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Direct extraction of helicity amplitude ratios in exclusive ρ^0 electroproduction

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Exclusive ρ^0-meson electroproduction is studied in the HERMES experiment performed with a 27.57 GeV longitudinally polarized electron/positron beam and unpolarized hydrogen and deuterium targets in the region 0.5 GeV^2 $< Q^2 <$ 7 GeV^2, 3 GeV $< W <$ 6.3 GeV, and $-t' < 0.4$ GeV^2. Not only the real but also the imaginary parts of the ratios of the natural-parity-exchange helicity amplitudes T_{11} (transition of the transverse virtual photon to the transverse ρ^0 meson $\gamma^*_T \to \rho^0_T$) and T_{01} ($\gamma^*_T \to \rho^0_L$) to T_{00} ($\gamma^*_L \to \rho^0_L$) are extracted from the data using the polarized beam. For the unnatural-parity-exchange amplitude U_{11}, the ratio $|U_{11}/T_{00}|$ is obtained. The dependences of all these ratios on photon virtuality, Q^2 and the ρ^0-meson transverse momentum squared, $-t'$ are presented and compared with perturbative QCD predictions. The HERMES results are in agreement with those of the H1 collaboration.

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1. Introduction

Exclusive electroproduction of vector mesons (V) on nucleons (N) provides valuable information both on the strong interaction and the structure of hadrons involved in the process. Recent new interest in exclusive meson production in deep-inelastic scattering (DIS) of leptons is caused by a possibility to extract generalized parton distributions (GPDs) which give a wealth of information on the nucleon structure (see, for instance, review [1]). In the one-photon-exchange approximation, all observables in electroproduction can be expressed in terms of the helicity amplitudes $F_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ of the process

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\mu_N), \tag{1.1}$$

where the helicities are given in parentheses. Since the spin-density matrix of the virtual photon is well known from QED and spin-density-matrix elements (SDMEs) of vector mesons may be extracted from angular distributions of final particles, the properties of helicity amplitudes can be studied in detail.

The formalism for the description of process (1.1) for unpolarized targets was elaborated in [2] and generalized for polarized targets in [3, 4] where expressions of SDMEs in terms of the helicity amplitudes were established. These expressions can be rewritten identically in terms of the ratios of amplitudes $F_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ to any amplitude. As a result of the symmetry properties [2, 3, 4] of the helicity amplitudes the number of independent amplitudes is 18. Since SDMEs depend on ratios of amplitudes the number of independent real parameters in any small bin of kinematic variables is 34. The hierarchy of amplitudes established in the HERMES kinematic region [5]

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |U_{11}|^2 > |T_{01}|^2 \gg |T_{10}|^2 \sim |T_{1-1}|^2 \sim |U_{01}|^2 \sim |U_{10}|^2 \sim |U_{1-1}|^2 \tag{1.2}$$

permits to reduce the number of significant free parameters to 5: Re(t_{11}), Im(t_{11}), Re(t_{01}), Im(t_{01}), and $|u_{11}|$, where $t_{\lambda_V \lambda_\gamma} = T_{\lambda_V \lambda_\gamma}/T_{00}$, $|u_{11}| = |U_{11}|/|T_{00}|$ with $|U_{\lambda_V \lambda_\gamma}|^2 = |U_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}|^2 + |U_{\lambda_V -\frac{1}{2} \lambda_\gamma \frac{1}{2}}|^2$. The abbreviated notation $T_{\lambda_V \lambda_\gamma}$ is used for the amplitudes $T_{\lambda_V \frac{1}{2} \lambda_\gamma \frac{1}{2}}$ of natural-parity exchange (NPE) without nucleon helicity flip, while $U_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ denotes the amplitude of unnatural-parity exchange (UPE). They are related to $F_{\lambda_V \mu_N \lambda_\gamma \lambda_N}$ by the equations $T_{\lambda_V \mu_N \lambda_\gamma \lambda_N} = (F_{\lambda_V \mu_N \lambda_\gamma \lambda_N} + (-1)^{\lambda_V - \lambda_\gamma} F_{-\lambda_V \mu_N -\lambda_\gamma \lambda_N})/2$, and $U_{\lambda_V \mu_N \lambda_\gamma \lambda_N} = (F_{\lambda_V \mu_N \lambda_\gamma \lambda_N} - (-1)^{\lambda_V - \lambda_\gamma} F_{-\lambda_V \mu_N -\lambda_\gamma \lambda_N})/2$ [2, 3, 4]. In Regge phenomenology, exchange by reggeons of natural parity with $P = (-1)^J$ (Pomeron, ρ, f_2, a_2, ...) contributes to the NPE amplitudes, while exchange by reggeons of unnatural parity with $P = -(-1)^J$ (π, a_1, b_1, ...) contributes to the UPE amplitudes.

