SPIN EFFECTS IN HARD EXCLUSIVE ELECTROPRODUCTION OF MESONS

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Abstract

In this talk various spin effects in hard exclusive electroproduction of mesons are briefly reviewed. The data are discussed in the light of recent theoretical calculations within the framework of the handbag approach. This talk has been presented at the Conference in Honor of Prof. Anatoly Efremov’s 75th Birthday held at Trento, July, 2009.

PACS Nos. 12.38.Bx, 13.60.Le, 13.88.+e

1 Introduction

Electroproduction of mesons allows for the measurement of any spin effects. For instance, one may measure the dependence of the cross sections on the polarization of the virtual photon by separation. Through the decay of vector mesons, e.g. $^0 \pi^+$, one can measure the spin density matrix elements (SDME) of the decaying meson which also provide a wealth of information on spin effects. Last not least one may work with longitudinally or transversely polarized targets and/or longitudinally polarized beams and measure various spin asymmetries. The investigation of spin-dependent observables allows for a deep insight in the underlying dynamics. Provided a sufficient number of them has been measured the strength of the various contributing amplitudes and even their relative phases can be determined from the experimental data. Here, in this article, it will be reported upon some spin effects and their dynamical interpretation in the framework of the so-called handbag approach which offers a partonic description of meson electroproduction provided the virtuality of the exchanged photon, $Q^2$, is sufficiently large. The theoretical basis of the handbag approach is the factorization of the process amplitudes into a hard partonic subprocess and in soft hadronic matrix elements, the so-called generalized parton
distributions (GPDs) as well as wave functions for the produced mesons, see Fig. 1. In collinear approximation factorization has been shown to hold rigorously for hard exclusive meson electroproduction. It has been also shown by these authors that the transitions from a longitudinally polarized photon to a likewise polarized vector meson or a pseudoscalar one, \( L \rightleftharpoons V \), dominate for large \( Q^2 \). Other photon-meson transitions are suppressed by inverse powers of the hard scale.

As mentioned, spin effects in hard exclusive meson electroproduction will be briefly reviewed and their implications on the handbag approach and above all for the determination of the GPDs, discussed. In Sect. 2 evidences for contributions from transversely polarized photons in vector-meson production are introduced. Next, in Sect. 3, the role of target spin asymmetries in meson electroproduction is examined and results for vector mesons are shown. In Sect. 4 an estimate of the GPD \( E \), needed for a calculation of the target spin asymmetries for vector mesons, is presented. Sect. 5 is devoted to a discussion of the target spin asymmetries in pion electroproduction. Finally, in Sect. 6, a summary is given.

2 Transversely polarized photons in vector-meson electroproduction

In a number of experiments, e.g. Refs. [3-5], the ratio of the longitudinal and transversal cross sections has been determined from the SDM \( R_{00}^{04} \):

\[
R = \frac{L}{T} = \frac{1}{\pi} \frac{r_{00}^{04}}{r_{00}^{40}};
\]

where \( " \) is the ratio of the longitudinal and transversal photon fluxes. With regard to the factorization properties of meson electroproduction one expects \( R / Q^2 \). In Fig. 2 the HERA data for \( R \) are displayed. One observes that \( R \) is not at all large. At \( Q^2 \approx 4 \text{ GeV}^2 \) it is about 2, i.e. \( L \approx 2T \) only. For larger \( Q^2 \) the ratio seems to increase slowly. Evidently, there are substantial contributions from \( T \rightleftharpoons V \) transitions to vector-meson electroproduction.

