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Exclusive photoproduction of light vector meson in coherent collisions at the LHC energies

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Abstract. In this work we present our predictions for the rapidity distribution for ρ^0 and ϕ photoproduction in coherent pp and AA collisions at the LHC energies using the color dipole approach. In particular, we perform an analysis on the uncertainties associated to the choice of vector meson wavefunction and the phenomenological models for the dipole cross section. Comparison is done with the recent ALICE analysis on coherent production of ρ^0 at 2.76 TeV in PbPb collisions.

1. Exclusive vector meson photoproduction in ultraperipheral collisions

The exclusive photoproduction of vector mesons has been investigated recently both experimentally and theoretically [1, 2, 3, 4, 5] as it allows to test the interface between the Quantum Chromodynamics scenarios. In particular, the light vector mesons as ρ and ϕ have not a perturbative scale associated to the process in photoproduction limit and so they test the non-perturbative regime of QCD. At high energies, i.e. small- x region, it is expected a transition between the regime described by the linear dynamics of emissions chain and a new regime where the physical process of recombination of partons turn out to be crucial, which can be addressed by the so-called saturation approaches [6, 7, 8] within the color dipole formalism [9]. In such theoretical framework, the $q\bar{q}$ fluctuation (color dipole) of the incoming quasi-real photon (from the protons or nuclei) interacts with the target via the dipole cross section and the result is projected in the wavefunction of the observed hadron. The typical scale driven the dynamics of light meson production is the saturation scale, which characterizes the limitation on the maximum phase-space parton density that can be reached in the hadron wavefunction. For this energy domain hadrons and photons can be considered as color dipoles in the mixed light cone representation, where their transverse size can be considered frozen during the interaction [10]. Accordingly, the scattering process is characterized by the color dipole cross section describing the interaction of those color dipoles with the nucleon or nucleus target. For interaction at large impact parameter and at ultrarelativistic energies, e.g. ultraperipheral collisions, where the impact parameter should be larger than the sum of the hadron/nuclei radius it is expected that the electromagnetic interaction to be dominant. Therefore, in this case the photoproduction is highly favored. The main advantage of using colliding hadrons and nuclear beams for studying photon induced interactions is the high equivalent photon energies and luminosities achieved at the LHC. Consequently, studies of γp or γA interactions at the LHC could provide valuable information on the QCD dynamics at high energies. The basic idea in coherent hadronic collisions



is that the cross section for a given process can be factorized in terms of the equivalent flux of photons into the hadron projectile and the photon-photon or photon-target production cross section [11, 12, 13]. Namely, the cross section of vector meson production can be evaluated within the Weizsäcker-Williams approximation as a product of the photon flux emitted by one of the colliding participants and the cross section of vector meson photoproduction on the remaining hadron or nucleus. The photon energy spectrum for protons and nuclei, $dN_\gamma^p/d\omega$ and $dN_\gamma^A/d\omega$, which depends on the photon energy ω , are well known [11, 12, 13]. The rapidity distribution y for vector meson photoproduction in pp collisions can be written down as,

$$\frac{d\sigma}{dy}(pp \rightarrow p \otimes V \otimes p) = \left[\omega \frac{dN_\gamma^p}{d\omega} \sigma(\gamma p \rightarrow V p) + (y \rightarrow -y) \right], \quad (1)$$

with $y \simeq \ln(2\omega/m_V)$ being the rapidity of the produced state with mass m_V and the square of the γp center-of-mass energy is given by $W_{\gamma p}^2 \simeq 2\omega\sqrt{s}$. In the present analysis, we consider the photon-hadron/nucleus scattering in the color dipole formalism, where the probing projectile fluctuates into a quark-antiquark pair with transverse separation r (and momentum fraction z) long after the interaction, which then scatters off the target (proton or nucleus). Similarly, the rapidity distribution y in nucleus-nucleus collisions has the same factorized form,

$$\frac{d\sigma}{dy}(AA \rightarrow A \otimes V \otimes Y) = \left[\omega \frac{dN_\gamma^A}{d\omega} \sigma(\gamma A \rightarrow V + Y) + (y \rightarrow -y) \right], \quad (2)$$

where $Y = A$ represents the coherent case. The cross section for exclusive photoproduction of vector meson off a nucleon target is given by [10]

$$\sigma(\gamma p \rightarrow V p) = \frac{1}{16\pi B_V} \left| \int dz d^2r \Phi_T^{\gamma*V}(z, r, m_q) \sigma_{dip}(x, r) \right|^2, \quad (3)$$

where the dipole cross section is denoted by $\sigma_{dip}(x, r)$ and the diffractive slope parameter by B_V . Moreover, the nuclear version of the cross section can be written as [14]