2. Selection of Exclusive ρ^0 Mesons

The ρ^0 mesons were produced in DIS of 27.57 GeV electrons and positrons on unpolarized hydrogen and deuterium targets. The HERMES experiment used a longitudinally polarized beam with $P_b = \pm 0.53$. The scattered electrons (positrons) and pions from the decay $\rho^0 \to \pi^+\pi^-$ were detected and identified by the HERMES spectrometer [6]. Particle identification in 1996-2000 was done using a Cherenkov detector, while a RICH detector [7] has been employed since 2000. The requirement 0.6 GeV $< M_{\pi\pi} <$ 1.0 GeV was applied on the invariant mass of the final pions to identify ρ^0 mesons. Since a recoil nucleon was not detected, exclusive events were selected by the requirement -1 GeV $< \Delta E < 0.6$ GeV, where $\Delta E = (M_X^2 - M^2)/(2M)$, M denotes the nucleon mass and M_X is the missing mass of the hadronic system. Diffractive events were selected by the constraint $-t' < 0.4$ GeV^2 with $t' = t - t_0$. Here, t denotes the squared four-momentum transfer to the nucleon, and $-t_0$ is the smallest value of $-t$ at fixed Q^2, the center-of-mass energy of the $\gamma^* N$ system, W, and the vector-meson mass, M_V. The semi-inclusive DIS background was subtracted with Monte Carlo events generated by PYTHIA. The fraction of semi-inclusive DIS events for the entire kinematic region 0.5 GeV$^2 < Q^2 < 7$ GeV^2, 3 GeV $< W < 6.3$ GeV was found to be 8%. The binned maximum likelihood method was used for treating the data in 4×4 bins in Q^2 and t'. Error calculations were performed using the MINUIT code (see details in [5]).

3. Direct Extraction of Helicity Amplitude Ratios

Fitting the angular distribution of decay pions in correlation with the scattered lepton provides the amplitude ratios for ρ^0 production if the SDMEs are expressed in terms of the amplitude ratios. The Q^2 dependence of $\mathrm{Re(t_{11})}$ ($\mathrm{Im(t_{11})}$) is shown in the left (right) panel of Fig. 1 both for the hydrogen and deuterium targets. The parameterization $\mathrm{Re(t_{11}) = a/Q}$, $\mathrm{Im(t_{11}) = bQ}$ permits to describe the Q^2 dependence in the HERMES kinematic region for both targets. Since the angular distributions for production on the proton and deuteron are compatible within the experimental accuracy a fit of combined data is performed giving the results $a = (1.129 \pm 0.024)$ GeV with χ^2 per degree of freedom $\chi^2/N_{df} = 1.02$, and $b = (0.344 \pm 0.014)$ GeV^{-1} with $\chi^2/N_{df} = 0.87$. The result for $\mathrm{Re(t_{11})}$ is in agreement with the large-Q^2 behaviour of t_{11} which is proportional to M_V/Q as established in Refs. [8, 9] in the perturbative QCD (pQCD) framework. The linear increase of $\mathrm{Im(t_{11})}$ with Q disagrees with the asymptotic behaviour of t_{11} predicted in pQCD. The phase difference δ_{11} between the amplitudes T_{11} and T_{00} increases with Q^2 (since $\tan\delta_{11} = \mathrm{Im(t_{11})/Re(t_{11}) = bQ^2/a}$) and its mean value is about 30°. This is in clear disagreement with the calculation [11] performed in the GPD based approach and leaves us with no model that explains this value and the Q^2 dependence of δ_{11}.

No t' dependence of $\mathrm{Re(t_{11})}$ and $\mathrm{Im(t_{11})}$ was observed in the region $-t' < 0.4$ GeV^2. This means that the slope parameters b_L and b_T of the t' dependence of $T_{00} \propto \exp\{b_L t'/2\}$ and $T_{11} \propto \exp\{b_T t'/2\}$ coincide within the experimental accuracy.

