REVIEW ON HARD EXCLUSIVE REACTIONS

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I discuss selected aspects of hard exclusive processes, focusing on the impact parameter representation.

In recent years, important results have been obtained in the theory of hard exclusive reactions. Given the limited space I will concentrate here on the concept of impact parameter, which allows for a simple and physically intuitive description of high-energy phenomena in different contexts. The impact parameter of a particle is obtained by Fourier transform with respect to the transverse momentum, $|p^+, \boldsymbol{b}\rangle = (2\pi)^{-2} \int d^2\boldsymbol{p}\, e^{-i\boldsymbol{b}\boldsymbol{p}}\, |p^+, \boldsymbol{p}\rangle$, where p^+ is the light-cone momentum. One then has a mixed representation of states with definite momentum in the light-cone direction and definite position $\boldsymbol{b}$ in the transverse plane. For a multi-particle system, the impact parameter turns out to be the weighted average of all particles, with the weights given by their light-cone momenta, $\boldsymbol{b} = \sum_i p_i^+ \boldsymbol{b}_i \,/\, \sum_i p_i^+$ [1].

1. Impact parameter in the dipole representation

The impact parameter plays a special role in small-x physics because, unlike transverse momentum, it is conserved in the high-energy limit. Consider for instance the imaginary part of the forward Compton amplitude (which gives the inclusive DIS cross section via the optical theorem). In the leading logarithmic BFKL approximation, it can be written in terms of the transverse momentum dependent gluon density $f(x, \boldsymbol{l})$ and of photon-gluon scattering via a quark loop, see Figure 1a. By a Fourier transform one can trade the loop integration over the transverse quark momentum $\boldsymbol{k}$ for the integral over the transverse distance $\boldsymbol{r}$ between the quark and antiquark. To leading logarithm in the collision energy, one can neglect the kinematic correlation between $\boldsymbol{k}$ and the gluon momentum fraction x, taking the gluon density at the Bjorken variable x_B. With this approximation, the transverse distance between the quark and antiquark is the same before and after

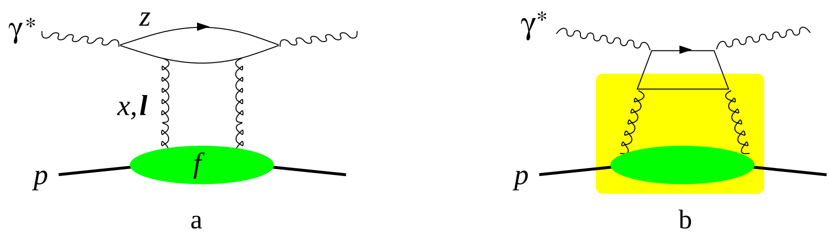

Figure 1. a: Graph for the Compton amplitude in the BFKL framework. b: Emergence of the quark distribution in the aligned-jet configuration with $z \to 1$.

the scattering [2]. The DIS cross section can then be written in terms of the squared photon wave function and the cross section for the scattering of a quark-antiquark color dipole with size $\boldsymbol{r}$ on the proton target. Note that this dipole formulation has not been extended as yet to the accuracy of next-to-leading $\log x$.

An analogous discussion holds for the amplitude of DVCS ($\gamma^* p \to \gamma p$) or meson production with a hard scale (e.g. $\gamma^* p \to \rho p$ or $\gamma p \to J/\Psi p$). By a Fourier transform one can now also trade the transverse momentum transfer $\boldsymbol{\Delta}$ to the proton for the impact parameter $\boldsymbol{b}$, which gives the transverse distance between the colliding photon and proton. The scattering amplitude is then described in terms of the wave functions for the incoming photon and the outgoing photon or meson, and of the amplitude $N(x_B, \boldsymbol{r}, \boldsymbol{b})$ for the scattering of a quark-antiquark dipole with size $\boldsymbol{r}$ and distance $\boldsymbol{b}$ from the proton target (see e.g. [3]).

2. Impact parameter in collinear factorization

Hard exclusive processes like DVCS and meson production can be described in collinear factorization, where the long-distance physics on the proton side is described by generalized parton distributions (see e.g. [4] for recent reviews). This description requires a large virtuality, but it is valid beyond the high-energy limit and can be applied both at fixed-target and collider energies. Fourier transform with respect to $\boldsymbol{\Delta}$ gives parton distributions in impact parameter space, where $\boldsymbol{b}$ is the transverse distance of the struck quark or gluon from the center of the proton [5]. The role of skewness, *i.e.*, of a finite momentum transfer in the light-cone direction is discussed in [6]. Combining the information on $\boldsymbol{b}$ and on the light-cone momentum fraction of the partons, one obtains three-dimensional "tomographic images" of the nucleon. The dependence of impact parameter distributions on the resolution scale is given by evolution equations. From those it is straightforward to obtain evolution equations for the average squared impact parameter $\langle \boldsymbol{b}^2 \rangle$ of partons with given parton momentum fraction [7].

