PROCEEDINGS OF SCIENCE

Absorptive corrections in leading neutron production

F. Carvalho[1,*] **V.P. Gonçalves**[2], **F.S. Navarra**[3] **and D. Spiering**[3]

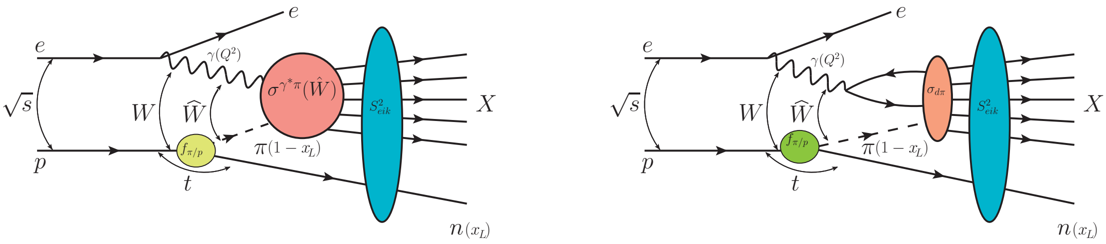
[1]*Departamento de Física, Universidade Federal de São Paulo,*
Campus Diadema, Rua Prof. Artur Riedel, 275, Jd. Eldorado, 09972-270, Diadema, SP, Brazil.
[2] *High and Medium Energy Group, Instituto de Física e Matemática, Universidade Federal de Pelotas Caixa Postal 354, 96010-900, Pelotas, RS, Brazil.*
[3]*Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970 São Paulo, SP, Brazil.*
E-mail: babi.usp@gmail.com, barros@ufpel.edu.br, navarra@if.usp.br, spiering@usp.br

Leading neutron (LN) production in *ep* collisions at high energies is investigated using the color dipole formalism and taking into account saturation effects. We update the treatment of absorptive effects and estimate the impact of these effects on LN spectra in the kinematical range that will be probed by the Electron Ion Collider (EIC) and by the Large Hadron electron Collider (LHeC). Our results indicate that the LN spectrum is strongly suppressed at small photon virtualities. These results suggest that absorptive effects cannot be disregarded in future measurements of the $\gamma\pi$ cross section to be extracted from data on leading neutron production.

XV International Workshop on Hadron Physics (XV Hadron Physics) 13 - 17 September 2021
Online, hosted by Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil

*Speaker

PoS(XVHadronPhysics)053



(a) (b)

Figure 1: (a) Leading neutron n production in $ep \to enX$ interactions at high energies. (b) Description of the process in the color dipole model.

1. Introduction

The pion structure can be probed in electron - proton collisions through the Sullivan process, where the electron scatters off the meson cloud of the proton target. The associated processes can be separated by tagging a forward ("leading") neutron in the final state, which carries a large fraction of the proton energy. Theoretically, this leading neutron production, is usually described assuming that the splitting $p \to \pi^+ n$ and the photon – pion interaction can be factorized, as represented in Fig. 1 (a), where $f_{\pi/p}$ represents the pion flux. Assuming the validity of the factorization hypothesis and the universality of the fragmentation process, which allows us to constrain $f_{\pi/p}$ using the data of leading neutron production in pp collisions, we can obtain $\sigma^{\gamma^*\pi}$ and, consequently, determine the x and Q^2 dependencies of the pion structure function. However, the validity of this procedure is limited by absorptive effects, denoted by S^2_{eik} in Fig. 1, that are associated to soft rescatterings between the produced and spectator particles. The studies performed in Refs. [1–3] indicated that these effects strongly affect leading neutron production in pp collisions. In contrast, the absorptive corrections are predicted to be smaller in ep collisions and their effects become weaker at larger photon virtualities.

In Refs. [4] we proposed a model to treat leading neutron production in ep processes based on the color dipole formalism [5]. In this model, the virtual photon - pion cross section can be factorized in terms of the photon wave function (which describes the photon splitting into a $q\bar{q}$ pair) and the dipole - pion cross section $\sigma_{d\pi}$, as represented in Fig. 1 (b). As shown in Refs. [4], the HERA data are quite well described by this approach assuming that absorptive corrections can be factorized and represented by a multiplicative constant factor, denoted by K in Ref. [4].

