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THE HANDBAG MECHANISM IN WIDE-ANGLE EXCLUSIVE REACTIONS

P. KROLL

Fachbereich Physik, Universität Wuppertal, D-42097 Wuppertal, Germany
E-mail address: kroll@physik.uni-wuppertal.de

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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.

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1. *Introduction*

Recently a new approach to wide-angle Compton scattering off protons has been proposed [1, 2] where, for Mandelstam variables $s, -t, -u$ that are large as compared to a typical hadronic scale, Λ^2 of the order of 1 GeV^2, the process amplitudes factorize into a hard parton-level subprocess, Compton scattering off quarks, and in soft form factors which represent $1/x$ moments 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 photo- and electroproduction [4] or two-photon annihilations into pairs of mesons [5] or baryons [5, 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., $\gamma q \to \gamma q$ 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., $\gamma qq \to \gamma qq$). However, it can be shown that in these graphs either a large

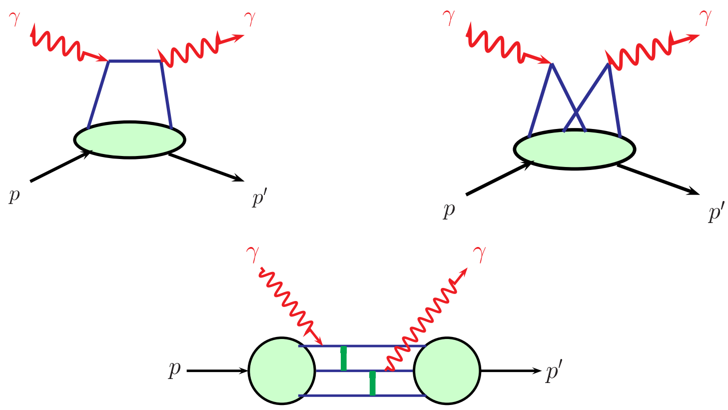

Fig. 1. Handbag diagram for Compton scattering (upper left), cat's ears (upper right), and a leading-twist graph (bottom).

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., $\gamma qqq \to \gamma qqq$) and, obviously, require the exchange of at least two hard gluons. For, say, Compton scattering off 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., $\gamma qqq \to \gamma qqq$ in Compton scattering off protons, and distribution amplitudes encoding the soft physics. This contribution is expected to dominate for asymptotically large momentum transfer[1]. Formally, the handbag contribution is a power correction to the leading-twist one.

Since hadrons are not made just off their valence quarks we 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 different contributions have to be added coherently. However, this is in practice a difficult, currently almost impossible task[2] 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 GeV^2, whether one of the mentioned mechanisms is dominant or the coherent sum of some or all topologies is actually needed.

The handbag mechanism in real Compton scatering 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

[1] Interestingly, for the pion-photon transition form factor the handbag and the leading-twist contributions fall together.

[2] An exception are the pion's electromagnetic form factors where this has been attempted by several groups, see for instance Ref. [9].

pairs of hadrons are presented in Sects. 4 and 5, respectively. The paper ends with a summary (Sect. 6).

2. *Wide-angle Compton scattering*

For Mandelstam variables s, $-t$ and $-u$ large in comparison to a typical hadronic scale Λ^2, where Λ is of the 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 symmetrical frame which is cms rotated in such a way that the momenta of the incoming (p) and outgoing (p') proton have the same light-cone plus components. In this frame the skewness, defined as

$$\xi = \frac{(p-p')^+}{(p+p')^+}\,, \tag{1}$$

is zero. The bubble in the handbag is viewed as a sum over all possible parton configurations as in deep ineleastic lepton-proton scattering. The crucial assumptions in the handbag approach are those of restricted parton virtualities, $k_i^2 < \Lambda^2$, and of intrinsic transverse parton momenta, $\mathbf{k_{\perp i}}$, defined with respect to their parent hadron's momentum, which satisfy $k_{\perp i}^2/x_i < \Lambda^2$, where x_i is the momentum fraction parton i 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 off protons, up to corrections of order Λ^2/t

$$\hat{s} = (k_j+q)^2 \simeq (p+q)^2 = s\,, \quad \hat{u} = (k_j-q')^2 \simeq (p-q')^2 = u\,. \tag{2}$$