In a series of papers [6-8] a handbag approach has been advocated for which the subprocess amplitudes are calculated within the modified perturbative approach [9], and the GPDs are constructed from reggeonized double distributions [10,11]. In this approach the quark transverse momentum is retained in the subprocess and Sudakov suppressions are taken into account. The partons are still emitted and re-absorbed by the proton collinearly. For the meson wave functions Gaussians in the variable \( K_z^2 = (1 - \frac{x}{Q^2}) \) are assumed with transverse size parameters tied to experiment [12]. The variable \( x \) denotes the fraction of the meson’s momentum the quark entering the meson carries. It is to be emphasized that the \( T \rightleftharpoons V \) transitions which are infrared divergent in collinear approximation, are regularized by the quark transverse momentum in the modified perturbative approach.
Figure 1: A typical lowest order Feynman graph for meson electroproduction. The signs indicate helicity labels for the contribution from transversity GPDs to the amplitude $M_{0^+;\rho^+}$, see text.

Figure 2: The ratio $R$ for $0^+$ production versus $Q^2$ at $W = 90$ GeV. Data taken from H1 [5] (filled symbols) and ZEUS [4] (open symbols). The solid line represents the handbag results with the shaded bands indicating the theoretical uncertainties [5].

With this model the available data on cross sections and SDME for $0^+$ and $0^-$ production have been fitted in the kinematical range $Q^2 > 3$ GeV$^2$, $W > 5$ GeV (i.e. for small values of skewness $\kappa_0^f = 2 < 0.1$) and for the squared invariant momentum transfer $t^2 = t + t_0 < 0.6$ GeV$^2$ where $t_0$ is the value of $t$ for forward scattering. Good agreement with experiment is found. An example of the results obtained in Ref. [3] for $R(0^+)$ are displayed in Fig. 2 and compared to experiment. The data are well described within this approach and the increase of $R$ according to Eq. (1) is clearly visible. Results of similar quality have been obtained for $0^-$ production. The analysis carried through in [6,7,8] x the GPD $H$ for quarks and gluons. The other GPDs do practically not contribute to the cross sections and SDME at small skewness.

In experiment, e.g. [3,5], there have also been observed small but clearly non-zero contributions from $V_L$ and $V_T$ transitions for instance in the SDME $E_{0^+}$. Such transitions, which violate $s$-channel helicity conservation, are not yet understood in the handbag approach. They are suppressed by $1/Q$ as compared to the leading amplitude $M_{0^+;\rho^+}$. For the even stronger suppressed $V_L$ and $V_T$ transitions there is no indication in experiment.

3 Target asymmetries

The electroproduction cross sections measured with a transversely or longitudinally polarized target consist of many terms, each can be projected out by a sin’ or cos’ moment where ’ is a linear combination of , the azimuthal
Table 1: Features of the asymmetries for transversally and longitudinally polarized targets. The angle describes the rotation in the lepton plane from the direction of the incoming lepton to the virtual photon one; it is very small.

| observable | dominant interfering term | amplitudes | low $t^0$ behavior |
|------------|---------------------------|------------|---------------------|
| $A_{UT}^{\sin (s)}$ | LL | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |
| $A_{UT}^{\sin (s)}$ | LT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $\text{const.}$ |
| $A_{UT}^{\sin (2s)}$ | LT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |
| $A_{UT}^{\sin (s+)}$ | TT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |
| $A_{UT}^{\sin (2s+)}$ | TT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |
| $A_{UT}^{\sin (3s)}$ | TT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |
| $A_{UL}^{\sin (2s)}$ | LT | $\text{Im} M_0 \rho_+ M_0 \rho_+^*$ | $P^{-t^0}$ |

angle between the lepton and the hadron plane and $s$, the orientation of the target spin vector $[13]$. In Tab. 3 the features of some of these moments are displayed. As the dominant interference terms reveal the target asymmetries provide detailed information on the $p!VB$ amplitudes and therefore on the underlying dynamics that generates them.

A number of these moments have been measured recently. A particularly striking result is the $\sin (s)$ moment which has been measured by the HERMES collaboration for $p!e$ electroproduction [14]. The data on this moment, shown in Fig. 3, exhibit a mild $t$-dependence and do not show any indication for a turnover towards zero for $t^0 = 0$. Inspection of Tab. 3 reveals that this behavior of $A_{UT}^{\sin (s)}$ at small $t^0$ requires a contribution from the interference term $\text{Im} M_0 \rho_+ M_0 \rho_+^*$. Both the contributing amplitudes are helicity non-conserving and are therefore not forced to vanish in the forward direction by angular momentum conservation. Thus, we see that for $p!e$ electroproduction there are strong contributions from $t^0$ transitions. The underlying dynamical mechanism for such transitions will be discussed in Sect. 5.

