DIFFRACTIVE DI-HADRON PRODUCTION AT NLO WITHIN THE SHOCKWAVE FORMALISM*

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We compute the next-leading-order cross sections for diffractive electro- or photoproduction of a pair of hadrons with large p_{T}, out of a nucleus or a nucleon. A hybrid factorization is used, mixing collinear and small-x factorizations, more precisely the shockwave formalism. We demonstrate the cancellation of divergences and extract the finite parts of the differential cross section in general kinematics.

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1. Introduction

To accurately uncover gluon saturation in nucleons and nuclei, precision observables of experimentally-relevant processes are essential. In the last few years, several processes have been investigated in diffractive DIS, such as exclusive dijet production [1–3], exclusive meson production [4], as well as in inclusive DIS, the production of single hadron [5], double hadron [6], and dijet [7]. We propose here the diffractive di-hadron production in $\gamma^{(*)} + p/A$ as another path to saturation. The results are built upon [2] where the Next-Leading-Order (NLO) impact factors are computed in the shockwave formalism. We will emphasize the cancellation of infrared (IR) divergences between the virtual, real, and counterterms contributions.

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2. Theoretical framework

We consider the inclusive production of a pair of hadrons with $\vec{p}_{h_1}^{\,2} \sim \vec{p}_{h_2}^{\,2}$

$$\gamma^{(*)}(p_\gamma) + P(p_0) \rightarrow h_1(p_{h1}) + h_2\left(p_{h2}\right) + X + P'\left(p_0'\right) , \tag{1}$$

where X stands for the other undetected particles on the projectile side. A hybrid factorization (shockwave, collinear) is used.

The shockwave framework describes the interaction of the probe with the target, including saturation effects. The space-time dimension is $D = 2 + d = 4 + 2\epsilon$. We introduce two light-cone vectors n_1, n_2 that define the $+/-$ directions, respectively, and work in the $n_2 \cdot A = A^+ = 0$ gauge. The gluon field is decomposed into external (internal) field b^μ ($\mathcal{A}^\mu$), depending on the value of their $+$ momentum being below (above) an arbitrary cut-off $e^\eta p_\gamma^+$. We boost from the target rest frame to our working frame where the photon and target move ultra-relativistically and $p_0^- \sim p_\gamma^+ \sim \sqrt{s}$ with s the center-of-mass frame of the photon and the target. The b^μ field then has the form of $b^\mu(z) = b^-(\vec{x})\delta(x^+)n_2^\mu$. The Wilson lines

$$U_{\vec{z}} = \mathcal{P} \exp\left\{ ig \int\limits_{-\infty}^{+\infty} \mathrm{d}z^+ b^-(z) \right\} \tag{2}$$

resum to all orders the eikonal interactions with those fields.

All momenta in the projectile side are decomposed as

$$p_i^\mu = x_i p_\gamma^+ n_1^\mu + \frac{p_i^2 + \vec{p}^{\,2}}{2x_i p_\gamma^+} n_2^\mu + p_{i\perp}^\mu \,. \tag{3}$$

The Pomeron exchange between the probe and the target is represented by color-singlet operators built on Wilson lines, *e.g.* the dipole operator

$$\mathcal{U}_{ij} = \mathrm{Tr}\left(U_{\vec{z}_i} U_{\vec{z}_j}^\dagger\right) - N_\mathrm{c} \,. \tag{4}$$

Those operators evolve according to the B-JIMWLK equation [8–20].

Amplitudes are factorized between the impact factors and the non-perturbative matrix elements of those operators between the target in and out state. Collinear factorization describes the fragmentation part and its use is possible thanks to the hard scale $\vec{p}_h^{\,2} \gg \Lambda_\mathrm{QCD}^2$. We also impose $\vec{p}^{\,2} \gg \vec{p}_h^{\,2}$, $\vec{p}$ being the relative transverse momentum of the two hadrons. This implies that they have a large separation angle, eliminating the possibility of them being produced from one single parton. From this theorem and the collinearity of the fragmenting parton and the produced hadrons, the LO cross section is the convolution of Fragmentation Functions (FF) and coefficient functions,