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, $x_j, x_j' \simeq 1$. Thus, like in deep virtual Compton scattering, the physical situation is that of a hard parton-level subprocess, $\gamma q \to \gamma q$, and a soft emission and reabsorption of quarks from the proton. The light-cone helicity amplitudes [10] for wide-angle Compton scattering then read

$$\begin{aligned} M_{\mu'+,\,\mu+}(s,t) &= \frac{e^2}{2}\,\big[T_{\mu'+,\,\mu+}(s,t)\,(R_\mathrm{V}(t)+R_\mathrm{A}(t)) \\ &\qquad + T_{\mu'-,\,\mu-}(s,t)\,(R_\mathrm{V}(t)-R_\mathrm{A}(t))\big]\,, \\ M_{\mu'-,\,\mu+}(s,t) &= \frac{e^2}{2}\,\frac{\sqrt{-t}}{2m}\,\big[T_{\mu'+,\,\mu+}(s,t) + T_{\mu'-,\,\mu-}(s,t)\big]\,R_\mathrm{T}(t)\,. \end{aligned} \tag{3}$$

μ, μ' 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 $1/\bar{x}$-moments 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 momenta but also their minus and transverse components are large here. The hard scattering has been calculated to next-to-leading order (NLO) perturbative QCD [11], 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 Comton amplitudes within the handbag approach is justified to (at least) NLO. To this order the gluonic subprocess, $\gamma g \to \gamma g$, has to be taken into account as well, which goes along with corresponding gluonic GPDs and their associated form factors.

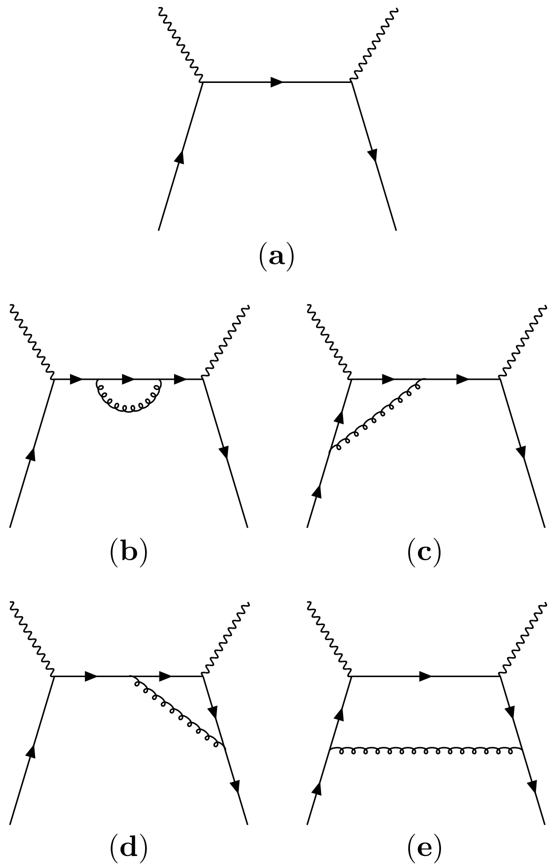

Fig. 2. Sample LO (a) and NLO (b-e) pQCD Feynman graphs for the partonic subprocess, $\gamma q \to \gamma q$, in the handbag mechanism.