For $0!e$ production the $\sin (s)$ moment has been measured by HERMES [15] and COMPASS [16]; the latter data being still preliminary. The HERMES data are shown in Fig. 4. In the handbag approach $A_{UT}^{\sin (s)}$ can also be expressed by an interference term between the convolutions of the GPDs $H$ and $E$ with hard scattering kernels

$$A_{UT}^{\sin (s)} = \text{Im} [H E]$$

Instead of the helicity amplitudes. Given that $H$ is known from the analysis of the $0$ and $s$ cross sections and SDMEs, $A_{UT}^{\sin (s)}$ provides information on $E$ [8]. Let us recapitulate what we know about the GPD $E$. ...
Figure 3: The $\sin s$ moment for a transversely polarized target at $Q^2 = 2.45 ~\text{GeV}^2$ and $W = 3.99 ~\text{GeV}$ for $^+$ production. The predictions from the handbag approach of Ref. [18] are shown as a solid line. The dashed line is obtained disregarding the twist-3 contribution. Data are taken from [14].

Figure 4: The asymmetry $A_{UT}^{\sin s}$ for $^0$ production at $W = 5 ~\text{GeV}$ and $Q^2 = 2 ~\text{GeV}^2$. Data taken from Ref. [15]. The lines represent the results presented in Ref. [19]. For further notations see text and Ref. [15].

4 The GPDs

In Ref. [17] the electromagnetic form factors of the proton and neutron have been utilized in order to determine the zero-skewness GPDs for valence quarks through the sum rules which for the case of the Pauli form factor, reads

$$F_2^{P(n)} = \frac{Z}{h} \int_0^1 dx \ e_{u(d)} E_{\nu}^{u} (x; = 0; t) + e_{d(u)} E_{\nu}^{d} (x; = 0; t) \ ;$$  (3)

In order to determine the GPDs from the integral a parameterization of the GPD is required for which the ansatz

$$E_{\nu}^{a} (x; 0; t) = e_{\nu}^{a} (x) \exp \left( \ln (1-x) + b_{\nu} \right)$$  (4)

is made in a small $t$ approximation [17]. The forward limit of $E_{\nu}$ is parameterized analogously to that of the usual parton distributions:

$$e_{\nu}^{a} = N_{a} x ^\nu (1-x)^{1-\nu}$$  (5)

where $\nu (0) = 0.68$ is the intercept of a standard Regge trajectory and $\nu$ in Eq. 4 is its slope. The normalization $N_{a}$ is fixed from the moment

$$Z = \int dx E_{\nu}^{a} (x; ; t = 0)$$  (6)

where $a$ is the contribution of flavor quarks to the anomalous magnetic moments of the proton and neutron ($u = 1.57$, $d = 2.03$). A best fit to the
data on the nucleon form factors provides the powers $\eta = 4$ and $\xi = 5.6$. However, other powers are not excluded in the 2004 analysis of Ref. [17]; the most extreme set of powers, still in agreement with the form factor data, is $\eta = 10$ and $\xi = 5$. The analysis performed in [19] should be repeated since new from factor data are available from Jefferson Lab, e.g., $G^n_1$ and $G^n_2$ are now measured up to $Q^2 = 3.5$ and 50 GeV$^2$, respectively [20, 21]. These new data seem to favor $\eta < \xi$. The zero-skewness GPDs $E_\nu$ are used as input to a double distribution from which the valence quark GPDs for non-zero skewness are constructed [19].