$$\frac{\mathrm{d}\sigma_{0JI}^{h_1 h_2}}{\mathrm{d}x_{h_1}\mathrm{d}x_{h_2}\mathrm{d}^d\vec{p}_{h_1}\mathrm{d}^d\vec{p}_{h_2}} = \sum_q \int_{x_{h_1}}^{1} \frac{\mathrm{d}x_q}{x_q} \int_{x_{h_2}}^{1} \frac{\mathrm{d}x_{\bar{q}}}{x_{\bar{q}}} \left(\frac{x_q}{x_{h_1}}\right)^d \left(\frac{x_{\bar{q}}}{x_{h_2}}\right)^d$$
$$\times D_q^{h_1}\left(\frac{x_{h_1}}{x_q}\right) D_{\bar{q}}^{h_2}\left(\frac{x_{h_2}}{x_{\bar{q}}}\right) \frac{\mathrm{d}\hat{\sigma}_{JI}}{\mathrm{d}x_q\,\mathrm{d}x_{\bar{q}}\,\mathrm{d}^d\vec{p}_q\,\mathrm{d}^d\vec{p}_{\bar{q}}} + (h_1 \leftrightarrow h_2)\,, \tag{5}$$

expressed in terms of the partonic cross section, J, I representing the photon polarization for the complex amplitude and the amplitude, respectively.

3. NLO computations in a nutshell

The NLO density matrix contains all types of contributions depending on the nature of the impact factors, *i.e.*

$$\mathrm{d}\sigma_{JI}^{\mathrm{NLO}} = \mathrm{d}\sigma_{1JI} + \mathrm{d}\sigma_{2JI} + \mathrm{d}\sigma_{3JI} + \mathrm{d}\sigma_{4JI} + \mathrm{d}\sigma_{5JI}\,. \tag{6}$$

Here, $\mathrm{d}\sigma_{1JI}$ and $\mathrm{d}\sigma_{2JI}$ are the dipole × dipole and dipole × double dipole virtual contributions while $\mathrm{d}\sigma_{3JI}$, $\mathrm{d}\sigma_{4JI}$, and $\mathrm{d}\sigma_{5JI}$ are the dipole × dipole, dipole × double dipole and double dipole × double dipole real parts. These various contributions also depend on the detail of the FF used, as shown in Fig. 1.

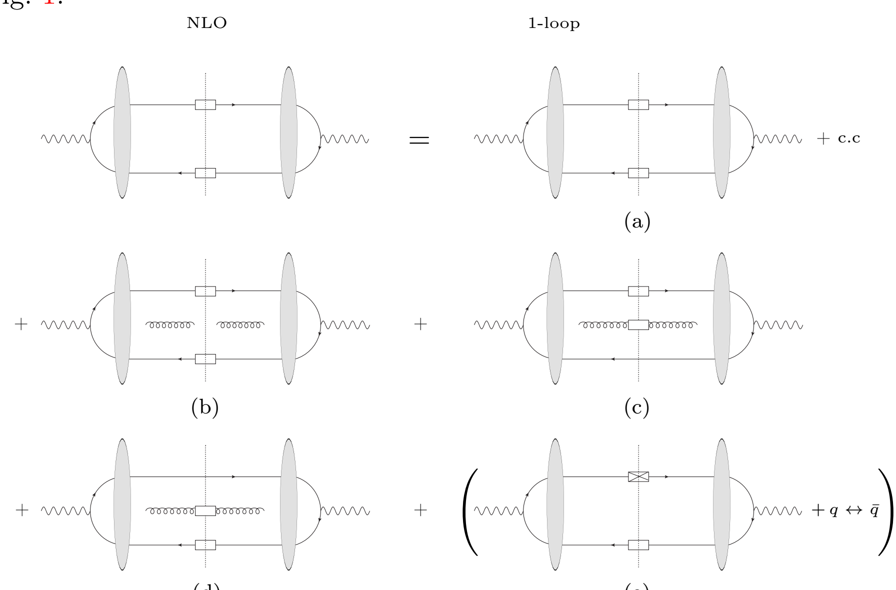

Fig. 1. NLO cross-section dependence on FF, represented by the box.