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

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}t} &= \frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}t}\left\{\frac{1}{2}\left[R_{\mathrm{V}}^2(t)\,(1+\kappa_{\mathrm{T}}^2)+R_{\mathrm{A}}^2(t)\right]\right.\\ &\qquad\left.-\frac{us}{s^2+u^2}\left[R_{\mathrm{V}}^2(t)\,(1+\kappa_{\mathrm{T}}^2)-R_{\mathrm{A}}^2(t)\right]\right\}+O(\alpha_s)\,, \end{aligned}\tag{4}$$

where $\mathrm{d}\hat{\sigma}/\mathrm{d}t$ is the Klein-Nishina cross section for Compton scattering off massless, point-like spin-1/2 particles of charge unity. The parameter κ_{T} is defined as

$$\kappa_{\mathrm{T}} = \frac{\sqrt{-t}}{2m}\,\frac{R_{\mathrm{T}}}{R_{\mathrm{V}}}\,. \tag{5}$$

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 [3, 11]

$$A_{\mathrm{LL}} = K_{\mathrm{LL}} \simeq \frac{s^2-u^2}{s^2+u^2}\,\frac{R_{\mathrm{A}}}{R_{\mathrm{V}}} + O(\kappa_{\mathrm{T}},\alpha_s)\,, \tag{6}$$

where the factor in front of the form factors is the corresponding observable for $\gamma q \to \gamma q$. 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 parameterize the GPDs H and $\widetilde{H}$ at zero skewness is [1, 2, 11]

$$\begin{aligned} H^a(\bar{x},0;t) &= \exp\left[a^2 t\frac{1-\bar{x}}{2\bar{x}}\right] q_a(\bar{x})\,,\\ \widetilde{H}^a(\bar{x},0;t) &= \exp\left[a^2 t\frac{1-\bar{x}}{2\bar{x}}\right] \Delta q_a(\bar{x})\,, \end{aligned}\tag{7}$$

where $q(\bar{x})$ and $\Delta q(\bar{x})$ are the usual unpolarized and polarized parton distributions in the proton[3]. The transverse size of the proton, a, is the only free parameter and it is restricted to the range of about 0.8 to 1.2 GeV^{-1}. Note that a essentially refers

[3]The parameterization (7) can be motivated by overlaps of light-cone wave functions which have a Gaussian $\boldsymbol{k}_\perp$ dependence [1, 2, 12].

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 $\bar{x}$ 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. Ref. [13], suffer from large uncertainties at large x, the GPDs (7) have been improved in Ref. [2] by using overlaps of light-cone wave functions for $x \gtrsim 0.6$ instead of the GRV parameterization [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

$$F_1 = \sum_q e_q \int_{-1}^{1} \mathrm{d}\bar{x} H^q(\bar{x}, 0; t), \quad F_\mathrm{A} = \int_{-1}^{1} \mathrm{d}\bar{x} \Big[\widetilde{H}^u(\bar{x}, 0; t) - \widetilde{H}^d(\bar{x}, 0; t) \Big], \tag{8}$$

while the Compton form factors read

$$R_\mathrm{V} = \sum_q e_q^2 \int_{-1}^{1} \frac{\mathrm{d}\bar{x}}{\bar{x}} H^q(\bar{x}, 0; t), \quad R_\mathrm{A} = \sum_q e_q^2 \int_{-1}^{1} \frac{\mathrm{d}\bar{x}}{\bar{x}} \mathrm{sign}(\bar{x}) \, \widetilde{H}^q(\bar{x}, 0; t). \tag{9}$$

Results for the nucleon form factors are shown in Fig. 3. Obviously, as the comparison with experiment [14, 15] 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 GeV^2. 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 $t^2 F_{1,\mathrm{A}}$ and $t^2 R_i$ exhibit broad maxima which mimick dimensional counting in a range of $-t$ from, say, 5 to about 20 GeV^2. The position of the maximum of any of the scaled form factors is approximately located at [3]

$$t_0 \simeq -4a^{-2} \left\langle \frac{1 - \bar{x}}{\bar{x}} \right\rangle_{F(R)}^{-1} . \tag{10}$$

The mildly t-dependent mean value $\langle (1 - \bar{x})/\bar{x} \rangle$ comes out around $1/2$. A change of a 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 [3][4]. The experimentally observed approximate scaling behaviour of these cross sections is then attributed to the broad maxima the scaled form factors show. That is, the scaling behaviour observed for momentum transfers of the order of 10 GeV^2 reflects rather the transverse size of the hadrons (10) than a property of the leading-twist contribution[5].

