Exclusive vector meson photoproduction with proton dissociation in photon-hadron interactions at the LHC

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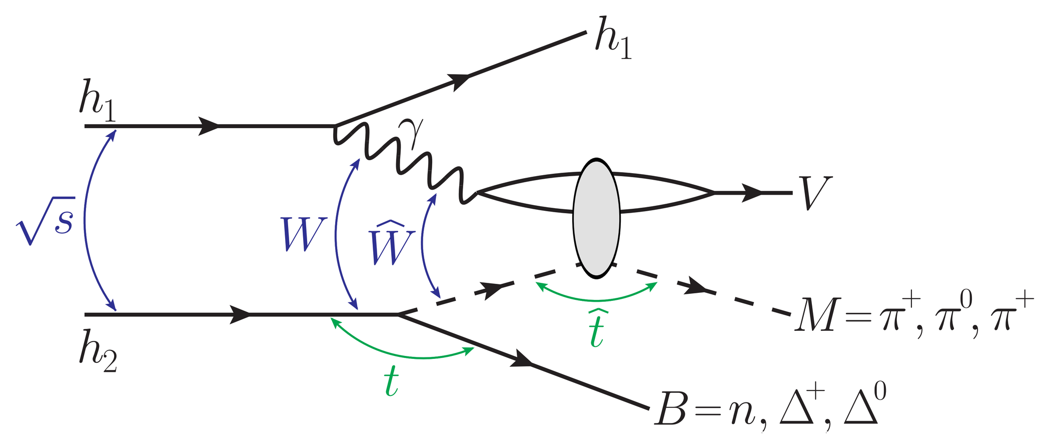
Introduction

One of the most promising observables to constrain the QCD dynamics in high energy regime is the exclusive vector meson photoproduction (EVMP). In ep collisions, processes in which the proton dissociates can significantly affect EVMP. In addition to the main reaction $e + p \to e + V + p$, a non-negligible fraction of vector mesons V may come from the reaction with proton dissociation $e + p \to e + V + X$. We have recently studied [1] one of the possible proton dissociation processes, where the proton dissociates into a leading neutron and a pion, with the former carrying a large fraction of the proton momentum. In principle, the presence of a leading neutron in EVMP can be used to tag the event. In this work we will extend and complement our previous study on EVMP and consider processes where the proton splits into $\Delta\pi$ states. These are, after $p \to n\pi$, the next most important proton dissociation process. More details can be found in Ref. [2].

Formalism



The EVMP associated with a leading particle in photon-induced interactions in hadronic collisions is represented in the figure above. This class of process can be factorized in terms of the equivalent flux of photons ($N_{\gamma/h}$), the flux of virtual pions ($f_{\pi/h}$) and the photon-pion cross section ($\sigma_{\gamma\pi}$) [1]:

$$\frac{d\sigma(h_1+h_2 \to h_3+V+\pi+B)}{dY\,dx_L\,dt} = \mathcal{K}\cdot N_{\gamma/h_1}(\omega_L)\cdot f_{\pi/h_2}(x_L,t)\cdot \sigma_{\gamma\pi}(Y) + \mathcal{K}\cdot N_{\gamma/h_2}(\omega_R)\cdot f_{\pi/h_1}(x_L,t)\cdot \sigma_{\gamma\pi}(Y) \qquad (1)$$