To deal with divergences, dimensional regularization, and an IR cut-off α are used for the transverse and longitudinal integrations respectively. Soft and collinear are the only divergences present and are only contained in $\mathrm{d}\sigma_{1JI}$ and $\mathrm{d}\sigma_{3JI}$. The rapidity divergences, proportional to some $\ln\alpha$ terms, have been removed at the level of amplitude using the B-JIMWLK equation, as explained in [2]. Diagram (e) in Fig. 1 corresponds to the counterterms produced by putting the FF renormalization and evolution equation taken from [21] into the LO cross section Eq. (5). Collinear divergences can only come from diagrams where the splitting occurs after the shockwave and the same is true for soft divergences, see Fig. 2.

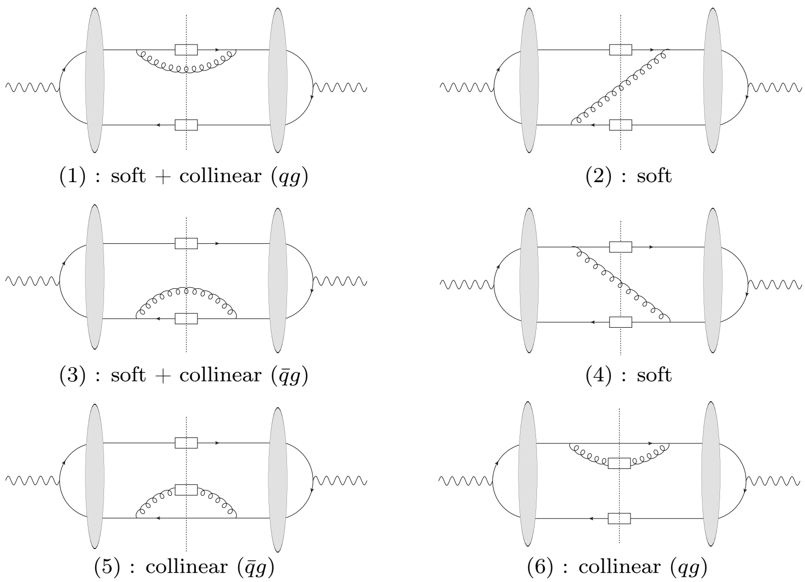

Fig. 2. Divergent diagrams in diagrams (b), (c), and (d) of Fig. 1. Diagrams (1)–(4) correspond to the divergent part of diagram (b), diagram (5) is the divergent diagram in diagram (c), and (6) for (d).

The collinear divergences appear as denominators of $(x_i'\vec{p}_g - x_g\vec{p}_i)^2$ with $i \in \{q, \bar{q}\}$ in $\mathrm{d}\sigma_{3JI}$. To extract those divergences, we need to Fourier transform the non-perturbative part to disentangle and integrate over the spectator parton (the non-fragmenting one) transverse momentum easily. We also need to change variables from (x_i', x_g) to (x_i, β), where $(x_i', x_g), x_i$ are the longitudinal fractions of the *children* and *parent* partons w.r.t. to the photon momentum and β is the longitudinal fraction w.r.t. to the parent parton. This is to be able to compare to the counterterms. When extracting the divergent part of diagrams (1) and (3) of Fig. 2, one has to introduce the + prescription and remove the resulting soft contribution to avoid double counting. This issue does not appear for diagrams (5) and (6).

The soft contribution of diagram (b) of Fig. 1 is computed from diagrams (1)–(4) of Fig. 2 altogether. We rescale $\vec{p}_g = x_g \vec{u}$ with $|\vec{u}| \sim |\vec{p}_h|$ to isolate the divergences in the form of $\int_\alpha^1 \frac{\mathrm{d}x_g}{x_g^{3-d}}$. In the rest of the integrand, we put safely x_g to 0 (as $x'_q, x'_{\bar{q}}$ cannot be arbitrarily small, being limited by x_h). Similar changes of variables as in the collinear case are realized too. Most of the soft divergences in (1)–(4) cancel with diagram (a) of Fig. 1. The rest cancel with divergences introduced by the + prescription in (1) and (3). The leftover divergences from diagrams in Fig. 2 cancel with the counterterms.

4. Conclusion and outlook

We have computed the NLO cross sections of the diffractive production of a pair of hadrons with large p_{T} out of $\gamma^{(*)}+p/A$ for all possible sets of photon polarization and in general kinematics (Q^2, t, p_{T}). Divergences have been cancelled altogether between the counterterms from the FF renormalization and evolution equation, dipole × dipole real, and virtual cross sections. They are applicable to both the LHC with Ultra-Peripheral collisions and to the Electron–Ion Collider.

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