Hard exclusive and semi-exclusive meson production

M. Diehl

Deutsches Elektronen-Synchrotron DESY, 22603 Hamburg, Germany

Abstract

I review recent theory developments for hard exclusive and semi-exclusive production of mesons, emphasising the variety of physics issues that can be studied in these processes.

1 EXCLUSIVE MESON PRODUCTION

1.1 Factorisation

The first part of this review is about exclusive electroproduction of a meson on a hadron, \( eh \rightarrow eh'M \), as shown in Fig. 1(a). The piece of theory at the origin of the recent theoretical and experimental interest in this topic is a factorisation theorem [1]: In the Bjorken limit of infinitely large photon virtuality \( Q^2 = -q^2 \) at fixed \( x_B = Q^2/(2pq) \) and momentum transfer \( t \) the amplitude for \( \gamma^*h \rightarrow h'M \) factorises into a skewed parton distribution (SPD) in the target, a hard parton-photon scattering calculable in perturbative QCD, and the distribution amplitude of the meson, see Fig. 1(b). The factorisation property makes this process a tool to measure leading-twist matrix elements of hadrons, in particular skewed parton distributions, which have aroused considerable interest, cf. [3].

This factorisation holds only for longitudinal polarisation of the virtual photon. As \( Q^2 \) becomes large (and \( t \) remains small) the amplitude from the diagrams in Fig. 1(b) scales like \( A(\gamma^*_L) \sim 1/Q \) up to logarithmic corrections. For transverse photons factorisation cannot be established because the corresponding diagrams contain dangerous infrared regions, but the theorem tells us that the amplitude should be suppressed by at least one power:

*Talk given at the Workshop on the Structure of the Nucleon (NUCLEON 99), Frascati, Italy, 7–9 June 1999, to appear in the proceedings.
Figure 1: (a) Exclusive meson electroproduction. (b) Factorisation in the Bjorken limit. $x$ and $z$ are parton momentum fractions in $h$ and $M$, respectively.

$A(\gamma^*_T) \sim 1/Q^2$. Of course, there are also power corrections to the leading behaviour of $A(\gamma^*_L)$.

In the expression of the amplitude one has to perform an integral over the longitudinal momentum fractions $x$ and $z$ of the partons. An important point (to which we will come back in Sect. 1.5) is that in order to obtain the leading power behaviour of the diagrams in Fig. 1(b) the relative transverse momenta $k_T$ of the partons within their parent hadrons are approximated by zero in the hard scattering $T_H$. Therefore the SPDs and the meson distribution amplitude are themselves integrated over $k_T$. Taking into account the effect of finite $k_T$ in $T_H$ is part of the power corrections to the amplitude.

Important theoretical work has been done in the context of the high-energy limit, where $W^2$ is much larger than all other variables, including $Q^2$. Many aspects of it are common with what we will discuss here, but others are specific to the small-$x_B$ limit (such as the use of $k_T$-factorisation where the finite parton $k_T$ is not neglected in the hard scattering subprocess). For reasons of space/time I will not cover this field here.

1.2 Flavour

Meson production comes in a variety of different channels, such as

\[
\begin{align*}
\gamma^* p & \rightarrow p (\pi^0, \eta, \eta', K^0, \bar{K}^0, \ldots) \quad \text{(pseudoscalar mesons),} \\
\gamma^* p & \rightarrow p (\rho, \rho', \omega, \phi, \ldots) \quad \text{(vector mesons),} \\
\gamma^* p & \rightarrow n (\pi^+, \rho^+, \ldots), \quad \gamma^* n \rightarrow p (\pi^-, \rho^-, \ldots) \quad \text{(charge exchange),} \\
\gamma^* p & \rightarrow (\Lambda, \Sigma^0) K^+ \quad \text{(exchange of strangeness).}
\end{align*}
\]

The multitude offers us a way to disentangle the SPDs for different parton species and with different spin structure. Whereas the distributions $H$ and $E$ (in Ji’s notation, corresponding to Radyushkin’s $F$ and $K$) occur in vector meson production their parton helicity dependent counterparts $\tilde{H}$ and $\tilde{E}$ (resp. $\tilde{G}$ and $\tilde{P}$) contribute to the production of pseudoscalars. Note that all four distributions appear in the amplitude for deep virtual Compton scattering, cf. [3].
Figure 2: $\gamma^* p \rightarrow n \pi^+$: the lower frame shows pion exchange as a contribution to the skewed parton distribution $\tilde{E}$, the upper frame the (off-shell) pion form factor.