In Ref. [19], following Diehl and Kugler [22], E for gluons and sea quarks has been estimated from positivity bounds and a sum rule for the second moment of $E$ which follows from a combination of Ji’s sum rule [23] and the momentum sum rule of deep inelastic lepton-nucleon scattering. It has turned out that the valence quark contribution to that sum rule is very small, in particular if $\eta < \xi$, with the consequence of an almost exact cancellation of the gluon and sea quark moments. The GPDs $E^g$ and $E^{sea}$ are parameterized analogously to $E_\nu$, see Eqs. (3a, 3b). The normalization of $E^{sea}$ is fixed by assuming that an appropriate positivity bound [24, 25] is saturated while that of $E^g$ is determined from the sum rule. Several variants of $E$ have been exploited in Ref. [19] in a calculation of $A_{UT}^{\pi^0}(\vec{x})$ within the handbag approach. The results for a few variants are compared to the HERMES data on $\pi^0$ production [15] in Fig. 4. A good agreement between theory and experiment is to be noted. Similar agreement is obtained for the preliminary COMPASS data [16]. Combining both the experiments a negative value of $A_{UT}^{\pi^0}(\vec{x})$ for $\pi^0$ production is favored in agreement with the theoretical results obtained in [19], only the extreme variant $\eta = 10$ and $\xi = 5$ (dashed-dotted line in Fig. 4) seem to be ruled out. In Ref. [19] predictions for $\eta^+, K^0$ and $\eta^+$ productions are also given. Their comparison with forthcoming data from HERMES and COMPASS may provide valuable restrictions on the GPD $E$.

With $E$ at hand one may exploit Ji’s sum rule for the parton angular momenta. At zero skewness the sum rule reads

$$h^{\eta^0} = \frac{1}{2} q_{g0}^2 + e_{g0}^2; \quad h^{\eta^g} = \frac{1}{2} q_{g0}^2 + e_{g0}^2; \quad h^{\eta^{sea}} = \frac{1}{2} q_{sea}^2 + e_{sea}^2; \quad h^{\eta^{sea}} = \frac{1}{2} q_{sea}^2 + e_{sea}^2; \quad (7)$$

From a variant with $\eta = 4$, $\xi = 5.6$ and neglected $E^g$ and $E^{sea}$ (solid line in Fig. 4) for instance one obtains

$$h^{\eta^0} = 0.250; \quad h^{\eta^g} = 0.020; \quad h^{\eta^{sea}} = 0.015; \quad h^{\eta^{sea}} = 0.214; \quad (8)$$

at the scale of 4 GeV$^2$. The angular momenta sum up to $I = 2$, the spin of the proton. A very characteristic stable pattern is obtained in [19]: For all variants investigated, $J^{u^0}$ and $J^{g^0}$ are large while the other two angular momenta are very small. The angular momenta of the valence quarks are $h^{\eta^u} = 0.222$ and $h^{\eta^g} = 0.015$. These values are identical to the results quoted in [17] (for variant 1). They are also in agreement with a recent lattice result [20].
5 Target spin asymmetries in $^+$ production

In Ref. [13] electroproduction of positively charged pions has been investigated in the same handbag approach as applied to vector meson production [3,7,8]. To the asymptotically leading amplitudes for longitudinally polarized photons the GPDs $f^\pi$ and $g^\pi$ contribute in the isovector combination

$$f^{(1)} = f_u^\pi - f_d^\pi,$$

instead of $h$ and $E$ for vector mesons. In deviation to work performed in collinear approximation the full electromagnetic form factor of the pion as measured by the $F_2$ collaboration [27] is naturally taken into account (see also the recent work by Bechler and Mueller, Ref. [28]). The GPDs $f^\pi$ and $g^\pi$ are again constructed with the help of double distributions with the forward limit of $f^\pi$ being the polarized parton distributions while that of $g^\pi$ is parameterized analogously to Eq. (5).

$$f^\pi = f_u^\pi - f_d^\pi = e^\pi u - e^\pi d.$$ (10)

The normalization $e_{\pi}$ is fitted to experiment.

