Particle production at large momentum transfer

V.P. Gonçalves, Werner K. Sauter†
High and Medium Energy Group
Instituto de Física e Matematica
Universidade Federal de Pelotas, Rio Grande do Sul, Brasil

Diffractive particle production in ep collisions and coherent pp interactions is studied assuming that the color singlet t channel exchange carries large momentum transfer. The differential and total cross sections for vector meson and photon production are calculated using the non-forward solution of the LO and NLO BFKL equation at high energy and large momentum transfer and the predictions are compared with the DESY HERA data. Moreover, we estimate the rapidity distributions and total cross section for the J/Ψ and ρ production in coherent pp interactions at LHC energies. We predict large rates, which implies that the experimental identification can be feasible at the LHC.

1. Introduction

The description of exclusive diffractive processes has been proposed as a probe of the Quantum Chromodynamics (QCD) dynamics in the high energy limit (For a recent review c.f. Ref. [1]). It is expected that the study of these processes provide insight into the parton dynamics of diffractive exchange when a hard scale is present. In particular, the diffractive vector meson and photon production at large momentum transfer is expected to probe the QCD Pomeron, which is described by the Balitsky, Fadin, Kuraev, and Lipatov (BFKL) equation [2, 3, 4, 5]. In this contribution, we present a brief summary of the results obtained in Refs. [6, 7, 8], where the vector meson and photon production at large momentum transfer were studied considering the non-forward solution of the BFKL equation at leading order (LO) and next-to-leading order (NLO). In particular, we have estimated the cross sections for the ρ, J/Ψ and γ production at large-t in ep collisions at HERA energy which can represented by the diagram presented in Fig. 1 (left panel). Moreover, we have studied vector meson production at large-t in coherent pp interactions as represented in Fig. 1 (right panel), which is an alternative way to study QCD dynamics at high energies.

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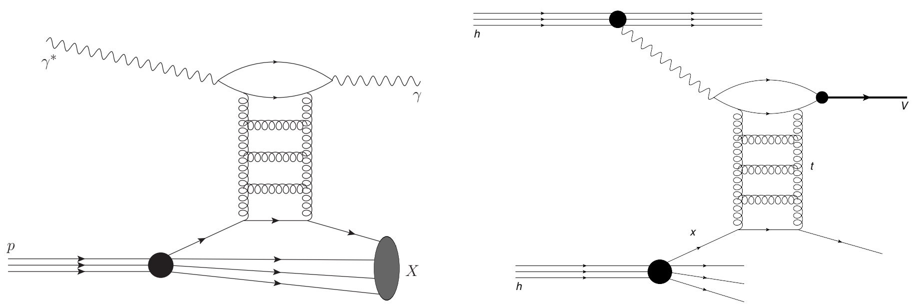

Fig. 1. The exclusive photon and vector meson production at large-t in ep collisions (left panel) and coherent pp interactions (right panel).

This contribution is organized as follows. In the next section we summarize the formalism used in the calculation. Our results are presented in Section 3 and the main conclusions are discussed in Section 4.

2. Formalism

The differential and total cross sections for diffractive particle photoproduction at large momentum transfer reads

$$\frac{d\sigma_{\gamma h \to YX}}{dt} = \int_{x_{\min}}^{1} dx_j \, \frac{d\sigma}{dt dx_j}, \quad \sigma_{\rm tot} = \int_{t_{\min}}^{t_{\max}} dt \, \frac{d\sigma_{\gamma h \to YX}}{dt}\,, \qquad (1)$$

where h denotes a hadron, Y the produced particle ($J/\psi, \Upsilon, \rho$ and γ), X the hadron fragments and

$$\frac{d\sigma}{dt dx_j} = \left[\frac{81}{16} G(x_j, |t|) + \sum_j (q_j(x_j,|t|) + \bar{q}_j(x_j,|t|)) \right] \frac{d\hat{\sigma}}{dt}. \qquad (2)$$