In this contribution we describe the studies of absorptive effects published in [6], where an update of Ref. [1] was performed. This approach allows us to estimate these effects in terms of the color dipole formalism, i.e. using the same ingredients of the model proposed in [4].

2. Formalism

At high center - of - mass energies, leading neutron production can be seen as a set of three factorizable subprocesses [See Fig. 1 (b)]: i) the photon emitted by the electron fluctuates into a quark-antiquark pair (the color dipole), ii) the color dipole interacts with the pion and iii) the leading neutron is formed. In the color dipole formalism, when we include the absorptive corrections, the differential cross section reads:

$$\frac{d\sigma(W,Q^2,x_L)}{dx_L} = \int d^2\boldsymbol{b}\, \rho_{n\pi}(x_L,\boldsymbol{b}) \int dz\, d^2\boldsymbol{r} \sum_{L,T} \left|\Psi_{T,L}(z,\boldsymbol{r},Q^2)\right|^2 \sigma_{d\pi}(x_\pi,\boldsymbol{r})\, S^2_{eik}(\boldsymbol{r},\boldsymbol{b}) \quad (1)$$

where $\rho_{n\pi}(x_L,\boldsymbol{b})$ is the probability density of finding a neutron and a pion with momenta x_L and $1-x_L$, respectively, and with a relative transverse separation $\boldsymbol{b}$, which is given by

$$\rho_{n\pi}(x_L,\boldsymbol{b}) = \sum_{\lambda\lambda'} |\psi^{\lambda\lambda'}_{n\pi}|^2 \qquad \psi^{\lambda\lambda'}_{n\pi} = \frac{1}{2\pi}\int d^2\mathbf{p}_T\, e^{i\boldsymbol{b}\cdot\mathbf{p}_T} \sqrt{\frac{2}{3}}\, \phi^{\lambda\lambda'}_{n\pi}\, G(x_L,p_T) \quad (2)$$

where $\phi^{\lambda\lambda'}_{n\pi}(x_L,\mathbf{p}_T)$ is the probability amplitude to find, inside a proton with spin up, a neutron with longitudinal momentum fraction x_L, transverse momentum $\mathbf{p}_T$ and helicity λ and a pion, with longitudinal momentum fraction $1-x_L$, transverse momentum $-\mathbf{p}_T$ and helicity λ'. Because of the extended nature of the hadrons involved, we need to include a phenomenological πNN form factor, $G(x_L,p_T)$. We use the covariant form factor given by

$$G(x_L,p_T) = \exp[R_c^2(t-m_\pi^2)]\,(1-x_L)^{-t} \quad (3)$$

where R_c was fixed using the HERA data (For details see Ref. [4]).

In Eq. (1) Q^2 is the virtuality of the exchanged photon, x_L is the proton momentum fraction carried by the neutron and t is the square of the four-momentum of the exchanged pion. In Eq. (1), the virtual photon - pion cross section was expressed in terms of the transverse and longitudinal photon wave functions Ψ_i, which describe the photon splitting into a $q\bar{q}$ pair of size $r \equiv |\boldsymbol{r}|$, and the dipole-pion cross section $\sigma_{d\pi}$, which is determined by the QCD dynamics at high energies [7]. The variable z represents the longitudinal photon momentum fraction carried by the quark, the variable $\boldsymbol{r}$ defines the relative transverse separation of the pair (dipole) and the scaling variable x_π is defined by $x_\pi = x/(1-x_L)$, where x is the Bjorken variable.