[4] This is similar to the parton scattering model discussed 30 years ago, see e.g. Ref. [16].

[5] The apparent absence of perturbative logs generated by the running of α_s and the evolution of the distribution amplitudes and which are characteristic of a perturbative calculation, is a clear signal against the latter interpretation.

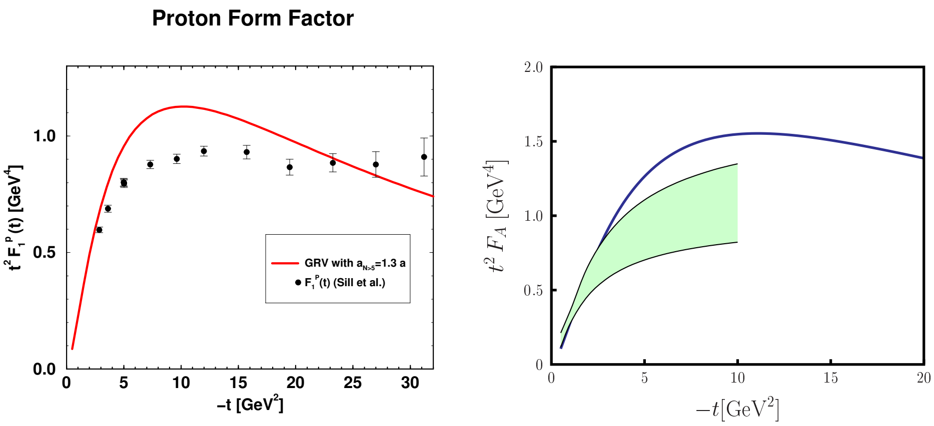

Fig. 3. The Dirac form factor of the proton (left) and the axial vector form factor (right) scaled by t^2, are plotted vs. t. Data are taken from Ref. [14]. The band represents a dipole fit to the neutrino data [15]. The theoretical results are taken from [2].

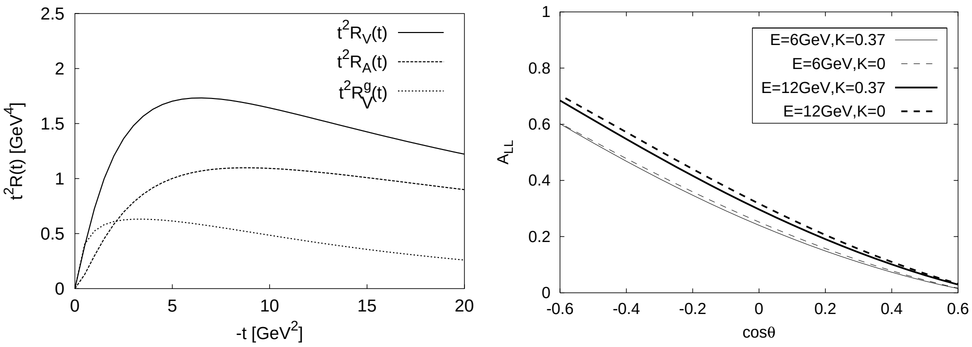

Fig. 4. Predictions for the Compton form factors (left) and for the helicity correlations $A_{\rm LL} = K_{\rm LL}$ (right). NLO corrections and the tensor form factor are taken into account (scenario A), in scenario B they are neglected.

The Pauli form factor F_2 and its Compton analogue $R_{\rm T}$ contribute to proton helicity flip matrix elements and are related to the GPD E analogously to (8). This connection suggests that, at least for not too small values of $-t$, $R_{\rm T}/R_{\rm V}$ roughly behaves as F_2/F_1. Thus, the recent JLab data [17] on F_2 indicate a behaviour as $R_{\rm T}/R_{\rm V} \propto m/\sqrt{-t}$. The form factor $R_{\rm T}$ therefore contributes to the same order in $\Lambda/\sqrt{-t}$ as the other ones, see Eq. (4). Predictions for Compton observables are given for two different scenarios[6]. Both $R_{\rm T}$ and $\alpha_{\rm s}$ corrections are omitted in scenario B but taken into account in A where the ratio $\kappa_{\rm T}$ is assumed to have a value of 0.37 as estimated from the JLab form factor data [17].