Moreover, G, q and $\bar{q}$ are parton distribution functions (we are using CTEQ6L parametrization). The partonic cross section for vector meson production is given by

$$\frac{d\hat{\sigma}}{dt}(\gamma q \to V q) = \frac{1}{16\pi} |\mathcal{A}_V(s,t)|^2. \qquad (3)$$

and for photon production,

$$\frac{d\hat{\sigma}}{dt}(\gamma^* q \to \gamma q) = \frac{1}{16\pi} \left\{ |\mathcal{A}_{(+,+)}(s,t)|^2 + |\mathcal{A}_{(+,-)}(s,t)|^2 \right\}. \qquad (4)$$

The amplitudes, in both cases, have a general expression (for details, see [7, 8]),

$$\mathcal{A} \propto \int d\nu \; G_{V,\gamma}(\nu) \left(\frac{s}{\Lambda^2}\right)^{\omega(\nu)} I_{\gamma/V,\gamma}(\nu) I_{q,q}(\nu)\,, \tag{5}$$

where G depends on the produced particle, $\omega(\nu) = \bar{\alpha}_s \chi(1/2 + i\nu)$ is the BFKL characteristic function and I are related with the impact factors for the transitions $\gamma \to (V, \gamma)$ and $q \to q$.

At leading order the BFKL function $\chi(\gamma)$ is given by

$$\chi^{\mathrm{LO}}(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)\,, \tag{6}$$

where $\psi(z)$ is the digamma function. In what follows this expression is used in our calculations of the vector meson production at large-t. Several shortcomings are present in a leading order calculation: the energy scale Λ is arbitrary; α_s is not running at LO BFKL and the power growth with energy violates s-channel unitarity at large rapidities. Some of these shortcomings are reduced if we consider the NLO corrections for the BFKL kernel obtained originally in Refs. [9, 10]. In this case, we have that

$$\chi(\gamma) = \chi^{\mathrm{LO}}(\gamma) + \overline{\alpha}_s \chi^{\mathrm{NLO}}(\gamma), \quad \bar{\alpha}_s = N_c \alpha_s/\pi, \tag{7}$$

with the χ^{NLO} function being given by

$$\begin{aligned} \chi^{\mathrm{NLO}}(\gamma) \;&=\; \mathcal{C}\chi^{\mathrm{LO}}(\gamma) + \frac{1}{4}\left[\psi''(\gamma) + \psi''(1-\gamma)\right] - \frac{1}{4}\left[\phi(\gamma) + \phi(1-\gamma)\right] \\ &\quad - \frac{\pi^2 \cos(\pi\gamma)}{4\sin^2(\pi\gamma)(1-2\gamma)} \left\{3 + \left(1 + \frac{N_f}{N_c^3}\right) \frac{(2 + 3\gamma(1-\gamma))}{(3-2\gamma)(1+2\gamma)}\right\} \\ &\quad + \frac{3}{2}\zeta(3) - \frac{\beta_0}{8N_c}\left(\chi^{\mathrm{LO}}(\gamma)\right)^2, \end{aligned} \tag{8}$$

with $\mathcal{C} = \left(4 - \pi^2 + 5\beta_0/N_c\right)/12$, $\beta_0 = (11N_c - 2N_f)/3$ is the leading coefficient of the QCD β function, N_f is the number of flavours, $\psi^{(n)}(z)$ is the poligamma function, $\zeta(n)$ is the Riemann zeta-function and

$$\phi(\gamma) + \phi(1-\gamma) = \sum_{m=0}^{\infty} \left[\frac{1}{\gamma + m} + \frac{1}{1-\gamma+m}\right] \left[\psi'(\frac{2+m}{2}) - \psi'(\frac{1+m}{2})\right]. \tag{9}$$

However, there are several problems associated with these corrections (c.f. Ref. [11]). Among of them exist problems associated to the choice of energy scale, the renormalization scheme and related ambiguities.