As for the different parton species, one has for instance the following separation in the vector meson channel [4]:

$$
\begin{align*}
\rho^0 & \sim \frac{2}{3}(u + \bar{u}) + \frac{1}{3}(d + \bar{d}) + \text{gluons}, \\
\omega^0 & \sim \frac{2}{3}(u + \bar{u}) - \frac{1}{3}(d + \bar{d}) + \text{gluons}, \\
\phi & \sim \frac{1}{3}(s + \bar{s}) + \text{gluons}, \\
\rho^\pm & \sim (\ldots) \left[ (u - \bar{u}) - (d - \bar{d}) \right] \pm (\ldots) \left[ (u + \bar{u}) - (d + \bar{d}) \right] \quad \text{(no gluons)},
\end{align*}
$$

where the (\ldots) stand for different $x$-dependent coefficients. For the charged mesons one has here made use of isospin relations to relate the SPDs for the transitions $p \rightarrow n$ and $n \rightarrow p$ to the ones for $p \rightarrow p$ (just as one relates the distribution amplitude of $\pi^0$, $\pi^-$ and $\pi^+$). A similar separation of flavours can be achieved in the pseudoscalar channel with pions and kaons [5].

SPDs contain nonperturbative physics that cannot be accessed in the usual, diagonal parton distributions. An example is the exchange of particles in the $t$-channel, which can contribute in the region of $x$ where both partons come out of the hadron $h$, instead of one coming out of $h$ and the other going into $h'$ (cf. [2]). This is especially important for the distributions $\tilde{E}$, which have the quantum numbers of pseudoscalar meson exchange: if $t$ is not too large then an exchanged pion (and to a lesser extent a kaon) are not very far from their mass shell [5, 6]. This consideration has important consequences for the process $\gamma^* p \rightarrow n\pi^+$, which has been used to extract the pion form factor at large spacelike momentum transfer, cf. Fig. 2. Identifying the off-shell pion in the $t$-channel as a part of the nonperturbative quantity $\tilde{E}$ it is immediately clear that there are other contributions to the process, corresponding to contributions in $\tilde{E}$ which cannot be described by meson exchange. Modelling the SPDs allows one to estimate the size of such contributions, and to study in which kinematical region one may hope to extract the pion form factor [6]. This example illustrates how SPDs relate rather different physics (such as the distribution of quarks in the proton and the quark-antiquark distribution in the pion).

A different aspect of pseudoscalar production has been investigated in [7], where it was proposed to compare the production of $\pi^0$, $\eta$ and $\eta'$ to study chiral dynamics and the
breaking of flavour $SU(3)$ in the distribution amplitudes of these mesons. The weighting of $u$-, $d$- and $s$-quarks in electroproduction is different than from the one in the transitions $\gamma^*\gamma \rightarrow \pi^0, \eta, \eta'$ and thus can provide a handle to separate the quark flavours.

1.3 Target Spin

The cross section for meson production is always quadratic in the distributions $H$ and $E$ (or $\tilde{H}$ and $\tilde{E}$), even if the target and recoil hadrons are not polarised. To fully separate the different distributions one needs to measure the polarisation of at least one of the hadrons. A kinematic, Rosenbluth-type separation as can be done for the elastic form factors $F_1$ and $F_2$ is not possible here, because the functions $H$ and $E$ ($\tilde{H}$ and $\tilde{E}$) are themselves dependent on the energy of the scattering process, via the skewedness parameter $\zeta$ (cf. [2]). As an example of a polarisation observable the transverse asymmetry of the target or the recoil hadron has been pointed out in [5]. For pion production it is proportional to the product $\tilde{E} \cdot \tilde{H}$ and therefore a good candidate to obtain information on $\tilde{E}$.

