THE HANDBAG MECHANISM IN WIDE-ANGLE EXCLUSIVE REACTIONS

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The handbag mechanism for wide-angle exclusive scattering reactions is discussed and compared with other theoretical approaches. Its application to Compton scattering, meson photoproduction and two-photon annihilations into pairs of hadrons is reviewed in some detail.

1. Introduction

Recently a new approach to wide-angle Compton scattering of protons has been proposed\(^1,^2\) where, for Mandelstam variables \(s; t; u\) that are large as compared to a typical hadronic scale, \(^2\) of the order of \(1 \text{ GeV}^2\), the process amplitudes factorize into a hard parton-level subprocess, Compton scattering of quarks, and in soft form factors which represent \(1-x\) mom ents of generalized parton distributions (GPDs) and encode the soft physics (see Fig. 1). Subsequently it has been realized that this so-called handbag mechanism also applies to a number of other wide-angle reactions such as virtual Compton scattering\(^3\) (provided the photon virtuality, \(Q^2\) is smaller than \(t\)), meson photoproduction\(^4\) or two-photon annihilations into pairs of mesons\(^5\) or baryons\(^6\). It should be noted that the handbag mechanism bears resemblance to the treatment of inelastic Compton scattering advocated for by Bjorken and Paschos\(^7\) long time ago.

There are other mechanisms which also contribute to wide-angle scattering besides the handbag which is characterized by one active parton, i.e., one parton from each hadron participates in the hard subprocess (e.g. \(q! \ q\) in Compton scattering) while all others are spectators. On the one hand, there are the so-called cat’s ears graphs (see Fig. 1) with two active partons participating in the subprocess (e.g. \(qq! \ qq\)). It can be shown however that in these graphs either a large parton virtuality or a large parton transverse momentum occurs. This forces the exchange of at least one hard gluon. Hence, the cat’s ears contribution is expected to
be suppressed as compared to the handbag one. The next class of graphs are characterized by three active quarks (e.g. \( \bar{q}qq \)) and, obviously, require the exchange of at least two hard gluons. For, say, Compton scattering on protons, the so-called leading-twist contribution (see Fig. 1) for which all valence quarks participate in the hard process, belong to this class\(^8\). The leading-twist factorization is given by a convolution of the hard subprocess, e.g. \( \bar{q}qq \) in Compton scattering on protons and distribution amplitudes encoding the soft physics. This contribution is expected to dominate for asymptotically large momentum transfer \(^a\). From ally, the handbag contribution is a power correction to the leading-twist one.

Since hadrons are not just made o their valence quarks one go on and consider four active partons and so forth. The series generated that way, bears resemblance to an expansion in terms of \(n\)-body operators used in many-body theory. In principle, all the different contributions have to be added coherently. In practice, however, this is a difficult, currently almost impossible task \(^b\) since each contribution has its own associated soft hadronic matrix element which, as yet, cannot be calculated from QCD and is often even phenomenologically unknown. We have to learn from experiment, presently characterized by momentum transfers of the order of \(10 \text{ GeV}^2\), whether one of the mentioned mechanisms is dominant or whether

\(^{a}\)Interestingly, for the pion-photon transition form factor the handbag and the leading-twist contributions fall together.

\(^{b}\)An exception is the pion’s electromagnetic form factors where this has been attempted by several groups, see for instance \(^9\).
the coherent sum of some or all topologies is actually needed.

The handbag mechanism in real Compton scattering is reviewed in some detail in Sect. 2. The large t behaviour of the GPDs and their associated form factors is discussed in Sect. 3 and predictions for Compton scattering are given. A few results for wide-angle meson photoproduction and two-photon annihilations into pairs of hadrons are presented in Sect. 4 and 5, respectively. The paper ends with a summary (Sect. 6).

2. Wide-angle Compton scattering

For Mandelstam variables \( s, t \) and \( u \) that are large as compared to a typical hadronic scale \( ^2 \) where being of order 1 GeV, it can be shown that the handbag diagram shown in Fig. 1, is of relevance in wide-angle Compton scattering. To see this it is of advantage to work in a symmetric frame which is a c.m.s rotated in such a way that the momenta of the incoming \( (p) \) and outgoing \( (p^0) \) proton momenta have the same light-cone plus components. In this frame the skewness defined as

\[
\epsilon = \frac{(p - p^0)^+}{(p + p^0)^+};
\]

is zero. The bubble in the handbag is viewed as a sum over all possible parton configurations as in deep inelastic lepton-proton scattering. The crucial assumptions in the handbag approach are that of restricted parton virtualities, \( k_i^2 < \frac{1}{2} \), and of intrinsic transverse parton momenta, \( k_i^T \), defined with respect to their parent hadron’s momentum, which satisfy

\[
k_i^T = x_i < \frac{1}{2}, \text{where } x_i \text{ is the momentum fraction parton } i \text{ carries.}
\]