An alternative is to use the ω-expansion, developed to resum collinear effects at all orders in a systematic way. This approach was revisited in

Ref. [12] obtaining an expression for the collinearly improved BFKL kernel characteristic function, denoted All-poles hereafter, given by

$$\omega_{\mathrm{All-poles}} = \overline{\alpha}_s \chi^{\mathrm{LO}}(\gamma) + \overline{\alpha}_s^2 \chi^{\mathrm{NLO}}(\gamma) +$$
$$+ \sum_{m=0}^{\infty} \left[\left(\sum_{n=0}^{\infty} \frac{(-1)^n (2n)!}{2^n n! (n+1)!} \frac{(\overline{\alpha}_s + a\overline{\alpha}_s^2)^{n+1}}{(\gamma + m - b\overline{\alpha}_s)^{2n+1}} \right) - \frac{\overline{\alpha}_s}{\gamma + m} - \right.$$
$$\left. -\overline{\alpha}_s^2 \left(\frac{a}{\gamma + m} + \frac{b}{(\gamma + m)^2} - \frac{1}{2(\gamma + m)^3} \right) \right] + \{\gamma \to 1 - \gamma\}\,, \tag{10}$$

where

$$a = \frac{5\beta_0}{12 N_c} - \frac{13 N_f}{36 N_c^3} - \frac{55}{36}, \quad b = -\frac{\beta_0}{8 N_c} - \frac{N_f}{6 N_c^3} - \frac{11}{12}. \tag{11}$$

Another alternative to solve the problems present in the original NLO kernel was proposed in Ref. [13]. To solve the energy scale ambiguity, the Brodsky-Lepage-Mackenzie (BLM) optimal scale setting [14] and the momentum space subtraction (MOM) scheme of renormalization were used to obtain the following BFKL characteristic function,

$$\omega_{\mathrm{BLM}}^{\mathrm{MOM}} = \chi^{\mathrm{LO}}(\gamma) \frac{\alpha_{\mathrm{MOM}}(\hat{Q}^2) N_c}{\pi} \left[1 + \hat{r}(\nu) \frac{\alpha_{\mathrm{MOM}}(\hat{Q}^2)}{\pi} \right], \tag{12}$$

where α_{MOM} is the coupling constant in the MOM scheme,

$$\alpha_{\mathrm{MOM}} = \alpha_s \left[1 + \frac{\alpha_s}{\pi} T_{\mathrm{MOM}} \right], \tag{13}$$

with T being a function of number of colors, number of flavors and of a gauge parameter. Moreover, the function $\hat{Q}$ is the BLM optimal scale, which is given by

$$\hat{Q}^2(\nu) = Q^2 \exp\left[\frac{1}{2} \chi^{\mathrm{LO}}(\gamma) - \frac{5}{3} + 2\left(1 + \frac{2}{3}\varrho\right) \right], \tag{14}$$

with $\varrho \approx 2.3439$. Finally, $\hat{r}$ is the NLO coefficient of the characteristic function,

$$\hat{r}(\nu) = -\frac{\beta_0}{4} \left[\frac{\chi^{\mathrm{LO}}(\nu)}{2} - \frac{5}{3} \right] - \frac{N_c}{4\chi^{\mathrm{LO}}(\nu)} \left\{ \frac{\pi^2 \sinh(\pi\nu)}{2\nu \cosh^2(\pi\nu)} \right.$$
$$\times \left[3 + \left(1 + \frac{N_f}{N_c^3}\right) \frac{11 + 12\nu^2}{16(1+\nu^2)} \right] - \chi''^{\mathrm{LO}}(\nu) + \frac{\pi^2 - 4}{3} \chi^{\mathrm{LO}}(\nu)$$
$$\left. - \frac{\pi^3}{\cosh(\pi\nu)} - 6\zeta(3) + 4\tilde{\phi}(\nu) \right\} + 7.471 - 1.281\beta_0, \tag{15}$$

with

$$\tilde{\phi}(\nu) = 2\int_0^1 dx \, \frac{\cos(\nu \ln(x))}{(1+x)\sqrt{x}} \left[\frac{\pi^2}{6} - \mathrm{Li}_2(x)\right], \qquad (16)$$

where $\mathrm{Li}_2(x)$ is the Euler dilogarithm or Spence function.