1.4 From $\rho$ to $\pi\pi$

So far we have looked at the reaction $\gamma^*p \rightarrow p \rho^0 \rightarrow p(\pi^+\pi^-)$ as the production of a $\rho$, described in the factorised form of Fig. 1(b), followed by the decay $\rho \rightarrow \pi^+\pi^-$. It is however possible to directly describe the reaction $\gamma^*p \rightarrow p(\pi^+\pi^-)$ in a factorised framework, without referring to the formation and decay of a resonance: the distribution amplitude of the $\rho$ in Fig. 1(b) is then replaced with a generalised distribution amplitude (GDA) describing the transition from the $q\bar{q}$-pair to $\pi^+\pi^-$, cf. Fig. 3(a). This was noticed in [10], and the formal extension of the factorisation proof was given in [11]. It is very natural that this should be possible: the hadronisation of a $q\bar{q}$-pair into $\pi^+\pi^-$, be it through resonance formation or not, is all long distance physics and can be put into one nonperturbative quantity. This tells us that the study of SPDs in this reaction does not require separation of a resonance “signal” from a continuum “background”, and is in fact not restricted to pion pairs on a resonance peak.

A GDA depends on several variables: (a) the momentum fraction $z$ of the quark with respect to the total momentum, just as for an ordinary distribution amplitude, (b) the factorisation scale $\mu$—this dependence is given by the same ERBL evolution equations.
describing ordinary distribution amplitudes, (c) the invariant mass $M_{\pi\pi}$ of the pion pair, and (d) the polar angle $\theta^*$ of the $\pi^+$ in the $\pi^+\pi^-$ c.m.

The dependence on $\theta^*$ can be described via a decomposition into partial waves of the $\pi^+\pi^-$ system, and one has two distinct quantum number combinations: Even partial waves $l = 0, 2, 4, \ldots$ correspond to states with positive charge conjugation parity $C = +1$, having the quantum numbers of $f$-mesons, and the odd ones, $l = 1, 3, \ldots$ to $C = -1$, i.e. to $\rho$ quantum numbers. In the $\rho$-channel the asymptotic form of the GDA, i.e. the form one has at very large factorisation scale $\mu$, has its mass dependence given by the timelike pion form factor $F_\pi(M^2_{\pi\pi})$, which is well measured from $e^+e^- \rightarrow \pi^+\pi^-$ [12]. This nicely illustrates that, even in the asymptotic regime, there is more than the $\rho$-resonance produced—the pion form factor is not described by a Breit-Wigner form for the $\rho$ alone.

In electroproduction pion pairs in both channels can be produced, which implies that there is always some “contamination” of $\rho$-production with the “wrong” quantum numbers. The two channels go with different flavour combinations of the SPDs:

\begin{align*}
\text{\rho-channel} & \sim \frac{2}{3}(u + \bar{u}) + \frac{1}{3}(d + \bar{d}) + \text{gluons}, \\
\text{\text{f-channel}} & \sim \frac{2}{3}(u - \bar{u}) - \frac{1}{3}(d - \bar{d}) \quad \text{(no gluons)}.
\end{align*}

With a number of simplifying assumptions one can model the GDAs in both channels, and finds that while on the $\rho$ mass peak the $\rho$-channel is clearly dominant, the $f$-channel contribution may be visible if $M_{\pi\pi}$ is a few 100 MeV off peak, provided that $x_B$ is in the valence region so that gluon exchange does not completely dominate over quarks [13]. Observable signatures of the presence of $f$-channel pairs are on one hand a modified angular distribution of the pion pair compared with a pure $P$-wave, and in particular the presence of interference terms which are odd under the exchange of $\pi^+$ and $\pi^-$ momenta. Another signature of $f$-channel pairs is the production of $\pi^0\pi^0$-pairs along that of charged pions.

Beyond providing an extended description of meson electroproduction the GDAs are of interest in themselves, notably because they are related by crossing symmetry to the (skewed and ordinary) parton distributions in the pion, cf. Fig. 3. The two types of nonperturbative quantities can thus be related by analytic continuation in the invariant mass variable $M_{\pi\pi}$, resp. $t$ [12]. Finally it is clear that the concept of GDAs is not limited to the $\pi\pi$ system, but can be extended e.g. to kaon pairs, to $p\bar{p}$ or to three pions.