[6]There is a discrepancy between the SLAC data [18] on F_2/F_1, obtained by Rosenbluth separation, and the JLab ones. According to Ref. [19], part of the discrepancy can be assigned to two-photon exchange which affects the Rosenbluth data [18].

Employing the model GPDs and the corresponding form factors, various Compton observables can be calculated [2, 3, 11]. The predictions for the differential cross section are in fair agreement with the Cornell data [20]. Due to the broad maxima that the scaled form factors exhibit, the handbag mechanism approximately predicts a s^6-scaling behaviour at fixed c.m.s. scattering angle according to dimensional counting. However, inspection of the handbag predictions 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 [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 model GPDs (7).

Predictions for $A_{\rm LL} = K_{\rm LL}$ are shown in Fig. 4. The JLab E99-114 collaboration [21] has presented the first measurement of $K_{\rm LL}$ at a c.m.s. scattering angle of 120° and a photon energy of 3.23 GeV. This still preliminary data point is in fair agreement with the predictions from the handbag given the small energy at which they are available. The kinematical requirement of the handbag mechanism $s,\ -t,\ -u \gg \Lambda^2$ is not well satisfied and, therefore, 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. in Ref. [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][7] that the proton's leading-twist distribution amplitude is close to the asymtotic form $\propto x_1 x_2 x_3$. 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 $K_{\rm LL}$ 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 $Q^2/-t \lesssim 1$. 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 fails with the normalization of the photoproduction

[7] A perturbatively calculated $J/\Psi \to p\bar{p}$ decay width agrees with experiment only if a proton distribution amplitude close to the asymptotic form is employed [25].

cross section by an 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 [9].

One may investigate the handbag contribution to photoproduction of pseudoscalar mesons (P) in a more general way [28] by writing down a covariant decomposition [29] of the subprocess $\gamma q \to \mathrm{P} q$ 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-flip, one finds, for instance, that the helicity correlation $\hat{A}_{\mathrm{LL}}$ for the subprocess $\gamma q \to \mathrm{P} q$ is the same as for $\gamma q \to \gamma q$, 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 π^+ and π^-. The ratio is approximately given by

$$\frac{\mathrm{d}\sigma(\gamma\mathrm{n} \to \pi^-\mathrm{p})}{\mathrm{d}\sigma(\gamma\mathrm{p} \to \pi^+\mathrm{n})} \simeq \left[\frac{e_d u + e_u s}{e_u u + e_d s}\right]^2 . \tag{11}$$

The form factors which, for a given flavour, 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 [30] which, at 90°, provides values of 1.73 ± 0.15 and 1.70 ± 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-flip.

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. [5] (see also Ref. [6]). The cross section for the production of a pair of pseudoscalar mesons reads

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to \mathrm{M}\overline{\mathrm{M}}) = \frac{8\pi\alpha_{\mathrm{elm}}^2}{s^2 \sin^4\theta}\left|R_{\mathrm{M}\overline{\mathrm{M}}}(s)\right|^2 , \tag{12}$$

while for baryon pairs, it is given by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to \mathrm{B}\overline{\mathrm{B}}) = \frac{4\pi\alpha_{\mathrm{elm}}^2}{s^2 \sin^2\theta}\Big\{\left|R_A^B(s) + R_P^B(s)\right|^2 + \cos^2\theta\left|R_V^B(s)\right|^2 + \frac{s}{4m^2}\left|R_P^B(s)\right|^2\Big\} . \tag{13}$$