The asymptotic behaviour of t_{01} at large Q^2 looks like [8, 9] $t_{01} \propto \sqrt{-t'}/Q$ according to pQCD. The fit of the combined proton and deuteron data gives $\mathrm{Re(t_{01}) = c\sqrt{-t'}}$, $c = 0.40 \pm 0.02$ GeV^{-1} with $\chi^2/N_{df} = 0.72$; $\mathrm{Im(t_{01}) = d\sqrt{-t'}/Q}$, $d = 0.20 \pm 0.07$ with $\chi^2/N_{df} = 1.09$. The result of the fit for $\mathrm{Re(t_{01})}$ is in fair disagreement with the pQCD asymptotic behaviour while the behaviour of $\mathrm{Im(t_{01})}$ is not in contradiction to pQCD. A comparison of the curves calculated with the parameters c and d with values of the real and imaginary parts of t_{01} in four $-t'$ bins is presented in Fig. 2.

As seen from the left panels of Figs. 1 and 2 the H1 result [10] obtained at 35 GeV $< W <$ 180 GeV for $\mathrm{Re(t_{11})}$ and $\mathrm{Re(t_{01})}$ (only the result on $\mathrm{Re(t_{01})}$ at a mean value of Q^2 equal to 3.3 GeV^2 is shown) is in good agreement with that of the HEREMES collaboration. This means that i) there is no crucial W dependence of the amplitude ratios $\mathrm{Re(t_{11})}$ and $\mathrm{Re(t_{01})}$, ii) the Q^2 dependence of $\mathrm{Re(t_{01})}$ up to $\langle Q^2 \rangle = 3.3$ GeV^2 is absent. Since the electron and positron beams have no longitudinal polarization component at H1 [10], an extraction of the imaginary part of the ratios $t_{\lambda_V \lambda_\gamma}$ was not possible and the approximation $|t_{\lambda_V \lambda_\gamma}|^2 \approx [\mathrm{Re(t_{\lambda_V \lambda_\gamma})}]^2$ was used instead.

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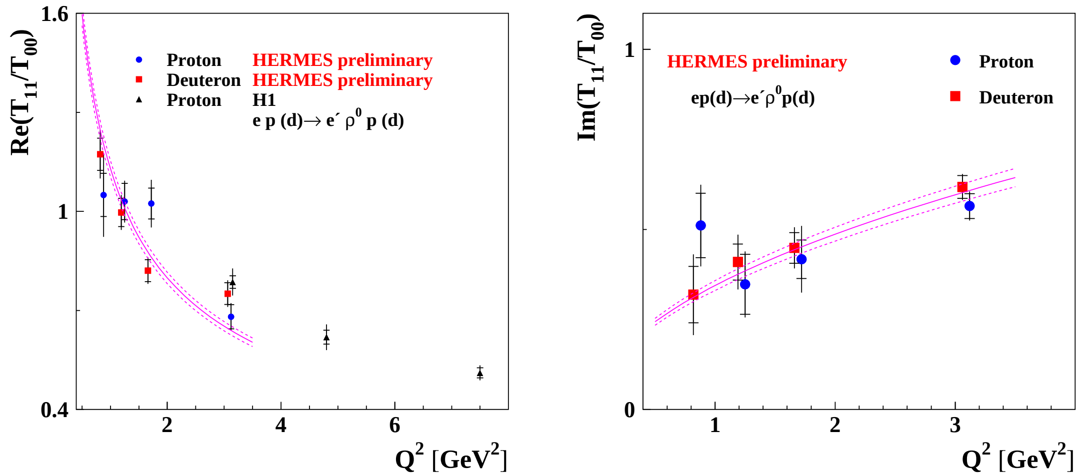

Figure 1: Q^2 dependence of $\mathrm{Re}(\mathrm{T}_{11}/\mathrm{T}_{00})$ and $\mathrm{Im}(\mathrm{T}_{11}/\mathrm{T}_{00})$ for hydrogen and deuterium targets. Full circles and squares show results of the present work, triangles are results of the H1 collaboration [10]. The inner error bars show statistical uncertainty while the outer ones indicate statistical and systematic uncertainties added in quadratures. Parameterization of curves is given in text. Solid lines are calculated with mean values of parameters. Dashed lines correspond to one standard deviation of curve parameters.

The ratio $|u_{11}|$ versus Q^2 and t' is presented in Fig. 3. No kinematic dependences are seen and therefore they are fitted to a constant $|u_{11}| = g$ (with $g = 0.391 \pm 0.013$ and $\chi^2/N_{df} = 0.44$) which is presented in Fig. 3 with straight lines. This is in contradiction to the pQCD asymptotic behaviour of $u_{11} \propto M_V/Q$. The absence of any t dependence means that U_{11} cannot be described by only one-pion-exchange.