$$\sigma(\gamma A \rightarrow V A) = \int d^2b \left| \sum_{h, \bar{h}} \int dz d^2r \Phi_T^{\gamma*V} \left\{ 1 - \exp \left[-\frac{1}{2} T_A(b) \sigma_{dip}(x, r) \right] \right\} \right|^2, \quad (4)$$

being $T_A(b)$ the nuclear profile function. The expressions for the overlap functions we have used appropriately summed over the helicity and flavor indices,

$$\Phi_T^{\gamma*V} = \hat{e}_q \frac{\sqrt{4\pi \alpha_{em}}}{(2\pi)^2} N_c \left\{ m_q^2 K_0(r m_q) \phi_T(r, z) - [z^2 + (1-z)^2] m_q K_1(r m_q) \partial_r \phi_T(r, z) \right\}, \quad (5)$$

where the constant \hat{e}_q stands for an effective charge. In the numerical evaluations, we have considered for the vector meson wavefunctions the Boosted Gaussian [15] (BG) and the Light-Cone Gaussian [16] (LCG) wavefunctions

$$\phi_T^{BG} = N_T 4\sqrt{2\pi R^2} \exp \left[-\frac{m_q^2 R^2}{8z(1-z)} + \frac{m_q^2 R^2}{2} - \frac{2z(1-z)r^2}{R^2} \right], \quad (6)$$

$$\phi_T^{LCG} = N_T z(1-z) \exp \left[-r^2/(2R^2) \right]. \quad (7)$$

The parameters R and N_T are constrained by unitarity of the wavefunction as well as by the electronic decay widths. Besides, for the phenomenological models for the dipole-proton cross section we have adopted the GBW model [17]

$$\sigma_{dip}^{GBW}(x, r) = \sigma_0 \left[1 - \exp \left(-\frac{r^2 Q_{sat}^2}{4} \right)^{\gamma_{eff}} \right], \quad (8)$$

where the the effective anomalous dimension is taken as $\gamma_{\text{eff}} = 1$ and the IIM model [18]

$$\sigma_{dip}^{IIM}(x, r) = \sigma_0 \begin{cases} 0.7 \left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\text{eff}}(x, r)}, & \text{for } \bar{\tau} \leq 2, \\ 1 - \exp\left[-a \ln^2(b \bar{\tau})\right], & \text{for } \bar{\tau} > 2, \end{cases}$$

where $\bar{\tau} = rQ_{\text{sat}}(x)$ and the expression for $\bar{\tau} > 2$ (saturation region) has the correct functional form, as obtained from the theory of the Color Glass Condensate (CGC). For the color transparency region near saturation border ($\bar{\tau} \leq 2$), the behavior is driven by the effective anomalous dimension, $\gamma_{\text{eff}}(x, r) = \gamma_{\text{sat}} + \frac{\ln(2/\bar{\tau})}{\kappa \lambda y}$ with $\kappa = 9.9$. The saturation scale is defined as $Q_{\text{sat}}^2(x) = (x_0/x)^\lambda$ and $\sigma_0 = 2\pi R_p^2$. We have considered two set of parameters for the IIM parameterization. The first set (labeled by IIM-old [19]) considers the previous DESY-HERA data and the values for parameters are $\gamma_{\text{sat}} = 0.7376$, $\lambda = 0.2197$, $x_0 = 0.1632 \times 10^{-4}$ and $R_p = 3.344 \text{ GeV}^{-1}$ ($\sigma_0 = 27.33 \text{ mb}$). The second set (labeled IIM-new [20]) considered the extremely small error bars on the recent ZEUS and H1 combined results for inclusive DIS. In this case, the parameters are $\gamma_{\text{sat}} = 0.762$, $\lambda = 0.2319$, $x_0 = 0.6266 \times 10^{-4}$ and $\sigma_0 = 21.85 \text{ mb}$.