One can then show \( ^2 \) that the subprocess Mandelstam variables \( \hat{s} \) and \( \hat{u} \) are the same as the ones for the full process, Compton scattering on protons, up to corrections of order \( ^2 \): \( t \):

\[
\hat{s} = (k_j + q)^2, \quad (p + q)^2 = s; \quad \hat{u} = (k_j \cdot q)^2, \quad (p \cdot q)^2 = u ;
\]

The active partons, i.e. the ones to which the photons couple, are approximately on-shell, move collinear with their parent hadrons and carry a momentum fraction close to unity, \( x_j; x_j^0 \), 1. Thus, like in deep virtual Compton scattering, the physical situation is that of a hard parton-level subprocess, \( q! \rightarrow q \), and a soft emission and reabsorption of quarks from the proton. The light-cone helicity amplitudes \( ^{10} \) for wide-angle Compton scattering then read

\[
M \rightarrow (s; t) = \frac{e^2}{2} \left[ T \rightarrow (s; t) (R_V(t) + R_A(t)) + T \rightarrow (s; t) (R_V(t) - R_A(t)) \right];
\]

\[
(3)
\]
Figure 2. Sample LO (a) and NLO (b-e) pQCD Feynman graphs for the partonic subprocess, $q' \rightarrow q$, in the handbag mechanism.

$$M_{i_{+ j_{+}}}^{0_{+}} (s; t) = \frac{e^2}{2} \frac{p}{2m} [T_{i_{+ j_{+}}}^{0_{+}} (s; t) + T_{i_{+ j_{+}}}^{0_{+}} (s; t) + R^2 (t) + A^2 (t)] R^2 (t);$$

where $0_{+}$ denote the helicities of the incoming and outgoing photons, respectively. The helicities of the protons in $M$ and of the quarks in the hard scattering amplitude $T$ are labeled by their signs. $m$ denotes the mass of the proton. The form factors $R_{i}$ represent the matrix elements of GPDs at zero skewness. This representation which requires the dominance of the plus components of the proton matrix elements, is a non-trivial feature given that, in contrast to deep inelastic lepton-nucleon and deep virtual Compton scattering, not only the plus components of the proton matrix elements but also their minus and transverse components are large here. The hard scattering has been calculated to next-to-leading order (NLO) perturbative QCD, see Fig. 2. It turned out that the NLO amplitudes are ultraviolet regular but those amplitudes which are non-zero to LO, are infrared divergent. As usual the infrared divergent pieces are interpreted as non-perturbative physics and absorbed into the soft form factors, $R_{i}$. Thus, factorization of the wide-angle Compton amplitudes within the handbag approach is justified to (at least) NLO. To this order the gluonic subprocess, $g' \rightarrow g$, has to be taken into account as well which goes along with corresponding gluonic GPDs and their associated form factors.

The handbag amplitudes (3) lead to the following result for the Compton cross section

$$\frac{1}{2} \frac{d}{dt} \frac{1}{2} R^2 (t) (1 + \frac{2}{s}) + R^2 (t)$$

$$\frac{2}{s^2 + u^2} R^2 (t) (1 + \frac{2}{s}) \ R^2 (t) + O (s)$$

(4)
where \( d^5 = d \tau \) is the Klein-Nishina cross section for Compton scattering of massless, point-like spin-1/2 particles of charge unity. The parameter \( \tau \) is defined as

\[
\tau = \frac{p \cdot R_T}{2m R_V}.
\]

Another interesting observable in Compton scattering is the helicity correlation, \( A_{LL} \), between the initial state photon and proton or, equivalently, the helicity transfer, \( K_{LL} \), from the incoming photon to the outgoing proton. In the handbag approach one obtains

\[
A_{LL} = K_{LL} \left( \frac{s^2}{s^2 + u^2} \frac{R_A}{R_V} \right) + O(\tau; z);
\]

where the factor in front of the form factors is the corresponding observable for \( q!q \). The result (6) is a robust prediction of the handbag mechanism, the magnitude of the subprocess helicity correlation is only diluted somewhat by the ratio of the form factors \( R_A \) and \( R_V \).