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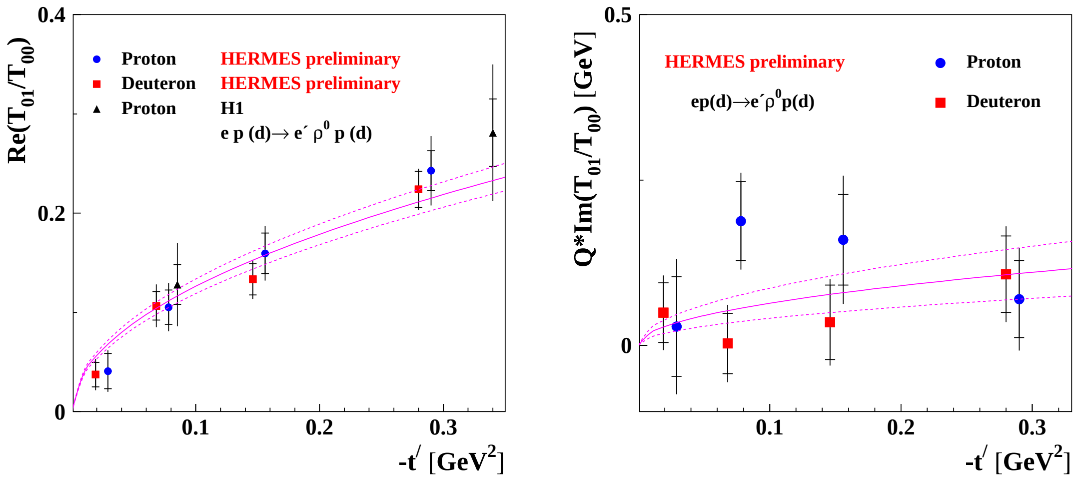

Figure 2: t' dependence of $\mathrm{Re}(\mathrm{T}_{01}/\mathrm{T}_{00})$ and $\mathrm{Im}(\mathrm{T}_{01}/\mathrm{T}_{00})$ for hydrogen and deuterium targets. Full circles and squares show results of the present work, triangles are results of the H1 collaboration [10]. Inner (outer) error bars show statistical (total) uncertainty. Meaning of curves is the same as in Fig. 1.

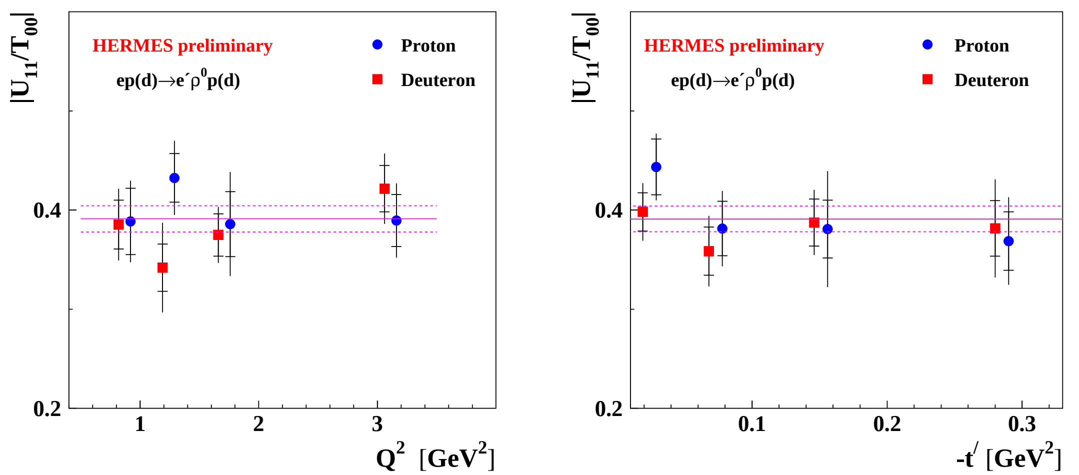

Figure 3: Q^2 and t' dependences of $|U_{11}/T_{00}|$ for hydrogen and deuterium targets. Full circles and squares show preliminary HERMES results . Inner (outer) error bars show statistical (total) uncertainty. Meaning of curves is the same as in Fig. 1.