3. Results

The results strongly depend on the coupling constant and the choice of energy scale Λ. In Refs. [6, 7] we have performed an detailed study of these choices in the predictions. We assumed a fixed coupling constant ($\alpha_s = 0.21$) and that the energy scale for vector mesons can be expressed by $\Lambda^2 = \beta M_V^2 + \gamma|t|$, following [15], where β and γ are free parameters to be fixed by the data. Our results are presented in Fig. 2, where we demonstrated that LO BFKL formalism is able to describe the HERA data[16, 17, 18].

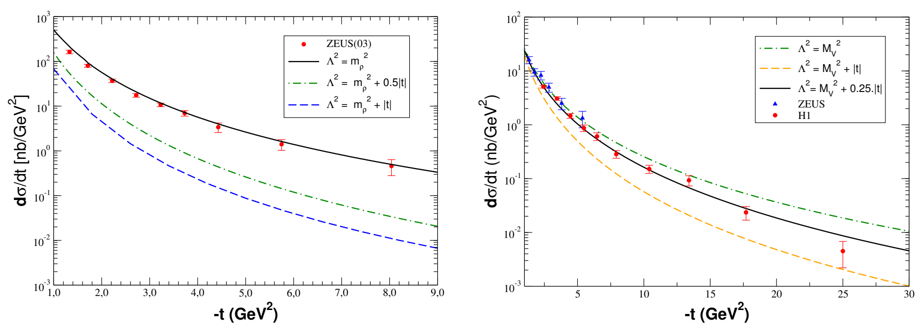

Fig. 2. Cross section for the exclusive production of vector mesons at large-t in ep collisions. Left: ρ production. Right: J/ψ production. Data from HERA[16, 17, 18].

In the case of photon production at large-t, we assumed that the scale can be expressed by $\Lambda^2 = \gamma'|t|$, with γ' depending on the BFKL function (see [8]). The results for the differential and total cross sections are presented in Fig. 3. In this case, we analyze the effects of change the BFKL dynamics, using distinct analytically forms for the NLO BFKL kernel as well as the LO one. We have obtained a reasonable agreement with the HERA experimental data. This results must be taken as an educated estimate, due the fact that we have used the impact factors of the transition $\gamma^* \to \gamma$ at leading order. The NLO expression was obtained recently in Ref. [23].

Let's now consider vector meson production at large-t in coherent pp collisions. The cross section in a coherent hadron-hadron collision is given

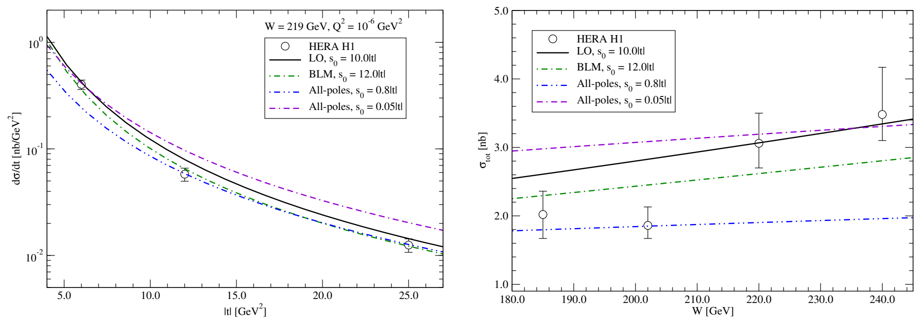

Fig. 3. Exclusive photon production at large-t in ep collisions. Data from HERA[22].

