Abstract

In this talk various spin effects in hard exclusive electroproduction of mesons are briefly reviewed and the data discussed in the light of recent theoretical calculations within the framework of the handbag approach. For $^+\,e\,l\,e\,c\,t\,r\,o\,p\,r\,o\,d\,u\,c\,t\,i\,o\,n$ it is shown that there is a strong contribution from $^T\,\alpha\,t\,r\,a\,n\,s\,i\,t\,i\,o\,n\,s$ which can be modeled by the transversity GPD $H_T$ accompanied by the twist-3 meson wave function.

1 Introduction

Electroproduction of mesons allows for the measurement of many spin effects. For instance, using a longitudinally or transversely polarized target and/or a longitudinally polarized beam various spin asymmetries can be measured. The investigation of spin-dependent observables allows for a deep insight in the underlying dynamics. 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 providing 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 [1,2]. It has also been shown that the transitions from a longitudinally polarized photon to a likewise polarized vector meson or a pseudoscalar one, $^L\alpha\,V_L(P)$, dominate at large $Q^2$. Other photon-meson transitions are suppressed by inverse powers of the hard scale.

Here, in this article a variant of the handbag approach is utilized for the interpretation of the data in which the subprocess amplitudes are calculated within the modified perturbative approach [3], and the GPDs are constructed from reggeized double distributions [4,5]. In the modified perturbative approach the quark transverse momenta are 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 $k_t^2 = (1 - x)\,Q^2$ are assumed with transverse size parameters fitted to experiment [6]. The variable $x$ denotes the fraction of the meson’s momentum the quark entering the meson carries. In a series of papers [7] it has been shown that with the proposed handbag approach the data on the cross sections and spin density matrix elements (SDM Es) for $^0\,e\,l\,e\,c\,t\,r\,o\,p\,r\,o\,d\,u\,c\,t\,i\,o\,n$ are well fitted in the kinematical range of $Q^2 > 3\,\text{GeV}^2$, $W > 5\,\text{GeV}$ (i.e. for small values of skewness $x_{hj} = 2 < 0.1$) and
for the squared invariant momentum transfer $t^0 = t + t_0 < 0.6$ GeV$^2$ where $t_0$ is the value of $t$ for forward scattering. This analysis uses the GPD $H$ for quarks and gluons quite well. The other GPDs do practically not contribute to the cross sections and SDMESs at small skewness.

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 the role of target spin asymmetries in meson electroproduction is examined. Sect. 3 is devoted to a discussion of the the target spin asymmetries in pion electroproduction and Sect. 4 to those for vector mesons and the GPD $E$. Finally, in Sect. 5, a summary is presented.

2 Target asymmetries

The electroproduction cross sections measured with a transversely or longitudinally polarized target consist of some term $s$, each can be projected out by a sine or cosine momentum where $\gamma$ is a linear combination of $\gamma$, the azimuthal angle between the lepton and the hadron plane and $s$, the orientation of the target spin vector [8]. In Tab. 1 the features of some of these moments are displayed. As the dominant interference terms reveal the target asymmetries provide detailed information on the $p \gamma M B$ 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 sine moment which has been measured by the HERMES collaboration for $^+\gamma$ electroproduction [9]. The data on this moment, shown in Fig. 2, exhibit a mild $t$-dependence and do not show any indication for a turnover towards zero for $t^0 > 0.4$. Inspection of Tab. 1 reveals that this behavior of $A_{UT}^{s\gamma} \sin s$ 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-physical ones and are therefore not forced to vanish in the forward direction by angular momentum conservation. Thus, we see that for pion electroproduction there are strong contributions from $\gamma$ transitions. The underlying dynamical mechanism for such transitions will be discussed in Sect. 3.

For $^0\gamma$ production the sine moment has been measured by HERMES [10] and COMPASS [11]; the latter data being still preliminary. The HERMES data are shown in Fig. 3. In the handbag approach $A_{UT}^{s\gamma} \sin s$ can also be expressed by an interference term of the convolutions of the GPDs $H$ and $E$ with hard scattering kernels $A_{UT}^{s\gamma} \sin s = \text{Im} \langle H E_H I i \rangle$ (1)

instead of the helicity amplitudes. Given that $H$ is known from the analysis of the $^0\gamma$ and $^+\gamma$ cross sections and SDMESs, $A_{UT}$ provides information on $E$ [12]. In order to calculate this
The angle \( \delta \) describes the rotation in the lepton plane from the direction of the incoming lepton to the virtual photon one; \( \pi \) is very small.