2. Results

Let us start by calculating the rapidity distribution for ρ^0 and ϕ production in proton-proton collisions at the energy of 7 TeV. In Fig.1-a we present the predictions for ρ^0 taking into account the BG wavefunction and the GBW and IIM models for the dipole cross section. The dot-dashed curve stands for the IIM-old model, the solid line represents the IIM-new model, whereas the dashed curve stands for the GBW parametrisation. At large rapidities the behavior is similar for the distinct models. However, at mid-rapidities there is an evident model dependence. It is obtained the values $d\sigma/dy(y=0) = 0.9, 0.83, 0.95 \mu\text{b}$ for IIM-old, IIM-new and GBW, respectively. The deviation is order 14% in that case. Now, in Fig.1-b the results are presented for the LCG wavefunction, where we adopt the same set for phenomenological models for the dipole cross section. In the mid-rapidity region it is found $d\sigma/dy(y=0) = 0.80, 0.45, 0.85 \mu\text{b}$ for IIM-old, IIM-new and GBW, respectively. The predictions taking into account the LCG wavefunction are smaller than the results for BG wavefunction. We notice that there is an intense suppression when IIM-new model is considered (a reduction by a factor 1.8). In Fig.2-a we show the results for the rapidity distribution of ϕ using BG wavefunction, while the corresponding values for LCG wavefunction are presented in Fig.2-b. In both plots the notation is that same as for the ρ^0 case. For the ϕ meson production, at mid-rapidity we get $d\sigma/dy(y=0) = 108.8 \text{ nb}$ (IIM-old), 101 nb (IIM-new) and 121.3 nb (GBW) considering the BG wavefunction and $d\sigma/dy(y=0) = 132.4 \text{ nb}$ (IIM-old), 80.4 nb (IIM-new) and 147.7 nb (GBW) using the LCG wavefunction. The mid-rapidity value of cross sections are higher using LCG instead of BG wavefunction by a factor 20% at least for IIM-old and GBW models, in contrast with the ρ^0 predictions. Once again, when we choose the IIM-new model a reduction is observed.

Finally, in Fig.3 the investigation for the photonuclear production of ρ meson in PbPb collisions at the energy of 2.76 TeV is done. We present the results for the rapidity distributions of ρ^0 photoproduction, where the preliminary ALICE data [21] for coherent ρ^0 production, $\frac{d\sigma}{dy}(y=0) = 420 \pm 10 \text{ (stat.)} \pm_{55}^{30} \text{ (syst.) mb}$, is also presented and the notation follows the same as for the proton-proton case. In Fig.3-a the predictions are obtained considering the BG wavefunction (without nuclear break up). It was found the following estimates $d\sigma/dy(y=0) = 661.5 \text{ mb}$ (IIM-old), 747 mb (IIM-new) and 685.6 mb (GBW), respectively. In any case, the results are in average 50% larger than the experimental result. In Fig.3-b we presented the values for $d\sigma/dy$ taking into account the LCG wavefunction, including the previous BG prediction (dotted line) that also considered the color dipole approach. We checked the results $d\sigma/dy(y=0) = 469.5 \text{ mb}$ (GM), 585.1 mb (IIM-old), 409 mb (IIM-new) and 603.3 mb (GBW),

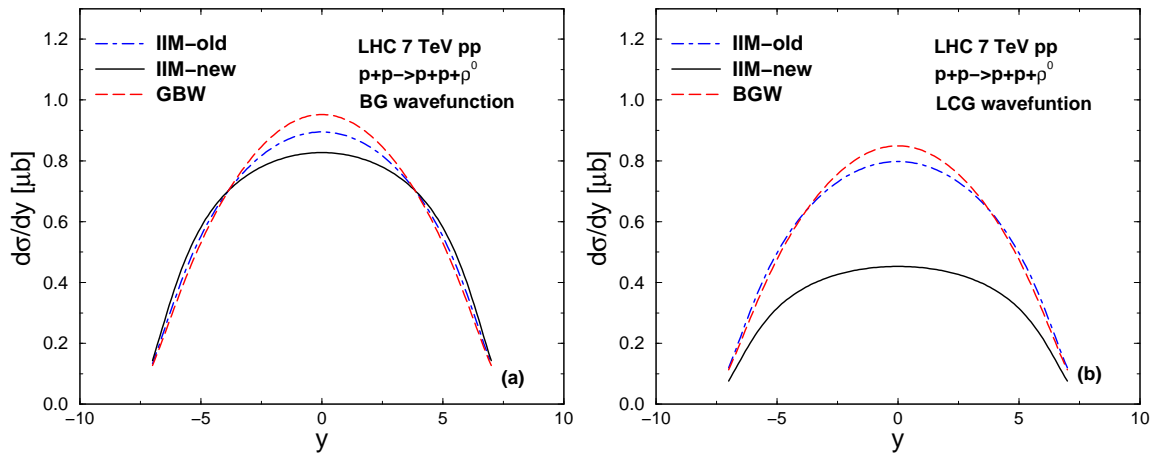


Figure 1. Rapidity distribution for ρ^0 production in pp collisions at the LHC.

