The QCD analysis of hadron-antihadron $\to \gamma^*\gamma$ in the forward region and related processes[1]

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A QCD analysis of the reactions $AB \to \gamma^*\gamma$ and $\gamma^*\gamma \to AB$ in the forward region shows that they can be factorized in a way which is quite similar to the frameword developped for deeply virtual Compton scattering. The generalized parton distributions (GPDs) related to this latter process being replaced by new non perturbative hadronic matrix elements, the transition distribution amplitudes (TDAs).

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1 Introduction

The recent successes of the colinear factorization approach in exclusive hard processes motivates further studies where a scaling regime may be reached for amplitudes which factorize at leading twist into a short-distance matrix element and long-distance dominated matrix elements between hadron (or hadron and vacuum) states. We thus propose [1] to write the $AB \to \gamma^* \gamma$ amplitude in the scaling regime with large Q^2 and s with fixed Q^2/s and $-t << Q^2$ as

$$\mathcal{M}(Q^2, \xi, t) = \int dxdy \phi_A(y_i, Q^2) T_H(x_i, y_i, Q^2) T(x_i, \xi, t, Q^2) \;, \tag{1}$$

where $\phi_A(y_i, Q^2)$ is the A-hadron distribution amplitude, T_H the hard scattering amplitude, calculated in the colinear approximation and $T(x_i, \xi, t, Q^2)$ the new $B \to \gamma$ TDAs. x_i and y_i are light cone momentum fractions of quarks in hadrons. The same formula applies as well to the time reversed reaction $\gamma^* \gamma \to AB$. Backward VCS can also be described in the same framework.

2 $\gamma \to \pi$ Transition Distribution Amplitude

The $\gamma \to \pi$ TDAs are defined as [1]

$$\begin{aligned}
&\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p')| \, \bar{d}(-z/2)[-z/2, z/2] \, \gamma^\mu \, u(z/2) \, |\gamma(p, \varepsilon)\rangle \Big|_{z^+ = z_T = 0} \\
&\quad = \frac{1}{P^+} \frac{i\, e}{f_\pi} \epsilon^{\mu\nu\rho\sigma} \varepsilon_{\perp\nu} P_\rho \Delta_{\perp\sigma} \, V(x, \xi, t) \;, \\
&\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p')| \, \bar{d}(-z/2)[-z/2, z/2] \, \gamma^\mu \gamma_5 \, u(z/2) \, |\gamma(p, \varepsilon)\rangle \Big|_{z^+ = z_T = 0} \\
&\quad = \frac{1}{P^+} \frac{e}{f_\pi} (\vec{\varepsilon} \cdot \vec{\Delta}) P^\mu \, A(x, \xi, t) \;, \\
&\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle \pi^-(p')| \, \bar{d}(-z/2)[-z/2, z/2] \, \sigma^{\mu\nu} \, u(z/2) \, |\gamma(p, \varepsilon)\rangle \Big|_{z^+ = z_T = 0} \\
&\quad = \frac{e}{P^+} \epsilon^{\mu\nu\rho\sigma} P_\sigma \left[\varepsilon_{\perp\rho} T_1(x, \xi, t) - \frac{1}{f_\pi} (\vec{\varepsilon} \cdot \vec{\Delta}) \Delta_{\perp\rho} T_2(x, \xi, t) \right] \;,
\end{aligned} \tag{2}$$

where the first two TDAs, $V(x, \xi, t)$ and $A(x, \xi, t)$ are chiral even and the latter ones, $T_i(x, \xi, t), i = 1, 2$, are chiral odd. In definitions (2) we include the Wilson line $[y; z] \equiv \mathrm{P} \, \exp \left[ig(y - z) \int_0^1 dt \; n_\mu A^\mu(ty + (1 - t)z) \right]$, which provides the QCD-gauge invariance for non local operators and equals unity in a light-like (axial) gauge. We also introduce standard vectors $P = (p + p')/2$ and $\Delta = p' - p$. f_π is the pion decay constant. The four leading twist TDAs are linear combinations of the four independent helicity amplitudes for the process $q\gamma \to q\pi^-$. The x and ξ variables, see Fig. 1, have the same meaning as in the GPDs. The TDAs have polynomiality properties as GPDs.

The TDAs obey QCD evolution equations which are the GPD mixed DGLAP-ERBL evolution equations. Contrarily to the case of the forward photon structure functions, we do not expect that the pointlike nature of the photon induces new terms in the DGLAP evolution of the $\gamma \to \pi$ TDA with respect to the $\pi \to \pi$ GPD.