As is mentioned in Sect. 2 experiment requires a strong contribution from the helicity-non- $i\sigma$ amplitude $M_{0;\pi}^+$ which does not vanish in the forward direction. How can this amplitude be modeled in the framework of the handbag approach? From the usual helicity non- $i\sigma$ GPDs $H;E;:\ldots$ one obtains a contribution to $M_{0;\pi}^+$ that vanishes if $t^\sigma$ is non-zero at all. However, there is a second set of GPDs, the helicity- $i\sigma$ or transversity ones $H_T;E_T;:\ldots$ [29,30]. A inspection of Fig. 4 where the helicity configuration of the process is specified reveals the proton-parton vertex is of non- $i\sigma$ nature in this case and, hence, is not forced to vanish in the forward direction by angular momentum conservation. One also sees from Fig. 1, that the helicity configuration of the subprocess is the same as for the full amplitude. Therefore, also the subprocess amplitude has not to vanish in the forward direction and so the full amplitude. The prize to pay is that quark and antiquark forming the pion have the same helicity. Therefore, the twist-3 pion wave function is needed instead of the familiar twist-2 one. The dynamical mechanism building up the amplitude $M_{0;\pi}^+$ is of twist-3 order consisting of leading-twist helicity- $i\sigma$ GPDs and the twist-3 pion wave function. This mechanism has been first proposed in [31] for photo- and electroproduction of mesons where $t$ is considered as the large scale [32].

In Ref. [13] the twist-3 pion wave function is taken from [33] with the three-particle Fock component neglected. This wave function, still containing a pseudoscalar and a tensor component, is proportional to the parameter

$$m^2 = (m_u + m_d),$$

2 GeV at the scale of 2 GeV as a consequence of the divergent of the axial-vector current ($m_u$ and $m_d$ are current quark masses). It is further assumed that the dominant transversity GPD is $H_T$ while the other three can be neglected. The forward limit of $H_T^2$ is the transversity distribution

$\text{As compared to other work } f^\pi \text{ contains only the non-pole contribution.}$
\(a(x)\) which has been determined in \([34]\) in an analysis of data on the asymmetries in semi-inclusive electroproduction of charged pions measured with a transversely polarized target. Using these results for \(a(x)\) the GPDs \(H_T^2\) have been modeled in a manner analogous to that of the other GPDs (see Eq. \(3\)).

It is shown in \([13]\) that with the described model GPDs, the \(\pi^+\) cross sections as measured by HERMES \([35]\) are nicely fitted as well as the transverse target asymmetries \([14]\). This can be seen for \(A_{UT}^{\sin}\) from Fig. 2. A loop in this case good agreement between theory and experiment is to be seen. In both cases, \(A_{UT}^{\sin}\) and \(A_{UL}^{\sin}\) the prominent role of the twist-3 mechanism is clearly visible. Switching to one obtains the dashed lines which are significantly at variance with experiment. In this case the transverse amplitudes for \(L^+\), transition, \(M_0^+\beta^+\), Results for \(A_{UL}^{\sin}\) are displayed in Fig. 3 and compared to the data \([36]\). A loop in this case good agreement between theory and experiment is to be seen. In both cases, \(A_{UT}^{\sin}\) and \(A_{UL}^{\sin}\) the prominent role of the twist-3 mechanism is clearly visible. Switching to one obtains the dashed lines which are significantly at variance with experiment. In this case the transverse amplitudes are only fit by the pion-pole contribution. The other transverse target asymmetries quoted in Tab. 3 are predicted to be small in absolute value which is in agreement with experiment \([14]\). Thus, in summary, there is strong evidence for transversity in hard exclusive pion electroproduction. It should be considered as a non-trivial result that the transversity distributions determined from data on inclusive processes lead to a transversity GPD which is nicely in agreement with target asymmetries measured in exclusive pion electroproduction.