1.5 Meson Polarisation

As mentioned in sect. [11] the factorisation theorem states that at sufficiently large $Q^2$ longitudinally polarised photons dominate over transverse ones, i.e. it provides us with a helicity selection rule in the scaling limit. This is important since the measurement of the azimuthal angle between the electron and hadron planes in $eh \rightarrow eh'M$ contains information about the relative importance of $\gamma^*_L$ and $\gamma^*_T$ contributions, i.e. information on how important power corrections are, in other words how far one is from the asymptotic limit at finite $Q^2$. 

}\end{document}
It turns out that for vector meson production there is a second selection rule, stating that to leading power in $1/Q$ only longitudinally polarised mesons are produced \[4, 14\]. It easily generalises to the production of meson pairs: to leading power accuracy the pair has zero angular momentum along its direction of flight in the $\gamma^* p$ c.m. Again these selection rules can be tested by measuring angular distributions.

In the existing data on $\rho$-production, both at fixed-target and at collider energies, the transition $\gamma^* T p \rightarrow p \rho_T$ is important: even for values of $Q^2$ of 5 to 10 GeV\(^2\) the ratio of longitudinal to transverse polarisation is about 2 to 4 at cross section level \[15\]. The H1 and ZEUS collaborations have also analysed the full angular distributions in $ep \rightarrow ep (\pi^+\pi^-)$ and found a hierarchy $|A(\gamma^*_L \rightarrow \rho_L)| > |A(\gamma^*_T \rightarrow \rho_T)| > |A(\gamma^*_T \rightarrow \rho_L)|$ for those transition amplitudes that are non-zero within experimental accuracy.

Power corrections are thus seen to be important, certainly in $\rho$-production. The physics of these corrections contains several important ingredients. To date most theoretical work has focused on the effect of finite transverse parton momentum in the hard scattering subprocess. In the high-energy regime several different estimates of this give a fair description of the present HERA data on the photon and $\rho$ polarisation \[16\]. Note that meson wave functions for finite transverse momentum are related by gauge invariance to wave functions of higher Fock states such as $q\bar{q}g$ \[17\]. Higher Fock states may thus also play an important role, but no detailed estimation of this has been performed so far.

In the loop integral of the diagrams in Fig. 1(b) there is a region where the momentum fraction $z$ of the quark in the meson is close to 0 or 1, so that the quark or antiquark becomes slow and therefore soft. It has long been realised \[18\] that for transverse initial photons such infrared sensitive configurations are not sufficiently suppressed; this is why the simple factorisation of Fig. 1 cannot be established for a $\gamma_T$ \[4\]. There is an ongoing debate on how serious an infrared-dependence this introduces in the calculation and to what extent meson production from a $\gamma_T$ can be described in a perturbative framework, cf. for instance \[19, 20\].

Closely related with this problem is the question how important soft overlap contributions are relative to the factorising, hard scattering diagrams. Soft overlap contributions can be obtained from diagrams such as in Fig. 2 by removing the gluon when the quark line that directly connects the meson and the proton is soft. This is the same physics that is being intensively discussed for elastic form factors and other hard exclusive processes \[21\]. A first attempt to estimate the soft overlap contribution to meson electroproduction has been made in \[22\].

The theory of power corrections is still far from being complete or uncontroversial, and it is important to realise that the various helicity transitions from the photon to the meson (or mesons) provide a wealth of observables where such effects can be studied without the need to subtract a leading-twist contribution.

### 1.6 Meson production versus Compton scattering

At this point we have considered several aspects of exclusive meson production, and it might be useful to confront this reaction with deep virtual Compton scattering (DVCS)
1.7 Proton dissociation

In addition to quasielastic production $\gamma^* N \rightarrow N + M$ one can consider processes where the nucleon $N$ is excited, e.g. into a nucleon resonance $N^*$ or a $\Delta$, or a $N\pi$ continuum state with low invariant mass. Being on one hand a background to the quasielastic process these reactions are interesting in themselves: factorisation remains valid as long as the meson (or meson pairs) in the upper part of Fig. [4] and the final state hadrons from the lower part are well separated in phase space. Then one has access to SPDs describing transitions such as $N \rightarrow \Delta$ or $N \rightarrow N\pi$, on which only little is known so far [24].