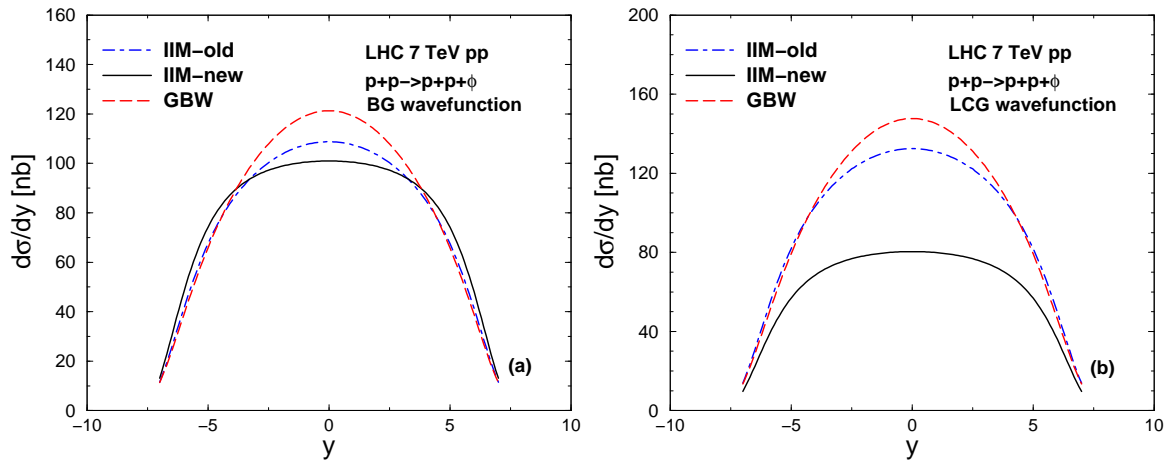


Figure 2. Rapidity distribution for ϕ production in pp collisions at the LHC.

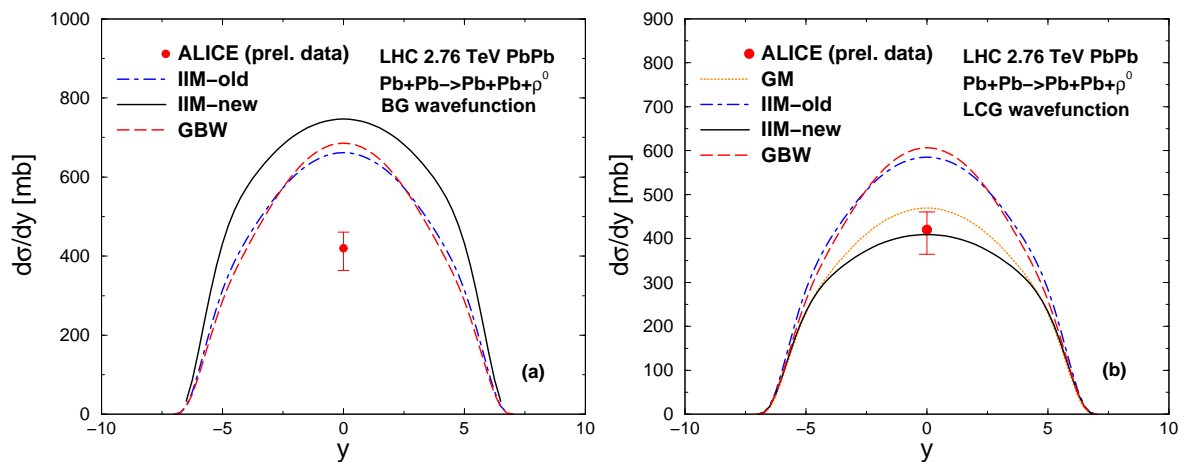


Figure 3. Rapidity distribution for ρ^0 production in $PbPb$ collisions at the LHC.

respectively. The values are smaller than for the BG wavefunction and the IIM-new result is consistent with data within the error bars. For the recent investigation of heavy vector meson photoproduction using also the color dipole approach see [22].

3. Conclusions

An investigation was done on the coherent photoproduction of the light vector as ρ and ϕ in interactions at the LHC energies for pp and $PbPb$ collisions. Predictions for the rapidity distributions are presented using the color dipole formalism and including saturation effects that are expected to be relevant at high energies. We show that the theoretical uncertainty is considerably large and the main sources are the models for the meson wavefunction and the phenomenological models for the dipole cross section. At mid-rapidity, we verified that BG wavefunction provides larger cross sections compared to the LCG wavefunction. Moreover, the dependence of the overall normalization with the color dipole model is important. In particular, the set LCG wavefunction and IIM-new model seems to be more consistent in describing the recent ALICE preliminary data. Our results demonstrate that the production rates in LHC are fairly described by the color dipole approach.

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