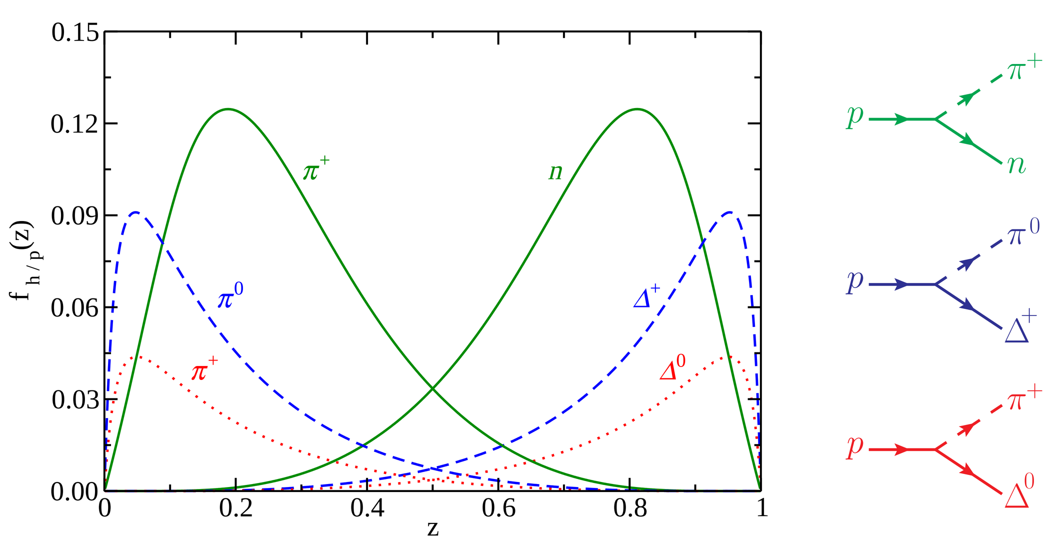
where $Y = \ln(2\omega/M_V)$ is the rapidity of the vector meson with mass M_V, x_L is the leading particle longitudinal momentum and t is square of the four-momentum of the exchaged pion. Moreover, h_3 corresponds to the initial hadron (h_1 or h_2) which has emitted the photon and ω is the energy of the photons emitted by the h_1 ($\omega_L \propto e^{-Y}$) and the h_2 ($\omega_R \propto e^{+Y}$) hadrons. The constant factor $\mathcal{K}$ represents the absorptive corrections associated to soft rescatterings. Now let us discuss each term of expression (1). The $N_{\gamma/h}(\omega)$ describes the equivalent flux of photons (with energy ω) of the hadron h. The photon flux associated to the proton and nucleus can be described by the Drees-Zeppenfeld and relativist point-like charge models, respectively. The photon flux of a nucleus is enhanced by a factor Z^2 in comparison to the proton one. Because of this, in proton-nucleus collisions we will only consider the processes in which the photon is emitted by the nucleus and the pion is emitted by the proton. The function $f_{\pi/p}(x_L,t)$ represents the flux of virtual pions emitted by the proton [3]:

$$f_{\pi/p}(x_L,t) = \frac{g^2_{p\pi B}\,\mathcal{B}(t,m_p,m_B)}{16\pi^2\,(t-m_\pi^2)^2}(1-x_L)^{1-2t}\exp\left[2b(t-m_\pi^2)\right] , \qquad (2)$$

where $g_{p\pi B}$ is the proton-pion-baryon coupling constant, m_π is the pion mass and b is related to the $p\pi B$ form factor. The term $\mathcal{B}$ depends on the type of the produced baryon:

$$\mathcal{B}(t,m_p,m_B) = \begin{cases} -t + (m_n - m_p)^2 , & \text{for } B=n, \\ \dfrac{\left[(m_\Delta + m_p)^2 - t\right]^2\left[(m_\Delta - m_p)^2 - t\right]}{12\,m_p^2 m_\Delta^2} , & \text{for } B=\Delta, \end{cases} \qquad (3)$$

where m_p, m_n and m_Δ are the respective masses of the proton, neutron and delta. In the figure below we present the behavior of the meson (baryon) flux as a function of the fractional momentum z which the meson (baryon) takes away from the proton. As it can be seen, baryons carry the largest fraction of the proton momentum, whereas pions populate the low z region.