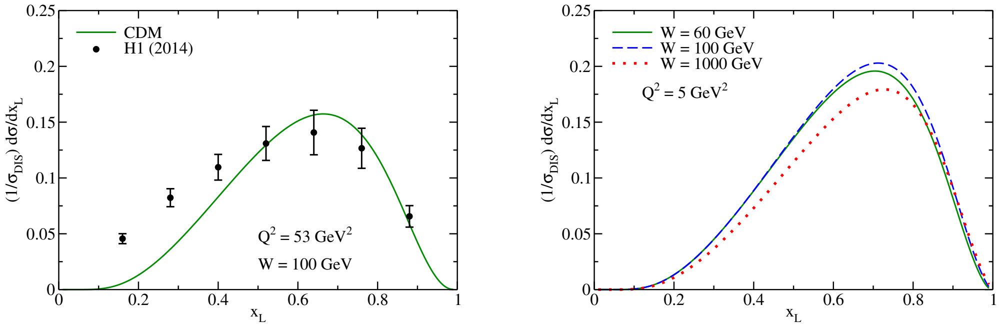
In Ref. [1] and later in [6] it was suggested that absorptive effects can be implemented in impact parameter space. Assuming that the scattering amplitude for the dipole - neutron scattering can be expressed by a Gaussian profile function, the survival factor S^2_{eik} associated to the absorptive effects will be given by [1]

$$S^2_{eik}(\boldsymbol{r},\boldsymbol{b}) = \left\{1 - \Lambda^2_{\text{eff}}\frac{\sigma_{dn}(x_n,\boldsymbol{r})}{2\pi}\exp\left[-\frac{\Lambda^2_{\text{eff}}\boldsymbol{b}^2}{2}\right]\right\}, \quad (4)$$

where $x_n = x/x_L$ and Λ^2_{eff} is an effective parameter which was determined in Ref. [1]. In our analysis, we assume that σ_{dn} is equal to the dipole - proton cross section, σ_{dp}, constrained by the HERA data. As in Ref. [4], we assume that the dipole-pion cross section can be related to the dipole - proton cross section using the additive quark model. Finally, σ_{dp} is described by the Color Glass Condensate formalism, as given by the IIM model proposed in Ref. [8]. With this assumption, we have $\sigma_{d\pi}(x,\boldsymbol{r}) = \frac{2}{3}\cdot\sigma_{dp}(x,\boldsymbol{r})$.

3. Results and dicussion

In Fig. 2 (a) the Color Dipole Model (CDM) prediction for the kinematical range probed by HERA is presented. As it can be seen, the H1 data [9] are quite well described in the region



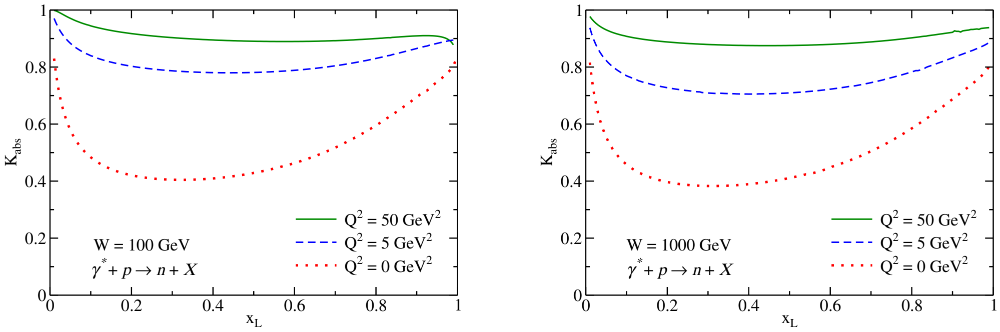
(a) (b)

Figure 2: (a) Comparison of the CDM prediction with the H1 data [9]. (b) Predictions for the spectra considering different center - of - mass energies and $Q^2 = 5$ GeV^2.

$x_L \gtrsim 0.5$. As shown in previous studies [2], for smaller values of x_L, additional contributions are expected to play a significant role. In Fig. 2 (b), we show spectra calculated at hgiher energies. From the figure we see that the predictions are not strongly dependent on W. This is expected from the results presented in Ref. [4], where we have demonstrated that saturation leads to Feynman scaling, i.e. the energy independence of the x_L spectra. Such scaling is expected to be strict when the saturation scale becomes larger than the photon virtuality, which is satisfied for small values of Q^2 ($\lesssim 2$ GeV^2). In contrast, the DGLAP evolution leads to stronger violation of Feynman scaling, as shown in Ref. [4].