It is to be stressed that information on the amplitude \(M_0^+\beta^+\) can also obtained from the asymmetries measured with a longitudinally polarized beam or with a longitudinally polarized beam and target. The first asymmetry, \(A_{UU}^{\sin}\), is dominated by the same interference term as \(A_{UL}^{\sin}\) but diluted by the factor \(\Gamma^2(L^+e^{-})=1+\Gamma^2\). A loop in this case good agreement between theory and experiment is to be seen. In both cases, \(A_{UT}^{\sin}\) and \(A_{UL}^{\sin}\) the prominent role of the twist-3 mechanism is clearly visible. Switching to one obtains the dashed lines which are significantly at variance with experiment. In this case the transverse amplitudes would constitute a serious check of the twist-3 effect.

Although the main purpose of the work presented in \([13]\) is focused on the analysis of the HERMES data one may also be interested in comparing this approach with the Jefferson Lab data on the cross sections \([27]\). With the GPDs \(H_T^2\), \(H_F^2\) and \(H_T\) in their present form the agreement with these data is reasonable for the transverse cross section while the longitudinal alone is somewhat too small. It is however to be stressed that the approach advocated for in \([6, 13, 19]\) is designed for small skewness. At larger values of \(x\) the parametrizations of the GPDs are perhaps too simple and may require improvements. It is also

\(^{2}\text{While the relative signs of } u \text{ and } d \text{ are fixed in the analysis performed by Ref. [34] the absolute sign is not. Here, in } \pi^+\text{ electroproduction a positive } u \text{ is required by the signs of the target asymmetries.}\)
important to realize that the GPDs are probed by the HERMES, COMPASS and HERA data only at $x$ less than about 0.6. One may therefore change to some extent the GPDs for large $x$ without changing the results for cross sections and asymmetries in the kinematical region of small skewness. For Jefferson Lab kinematics, on the other hand, such changes of the GPDs may matter.

6 Summary

Recent measurements of spin effects in hard meson electroproduction have been reviewed. The spin effects include separated electroproduction cross sections, SDME and target as well as beam asymmetries. The data clearly show that a leading-twist calculation of meson electroproduction within the handbag approach is insufficient. They demand higher-twist and/or power corrections which manifest themselves through substantial contributions from $\tau$ to meson transitions.

A most striking effect is the target asymmetry $A_{UT}^{\sin^s}$ in $^+\pi^+$ electroproduction. The interpretation of this effect requires a large contribution from the helicity non-parallel amplitude $M_{0++}$. Within the handbag approach such a contribution is generated by the helicity-parallel or transversity GPDs in combination with a twist-3 pion wave function [18]. This explanation establishes an interesting connection to transversity parton distributions measured in inclusive processes. Further studies of transversity in exclusive reactions are certainly demanded. For instance, data on the asymmetries obtained with a longitudinally polarized beam and with like- or opposite-polarized beam and target would be very helpful in settling this dynamical issue.
Good data on $^0$ electroproduction would also be highly welcome. They would not only allow for an additional test of the twist-3 mechanism but also give the opportunity to verify the model GPDs $H_{1/2}$ and $E_{1/2}$ as used in [18].

One may wonder whether the twist-3 mechanism does not apply to vector-meson electroproduction as well and offers an explanation of the experimentally observed $V_L$ transitions mentioned in Sect. 2. It however turned out that this effect is too small in comparison to the data, for instance, $r_0^{05}$. The reason is that instead of the parameter $r_0$ the mass of the vector meson sets the scale of the twist-3 effect. This amounts to a reduction by about a factor of three. Further suppression comes from the unfavorable flavor combination of $H_1$ occurring for uncharged vector mesons, e.g., $e_u H_{1/2}$, $e_d H_{3/2}$ for $^0$ production instead of $H_{1/2}$, $H_{3/2}$ for $^+$ production. Perhaps the gluonic GPD $H_{3/2}$ may lead to a larger effect.

Acknowledgements This work is supported in part by the Heisenberg-Landau program and by the BM BF, contract number 06RY 258.

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