

VECTOR MESON PHOTOPRODUCTION IN HADRONIC COLLISIONS: RECENT RESULTS AND PROSPECTS*

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The recent results that demonstrate that the vector meson photoproduction in hadronic collisions can be used to constrain the QCD dynamics at high energies and improve our understanding of the gluon Sivers function are reviewed.

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1. Introduction

One of the goals of hadron physics is to achieve a deeper knowledge of the hadronic structure. An important phenomenological and experimental tool for this purpose are the photon-induced interactions, as those present in the deep inelastic scattering (DIS) process and in ultraperipheral hadronic collision (UPC). In particular, photon-induced interactions can be used to improve our understanding of the strong interactions in the high- [1] and low-energy [2] regimes as well as of the polarized gluon structure of the hadrons [3]. In a UPC at high energies, two charged hadrons (or nuclei) interact at impact parameters larger than the sum of their radii [4]. Under these circumstances, it is well-known that the hadron acts as a source of almost real photons and photon-photon or photon-hadron interactions may happen. The photon emission is a pure QED process, while in the photon-photon or photon-hadron interactions, electroweak or strong interactions may take place. In this contribution, we present some recent results for the vector meson production in photon-hadron interactions as well as prospects for a near future.

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2. Probing the QCD dynamics at high energies

During the last years, the study of photon-induced interactions [4] at Tevatron, RHIC and the LHC has become a reality. One of the main motivations to the study of these processes is the possibility to constrain the main aspects of the treatment of the QCD dynamics at high energies and large nuclei. The basic idea is that at high energies, a hadron becomes a dense system and the nonlinear effects inherent to the QCD dynamics may become visible. An important source of information about the hadronic structure and also about QCD dynamics at high energies is the exclusive vector meson photoproduction in hadronic collisions [5]. As exclusive processes are driven by the gluon content of the target, with the cross sections being proportional to the square of the scattering amplitude, they are strongly sensitive to the underlying QCD dynamics.

In order to estimate the exclusive vector meson photoproduction in hadronic collisions, we need to know the cross section for exclusive vector meson photoproduction, which is given by

$$\sigma(\gamma h \rightarrow Vh) = \int_{-\infty}^0 dt \frac{d\sigma}{dt} = \frac{1}{16\pi} \int_{-\infty}^0 \left| \mathcal{A}^{\gamma h \rightarrow Vh}(x, \Delta) \right|^2 dt. \quad (2.1)$$

The scattering amplitude $\mathcal{A}^{\gamma h \rightarrow Vh}(x, \Delta)$ can be derived using the color dipole formalism, which allows us to study the γh interaction in terms of a (color) dipole–hadron interaction. In this formalism, we assume that the photon fluctuates into a color dipole which interacts with the hadron target and then forms a vector meson at the final state. If the lifetime of the dipole is much larger than the interaction time, a condition which is satisfied in high-energy collisions, the quasi-elastic scattering amplitude for the process $\gamma h \rightarrow Vh$ can be factorized as follows [1]:

$$\mathcal{A}^{\gamma h \rightarrow Vh}(x, \Delta) \propto [\Psi^{V*}(\mathbf{r}, z) \Psi(\mathbf{r}, z)]_T \otimes \mathcal{N}_h(x, \mathbf{r}, \mathbf{b}_h), \quad (2.2)$$

where the function $[\Psi^{V*}(\mathbf{r}, z) \Psi(\mathbf{r}, z)]_T$ is the overlap between the wave functions of the transverse photon and the vector meson, which describes the fluctuation of the photon with transverse polarization into a color dipole and the subsequent formation of the vector meson. Furthermore, $\mathcal{N}_h(x, \mathbf{r}, \mathbf{b}_h)$ is the imaginary part of the forward dipole–hadron scattering amplitude and it carries all the information about the strong interactions in the process. The variables $z, \mathbf{r}, \mathbf{b}_h$ are, respectively, the light-cone longitudinal momentum fraction of the photon carried by the quark (and $1 - z$, for the antiquark), the transverse separation of the color dipole and the impact parameter, the separation between the dipole center and the target center. Further, x is

the Bjorken variable for a diffractive event and Δ is the Fourier conjugate of $\mathbf{b}_h$. It is related to the squared momentum transfer by $\Delta = \sqrt{-t}$. In order to estimate the current theoretical uncertainty present in the color dipole predictions, in Ref. [1], we have considered the Boosted Gaussian (BG) and the Light-Cone Gaussian (LCG) wave functions and the phenomenological models for dipole scattering amplitude: IIM, bCGC and IP-SAT models, which encode the main properties of the saturation approaches and describe the HERA data. In Fig. 1, we present our predictions [1] for the exclusive ρ and J/ψ photoproduction in $p\text{Pb}$ collisions at $\sqrt{s} = 8.1$ TeV assuming the BG model for the vector meson wave function. As we can see the difference between the predictions depends on the vector meson considered. The IIM, bCGC and IP-SAT predictions differ significantly in the ρ production. For J/ψ , the uncertainty is smaller, but still significant at small rapidities. Finally, it is important to emphasize that the position of the maximum of the distribution is model- and vector-meson-dependent. This fact can be used to test details of the QCD dynamics in a future global analysis of exclusive vector meson photoproduction in $p\text{Pb}$ collisions [1].