### 3 Target spin asymmetries in \( \pi^+ \) production

In Ref. [13] electroproduction of positively charged pions has been investigated in the same handbag approach as applied to vector meson production [7]. To the asymptotically leading amplitudes for longitudinally polarized photons the GPDs \( \mathbb{P} \) and \( \mathbb{P}^\prime \) contribute in the isovector combination

\[
\mathbb{P}^{(3)} = \mathbb{P}^u_v \quad \mathbb{P}^d_v ;
\]

instead of \( H \) and \( E \) for vector mesons. In deviation to work performed in collinear approximation the full electron magnetic form factor of the pion as measured by the \( \pi^+ \) collaboration [14] is naturally taken into account (see also the recent work by Bechler and Mueller [15]). The GPDs \( \mathbb{P}^u \) and \( \mathbb{P}^d \) are again constructed with the help of double distributions with the forward limit of \( \mathbb{P}^u \) being the polarized parton distributions while that of \( \mathbb{P}^d \) is parameterized analogously to the familiar parton distributions

\[
e^u = e^d = N_{e}x^{0.18}(1-x)^5 ;
\]

with \( N_{e} \) fitted to experiment.

As mentioned in Sect. 2 experiment requires a strong contribution from the helicity-\( \mathbb{P}^u \) amplitude \( M_{0,\mu^+} \), 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-\( \mathbb{P} \) GPDs \( H \) and \( E \); \( \ldots \) one obtains a contribution to \( M_{0,\mu^+} \) that vanishes \( t^0 \) if it is non-zero at all. However, there is a second set of GPDs, the helicity-\( \mathbb{P}^d \) or transversity

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**Table 1. Features of the asymmetries for transversally and longitudinally polarized targets.**

| Observable | Dominant | Amplitude | Low \( t^0 \) Behavior |
|------------|----------|-----------|------------------------|
| \( A_{UL}^{\sin(\mu)} \) | LT | \( \text{Im } M_{0,\mu^+} \) | \( / \mathbb{P}^d / t^0 \) |
| \( A_{UL}^{\sin(\mu)} \) | LT | \( \text{Im } M_{0,\mu^+} \) | \( \text{const.} \) |
| \( \mathbb{A}_{UL}^{\sin(\mu)} \) | LT | \( \text{Im } M_{0,\mu^+} \) | \( / t^0 \) |
| \( \mathbb{A}_{UL}^{\sin(\mu)} \) | LT | \( \text{Im } M_{0,\mu^+} \) | \( \text{const.} \) |
| \( \mathbb{A}_{UL}^{\sin(\mu)} \) | LT | \( \text{Im } M_{0,\mu^+} \) | \( \text{const.} \) |

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1 As compared to other work \( \mathbb{P}^d \) contains only the non-pole contribution.
ones $H_T; E_T; \cdots \ [16,17]$. A s inspection of Fig. 1 where the helicity configuration of the process is specified, reveals the proton-parton vertex is of non- ip 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 $M_{0, -+}$ is so of twist-3 order. This mechanism has been first proposed in Ref. [18] for photo- and electroproduction of mesons where the forward limit $H_T$ is considered as the large scale $[19]$.

In Ref. [13] the twist-3 pion wave function is taken from Ref. [20] with the three-particle Fock component neglected. This wave function, still containing a pseudoscalar and a tensor component, is proportional to the parameter $m^2 = (m_u + m_d)' 2 \mathrm{GeV}$ at the scale of $2 \mathrm{GeV}$ as a consequence of the divergency 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 $H_T$ is the transversity distribution $a(x)$ which has been determined in [21] 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 $H_T$ have been modeled in a manner analogously to that of the other GPDs (see Eq. (5))

It is shown in Ref. [13] that with the described model GPDs, the $+\pi$ cross sections

