versus the angle $\phi - \phi_s$. The curve represents the results of a $\sin(\phi - \phi_s)$ fit of the asymmetry yielding as an amplitude the value of the $A_{UT}^{\sin(\phi-\phi_s)}$ moment which is printed in left-hand panel. This value of $A_{UT}^{\sin(\phi-\phi_s)}$ represents the average over the acceptance of the experiment. Right: Plot of the moment $A_{UT}^{\sin(\phi-\phi_s)}$ versus x , compared with GPD based calculations assuming different values of J^u ($J^u = 0, 0.2, 0.4$ and $J^d = 0$) [8].

SDMES FOR ρ^0 PRODUCTION

A separation of the longitudinal and the transverse cross section for ρ^0 production can be performed for an unpolarized target by using Spin-Density Matrix Elements (SDMEs). SDMEs provide information about the spin transfer from the exchanged virtual photon to the produced vector meson. They can be extracted from the angular distributions of the vector meson decay products [9]. Recently new results have become available for the SDMEs for ρ^0 production measured at HERMES. They have been extracted from data taken during the years 1996-2000 with an unpolarized and a longitudinally polarized lepton beam on unpolarized hydrogen and deuterium targets.

Fig. 4 shows the obtained values of the SDMEs (denoted by $r_{ij}^{\alpha\beta}$) for ρ^0 production on a hydrogen target, integrated over the kinematical variables. The fractional vertical lines in this plot indicate the SDMEs which are equal to zero if there is s-Channel Helicity Conservation (SCHC). SCHC implies that the helicity of the virtual photon is preserved by the produced vector meson. Small violations of SCHC of the order of 5-10% are observed.

The longitudinal contribution to the ρ^0 production cross section σ can be determined using the ratio $R = \sigma_L / \sigma_T$ of longitudinal to transverse production cross sections:

$$\sigma_L = \frac{R}{1 + \epsilon R} \sigma_{total}, \quad (3)$$

FIGURE 4. SDMEs for ρ^0 production on a proton target. The upper part of the panel shows the 15 SDMEs corresponding to an unpolarized lepton beam and the lower part of the panel shows the 8 SDMEs corresponding to a longitudinally polarized lepton beam. The fractional vertical lines indicate which SDMEs are equal to zero assuming SCHC.

Assuming SCHC this ratio is related to the SDME r_{00}^{04} by

$$R = \frac{r_{00}^{04}}{\varepsilon(1 - r_{00}^{04})}. \quad (4)$$

Using this equation R has been determined from the results for r_{00}^{04} . The extraction of R through equation (4) is relatively insensitive to the observed violations of SCHC. The obtained values of R for a hydrogen target are shown in Fig. 4 together with existing data from other experiments. It is seen that all data are in mutual agreement despite the considerable differences in the center-of-mass energies used in the various experiments.

FIGURE 5. The ratio $R = \sigma_L/\sigma_T$ of longitudinal over transverse cross sections obtained at HERMES for ρ^0 production on a hydrogen target. The result is compared to the world data [10].

SUMMARY AND OUTLOOK

The cross section for exclusive π^+ production has been measured as a function of Q^2 for different x ranges. These results have been compared to calculations based on a GPD model.

Results have been shown for the transverse target spin asymmetry in exclusive ρ^0 production. The moment $A_{UT}^{\sin(\phi-\phi_s)}$ has been compared with model dependent calculations for different values of the up-quark total angular momentum contribution J^u to the proton spin. The results are consistent with these calculations, but the current statistical precision does not allow to distinguish between the different values of J^u .

New results are available for the SDMEs for exclusive ρ^0 production on an unpolarized target. Small violations of SCHC of the order of 5-10% have been observed. The ratio R of longitudinal over transverse production cross sections has been determined from the SDME r_{00}^{04} assuming SCHC. The extracted value of R is in agreement with the world data.

The coming 2005 data production will be the last production with transversely polarized target data. It will double the amount of available data for the analysis of transverse target spin asymmetries. A recoil detector [11] will be installed surrounding the target region by the end of 2005. It will allow one to detect the recoil proton, which will result

in a better identification of exclusive reactions. Furthermore, the data will be taken on a high density target resulting into data with higher statistics.

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