3. The large-\( t \) behaviour of GPDs

In order to make actual predictions for Compton scattering a model for the form factors or rather for the underlying GPDs is required. A first attempt to parametrize the GPDs \( H^a \) and \( \Phi^a \) at zero skewness is

\[
H^a(x;0;t) = \exp a^2 t \frac{1}{2x} q_a(x); \]
\[
\Phi^a(x;0;t) = \exp a^2 t \frac{1}{2x} q_a(x); \]

(7)

where \( q(x) \) and \( q_a(x) \) are the usual unpolarized and polarized parton distributions in the proton. The transverse size of the proton, \( a \), is the only free parameter and even it is restricted to the range of about 0.8 to 1.2 GeV. Note that a essentially refers to the lowest Fock states of the proton which, as phenomenological experience tells us, are rather compact. The model (7) is designed for large \( t \). Hence, forced by the Gaussian in (7), large \( x \) is implied, too. Despite of this the normalizations of the model GPDs at \( t = 0 \) are correct. Since the phenomenological parton distributions, see e.g. 13, suffer from large uncertainties at large \( x \), the GPDs (7) have been improved in 2 by using overlaps of light-cone wave functions for \( x > 0.5 \) instead of the GRV parametrization 13.
With the model GPDs (7) at hand one can evaluate the various form factors by taking appropriate moments. For the Dirac and the axial form factor one has

\[ F_1 = \int \frac{Z_1}{1} e_q^2 \text{d}x H_q(x;0;t), \quad F_A = \int \frac{Z_1}{1} \frac{h}{1} e_q^2 \text{d}x \gamma^u(x;0;t) \gamma^d(x;0;t); \] (8)

while the Compton form factors read

\[ R_V = \int \frac{Z_1}{1} e_q^2 \text{d}x H_q(x;0;t), \quad R_A = \int \frac{Z_1}{1} \frac{\text{sign}(x)}{1} e_q^2 \text{d}x \gamma^q(x;0;t); \] (9)

Results for the nucleon form factors are shown in Fig. 3. Obviously, as the comparison with experiment reveals, the model GPDs work quite well although the predictions for the Dirac and the axial form factors overshoot the data by about 20–30% for t around 5 GeV². An effect of similar size can be expected for the Compton form factors for which predictions are shown in Fig. 4. The scaled form factors \( t^2 F_{1,3} \) and \( t^2 R_1 \) exhibit broad maxima which manifest dimensional counting in a range of t from, say, 5 to about 20 GeV². The position of the maximum of any of the scaled form factors is approximately located at

\[ t \approx 4a^2 \frac{1}{x} \int \text{d}x \frac{1}{F(R)}: \] (10)

The mildly t-dependent mean value \( h(1-x) = \frac{1}{2} \) comes out around 1=2. A change of a in moves the position of the maximum of the scaled form factors but leaves their magnitudes essentially unchanged. It is tempting to assume that form factors of the type discussed here also control other wide-angle reactions as, for instance, elastic hadron-hadron scattering. The experimentally observed approximate scaling behaviour of these cross sections is then attributed to the broad maximum of the scaled form factors. I.e., the scaling behaviour observed for momentum transfers of the order of 10 GeV², re ects rather the transverse size of the hadrons (10) than a property of the leading-twist contribution.

The Pauli form factor \( F_2 \) and its Compton analogue \( R_T \) contribute to proton helicity matrix elements and are related to the GPD E analogously to (8). This connection suggests that, at least for not too small values of t, \( R_T = R_V \) roughly behaves as \( F_2 = F_1 \). Thus, the recent JLab
Figure 3. The Dirac form factor of the proton (left) and the axial vector form factor (right) scaled by $t^2$, are plotted vs. $t$. Data are taken from Ref.\textsuperscript{14}. The band represents a dipole fit to the neutrino data\textsuperscript{15}. The theoretical results are taken from \textsuperscript{2}.

Data\textsuperscript{17} on $F_2$ indicate a behaviour as $R_T = R_V / m = P_t / t$. The form factor $R_T$ therefore contributes to the same order in $P_t / t$ as the other ones, see (4). Predictions for Compton observables are given for two different scenarios\textsuperscript{5}. Both $R_T$ and $s$ corrections are omitted in scenario B but taken into account in A where the ratio $\gamma$ is assumed to have a value of 0.37 as estimated from the JLab form factor data\textsuperscript{17}.