3. Relating the two formulations

In the leading double logarithmic approximation ($\log x \, \log Q^2$) the two descriptions just discussed coincide. To leading $\log x$, the gluon density in the collinear factorization formula for DIS can be evaluated at x_B, and in generalized parton distributions the effect of skewness becomes negligible.

In the dipole formulation, the large Q^2 limit selects small values of $z(1-z)\boldsymbol{r}^2$, where z is the light-cone momentum of the quark with respect to the virtual photon. For configurations with $z \sim \frac{1}{2}$ the typical size $\boldsymbol{r}$ of the color dipole then tends to zero, and the dipole expression can be matched to the contribution of the usual or generalized gluon distribution in the collinear factorization formula. For aligned-jet configurations where $z \to 1$ the typical dipole size $\boldsymbol{r}$ remains large, and a proper factorization into short and long distance quantities leads to the usual or generalized quark distribution, see Figure 1b. For aligned-jet configurations where $z \to 0$ one obtains antiquark distributions. In all cases the meaning of $\boldsymbol{b}$ in the dipole and the collinear formulation coincides: the distance between color dipole and target equals the distance of the struck gluon, quark or antiquark from the target center.

4. Experimental results on the t dependence

The dependence of exclusive cross sections on the invariant momentum transfer t is conveniently parameterized by an exponential $d\sigma/dt \propto e^{-B|t|}$ at small t. Recalling that $t \approx -\boldsymbol{\Delta}^2$ at small x, one finds that the average squared impact parameter at amplitude level is $\langle \boldsymbol{b}^2 \rangle = 2B$. The measured t slopes B in ρ and ϕ production strongly decrease with Q^2 (see e.g. [8]). In the dipole formulation this is understood as the slow decrease with Q^2 of the typical dipole size $\boldsymbol{r}$ resulting from the overlap of the meson and virtual photon wave functions. As long as this size is not small on a hadronic scale, one has large corrections to the collinear factorization formulae. Within experimental errors, the t slope in J/Ψ production shows little variation with Q^2 over the entire range from photoproduction to 16 GeV^2. This suggests that the charm quark mass is quite efficient in selecting small dipole sizes, and that collinear factorization may be applicable here down to $Q^2 = 0$. This is corroborated by the steep rise of the cross section with the photon-proton c.m. energy W. Results of fits to $\sigma(\gamma p \to J/\Psi p) \propto W^\delta$ are $\delta = 0.69 \pm 0.02 \pm 0.03$ from ZEUS and $\delta = 0.75 \pm 0.03 \pm 0.03$ from H1 [9]. Values of the t slope in photoproduction are $B = (4.15 \pm 0.05^{+0.30}_{-0.18})\ \mathrm{GeV}^{-2}$ from ZEUS and $B = (4.630 \pm 0.060^{+0.043}_{-0.163})\ \mathrm{GeV}^{-2}$ from H1, both at $W = 90$ GeV [9].

The t slope in DVCS turns out to be larger, with $B = (6.02 \pm 0.35 \pm 0.39)\ \mathrm{GeV}^{-2}$ at $Q^2 = 8\ \mathrm{GeV}^2$ and $W = 82$ GeV [10]. Within the dipole formulation, this may be understood as due to the contribution from aligned-jet configurations with their large average $\boldsymbol{r}$. In the language of collinear factorization, it may be due to the contribution from sea quarks (at sufficiently large Q^2 the sea quark distribution is smaller than the one for gluons, but the latter appears with an extra factor of α_s in the Compton amplitude). From this point of view, the combination of t slopes measured in J/Ψ production and DVCS gives information on the typical impact parameters of small-x gluons *and* quarks. An interesting observation [11] is that DVCS has a larger t slope than J/Ψ production but an equally steep energy dependence, with $\delta = 0.77 \pm 0.23 \pm 0.19$ at $Q^2 = 8\ \mathrm{GeV}^2$ [10]. A consistent quantitative description of both processes will be a challenge for both the dipole and the collinear formulation.

Acknowledgments

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