Nuclear form factor of xenon from photoproduction of vector mesons in Xe-Xe ultraperipheral collisions at the LHC

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Abstract. Using the Gribov-Glauber model for photon-nucleus scattering and a generalization of the vector meson dominance model for the hadronic structure of the photon, we calculate cross sections of light and heavy vector meson photoproduction in ultraperipheral Xe-Xe collisions at 5.44 TeV at the Large Hadron Collider. Analyzing the momentum transfer distribution in this process, we examine the feasibility to extract the nuclear isoscalar form factor of Xe isotopes, which are needed in searches for dark matter with Xenon-based detectors.

1. Introduction
Precise knowledge of the nuclear isoscalar form factor (nuclear structure factor) is a key component in searches for weakly interacting massive particles (WIMPs) using their spin-independent elastic scattering off nuclei with Xenon-based detectors, see, e.g. [1]. While electron elastic scattering measures the nucleus charge and magnetic form factors, the isoscalar form factor is probed in scattering and production of neutral particles, notably, in coherent photoproduction of vector mesons $\gamma A \rightarrow VA$.

This process can be studied in heavy-ion ultraperipheral collisions (UPCs), which are characterized by scattering at large impact parameters, where strong hadron interactions are suppressed and, in the equivalent photon approximation, the reaction is dominated by emission of quasi-real photons. The flux of equivalent photons is characterized by high intensity and the high photon energy extending into a TeV range in the rest frame of the target nucleus in the Large Hadron Collider (LHC) kinematics. Thus, these collisions allow one to study photon-proton and photon-nucleus collisions at unprecedentedly high energies [2].

In heavy-ion scattering at the LHC, the UPC program focuses on photoproduction of light and heavy vector mesons, namely $\rho$ and $J/\psi$ and $\psi'$ charmonia. Theoretical analyses of these data explore the dynamics of nuclear shadowing (suppression) in photon-nucleus scattering at high energies. In particular, the account of inelastic nuclear shadowing in coherent and incoherent photoproduction of $\rho$ mesons in Pb-Pb UPCs leads to an additional 25 – 30% suppression of the nuclear cross sections, which allows one to successfully describe the energy dependence and normalization of the available data [3, 4] and make predictions for future measurements [5]. In the case of coherent charmonium photoproduction in Pb-Pb UPCs, analyses of the data in terms of the nuclear suppression factor provided direct evidence for strong nuclear gluon shadowing.
in lead, \( R_p(x = 0.001) = 0.6 \) \([6, 7]\) \((R_p(x, \mu^2) = g_A(x, \mu^2)/[Ag_p(x, \mu^2)]\) is the ratio of the gluon density in lead and the proton).

Besides Pb beams, a test run with collisions of Xenon ions was performed in Fall 2017 and collected several \( \mu b^{-1} \) of statistics. Extending the formalisms \([3, 4, 5, 6, 7]\), we made predictions for coherent and incoherent \( \rho, \phi, \) and \( J/\psi \) vector meson photoproduction in Xe-Xe UPCs at \( \sqrt{s_{NN}} = 5.44 \text{ TeV} \) at the LHC \([8]\). The goal of this is two-fold. First, these predictions combined with our earlier results for Pb-Pb UPCs provide the nuclear mass number \( A \) and vector meson type dependence of our approach to nuclear shadowing in photoproduction on nuclei. Second, the momentum transfer \( t \) dependence of these cross sections (positions of diffractive minima) probes the isoscalar nuclear density (nuclear matter radius) of Xenon, whose knowledge is of key importance for Dark Matter Experiments searching for WIMPs with Xenon-based detectors.

2. Vector meson photoproduction in UPCs

The cross section of coherent and incoherent (the target nucleus breaks up) cross section of vector meson \( V (V = \rho, \phi, J/\psi) \) photoproduction in symmetric nucleus–nucleus UPCs reads \([2]\):

\[
\frac{d\sigma_{AA\to VAA}}{dy dt} = N_{\gamma/A}(y)\frac{\sigma_{\gamma A\to VA'}(y,t)}{dt} + N_{\gamma/A}(-y)\frac{\sigma_{\gamma A\to VA'}(-y,t)}{dt},
\]

where \( N_{\gamma/A} \) is the photon flux; \( y \) is the rapidity of the produced vector meson \( V \); \( t \) is the invariant momentum transfer squared; \( \sigma_{\gamma A\to VA'}(y) \) is the photoproduction cross section; \( A' \neq A \) correspond to coherent and incoherent nuclear scattering, respectively. The presence of two terms with opposite rapidities reflects the fact that each colliding ion can serve as a source of photons and as a target.