\footnote{While the relative signs of $u$ and $d$ is fixed in the analysis performed in Ref. [21] the absolute sign is not. Here, in $+\pi$ electroproduction a positive $u$ which goes along with a negative $d$ is required by the signs of the target asymmetries.}
as measured by HERMES [22] are nicely fitted as well as the transverse target asymmetries [9]. This can be seen for \( A_{UT}^{\sin} \) from Fig. 4. Also the \( \sin(\phi) \) moment which is dominantly fed by an interference term of the two amplitudes for longitudinally polarized photons (see Tab. 1), is fairly well described as is obvious from Fig. 4. Very interesting is also the asymmetry for a longitudinally polarized target which is dominated by the interference term between \( M_0 \mu^+ \) which comprises the twist-3 effect, and the nucleon helicity-1 amplitude for \( L' \) transition, \( M_0 \rho^+ \). Results for \( A_{UL}^{\sin} \) are displayed in Fig. 5 and compared to the data [23]. Also in this case good agreement between theory and experiment is to be noticed. In both the cases, \( A_{UT}^{\sin} \) and \( A_{UL}^{\sin} \), the prominent role of the twist-3 mechanism is clearly visible. Switching it on one obtains the dashed lines which are significantly at variance with experiment. In this case the transverse amplitudes are only fed by the pion-pole contribution. The other transverse target asymmetries quoted in Tab. 1 are predicted to be small in absolute value which is in agreement with experiment [9]. Thus, in summary, there is strong evidence for transversity in hard exclusive pion electroproduction. It can be regarded as a non-trivial result that the transversity distributions determined from data on inclusive pion production 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 \( M_0 \mu^+ \) can also obtained from the asymmetries measured with a longitudinally polarized beam or with a longitudinally polarized beam and target. The first asymmetry, \( A_{UT}^{\sin} \), is dominated by the same interference term as \( A_{UL}^{\sin} \) but diluted by the factor \( (1 - n) = (1 + n) \). Also the second asymmetry, \( A_{LL}^{\cos} \), is dominated by the interference term \( M_0 \mu^+ M_0 \rho^+ \). However, in this case its real part occurs. For HERMES kinematics it is predicted to be rather large and positive at small \( t^0 \) and changes sign at \( t^0 \leq 0.4 \text{ GeV}^2 \) [13]. A measurement of these asymmetries would constitute a serious check of the twist-3 effect.
Although the main purpose of the work presented in Ref. [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 [14]. With the GPDs $F^p_F$, $F^E_E$, 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 Refs. [7, 12, 13] is designed for small skewness. At larger values of it the parametrizations of the GPDs are perhaps to simple and many require improvements. It is also inportant 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 the GPDs at large $x$ to some extent without changing the results for cross sections and asymmetries in the kinematic region of small skewness. For Jefferson Lab kinematics, on the other hand, such changes of the GPDs may matter.

## 4 The GPD E

In Ref. [24] 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

$$F_2^{p(n)} = \int_0^1 dx \, e_{u_{(1)}} E^u_{\perp}(x; t = 0) + e_{d_{(1)}} E^d_{\perp}(x; t = 0);$$

(4)

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

$$E^a_{\perp}(x; 0; t) = e^a_{\perp}(x) \exp t(0_{\perp} \ln(1-x) + h^a_{\perp});$$

(5)

is made in a small $t$ approximation [24]. The forward limit of $E$ is parameterized analogously to that of the usual parton distributions:

$$e^a_{\perp} = N_a x^{v(0)} (1-x)^{d_{\perp}};$$

(6)

where $v(0)$ ($'0\times 48$) is the intercept of a standard Regge trajectory and $0_{\perp}$ in Eq. (5) its slope. The normalization $N_a$ is fixed from the momentum

$$Z^a = \int dx E^a_{\perp}(x; t = 0);$$

(7)