The function $\sigma_{\gamma\pi}$ describes the cross section of the diffractive interaction $\gamma + \pi \to V + \pi$ and in the dipole formalism it is given by [4]:

$$\sigma_{\gamma\pi\to V\pi} = \frac{1}{16\pi}\int_{-\infty}^{0}\left|\int d\alpha\, d^2\boldsymbol{r}\, d^2\boldsymbol{b}\, e^{-i[\boldsymbol{b}-(1-\alpha)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\,(\Psi^{V*}\Psi)\,2\mathcal{N}_\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})\right|^2 d\hat{t} , \qquad (4)$$

where $\hat{t} = -\Delta^2$ denotes the transverse momentum lost by the outgoing pion and $\hat{x} = M_V^2/\hat{W}^2$ is the scaled Bjorken variable. There are three center-of-mass energies present in this scattering: $\hat{W}^2 = (1-x_L)W^2$ of the photon-pion system, $W^2 = M_V e^Y\sqrt{s}$ of the photon-proton system and $\sqrt{s}$ of the hadron-hadron system. The dipole variables are: α $(1-\alpha)$ is the longitudinal momentum fraction of the quark (antiquark), $\boldsymbol{b}$ is impact parameter and $\boldsymbol{r}$ is the size of the dipole. Finally, $(\Psi^{V*}\Psi)$ denotes the overlap between the real photon and exclusive final state wave functions, which we assume to be given by the Gauss-LC model [5] and $\mathcal{N}^\pi(\hat{x},\boldsymbol{r},\boldsymbol{b})$ is the imaginary part of the dipole-pion forward scattering amplitude. This quantity is directly related to the QCD dynamics at high energies. As in Ref. [6], we will assume that $\mathcal{N}^\pi$ can be expressed in terms of the dipole-proton scattering amplitude $\mathcal{N}^p$ (with R_q being a constant):

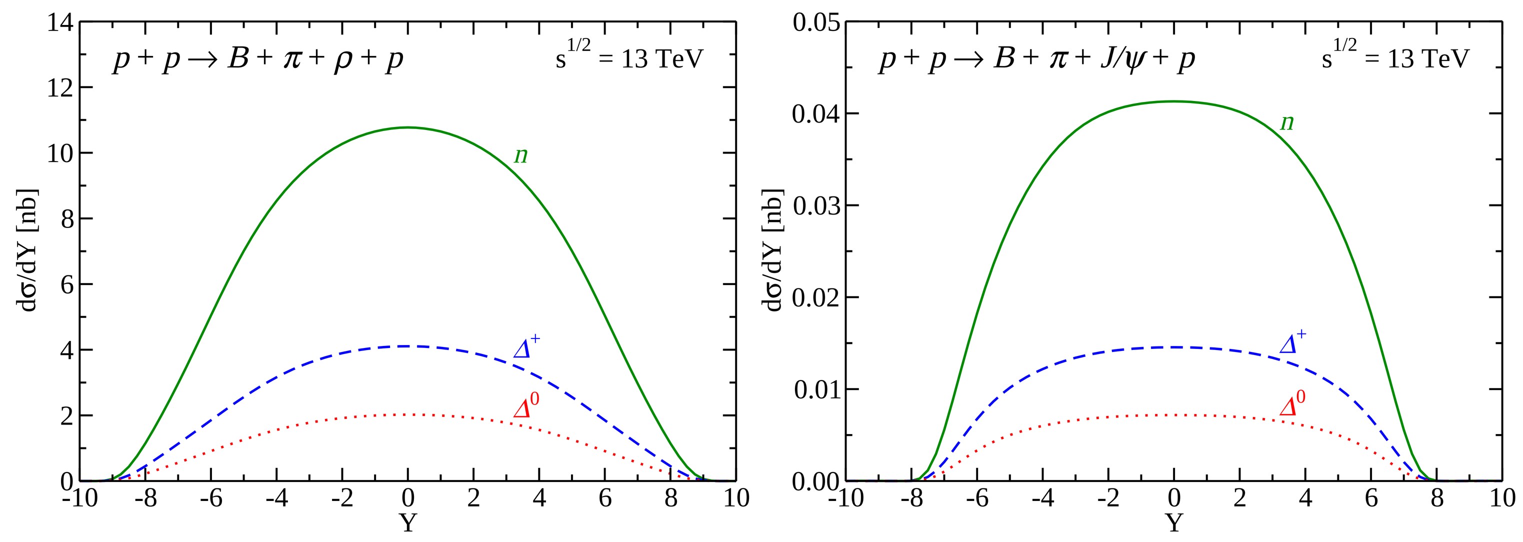
$$\mathcal{N}^\pi(\hat{x},\boldsymbol{r},\boldsymbol{b}) = R_q\cdot\mathcal{N}^p(\hat{x},\boldsymbol{r},\boldsymbol{b}) . \qquad (5)$$