by

$$\frac{d\sigma\ [h_1 + h_2 \to h_1 \otimes Y \otimes X]}{dy} = \int_{t_{\min}}^{t_{\max}} dt\ \omega \frac{dN_\gamma(\omega)}{d\omega}\ \frac{d\sigma_{\gamma h \to YX}}{dt}\,(\omega)\ , \qquad (17)$$

where $dN_\gamma(\omega)/d\omega$ is the equivalent photon flux as a function of photon energy ω. In our calculations we have used the photon flux proposed in Ref. [20] for the proton and in Ref. [21] for the nucleus. Our predictions for the rapidity distributions for ρ and J/Ψ production are shown in Fig. 4 considering different t-ranges. In Ref. [7] we also have calculated Υ production. In Table 1, we present our predictions for the event rates at LHC energy. Our results indicate that experimental identification of these processes can be feasible at the LHC.

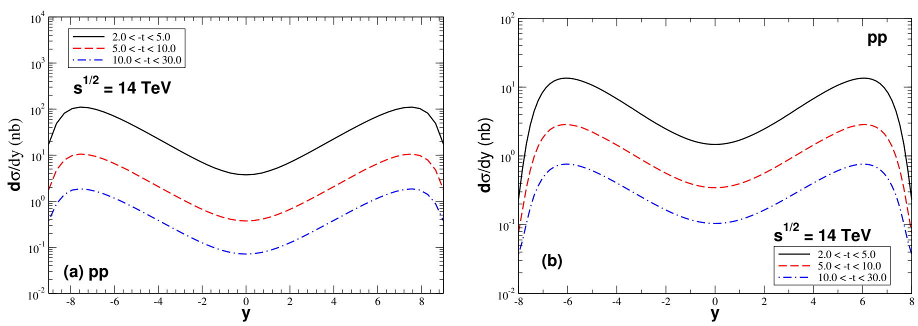

Fig. 4. Rapidity distribution for the ρ (left panel) and J/Ψ (right panel) production in coherent pp interactions at LHC energy.

Table 1. The integrated cross section (event rates/second) for diffractive vector meson photoproduction at large momentum transfer in pp and $PbPb$ collisions at LHC.

Meson	t range	pp	$PbPb$
ρ	$2.0 < \|t\| < 5.0$	751.0 nb (7510.0)	20.0 mb (8.4)
	$5.0 < \|t\| < 10.0$	71.0 nb (710.0)	2.2 mb (0.9)
	$10.0 < \|t\| < 30.0$	12.0 nb (120.0)	0.4 mb (0.17)
J/ψ	$2.0 < \|t\| < 5.0$	97.0 nb (970.0)	3.0 mb (13.0)
	$5.0 < \|t\| < 10.0$	21.0 nb (210.0)	0.9 mb (0.38)
	$10.0 < \|t\| < 30.0$	6.0 nb (60.0)	0.3 mb (0.12)
Υ	$2.0 < \|t\| < 5.0$	0.8 nb (8.0)	0.26 mb (0.1)
	$5.0 < \|t\| < 10.0$	0.4 nb (4.0)	0.17 mb (0.07)
	$10.0 < \|t\| < 30.0$	0.3 nb (3.0)	0.16 mb (0.06)

4. Conclusions and perspectives

The description of the high energy limit of Quantum Chromodynamics (QCD) is an important open question in the Standard Model. During the last decades several approaches were developed in order to improve our understanding from a fundamental perspective. In particular, after a huge theoretical effort, now we have available the NLO corrections for the BFKL characteristic function, which allow us to improve the analysis of the exclusive vector meson and photon production at large-t which are expected to probe the underlying QCD dynamics. Our results for vector meson and photon production in ep collisions at HERA demonstrated that the BFKL formalism is able to describe the current experimental data. Moreover, our estimates for vector meson production in coherent pp interactions at LHC demonstrated that the study of this process can constrain QCD dynamics. It is important to emphasize that our results are complementary to the recent theoretical and phenomenological studies that use NLO BFKL Pomeron [24, 25, 26, 27]. Presently, we are performing a more accurate analysis on the choice of the energies scales in exclusive production using the principle of maximum conformality in NLO BFKL Pomeron[28].

Acknowledgments

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