The question what happens when one replaces the final state nucleon with a continuum state whose invariant mass is not small leads us to the second part of this review.
2 SEMI-EXCLUSIVE MESON PRODUCTION

2.1 From exclusive to semi-exclusive

Let us now look at the process $\gamma^* p \rightarrow Y + M$, where $Y$ is a hadronic system with invariant mass $M_Y$ above the resonance region, and let us keep the requirement that $Y$ and $M$ be well separated in phase space. Going through the kinematics of the diagram in Fig. 1(b) one finds that for $M_Y \gg m_p$ the fractional parton momentum $x$, which was previously to be integrated over all its possible range, becomes “trapped” at a particular value (otherwise one the quarks attached to the soft proton blob in the diagram must go far off-shell). Moreover, it becomes trapped at a value for which the photon-parton subdiagrams $T_H$ have internal lines close to their mass-shell. This means that the “hard scattering” is no longer hard, and that to factorise diagrams as it is done in Fig. 1(b) is no longer the correct way to describe the process.

A way out of this situation is to require a large invariant momentum transfer $t$ between the proton and $Y$, i.e. between the photon and $M$. Then the value of $x$ where the integration is “trapped” no longer corresponds to a singularity of the hard scattering process, which remains under perturbative control. Once we have large $t$ we can allow $Q^2$ to be small or zero (and even replace the photon projectile with a hadron, say a pion). This defines then the “semi-exclusive” kinematics introduced and studied in [25]:

- $-t, M_Y^2 \gg 1 \text{ GeV}^2$,
- $-t, M_Y^2 \ll W^2$ so that $Y$ and $M$ are well separated,
- $Q^2$ zero, small or large.

The process can then be calculated in a factorised way, shown in Fig. 4(a). The upper part of the diagram is the same as for exclusive meson production in the Bjorken region, composed of a hard parton-photon scattering and a meson distribution amplitude (or GDA), while the lower part has changed. The reason is that the parton “coming back” from the hard scattering has a large transverse momentum compared to the spectator partons in the proton, and therefore hadronises independently from the spectators. This

![Figure 4](https://example.com/figure4.png)

Figure 4: (a) Factorisation in semi-exclusive meson production, $\gamma^* p \rightarrow Y + M$, with an example for the hard-scattering subdiagrams. (b) Inclusive DIS, $\gamma^* p \rightarrow X$. 

8
is precisely the same situation as in inclusive deep inelastic scattering (DIS), cf. Fig. \[\text{4(b)}\], so that in the calculation we can treat the scattered parton as a free final-state particle. In the squared transition amplitude the parton emission from the target is just described by an ordinary (non-skewed) parton distribution. If the target is polarised then one probes the usual helicity-dependent parton distributions.

Reminding ourselves that in DIS we have a hard scattering on a parton with momentum fraction \( x_B = Q^2/(W^2 + Q^2) \) and making the necessary translation of variables we find that in our semi-exclusive reaction the extracted parton has momentum fraction \( x_S = (−t)/(M_Y^2 − t) \). The analogy with DIS also indicates that one may invoke parton-hadron duality to use the description of Fig. \[\text{4(a)}\] even when the mass \( M_Y \) is in the resonance region, on the condition of integrating over a sufficiently large \( M_Y \)-range so that individual resonances average out.

At first sight it may appear that our process is just a special case of a semi-exclusive reaction, the formation of the meson \( M \) being described by an ordinary fragmentation function with momentum fraction \( z \) close to 1. The example diagram in Fig. \[\text{4(a)}\] shows that this is not the case: we do not have there a two-step process where a quark from the proton is first scattered off the photon, and then fragments into the meson \( M \) and some other partons. Taking suitable kinematical limits one can however find situations where the close connection between the semi-exclusive and semi-inclusive mechanisms becomes apparent; such cases have in fact been considered in the literature \[26, 27\].

### 2.2 What one can learn in semi-exclusive processes

Semi-exclusive processes have several features that make them interesting. Let me just mention, but not elaborate on the possibility of investigating large-\( t \) Regge exchange in the context of perturbative QCD. Vector meson production is already being extensively studied under this aspect, both theoretically and experimentally (cf. \[25\] for references).