We will assume that $\mathcal{N}^p(\hat{x},\boldsymbol{r},\boldsymbol{b})$ is given by the bCGC model [5].

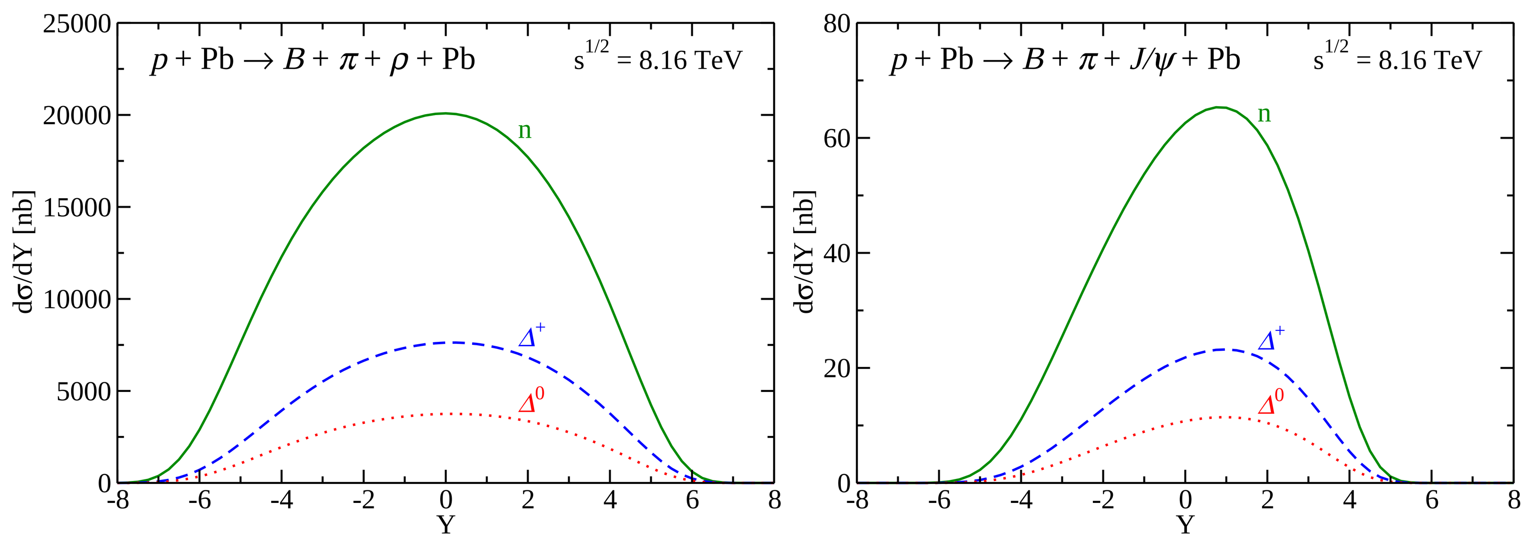
Results

Following our previous paper [1], we will assume that absorptive corrections can be represented by a $\mathcal{K}$ factor, and it value was fixed in Ref. [4] using HERA data [7] on $\sigma(\gamma p \to \rho\pi n)$. As for the constant R_q, we shall, as in Refs. [1, 4], assume that $R_q = 2/3$, as expected from the additive quark model. As implemented in the analysis of the H1 Collaboration [7], we will assume that $p_T = \sqrt{|t|} < 0.2$ GeV.