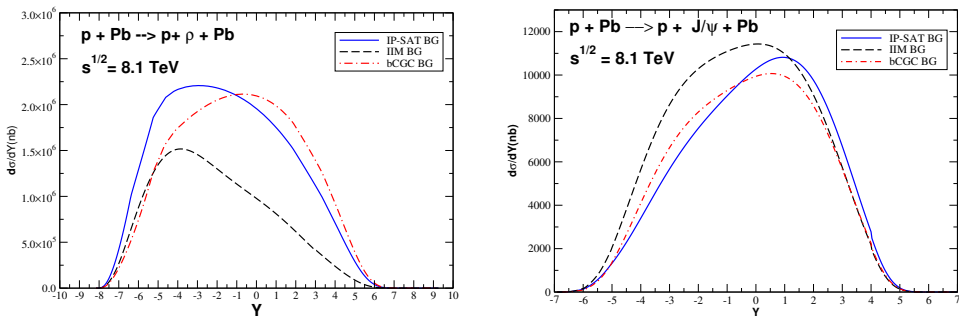


Fig. 1. Rapidity distributions for the exclusive photoproduction of ρ (left) and J/ψ (right) in $p\text{Pb}$ collisions at $\sqrt{s} = 8.1$ TeV.

3. Probing the gluon Sivers function

The study of high-energy processes involving polarized hadrons allows to improve our understanding of the polarized quark and gluon structure of the hadrons and the QCD dynamics at a high-energy scale. In particular, the analysis of the transverse spin phenomena in hard processes is expected to provide a three-dimensional picture of the partons inside the nucleon. One of the current challenges in hadronic physics is the understanding of the large transverse single-spin asymmetries (SSAs), which have been observed in several experiments. A possible explanation for the presence of this asymmetry was proposed many years ago [6] and is known as Sivers

effect, which considers the correlation between the transverse momentum of partons and the polarization vector of the nucleon. One important open question is the size of the gluon Sivers function, with no hard constraint existing apart from the positivity bound [7]. One process that can be used to probe gluons inside hadrons is the inelastic vector meson photoproduction, described by the reaction $\gamma p^\uparrow \rightarrow V X$. In Ref. [3], we have proposed the study of the gluon Sivers function in the photoproduction of vector mesons in $p^\uparrow p$ and $p^\uparrow A$ collisions at high energies. In particular, we have estimated the impact of different models for the gluon Sivers function on the transverse single-spin asymmetry. In what follows, we summarize our main results and conclusions derived in Ref. [3].

The inelastic J/Ψ photoproduction in $p^\uparrow p$ and $p^\uparrow A$ collisions is described assuming that the unpolarized hadron (p or A) is the source of photons, which interact with the transversely polarized protons at high energies, producing a J/Ψ and dissociating the proton target. In the nuclear case, such approximation is justified due to enhancement by a factor Z^2 in the nuclear photon flux in comparison to that for a proton, which implies that the photon-induced interactions are dominated by photons from the nucleus. The hadronic cross section will be factorized as follows:

$$\sigma_{Ap^\uparrow \rightarrow hJ/\Psi X}(\sqrt{s}) = \int dx_\gamma d^2\mathbf{k}_{\perp\gamma} f_{\gamma/A}(x_\gamma, \mathbf{k}_{\perp\gamma}) \cdot \sigma_{\gamma p^\uparrow \rightarrow J/\Psi X}(W_{\gamma p}^2), \quad (3.1)$$

where x_γ is the energy fraction of hadron carried by the photon with transverse momentum $\mathbf{k}_{\perp\gamma}$ and $f_{\gamma/h}$ is the photon flux associated to hadron h . Moreover, $W_{\gamma h}$ is the c.m.s. photon-proton energy given by $W_{\gamma p} = [2\omega\sqrt{s}]^{1/2}$, where ω is the photon energy and $\sqrt{s}$ is the c.m.s. energy of the hadron-proton system. The final state will be characterized by the presence of one rapidity gap and an intact hadron, which we assume to be the unpolarized one. Both aspects can be in principle used to experimentally separate the vector mesons produced by photon-induced interactions. In our analysis, we have assumed that the inelastic J/Ψ photoproduction can be described by the Color Evaporation Model (CEM), generalized to take into account the transverse momentum dependence of the gluon distribution function. The cross section for the inelastic J/Ψ photoproduction is proportional to the number density of gluons inside a proton with transverse polarization $\mathbf{S}$ and momentum $\mathbf{P}$, which is usually parameterized as [8]