Semi-exclusive reactions have a hybrid nature: the upper part of the diagram in Fig. \[\text{4(a)}\] is typical of exclusive reactions, and offers a way to study meson distribution amplitudes. It may be particularly attractive to consider ratios of cross sections, where many details of (and corrections to) the calculation cancel out. The cross section ratio \( d\sigma(ρ^+)/d\sigma(π^+) \) for instance only depends on the distribution amplitudes \( φ_ρ(z) \) and \( φ_π(z) \).

The lower part of the same diagram is reminiscent of usual inclusive or semi-inclusive reactions; the cross section of our process is linear in the ordinary parton distributions, not quadratic in skewed distributions as the exclusive processes we have discussed in Sect. \[1\]. Producing different mesons one can select particular flavour combinations of parton distributions (in a similar way as in semi-inclusive processes, but without the uncertainties due to “unfavoured” fragmentation functions). Examples are the ratios

\[
\frac{d\sigma(γp → Yπ^-)}{d\sigma(γp → Yπ^+)} = \frac{d(x_S) + \overline{u}(x_S)}{u(x_S) + \overline{d}(x_S)}, \quad \frac{d\sigma(γp → YK^-)}{d\sigma(γp → YK^+)} = \frac{s(x_S) + \overline{u}(x_S)}{u(x_S) + \overline{s}(x_S)},
\]

and those with \( \Delta d(x_S), \Delta π(x_S), \ldots \) one can measure with longitudinal target polarisation. Note that the comparison of \( d(x) \) with \( u(x) \), or \( \overline{π}(x) \) with \( s(x) \) provides valuable information
on non-perturbative dynamics in the proton.

To obtain a feeling for accessible values of $x_S$ let us consider some example kinematics for $ep$ c.m. energies $\sqrt{s}$ attainable at ELFE and at COMPASS:

| $\sqrt{s}$ [GeV] | $W$ [GeV] | $M_Y^2$ [GeV$^2$] | $-t$ [GeV$^2$] | $x_S = (-t)/(M_Y^2 - t)$ |
|------------------|-----------|------------------|----------------|-----------------------------|
| 8                | 6         | 2                | 6              | 0.75                        |
|                  |           | 6                | 2              | 0.25                        |
| 20               | 15        | 20               | 3              | 0.13                        |
|                  |           | 25               | 2              | 0.07                        |

At ELFE with $\sqrt{s} \approx 8$ GeV the range of masses $M_Y$ for which $Y$ and the meson are well separated is rather limited, and one always remains in the valence region of the parton distributions. On the other hand, high luminosity may allow one to go to rather high $t$ and thus to access parton distributions at large $x$. For COMPASS energies there is a comfortable range of $W$ and hence of $M_Y$, and one would be able to go down to the $x$-region where sea quarks and gluons are important.

### 3 SUMMARY

Exclusive production of mesons in the Bjorken region provides an opportunity to study meson distribution amplitudes and skewed parton distributions, and is in several ways complementary to deep virtual Compton scattering. It offers a large variety of channels and thus the possibility to disentangle the many flavour degrees of freedom. Some channels have (unexpected) connections to other processes, for instance $\pi^+$ production with its relation to the elastic pion form factor.

The spin degrees of freedom of SPDs can partly be disentangled by comparing different meson channels and DVCS, but full information can only be obtained if the polarisation of the target and/or recoil hadron is measured. The polarisations of the virtual photon and of the produced meson play a rather different role: they are indicators of how important power corrections are. This should help us to judge when a leading-twist interpretation of the data is adequate, and beyond this to learn more about non-leading twist physics.

Generalised distribution amplitudes open further channels to a factorised description within QCD, with low-mass meson pairs instead of single mesons. They provide a new way to think about and analyse the production of unstable resonances such as the $\rho$. By crossing they are connected to parton distributions in mesons and thus allow one to relate different pieces of information on hadron structure.

Semi-exclusive production combines typical features of exclusive and inclusive physics. Next to the possibility to study Regge physics in the perturbative region it offers ways to compare different meson distribution amplitudes, and to measure “exotic” flavour combinations of unpolarised and polarised parton distributions.

Clearly there remains much theoretical work to be done on several of these issues, and much experimental work, too. The physics potential I have tried to outline will hopefully
make these efforts worthwhile.

References

[1] J.C. Collins, L. Frankfurt and M. Strikman, Phys. Rev. D56, 2982 (1997), hep-ph/9611433; A.V. Radyushkin, Phys. Rev. D56, 5524 (1997), hep-ph/9704207.