The photon flux \( N_{\gamma/A}(y) \) in equation (1) can be calculated with high precision in the equivalent photon approximation taking into account the effect of suppression of inelastic strong interactions at small impact parameters. To a good accuracy, in practical applications \( N_{\gamma/A}(y) \) can be very well approximated by the photon flux produced by a point-like charge.

The coherent \( d\sigma_{\gamma A\to VA}/dt \) cross section can be calculated using the combination of the Gribov–Glauber model (GGM) for nuclear shadowing and a model for hadronic fluctuations for the \( \gamma N \to VN \) cross section on the nucleon. It is based on the space-time picture of strong interactions, where the real photon interacts with hadrons by means of its long-lived hadronic components (fluctuations). Each fluctuation is characterized by the cross section \( \sigma \), whose probability distribution \( P(\sigma) \) is constrained by experimental data on the elastic \( \gamma p \to V p \) and the diffraction dissociation \( \gamma p \to X p \) cross sections. In this approach, the \( \gamma A \to VA \) cross section in the large \( W_{\gamma N} \) limit \( (W_{\gamma N} = \sqrt{2E_A M_V}e^{y/2}) \) is the invariant photon–nucleus energy per nucleon, \( E_A \) is the nuclear beam energy, and \( M_V \) is the vector meson mass) is given by the following expression:

\[
\frac{d\sigma_{\gamma A\to VA}}{dt}(W_{\gamma N}, t = 0) = \int d^2 b e^{i\vec{q}_b \cdot \vec{b}} \left| \int \frac{d\sigma}{d\sigma(\sigma)} P(\sigma) \left( 1 - e^{-\frac{2}{q^2} T_A(b)} \right) \right|^2 dt,
\]

where \( \sigma^2 \approx -t; \sigma^2 = \int d\sigma P(\sigma)\sigma^2; T_A(b) = \int_{-\infty}^{\infty} d\rho A(\vec{b}, z) \) is the nuclear optical density calculated using the nuclear matter density \( \rho A(r) \), which we evaluate using the standard spherical Hartree–Fock-Skyrme model. The \( \ldots \) factor in equation (2) gives the effect of nuclear shadowing (suppression) due to multiple rescattering of the hadronic fluctuations on nucleons of the nuclear target.

For light \( \rho \) and \( \phi \) mesons, the shape of the distribution \( P(\sigma) \) is modeled to be similar to that of the pion and is constrained using the available fixed-target and HERA data on elastic and diffractive-dissociation photoproduction on the proton. In particular, its energy dependence is
inspired by the Donnachie-Landshoff (DL) Regge-exchange model [9], where the free coefficients are fitted to the data leading to modifications of the vector meson dominance model (mVMD).

In the charmonium case, where the $J/\psi$-nucleon cross section is smaller resulting in a smaller nuclear suppression, it is possible to express $\sigma_{\gamma A\rightarrow J/\psi A}$ in terms of first two moments of $P(\sigma)$

$$\frac{d\sigma_{\gamma A\rightarrow J/\psi A}(W_{\gamma N},t)}{dt} = \frac{d\sigma_{\gamma N\rightarrow J/\psi N}(W_{\gamma N},t = 0)}{dt} \left(1 - \frac{\sigma_2}{\sigma_3} + \frac{\sigma_2}{\sigma_3} \langle \sigma^2 A \rangle \right)^2 |F_A(t)|^2$$

$$= \frac{d\sigma_{\gamma N\rightarrow J/\psi N}(W_{\gamma N},t = 0)}{dt} \left(\frac{g_A(x,\mu^2)}{A\bar{g}_p(x,\mu^2)}\right)^2 |F_A(t)|^2,$$ (3)