Now we will present our predictions for the EVMP associated with a leading baryon in photon-induced interactions considering pp/pPb collisions at LHC energies. In the figure below we present our predictions for the rapidity distributions of the vector mesons ρ and J/Ψ produced in pp collisions at $\sqrt{s} = 13$ TeV. Due to the fact that the $p\,\pi^0\Delta^+$ coupling constant is bigger than the $p\,\pi^+\Delta^0$ one, we can observe that the values of the cross sections for leading Δ^+ production are about two times bigger than the values observed for leading Δ^0 production.



In the figure below we present our predictions for the rapidity distributions of the vector mesons ρ and J/ψ produced in pPb collisions at $\sqrt{s} = 8.16$ TeV. Since $N_{\gamma/\text{Pb}} \gg N_{\gamma/p}$, the pPb distributions are amplified in comparison with the pp one, also, in this case we have asymmetric distributions. As in the pp case, due to the magnitude of each coupling constant and the typical values of z probed (and consequently $\hat{W}^2$), the EVMP associated with a leading neutron is a factor $\sim 2.7\,(5.4)$ larger than those associated to a leading Δ^+ (Δ^0).



In the case of ρ production associated with a leading neutron, we predict values for the total cross section of the order of 10^2 (10^5) nb in pp (pPb) collisions. Furthermore, the total cross section of vector meson production associated with a leading delta is just one order of magnitude smaller, such that in the ρ case we predict values of the order of 10^1 (10^4) nb in pp (pPb) collisions at the same energies. The decay channel $\Delta \to N\pi$ corresponds to 99.4% of the delta decays and hence delta resonances can be an important background in processes with a leading nucleon. In the case of measurements of vector meson production associated with a leading neutron, the channels $\Delta^0 \to n\,\pi^0$ and $\Delta^+ \to n\,\pi^+$ together give a contribution of the order of $20 \sim 28\%$ of the direct leading neutron production. The secondary Δ decay into $n\pi$ will not affect the rapidity distribution of the vector meson, but it will give a contribution to the neutron spectrum which is softer than the one coming from the primary $p \to n\pi$ splitting.

In comparison with the photoproduction of vector mesons (in γp interactions) in processes without the presence of a leading baryon [8], our predictions are smaller by approximately two (three) orders of magnitude for the leading neutron (delta). However, it is important to emphasize that these events will be characterized by very forward baryons, which can be used to tag the events.

Summary

Recent results on photon-induced interactions at hadronic colliders have demonstrated that the analysis of these processes is feasible at the LHC. This possibility has stimulated the improvement of the theoretical description of these processes as well as the proposal of complementary processes that also probe the QCD dynamics and are more easily tagged in collisions with a high pileup. Along this line, we have recently proposed the study of EVMP associated with a leading neutron in γp interactions at pp and pA collisions and obtained large values for the total cross sections. This result motivated the analysis performed in the present work, where we have extended the study to other leading particles, which also generate a neutron in the final state through their decay. We have estimated the cross section for exclusive ρ and J/ψ photoproduction in association with a leading neutron and a leading Δ in pp and pPb collisions at LHC energies. We have found that the production associated with a leading Δ is non-negligible, being almost 30 % of the one with a leading neutron. Our results indicate that the experimental analysis of this process is, in principle, feasible. In particular, if a combined analysis of the events using central and forward detectors is performed, as those expected to occur using the CMS-TOTEM-PPS and ATLAS-LHCf experiments.

Acknowledgments

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