[2] A.V. Radyushkin, these proceedings.

[3] P.A.M. Guichon, these proceedings.

[4] L. Mankiewicz, G. Piller and T. Weigl, Eur. Phys. J. C5, 119 (1998), hep-ph/9711227 and Phys. Rev. D59, 017501 (1999), hep-ph/9712508.

[5] L.L. Frankfurt, P.V. Pobylitsa, M.V. Polyakov and M. Strikman, Phys. Rev. D60, 014010 (1999), hep-ph/9901429.

[6] L. Mankiewicz, G. Piller and A. Radyushkin, hep-ph/9812467.

[7] M.I. Eides, L.L. Frankfurt and M.I. Strikman, Phys. Rev. D59, 114025 (1999), hep-ph/9809277.

[8] D. Müller, D. Robaschik, B. Geyer, F.M. Dittes and J. Hořejší, Fortsch. Phys. 42, 101 (1994), hep-ph/9812448.

[9] M. Diehl, T. Gousset, B. Pire and O. Teryaev, Phys. Rev. Lett. 81, 1782 (1998), hep-ph/9805380.

[10] M.V. Polyakov and C. Weiss, Phys. Rev. D59, 091502 (1999), hep-ph/9806390.

[11] A. Freund, hep-ph/9903489.

[12] M.V. Polyakov, hep-ph/9809483; M.V. Polyakov and C. Weiss, hep-ph/9902451.

[13] M. Diehl, T. Gousset and B. Pire, to appear in the Procs. of the Workshop on Exclusive and Semiexclusive Processes at High Momentum Transfer, Jefferson Lab, USA, 20–22 May 1999.

[14] M. Diehl, T. Gousset and B. Pire, Phys. Rev. D59, 034023 (1999), hep-ph/9808479.

[15] ZEUS Collaboration, Eur. Phys. J. C6, 603 (1999), hep-ex/9808020; B. Clerbaux (H1 Collaboration), hep-ph/9905507; A. Borissov (HERMES Collaboration), to appear in the Procs. of the 7th International Workshop on Deep Inelastic Scattering and QCD (DIS 99), Zeuthen, Germany, 19–23 Apr. 1999.
[16] D.Yu. Ivanov and R. Kirschner, Phys. Rev. D58, 114026 (1998), hep-ph/9807324; E.V. Kuraev, N.N. Nikolaev and B.G. Zakharov, JETP Lett. 68, 696 (1998), hep-ph/9809539.

I. Royen, to appear in the Proc. or the 7th International Workshop on Deep Inelastic Scattering and QCD (DIS 99), Zeuthen, Germany, 19-23 Apr. 1999.

[17] I. Halperin, Phys. Rev. D57, 1680 (1998), hep-ph/9704265;
P. Hoodbhoy, Phys. Rev. D56, 388 (1997), hep-ph/9611207.

[18] S.J. Brodsky et al., Phys. Rev. D50, 3134 (1994), hep-ph/9402283.

[19] A.D. Martin, M.G. Ryskin and T. Teubner, Phys. Rev. D55, 4329 (1997), hep-ph/9609448.

[20] L. Mankiewicz and G. Piller, hep-ph/9905287.

[21] P. Kroll, these proceedings.

[22] M. Vanderhaeghen, P.A.M. Guichon and M. Guidal, hep-ph/9905372.

[23] M. Diehl, T. Gousset, B. Pire and J.P. Ralston, Phys. Lett. B411, 193 (1997), hep-ph/9706344.

[24] L.L. Frankfurt, M.V. Polyakov and M. Strikman, hep-ph/9808449.

[25] S.J. Brodsky, M. Diehl, P. Hoyer, S. Peigné, Phys. Lett. B449, 306 (1999), hep-ph/9812277.

[26] A. Brandenburg, V.V. Khoze and D. Müller, Phys. Lett. B347, 413 (1995), hep-ph/9410324.

[27] C.E. Carlson and A.B. Wakely, Phys. Rev. D48, 2000 (1993);
A. Afanasev, C.E. Carlson and C. Wahlquist, Phys. Lett. B398, 393 (1997), hep-ph/9701215 and Phys. Rev. D58, 054007 (1998), hep-ph/9706522.