3 Other cases

3.1 mesonic channels

The $\gamma \to \rho$ TDAs are of direct phenomenological interest, since the reaction $\gamma^* \gamma \to \rho\rho$ has turned out to be accessible by LEP experiments [2], although in a slightly different kinematical domain [3]. Their

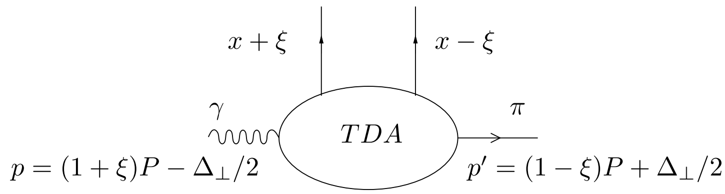

Figure 1: The $\gamma\to\pi$ transition distribution amplitude (TDA).

general decomposition at leading twist can be written as

$$\begin{aligned}
&\int \frac{d\kappa}{2\pi}\, e^{ix\kappa P.n}\langle \rho^-(p',\epsilon')|\, \bar{d}(-\kappa n)\,\gamma.n\, u(\kappa n)\,|\gamma(p,\epsilon)\rangle \\
&= H_1^{(\rho\gamma)}(x,\xi,t)\left[-(\epsilon'^*\cdot\epsilon)+\frac{8(\epsilon'^*\cdot P)(\epsilon\cdot P)}{M^2-t}\right] \\
&+H_2^{(\rho\gamma)}(x,\xi,t)\left[(\epsilon'^*\cdot P)\frac{\epsilon\cdot n}{P\cdot n}+(\epsilon\cdot P)\frac{\epsilon'^*\cdot n}{P\cdot n}-\frac{(\epsilon\cdot P)(\epsilon'^*\cdot P)}{6M^2(1+\xi)}\left(-1+\frac{24M^2(1+\xi)^2}{M^2-t}\right)\right. \\
&\left.-\frac{M^2-t}{48M^2(1+\xi)}\left((\epsilon'^*\cdot\epsilon)+\frac{12M^2(\epsilon\cdot n)(\epsilon'^*\cdot n)}{(P\cdot n)^2}\right)\right] \\
&+H_4^{(\rho\gamma)}(x,\xi,t)\left[(\epsilon'^*\cdot P)\frac{\epsilon\cdot n}{P\cdot n}-(\epsilon\cdot P)\frac{\epsilon'^*\cdot n}{P\cdot n}-\frac{(\epsilon\cdot P)(\epsilon'^*\cdot P)}{6M^2(1+\xi)}\left(1+\frac{24M^2(1+\xi)^2}{M^2-t}\right)\right. \\
&\left.+\frac{M^2-t}{48M^2(1+\xi)}\left((\epsilon'^*\cdot\epsilon)+\frac{12M^2(\epsilon\cdot n)(\epsilon'^*\cdot n)}{(P\cdot n)^2}\right)\right] \qquad (3)
\end{aligned}$$

$$\begin{aligned}
&\int \frac{d\kappa}{2\pi}\, e^{ix\kappa P.n}\langle \rho^-(p',\epsilon')|\, \bar{d}(-\kappa n)\,\gamma.n\gamma_5\, u(\kappa n)\,|\gamma(p,\epsilon)\rangle \\
&= i\tilde{H}_1^{(\rho\gamma)}(x,\xi,t)\left[-\frac{\epsilon_{\mu\alpha\beta\gamma}n^\mu\epsilon'^{*\alpha}\epsilon^\beta P^\gamma}{(P\cdot n)}-\frac{2\epsilon_{\mu\alpha\beta\gamma}n^\mu\Delta^\alpha P^\beta(\epsilon^\gamma(\epsilon'^*\cdot P)+\epsilon'^{*\gamma}(\epsilon\cdot P))}{(M^2-t)(P\cdot n)}\right] \\
&+i\tilde{H}_2^{(\rho\gamma)}(x,\xi,t)\left[-\frac{\epsilon_{\mu\alpha\beta\gamma}n^\mu\epsilon'^{*\alpha}\epsilon^\beta P^\gamma}{(P\cdot n)}+\frac{2\epsilon_{\mu\alpha\beta\gamma}n^\mu\Delta^\alpha P^\beta(\epsilon^\gamma(\epsilon'^*\cdot P)+\epsilon'^{*\gamma}(\epsilon\cdot P))}{(M^2-t)(P\cdot n)}\right. \\
&\left.-\frac{\epsilon_{\mu\alpha\beta\gamma}n^\mu\Delta^\alpha P^\beta(\epsilon^\gamma(\epsilon'^*\cdot n)+\epsilon'^{*\gamma}(\epsilon\cdot n))}{(1+\xi)(P\cdot n)^2}\right] \\
&+i\tilde{H}_3^{(\rho\gamma)}(x,\xi,t)\left[\frac{\epsilon_{\mu\alpha\beta\gamma}n^\mu\Delta^\alpha P^\beta(\epsilon^\gamma(\epsilon'^*\cdot P)-\epsilon'^{*\gamma}(\epsilon\cdot P))}{M^2(P\cdot n)}\right. \\
&\left.+\frac{\epsilon_{\mu\alpha\beta\gamma}n^\mu\Delta^\alpha P^\beta(\epsilon^\gamma(\epsilon'^*\cdot n)+\epsilon'^{*\gamma}(\epsilon\cdot n))(M^2-t)}{4M^2(1+\xi)(P\cdot n)^2}\right]. \qquad (4)
\end{aligned}$$