where $a$ is the contribution of flavor-$a$ quarks to the anomalous magnetic moments of the proton and neutron ($u = 1.07$, $d = 2.03$). A best fit to the data on the nucleon form factors provides the powers $u = 4$ and $d_{\perp} = 5.6$. However, other powers are not excluded in the 2004 analysis presented in [24]; the most extreme set of powers, still in agreement with the form factor data, is $u = 10$ and $d_{\perp} = 5$. The analysis performed in [24] should be repeated since new form factor data are available from Jefferson Lab, e.g. $G^d_{1}$ and $G^u_{1}$ are now measured up to $Q^2 = 3.5$ and $50$ GeV$^2$, respectively [25, 26]. These new data seem to favor $u < d_{\perp}$. The zero-skewness GPDs $E_{\perp}$ are used as input to a double distribution from which the valence quark GPDs for non-zero skewness are constructed [12].
In [12], following Diehl and Kugler [27], E, for gluons and sea quarks has been estimated from positivity bounds and a sum rule for the second moments of E which follows from a combination of Ji’s sum rule [28] and the momentum sum rule of deep inelastic lepton-nucleon scattering. It turned out that the valence quark contribution to that sum rule is very small, in particular if \( v < d \), with the consequence of an almost exact cancellation of the gluon and sea quark moments. The GPDs \( E^g \) and \( E^{sea} \) are parametrized analogously to \( E_v \), see Eqs. (5), (6). The normalization of \( E^{sea} \) is fixed by assuming that an appropriate positivity bound (see Refs. [29,30]) is saturated while that of \( E^g \) is determined from the sum rule. Several variants of E have been exploited in [12] in a calculation of \( A^{\sin (\Lambda)}_{UT} \) within the handbag approach. The results for a few variants are compared to the HERMES data on \( \pi^0 \) production [10] in Fig. 3. Agreement between theory and experiment is to be noted. Similar agreement is obtained for the preliminary COMPASS data [11]. Combining both the experiments a negative value of \( A^{\sin (\Lambda)}_{UT} \) for \( \pi^0 \) production is favored in agreement with the theoretical results obtained in [12], only the extreme variant \( u = 10 \) and \( d = 5 \) (dashed-dotted line in Fig. 3) seem to be ruled out. In [12] predictions for \( J^+ \), \( K^0 \) and \( \eta \) productions are also given. Their comparison with forthcoming data from HERMES and COMPASS may lead to a fair determination of 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

\[
hJ^u_i = \frac{1}{2} q^u_{i0} + e^u_{20} ; \quad hJ^d_i = \frac{1}{2} q^d_{i0} + e^d_{20} ;
\]

From a variant with \( u = 4 \), \( d = 5 \) and neglected \( E^g \) and \( E^{sea} \) (solid line in Fig. 3) for instance one obtains

\[
hJ^u_i = 0.250 ; \quad hJ^d_i = 0.020 ; \quad hJ^g_i = 0.015 ; \quad hJ^{g'}_i = 0.214 ;
\]

at the scale of 4 GeV\(^2\). The angular momenta sum up to \( l = 2 \), the spin of the proton. A very characteristic stable pattern is obtained in Ref. [12]: For all variants investigated, \( J^u \) and \( J^g \) are large while the other two angular momenta are very small. The angular momenta of the valence quarks are \( hJ^u_i = 0.222 \) and \( hJ^d_i = 0.015 \). These values are identical to the results quoted in Ref. [24] (for variant 1). They are in agreement with a recent lattice result [31].

5 Sum m ary

Recent measurements of single spin asymmetries in hard meson electroproduction has been reviewed. The data clearly show that a leading-twist calculation of meson electroproduction within the handbag approach is sufficient. They demand and higher-twist and/or power corrections which manifest themselves through substantial contributions from \( \gamma^V\gamma^P \) transitions.

A most striking effect is the target asymmetry \( A^{\sin (\Lambda)}_{UT} \) in \( \gamma^V\gamma^P \) electroproduction. The interpretation of this effect requires a large contribution from the helicity non-\( \gamma \) amplitude \( M_{0,+,+} \). Within the handbag approach such a contribution is generated by the helicity-\( \gamma \) or transversity GPDs in combination with a twist-3 pion wave function [13].
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 likewise 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 GPD $s\bar{s}$ and $g$ as used in Ref. [13].

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 $^T_V$ $V_L$ transitions seen for instance in the SDM E $r_{00}^{05}$. It however turned out that this effect is too small in comparison to the data. The reason is that instead of the parameter 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 $H_T$ occurring for uncharged vector mesons, e.g. $e_\gamma H_T^u - e_d H_T^d$ for $^0$ production instead of $H_T^u - H_T^d$ for $^+/-$ production. Perhaps the gluonic GPD $H_T^g$ may lead to a larger effect.

From the small value of the ratio of the longitudinal and transverse electroproduction cross sections for $^0$ and $^+$ mesons it also clear that the transitions from transversely polarized virtual photons to like- and unlike- polarized vector mesons are large too. In the handbag approach advocated in [7] such transitions are also well described. The infrared divergence occurring in collinear approximation is regularized by the quark transverse momentum in the modified perturbative approach.

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