Employing the modelGPDs and the corresponding form factors, various Compton observables can be calculated\textsuperscript{2,3,11}. The predictions for the differential cross section are in fair agreement with the Cornell data\textsuperscript{20}. Due to the broad maxima in the scaled form factors exhibit, the handbag mechanism approximately predicts a $s^2$-scaling behaviour at fixed c.m. scattering angle according to dimensional counting. Closer inspection of the handbag predictions however reveals that the effective power of $s$ depends on the scattering angle and on the range of energy used in the determination of the power. The JLab E99-114 collaboration\textsuperscript{21} will provide accurate cross section data soon which will allow for a crucial examination of the handbag mechanism and may necessitate an improvement of the modelGPDs (7).

Predictions for $A_{LL} = K_{LL}$ are shown in Fig. 4. The JLab E99-114 collaboration\textsuperscript{21} has presented a new measurement of $K_{LL}$ at a c.m. scattering angle of 120° and a photon energy of 3.23 GeV. This is still preliminary data point in fair agreement with the predictions from the handbag given the small energy at which they are available. The kinematic requirement of the handbag mechanism $s; t; u$ \textsuperscript{2} is not well satisfied and there-

\textsuperscript{5}There is a discrepancy between the SLAC data\textsuperscript{18} on $F_2/F_1$, obtained by Rosenbluth separation, and the JLab ones. According to Ref.\textsuperscript{19}, part of the discrepancy can be assigned to two-photon exchange which affects the Rosenbluth data\textsuperscript{18}.
Figure 4. Predictions for the Compton form factors (left) and for the helicity correlations $A_{LL} = K_{LL}$ (right). NLO corrections and the tensor form factor are taken into account (scenario A), in scenario B they are neglected.

For one has to be aware of large dynamical and kinematical corrections (proton mass effects have been investigated in Ref. 22).

In the introduction I mentioned the leading-twist factorization scheme 8 for which all valence quarks of the involved hadrons participate in the hard scattering and not just a single one. The leading-twist calculations, e.g. 23, reveal difficulties in getting the size of the Compton cross section correctly, the numerical results are way below experiment. There is growing evidence 24 9 that the proton’s leading-twist distribution amplitude is close to the asymptotic form / $x_1x_2x_3$. Using such a distribution amplitude in a leading-twist calculation of the Compton cross section, the result turns out to be too small by a factor of about 10 3. Moreover, the leading-twist approach 23 leads to a negative value for $K_{LL}$ at angles larger than 90° in conflict with the JLab result 21. Thus, we are forced to conclude that wide-angle Compton scattering at energies available at JLab is not dominated by the leading-twist contribution.

The handbag approach to real Compton scattering can straightforwardly be extended to virtual Compton scattering 3 provided $Q^2 = t < 1$. Recently, the NLO corrections to the hard subprocess have been calculated for virtual Compton scattering 26.

4. Meson photoproduction

Photo- and electroproduction of mesons have also been discussed within the handbag approach 4 using, as in deep virtual electroproduction 27, a
one-gluon exchange mechanism for the generation of the meson. As it turns out the one-gluon exchange contribution falls with the normalization of the photoproduction cross section by order of magnitude. Either vector meson dominance contributions are still large or the generation of the meson by the exchange of a hard gluon underestimates the handbag contribution. Since the same Feynman graphs contribute here as in the case of the pion's electromagnetic form factor the failure of the one-gluon exchange contribution is perhaps not a surprise.\footnote{9}

One may investigate the handbag contribution to photoproduction of pseudoscalar mesons ($\pi$) in a more general way\footnote{28} by writing down a covariant decomposition of the subprocess $q!Pq$ in terms of four covariants which take care of the helicity dependence in the subprocess, and four invariant functions which encode the dynamics. Assuming dominance of quark helicity non-\$^{\pm}$ one ends, for instance, that the helicity correlation $A_{LL}$ for the subprocess $q!Pq$ is the same as for $q!q$, see (6). $A_{LL}$ for the full process is similar to the result (6) for Compton scattering, too. Another interesting result is the ratio of the cross sections for photoproduction of $^+$ and $^-$. The ratio is approximately given by

$$\frac{d(n!p)}{d(p!n)} = \frac{e_u^2 s_m^2}{e_v^2 s_m^2}.$$ \hspace{1cm} (11)

The form factors which, for a given flavor, are the same as those appearing in Compton scattering, cancel in the ratio. The prediction (11) is in fair agreement with a recent JLab measurement\footnote{30} which, at $90^\circ$, provides values of 1.73 $\pm$ 0.15 and 1.70 $\pm$ 0.20 for the ratio at beam energies of 4.158 and 5.536 GeV, respectively. This result supports the handbag mechanism with dominant quark helicity non-$^{\pm}$.