We can estimate the impact of the absorptive effects through the calculation of the ratio between the cross sections with and without absorption, where the latter is estimated assuming $S^2_{eik} = 1$. Our predictions for this ratio, denoted K_{abs} hereafter, are presented in Fig. 3. Our results show that the impact increases for smaller values of Q^2 and larger energies W. For $Q^2 = 50$ GeV^2, we see that $K_{abs} \approx 0.9$ for $x_L \gtrsim 0.5$. This weak absorption is expected in the Color Dipole Model, since at large values of Q^2 the main contribution for the cross section comes from dipoles with a small pair separation. In this regime, denoted color transparency, the impact of the rescatterings is small, which implies that the absorptive effects become negligible. Another important aspect, is that for large photon virtualities, the main effect of absorption is to suppress the cross section by a constant factor. Similar results were derived in Ref. [1]. On the other hand, for photoproduction ($Q^2 = 0$), we observe strong absorptive effects, which reduce the cross sections by a factor ≈ 0.4 for $x_L = 0.5$. This result is also expected, since for small Q^2 the cross section is dominated by large dipoles and, consequently, the contribution of the rescatterings cannot be disregarded. Our results indicate that the contribution of the absorptive effects is not strongly energy dependent. This result suggests that the main conclusion of Ref. [4], that the spectra will satisfy Feynman scaling, is still valid when the absorptive effects are estimated using a more realistic model, as already observed in Fig. 2 (b).

We demonstrated that our model describes the HERA data in the region where the pion exchange is expected to dominate. Moreover, we have presented predictions for the kinematical ranges that will be probed by the future EIC and LHeC. Our results indicate that the leading neutron spectra are not strongly energy dependent at small photon virtualities. We have estimated the impact of the absorptive effects, demonstrated that they increase at smaller photon virtualities and that they



(a) (b)

Figure 3: Dependence of the absorptive effects on x_L in leading neutron production in *ep* collisions for differents values of the photon virtuality and (a) W = 100 GeV and (b) W = 1000 GeV.

depend on the longitudinal momentum x_L. Our results show that modelling these effects by a constant factor is a good approximation only for large Q^2.

Acknowledgments

This work was partially financed by the Brazilian funding agencies CNPq, FAPESP, FAPERGS and INCT-FNA (process number 464898/2014-5).

References

[1] U. D′Alesio and H.J. Pirner, Eur. Phys. J. A **7**, 109 (2000).

[2] B. Z. Kopeliovich, H. J. Pirner, I. K. Potashnikova, K. Reygers and I. Schmidt, Phys. Rev. D **91**, 054030 (2015).

[3] V. A. Khoze, A. D. Martin and M. G. Ryskin, Phys. Rev. D **96**, 034018 (2017).

[4] F. Carvalho, V. P. Goncalves, D. Spiering and F. S. Navarra, Phys. Let B **752**, 76 (2016).; V. P. Goncalves, D. Spiering and F. S. Navarra, Phys. Rev. D **93** , 054025 (2016).

[5] N. N. Nikolaev, B. G. Zakharov, Z. Phys. C **64**, 631 (1994).

[6] F. Carvalho, V. P. Gonçalves, F. S. Navarra and D. Spiering, Phys. Rev. D **103**, 034021 (2021).

[7] V. P. Gonçalves, M. V. T. Machado, B. D. Moreira, F. S. Navarra and G. S. dos Santos, Phys. Rev. D **96**, 094027 (2017).

[8] E. Iancu, K. Itakura, S. Munier, Phys. Lett. B **590**, 199 (2004).

[9] V. Andreev et al. [H1 Collaboration], Eur. Phys. J. C **74**, 2915 (2014).

[10] V. P. Goncalves, B. D. Moreira, D. Spiering and F. S. Navarra, Phys. Rev. D **94**, 014009 (2016); F. Carvalho, V. P. Goncalves, D. Spiering and F. S. Navarra, Phys. Rev. D **97**, 074002 (2018).