$$f_{g/p^\uparrow}(x_g, \mathbf{k}_{\perp g}, \mathbf{S}) \equiv f_{g/p}(x_g, k_{\perp g}) + \frac{1}{2}\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g}) \hat{\mathbf{S}} \cdot (\hat{\mathbf{P}} \times \hat{\mathbf{k}}_{\perp g}), \quad (3.2)$$

where x_g is the longitudinal momentum fraction of the gluon and $\mathbf{k}_{\perp g}$ its transverse momentum. Moreover, $f_{g/p}(x_g, k_{\perp g})$ is the unpolarized transverse-momentum-dependent (TMD) gluon distribution and $\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g})$ is

the gluon Sivers function. In order to probe the gluon Sivers function in the inelastic J/Ψ photoproduction in $p^\uparrow A$ collisions, in what follows, we will investigate the impact of different models for $\Delta^N f_{g/p^\uparrow}(x_g, k_{\perp g})$ in the rapidity (Y) dependence of the single-spin asymmetry, defined as

$$A_N(Y) = \frac{\frac{d\sigma^\uparrow}{dY} - \frac{d\sigma^\downarrow}{dY}}{\frac{d\sigma^\uparrow}{dY} + \frac{d\sigma^\downarrow}{dY}}, \quad (3.3)$$

where $\frac{d\sigma^\uparrow}{dY}$ and $\frac{d\sigma^\downarrow}{dY}$ are, respectively, the differential cross sections measured when the proton is transversely polarized up ($\uparrow$) and down ($\downarrow$) with respect to the scattering plane.

Our predictions for the single-spin asymmetry are presented in Fig. 2 considering $p^\uparrow p$ collisions at 500 GeV. We can see that the magnitude and signal of $A_N(Y)$ is strongly dependent on the model used for the gluon Sivers function, with the position of the peak occurring at larger values of Y with the increasing of the energy. In Ref. [3], we have verified that the maximum and minimum values of A_N are almost independent of energy. Our results indicate that the signal and magnitude of the asymmetry can be probed by the analysis of the J/Ψ production at forward rapidities. Additionally, in Ref. [3], we have also estimated A_N for $p^\uparrow \text{Au}$ collisions and obtained that its rapidity dependence, position of the peak and value of the maximum and minimum are very similar to those obtained in $p^\uparrow p$ collisions. Such a behaviour is expected, since the photon flux is present in the numerator and denominator of Eq. (3.3), which implies that the Z^2 enhancement of the nuclear flux does not affect A_N . Therefore, we predict similar asymmetry in $p^\uparrow p$ and $p^\uparrow \text{Au}$ collisions. However, it is important to emphasize that the

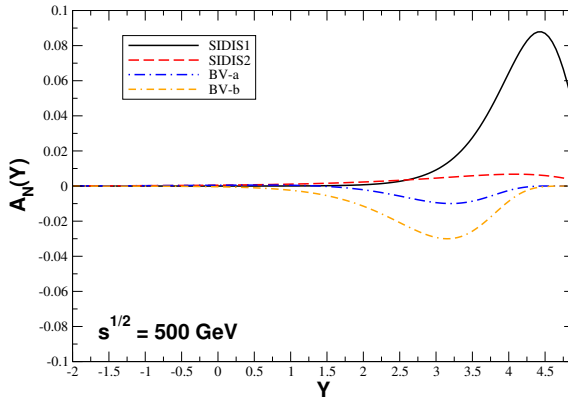


Fig. 2. Predictions for the single-spin asymmetry in the inelastic J/Ψ photoproduction in $p^\uparrow p$ collisions at 500 GeV considering different models for the gluon Sivers function.

magnitude of the rapidity distribution in nuclear collisions is almost three orders of magnitude larger than in proton–proton collisions, which implies that the study of the single-spin asymmetry in $p^\uparrow$ Au collisions is expected to be more easily performed.

4. Summary

During the last years, the experimental results from Tevatron, RHIC and LHC have demonstrated that the study of hadronic physics using photon-induced interactions in $pp/pA/AA$ colliders is feasible. In this contribution, we have summarized the results presented in Refs. [1, 3], which indicated that a future global analysis of the vector meson photoproduction at the LHC will be able to constrain the QCD dynamics at high energies as well as that the RHIC data for polarized collisions can be used to improve our understanding of the modelling of the gluon Sivers function. Finally, it is important to emphasize that complementary studies on the vector meson photoproduction can be performed in the fixed-target collisions at the LHC, as recently demonstrated in Ref. [2].

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