where $\sigma_2 = \langle \sigma^2 \rangle / \langle \sigma \rangle$ is determined by the ratio of diffractive and usual gluon distributions of the proton measured at HERA; $\sigma_3 = \langle \sigma^3 \rangle / \langle \sigma^2 \rangle$ is a model-dependent effective cross section controlling the shadowing correction due to interaction with $N \geq 3$ nucleons of the target nucleus; $\sigma_3^2 = 2\int d^2\vec{b}(1 - \exp[-\sigma_3 T_A(\vec{b})/2])$; $F_A(t)$ is the nuclear isoscalar form factor. In the second line, we expressed the nuclear suppression of the $\gamma A \rightarrow J/\psi A$ cross section in terms of the ratio of the nucleus and proton gluon densities at $x = M^2 / W^2_{\gamma p}$ and $\mu^2 \approx 3$ GeV$^2$. In our analysis, we used the EPS09 nuclear parton distribution functions [10].

Using the same framework, one can also calculate the cross section of incoherent vector meson photoproduction on nuclei. For instance, for light vector mesons, one obtains

$$\frac{d\sigma^{\text{mVMD-GGM}}_{\gamma A\rightarrow V A'}(W_{\gamma N},t)}{dt} = \frac{d\sigma_{\gamma N\rightarrow V N}(W_{\gamma N},t)}{dt} \int d^2\vec{b} T_A(b) \left|\int d\sigma P(\sigma) \frac{\sigma}{\langle \sigma \rangle} e^{-\frac{\sigma}{\langle \sigma \rangle} T_A(\vec{b})} \right|^2,$$ (4)

where $\sigma_{\text{in}}$ is the inelastic cross section. A similar expression in terms of $\sigma_2$ and $\sigma_3$ can be written in the $J/\psi$ case.

3. Predictions for $\phi$ and $J/\psi$ photoproduction in Xe-Xe UPCs at the LHC

Figures 1 and 2 show our predictions for the $t$ dependence of $\phi$ and $J/\psi$ photoproduction cross section in Xe-Xe UPCs at $\sqrt{s_{NN}} = 5.44$ TeV and $y = 0$ and $y = -4$, respectively.

Figure 1. The $t$ dependence of $\phi$ photoproduction in Xe-Xe UPCs at $y = 0$ and $\sqrt{s_{NN}} = 5.44$ TeV. 

Figure 2. The same for $J/\psi$ at $y = -4$. 

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In figure 1, the coherent cross section is shown by the red dashed line, the incoherent one – by the blue dotted line, and the summed cross section is given by the solid black curve. In figure 2, the solid red line gives the corresponding coherent cross section. In our analysis, we neglected the washing out of the diffractive dip in the coherent cross section due to a small, but non-vanishing transverse momentum of quasi-real photons and the real part of the vector meson-nucleon amplitude.

In the coherent case, the shape of the $t$ dependence and positions of diffractive dips are very sensitive to the isoscalar nucleus form factor (the effective radius of the target nucleus). However, diffractive peaks are noticeably shifted to lower values of $|t|$ by nuclear shadowing (compare figures 1 and 2). Hence, to minimize the effect of nuclear shadowing it is advantageous to study photoproduction of vector mesons, whose cross sections with nucleons are small; $\phi$ and $J/\psi$ present an example of such vector mesons.

As one can see from figure 1, the incoherent contribution for $t \neq 0$ dominates the photoproduction cross section and makes it difficult to discern the diffractive dips. To suppress it, one can study UPCs accompanied by additional electromagnetic excitation of colliding ions followed by forward neutron emission. In particular, selecting the $0n0n$ channel, where one requires no forward neutron emission, will effectively eliminate the incoherent contribution.

4. Conclusions
We presented predictions for photoproduction of light and heavy vector mesons in ultraperipheral Xe-Xe collisions at the LHC. We showed that the analysis of the data on this process will provide useful information on nuclear shadowing in photoproduction, in particular, on the nuclear mass number $A$ and vector meson type dependence. We argued that the momentum transfer distributions can be used to gain new information on the isoscalar nuclear form factor of Xenon, which is essential in searches for WIMPs with Xenon-based detectors.

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