5. Two-photon annihilations into pairs of hadrons

The arguments for handbag factorization hold as well for two-photon annihilations into pairs of hadrons as has recently been shown in Ref.\footnote{5} (see also Ref.\footnote{6}). The cross section for the production of a pair of pseudoscalar mesons reads

$$\frac{d}{ds} (\gamma \gamma \to M\bar{M}) = \frac{8 \alpha^2}{s^2 \sin^4 \theta} R_\alpha \Pi(s)^2,$$ \hspace{1cm} (12)

while for baryon pairs it is given by

$$\frac{d}{ds} (\gamma \gamma \to BB) = \frac{4 \alpha^2 n}{s^2 \sin^2 \theta} R_b^B(s) + R_f^B(s)^2$$

$$+ \cos^2 \theta R_v^B(s)^2 + \frac{s}{4m^2} R_p^B(s)^2.$$ \hspace{1cm} (13)
In analogy to Eq. (9) the form factors represent moments of two-hadron distribution amplitudes, \( M \), which are timelike versions of GPDs. In the case of pion pair production one has for instance

\[
R^2(s) = \int_0^1 \frac{dz}{2} (2z - 1) \left( \frac{1}{2} \sum_{q} e_q^2 R^3_q(s) \right); \quad R^3_q(s) = \frac{1}{2} \int_0^1 dz (2z - 1) \left( \frac{1}{2} \sum_{q} e_q^2 R^3_q(s) \right). \tag{14}
\]

The angle dependencies of the cross sections which are (almost) independent of the form factors, are in fair agreement with experiment, see Fig. 5. The form factors have not been modelled in Refs. but rather extracted ('measured') from the experimental cross section. The form factor \( R^2 \) obtained that way, is shown in Fig. 5, too. The average value of the scaled form factor \( sR^2 \) is 0.75 GeV\(^2\). The closeness of this value to that of the scaled timelike electromagnetic form factor of the pion (0.93 0.12 GeV\(^2\)) hints at the internal consistency of the handbag approach.

A characteristic feature of the handbag mechanism in the timelike region is the intermediate \( q\bar{q} \) state in playing the absence of isospin-two components in the final state. A consequence of this property is

\[
\frac{d}{dt} \left( \begin{array}{c} 0 \\ 1 \\ 0 \\ 0 \end{array} \right) = \frac{d}{dt} \left( \begin{array}{c} 1 \\ 2 \end{array} \right); \tag{15}
\]

which is independent of the soft physics input and is, in so far, a robust prediction of the handbag approach. The absence of the isospin-two components combined with avar symmetry allows one to calculate the cross sections for other \( B \bar{B} \) channels using the form factors for \( p\bar{p} \) as the only soft physics input. It is to be stressed that the leading-twist mechanism has again difficulties to account for the size of the cross sections while
the diquark model \(^{32}\) which is a variant of the leading-twist approach in which diquarks are considered as quasielementary constituents of baryons, is in fair agreement with experiment for \( BB \).

6. Summary

I have reviewed the theoretical activities on applications of the handbag mechanism to wide-angle scattering. There are many interesting predictions, some are in fair agreement with experiment, others still awaiting their experimental examination. It seems that the handbag mechanism plays an important role in exclusive scattering for moment transfers of the order of \( 10 \text{ GeV}^2 \). However, before we can draw conclusions more experimental tests are needed. The leading-twist approach, on the other hand, typically provides cross sections which are way below experiment. As is well known, the cross section data for any hard exclusive processes exhibit approximate dimensional counting rule behaviour. Inferring from this fact the dominance of the leading-twist contribution is premature. The handbag mechanism can explain this approximate power law behaviour (and often the magnitude of the cross sections), too. It is attributed to the broad maxima the so-called form factors show and, hence, reicts the transverse size of the lowest Fock states of the involved hadrons.

Finally emphasize that the structure of the handbag amplitude, namely its representation as a product of perturbatively calculable hard scattering amplitudes and t-dependent form factors is the essential result. Refitting the handbag approach necessitates experimental evidence against this factorization.

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