The $H_i^{(\rho\gamma)}$ and $\tilde{H}_i^{(\rho\gamma)}$ TDAs can be identified with the corresponding GPDs for the deuteron case, H_i and $\tilde{H}_i$, which have been defined in Ref. [4].

3.2 Baryonic channels

When the hadron is a baryon, one needs to consider 3 quark correlators (see [5]) and the formulae become more cumbersome. Denoting by $x_i, i=1,2,3$ the momentum fractions carried by the three exchanged quarks, we have $\Sigma_i x_i = 2\xi$. The discussion of the different domains requires more care since one or two of the exchanged partons may have to be reinterpreted as antiquarks. Lack of space prevents us from describing here these TDAs which may become a central concept for understanding hard $\bar{p}p$ collisions at forward angles.

4 Phenomenology

Not much is presently known about the TDAs. Sum rules relate some of them to transition form factors as the $\pi\gamma$ form factor which is experimentally well measured. There is no *forward* limit as in the case of the GPDs. There may be positivity constrains which give inequalities relating TDAs to parton distributions in mesons or photons. In some cases implying the π meson, the chiral limit give some useful information, for instance the $\gamma \to \pi$ TDA is related to the photon distribution amplitude when the meson becomes soft.

When the pion is not soft one can try to approximate TDAs by extracting the pole contribution related to the appropriate exchange in $t-$channel. In particular, the use of the effective interaction lagrangian of π's and γ leads in the case of $\gamma \to \pi$ axial TDA $A(x,\xi,t)$ to the expression

$$A(x,\xi,t) = \frac{2f_\pi^2}{m_\pi^2 - t}\,\phi_\pi\left(\frac{x+\xi}{2\xi}\right)\,\theta(\xi \geq x \geq -\xi)\;, \tag{5}$$

approximating A TDA in the ERBL region. The advantage of such approach is that it leads to formulas being to some extent model independent, the disadvantage is their rather restricted domain of applicability.

Some model estimates are possible [7]. Without having yet performed a complete phenomenological study, we are confident that the expected orders of magnitudes of the cross sections of processes we discuss are amply sufficient to be measurable in feasible experimental set ups. Whether the mechanism described here will be dominant at accessible values of Q^2 cannnot be determined from theory in its present state of the art.

In analogy to the case of form factors, one may be more optimistic on the validity of the factorized description at fairly small values of Q^2 in the mesonic case than in the baryonic case. Let us stress however that the phenomenological difficulties of the hard description of baryonic form factors at accessible values of Q^2 [8] does not prevent us from being optimistic on the possible dominance of the hard process in the new case. The physical reason of this optimism relies in the following statement : it may be difficult for a baryon to be in its valence Fock state, but it should be easier for it to be in a higher Fock state such as $|qqq\pi\rangle$.

5 Conclusion

The TDAs are new objects with interesting properties. Their physics content seems quite rich and more developments should helpfully follow. Their $x, \xi, t-$ dependences each map out different features of the hadronic structure. For instance the (Fourier transformed) $t-$ dependence maps out [6] the impact parameter of a short transverse size $\bar{q}q$ pair in a meson. On the experimental size, we expect sizable cross sections for both the $\gamma^*\gamma \to AB$ reactions accessible at existing high luminosity electron positron colliders on the one hand, and the $\bar{p}N \to \gamma^*\gamma$ and $\bar{p}N \to \gamma^*\pi$ which will be measured at the FAIR project in GSI [9]. Backward VCS and backward exclusive meson electroproduction experiments may (and will) also be analyzed in this framework. Finally let us note that generalized version of TDAs, with γ and hadrons in the same (final or initial) state is a natural framework for description of the timelike DVCS processes, e.g. $e^+e_- \to \pi^+\,\pi^-\,\gamma$ [10]

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