In analogy to Eq. (9), the form factors represent moments of two-hadron distribution amplitudes, Φ_{2h}, which are time-like versions of GPDs. In the case of pion pair production, one has for instance

$$R_{2\pi}(s) = \sum_q e_q^2 R_{2\pi}^q(s) , \quad \text{and} \quad R_{2\pi}^q(s) = \frac{1}{2}\int_0^1 \mathrm{d}z(2z-1)\Phi_{2\pi}(z, 1/2, s) . \tag{14}$$

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. [5] but rather extracted ('measured') from the experimental cross section. The form factor $R_{2\pi}$ obtained that way, is shown in Fig. 5, too. The average value of the scaled form factor $sR_{2\pi}$ is 0.75 GeV^2. The closeness of this value to that of the scaled time-like electromagnetic form factor of the pion (0.93 ± 0.12 GeV^2) hints at the internal consistency of the handbag approach.

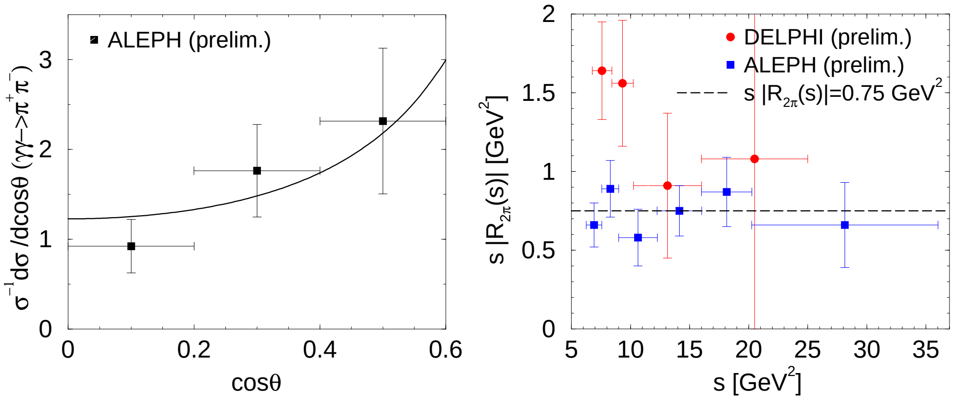

Fig. 5. Handbag predictions for the angular dependence of the cross section for $\gamma\gamma \to \pi^+\pi^-$ (left) and the form factor $s|R_{2\pi}|$ versus s (right). Preliminary data are taken from ALEPH [33] and DELPHI [34].

A characterisic feature of the handbag mechanism in the time-like region is the intermediate $q\bar{q}$ state implying the absence of isospin-two components in the final state. A consequence of this property is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to \pi^0\pi^0) = \frac{\mathrm{d}\sigma}{\mathrm{d}t}(\gamma\gamma \to \pi^+\pi^-)\,, \tag{15}$$

which is independent of the soft physics input, and is, so far, a robust prediction of the handbag approach. The absence of the isospin-two components combined with flavour symmetry allows one to calculate the cross sections for other $\mathrm{B\overline{B}}$ channels using the form factors for $\mathrm{p\overline{p}}$ 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 [31] while the diquark model [32] which is a variant of the leading-twist approach in which diquarks are considered as quasi-elementary constituents of baryons, is infair agreement with experiment for $\gamma\gamma \to \mathrm{B\overline{B}}$.

6. Summary

A review is given of 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 momentum transfers of the order of 10 GeV^2. However, before we can draw firm 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 many 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 scaled form factors show and, hence, reflects the the transverse size of the lowest Fock states of the involved hadrons.

I 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. Refuting the handbag approach necessitates experimental evidence against this factorization.

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MEHANIZAM TORBE U EKSKLUZIVNIM REAKCIJAMA NA VELIKIM KUTOVIMA

Uspoređujemo tzv. mehanizam torbe u ekskluzivnim reakcijama pri raspršenju na velikim kutovima s drugim teorijskim pristupima. Posebno se izlaže njegova primjena na Comptonovo raspršenje, fototvorbu mezona i na dvofotonsko poništenje u parove hadrona.